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Evaluation of Dose Coefficients Implemented in MACCS

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ABSTRACT

A variety of dose conversion factor files (DCF files) have been supplied for use with the MACCS code since it was initially released. For MACCS 4.2, the MACCS DCF files have been updated to include coefficients used in the computation of acute skin doses from within the MACCS software to increase functionality and to add a pseudo-organ to represent the total effective dose equivalent (TEDE) (as defined in 10 CFR 20.1003) based on International Commission on Radiological Protection (ICRP) Publication 30. This report provides a description of how these changes have been implemented and a summary of the various DCF files supplied with MACCS 4.2. The report also provides supplemental discussions to assist the reader in understanding the technical basis for the MACCS DCFs. These supplemental discussions include a summary of basic dosimetry modeling concepts and a brief review of the Federal Guidance Reports (FGRs) upon which MACCS dose coefficients have historically been based.

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ACRONYMS AND TERMS

Acronym/Term	Definition
AI	alveolar-interstitial
CEDE	committed effective dose equivalent
DAC	derived air concentration
DCF	dose conversion factor
E	Effective dose (ICRP 60)
EDE	effective dose equivalent (ICRP 26)
EPA	U.S. Environmental Protection Agency
FGR	Federal Guidance Report
GI	gastrointestinal
H_E	Effective dose equivalent (ICRP 26)
HATM	Human Alimentary Tract Model
HRTM	Human Respiratory Tract Model
ICRP	International Commission on Radiological Protection
NRC	Nuclear Regulatory Commission
NRPB	National Radiological Protection Board
ORNL	Oak Ridge National Laboratory
RBE	Relative biological effectiveness
RSS	Reactor Safety Study
TED	Total effective dose
TEDE	Total effective dose equivalent (ICRP 26)
TGLD	Task Group on Lung Dynamics

1. DOSIMETRY MODELING CONCEPTS

For radiation protection, health effects are separated into two categories: stochastic and non-stochastic. Stochastic health effects include cancer and genetic disorders and are assumed to be initiated by random ionizing events. The risk due to these events is proportional to the dose to the relevant tissue, and the severity of the stochastic health effect is independent of the dose.

Non-stochastic health effects include acute radiation syndrome, temporary impairment to fertility, cataract formation, and erythema[1] of the skin. For these effects, there seems to be an effective threshold below which the clinically observable effects do not occur. The degree of damage associated usually depends on the magnitude of the dose incurred above the effective threshold [1].

The major use of the MACCS software is geared towards risk assessment, particularly Level 3 probabilistic risk assessments like those for nuclear reactor analysis, which focusses on evaluating the health and economic consequences of a radiological dispersal event. This use of the program still considers the health effects one would consider in radiation protection, but the limits incorporated are derived from the radiation protection programs developed by the Nuclear Regulatory Commission (NRC) (i.e., the nuclear reactor power plant licensing agent for the United States).

1.1. Biokinetics and Dosimetry Models

The models used for calculating dose to the body have been built and refined through an iterative process through the years. Work on the models has been done by individual labs and countries, and then this work was pulled together and discussed by task groups formed by the ICRP to decide on a "best practice" method suggested for use worldwide. The models that drive the U.S. regulatory accepted standard for radiation protection build on the work published by the ICRP. The basis for all other respiratory internal dosimetry is from the 1966 ICRP publication by the Task Group on Lung Dynamics [2].

1.1.1. Reference Man – ICRP 23

Referencing individual models is necessary for use in estimating radiation dose to the human body, especially for the more involved calculations such as maximum permissible annual intakes and estimation of dose due to a specific intake of materials entering the body. There were a few models that were used before the Reference Man model that was released by the ICRP in 1975, in ICRP 23 - *Report of the Task Group on Reference Man* [3]. The Reference Man model, created by the task group, was expected to be well defined for planning for low level exposures.

The Reference Man model was built upon a series of modifications to the Standard Man data set that was originally discussed at the Chalk River Conference on Permissible Dose in 1949. The Standard Man was originally created to provide a set of biological parameters which would be acceptable for calculating permissible levels for work with radioactive nuclides. The parameters decided upon were as follows [3]:

- Organ masses,
- Chemical composition of the body and various tissues within, and
- The Standard Man's patterns of intake and excretion and the duration of operational exposure, which were decided to be based on averages of normal activity in the temperate

[1]" Erythema: Redness of the skin, caused by hyperemia of the capillaries in the lower layers of the skin." HPO: HP:0010783

zone. Data within this category contained the following: water balance, respiration, duration of occupation exposure, and the retention of particulate matter in the lungs.

Following the Chalk River Conference, the Standard Man values were again modified at several conferences on radiology and permissible dose. Changes made were meant to better reflect the reality of how different elements move through the GI tract, between the different sections of the body, and to correct the weights of the contents of different sections.

The Reference Man model contained some major upgrades compared to the past iterations of human models, including the following [3]:

- An expanded list of elements in the composition of the human body,
- updated data for elimination half-times and deposition parameters, and
- expanding the range of the population to which the model applies – adding consideration for differences in age, sex, and habits.

Elements of the Reference Man data set that should be remembered when considering its applications are as follows [3]:

- The data primarily represents what is believed to be a typical individual of European or American descent, but overall, the data comes from a wide variety of sources around the world, so should not be considered as representative for a particular population.
- Reference Man is between 23-30 years old, weighs 70 kg, 170 cm tall, and lives in a climate with an average temperature range of 10° to 20°C. He is Caucasian and Western European or North American in habitat and custom.

1.1.2. ICRP 26 Recommendations and Subsequent Model Edits

ICRP 26 [4], *Recommendations of the International Commission on Radiological Protection*, documents the basic recommendations of the group as it stood in 1977. These recommendations were related to how radiation protection methods should be implemented, as well as the bases behind their justification. This report deals with ionizing radiation only, and was built upon a system of dose limitation, wherein the main features are as follows:

- "no practice shall be adopted unless its introduction produces a positive net benefit;
- all exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account; and
- the dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commission."

To this end, basic concepts were defined for evaluating dose to the human body, as expressed in an immediate situation, and over time. As part of the dose evaluation system, the important organs that would be affected by radiation moving through each pathway were identified, and mathematical equations created to represent the movement of radioactive material through the body. Relative effects of each radioisotope were considered and documented, based on present research and data, and a system of protection was derived.

A key aspect of radiation protection systems are that they take into account several key groups of people. At a major level, radiation workers and the general public are considered under different recommended dose limits, as the understood consent to radiation is different. Within these two

categories, different sexes and age groups are considered as well as some differences in the location a population is in, and their common cultural practices.

ICRP 26 is of great importance, as it defined the basis of the radiation protection model that includes the human models used to define and calculate dose for a number of years, including the basis of US regulated/mandated radiation protection standards as defined in FGRs 11, 12, and 13. These recommendations would not be phased out by the ICRP until the release of ICRP Publication 60, released in 1991.

ICRP 30, *Limits for Intakes of Radionuclides by Workers*, developed a dosimetric model for the inhalation of radioactive aerosols, which included consideration for special cases of gas and free ion deposition, as well as some special cases for which metabolic data is applied.

Radioactive aerosols, when inhaled, irradiate the respiratory system, as well as other organs and tissues of the body, by radiation originating from the lungs and from the translocation of inhaled material to other areas of the body by the respiratory system. The size distribution of the inhaled material affects the dose received by various regions of the respiratory system.

There are several assumptions that the ICRP 30 model makes. These include the following [5]:

- Dose to the nasopharyngeal region has been neglected since for most particle sizes it is usually small in comparison with the doses received by other regions.
- Irradiation of the lung is likely to be more limiting than that of lymphoid tissue – it has been considered satisfactory to consider the tracheobronchial region, pulmonary region, and pulmonary lymph nodes as one composite organ to which the lung weight factor applies.

ICRP Publications in this era that contain dose coefficients used to ascertain dose to humans based on models following the basis described in ICRP Publication 26 include the following:

- ICRP Publication 30: *Limits for Intakes of Radionuclides by Workers*
- ICRP Publication 56: *Age-dependent Doses to Members of the Public from Intake of Radionuclides*

1.1.2.1. Dosimetric Quantities per ICRP26

ICRP 26 introduced the EDE term on which the dose limitation system was designed. This allowed for a limit for stochastic dose to be considered, independent of whether the radiation incurred was uniform or non-uniform [4].

The standard dose equation defined in ICRP 26 is as follows:

$$H = DQN \qquad \text{(Eq. 1-1)}$$

Where:

- H = dose equivalent
- D = absorbed dose
- Q = quality factor
- N = the product of all other modifying factors

The absorbed dose is the amount of energy deposited by radiation in an amount of mass. [6] The dose equivalent is the absorbed dose weighted by the above modifying factors.

The quality factor is a value that amends the dose calculation to reflect the type of radiation output and thus its relative strength. The $\bar{Q}$ is the effective quality factor and is commonly used in radiation protection calculations. Table 1-1 below shows the quality factors as defined by ICRP 26 [4].

Table 1-1. The effective quality factor, $\bar{Q}$, for various forms of radiation as defined by ICRP 26.

Type of Radiation	$\bar{Q}$
x-rays, γ rays, and electrons	1
Neutrons, protons, and singly charged particles of rest mass greater than one atomic mass unit of unknown energy	10
α-particles and multiply charged particles (and particles of unknown charge), of unknown energy	20

ICRP 26, and the statement from the 1978 Stockholm meeting of the ICRP, denoted the term "EDE" to be the weighted sum of doses to all irradiated organs and tissues. Notice that this term is effectively "double weighted", as it takes into concern both a quality factor and a tissue weighting factor that is normalized [4],[7]. The equation is as follows:

$$H_E = \sum_T w_T H_T \qquad \text{(Eq. 1-2)}$$

Where:

- H_E = effective dose equivalent (EDE or H_E)
- w_T = tissue weighting factor, which is normalized so that $\sum_T w_T = 1$
- H_T = mean dose equivalent to organ or tissue T

The weighting factors used for Equation 1-2 are tabulated in Table 1-3. The tissue weighting factors here are defined based on the proportional stochastic risk to the organ or tissue based on an assumed whole body uniform irradiation event.[4]

Table 1-2. The tissue weighting factors for ICRP 26 model dosimetry equations.

Organ/Tissue	w_T
Gonads	0.25
Breast	0.15
Red Marrow	0.12
Lungs	0.12
Thyroid	0.03
Bone Surface	0.03
Remainder[2]	0.30

Table 1-3. Primary guide for annual assessed dose based on the ICRP 26 dosimetry model.

Affected Region	Dose Guidance
For stochastic effects	$H_E \leq 5$ rem (50 mSv)
For the lens of the eye	$H_T \leq 15$ rem (150 mSv)
For all other organs	$H_T \leq 50$ rem (500 mSv)

For worker dose intake, another important number to consider is the sum of all doses projected to be received in the future from an intake within the current year. This sum is generally considered over the 50-year period following intake and is known as the committed dose. The 50-year period assumes the arbitrary remaining lifespan of the worker [1]. The committed dose equivalent, $H_{E,50}$, is defined by the following equation:

$$H_{E,50} = \sum_T w_T H_{T,50} \qquad \text{(Eq. 1-3)}$$

Where:

- $H_{E,50}$ = committed effective dose equivalent (CEDE) for the 50-year period
- $H_{T,50}$ = mean dose equivalent to organ or tissue T over the 50-year period following intake of the radionuclide

Table 1-4. Primary guides for control of dose received in the workplace in a given year.

Effect Type	Dose Guidance
For stochastic effects	$H_{E,50} + H_{E,ext} \leq 5$ rem
For non-stochastic effects	$H_{T,50} + H_{T,ext} \leq 50$ rem

[2] The value $w_T = 0.6$ is applicable for each of the five remaining organs or tissues (such as liver, kidneys, spleen, brain, small intestine, upper large intestine, lower large intestine, etc., but excluding the skin, lens of the eye, or the extremities) receiving the highest doses.

Where:

- $H_{E,ext}$ = EDE from any external exposure in that year
- $H_{T,ext}$ = dose equivalent to any organ or tissue T from any external exposure in that year

1.1.3. The ICRP 60 Era and Updates to the Respiratory Tract Model

ICRP 60 [8], the *1990 Recommendations of the International Commission on Radiological Protection,* published in 1991, contains the 1990 current state recommendations of the group. This document updated the model set out ICRP Publication 26 and its supplementary statements, as it was found that there were enough developments to necessitate the release of a new set of recommendations. Supplements to Publication 26 were released in 1978, 1980, 1983, 1984, 1985, and 1987.

Here, updates to the existing knowledge on the biological effects of radiation necessitated a change to the way dose is calculated.

ICRP 66, the *Human Respiratory Tract Model for Radiological Protection*, [9] published in 1994, updated the respiratory model initially laid out in ICRP 30 in a variety of ways. One of the major updates was changing from the clearance classification system of D, W, and Y to F, M, and S. This change was due to the criticism that many of the compounds tested were found to clear from the respiratory tract at rates substantially different than the assigned rates. In addition, mixtures of radioactive compounds were not addressed in previous models, and the particle size range has since been expanded. The regions of the respiratory tract were also more subdivided in this model as compared to the previous iteration. The updates allowed for this newer model to be applicable to a wider section of the world's population, better address dose from a single event, and consider the impact of smoking, air pollutants, and diseases on the inhalation, deposition, and clearance of radioactive particles from the respiratory tract.

ICRP 60 started an era of new recommendations, and publications that updated the dose coefficients in use included:

- ICRP Publication 66: *Human Respiratory Tract Model for Radiological Protection*
- ICRP Publication 68: *Dose Coefficients for Intakes of Radionuclides by Workers*
- ICRP Publication 72: *Age-dependent Doses to Members of the Public from Intake of Radionuclides – Part 5 Compilation of Ingestion and Inhalation Coefficients*
- ICRP Publication 88: *Doses to the Embryo and Fetus from Intakes of Radionuclides by the Mother*
- ICRP Publication 95: *Doses to Infants from Ingestion of Radionuclides in Mothers' Milk*

1.1.3.1. Dosimetric Quantities per ICRP 60

ICRP 60 renamed EDE to equivalent dose E and the equation was updated as follows [5]:

$$H_T = \sum_R w_R \cdot D_{T,R} \qquad \text{(Eq. 1-4)}$$

Where:

- H_T = equivalent dose in tissue or organ T (Sv)

- w_R = radiation weighting factor, which is selected for the type and energy of the radiation incident on the body or emitted by the source
- $D_{T.R}$ = absorbed dose averaged over the organ or tissue T, due to radiation R

The radiation weight factors are tabulated in Table 1-6:

Table 1-5 Radiation weighting factors for radiation incident on the body or from internal sources within. Used with Equation (1-7).

Type and Energy Range	w_R
Photons, all energies	1
Electrons and muons, all energies[3]	1
Neutrons, energy < 10 keV	5
10 keV to 100 keV	10
> 100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
Protons, other than recoil protons, energy > 2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

The effective dose is then calculated as follows [5]:

$$E = \sum_T w_T \cdot H_T \qquad \text{(Eq. 1-5)}$$

Where:

- E = effective dose (Sv)
- w_T = tissue weighting factor for tissue T
- H_T = equivalent dose in organ or tissue T

1.1.3.2. Changes between ICRP 26 and ICRP 60 and Additions

The ICRP 26 dosimetric quantity EDE was replaced with the ICRP 60 dosimetric quantity E. The tissue weighting factors were also updated between the two publications. These are compared in Table 1-7 [4], [5].

[3] Excluding Auger electrons emitted from nuclei bound to DNA.

Table 1-6. Comparison of ICRP 26 and ICRP 60 included organs and w_T values.

ICRP-26		ICRP-60	
Organ or Tissue	**w_T**	**Organ or Tissue**	**w_T**
Gonads	0.25	Gonads	0.20
Red Marrow	0.12	Red Marrow	0.12
		Colon	0.12
Lung	0.12	Lung	0.12
		Stomach	0.12
		Bladder	0.05
Breast	0.15	Breast	0.05
		Liver	0.05
		Esophagus	0.05
Thyroid	0.03	Thyroid	0.05
		Skin	0.01
Bone Surfaces	0.03	Bone Surfaces	0.01
Remainder[4]	0.30	Remainder[5,6]	0.05

The introduction of this new term leaves questions in how the old EDE fits into the dose calculation and worker and public protection scheme. Eckerman and Leggett described it as "the effective dose equivalent, H_E, may be interpreted as a special case of the effective dose, E [10]". This would be because the tissue weighting factors used for the two values are not equivalent. The tissue weighting factors used for the ICRP 26 term EDE are normalized to sum to 1.0, which then gives the fractional contribution of that tissue to the total risk of stochastic health effects when the body is uniformly irradiated. The tissue weighting factor used for the ICRP 60 term E is not as specialized [10].

1.1.4. ICRP 100 Updates to the Alimentary Tract Model

ICRP 100, the *Human Alimentary Tract Model for Radiological Protection*, published in 2006, updated the human alimentary model from the model discussed in ICRP 30. ICRP 30 was based on the GI model originally developed by Dolphin and Eve in two papers published in the Health Physics Journal in 1966. [11], [12] Major changes include the following [13]:

[4] This value is applied to the average of the five remaining tissues that receive the highest dose, excluding the skin, lens of the eye, and extremities.
[5] The remainder for the ICRP 60 model consists of: adrenals, brain, extrathroacic airways, small intestine, kidneys, muscle, pancreas, spleen, thymus, and uterus.
[6] This value applies to the mass-weighted average dose to the Remainder tissue group, except when the "splitting rule" applies. The splitting rule is as follows; 'if a tissue of Remainder receives a dose in excess to that received by any of the 12 tissues for which weighting factors are specified, as weighting factor of 0.025 is applied to that tissue and 0.025 to the mass-averaged committed equivalent dose in the rest of the Remainder tissues.

- Inclusion of more organs to the alimentary tract – the point of entry of a radionuclide to the alimentary tract is now the oral cavity and esophagus per ICRP 100 rather than the stomach per ICRP 30.
- The HATM model now divides the large intestine into three regions rather than two.
- ICRP 30 only accounted for radionuclide decays during transit through the lumen of the stomach and intestines. HATM accounts for nuclear transformation in a larger variety of locations.
- ICRP 30 only considered absorption through the small intestine. HATM accounts for absorption from the oral mucosa, stomach, and segments of the colon as information is available.
- HATM provides age and gender-specific transit times for all segments of the tract and also material-specific transit times for upper segments of the alimentary tract rather than values independent of age, gender, and type of material.

Following the publication of this model and the accompanying dose coefficients, additional updated dose coefficients were released in the following publications:

- ICRP Publication 119: *Compendium of Dose Coefficients based on ICRP Publication 60*
- ICRP Publication 130: *Occupation Intakes of Radionuclides: Part 1*

1.1.5. Recap of ICRP Publications

As the basis of knowledge for radiation protection evolved, the ICRP published updated recommendations to recap the standard of practice at a point in time for the field. Following publications in the era updated methods, theory, and practices based on knowledge gained through research and post-event analysis that at times rendered past publications obsolete or presented major updates to the methods or data used within the methods defined. The dates of publication of these publications are important to consider. From a retrospective analysis, other papers published in the field may contain work that is in line with parts of a method but not all of it as they did not have certain updates as are known to exist now. A selection of ICRP publications that it may be useful to keep the publication dates of in mind for the purpose of this paper are listed in Table 1-1.

Table 1-7. Selection of ICRP Publications for this report

Internal Dosimetry – Human Model	Calculation of Dosimetric Quantities	Clearance Classes
Standard Man (1949)	ICRP 26 (1977)	TGLD (1966)
ICRP 23 (1975) – Reference Man	ICRP 60 (1991)	ICRP 30 (1979)
ICRP 30 (1979)		ICRP 66 (1994)
ICRP 66 (1994)		ICRP 72 (1995)
ICRP 100 (2006)		
f1 Values – The Worker	**f1 values – the Public**	**Radionuclide Data**
ICRP 30 (1979)	ICRP 56 (1990)	ICRP 38 (1983)
	ICRP 67 (1993)	ICRP 107 (2008)
	ICRP 69 (1995)	
	ICRP 71 (1995)	

1.2. Exposure Pathways

In radiation protection there are a variety of ways by which the body can be exposed to radiation. Each of these is called a pathway, and there are dosimetry models—sets of equations and associated data—used to calculate the dose to the body from each. There are external and internal methods by which one could be exposed to radiation. External pathways include groundshine and cloudshine. Internal exposure pathways include inhalation and ingestion, wherein radioactive particles are inhaled or ingested by a person and move internally and deposit dose to different organs from within the body.

Examples of external exposure pathways include groundshine, cloudshine, and the skin deposition pathway. Groundshine is an external pathway that reflects the dose from ground contamination. Cloudshine is an external pathway that reflects the dose from the plume of radioactive aerosols [14]. The skin deposition pathway reflects the dose received due to material deposited on the skin that stays there for a specified amount of time [15].

Internal exposure pathways force higher consideration of variables beyond what the source and strength of the radiation may be. For internal exposure, biokinetics and chemical form of the radioactive material are just two of the many variables that must be considered to ensure accurate estimation of dose to the person examined.

1.2.1. Clearance Classes and f_1 Values

Clearance classes and $\boldsymbol{f_1}$ values are important considerations for the internal pathways as these are biokinetic-related variables that reflect the rate at which the material moves through different compartments within the body. These values are defined by the chemical compound and material form of the radionuclide in question. Clearance classes define the rate at which material moves through the body. $\boldsymbol{f_1}$ values define the fraction of an inhaled or ingested radionuclide that goes directly to the bodily fluids, rather than moving through the inhalation or alimentary tracts.

When creating the MACCS DCF files, the chemical forms of the radionuclides chosen was an important decision to be made, as reflected in the *Reactor Safety Study* [16] and more recent follow-ups like *Reviewing MACCS Capabilities for Modeling Variable Physiochemical Forms* [17]. The exact dose coefficient values for each isotope chosen for the DCF files was based on an analysis of the material that would likely be released from the major types of reactors analyzed from potential accident situations. MACCS historically has been used for pressurized water reactor analysis, and the packaged released DCF files reflect this by their choice of chemical form.

1.2.1.1. Base Clearance Classes and Assignment

ICRP 30 [18], published in 1979, initially created the inhalation classes D, W, and Y – days, weeks, and years. Then, in 1994, ICRP 66 [9] defined the classes fast (F), moderate (M), and slow (S). These classes are about the same, but do not absolutely overlap. D, W, and Y define overall clearance, whereas F, M, and S apply only to absorption into blood.

ICRP 30 was based on the work done by the Task Group on Lung Dynamics (TGLD), published in 1966, which used retention time in the pulmonary region as the basis upon which to assign inhalation class. The pulmonary region is the main long-term retention site in the lungs in the TGLD model, equivalent to the alveolar-interstitial (AI) region of the ICRP 66 model. The criteria for class assignment according to the TGLD [18] were as follows:

- Class D: retention half time in the pulmonary region was less than 10 days.
- Class W: retention half time in the pulmonary region was between 10 to 100 days.
- Class Y: retention time in the pulmonary region was beyond 100 days.

The ICRP 66 model assigns the default class for all elements as Type M, with quantitative criteria to assign materials to Type F or S. Additionally, clearance in the ICRP 66 model is treated as the sum of particle transport to the gastrointestinal (GI) tract and absorption to body fluids from the AI region. Generally, the rate of particle transport to the GI tract from the AI region decreases with time, and so the AI region has three compartments. The criteria for assigning the classes F and S are as follows, when examining the absorption characteristic of the material within the AI region:

- Type F: the rate of absorption is 100 d^{-1}, which corresponds to a half time of about 10 min, so virtually all of the material is absorbed within a few hours.
- Type S: the rate of absorption of most of the material is 0.0001 d^{-1}, which corresponds to a half time of about 7,000 days, meaning that after 1 year only about 4% of the material has been absorbed [9].

Type M is the default type otherwise, but materials in this class show two distinct phases:

- 10% dissolves very rapidly, at about the same rate as Type F materials, and
- 90% (the rest) dissolves at a moderate rate of 0.005 d^{-1}, which corresponds to a half time of about 140 days, meaning that after 1 year about 85% has been absorbed [9].

When creating the new F, M, and S types, consideration was given to the existing criteria for D, W, and Y to ensure that the conversion to the new classes would go smoothly. Even so, it should be noted that lung retention in the Type M and S parameters is greater than that in Classes W and Y, respectively [9].

ICRP 72 [19], published in 1995, defined an official fourth class, Type V, as a new option should an alternative to the defaults be recommended. The publication lists the types of materials according to their rates of absorption from the respiratory tract to body fluids and their definitions as follows:

- Type F – fast absorption: deposited materials that are readily absorbed into body fluids from the respiratory tract,
- Type M – moderate absorption: deposited materials that have intermediate rates of absorption into body fluids from the respiratory tract,
- Type S – slow absorption: deposited materials that are relatively insoluble in the respiratory tract, and
- Type V – very fast absorption: deposited materials that, for dosimetric purposes, are assumed to be instantaneously absorbed into body fluids from the respiratory tract – for this iteration of the model, only certain gases and vapors [19].

1.2.1.2. Clearance Types for Gases and Vapors

ICRP 30 detailed the biokinetic vapor for certain gases and vapors but did not formally categorize them. ICRP 66 assigned gases and vapors to three classes, based on the initial pattern of respiratory tract deposition [9]:

- Class SR-0 – insoluble and non-reactive: negligible disposition in the respiratory tract
- Class SR-1 – soluble or reactive: deposition may occur throughout the respiratory tract. Exposure to these elements is dominated by activity absorbed into body fluids. Here, regional deposition is of secondary importance, as is the rate of absorption to body fluids, unless this is low compared to the rate of nuclear transformation.
- Class SR-2 – highly soluble or reactive: total deposition in the extrathoracic airways (ET2). The models for these compounds assume that all of the inhaled material is completely and instantaneously translocated to "body fluids" or to the "transfer compartment" without changing its chemical form (Type V).

Following deposition, subsequent retention in the respiratory tract and absorption to bodily fluids is determined by the chemical properties of the specific gas or vapor.

For elements where the inhalation of radionuclides in their gas or vapor form is particularly important, the default is recommended to use the SR class and corresponding absorption type (V or F) to be used for gases and vapors when no further information is given [9].

1.2.1.3. f_1 Values

The f_1 value is the fraction of an ingested or inhaled element that is absorbed directly into body fluids. Generally, a single f_1 value is used for all chemical forms of the same element, but in some cases, there is enough evidence to support the use of different f_1 values for compounds of an element that have different solubilities and intestinal absorption.

The f_1 values recommended in ICRP 30 apply to worker protection whereas those in ICRP Publications 56 (published in 1990), 67 (published in 1993), 69 (published in 1995), and 71 (published in 1995) were created for members of the public. In some case, f_1 values for adult members of the public differ from that for workers as they account for the absorption of environmental forms of radionuclides incorporated into food and are usually greater than that of the chemical forms encountered in the workplace.

The f_1 values assigned in ICRP 71 considered that for environmental exposures, the radionuclides might typically be present as minor constituents of the inhaled particles, and that absorption would therefore depend on the dissolution of the particle matrix as well as the chemical nature of the element. The assignment rules are as follows [20]:

- the f_1 values used for Type F materials were those applied to direct ingestion.
- For Types M and S, the default values of 0.1 and 0.01, respectively, were applied, unless the f_1 values for direct ingestion was lower than these or a lower value had been specified previously.

1.2.2. Discussion on the Relationship between the Inhalation and Ingestion Pathways

ICRP 100, published in 2006, discuses a new human alimentary tract model (HATM) to go with the updated human respiratory tract model (HRTM) presented in ICRP 66, both of which replace the iterations in ICRP 30. The improvements included expansion of the model applicability to a wider range of age groups, the inclusion of more organs, and a greater understanding of biokinetics within the body [13].

ICRP 30 had assumed that absorption into blood takes place solely in the small intestine, which has been amended in the new model, but the concept about how the intake eventually gets to the blood is an important concept to discuss. The f_1 value describes the absorption of radionuclides to the blood, and these terms are listed for both the ingestion and inhalation tracts. Figure 1-1 shows how both pathways navigate to the blood. The f_1 values that were supplied for ICRP 30 were applied across chemical forms per nuclide for both the ingestion and inhalation pathways [13].

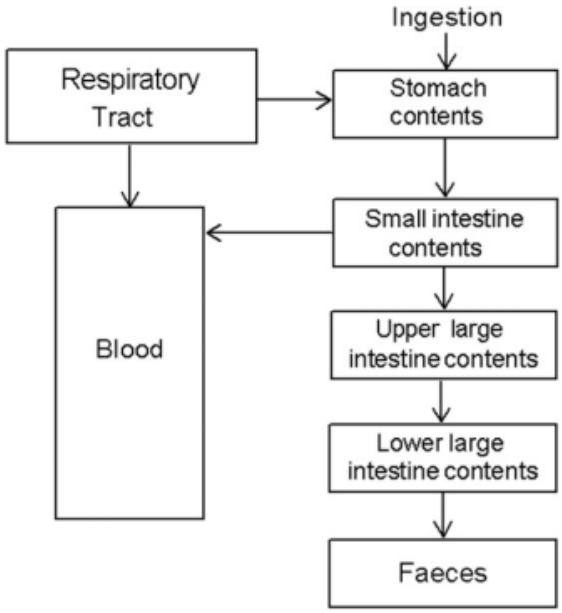

Figure 1-1. Structure of Model of Gastrointestinal Transfer from ICRP 30.

Looking at this explanation of the models and how they are connected as systems within the human body, it could make sense to then cross-apply the same f_1 value when doing a simulation in which the same chemical form per nuclide is chosen to be within the source term generated. That is, following the ICRP 30 model, it would make sense to choose the same $\boldsymbol{f_1}$ value across both the alimentary and inhalation tracts as they may cross between the two tracts.

Examining the history of the $\boldsymbol{f_1}$ values in ICRP, the 26/30 model used common values for both pathways. ICRP 60+ started implementing more choices, but the best practices for choosing the $\boldsymbol{f_1}$ values was not explored in the same document – rather this was an ICRP 71 decision.

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2. FEDERAL GUIDANCE REPORTS FOR DOSIMETRY

Federal Guidance Reports (FGRs) are documents issued by the U.S. Environmental Protection Agency (EPA) to aid federal and state agencies in developing radiation protection regulations and standards. These include two types – technical reports and policy recommendations. Technical reports provide scientific and technical information to aid in conducting radiation dose and risk assessments. State and federal agencies use these to develop and implement radiation protection regulations and standards, and regulated entities can use these reports to demonstrate compliance. Policy recommendations are guidelines for radiation protection of both workers and the public that are signed by the President and issued by the EPA [21] . Technical reports FGR-11 [22], FGR-12 [23], and FGR-13 [24] played major roles in influencing how the dose coefficient set was decided for implementation in the MACCS program.

2.1.1. FGR 11 – Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion (1988)

FGR 11 [22] provides limiting values for radionuclide intakes and derived air concentrations (DACs) for control of occupational exposure that are consistent with the 1987 policy recommendation *Radiation Protection Guidance to Federal Agencies for Occupational Exposure*. The derived guides assist with setting bounds on the limits for ingestion and inhalation of, and submersion in, radioactive materials in the workplace. Tables of exposure-to-dose conversion factors are also included for use in assessing average individual committed doses to populations adequately characterized by the Reference Man created in ICRP 23 [3].

The data compiled in FGR 11 comes from a variety of sources. Annual limit on intake and DAC values primarily came from ICRP 30, except for plutonium and related elements, who's values came from ICRP 48, and a few other radionuclides whose data came from ICRP 38. More specifically, the annual limit on intake and DAC values of the isotopes of Np, Pu, Am, Cm, Bk, Cf, Es, Fm, and Md are not identical to those in ICRP 30 and rather, were computed with updated metabolic information. Additionally, Sr-82, Tc-95, Tc-95m, Sb-116, Pu-246, and Cm-250 were not accounted for in ICRP 30 but have been included in FGR 11 [1].

The values listed in FGR 11 are calculated for the Reference Man. The application of the ALIs and DACs and the exposure-to-dose conversion factors for inhalation and ingestion (Tables 1 and 2 in FGR 11) to situations other than normal occupational exposure require careful consideration. The derived values also only reflect radiation dose and dose effects. Chemical toxicity is not considered, but it should be noted that in practice some materials have chemical toxicity risks greater than radiation risks [1].

The ICRP publications referenced in the creation of FGR 11 include the following:

- ICRP Publication 2 (1959): *Permissible Dose for Internal Radiation*
- ICRP Publication 6 (1964): *Recommendations of the International Commission on Radiological Protection*
- ICRP Publication 19 (1972): *The Metabolism of Compounds of Plutonium and Other Actinides*
- ICRP Publication 20 (1973): *Alkaline Earth Metabolism in Adult Man*
- ICRP Publication 21 (1973): *Data for Protection Against ionizing Radiation from External Sources*

- ICRP Publication 23 (1975): *Report of the Task Group on Reference Man*
- ICRP Publication 26 (1977): *Recommendations of the International Commission on Radiological Protection*
- ICRP Publication 30, Parts 1-3 and Supplements (1979-1982): *Limits for Intake by Workers*
- ICRP Publication 32 (1981): *Limits for Inhalation Daughters by Workers*
- ICRP Publication 38 (1983): *Radionuclide Transformations: Energy and Intensity of Emissions*
- ICRP Publication 39 (1984): *Statement from the 1983 Washington Meeting of the ICRP*
- ICRP Publication 48 (1986): *The Metabolism of Plutonium and Related Elements*

Table 1 in FGR 11 does not contain information that is particularly important to the DCF files in MACCS, as ALI and DAC information is not considered by the code. Table 3 in FGR 11 contains the GI absorption fractions and lung clearance classes for chemical compounds. Table 2 in FGR 11 contains the relevant exposure to dose conversion factors used in MACCS. The pathways detailed include inhalation, ingestion, and submersion. Examples of the first few entries from FGR 11 Table 2 are as follows:

Table 2-1. Exposure to Dose Conversion Factors for Inhalation Excerpt (FGR 11, Table 2.1).

	Committed Dose Equivalent per Unit Intake (Sv/Bq)								
Nuclide	**Class/f_1**	**Gonad**	**Breast**	**Lung**	**R Marrow**	**B Surface**	**Thyroid**	**Remainder**	**Effective**
Hydrogen									
H-3	V[7] 1.0	$1.73\ 10^{-11}$	$1.73\ 10^{-11}$	$1.73\ 10^{-11}$	$1.73\ 10^{-11}$	$1.73\ 10^{-11}$	$1.73\ 10^{-11}$	$1.73\ 10^{-11}$	$1.73\ 10^{-11}$
Beryllium									
Be-7	W $5\ 10^{-3}$	$3.72\ 10^{-11}$	$3.12\ 10^{-11}$	$2.15\ 10^{-10}$	$4.58\ 10^{-11}$	$4.09\ 10^{-11}$	$2.60\ 10^{-11}$	$5.46\ 10^{-11}$	$6.37\ 10^{-11}$
	Y $5\ 10^{-3}$	$3.17\ 10^{-11}$	$3.82\ 10^{-11}$	$3.73\ 10^{-10}$	$3.99\ 10^{-11}$	$2.98\ 10^{-11}$	$3.10\ 10^{-11}$	$7.23\ 10^{-11}$	$8.67\ 10^{-11}$

Table 2-2. Exposure to Dose Conversion Factors for Ingestion Excerpt (FGR 11, Table 2.2)

	Committed Dose Equivalent per Unit Intake (Sv/Bq)								
Nuclide	**f_1**	**Gonad**	**Breast**	**Lung**	**R Marrow**	**B Surface**	**Thyroid**	**Remainder**	**Effective**
Hydrogen									
H-3	1.0	$1.73\ 10^{-11}$	$1.73\ 10^{-11}$	$1.73\ 10^{-11}$	$1.73\ 10^{-11}$	$1.73\ 10^{-11}$	$1.73\ 10^{-11}$	$1.73\ 10^{-11}$	$1.73\ 10^{-11}$
Beryllium									
Be-7	$5\ 10^{-3}$	$5.67\ 10^{-11}$	$6.97\ 10^{-12}$	$1.41\ 10^{-12}$	$1.23\ 10^{-11}$	$5.03\ 10^{-12}$	$6.08\ 10^{-13}$	$5.83\ 10^{-11}$	$3.45\ 10^{-11}$

Table 2-3. Exposure to Dose Conversion Factors for Submersion Excerpt (FGR 11, Table 2.3)

	Committed Dose Equivalent per Unit Intake (Sv/hr per Bq/m^3)							
Nuclide	**Gonad**	**Breast**	**Lung**	**R Marrow**	**B Surface**	**Thyroid**	**Remainder**	**Effective**
Hydrogen								
H-3			$9.90\ 10^{-15}$					$1.19\ 10^{-15}$
Argon								
Ar-37			$3.80\ 10^{-15}$					$4.56\ 10^{-16}$

[7] V = water vapor

2.1.2. FGR 12 – External Exposure to Radionuclides in Air, Water, and Soil (1993)

FGR 12 provides external dose coefficients that are intended to be used by federal agencies who have regulatory responsibilities for protection of members of the public and/or workers [23]. This report was written as a companion to FGR 11. The pathways of exposure considered in this report are the following:

- Submersion in a contaminated atmospheric cloud assuming a semi-infinite source region (i.e., air submersion),
- immersion in contaminated water assuming an infinite source region (i.e., water immersion), and
- exposure to contamination on or in the ground assuming an infinite source region (i.e., ground exposure).

The weighting factors recommended for use by the EPA in this report are consistent with those recommended by ICRP 26. FGR 12 contains both ICRP 26 weighting factors and EDE data. The decision to move to the next dosimetric model iteration, which would include ICRP 60 weighting factors, the HRTM model, and E data, had not been made at the time of this publication.

The ICRP publications referenced in the creation of FGR 12 include the following:

- ICRP Publication 2 (1959): *Report of Committee II on Permissible Dose for Internal Radiation*
- ICRP Publication 23 (1975): *Report of the Task Group on Reference Man*
- ICRP Publication 26 (1977): *Recommendations of the International Commission on Radiological Protection*
- ICRP Publication 30 (1979): *Limits for Intakes of Radionuclides by Workers*
- ICRP Publication 38 (1983): *Radionuclide Transformations: Energy and Intensity of Emissions*
- ICRP Publication 51 (1987): *Data for Use in Protection Against External Radiation*
- ICRP Publication 56 (1990): *Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 1*
- ICRP Publication 60 (1991): *1990 Recommendations of the International Commission on Radiological Protection*

The tables in FGR 12 include the following [25]:

- Dose Coefficients for Air Submersion, updating those given in FGR 11
- Dose Coefficients for Water Immersion
- Dose Coefficients for Exposure to Contaminated Ground Surface
- Dose Coefficients for Exposure to Soil Contaminated at a Depth of 1 cm
- Dose Coefficients for Exposure to Soil Contaminated to a Depth of 5 cm
- Dose Coefficients for Exposure to Soil Contaminated to a Depth of 15 cm
- Dose Coefficients for Exposure to Soil Contaminated to an Infinite Depth.

2.1.3. FGR 13 – Cancer Risk Coefficients for Environmental Exposure to Radionuclides (1999)

FGR 13 [24] provides methods and data for estimating risk due to internal and external radionuclide exposures. Included are coefficients for assessing cancer risks from environmental exposure to around 800 isotopes. Mortality and incidence risk coefficient tables for inhalation, food and water ingestion, submersion in air, and exposure to uniform soil concentration are included. The age-averaged coefficients take into consideration age-specific intake rates, dose modeling, and risk modeling. The data presented is for use in assessing risk from radionuclide exposures.

The risk coefficients presented in FGR 13 were calculated using the DCAL (Dose and Risk Calculation software, developed by Oak Ridge National Laboratory (ORNL) for the EPA. DCAL is meant to be a comprehensive system for calculating dose and risk coefficients using age-dependent models. The set of risk coefficients printed in FGR 13 are meant to apply to an average member of the public, as it is averaged over the age and gender distribution of a hypothetical "stationary" U.S. population. Here, stationary refers to the assumption that the gender-specific birth rates and survival functions remain stable over time [24].

For each radionuclide and exposure mode, a mortality risk coefficient and morbidity risk coefficient are given. The mortality risk coefficient is defined as the estimate of risk to the average member of the U.S. population of dying from cancer as a result of intake of the radionuclide or external exposure to radiation emitted from it. This term is given in units of per unit activity inhaled or ingested for internal exposure or per unit time-integrated activity concentration in air or soil for external exposure. The morbidity risk coefficient is defined as the comparable estimate of the average total risk of experiencing a radiogenic cancer, whether the cancer is fatal or not.

It should be noted that some of the calculations for values in FGR 13 reference methods from the ICRP 60+ series of technical bases for calculating the health effects of radiation exposure.

The ICRP publications referenced in the creation of FGR 13 include the following:

- ICRP Publication 23 (1975): *Report of the Task Group on Reference Man*
- ICRP Publication 30, Parts 1-4 (1979-1988): *Limits for Intakes by Workers*
- ICRP Publication 38 (1983): *Radionuclide Transformation Energy and Intensity of Emissions*
- ICRP Publication 56 (1989): *Age-Dependent Doses to Members of the Public from Intake of Radionuclides, Part 1*
- ICRP Publication 60 (1991): *1990 Recommendations of the International Commission on Radiological Protection*
- ICRP Publication 59 (1992): *The Biological Basis for Dose Limitation in the Skin*
- ICRP Publication 67 (1993): *Age-Dependent Doses to Members of the Public from Intake of Radionuclides, Part 2*
- ICRP Publication 66 (1994): *Human Respiratory Tract Model for Radiological Protection*
- ICRP Publication 68 (1994): *Dose Coefficients for Intakes of Radionuclides by Workers*
- ICRP Publication 69 (1995): *Age-Dependent Doses to Members of the Public from Intake of Radionuclides, Part 3*

- ICRP Publication 71 (1995): *Age-Dependent Doses to Members of the Public from Intake of Radionuclides, Part 4*
- ICRP Publication 70 (1995): *Basic Anatomical and Physiological Data for Use in Radiological Protection: The Skeleton*
- ICRP Publication 72 (1996): *Age-Dependent Doses to Members of the Public from Intake of Radionuclides, Part 5*

The tables in FGR 13 include the following [24]:

- Mortality and morbidity risk coefficients for inhalation,
- mortality and morbidity risk coefficients for ingestion of tap water and food,
- mortality and morbidity risk coefficients for external exposure from environmental media, and
- uncertainty categories for selected risk coefficients.

2.1.4. Total Effective Dose Equivalent (TEDE) per NRC

As discussed in Compton et al. [26] the Total Effective Dose Equivalent (TEDE) as defined in 10 CFR 20.1003 as the sum of the EDE for external exposures and the CEDE for internal exposures. The NRC practice for computing the external exposure component of TEDE is to use the exposure-to-effective dose equivalent factors for external exposure of radioactive material from FGR-12. Table III.3 of FGR-12 contains the dose coefficients corresponding to a contaminated ground surface. The coefficients in the column headed "effective" yield doses corresponding to the EDE. For computing the internal exposure component of TEDE, the NRC practice is to apply the exposure-to-CEDE factors for inhalation of radioactive material found in Table 2.1 of FGR-11. The factors in the column headed "effective" yield doses corresponding to the CEDE. As noted in FGR 12, "In applying the dose coefficients of Tables III.1 through III.7 it is important to note that the values for each radionuclide do not include any contribution to dose from radioactive decay products formed in the spontaneous nuclear transformation of the nuclide. Rather, the tabulations contain separate entries for all such progeny." [23]

3. HISTORICAL CONTEXT FOR MACCS DOSIMETRY DECISIONS

Documentation for the past MACCS dosimetric decisions was reviewed to ensure that the DCFs selected for use in MACCS would align with the thought process that guided the past decisions as best as possible. A small review of the documentation available was written up. The information available for the health physics guidance for MACCS came from a variety of sources – the MACCS manual, theory book, and user guide, some specific documents detailing DCF decisions made, and documentation for DCF preprocessors.

3.1. Documentation for Decision Making

There are several papers that have been published alongside MACCS software releases that detail the decisions made for inclusion of certain isotopes in the MACCS DCF files. Of particular importance is a discussion that could be found on how the clearance classes and accompanying f_1 values were decided for each radionuclide, especially as these were chosen as one per nuclide to simplify the model as much as possible.

3.1.1. NUREG-CR-4185/SAND85-0283: An Assessment of Dosimetry Data for Accidental Radionuclide Releases from Nuclear Reactors

NUREG-CR-4185 [27] is thought to be the initial decision document regarding the implementation of dosimetry methods within the MACCS program. The general assumptions and initial choices for implementation are discussed, as well as the thought process behind each, which are reiterated in this section.

External dosimetry considerations included cloudshine, groundshine, and external beta exposure to the skin. All of these modeling approaches assume that a homogeneous distribution of the radioactive material within a large region of the medium are the source.

Cloudshine accounts for dose due to external gamma-ray and beta doses due to being immersed within or in close proximity to a radioactive plume. At the point of this publication, the Kocher modeling approach [28] was considered the most appropriate for use in MACCS.

Groundshine in MACCS is the product of external dose due to radionuclides deposited on the ground as ground contamination, a shielding factor, and a DCF assuming a smooth infinite planar source. Again, the Kocher [28] dose factor data are considered to be the most appropriate for use in MACCS.

External beta exposure due to immersion within the plume, exposure to deposits on the ground, and/or direct deposition of beta emitters to the skin, is accounted for in MACCS through the use of the Ostmeyer and Helton [29] method. The real-life effect of this exposure could be radiation burns and would largely affect the early health effects an individual may experience due to a reactor accident.

Internal dosimetry considerations included inhalation and ingestion.

Inhalation dose depends on a variety of factors. These include the following:

- Chemical form of the radionuclide,
- Properties of the aerosol containing the radionuclide,
- Particle size of the inhaled aerosol,

- Transport of the particles within the respiratory system, clearance to the GI tract, and absorption to the blood circulatory system,
- Distribution of the radionuclide among the organs and tissues,
- Retention of radionuclide among the organs and tissues,
- Radionuclide decay and the build-up of daughters within the body, and
- Excretion from the body.

ICRP 30 inhalation models were adopted for use in the MACCS program at the time of NUREG-CR-4185/SAND85-0283. Thus, the D, W, Y clearance classes were used in MACCS.

These clearance classes determine the rate at which radionuclides are cleared from the respiratory system and the extent of transfer to the systemic system. The most probable chemical forms of the inhaled radionuclides were used to assign clearance classes for MACCS from the consequences of reactor accidents. One clearance class was selected per radionuclide for simplicity's sake.

The *Reactor Safety Study* [16] (RSS) conducted by the NRC in 1975 investigated what chemical forms may be present in the incident of a nuclear reactor accident. The study also suggested clearance classes based on the information found. In the end, the ICRP-30 clearance classes were adopted for use in the MACCS program. The table below shows this information, as well as the United Kingdom National Radiological Protection Board's (NRPB) publication NRPB-R-53 clearance class definitions for comparison. NRPB-R-53 [30] was the UK's equivalent to the RSS.

Table 3-1. The first 24 elements chosen to be incorporated into MACCS and the clearance class associated as chosen by the RSS, NRPB-R-53, and ICRP-30. ICRP-30 clearance classes were implemented for MACCS.

Elements	RSS Chemical Classification	RSS Clearance Class	NRPB-R-53 Clearance Class	ICRP-30 Clearance Class
Americium (Am)	Oxide	Y	W	W – all compounds
Antimony (Sb)	Oxides	W	W	W – oxides, hydroxides, sulfides, sulfates, nitrates
Barium (Ba)	Oxides	D	D	D – all compounds
Cerium (Ce)	Oxide	Y	Y	Y – oxide, hydroxide, fluorides
Cesium (Cs)	Oxides, hydroxides	D	D	D – all compounds
Cobalt (Co)	Oxides, hydroxides	Y	-	Y – nitrates, halides, oxides, hydroxides
Curium (Cm)	Oxide	Y	W	W – all compounds
Iodine (I)	I_2, CH_3I, iodides, iodates	D	D	D – all compounds
Lanthanum (La)	Oxide	W	Y	W – oxides, hydroxide, chloride
Molybdenum (Mo)	Molybdates, (? oxides)	Y	Y	Y – oxides, hydroxides, molybdates
Neodymium (Nd)	Oxide	Y	Y	Y – oxide, hydroxide, carbides, fluorides
Neptunium (Np)	Oxide	Y	Y	W – all compounds
Niobium (Nb)	Oxide	Y	Y	Y – oxide, hydroxide
Plutonium (Pu)	Oxide	Y	Y	Y - oxides
Praseodymium (Pr)	Oxide	Y	Y	Y – oxide, hydroxide, carbides, fluorides
Promethium (Pm)	Oxide	Y	Y	Y – oxide, hydroxide, carbides, fluorides
Rubidium (Rb)	Oxides, hydroxides	D	D	D – all compounds
Ruthenium (Ru)	Oxides, hydroxides	Y	Y	Y – oxides, hydroxides
Sodium (Na)	---	-	-	D – all compounds
Strontium (Sr)	Oxides	D	D	D – chlorides, all others ($SrTiO_3$ = Y)
Technetium (Tc)	Oxide, pertechnetate	D	W	W – oxide, hydroxide, halides, nitrates (pertechnetate = D)
Tellurium (Te)	Oxides	W	W	W – oxides, hydroxides, nitrates
Yttrium (Y)	Oxide	W	Y	Y – oxide, hydroxide
Zirconium (Zr)	Oxide	Y	Y	W – oxide, hydroxide, halides, nitrates (Carbide = Y)

The two most important considerations for estimation of absorbed dose via ingestion are as follows:

1. The fraction of the ingested radionuclide that is absorbed from the gut, and
2. the irradiation of the gut itself.

Uncertainty in dose factors was identified as originating from two main sources:

- Uncertainty in defining the physical and chemical characteristics of the released radionuclides, and
- uncertainty in the dosimetry models.

The complexity of reactor accident situations and how the radionuclides irradiate the human body leads to the possibility of an overly complex model. To ensure model useability, certain choices were made to simplify the MACCS assumptions. These include the following [27]:

- Choosing a selection of radionuclides for consideration as most probable for release in the case of a nuclear reactor accident through the RSS.
- Selecting one inhalation clearance class per radionuclide considered – here, the ICRP 30 equivalent classes, as shown in the above table.
- Assuming that the activity median aerodynamic diameter is 1 micron.
- Choosing to use the adult model when running dose calculations – this affects body mass, metabolic parameters, ingestion rate, and breathing rate among others.

The list of radionuclides confirmed for the MACCS code as defined by NUREG/CR-4185 is detailed in Table 3-2. [27]

Table 3-2. List of Radionuclides included in MACCS per NUREG/CR-4185

Radionuclide	Half-Life (days)	Radionuclide	Half-Life (days)
Cobalt-58	71.0	Antimony-127	3.88
Cobalt-60	1,920	Antimony-129	0.179
Krypton-85	3,950	Iodine-131	8.05
Krypton-85m	0.183	Iodine-132	0.0958
Krypton-87	0.0528	Iodine-133	0.875
Krypton-88	0.117	Iodine-134	0.0366
Rubidium-86	18.7	Iodine-135	0.280
Strontium-89	52.1	Xenon-133	5.28
Strontium-90	11,030	Xenon-135	0.384
Strontium-91	0.403	Cesium-134	750

Radionuclide	Half-Life (days)	Radionuclide	Half-Life (days)
Yttrium-90	2.67	Cesium-136	13/0
Yttrium-91	59.0	Cesium-137	11,000
Zirconium-95	65.2	Barium-140	12.8
Zirconium-97	0.71	Lanthanum-140	1.67
Niobium-95	35.0	Cerium-141	32.3
Molybdenum-99	2.8	Cerium-143	1.38
Technetium-99m	0.25	Cerium-144	284
Ruthenium-103	39.5	Praseodymium-143	13.7
Ruthenium-105	0.185	Neodymium-147	11.1
Ruthenium-106	366	Neptunium-239	2.35
Rhodium-105	1.50	Plutonium-238	32,500
Tellurium-237	0.391	Plutonium-239	8.9E6
Tellerium-127m	109	Plutonium-240	2.4E6
Tellurium-129	0.048	Plutonium-241	5,350
Tellurium-129m	0.340	Americium-241	1.5E5
Tellurium-131m	1.25	Curium-242	163
Tellurium-132	3.25	Curium-244	6,630

3.1.2. NUREG/CR-4691/SAND86-1562: MELCOR Accident Consequence Code System (MACCS) User's Guide [31]

For this release of MACCS, a DCF file named DOSDATA was generated by an Oak Ridge National Laboratory-created preprocessor, and supplied to the user. This file contains data for 60 radionuclides, four of which are new, compared to the list provided in Table 3-2. These additional radionuclides are as follows:

- Y-92
- Y-93
- La-141
- La-142

3.1.3. NUREG/CR-6613/SAND97-0594: Code Manual for MACCS2 [32]

When MACCS2 was released, several updates were made to the enhance the useability of the code. DOSFAC and DOSFAC22 were made available to the user for the first time, to allow for the creation of user defined DCF files. Prior to the release of MACCS2, users could only use the provided DCF file that contained the 60 radionuclides considered important for nuclear power plant analysis. There are three preprocessors for DCFs that allowed the user to create their own DCF files for use in MACCS that were released with MACCS2 – DOSFAC2, FGRDCF, and IDCF2. These packages each had their own DCF databases and allowed user-defined input data. These preprocessors are described in a later section of this paper.

In total, seven DCF database files were included in the MACCS2 release:

- DOSDATA.INP - Created by DOSFAC2 and contains the 60 radionuclides considered important to commercial reactor accidents.
- DOSD825.INP - Created by FGRDCF and contains all of the radionuclides accessed by FGRDCF.
- DOSD60.INP - Created by FGRDCF and contains the 60 radionuclides contained in DOSDATA.INP.
- IDCF2_1.INP, IDCF2_2.INP, IDCF2_3.INP - Combined, these files contain all of the radionuclides that can be accessed by IDCF2.
- IDCF2_4.INP - Created by IDCF2 and contains the 60 radionuclides contained in DOSDATA.INP.

The documentation for DOSFAC2 listed the 60 radioisotopes used for offsite consequence assessment in MACCS. These nuclides are listed in Table 3-3 [33]. Information was not found that outrightly stated the chemical form assumed for each nuclide as that of most importance of origin in a reactor accident situation, and so a corresponding set of clearance classes and f_1 values was not tabulated.

Table 3-3. The 60 Radioisotopes used in MACCS per the DOSFAC2 User Guide [33].

Element	Nuclide
Americium (Am)	241
Antimony (Sb)	127, 129
Barium (Ba)	139.140
Cerium (Ce)	141, 143, 144
Cesium (Cs)	134, 136, 137
Cobalt (Co)	58, 60
Curium (Cm)	242, 244
Iodine (I)	131, 132, 133, 134, 135
Krypton (Kr)	85, 85m, 87, 88
Lanthanum (La)	140, 141, 142
Molybdenum (Mo)	99
Neodymium (Nd)	147
Neptunium (Np)	239
Niobium (Nb)	95
Plutonium (Pu)	238, 239, 240, 241
Praseodymium (Pr)	143
Rhodium (Rh)	105
Rubidium (Rb)	86
Ruthenium (Ru)	103, 105, 106
Strontium (Sr)	89,90,91,92
Technetium (Tc)	99m
Tellurium (Te)	127, 127m, 129, 129m, 131m, 132
Xenon (Xe)	133, 135
Yttrium (Y)	90, 91, 92, 93
Zirconium (Zr)	95, 97

3.1.4. FGR 13 Dose Conversion Factor Files [34]

In 2019, an updated document explaining some of the details of the DCF files for MACCS was released. The files FGR13DCF.inp and FGR13GyEquiv_RevA.inp were discussed, along with some of the changes made to ensure compliance with FGR 13. Significant differences between this document and the previous documents detailing MACCS dosimetry assumptions include the following [34]:

- Additional information on the use of the acute dose coefficient for inhalation,
- The addition of weighting factors used to account for cancer risk modeling,
- Adding FGR 13 compliant coefficients,
- Tissue-weighting based on the ICRP 60 modeling system,
- Updating the lung clearance class names, and
- pointing to the DCF file containing 825 nuclides as the best choice for use in future analysis.

The acute dose coefficients for inhalation were adopted as described in NUREG-CR-4691, Section 6.1, using relatively short commitment periods which span 1 to 365 days. The inhalation and ingestion dose coefficients were taken from FGR13 models, which were also influenced by ICRP Publication 72. There are a few minor differences between the two for certain compartments and radionuclides, but they are overall the same.

The lung clearance class names were changed from Years (Y), Weeks (W), and Days (D) to types Slow (S), Medium (M), and Fast (F), respectively.

The best choice for which MACCS DCF file to use is seemingly now the most complete one – that is, the one that contains all 825 nuclides. The complete list of elements included in MACCS DCF files for the software releases at this time are tabulated in Table 3-4. The elements that were available in the original DCF files released with earlier versions of MACCS are colored blue. Notice that the f_1 values are not consistent between the inhalation and ingestion pathways for all the radionuclides listed – these inconsistencies are marked with orange in Table 3-4. Reflecting what was presumably the best practice at the time this DCF file was released – the ICRP 60+ model, the f_1 values corresponding to the same chemical form would be different across the two pathways. In the FGR 11/12 or ICRP 26/30 method, the f_1 values would be consistent across the pathways as there wasn't updated knowledge at the time.

Lastly, the clearance classes were updated to the new names as part of this effort. There are a couple of elements that do not match the S/M/F type description – these are as follows:

- H: WV – here, WV refers to water vapor. In ICRP 119, tritiated water (HTO) is treated as a gaseous form with dose coefficients [5].
- Hg: V – here, V refers to vapor, the clearance type defined in ICRP 119 that denotes a very fast absorption rate [5].

Table 3-4. Table of elements in DCF file. The blue rows are elements that were present in previous versions of MACCS. In the heading row, INH and ING refer to inhalation and ingestion, respectively.

Elements	Clearance Type	f_1 value (INH)	Chemical Form	f_1 value (ING)
Ac	S	0.0005		0.0005
Ag	S	0.01		0.05
Al	F	0.01		0.01
Am	M	0.0005		0.0005
Ar	-	-	-	-
As	M	0.5		0.5
At	F	1		1
Au	S	0.1		0.1

Elements	Clearance Type	f_1 value (INH)	Chemical Form	f_1 value (ING)
Ba	F	0.2		0.2
Be	S	0.005		0.005
Bi	M	0.05		0.05
Bk	M	0.0005		0.0005
Br	F	1		1
C	F	1		1
Ca	M	0.1		0.3
Cd	S	0.05		0.05
Ce	S	0.0005		0.0005
Cf	S	0.0005		0.0005
Cl	F	1		1
Cm	M	0.0005		0.0005
Co	S	0.01		0.1
Cr	S	0.1		0.1
Cs	F	1		1
Cu	S	0.5		0.5
Dy	M	0.0005		0.0005
Er	M	0.0005		0.0005
Es	M	0.0005		0.0005
Eu	M	0.0005		0.0005
F	S	1		1
Fe	M	0.1		0.1
Fm	M	0.0005		0.0005
Fr	F	1		1
Ga	M	0.001		0.001
Gd	M	0.0005		0.0005
Ge	M	1		1
H	WV	1	Tritiated Water	1
Hf	F	0.002		0.002
Hg	V[8]	0.02	Inorganic	0.02
Ho	M	0.0005		0.0005
I	F	1		1
In	M	0.02		0.02
Ir	S	0.01		0.01
K	F	1		1
Kr	-	-	-	-
La	M	0.0005		0.0005
Lu	S	0.0005		0.0005
Md	M	0.0005		0.0005
Mg	M	0.5		0.5

[8] For absorption type V, f_1 values are not applicable since all activity deposited in the respiratory tract is instantaneously absorbed.

Elements	Clearance Type	f_1 value (INH)	Chemical Form	f_1 value (ING)
Mn	M	0.1		0.1
Mo	S	0.01		1
N	-	-	-	-
Na	F	1		1
Nb	S	0.01		0.01
Nd	S	0.0005		0.0005
Ne	-	-	-	-
Ni	M	0.05		0.05
Np	M	0.0005		0.0005
O	-	-	-	-
Os	S	0.01		0.01
P	F	0.8		0.8
Pa	S	0.0005		0.0005
Pb	F	0.2		0.2
Pd	S	0.005		0.005
Pm	S	0.0005		0.0005
Po	M	0.1	Soluble	0.5
Pr	S	0.0005		0.0005
Pt	F	0.01		0.01
Pu	S	1.00E-5		0.0005
Ra	M	0.1		0.2
Rb	F	1		1
Re	M	0.8		0.8
Rh	S	0.05		0.05
Rn	-	-	-	-
Ru	S	0.01		0.05
S	F	0.8		1
Sb	F	0.1		0.1
Sc	S	0.0001		0.0001
Se	M	0.1		0.8
Si	M	0.01		0.01
Sm	M	0.0005		0.0005
Sn	M	0.02		0.02
Sr	F	0.3		0.3
Ta	S	0.001		0.001
Tb	M	0.0005		0.0005
Tc	M	0.1		0.5
Te	M	0.1		0.3
Th	S	0.0005		0.0005
Ti	S	0.01		0.01
Tl	F	1		1

Elements	Clearance Type	f_1 value (INH)	Chemical Form	f_1 value (ING)
Tm	M	0.0005		0.0005
U	S	0.002		0.02
V	M	0.01		0.01
W	F	0.3		0.3
Xe	-	-	-	-
Y	S	0.0001		0.0001
Yb	S	0.0005		0.0005
Zn	S	0.01		0.5
Zr	M	0.002		0.01

Table 3-4 represents the full list of elements available in the MACCS DCF files since the MACCS2 rollout. The clearance classes and associated f_1 values tabulated are as shown in the FGR13DCF.inp file. The basis for choosing the clearance type and associated f_1 values for each new radionuclide is unknown, so the recommendations from the major ICRP dosimetry updates have been tabulated below for each. ICRP 68 [35], 71 [20], and 119 [5] recommendations were listed for the inhalation exposure route in Table 3-5. ICRP 68 and 119 recommendations for the ingestion exposure route are listed in Table 3-6.

Table 3-5. Clearance classes for the inhalation pathway for the elements with those associated values, as suggested by ICRP 68, ICRP 71, and ICRP 119. The data pulled from ICRP 71 is specifically for elements and forms that were classified as gases and vapors. The nuclides noted in Table 2 that do not have absorption types and f_1 values associated are not listed in this table.

Radionuclide	ICRP 68	ICRP 71 *Gases and Vapors*	ICRP 119 Type – f_1 – compounds
Actinium - Ac	F: Unspecified compounds M: halides and nitrates S: oxides and hydroxides		F 5.0E-04 Unspecified compounds M 5.0E-04 Halides and nitrates S 5.0E-04 Oxides and hydroxides
Silver - Ag	F: unspecified compounds and metallic silver M: nitrates and sulphides S: Oxides and hydroxides		F 0.05 Unspecified compounds and metallic silver M 0.05 Nitrates and sulphides S 0.05 Oxides, hydroxides, and carbides
Aluminum - Al	F: unspecified compounds M: oxides, hydroxides, carbides, halides, nitrates, and metallic aluminum		F 0.01 Unspecified compounds M 0.01 Oxides, hydroxides, carbides, halides, nitrates, and metallic aluminum
Arsenic - As	M: All compounds		M 0.5 All compounds
Astatine - At	F: Determined by combining cations M: Determined by combining cations		F 1.0 Determined by combining cations M 1.0 Determined by combining cations
Gold - Au	F: Unspecified compounds M: Halides and nitrates S: Oxides and hydroxides		F 0.1 Unspecified compounds M 0.1 Halides and nitrates S 0.1 Oxides and hydroxides
Beryllium - Be	M: unspecified compounds S: oxides, halides, and nitrates		M 0.005 Unspecified compounds S 0.005 Oxides, halides, and nitrates
Bismuth - Bi	F: Bismuth nitrate M: Unspecified compounds		F 0.05 Bismuth nitrate M 0.05 Unspecified compounds
Berkelium - Bk	M: all compounds		M 5.0E-04 All compounds
Bromine - Br	F: determined by combining cations M: determined by combining cations		F 1.0 Determined by combining cations M 1.0 Determined by combining cations
Carbon - C		Carbon monoxide: SR-1, V Carbon dioxide & organic compounds: SR-2, V	
Calcium - Ca	M: All compounds		M 0.3 All compounds

Radionuclide	ICRP 68	ICRP 71 *Gases and Vapors*	ICRP 119 Type – f_1 – compounds
Cadmium - Cd	F: Unspecified compounds M: Sulphides, halides, and nitrates S: Oxides and hydroxides		F 0.05 Unspecified compounds M 0.05 Sulphides, halides, and nitrates S 0.05 Oxides and hydroxides
Californium - Cf	M: all compounds		M 5.0E-04 All compounds
Chlorine - Cl	F: determined by combining cations M: determined by combining cations		F 1.0 Determined by combining cations M 1.0 Determined by combining cations
Chromium - Cr	F: unspecified compounds M: halides and nitrates S: oxides and hydroxides		F 0.1 Unspecified compounds M 0.1 Halides and nitrates S 0.1 Oxides and hydroxides
Copper - Cu	F: Unspecified inorganic compounds M: Sulphides, halides, and nitrates S: Oxides and hydroxides		F 0.5 Unspecified inorganic compounds M 0.5 Sulphides, halides, and nitrates S 0.5 Oxides and hydroxides
Dysprosium - Dy	M: All compounds		M 5.0E-04 All compounds
Erbium - Er	M: All compounds		M 5.0E-04 All compounds
Einsteinium - Es	M: all compounds		M 5.0E-04 All compounds
Europium - Eu	M: All compounds		M 5.0E-04 All compounds
Florine - F	F: determined by combining cations M: determined by combining cations S: determined by combining cations		F 1.0 Determined by combining cations M 1.0 Determined by combining cations S 1.0 Determined by combining cations
Iron - Fe	F: unspecified compounds M: Oxides, hydroxides, and halides		F 0.1 Unspecified compounds M 0.1 Oxides, hydroxides, and halides
Fermium - Fm	M: all compounds		M 5.0E-04 All compounds
Francium - Fr	F: all compounds		F 1.0 All compounds
Gallium - Ga	F: unspecified compounds M: oxides, hydroxides, carbides, halides, and nitrates		F 0.001 Unspecified compounds M 0.001 Oxides, hydroxides, carbides, halides, and nitrates
Gadolinium - Gd	F: Unspecified compounds M: Oxides, hydroxides, and fluorides		F 5.0E-04 Unspecified compounds M 5.0E-04 Oxides, hydroxides, and fluorides

Radionuclide	ICRP 68	ICRP 71 *Gases and Vapors*	ICRP 119 Type – f_1 – compounds
Germanium - Ge	F: unspecified compounds M: Oxides, sulphides, and halides		F 1.0 Unspecified compounds M 1.0 Oxides, sulphides, and halides
Hydrogen - H		Tritiated water: Class SR-2, V	
Hafnium - Hf	F: Unspecified compounds M: Oxides, hydroxides, halides, carbides, and nitrates		F 0.002 Unspecified compounds M 0.002 Oxides, hydroxides, halides, carbides, and nitrates
Mercury - Hg	F: Inorganic sulphates M: Inorganic oxides, hydroxides, halides, nitrates, and sulphides F: All organic compounds		F 0.02 Sulphates M 0.02 Oxides, hydroxides, halides, nitrates, and sulphides F 0.4 All organic compounds
Holmium - Ho	M: unspecified compounds		M 5.0E-04 Unspecified compounds
Indium - In	F: Unspecified compounds M: oxides hydroxides, halides, and nitrates		F 0.02 Unspecified compounds M 0.02 Oxides, hydroxides, halides, and nitrates
Iridium - Ir	F: Unspecified compounds M: Metallic iridium, halides, and nitrates S: Oxides and hydroxides		F 0.01 Unspecified compounds M 0.01 Metallic iridium, halides, and nitrates S 0.01 Oxides and hydroxides
Potassium - K	F: all compounds		F 1.0 All compounds
Lutetium - Lu	M: Unspecified compounds S: Oxides, hydroxides, and flourides		M 5.0E-04 Unspecified compounds S 5.0E-04 Oxides, hydroxides, and fluorides
Mendelevium - Md	M: all compounds		M 5.0E-04 All compounds
Magnesium - Mg	F: Unspecified compounds M: oxides, hydroxides, carbides, halides, and nitrates		F 0.5 Unspecified compounds M 0.5 Oxides, hydroxides, carbides, halides, and nitrates
Manganese - Mn	F: unspecified compounds M: oxides, hydroxides, halides, and nitrates		F 0.1 Unspecified compounds M 0.1 Oxides, hydroxides, halides, and nitrates
Nickel - Ni	F: Unspecified compounds M: Oxides, hydroxides, and carbides	Nickel Carbonyl: SR-1	F 0.05 Unspecified compounds M 0.05 Oxides, hydroxides, and carbides
Osmium - Os	F: unspecified compounds M: halides and nitrates S: oxides and hydroxides		F 0.01 Unspecified compounds M 0.01 Halides and nitrates S 0.01 Oxides and hydroxides

Radionuclide	ICRP 68	ICRP 71 *Gases and Vapors*	ICRP 119 Type – f_1 – compounds
Phosphorus - P	F: unspecified compounds M: some phosphates; determined by combining cation		F 0.8 Unspecified compounds M 0.8 Some phosphates: determined by combining cations
Protactinium - Pa	M: unspecified compounds S: oxides and hydroxides		M 5.0E-04 Unspecified compounds S 5.0E-04 Oxides and hydroxides
Lead - Pb	F: All compounds		F 0.2 All compounds
Palladium - Pd	F: Unspecified compounds M: nitrates and halides S: Oxides and hydroxides		F 0.005 Unspecified compounds M 0.005 Nitrates and halides S 0.005 Oxides and hydroxides
Polonium - Po	F: Unspecified compounds M: Oxides, hydroxides, and nitrates		F 0.1 Unspecified compounds M 0.1 Oxides, hydroxides, and nitrates
Platinum - Pt	F: all compounds		F 0.01 All compounds
Radium - Ra	M: all compounds		M 0.2 All compounds
Rhenium - Re	F: Unspecified compounds M: Oxides, hydroxides, halides, and nitrates		F 0.8 Unspecified compounds M 0.8 Oxides, hydroxides, halides, and nitrates
Rhodium - Rh	F: Unspecified compounds M: Halides S: Oxides and hydroxides		F 0.05 Unspecified compounds M 0.05 Halides S 0.05 Oxides and hydroxides
Sulphur - S	F: sulphides and sulphates; determined by combining cations M: elemental sulphur. sulphides and sulphates; determined by combining cations	Sulphur dioxide: SR-1, F Carbon disulphide: SR-1, F Unspecified: SR-1, F	F 0.8 Sulphides and sulphates: determined by combining cations M 0.8 Elemental sulphur. sulphides and sulphates: determined by combining cations
Scandium - Sc	S: all compounds		S 1.0E-04 All compounds
Selenium - Se	F: unspecified inorganic compounds M: elemental selenium, oxides, hydroxides, and carbides		F 0.8 Unspecified inorganic compounds M 0.8 Elemental selenium, oxides, hydroxides, and carbides
Silicon - Si	F: unspecified compounds M: oxides, hydroxides, carbides and nitrates S: Aluminosilicate glass aerosol		F 0.01 Unspecified compounds M 0.01 Oxides, hydroxides, carbides, and nitrates S 0.01 Aluminosilicate glass aerosol
Samarium - Sm	M: All compounds		M 5.0E-04 All compounds

Radionuclide	ICRP 68	ICRP 71 *Gases and Vapors*	ICRP 119 Type – f_1 – compounds
Tin - Sn	F: Unspecified compounds M: Stannic phosphate, sulphides, oxides, hydroxides, halides, and nitrates		F 0.02 Unspecified compounds M 0.02 Stannic phosphate, sulphides, oxides, hydroxides, halides, and nitrates
Tantalum - Ta	M: Unspecified compounds S: Elemental tantalum, oxides, hydroxides, halides, carbides, nitrates, and nitrides		M 0.001 Unspecified compounds S 0.001 Elemental tantalum, oxides, hydroxides, halides, carbides, nitrates, and nitrides
Terbium - Tb	M: All compounds		M 5.0E-04 All compounds
Thorium - Th	M: unspecified compounds S: oxides and hydroxides		M 5.0E-04 Unspecified compounds S 2.0E-04 Oxides and hydroxides
Titanium - Ti	F: unspecified compounds M: Oxides, hydroxides, carbides, halides, and nitrates S: Strontium titanate ($SrTiO_3$)		F 0.01 Unspecified compounds M 0.01 Oxides, hydroxides, carbides, halides, and nitrates S 0.01 Strontium titanate (SrTiO3)
Thallium - Tl	F: All compounds		F 1.0 All compounds
Thulium - Tm	M: All compounds		M 5.0E-04 All compounds
Uranium - U	F: Most hexavalent compounds, e.g.: UF_6, UO_2F_2, and $UO_2(NO_3)_2$ M: Less soluble compounds, e.g.: UO_3, UF_4, UCl_4, and most other hexavalent compounds S: Highly insoluble compounds, e.g.: UP_2 and U_3O_8		F 0.02 Most hexavalent compounds (e.g., UF6, UO2F2, UO2(NO3)2) M 0.02 Less-soluble compounds (e.g., UO3, UF4, UCl4, and most other hexavalent compounds) S 0.002 Highly insoluble compounds (e.g., UO2, U3O8)
Vanadium - V	F: unspecified compounds M: oxides, hydroxides, carbides, and halides		F 0.01 Unspecified compounds M 0.01 Oxides, hydroxides, carbides, and halides
Tungsten - W	F: All compounds		F 0.3 All compounds
Ytterbium - Yb	M: Unspecified compounds S: Oxides, hydroxides, and fluorides		M 5.0E-04 Unspecified compounds S 5.0E-04 Oxides, hydroxides, and fluorides
Zinc - Zn	S: all compounds		S 0.5 All compounds

Table 3-6. **f_1 values for the ingestion pathway for the elements with those associated values, as suggested by ICRP 68 and ICRP 119. The nuclides noted in Table 3-3 that do not have f_1 values associated are not listed in this table.**

Radionuclide	ICRP 68 f_1 - compounds	ICRP 119 f_1 – compounds
Actinium - Ac	5.0E-04 All compounds	5.0E-04 All compounds
Silver - Ag	0.050 All compounds	0.05 All compounds
Aluminum - Al	0.010 All compounds	0.01 All compounds
Arsenic - As	0.500 All compounds	0.5 All compounds
Astatine - At	1.000 All compounds	1.0 All compounds
Gold - Au	0.100 All compounds	0.1 All compounds
Beryllium - Be	0.005 All compounds	0.005 All compounds
Bismuth - Bi	0.050 All compounds	0.05 All compounds
Berkelium - Bk	5.0E-04 All compounds	5.0E-04 All compounds
Bromine - Br	1.000 All compounds	1.0 All compounds
Carbon - C	1.000 Labelled organic compounds	1.0 Labelled organic compounds
Calcium - Ca	0.300 All compounds	0.3 All compounds
Cadmium - Cd	0.050 All inorganic compounds	0.05 All inorganic compounds
Californium - Cf	5.0E-04 All compounds	5.0E-04 All compounds
Chlorine - Cl	1.000 All compounds	1.0 All compounds
Chromium - Cr	0.100 Hexavalent compounds 0.010 Trivalent compounds	0.1 Hexavalent compounds 0.01 Trivalent compounds
Copper - Cu	0.500 All compounds	0.5 All compounds
Dysprosium - Dy	5.0E-04 All compounds	5.0E-04 All compounds
Erbium - Er	5.0E-04 All compounds	5.0E-04 All compounds
Einsteinium - Es	5.0E-04 All compounds	5.0E-04 All compounds
Europium - Eu	5.0E-04 All compounds	5.0E-04 All compounds
Fluorine - F	1.000 All compounds	1.0 All compounds
Iron - Fe	0.100 All compounds	0.1 All compounds
Fermium - Fm	5.0E-04 All compounds	5.0E-04 All compounds
Francium - Fr	1.000 All compounds	1.0 All compounds
Gallium - Ga	0.001 All compounds	0.001 All compounds
Gadolinium - Gd	5.0E-04 All compounds	5.0E-04 All compounds
Germanium - Ge	1.000 All compounds	1.0 All compounds
Hydrogen - H	1.000 Tritiated water 1.000 Organically bound tritium	1.0 Tritiated water 1.0 Organically bound tritium
Hafnium - Hf	0.002 All compounds	0.002 All compounds
Mercury - Hg	0.020 All inorganic compounds 1.000 Organic methyl mercury 0.400 Other organic compounds	0.02 All inorganic compounds 1.0 Methyl mercury 0.4 Other organic compounds
Holmium - Ho	5.0E-04 All compounds	5.0E-04 All compounds
Indium - In	0.020 All compounds	0.02 All compounds

Radionuclide	ICRP 68 f_1 - compounds	ICRP 119 f_1 – compounds
Iridium - Ir	0.010 All compounds	0.01 All compounds
Potassium - K	1.000 All compounds	1.0 All compounds
Lutetium - Lu	5.0E-04 All compounds	5.0E-04 All compounds
Mendelevium - Md	5.0E-04 All compounds	5.0E-04 All compounds
Magnesium - Mg	0.500 All compounds	0.5 All compounds
Manganese - Mn	0.100 All compounds	0.1 All compounds
Nickel - Ni	0.050 All compounds	0.05 All compounds
Osmium - Os	0.010 All compounds	0.01 All compounds
Phosphorus - P	0.800 All compounds	0.8 All compounds
Protactinium - Pa	5.0E-04 All compounds	5.0E-04 All compounds
Lead - Pb	0.200 All compounds	0.2 All compounds
Palladium - Pd	0.005 All compounds	0.005 All compounds
Polonium - Po	0.100 All compounds	0.1 All compounds
Platinum - Pt	0.010 All compounds	0.01 All compounds
Radium - Ra	0.200 All compounds	0.2 All compounds
Rhenium - Re	0.800 All compounds	0.8 All compounds
Rhodium - Rh	0.050 All compounds	0.05 All compounds
Sulphur - S	0.800 Inorganic compounds 0.100 Inorganic elemental sulphur 1.000 Organic sulphur in food	0.8 Inorganic compounds 0.1 Elemental sulphur 1.0 Sulphur in food
Scandium - Sc	1.0E-04 All compounds	1.0E-04 All compounds
Selenium - Se	0.800 Unspecified compounds 0.050 Elemental selenium and selenides	0.8 Unspecified compounds 0.05 Elemental selenium and selenides
Silicon - Si	0.010 All compounds	0.01 All compounds
Samarium - Sm	5.0E-04 All compounds	5.0E-04 All compounds
Tin - Sn	0.020 All compounds	0.02 All compounds
Tantalum - Ta	0.001 All compounds	0.001 All compounds
Terbium - Tb	5.0E-04 All compounds	5.0E-04 All compounds
Thorium - Th	5.0E-04 Unspecified compounds 2.0E-04 Oxides and hydroxides	5.0E-04 Unspecified compounds 2.0E-04 Oxides and hydroxides
Titanium - Ti	0.010 All compounds	0.01 All compounds
Thallium - Tl	1.000 All compounds	1 All compounds
Thulium - Tm	5.0E-04 All compounds	5.0E-04 All compounds
Uranium - U	0.020 Unspecified compounds 0.002 Most tetravalent compounds (e.g., UO_2, U_3O_8, UF_4)	0.02 Unspecified compounds 0.002 Most tetravalent compounds (e.g., UO_2, U_3O_8, UF_4)
Vanadium - V	0.010 All compounds	0.01 All compounds
Tungsten - W	0.300 Unspecified compounds 0.010 Tungstic acid	0.3 Unspecified compounds 0.01 Tungstic acid
Ytterbium - Yb	5.0E-04 All compounds	5.0E-04 All compounds
Zinc - Zn	0.500 All compounds	0.5 All compounds

3.2. DCF File Packs Provided by MACCS

MACCS has historically provided a variety of options for DCF files to be used for simulations. Some of these datasets have been pre-generated and available for download, others were originally offered as preprocessor packages, and in general, the user has always been able to adjust the DCF files as needed.

The 1997 release of MACCS included DOSFAC2, FGRDCF, and IDCF2. COMIDA2 was also released as a food ingestion specific pathway model.

3.2.1. DOSFAC2

DOSFAC2 was a preprocessor set that allowed the user to specify input parameters defining relative biological effectiveness (RBE), acute dose reduction factors, clearance class, and particle size. The DCFs for cloudshine and groundshine in this database were pulled from a DOE 1988 database, referred to by its report number as DOE/EH-0070. The DCFS for ingestion and inhalation were generated from the 1987 DCF database provided by Keith Eckerman of ORNL [32].

DOSFAC2 was built upon DOSFAC, which generated DCFs for MACCS calculations. The newer version was released [33]:

- to ensure that proper documentation was provided for all code changes,
- to allow the user to generate the ICRP 60 effective dose, and
- to allow for the user to input code parameter values through a user input file.

DOSFAC2 only included the original library of 60 radioisotopes identified as important for commercial nuclear power plant analyses, particularly for light water reactors (LWR) [33]. This preprocessor was the DCF preprocessor of choice for the NRC for accessing the safety of commercial power plants, as there was a need to model acute health effects [32].

DOSFAC generated DCFs for the following exposure pathways:

- Cloudshine – dose that a particular organ of an individual would receive if exposed to a time-integrated unit air concentration in SI units of a single radionuclide (Sv/sec per Bq/m^3)
- Groundshine - dose rate per an initial unit of ground concentration (Sv/sec per Bq/m^2)
- Groundshine – time-integrated dose for an 8-hr exposure from an initial unit of ground concentration (Sv per Bq/m^2)
- Groundshine – time-integrated dose for a 1-week exposure from an initial unit of ground concentration (Sv per Bq/m^2)
- Inhaled Acute – (Sv/Bq)
- Inhaled Chronic – conventional 50-year committed dose from a unit intake (Sv/Bq)
- Ingestion – conventional 50-year committed dose from a unit intake (Sv/Bq)

The time integration of groundshine dose accounted for short-lived daughter products that are assumed to be in secular equilibrium with the parent radionuclide. In addition, the time integrated dose for an 8-hr exposure and 1-week exposure were used in the original MACCS releases of the code but not in the MACCS2 releases [33].

DOSFAC2 utilized an updated effective dose calculation. ICRP 26 first defined the EDE as the whole-body equivalent dose concept based on the summation of weighted organ doses. ICRP 60 created a new name for the weighted equivalent dose and introduced a revised set of tissue

weighting factors for use in calculating the weighted equivalent dose. The ICRP 26 EDE term was replaced with the ICRP 60 term effective dose, E [33].

3.2.2. FGRDCF

FGRDCF is a preprocessor that allowed the user to access the DCFs issued by the EPA in FGR 11 and FGR 12. This database gave inhalation and ingestion DCFs for over 600 radioisotopes and cloudshine and groundshine DCFs for 825 radioisotopes. These DCFs were deemed sufficient for lifetime dose calculations, but not for acute dose calculations. This database provided calculation for the EDE, which files from this preprocessor could provide [32].

This preprocessor was the preferred source of DCFs for DOE applications, but only included 50-year dose commitments from inhalation and as such, could not be used to calculate acute early health effects [32].

FGRDCF was based on the READEM program for FGR 11 and 12 data that was distributed by the Radiation Shielding Information Center [36].

3.2.3. IDCF2

IDCF2 is a preprocessor that provided the capability of generating inhalation DCFs that are required for acute dose calculations that DOSFAC2 or FGRDCF do not supply. IDCF2 provides access to immersion and groundshine DCFS for about 800 radioisotopes from DOE/EH-0070 and inhalation and ingestion DCFs for around 500 radioisotopes as calculated by the IDCF code developed by Idaho National Engineering Laboratory (INEL). The IDCF code developed by INEL was for assessment of hypothetical accidents at fusion power reactors and calculates inhalation DCFs based on ICRP 30 models [32].

3.2.4. FGR 13 File

The user guide for the release of MACCS 3.10 listed a new choice of DCF file – an FGR 13-based choice [34]. This file set was discussed in a document detailing some of the changes this modification of FGR database enforced and is further elaborated on in Section 3.1.3 of this document.

4. ADDING SKIN PATH TO THE MACCS DCF FILE

The MACCS DCF file sets have been replaced with new ones for the MACCS 4.2 release. This new set of DCF values still contain the values pertinent for the database from which they originate but contain an added column denoting an additional exposure pathway, the skin acute exposure pathway.

In total, the eight columns of DCF values in the file are now as follows:

- Cloudshine in Sv*m^3/Bq/s
- Groundshine (8 hr) – not currently implemented
- Groundshine (7 day) – not currently implemented
- Groundshine rate in Sv*m^2/Bq/s
- Inhaled (acute) in Sv/Bq
- Inhaled (chronic) in Sv/Bq
- Ingestion in Sv/Bq
- Skin deposition path (acute) in Sv*m^2/Bq

4.1. Skin Pathway Implementation in MACCS

The skin deposition pathway has been included in MACCS since early iterations of the software to take into consideration the dose that comes from deposition of material from the plume to bare skin. The calculation of the dose coefficients for this pathway had originally been implemented as an equation in the code, was then changed to a hard-coded value, and for this release, has been changed to be consistent with the other pathways as an additional column of DCF values in the DCF files.

4.1.1. Initial Implementation – MACCS 1989

The deposition to skin pathway was first discussed in the 1989 MACCS model description. [15]. This pathway was specifically used for calculating dose from deposition of material from the radioactive cloud to the exposed skin of individuals directly immersed within it. Here, the material was assumed to have a dry-deposition velocity of 0.01 m/s, and the skin dose during plume passage was calculated for each fine spatial element using the following equation:

$$DS = \left(\sum_i AC_i \cdot v_d \cdot DFS_i\right) J \cdot F \cdot SFS \qquad \text{(Eq. 4-1)}$$

Where:

- DS = skin dose (Sv) during passage of a plume segment over a fine spatial element
- AC_i = time-integrated ground level air concentration (Bq-s/m^3) of radionuclide i under the plume centerline
- v_d = deposition velocity to skin, here, 0.01 m/s
- DFS_i = skin DCF (Sv·m^2/Bq) for radionuclide i
- J = off-centerline correction factor (dimensionless) of the fine spatial element
- F = fraction of exposure during the plume passage, equal to TE/TO; where
  - TE is the exposure time (s) of an individual at the fine spatial element, and

- TO is the time duration (s) of a plume segment over the fine spatial element

- SFS = skin shielding factor (dimensionless), specified by the user

DFS_i is calculated inside the MACCS code with the following assumptions:

- Every radioactive disintegration of material deposited on the skin results in the emission of a single beta particle,
- There is no buildup of radioactive daughter products on the skin following the initial deposition of material, and
- All material deposited on the skin remains there for eight hours following deposition and then is immediately removed.

This method for calculating the skin DCFs is based on information presented in an article by Healy that was published in Atmospheric Science and Power Production [37]. The method takes into account the following points:

- Within the skin, the rapidly dividing basal cells below 0.09 mm are the most sensitive to damage, therefore, dose will be calculated for tissue at that depth.
- At this critical depth, the dose rate from material deposited on the skin does not show significant variability over the range of decay energy from 0.2 to 2.0 MeV. Within this range at the critical depth, the dose rate then is roughly 0.2 rads/s for skin contaminated to a unit of 1 Ci/m^2. Assuming a quality factor of 1 for β particles and converting to SI units, this equals 5.4E-14 Sv·m^2/Bq·s.

The skin DCF is calculated using the following equation:

$$DFS_i = 5.4 * 10^{-14} \cdot \frac{\left[1.0 - e^{-\lambda_i T}\right]}{\lambda_i} \quad \text{(Eq. 4-2)}$$

Where:

- DFS_i = skin DCF (Sv·m^2/Bq) for radionuclide i
- λ_i = decay constant (s^{-1}) of radionuclide i
- T = residence time (s) of radionuclide material on the skin, here, eight hours

4.1.2. Later Changes

In the 2021 MACCS Theory Manual that accompanied MACCS Version 3.10, the skin deposition pathway utilized a single dose rate coefficient. It was noted in this release, the dose rate coefficient for skin deposition, $DRCS_i$, is a fixed value in the code. The variables in the equations were updated to new names in this release. The equations in the 2021 MACCS Theory Manual are as follows [38]:

$$DS = \left(\sum_i DCS_i \cdot \chi_i^G\right) V_d \cdot Y \cdot F \cdot SFS \quad \text{(Eq. 4-3)}$$

Where:

- DS [Sv] = acute dose from skin deposition during passage of a plume segment over a fine spatial element
- DCS_i [$\frac{\text{Sv}\cdot \text{m}^2}{\text{Bq}}$] = acute skin dose coefficient from skin deposition for radionuclide i
- χ_i^G [$\frac{\text{Bq}\cdot\text{s}}{m^3}$] = time-integrated ground-level air concentration of radionuclide i under the plume centerline
- V_d [$\frac{\text{m}}{\text{s}}$] = deposition velocity to skin, which in the code is a fixed value of 0.01 m/s
- Y = off-centerline correction factor
- F = fraction of exposure duration during the plume passage, equal to TE/TO; where TE is the exposure time(s) of an individual at the fine spatial element and TO is the time duration(s) of a plume segment over the fine spatial element
- SFS = skin dose protection factor, specified by SKPFAC.

$$DCS_i = DRCS_i \cdot \int_0^T e^{-\lambda_i t} dt = DRCS_i \cdot \frac{1.0 - e^{-\lambda_i T}}{\lambda_i} \quad \text{(Eq. 4-4)}$$

Where:

- $DRCS_i$ = acute skin dose rate coefficient, which in MACCS has a fixed value of 5.4 x 10^{-14} Sv·m^2/Bq·s
- λ_i = decay constant (s^{-1}) of radionuclide i
- T = residence time (s) of radionuclide material on the skin, here, eight hours

4.2. Update Notes for the MACCS 4.2 Release

For the MACCS 4.2 release, the DCF files were amended to include the acute skin deposition pathway, instead of keeping it as an implicitly calculated pathway in the MACCS code.

An eighth column named, "SKIN PATH ACUTE", was added to the DCF file. Here, the skin deposition path rate DCFs were added to the SKIN organ row for each radionuclide – all other values in the column were set to 0.0.

All radionuclides except for isotopes of Xe and Kr had non-zero DCFs. Xe and Kr are noble gases that are assumed not to deposit and therefore would not deposit material to the skin. The value set came from the variables within the MACCS code labeled RADSEC and GRASEC, which calculated the value of the acute skin dose rate coefficient, $DRCS_i$.

From the MACCS 4.1 source code:

- RADSEC = .2
- GRASEC = RADSEC / 3.7e12 = 5.4054055e-14

For the DCF files, however, the value 5.4000000e-14 was used. The choice to round the value was dictated by the number of significant figures in the RADSEC and GRASEC calculation.

The user is now able to specify the residence time of the radionuclide material on the skin, which is input variable WASHTM. The user is also able to specify the deposition velocity of the material to the skin, variable SKINDV or SDV.

5. ADDING TEDE TO THE MACCS DCF FILE

The MACCS 4.2 release includes an additional DCF file, named FGR13GyEquiv_TEDE_v2.inp. This file contains the ICRP 30 TEDE value as an additional organ for each of the 825 isotopes listed.

5.1. General Method and Assumptions

TEDE values are the ICRP 30 values for equivalent total dose. Radionuclide Viewer[9], developed by Sandia on behalf of the Department of Energy (DOE), is a software tool that enables visualization of all the versions of the dose coefficient values that have been generated through the methods developed by Eckerman and Leggett at ORNL. DCFPAK 2007a was chosen as the most updated ICRP 30 value pack, and SQL query tools were used to pull the relevant values from the database.

The values necessary for the DCF file that MACCS uses are the following:

- Cloudshine in Sv*m^3/Bq/s – equivalent to External - Air Submersion in DCFPAK
- Groundshine (8 hr) – not currently implemented
- Groundshine (7 day) – not currently implemented
- Groundshine rate in Sv*m^2/Bq/s – equivalent to External - Surface Source in DCFPAK D
- Inhaled (acute) – N/A for ICRP 30
- Inhaled (chronic) in Sv/Bq – inhalation in DCFPAK for ICRP 30 values
- Ingestion in Sv/Bq – chronic ingestion in DCFPAK for ICRP 30 values
- Skin Deposition Path Rate (acute) – N/A for TEDE

The current 825 listed isotopes in the MACCS DCF files were used. There were several isotopes still listed in the -a and -b format rather than the current standard isotope and -m for metastable format. The naming convention was not found to be consistent where -a lined up with the standard isotope or vice versa. This was due to uncertainty whether the reported nuclide represented the ground or an excited state. The -a and -b convention is an artifact from ICRP Publication 38, and the following conversions were made by comparing the half-lives listed:

- Eu-150a → Eu-150m
- Eu-150b → Eu-150
- In-110a → In-110m
- In-110b → In-110
- Ir-186a → Ir-186
- Ir-186b → Ir-186m
- Nb-89a → Nb-89m
- Nb-89b → Nb-89
- Np-236a → Np-236
- Np-236b → Np-236m
- Re-182a → Re-182m
- Re-182b → Re-182
- Sb-120a → Sb-120
- Sb-120b → Sb-120m
- Sb-128a → Sb-128m
- Sb-128b → Sb-128
- Ta-178a → Ta-178
- Ta-178b → Ta-178m

[9] Radionuclide Viewer is available at the Sandia Nuclear Incident Response Program website upon request at the following link: https://nirp.sandia.gov/Software/RadionuclideViewer/RadionuclideViewer.aspx

For the inhalation dose coefficient values, the particle size is chosen to be 1 μm, to keep consistent with the rest of the DCF file. For some isotopes, not all the necessary dose coefficients were available. For the missing ones, 0 or -1 is assigned.

The f_1 values were chosen to as consistent with the values listed for the rest of the isotopes in the DCF file as possible, to reflect the chemical form presumably chosen. Since EDE is a ICRP 26/30 method, effort was made to stick with the state of practice from that era, when the f_1 values were consistent between the internal pathways. The full accounting for the isotope, absorption type, and f_1 value associated, if applicable, is shown in Table 5-1.

5.2. Verification of Values

A historical analysis was conducted to verify that the values pulled from DCFPAK are consistent with the methods outlined in FGR 11 and 12, with scientific updates implemented as knowledge gaps were identified and filled.

It should be noted that there were errors in the software initially used to generate the values for FGR 11 and 12 as published. These errors were progressively corrected with the first implementation of DCFPAK in 1983 and in subsequent releases of DCFPAK. The most recent release of the software (DCFPAK 4.0) occurred in 2015.

5.2.1. DCFPAK History

DCFPAK 2.0 corresponds with the 2007 r2 vintage of dose coefficient releases. Within the DCFPAK database, this corresponds with the 2007a list, which was what was used for the creation of the list of these values included in the updated DCF file for MACCS.

Each version of DCFPAK built upon the prior to expand the diversity of dose coefficients produced.

Developed in the mid-1990s, DCFPAK 1.0 provided dose coefficients as summarized in FGR 11 and FGR 12. Relevant specifically to this project, this version gave the EDE, H_E based on the tissue weight factors listed in ICRP 26 and the effective dose, E, based on the tissue weighting factors in ICRP 60 [39].

RDCPAK came about in 1999 which developed age-specific coefficients for cancer risk [39].

DCFPAK 1.2 in 2005 combined the work of DCFPAK 1.0 and RDCPAK to create a more flexible database, and corrections were made to errors identified from DCFPAK 1.0. DCFPAK 1.2 added several radionuclides not previously considered and provided inhalation dose coefficients for an expanded range of particle sizes. Additionally, deficiencies from DCFPAK 1.0 and RDCPAK were identified which included: inaccuracies in nuclear decay data and dose coefficients based on that data, incomplete or outdated information about some radionuclides, lack of dose coefficients for assessing short-term consequences, and lack of dose coefficients for certain particle sizes. These deficiencies were addressed with the updates in DCFPAK 3.0 [40].

Table 5-1. Corrections for radionuclides incorrectly identified in ICRP 38 or later renamed.

D As given in ICRP 38		Correction	
Nuclide	$T_{1/2}$	Nuclide	$T_{1/2}$
Nb-89a	66 m	Nb-89m	66m
Nb-89b	122 m	Nb-89	2.03 h
In-110a	69.1 m	In-110m	69.1 m
In-110b	4.9 h	In-110	4.9 h
Sb-120a	15.89 m	Sb-120	15.89 m
Sb-120b	5.76 d	Sb-120m	5.76 d
Sb-128a	10.4 m	Sb-128m	10.4 m
Sb-128b	9.01 h	Sb-128	9.01 h
Eu-150a	12.62 h	Eu-150m	12.8 h
Eu-150b	34.2 y	Eu-150	36.9 y
Ta-178a	9.31 m	Ta-178	9.31 m
Ta-178b	2.2 h	Ta-178m	2.36 h
Re-182a	12.7 h	Re-182m	12.7 h
Re-182b	64.0 h	Re-182	64.0 h
Ir-186a	15.8 h	Ir-186	16.64 h
Ir-186b	1.75 h	Ir-186m	1.92 h
Np-236a	115E3 y	Np-236	1.54E5 y
Np-236b	22.5 h	Np-236m	22.5 h

Table 5-2. Corrections of half-lives given in ICRP 38.

Nuclide	Half-life from ICRP 38	Corrected Half-life
Te-123	1E13 y	6E14 y
Fe-60	1E5 y	1.5E6 y
Se-79	6.5E4 y	2.95E5 y
Ag-128m	127 y	418 y
Sn-126	1E5 y	2.30E5 y
Hg-194	260 y	440 y
Ti-44	47.3 y	60.0 y
Cm-250	6900 y	8300 y
Rh-102m	207 d	3.742 y
In-115	5.1E15 y	4.4E14 y
Pb-202	3.0E5 y	3.25E4 y
Si-32	450 y	132 y
Tb-157	15- y	71 y
Ca-41	1.4E5 y	1.02E5 y

DCFPAK 1.4 merged DCFPAK 1.2 and the dosimetric portion of RDCPAK, giving the user age-specific dose coefficients based on FGR 13 models but not risk coefficients. This release gave the option of using dose coefficients based on FGR 11 and FGR 12 or on FGR 13 and made corrections to errors found in DCFPAK 1.2 [39].

DCFPAK 1.6 includes the capabilities of the past releases and increased the range of risk coefficients available based on the methods detailed in FGR 13, while increasing the range of particle sizes addressed. In addition, default inhalation absorption types for each radionuclide are provided for use when information on the form is unavailable [39].

DCFPAK 1.8 includes the capabilities of the past releases and builds upon them by adding inhalation dose coefficients for more mono- and poly-dispersed particle sizes [39].

DCFPAK 2.0 was not a software package but rather a library of building blocks for dose and risk coefficients and the algorithms necessary to generate dose and risk coefficients for inhaled radioactive material of arbitrary particle size. Here, "arbitrary particle size" refers to any fixed size or distribution of sizes within the bounds of 0.0001 to 200 microns [39].

5.2.2. Justification of Method

The history of the creation of DCFPAK shows how the work that created it is the same as that which generated the FGR 11 and FGR 12 DCF values. The authors of the software used to generate the FGRs extended and updated that software to generate the various vintages of DCFPAK. Each subsequent version of DCFPAK corrected prior programming bugs and errors from the version used in the initial generation of the FGR 11 and FGR 12.

To ensure the most up-to-date version of the TEDE values calculated was chosen, DCFPAK was used as the basis for the values.

5.2.3. Comparison to FGRDCF Values

In addition to the technical basis proof, a value comparison was done on the TEDE values from FGR13PAK, the approved database storing the FGR 12 and FGR 13 dose coefficient values by the EPA, to the values cataloged for the MACCS DCF file update. The values stored in FGR13PAK relevant to this report are stored in the following files:

- F12TIII1.EXT – file containing dose coefficients for exposure due to radionuclides in the air – also known as cloudshine, for several organs, expanded from the original FGR 12 text, the remainder, and the EDE.
- F12TIII3.EXT – file containing dose coefficients for exposure due to radionuclides on the surface of the ground – also known as groundshine, for several organs, expanded from the original FGR 12 text, the remainder, and the EDE.
- FGR13ING.GDB – file containing committed absorbed dose coefficients for 23 organs and the effective dose for intakes by ingestion for six age groups.
- FGR13INH.HDB – file containing committed absorbed dose coefficients for 23 organs and the effective dose for intakes by inhalation for six age groups for an AMAD of 1.0E-06 m.

Note that FGRs 11 and 12 are based on the ICRP 26/30+ model and FGR 13 is based on ICRP 60+. As such, the inhalation and ingestion effective dose values were the ED values, not the EDE values.

To check the inhalation and ingestion values, the FGRDCF database files would need to be used. Cloudshine and groundshine EDE values were also compared. The relevant files were as follows:

- FGR11T21.INH – file containing dose coefficients for six organs, the remainder, and EDE for exposure due to inhalation.
- FGR11T22.ING - file containing dose coefficients for six organs, the remainder, and EDE for exposure due to ingestion.
- FGR12T31.SUB – file containing dose coefficients for seven organs, the remainder, and EDE for exposure due to submersion – also known as cloudshine.
- FGR12T33.SUR – file containing dose coefficients for seven organs, the remainder, and EDE for exposure due to radionuclides on the ground – also known as groundshine.

The values retrieved from each file used the following criteria:

- Cloudshine and Groundshine – Identify HsubE
- Inhalation and ingestion – Identify HsubE, matching clearance class and $\boldsymbol{f_1}$ value

The results of the comparison are as given in Appendix A. The ratio of the values chosen for the MACCS DCF files was compared to the values listed in the FGRDCF was calculated and listed for each. Where there is a blank space, no terms were given in either set.

Discrepancies were found in the datasets were mainly due to the inputs used to extract the DCF values. One factor that may have influenced this is the larger range of f1 values available to choose from in the DCFPAK 2.0 database. Additionally, errors in the code for generating the values in the database were corrected in DCFPAK as compared to what was used for FGR13DCF. Based on these differences, the results from DCFPAK 2.0's database are expected to be more representative.

5.3. Update for the Current DCF File Version

The dose coefficients chosen for the TEDE values appended to the DCF file were done to match the clearance class and f_1 values listed from the FGR 13 update as closely as possible. Table 5-4 shows the corresponding clearance class and f_1 values for each, with the radionuclide cell colored in orange if there's a difference between the two files.

Note that the f_1 values chosen for the TEDE values do not line up with the recommendations per compound type noted in Table 3-4. It was decided that it was more important to have the f_1 values match each other across the inhalation and ingestion pathways within the clearance type stated in the DCF file list, rather than match a certain number.

Table 5-3. Table of Clearance Types and associated f_1 values chosen for the DCF file implemented in MACCS per the FGR 13 file creation [34] and the clearance type and f_1 value associated for the addition of the FGR 11/12 TEDE value. The previously published DCF file information is under the headings "DCF File" and the TEDE updates under the heading "TEDE".

	DCF File		TEDE Update	
	Clearance Type	f_1 value (INH)	Clearance Type	f_1 value
Ac	S	0.0005	S	0.001
Ag	S	0.01	S	0.05
Al	F	0.01	F	0.01
Am	M	0.0005	M	0.001
Ar				
As	M	0.5	M	0.5
At	F	1	F	1
Au	S	0.1	S	0.1
Ba	F	0.2	F	0.1
Be	S	0.005	S	0.005
Bi	M	0.05	M	0.05
Bk	M	0.0005	M	0.001
Br	F	1	F	1
C	F	1		1
Ca	M	0.1	M	0.3
Cd	S	0.05	S	0.05
Ce	S	0.0005	S	0.0003
Cf	S	0.0005	S	0.001
Cl	F	1	F	1
Cm	M	0.0005	M	0.001
Co	S	0.01	S	0.05
Cr	S	0.1	S	0.1
Cs	F	1	F	1
Cu	S	0.5	S	0.5
Dy	M	0.0005	M	0.0003
Er	M	0.0005	M	0.0003
Es	M	0.0005	M	0.001
Eu	M	0.0005	M	0.001
F	S	1	S	1
Fe	M	0.1	M	0.1
Fm	M	0.0005	M	0.001
Fr	F	1	F	1
Ga	M	0.001	M	0.001
Gd	M	0.0005	M	0.0003
Ge	M	1	M	1

	DCF File		TEDE Update	
	Clearance Type	f_1 value (INH)	Clearance Type	f_1 value
H	WV	1		1
Hf	F	0.002	F	0.002
Hg	V	0.02	F	0.02
Ho	M	0.0005	M	0.0003
I	F	1	F	1
In	M	0.02	M	0.02
Ir	S	0.01	S	0.01
K	F	1	F	1
Kr				
La	M	0.0005	M	0.001
Lu	S	0.0005	S	0.0003
Md	M	0.0005	M	0.001
Mg	M	0.5	M	0.5
Mn	M	0.1	M	0.1
Mo	S	0.01	S	0.05
N				
Na	F	1	F	1
Nb	S	0.01	S	0.01
Nd	S	0.0005	S	0.0003
Ne				
Ni	M	0.05	M	0.05
Np	M	0.0005	M	0.001
O				
Os	S	0.01	S	0.01
P	F	0.8	F	0.8
Pa	S	0.0005	S	0.001
Pb	F	0.2	F	0.2
Pd	S	0.005	S	0.005
Pm	S	0.0005	S	0.0003
Po	M	0.1	M	0.1
Pr	S	0.0005	S	0.0003
Pt	F	0.01	F	0.01
Pu	S	1.00E-5	S	1.00E-5
Ra	M	0.1	M	0.2
Rb	F	1	F	1

	DCF File		TEDE Update	
	Clearance Type	f_1 value (INH)	Clearance Type	f_1 value
Re	M	0.8	M	0.8
Rh	S	0.05	S	0.05
Rn				
Ru	S	0.01	S	0.05
S	F	0.8	F	0.8
Sb	F	0.1	F	0.1
Sc	S	0.0001	S	0.0001
Se	M	0.1	M	0.8
Si	M	0.01	M	0.01
Sm	M	0.0005	M	0.0003
Sn	M	0.02	M	0.02
Sr	F	0.3	F	0.3
Ta	S	0.001	S	0.001
Tb	M	0.0005	M	0.0003

	DCF File		TEDE Update	
	Clearance Type	f_1 value (INH)	Clearance Type	f_1 value
Tc	M	0.1	M	0.8
Te	M	0.1	M	0.2
Th	S	0.0005	S	0.0002
Ti	S	0.01	S	0.01
Tl	F	1	F	1
Tm	M	0.0005	M	0.0003
U	S	0.002	S	0.002
V	M	0.01	M	0.01
W	F	0.3	F	0.3
Xe				
Y	S	0.0001	S	0.0001
Yb	S	0.0005	S	0.0003
Zn	S	0.01	S	0.5
Zr	M	0.002	M	0.002

The differences between the associated clearance class and f_1 value for the FGR 13 DCF file and new TEDE values are explained in the following list. Note that when the explanation is "[number] is the only associated f_1 value choice for the [type] class," this means that when narrowing down the options per isotope for ICRP 30, inhalation, 1 micron particle size; the f_1 value choice made was the only one that had a corresponding set of ingestion dose coefficients.

- Ac: 0.001 was the only associated f_1 value choice for the S class
- Ag: 0.05 was the only associated f_1 value choice for the S class
- Am: 0.001 was the only associated f_1 value choice for the M class
- Ba: 0.1 was the only associated f_1 value choice for the F class
- Bk: 0.001 was the only associated f_1 value choice for the M class
- C: ICRP-30 TEDE did not have an inhalation dose coefficient → no clearance class associated
- Ca: 0.3 was the only associated f_1 value choice for the M class
- Ce: 0.0003 was the only associated f_1 value choice for the S class
- Cf: 0.001 was the only associated f_1 value choice for the S class
- Cm: 0.001 was the only associated f_1 value choice for the M class
- Co: 0.05 was the only associated f_1 value choice for the S class
- Dy: 0.0003 was the only associated f_1 value choice for the M class
- Er: 0.0003 was the only associated f_1 value choice for the M class
- Es: 0.001 was the only associated f_1 value choice for the M class
- Eu: 0.001 was the only associated f_1 value choice for the M class
- Fm: 0.001 was the only associated f_1 value choice for the M class
- Gd: 0.0003 was the only associated f_1 value choice for the M class

- H: ICRP-30 TEDE did not have an associated inhalation dose coefficient → no clearance class
- Hg: V is not a clearance class choice for ICRP-30. Class F was chosen instead, as V corresponds to very fast absorption, and the closest choice to that is F, which is fast absorption.
- Ho: 0.0003 was the only associated f_1 value choice for the M class
- La: 0.001 was the only associated f_1 value choice for the M class
- Lu: 0.0003 was the only associated f_1 value choice for the S class
- Md: 0.001 was the only associated f_1 value choice for the M class
- Mo: 0.05 was the only associated f_1 value choice for the S class
- Nd: 0.0003 was the only associated f_1 value choice for the S class
- Np: 0.001 was the only associated f_1 value choice for the M class
- Pa: 0.001 was the only associated f_1 value choice for the S class
- Pm: 0.0003 was the only associated f_1 value choice for the S class
- Pr: 0.0003 was the only associated f_1 value choice for the S class
- Ra: 0.2 was the only associated f_1 value choice for the M class
- Ru: 0.05 was the only associated f_1 value choice for the S class
- Se: 0.8 was the only associated f_1 value choice for the M class
- Sm: 0.0003 was the only associated f_1 value choice for the M class
- Tb: 0.0003 was the only associated f_1 value choice for the M class
- Tc: 0.8 was the only associated f_1 value choice for the M class
- Te: 0.2 was the only associated f_1 value choice for the M class
- Th: 0.0002 was the only associated f_1 value choice for the S class
- Tm: 0.0003 was the only associated f_1 value choice for the M class
- Yb: 0.0003 was the only associated f_1 value choice for the S class
- Zn: 0.5 was the only associated f_1 value choice for the S class

6. CONCLUSION

MACCS has a long history of evolution within its implementation of DCF values in its calculations. Over time, the source and extent of these values included for use with the software has evolved as the scope of reactor consequence and knowledge regarding dosimetric knowledge has grown. The DCF values have once again been amended for the 4.2 MACCS release. The major changes to the DCF file sets included with the software package are the conversion of the skin deposition DCF values from a hard-coded value in the MACCS code to its own column within each DCF file, and the addition of a file that includes the ICRP 30 TEDE values. The MACCS 4.2 DCF file sets and a short description for each are tabulated below:

Table 6-1. DCF file sets provided in the MACCS 4.2 release.

File Name	Description and Usage
dosdata21organs_v2.inp	DCF file set for MACCS where the values were pulled from the DOSFAC2 pre-processor, referencing data from DOE/EH-0070 and w_T from ICRP 26 and ICRP 60.
FGR13DCF_v2.inp	DCF file set for MACCS where the values were pulled from FGR 13. Uses w_R=20 for alpha radiation for all tissues and organs.
FGR13GyEquiv_v2.inp	DCF file set for MACCS where the values were pulled from FGR 13. Uses modified w_R to reflect RBE
FGR13GyEquiv_TEDE_v2.inp	DCF file set for MACCS where the values were pulled from FGR 13. Uses modified w_R to reflect RBE. Also includes the TEDE as an organ, with these DCF values pulled from FGR 11 and FGR 12.

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APPENDIX A. RATIOS

Ratio of TEDE values chosen for MACCS DCF File to TEDE values listed in FGR13PAK

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Ac-223	1.10	1.06		
Ac-224	1.12	1.07		
Ac-225	1.13	1.07		
Ac-226	1.08	0.92		
Ac-227	1.13	1.11		
Ac-228	1.06	0.99		
Ag-102	1.06	1.00	0.44	
Ag-103	1.07	1.00	0.51	
Ag-104	1.07	1.02	0.37	
Ag-104m	1.06	0.98	0.54	
Ag-105	1.08	1.04	1.48	
Ag-106	1.07	0.95	0.50	
Ag-106m	1.07	1.03	1.33	
Ag-108	0.74	0.22		
Ag-108m	1.08	1.04	2.02	
Ag-109m	1.21	1.29		
Ag-110	0.72	0.23		
Ag-110m	1.07	1.03	1.76	
Ag-111	0.93	0.51	0.96	
Ag-112	1.03	0.85	1.03	
Ag-115	1.04	0.88	0.66	
Al-26	1.06	1.01	1.92	1.13
Al-28	1.05	0.95		
Am-237	1.10	1.05		
Am-238	1.07	1.03		
Am-239	1.12	1.07		
Am-240	1.07	1.03		
Am-241	1.21	1.18		

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Am-242	1.01	0.98		
Am-242m	1.27	1.34		
Am-243	1.17	1.11		
Am-244	1.07	1.03		
Am-244m	0.17	0.05		
Am-245	1.00	0.75		
Am-246	1.07	0.99		
Am-246m	1.06	0.98		
Ar-37	0.00	0.00		
Ar-39	0.08	0.13		
Ar-41	1.06	0.98		
As-69	1.06	0.91	0.62	0.64
As-70	1.06	1.00	0.51	0.85
As-71	1.08	1.03	0.86	0.89
As-72	1.06	0.97	1.22	0.90
As-73	1.23	1.15	0.90	0.74
As-74	1.07	1.00	1.00	0.83
As-76	1.03	0.81	1.37	0.88
As-77	0.85	0.63	0.72	0.86
As-78	1.05	0.93	0.81	0.86
At-207	1.07	1.03	1.87	0.99
At-211	1.15	1.09	1.42	0.98
At-215	1.08	1.04		
At-216	1.16	1.09		
At-217	1.08	1.04		
At-218	1.22	1.15		
Au-193	1.13	1.08	0.65	1.14
Au-194	1.07	1.03	1.13	1.20
Au-195	1.17	1.11	2.00	1.11
Au-195m	1.10	1.05		

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Au-198	1.07	0.99	1.03	1.10
Au-198m	1.11	1.06	0.67	1.14
Au-199	1.11	1.06	0.51	1.10
Au-200	1.03	0.78	0.60	0.80
Au-200m	1.08	1.03	0.81	1.12
Au-201	0.98	0.59	0.36	0.69
Ba-126	1.10	1.07		
Ba-128	1.12	1.12		
Ba-131	1.09	1.05		
Ba-131m	1.15	1.11		
Ba-133	1.10	1.06		
Ba-133m	1.07	1.10		
Ba-135m	1.07	1.11		
Ba-137m	1.07	1.01		
Ba-139	0.85	0.31		
Ba-140	1.06	0.95		
Ba-141	1.06	0.92		
Ba-142	1.06	1.00		
Be-10	0.08	0.12	2.77	1.11
Be-7	1.08	1.04	1.57	1.24
Bi-200	1.07	1.03	0.48	0.96
Bi-201	1.07	1.01	0.64	1.09
Bi-202	1.07	1.03	0.39	1.08
Bi-203	1.06	1.03	0.82	1.17
Bi-205	1.06	1.03	1.24	1.19
Bi-206	1.07	1.03	1.04	1.17
Bi-207	1.07	1.02	0.96	1.16
Bi-210	0.13	0.03	0.57	1.32
Bi-210m	1.09	1.04	0.60	1.73
Bi-211	1.09	1.04		

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Bi-212	1.03	0.80	0.17	1.11
Bi-213	1.04	0.79	0.14	0.98
Bi-214	1.06	0.98	0.12	0.69
Bk-245	1.12	1.07	0.57	1.14
Bk-246	1.07	1.03	1.38	1.18
Bk-247	1.12	1.07	2.24	3.63
Bk-249	0.18	1.28	2.32	3.34
Bk-250	1.06	1.01	2.04	1.14
Br-74	1.05	1.00	0.90	0.60
Br-74m	1.06	0.99	1.12	0.60
Br-75	1.07	0.99	1.21	0.63
Br-76	1.06	1.00	1.36	0.79
Br-77	1.08	1.03	0.91	0.86
Br-80	1.03	0.77	1.25	0.51
Br-80m	1.31	1.23	2.79	0.65
Br-82	1.07	1.03	0.95	0.85
Br-83	0.72	0.28	1.45	0.57
Br-84	1.04	0.96	1.20	0.56
C-11	1.07	1.01	0.00	0.14
C-14	0.09	1.26	0.00	0.97
Ca-41	0.00	0.00		
Ca-45	0.06	1.22		
Ca-47	1.06	1.00		
Ca-49	1.04	0.99		
Cd-104	1.09	1.06	0.43	1.15
Cd-107	1.17	1.28	0.38	1.09
Cd-109	1.28	1.36	1.95	1.77
Cd-113	0.06	1.20	4.14	1.91
Cd-113m	0.08	0.15	3.47	1.89
Cd-115	1.07	0.95	1.06	1.13

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Cd-115m	0.79	0.25	1.52	1.33
Cd-117	1.06	0.99	0.67	1.09
Cd-117m	1.06	1.02	0.51	1.13
Ce-134	1.33	1.29	1.64	1.11
Ce-135	1.08	1.03	0.85	1.17
Ce-137	1.20	1.22	1.08	1.08
Ce-137m	1.07	1.12	0.86	1.09
Ce-139	1.12	1.09	1.27	1.17
Ce-141	1.10	1.06	0.65	1.10
Ce-143	1.07	0.93	1.10	1.10
Ce-144	1.12	1.10	1.92	1.09
Cf-244	1.45	1.39	0.19	0.73
Cf-246	1.39	1.37	0.32	1.17
Cf-248	1.45	1.39	1.74	3.20
Cf-249	1.09	1.04	5.03	3.64
Cf-250	1.45	1.38	3.90	3.67
Cf-251	1.11	1.08	5.10	3.65
Cf-252	6703.30	828.57		
Cf-253	0.06	1.25	0.52	2.64
Cf-254	88316831.68	9190751.45		
Cl-36	0.13	0.06	1.83	0.88
Cl-38	1.04	0.94	1.42	0.55
Cl-39	1.05	0.96	1.21	0.58
Cm-238	1.14	1.08		
Cm-240	1.44	1.36		
Cm-241	1.09	1.05		
Cm-242	1.42	1.36		
Cm-243	1.11	1.06		
Cm-244	1.44	1.36		
Cm-245	1.13	1.08		

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Cm-246	1.44	1.36		
Cm-247	1.08	1.04		
Cm-248	29618.64	2840.91		
Cm-249	0.92	0.59		
Cm-250	0.00	0.00		
Co-55	1.07	1.01	1.06	
Co-56	1.06	1.02	1.58	
Co-57	1.13	1.06	2.45	
Co-58	1.07	1.03	1.39	
Co-58m	1.44	1.39	1.52	
Co-60	1.06	1.02	1.92	
Co-60m	1.09	1.01	0.41	
Co-61	1.05	0.70	0.56	
Co-62m	1.05	0.98	0.46	
Cr-48	1.10	1.05	1.07	1.19
Cr-49	1.07	0.97	0.48	0.81
Cr-51	1.09	1.04	2.44	1.03
Cs-125	1.07	0.98	1.06	0.58
Cs-126	1.05	0.92		
Cs-127	1.08	1.05	0.80	0.87
Cs-128	1.06	0.94		
Cs-129	1.10	1.06	1.01	0.97
Cs-130	1.07	0.95	1.03	0.55
Cs-131	1.37	1.33	1.65	1.15
Cs-132	1.07	1.04	1.43	1.01
Cs-134	1.07	1.03	1.87	1.03
Cs-134m	1.14	1.15	0.83	0.66
Cs-135	0.06	1.24	1.78	0.96
Cs-135m	1.07	1.02	0.57	0.77
Cs-136	1.07	1.03	1.61	0.99

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Cs-137	0.08	0.10	1.85	1.00
Cs-138	1.05	0.97	1.11	0.57
Cu-60	1.06	1.00	0.46	0.74
Cu-61	1.07	0.99	0.65	1.00
Cu-62	1.06	0.90		
Cu-64	1.07	1.02	0.63	1.04
Cu-66	0.91	0.43		
Cu-67	1.10	1.06	0.55	1.05
Dy-155	1.08	1.04	0.77	1.19
Dy-157	1.10	1.05	0.71	1.23
Dy-159	1.25	1.20	1.72	1.15
Dy-165	0.88	0.39	0.60	0.90
Dy-166	1.15	1.14	1.07	1.09
Er-161	1.08	1.03	0.50	1.14
Er-165	1.23	1.18	0.99	1.15
Er-169	0.06	1.20	0.55	1.08
Er-171	1.09	0.97	0.69	1.09
Er-172	1.08	1.04	1.00	1.13
Es-250	1.08	1.04	2.12	1.51
Es-251	1.13	1.08	0.60	1.15
Es-253	1.14	1.23	0.39	1.50
Es-254	1.22	1.30	1.30	3.04
Es-254m	1.07	1.01	0.32	1.16
Eu-145	1.06	1.03	1.32	1.21
Eu-146	1.07	1.03	1.30	1.21
Eu-147	1.08	1.05	0.91	1.18
Eu-148	1.08	1.03	1.46	1.22
Eu-149	1.15	1.13	1.72	1.18
Eu-150a	1.00	0.69	1.61	1.07
Eu-150b	1.08	1.04	1.37	1.35

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Eu-152	1.07	1.03	1.42	1.28
Eu-152m	1.04	0.86	1.01	1.08
Eu-154	1.07	1.02	1.45	1.26
Eu-155	1.16	1.10	1.61	1.27
Eu-156	1.06	0.99	1.11	1.13
Eu-157	1.07	0.95	1.04	1.09
Eu-158	1.05	0.94	0.54	0.82
F-18	1.07	1.03	0.36	0.67
Fe-52	1.08	1.02	0.98	1.09
Fe-55	0.00	0.00	0.93	0.50
Fe-59	1.06	1.02	0.89	1.01
Fe-60	0.11	1.26	0.53	0.37
Fm-252	1.45	1.39	0.35	1.16
Fm-253	1.13	1.08	0.40	1.50
Fm-254	1.37	1.38	0.26	1.06
Fm-255	1.24	1.30	0.27	1.10
Fm-257	1.12	1.08	0.89	2.67
Fr-219	1.08	1.04		
Fr-220	1.12	1.06		
Fr-221	1.10	1.05		
Fr-222	0.20	0.04	0.24	0.92
Fr-223	1.04	0.73	1.87	0.99
Ga-65	1.07	0.96	0.45	0.65
Ga-66	1.05	0.99	1.14	1.10
Ga-67	1.11	1.06	0.63	1.10
Ga-68	1.07	0.94	0.63	0.90
Ga-70	0.55	0.12	0.46	0.65
Ga-72	1.06	1.01	0.95	1.13
Ga-73	1.06	0.91	0.71	1.07
Gd-145	1.06	1.00	0.52	0.76

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Gd-146	1.15	1.11	0.94	1.15
Gd-147	1.08	1.04	1.01	1.20
Gd-148	0.00	0.00	2.07	1.05
Gd-149	1.09	1.05	0.85	1.18
Gd-151	1.16	1.14	1.40	1.12
Gd-152	0.00	0.00	2.20	1.06
Gd-153	1.19	1.15	1.23	1.14
Gd-159	1.02	0.77	0.96	1.08
Ge-66	1.08	1.03	0.94	0.55
Ge-67	1.06	0.95	0.58	0.54
Ge-68	0.73	0.53	1.01	0.22
Ge-69	1.07	1.01	0.79	0.42
Ge-71	0.73	0.53	3.13	0.22
Ge-75	0.94	0.48	0.50	0.55
Ge-77	1.07	0.96	0.78	0.47
Ge-78	1.09	1.01	0.81	0.60
H-3	0.00	0.00		0.90
Hf-170	1.10	1.05	1.38	1.18
Hf-172	1.19	1.14	2.65	1.16
Hf-173	1.11	1.06	1.50	1.18
Hf-175	1.10	1.05	2.10	1.19
Hf-177m	1.09	1.05	0.60	0.91
Hf-178m	1.09	1.04	2.50	1.20
Hf-179m	1.09	1.05	2.50	1.17
Hf-180m	1.09	1.05	1.06	1.17
Hf-181	1.08	1.04	2.91	1.14
Hf-182	1.10	1.04	2.92	1.42
Hf-182m	1.08	1.04	0.78	0.93
Hf-183	1.07	0.98	1.31	0.93
Hf-184	1.09	0.98	1.62	1.10

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Hg-193	1.13	1.07		1.11
Hg-193m	1.08	1.04		1.15
Hg-194	1.11	0.92		1.20
Hg-195	1.10	1.05		1.11
Hg-195m	1.09	1.05		1.11
Hg-197	1.17	1.11		1.11
Hg-197m	1.12	1.07		1.09
Hg-199m	1.09	1.06		0.79
Hg-203	1.09	1.05		1.15
Ho-155	1.08	0.98	0.59	0.94
Ho-157	1.09	1.05	0.33	0.83
Ho-159	1.11	1.07	0.28	0.87
Ho-161	1.23	1.19	0.66	1.06
Ho-162	1.10	1.05	0.22	0.69
Ho-162m	1.08	1.04	0.32	0.99
Ho-164	1.12	0.90	0.28	0.71
Ho-164m	1.23	1.18	0.43	0.88
Ho-166	0.83	0.29	1.30	1.08
Ho-166m	1.08	1.03	1.74	1.10
Ho-167	1.09	1.02	0.41	1.07
I-120	1.05	0.98	1.20	0.61
I-120m	1.06	1.00	0.87	0.62
I-121	1.08	1.03	1.16	0.65
I-122	1.06	0.92		
I-123	1.12	1.08	1.07	0.66
I-124	1.07	1.01	1.18	0.66
I-125	1.39	1.35	1.25	0.68
I-126	1.07	1.01	1.22	0.66
I-128	0.96	0.51	0.98	0.53
I-129	1.34	1.32	1.31	0.71

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
I-130	1.07	1.02	1.06	0.65
I-131	1.08	1.03	1.20	0.66
I-132	1.07	1.00	1.10	0.63
I-132m	1.08	1.01	1.21	0.72
I-133	1.07	0.97	1.08	0.65
I-134	1.07	1.00	0.79	0.62
I-135	1.06	1.00	1.03	0.65
In-109	1.08	1.04	0.53	1.15
In-110a	1.06	0.99	1.43	2.82
In-110b	1.07	1.03	0.23	0.39
In-111	1.11	1.06	0.98	1.23
In-112	1.06	0.96	0.28	0.64
In-113m	1.08	1.05	0.45	0.99
In-114	0.87	0.98		
In-114m	1.07	1.06	1.97	1.13
In-115	0.07	0.51	1.70	1.31
In-115m	1.08	1.05	0.58	1.08
In-116m	1.06	1.02	0.33	0.93
In-117	1.08	1.02	0.27	0.84
In-117m	1.03	0.72	0.57	0.93
In-119	1.06	0.94		
In-119m	0.49	0.13	0.59	0.62
Ir-182	1.07	0.98	0.53	0.72
Ir-184	1.07	1.02	0.49	1.11
Ir-185	1.07	1.04	0.78	1.14
Ir-186a	1.07	1.03	0.77	1.19
Ir-186b	1.07	1.02	0.00	0.00
Ir-187	1.08	1.04	0.71	1.16
Ir-188	1.06	1.03	0.99	1.21
Ir-189	1.15	1.10	0.73	1.11

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Ir-190	1.08	1.04	0.74	1.17
Ir-190m	0.92	0.72	0.80	1.06
Ir-190n	1.08	1.04	0.00	0.00
Ir-191m	1.15	1.09		
Ir-192	1.08	1.03	1.15	1.13
Ir-192m	1.11	1.05	2.66	1.37
Ir-194	0.96	0.51	1.41	1.07
Ir-194m	1.08	1.04	1.46	1.16
Ir-195	1.06	0.75	0.52	0.91
Ir-195m	1.08	1.02	0.40	0.84
K-38	1.05	0.98		
K-40	1.02	0.72	1.61	0.81
K-42	0.99	0.67	2.94	0.70
K-43	1.07	1.02	1.32	0.82
K-44	1.04	0.96	1.12	0.55
K-45	1.05	0.96	0.92	0.56
Kr-74	1.07	0.96		
Kr-76	1.09	1.04		
Kr-77	1.08	0.96		
Kr-79	1.08	1.03		
Kr-81	1.09	1.03		
Kr-81m	1.10	1.04		
Kr-83m	1.25	1.06		
Kr-85	0.50	0.25		
Kr-85m	1.09	0.97		
Kr-87	1.04	0.87		
Kr-88	1.05	1.01		
La-131	1.08	1.01	0.48	0.92
La-132	1.06	1.00	0.84	1.11
La-134	1.06	0.93		

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
La-135	1.19	1.22	1.11	1.18
La-137	1.34	1.30	1.71	1.49
La-138	1.06	1.03	1.49	1.45
La-140	1.05	1.00	1.22	1.13
La-141	0.83	0.30	1.04	1.04
La-142	1.05	0.99	0.61	0.98
La-143	0.90	0.43	0.76	0.67
Lu-169	1.07	1.03	0.94	1.18
Lu-170	1.06	1.02	1.04	1.19
Lu-171	1.08	1.04	0.92	1.15
Lu-172	1.07	1.03	0.87	1.17
Lu-173	1.15	1.10	2.48	1.14
Lu-174	1.10	1.07	2.51	1.11
Lu-174m	1.18	1.13	1.62	1.09
Lu-176	1.09	1.05	3.23	1.11
Lu-176m	0.77	0.26	0.63	1.04
Lu-177	1.08	1.06	0.55	1.09
Lu-177m	1.10	1.05	1.23	1.16
Lu-178	0.99	0.62	0.49	0.70
Lu-178m	1.09	1.01	0.26	0.72
Lu-179	0.92	0.41	0.88	1.05
Md-257	1.11	1.07	0.62	1.52
Md-258	1.30	1.35	0.76	2.48
Mg-28	1.06	1.03	1.11	1.01
Mn-51	1.06	0.93	0.62	0.81
Mn-52	1.06	1.02	1.13	1.14
Mn-52m	1.06	0.97	0.53	0.70
Mn-53	0.00	0.00	2.48	0.97
Mn-54	1.07	1.03	1.15	1.04
Mn-56	1.05	0.98	0.73	1.03

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Mo-101	1.06	0.98	0.38	
Mo-90	1.08	1.02	0.92	
Mo-93	1.46	1.38	3.31	
Mo-93m	1.07	1.03	0.61	
Mo-99	1.04	0.83	1.08	
N-13	1.07	0.98		
Na-22	1.06	1.02	1.62	0.98
Na-24	1.05	1.01	1.17	0.88
Nb-88	1.07	1.00	0.25	0.38
Nb-89a	1.07	0.98	1.57	1.98
Nb-89b	1.05	0.95	0.40	0.48
Nb-90	1.06	1.01	0.93	1.16
Nb-93m	1.46	1.38	4.46	1.14
Nb-94	1.07	1.03	2.30	1.11
Nb-95	1.07	1.03	0.90	1.18
Nb-95m	1.07	1.06	0.75	1.10
Nb-96	1.06	1.02	0.93	1.15
Nb-97	1.06	0.96	0.50	0.92
Nb-97m	1.07	1.03		
Nb-98	1.06	0.99	0.57	0.89
Nd-136	1.10	1.06	0.58	0.97
Nd-138	1.19	1.18	1.12	1.08
Nd-139	1.07	0.98	0.55	0.82
Nd-139m	1.07	1.03	0.65	1.15
Nd-141	1.11	1.10	0.54	1.08
Nd-141m	1.07	1.02		
Nd-147	1.08	0.99	0.77	1.10
Nd-149	1.08	0.93	0.66	1.00
Nd-151	1.06	0.96	0.47	0.71
Ne-19	1.06	0.94		

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Ni-56	1.08	1.03	1.24	1.21
Ni-57	1.06	1.02	1.03	1.16
Ni-59	0.00	0.00	1.88	0.90
Ni-63	0.00	0.00	1.32	1.03
Ni-65	1.04	0.91	0.71	0.92
Ni-66	0.06	1.23	1.38	1.08
Np-232	1.08	1.04		
Np-233	1.13	1.08		
Np-234	1.06	1.02		
Np-235	1.21	1.28		
Np-236a	1.13	1.08		
Np-236b	1.11	1.07		
Np-237	1.16	1.14		
Np-238	1.06	0.99		
Np-239	1.10	1.06		
Np-240	1.07	1.02		
Np-240m	1.05	0.85		
O-15	1.07	0.94		
Os-180	1.17	1.11	0.26	0.81
Os-181	1.07	1.04	0.56	1.10
Os-182	1.10	1.05	0.96	1.17
Os-185	1.08	1.04	1.66	1.17
Os-189m	0.85	0.65	1.52	1.03
Os-190m	1.08	1.03		
Os-191	1.15	1.09	0.59	1.09
Os-191m	1.19	1.12	0.52	1.08
Os-193	1.03	0.75	1.03	1.08
Os-194	1.26	1.19	2.13	1.21
P-30	1.05	0.90		
P-32	0.18	0.03	2.11	0.99

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
P-33	0.06	1.22	1.84	1.01
Pa-227	1.15	1.09		
Pa-228	1.07	1.04		
Pa-230	1.08	1.03		
Pa-231	1.10	1.08		
Pa-232	1.07	1.03		
Pa-233	1.09	1.05		
Pa-234	1.07	1.02		
Pa-234m	0.59	0.14		
Pb-195m	1.08	1.02		
Pb-198	1.10	1.05		
Pb-199	1.07	1.03		
Pb-200	1.12	1.06		
Pb-201	1.08	1.04		
Pb-202	0.91	0.70		
Pb-202m	1.07	1.03		
Pb-203	1.11	1.05		
Pb-205	0.93	0.72		
Pb-209	0.08	0.09		
Pb-210	1.25	1.16		
Pb-211	0.96	0.54		
Pb-212	1.10	1.06		
Pb-214	1.07	1.02		
Pd-100	1.17	1.13	1.24	1.22
Pd-101	1.08	1.04	0.81	1.18
Pd-103	1.44	1.42	0.95	1.12
Pd-107	0.00	0.00	5.88	1.09
Pd-109	0.60	0.30	0.79	1.07
Pm-141	1.06	0.94	0.58	0.69
Pm-142	1.05	0.90		

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Pm-143	1.08	1.04	2.03	1.19
Pm-144	1.07	1.03	1.90	1.19
Pm-145	1.28	1.24	3.47	1.11
Pm-146	1.07	1.03	2.27	1.09
Pm-147	0.08	1.21	2.18	1.08
Pm-148	1.05	0.90	1.36	1.10
Pm-148m	1.07	1.03	1.06	1.17
Pm-149	0.76	0.28	1.09	1.08
Pm-150	1.06	0.96	0.74	1.04
Pm-151	1.08	0.99	1.00	1.10
Po-203	1.07	1.02	0.57	1.02
Po-205	1.07	1.03	0.43	1.08
Po-207	1.07	1.03	0.60	1.16
Po-210	1.07	1.03	0.71	2.10
Po-211	1.07	1.03		
Po-212	0.00	0.00		
Po-213	0.00	0.00		
Po-214	1.07	1.03		
Po-215	1.08	1.04		
Po-216	1.07	1.02		
Po-218	1.06	1.03		
Pr-136	1.06	0.99	0.49	0.67
Pr-137	1.07	0.99	0.62	0.97
Pr-138	1.05	0.91		
Pr-138m	1.07	1.02	0.49	1.08
Pr-139	1.09	1.04	0.79	1.11
Pr-142	0.90	0.39	1.41	1.07
Pr-142m	0.00	0.00	1.42	1.08
Pr-143	0.11	0.03	0.90	1.09
Pr-144	0.74	0.23	0.64	0.62

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Pr-144m	1.26	1.24		
Pr-145	0.66	0.17	1.09	1.06
Pr-147	1.06	0.94	0.43	0.64
Pt-186	1.08	1.04	1.07	1.17
Pt-188	1.12	1.07	1.99	1.17
Pt-189	1.10	1.05	1.24	1.16
Pt-191	1.11	1.06	1.54	1.15
Pt-193	0.98	0.77	2.91	1.04
Pt-193m	1.10	1.12	1.92	1.08
Pt-195m	1.16	1.11	1.86	1.09
Pt-197	1.03	0.95	1.79	1.07
Pt-197m	1.07	1.07	1.39	1.00
Pt-199	1.04	0.81	1.00	0.75
Pt-200	1.09	1.03	2.04	1.09
Pu-234	1.14	1.08		
Pu-235	1.13	1.08		
Pu-236	1.35	1.33		
Pu-237	1.14	1.09		
Pu-238	1.39	1.34		
Pu-239	1.21	1.29		
Pu-240	1.38	1.34		
Pu-241	1.14	1.12		
Pu-242	1.38	1.34		
Pu-243	1.07	1.06		
Pu-244	548.08	49.76		
Pu-245	1.07	1.00		
Pu-246	1.12	1.08		
Ra-222	1.09	1.04		
Ra-223	1.11	1.06		
Ra-224	1.10	1.05		

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Ra-225	1.16	1.24		
Ra-226	1.11	1.05		
Ra-227	1.05	0.87		
Ra-228	0.00	0.00		
Rb-79	1.07	0.97	0.80	0.56
Rb-80	1.05	0.91		
Rb-81	1.08	1.02	1.02	0.72
Rb-81m	1.15	1.11	0.77	0.65
Rb-82	1.06	0.92		
Rb-82m	1.07	1.03	0.71	0.86
Rb-83	1.08	1.03	1.91	1.11
Rb-84	1.07	1.02	1.70	0.97
Rb-86	0.97	0.56	1.92	0.90
Rb-87	0.06	1.20	1.76	0.90
Rb-88	1.01	0.80	1.40	0.52
Rb-89	1.05	0.97	0.86	0.57
Re-177	1.07	0.99	0.36	0.66
Re-178	1.06	0.98	0.36	0.63
Re-180	1.07	1.03		
Re-181	1.08	1.04	0.69	0.67
Re-182a	1.07	1.04	0.51	0.73
Re-182b	1.08	1.03	0.64	0.62
Re-184	1.08	1.03	0.73	0.59
Re-184m	1.09	1.04	0.61	0.54
Re-186	0.92	0.46	0.78	0.54
Re-186m	1.20	1.14	0.80	0.48
Re-187	0.00	0.00	2.34	0.50
Re-188	0.92	0.41	1.01	0.61
Re-188m	1.18	1.12	0.86	0.61
Re-189	1.04	0.80	0.76	0.60

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Rh-100	1.06	1.02	1.05	1.20
Rh-101	1.11	1.06	1.98	1.13
Rh-101m	1.08	1.05	0.96	1.22
Rh-102	1.07	1.03	1.85	1.09
Rh-102m	1.07	1.00	1.80	1.08
Rh-103m	1.46	1.41	0.47	0.83
Rh-105	1.07	1.03	0.73	1.09
Rh-106	0.98	0.61		
Rh-106m	1.07	1.02	0.44	1.06
Rh-107	1.06	0.91	0.35	0.67
Rh-99	1.08	1.04	0.95	1.18
Rh-99m	1.08	1.03	0.56	1.16
Rn-218	1.07	1.03		
Rn-219	1.09	1.04		
Rn-220	1.08	1.03		
Rn-222	1.07	1.03		
Ru-103	1.08	1.03	0.82	
Ru-105	1.07	0.98	0.69	
Ru-106	0.00	0.00	1.95	
Ru-94	1.08	1.04	0.70	
Ru-97	1.10	1.06	1.12	
S-35	0.08	1.26	1.58	
Sb-115	1.07	1.01	0.82	0.80
Sb-116	1.06	1.00	0.68	0.72
Sb-116m	1.07	1.03	0.64	0.99
Sb-117	1.11	1.07	0.78	1.11
Sb-118m	1.07	1.03	0.76	1.15
Sb-119	1.43	1.38	1.31	1.11
Sb-120a	1.07	0.96	0.77	0.65
Sb-120b	1.07	1.03	1.10	1.16

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Sb-122	1.05	0.90	1.72	1.08
Sb-124	1.06	1.01	1.15	1.04
Sb-124m	1.08	1.01		
Sb-124n	1.44	1.40	0.78	0.73
Sb-125	1.08	1.04	0.41	0.67
Sb-126	1.07	1.03	1.23	1.12
Sb-126m	1.07	0.99	0.75	0.70
Sb-127	1.07	1.00	1.51	1.08
Sb-128a	1.07	0.97	0.46	0.49
Sb-128b	1.07	1.02	1.58	1.48
Sb-129	1.06	1.01	1.56	1.09
Sb-130	1.07	1.01	0.85	0.85
Sb-131	1.06	0.99	1.12	0.79
Sc-43	1.08	1.01	0.61	1.11
Sc-44	1.06	1.00	0.72	1.09
Sc-44m	1.09	1.04	1.49	1.14
Sc-46	1.07	1.03	1.18	1.17
Sc-47	1.10	1.04	0.69	1.11
Sc-48	1.06	1.02	0.99	1.16
Sc-49	0.27	0.05	0.69	0.83
Se-70	1.07	0.98	0.54	
Se-73	1.08	1.00	0.64	
Se-73m	1.07	0.95	0.61	
Se-75	1.10	1.04	2.17	
Se-77m	1.11	1.05		
Se-79	0.08	1.25	1.01	
Se-81	0.60	0.14	0.43	
Se-81m	1.12	1.06	0.45	
Se-83	1.06	1.01	0.39	
Si-31	0.24	0.04	0.75	0.91

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Si-32	0.06	1.24	0.85	1.05
Sm-141	1.07	0.98	0.54	0.69
Sm-141m	1.07	1.01	0.49	0.81
Sm-142	1.10	1.06	0.82	0.91
Sm-145	1.28	1.23	1.79	1.13
Sm-146	0.00	0.00	2.09	1.01
Sm-147	0.00	0.00	2.10	1.01
Sm-151	1.46	1.42	2.04	1.07
Sm-153	1.11	1.02	0.84	1.09
Sm-155	1.05	0.65	0.40	0.66
Sm-156	1.10	1.04	0.86	1.10
Sn-110	1.10	1.06	0.87	1.16
Sn-111	1.07	0.98	0.52	0.83
Sn-113	1.21	1.30	1.08	1.13
Sn-117m	1.11	1.08	0.48	1.12
Sn-119m	1.43	1.38	0.78	1.09
Sn-121	0.06	1.19	0.61	1.07
Sn-121m	1.14	1.35	0.70	1.10
Sn-123	0.58	0.13	1.08	1.08
Sn-123m	1.06	0.78	0.39	0.77
Sn-125	1.03	0.79	1.36	1.08
Sn-126	1.14	1.13	0.95	1.10
Sn-127	1.06	1.00	0.65	1.04
Sn-128	1.08	1.05	0.50	0.96
Sr-80	1.31	1.16		
Sr-81	1.07	0.96		
Sr-82	1.31	1.16		
Sr-83	1.07	1.01		
Sr-85	1.08	1.04		
Sr-85m	1.11	1.05		

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Sr-87m	1.08	1.04		
Sr-89	0.18	0.03		
Sr-90	0.08	0.17		
Sr-91	1.06	0.93		
Sr-92	1.06	1.02		
Ta-172	1.07	1.00	0.44	0.81
Ta-173	1.08	0.99	0.74	1.09
Ta-174	1.08	0.99	0.42	0.93
Ta-175	1.07	1.04	0.77	1.16
Ta-176	1.06	1.02	0.63	1.16
Ta-177	1.17	1.12	0.79	1.12
Ta-178a	1.12	1.08		
Ta-178b	1.10	1.05	0.33	1.09
Ta-179	1.21	1.15	3.10	1.11
Ta-180	1.10	1.05	2.58	1.16
Ta-180m	1.19	1.12	0.61	1.09
Ta-182	1.07	1.03	1.16	1.14
Ta-182m	1.11	1.07	0.17	0.65
Ta-183	1.10	1.06	0.65	1.11
Ta-184	1.08	1.01	0.70	1.12
Ta-185	1.06	0.76	0.47	0.81
Ta-186	1.07	0.97	0.36	0.62
Tb-147	1.07	0.99	0.73	1.03
Tb-149	1.07	1.02	0.40	1.11
Tb-150	1.06	1.00	0.77	1.08
Tb-151	1.09	1.04	0.74	1.19
Tb-153	1.11	1.08	1.08	1.16
Tb-154	1.06	1.02	0.87	1.20
Tb-155	1.15	1.10	0.96	1.17
Tb-156	1.07	1.03	0.89	1.18

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Tb-156m	1.24	1.18	0.96	1.16
Tb-156n	1.19	1.16	0.61	1.12
Tb-157	1.26	1.21	2.04	0.98
Tb-158	1.07	1.03	1.49	1.05
Tb-160	1.07	1.03	0.96	1.13
Tb-161	1.14	1.17	0.73	1.09
Tc-101	1.07	0.90	0.33	
Tc-104	1.05	0.95	0.63	
Tc-93	1.06	1.03	0.38	
Tc-93m	1.06	1.03	0.38	
Tc-94	1.07	1.03	0.45	
Tc-94m	1.06	0.98	0.60	
Tc-95	1.07	1.03	0.63	
Tc-95m	1.08	1.03	1.18	
Tc-96	1.07	1.03	0.92	
Tc-96m	1.07	1.05	0.84	
Tc-97	1.47	1.39	1.22	
Tc-97m	1.24	1.39	0.41	
Tc-98	1.07	1.03	0.74	
Tc-99	0.06	1.20	0.56	
Tc-99m	1.12	1.06	0.37	
Te-116	1.15	1.17	0.58	
Te-121	1.08	1.04	1.34	
Te-121m	1.10	1.06	0.95	
Te-123	1.41	1.36	0.67	
Te-123m	1.12	1.08	0.72	
Te-125m	1.34	1.35	0.59	
Te-127	0.72	0.50	0.68	
Te-127m	1.30	1.31	0.78	
Te-129	0.96	0.53	0.57	

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Te-129m	0.99	0.66	0.99	
Te-131	1.06	0.86	4.35	
Te-131m	1.07	1.02	1.62	
Te-132	1.10	1.07	1.24	
Te-133	1.06	0.93	1.22	
Te-133m	1.06	1.00	1.24	
Te-134	1.08	1.02	0.48	
Th-226	1.11	1.07		
Th-227	1.10	1.06		
Th-228	1.13	1.10		
Th-229	1.14	1.08		
Th-230	1.17	1.18		
Th-231	1.14	1.19		
Th-232	1.20	1.21		
Th-234	1.15	1.11		
Ti-44	1.17	1.11	2.21	1.08
Ti-45	1.07	0.99	0.61	1.07
Tl-194	1.08	1.04	0.56	0.75
Tl-194m	1.08	1.02	0.64	0.66
Tl-195	1.07	1.03	0.81	0.77
Tl-197	1.08	1.04	0.96	0.80
Tl-198	1.07	1.03	0.72	0.93
Tl-198m	1.08	1.04	0.76	0.78
Tl-199	1.11	1.06	0.99	0.85
Tl-200	1.07	1.02	0.94	0.90
Tl-201	1.16	1.10	1.39	0.84
Tl-202	1.09	1.04	1.38	0.87
Tl-204	0.33	0.14	1.64	0.76
Tl-206	0.17	0.03		
Tl-207	0.36	0.07		

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Tl-208	1.05	1.00		
Tl-209	1.06	0.99		
Tm-162	1.06	1.01	0.37	0.75
Tm-166	1.06	1.03	0.59	1.17
Tm-167	1.12	1.09	0.70	1.11
Tm-170	0.61	0.22	1.02	1.08
Tm-171	1.21	1.15	1.79	1.09
Tm-172	1.05	0.92	1.17	1.09
Tm-173	1.08	0.99	0.72	1.10
Tm-175	1.07	0.98	0.34	0.68
U-230	1.14	1.16		
U-231	1.15	1.10		
U-232	1.20	1.25		
U-233	1.15	1.19		
U-234	1.24	1.28		
U-235	1.11	1.06		
U-236	1.29	1.29		
U-237	1.12	1.07		
U-238	1.36	1.30		
U-239	1.02	0.62		
U-240	0.67	1.32		
V-47	1.06	0.94	0.52	0.75
V-48	1.07	1.03	1.17	1.17
V-49	0.00	0.00	2.77	0.90
W-176	1.17	1.10	0.69	1.00
W-177	1.09	1.04	0.71	1.00
W-178	1.20	1.14	1.00	0.92
W-179	1.21	1.17	1.00	0.79
W-181	1.20	1.14	1.50	0.99
W-185	0.11	1.08	1.75	0.97

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
W-187	1.07	1.00	0.86	0.88
W-188	0.82	1.05	1.96	1.01
Xe-120	1.08	1.05		
Xe-121	1.06	1.00		
Xe-122	1.12	1.13		
Xe-123	1.07	1.01		
Xe-125	1.10	1.07		
Xe-127	1.11	1.07		
Xe-129m	1.15	1.27		
Xe-131m	1.11	1.28		
Xe-133	1.16	1.16		
Xe-133m	1.06	1.15		
Xe-135	1.07	0.97		
Xe-135m	1.07	1.01		
Xe-138	1.05	0.96		
Y-86	1.06	1.02	0.98	1.18
Y-86m	1.10	1.04	0.94	1.16
Y-87	1.08	1.03	1.20	1.19
Y-88	1.05	1.02	1.69	1.24
Y-90	0.24	0.05	1.52	1.08
Y-90m	1.09	1.03	1.25	1.10
Y-91	0.42	0.08	1.48	1.09
Y-91m	1.08	1.03	0.86	0.97
Y-92	0.98	0.66	1.19	1.04
Y-93	0.91	0.43	1.38	1.07
Y-94	1.04	0.90	0.68	0.65
Y-95	1.03	0.88	0.65	0.59
Yb-162	1.15	1.09	0.43	0.89
Yb-166	1.21	1.15	1.04	1.19
Yb-167	1.15	1.10	0.32	0.75

Nuclide	Cloudshine	Groundshine	Inhalation	Ingestion
Yb-169	1.14	1.09	0.73	1.14
Yb-175	1.07	1.05	0.60	1.09
Yb-177	1.05	0.83	0.57	0.89
Yb-178	1.03	0.96	0.59	0.91
Zn-62	1.08	1.04	1.02	
Zn-63	1.06	0.94	0.60	
Zn-65	1.06	1.03	2.75	
Zn-69	0.11	0.03	0.38	
Zn-69m	1.08	1.04	0.82	
Zn-71m	1.07	0.99	0.65	
Zn-72	1.11	1.05	1.04	
Zr-86	1.09	1.05	1.30	
Zr-88	1.08	1.04	1.11	
Zr-89	1.07	1.03	1.16	
Zr-93	0.00	0.00	2.20	
Zr-95	1.07	1.03	0.90	
Zr-97	1.01	0.70	1.15	

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