NUREG/CR-4185
SAND85-0283
AN, CF, C3, C4, 9U, 9G (Tech Only), RH, RE

Printed August 1985

An Assessment of Dosimetry Data for Accidental Radionuclide Releases from Nuclear Reactors

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Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

Prepared for
U. S. NUCLEAR REGULATORY COMMISSION

Available from

GPO Sales Program
Division of Technical Information and Document Control
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

and

National Technical Information Service
Springfield, Virginia 22161

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AN ASSESSMENT OF DOSIMETRY DATA FOR ACCIDENTAL RADIONUCLIDE RELEASES FROM NUCLEAR REACTORS

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operated by
Sandia Corporation
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U.S. Department of Energy

Prepared for
Division of Risk Analysis and Operations
Office of Nuclear Regulatory Research
US Nuclear Regulatory Commission
Washington, D.C. 20555
Under Memorandum of Understanding DOE 40-550-75
NRC FIN Nos. A-1339 and A-1042

ABSTRACT

This report reviews dosimetry models for estimating the absorbed dose from external and internal exposure to radionuclides. Important modeling parameters and assumptions are described. Recommendations for the dosimetry data to be used in the MELCOR health and economic consequence model are made. For estimating the dose from cloudshine and groundshine, the models for external exposure developed by Kocher are recommended. The ICRP-Publication 30 models and metabolic parameters are recommended for estimating the dose from radionuclides deposited internally via inhalation and ingestion. Dose conversion factors calculated with these models for a variety of radionuclides, clearance classes, particle sizes and integration periods were obtained from Oak Ridge National Laboratory for use in the MELCOR health and economic consequence model. Sources and magnitude of uncertainty in dose factors were evaluated. Recommendations are made for assessing the uncertainty in estimated consequences due to uncertainty in dose conversion factors.

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ACKNOWLEDGMENT

The authors would like to thank Dr. Keith Eckerman of Oak Ridge National Laboratory (ORNL) and Drs. D. J. Alpert and J. L. Sprung of Sandia National Laboratories for the technical support and review comments provided in the preparation of this report. We would also like to acknowledge the preparation of the dose conversion factors by Dr. Eckerman and the ORNL staff.

1.0 INTRODUCTION

The U.S. Nuclear Regulatory Commission has funded Sandia National Laboratories to develop an integrated package of modular risk assessment codes for evaluating the consequences of severe reactor accidents. This integrated code system, known as MELCOR, considers the fission product transport within the reactor vessel and the containment, the atmospheric transport of the released radionuclides, the radiation exposure to the surrounding population and the resulting health and economic consequences (Sprung, et al., 1983). The part of the MELCOR system which treats the ex-plant transport and consequence analysis is termed MACCS for MELCOR Accident Consequence Code System.

MACCS models the atmospheric transport of released radionuclides from the reactor to the surrounding environment and assesses the impact of radiation exposures received by the human population. As part of this evaluation, it is necessary to consider the absorbed dose to humans resulting from exposure to ionizing radiation. The absorbed dose is defined as the energy deposited in matter by ionizing radiation per unit mass of irradiated material. The International System of Units (SI) measure for the absorbed dose is the gray (Gy), which is equivalent to 100 rad in the old unit system. The SI units have been adopted for use in the MELCOR program and the unit conversions from the old to SI units are listed in Table 1.

The major modes by which a population may be exposed to radionuclides released during a nuclear reactor accident include external exposure from the passing plume (cloudshine), external exposure from radionuclides deposited on the ground and other surfaces (groundshine), internal exposure by radionuclides inhaled from the passing plume and from resuspended radionuclides in the air, and internal exposure from ingestion of contaminated food sources and drinking water. These exposure modes and their implementation within MACCS are discussed in detail elsewhere (see Ostmeyer and Helton, 1985) and are not considered extensively in this report.

The health effects models that have been adopted for MACCS (see Evans et al., 1985) require estimates of absorbed dose for evaluating early health effects and dose equivalent for evaluating the latent health effects. The dose equivalent is usually estimated with the use of dose conversion factors. These factors are ratios between the dose equivalent to body tissues and measurable radiological quantities. For example, in the case of groundshine, the dose conversion factor is the ratio between the dose equivalent and the ground concentration of a radionuclide. Since the publication of dosimetric information by the International Committee on Radiation Protection (ICRP) in 1959, many modeling modification and data improvements have been incorporated into the mathematical models for estimating dose to humans.

TABLE 1 SI Dose Units

Quantity	SI Units	Old Unit System	Conversion Factor
Absorbed Dose	gray (Gy)[J/kg]	rad (rad)	1 Gy = 100 rad
Dose Equivalent	sievert (Sv)[J/kg]	rem (rem)	1 Sv = 100 rem
Activity	becquerel(Bq)[s^{-1}]	curie (Ci)	1 Bq~2.7x10^{-11}Ci

The purpose of this report is to review currently available dosimetry models and data and to provide recommendations for treating variation in the dose factors in sensitivity/uncertainty analyses. The external and internal exposure modes pose different modeling problems from a dose assessment standpoint. Thus, these modes are discussed separately. The models for estimating the dose from external exposures are discussed in Section 2.0 while those for internal exposures are discussed in Section 3.0. In these sections, the most recent dosimetry models and data are reviewed and a standard set of dose conversion factors are recommended for use in the MACCS code.

Uncertainty in dose factors results from two main sources: 1) uncertainty in defining the physical and chemical characteristics of the released radionuclides and 2) uncertainty in the dosimetry models. The uncertainty introduced into the dose factors is discussed in Section 4.0. Where possible, this uncertainty is quantified and a discussion of the treatment of this uncertainty in sensitivity/uncertainty analyses is provided. A summary of the dose models for use in MACCS is provided in Section 5.0 of this report.

2.0 EXTERNAL DOSIMETRY

External exposure to the human population will result from gamma-ray and beta emissions from the released radionuclides. The two major exposure modes include irradiation from the contaminated plume (cloudshine) and irradiation from radionuclides deposited on the ground (groundshine). In addition to these exposure modes, beta-emitting radionuclides deposited on the skin surfaces may result in large beta doses to the skin. Deposition of radiation on skin has not been treated in previous consequence analyses, however, it is incorporated into MACCS and is further discussed in this report.

The dose from external sources depends upon the radionuclide concentration within the environmental media (air, soil),

radionuclide decay and build-up, the exposure interval to the contaminated media and the shielding provided by structures and surface geometries. Generally, the dose estimates assume a homogeneous distribution of the radioactivity within a large region of the medium. The modeling approaches that are used for estimating the external dose from cloudshine, groundshine and external beta to the skin are discussed in Sections 2.1, 2.2 and 2.3, respectively.

2.1 Cloudshine

External gamma-ray and beta doses can be received by individuals immersed within or in close proximity to a radioactive plume. MACCS utilizes the finite cloud model discussed in Slade (1968) for predicting cloudshine exposures (Ostmeyer and Helton, 1985). This model makes use of semi-infinite cloud (i.e., a plume of infinite extent above the ground surface) dose conversion factors and a correction factor to correct for finite plume dimensions.

Kocher (1979, 1981) has recently published external dose conversion factors for gamma and beta emitters. The most recent publication (Kocher, 1981) considers approximately 500 radionuclides and 22 body organs. These factors, which assume a uniformly mixed semi-infinite cloud, supercede earlier compilations of factors calculated with the use of EXREM III (Trubey and Kaye, 1973). The EXREM III computer code was used to calculate the external dose conversion factors for the Reactor Safety Study (RSS), (USNRC, 1975) and are still used by existing consequence assessment codes (e.g., CRAC2, Ritchie et al., 1983).

Kocher's dose rate factors for cloud immersion are in units of Sv/yr per Bq/cm^3. The dose rate factors (DRF_γ^k) are given by the equation (Kocher, 1981)

$$DRF_\gamma^k = 1/2\ K \frac{1}{\rho_a} \sum_i f_{i\gamma}\ E_{i\gamma}\ G_\gamma^k\ (E_{i\gamma}) \qquad (2.1)$$

where k denotes the organ and the subscript i denotes the photon energies of $E_{i\gamma}$ and a decay frequency $f_{i\gamma}$ (number/decay). The density of air, ρ_a, is expressed in units of g/cm^3 and the energy of the i^{th} photon, $E_{i\gamma}$ has units of MeV. The constant, K, is the product of 1.6×10^{-10} g-Gy/MeV and 3.15×10^7 s/yr. The factor of 1/2 accounts for the geometry of the source region at the air-ground interface (Dillman, 1974). The factor $G_\gamma^k\ (E_{i\gamma})$ is defined as the ratio of the dose rate in the kth organ to the air kerma for photons of energy, $E_{i\gamma}$. Detailed discussion of the equation for the dose rate factors for air immersion are available in Kocher 1979, 1980 and 1981.

From a modeling perspective, the equations used by Kocher are similar to those in the EXREM III code (Trubey and Kaye, 1973). The EXREM III code calculates the gamma dose rate to skin and then determines organ doses using data which relates organ doses to skin doses. The organ dose to skin dose ratios incorporate work by Poston and Snyder (1974). Kocher's (1981) dose-rate factors are based on data developed by Eckerman et al. (1980). Eckerman et al. developed factors which relate organ gamma doses to air kerma for isotropic monoenergetic gamma sources. The factors consider the energy spectra of scattered photons in air from the monoenergetic sources.

The modeling approach published by Kocher (1981) are considered to be the most appropriate for use in MACCS. The Kocher factors are adopted for use in the MELCOR code system.

2.2 Groundshine

Radionuclides may be deposited from a plume of radioactive material onto soil and other surfaces. These deposits will result in external gamma doses to persons inhabiting the area. The external gamma doses (i.e., groundshine) will be influenced by several physical processes that include radionuclide decay, weathering, and shielding afforded by structures and soil roughness. These processes are discussed in Ostmeyer and Helton (1985). In MACCS, the external dose from radionuclides deposited on the ground is the product of ground contamination (Bq/m^2), a shielding factor and the dose conversion factor for a smooth infinite planar source.

The publications by Kocher (1979, 1981) contain tabulations of dose factors for gamma emitting radionuclide deposits. These factors assume a smooth, infinite planar source with uniform concentration and are in terms of Sv/yr per Bq/cm^2. As noted earlier, the dose factors in Kocher (1981) data supercede earlier factors calculated with the use of the EXREM III (Trubey and Kaye, 1973).

The equation used by Kocher (1981) to estimate the ground gamma dose is defined as

$$DRF_{\gamma}^{k}(z) = K \sum_{i} E_{i\gamma} f_{i\gamma} G_{\gamma}^{k}(E_{i\gamma}) \int_{\sigma} Q_{\gamma}^{a}(r, E_{i\gamma}) d\sigma \qquad (2.2)$$

where k denotes the organ. The parameters K, $f_{i\gamma}$, $G_{\gamma}^{k}(E_{i\gamma})$ and $E_{i\gamma}$ are defined earlier for equation 2.1. The height, z, assumed for the calculations is 1 m. This 1 m height is representative

of the average height for most body organs, however individual organs may be sensitive to this assumption. The point-isotropic specific absorbed fraction, Q_γ^a (Berger, 1968), for photons in air is integrated over the ground surface denoted by σ. The specific absorbed fraction is defined to be the fraction of the ith photon energy which is absorbed per gram of air at a distance r from an isotropic point source. In this case, r is the distance from any point on the ground to the receptor position in air.

The specific absorbed fraction is given by Berger (1968) as

$$Q_\gamma^a (r, E_\gamma) = \frac{1}{4\pi r^2} (\mu_{en}/\rho)_a B_{en}^a (\mu_a r) \exp(-\mu_a r) \qquad (2.3)$$

where $(\mu_{en}/\rho)_a$ and μ_a are the mass energy-absorption and linear attenuation coefficients in air, respectively. B_{en}^a is the energy-absorption buildup factor in air. The buildup factor was given by Trubey (1966) as

$$B_{en}^a(\mu_a r) = 1 + C_a \mu_a r \exp(D_a \mu_a r) \qquad (2.4)$$

where the coefficients C_a and D_a are functions of E_γ.

Kocher (1983) assumes the ratio of the dose rate to the kth body organ to the dose rate in air, G_γ^k, is the same as the ratio for immersion in contaminated air. This assumption is valid only to the extent that the photon radiation field above ground is isotropic and independent of distance above the ground, and the extent that the energy spectrum of photons above ground is the same as the spectrum of scattered photons in an infinite atmospheric cloud source. However, the photon radiation field for groundshine is anisotropic with the energy spectra of scattered photons being different than that for the cloud immersion case. Kocher (1983) states that the magnitude of possible errors in the groundshine dose-rate factors due to the above assumption are not known -- although he does note that the possible errors for gammas with energies greater than 0.1 MeV should be at most a few tens of percent.

Kocher's (1981) dose factor data are considered to be the most appropriate for use in MACCS. Kocher's groundshine factors are implemented within the MELCOR code system.

2.3 External Beta Exposure to the Skin

Radiation burns may be a significant contributor to early occurring health effects for a severe reactor accident (Cooper et al., 1983). These burns would occur as a result of large beta doses to skin. External beta doses to the skin will result from three exposure routes: immersion within the plume, exposure to deposits on the ground and direct deposition of beta emitters to skin. The skin deposition pathway will generally dominate short-term beta doses to exposed skin following an accidental release of radioactivity. MACCS contains a provision to estimate beta doses for the skin deposition pathway (Ostmeyer and Helton, 1985).

Skin doses due to direct deposition of beta emitting radionuclides on the skin are highly dependent on parameters such as deposition rate to skin and the retention time of the radionuclides. MACCS determines the concentration of deposits to unprotected skin as the product of the integrated air concentration of radionuclides within the plume and a deposition velocity to skin (Ostmeyer and Helton, 1985). Doses due to these deposits are determined by integrating the skin dose rate from deposition to an assumed retention time. The beta dose rate to unprotected skin is defined to be the product of the deposition concentration and a skin deposition dose rate factor.

Tabulations of skin deposition dose rate factors are not available in the published literature. However, rough approximations of these rate factors can be obtained with the use of an equation developed by Loevinger et al., 1956. Figure 2.1, which is taken from Randerson (1984), shows beta dose rates above a plane surface as a function of maximum beta energy. These dose rates were calculated with the use of the Loevinger equation. These data can be used to estimate beta doses to skin by replacing the mass thickness of air above the planar source with the depth of concern in unprotected skin (0.1mm depth)(Evans, et al., 1985).

3.0 INTERNAL DOSIMETRY

Individuals can accumulate doses from internally deposited radionuclides via the inhalation and ingestion exposure pathways. During passage of the plume, inhalation exposures will be influenced by the time-integrated air concentration, the breathing rate of the individual, protection afforded by buildings, and respiratory protection measures. Inhalation exposures may also result from resuspension of radionuclides long after passage of the plume.

There are two distinct periods for the intake of radionuclides via ingestion. Immediately after deposition to plants, radionuclides are readily available for consumption by humans or animals. This direct deposition pathway is important

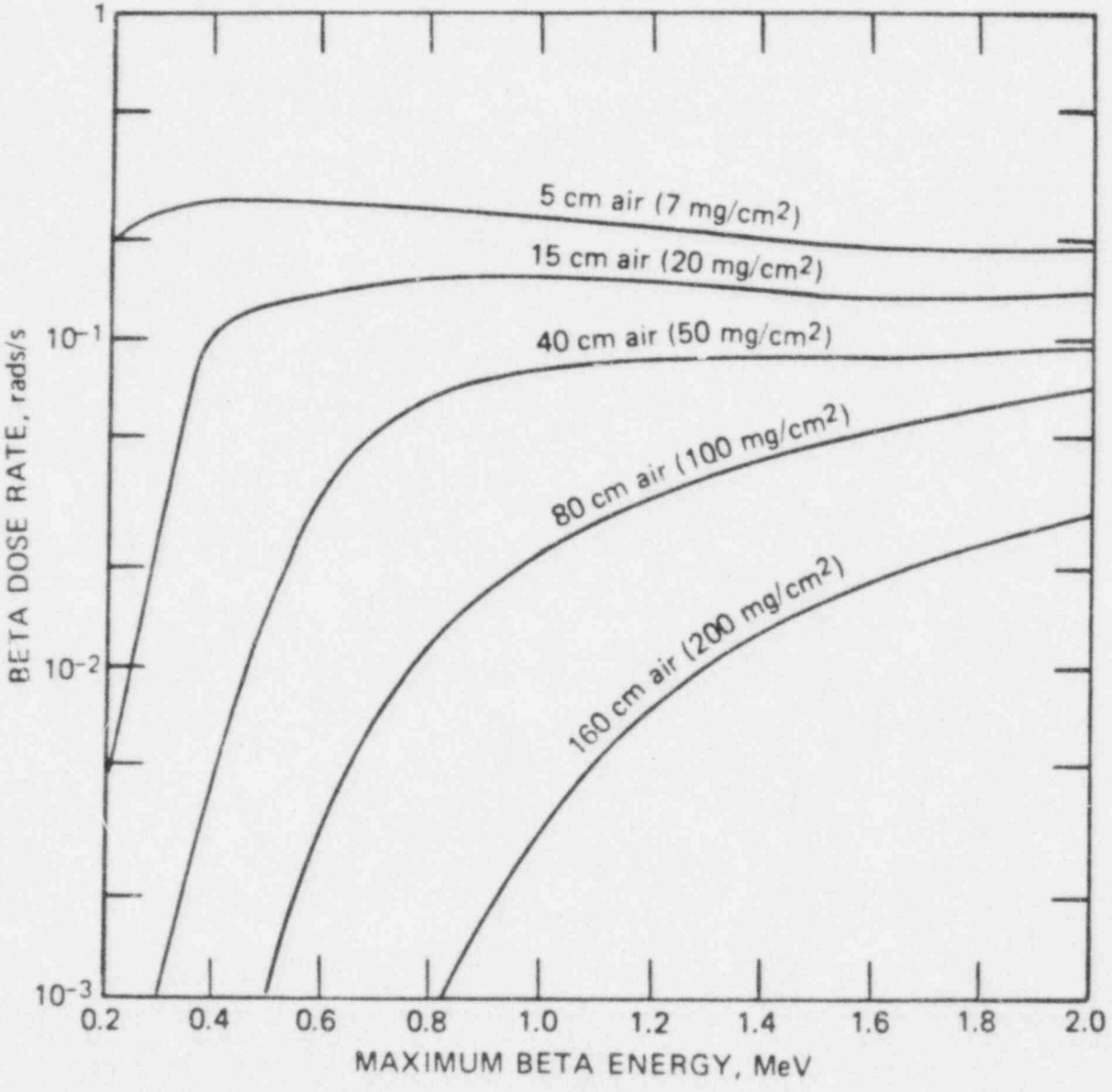


Figure 1 Beta dose rates above a plane surface with a deposition of 1 Ci/m^2 (3.7x10^{10} Bq/m^2) of a beta emitter with the maximum energy as given. The air thicknesses are vertical distances from ground surfaces. From Randerson, 1984.

particularly for the movement of I-131 through the milk pathway to humans (USNRC, 1975). The other exposure period is more long-term and involves the movement of the radionuclides deposited in the soil through the plant and animal foodchains to humans. The MACCS models for the inhalation and ingestion exposure pathways are discussed in Ostmeyer and Helton (1985). This section discusses the dosimetry models that are available for estimating doses to body organs from the internal exposures. The dosimetric models for estimating dose equivalents from inhaled and ingested radionuclides are discussed in Section 3.1 and 3.2, respectively.

3.1 Inhalation

Following intake of a radionuclide via inhalation, the dose received by any body organ depends on a number of factors including:

1. The chemical form of the radionuclide,
2. Properties of the aerosol containing the radionuclide,
3. The particle size of the inhaled aerosol,
4. The transport of the particles within the respiratory system, clearance to the gastrointestinal (GI) tract and absorption to the blood circulatory system,
5. Distribution of the radionuclide among the organs and tissues,
6. Retention of radionuclides by organs and tissues,
7. Radionuclide decay and the build-up of daughters within the body, and
8. Excretion from the body.

All of these factors are important when considering the dose equivalents to the lung and other body organs resulting from inhaled radionuclides.

The model used in ICRP-Publication 2 (ICRP, 1959) treated the lung as a single compartment with a transfer factor, f_L, describing the fraction of the inhaled radionuclide reaching the lung and f_a describing the fraction reaching the various body organs. The inhaled aerosol was designated as "soluble" or "insoluble." Inhaled "soluble" materials were assumed not to irradiate the lung but were instantaneously transferred to the gut or other body organs. "Insoluble" materials were assumed to irradiate the lung with clearance to the gut and with transfer to the other body organs. Radionuclides reached the gut via respiratory system clearance processes.

The ICRP-2 model and data are the basis for the dose conversion factors calculated with the INREM computer code (Turner et al., 1968; Killough et al., 1975) and by Hoenes and Soldat (1977). The dose conversion factors calculated by Hoenes and Soldat (1977) are used in the U. S. Nuclear Regulatory Commission Regulatory Guide 1.109 (USNRC, 1977) for calculating the annual doses from routine releases of reactor effluents.

In 1966, the ICRP Task Group on Lung Dynamics (TGLD) developed a lung model for predicting the deposition, absorption and clearance of particles within the respiratory tract (Morrow et al., 1966). The respiratory system is divided into the nasal passage, the tracheobronchial tree and the pulmonary region. For modeling purposes, each region is divided into two or more compartments from which clearance is governed by first order kinetics and the fractional deposition in each region is dependent upon the particle size of the inhaled aerosols. The retention of the material in each region depends on the chemical form of the radionuclides. Three clearance classes were defined for the TGLD Model and include: (1) Class D compounds - with retention times of days, (2) Class W compounds with clearance times from a few days to a few months and 3) Class Y compounds which are retained from 6 months to several years. The Class D compounds are similar to the "soluble" classification defined in ICRP-2, but the TGLD Model takes into account the compartmental clearance rates and absorption into the lymph and the blood. Class W closely approximates the "insoluble" ICRP-2 aerosol which was assumed to have a clearance half-time of 120 days. The Class Y compounds have longer clearance times.

The RSS (USNRC, 1975) used the TGLD Model updated with data from ICRP-Publication 19 (ICRP, 1972) to calculate the dose conversion factors for inhaled radionuclides. These factors were calculated for a 1 μm activity median aerodynamic diameter (AMAD) particle size distribution and three clearance classes (D, W or Y) for each radionuclide. The National Radiological Protection Board has also made use of the TGLD Model to describe the transport of inhaled material from the region of deposition (Adams et al., 1978).

The most recent dosimetric model for inhaled radionuclides is provided in ICRP Publication-30 (ICRP, 1979). The model used to describe the clearance from the respiratory tract is shown in Figure 2. The retention model has, in addition to the major respiratory regions, three other closely related organ systems: the gastrointestinal tract, systemic blood, and pulmonary lymph nodes. The letters "a" through "j" in Fig. 2 indicate the various absorption and translocation processes associated with the clearance of various compartments (Morrow et al., 1966):

(a) Rapid uptake of material deposited in the nasopharynx region directly into the systemic blood.

(b) Rapid clearance of all dusts from the nasopharynx region by ciliary-mucus transport.

(c) Rapid absorption of dust deposited in the tracheobronchial compartment into the systemic circulation.

(d) Analogous to (b) and represents the rapid ciliary clearance of the tracheobronchial region; the dust cleared by (d) goes to the gastrointestinal tract.

(e) Direct translocation of dust from the pulmonary region to the blood.

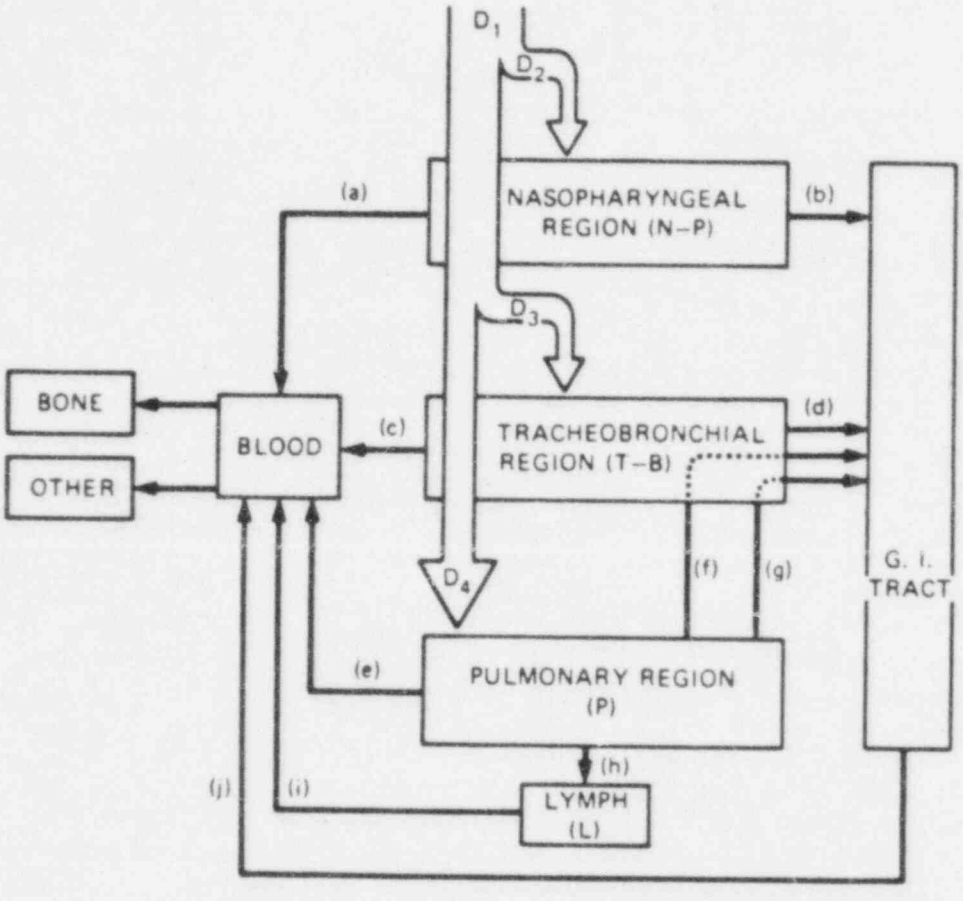
(f) Relatively rapid clearance phase of the pulmonary region, which depends on recruitable macrophages, and this in turn is coupled to the ciliary-mucus transport process; therefore, the dust cleared by (f) goes to the gastrointestinal tract via the tracheobronchial tree.

(g) Second pulmonary clearance process that is typically much slower than (f) but still depends on endocytosis and ciliary-mucus transport; the cleared dust goes via the tracheobronchial region to the gastrointestinal tract (the important distinction is that the clearance is apparently rate-limited in the pulmonary region by the nature of the deposited dust per se).

(h) Process describing the slow removal of dust from the pulmonary compartment via the lymphatic system; this process can be regarded as qualitatively similar to (g) with the exception that lymph transport replaces the ciliary-mucus transport.

(i) Secondary pathway in which dust cleared by the lymphatic system (h) is introduced into the systemic blood; this pathway obviously depends on the ability of the cleared material to penetrate the lymph tissue, especially the lymph nodes (this implies partial or complete dissolution of the dust particles, but the turnover of lymphocytes may contribute).

The fractional distribution of radionuclides between the processes and the biological half-time for each process are also given in Figure 2 for each of the lung clearance classes D, W and Y. The clearance of inhaled material is treated by a set of first order differential equations that account for ingrowth of decay daughters, rate of inhalation, biological and radiological decay and transfer from the lungs to the body fluids and GI tract.



REGION	PATHWAY	COMPOUND CLASS (D)	(W)	(Y)
N-P	(a)	0.01 d/0.5	0.01 d/0.1	0.01 d/0.01
	(b)	0.01 d/0.5	0.4 d/0.9	0.4 d/0.99
T-B	(c)	0.01 d/0.95	0.01 d/0.5	0.01 d/0.01
	(d)	0.2 d/0.05	0.2 d/0.5	0.2 d/0.99
P	(e)	0.5 d/0.8	50 d/0.15	500 d/0.05
	(f)		1 d/0.4	1 d/0.4
	(g)		50 d/0.4	500 d/0.4
	(h)	0.5 d/0.2	50 d/0.05	500 d/0.15
L	(i)	0.5 d/1.0	50 d/1.0	1000 d/0.9

Figure 2 Lung retention model. Adapted from ICRP Publication 30. The numbers listed under the compound class are biological half-life and fractional distribution constants for each compartment.

The ICRP Publication 30 dose equivalent factors are expressed as Sv per Bq intake of radionuclides. The published factors are for the inhalation of a 1 μm AMAD particle size distribution. Correction factors for other particle sizes are provided in ICRP Publication 30 to modify the deposition patterns of the inhaled particles within the various regions of the respiratory system. A functional relationship between the fraction deposited in each region of the respiratory system and the particle AMAD is given in Figure 3.

The dose equivalent factors for the isotopes of some 95 elements of Clearance Classes D, W and Y are provided in the ICRP Publication 30 data base. We feel these factors incorporate the most recent modeling approaches and compilations of decay and metabolic data that are available. Therefore, the Publication 30 inhalation models are adopted for use in the MACCS program.

3.2 Ingestion

Following the intake of radionuclides via ingestion, two considerations are important for estimating the absorbed dose: (1) the fraction of the ingested radionuclide that is absorbed from the gut and (2) the irradiation of the gut itself. Most of the transfer of radionuclides to the bloodstream takes place in the small intestine. For assessing the dose to the GI tract, the lower large intestine is usually considered the most important region due to the long residence time of the contents in this region of the gut.

The ICRP Publication 2 model contains a four compartment model that includes the stomach, small intestine, upper large intestine and lower large intestine. The fraction of radionuclide transferred from the GI tract to the blood is defined by a factor, f_1. The ICRP-2 modeling approaches and metabolic parameters were used in Turner et al., (1968); Killough et al. (1975); and Hoenes and Soldat (1977) for calculating dose conversion factors for ingested radionuclides.

A dosimetric model that describes the same four compartments as the ICRP-2 model for the GI tract was developed by Eve (1966). However, different masses and residence times were defined for each compartment. In addition, a special allowance was made for the transfer of radionuclides from the small intestine to the body fluids. Each segment is modeled as a compartment that is cleared to its successor by first order kinetics. It is assumed that absorption from the gut occurs in the small intestine. The absorbed fraction, f_1, of the radionuclide is then transferred to other body organs within the systemic system. The model developed by Eve (1966) has been incorporated into several computer codes for calculating dose conversion factors for ingested radionuclides (Killough et al., 1978a, 1978b; Dunning et al., 1979; 1981; Adams et al., (1978).

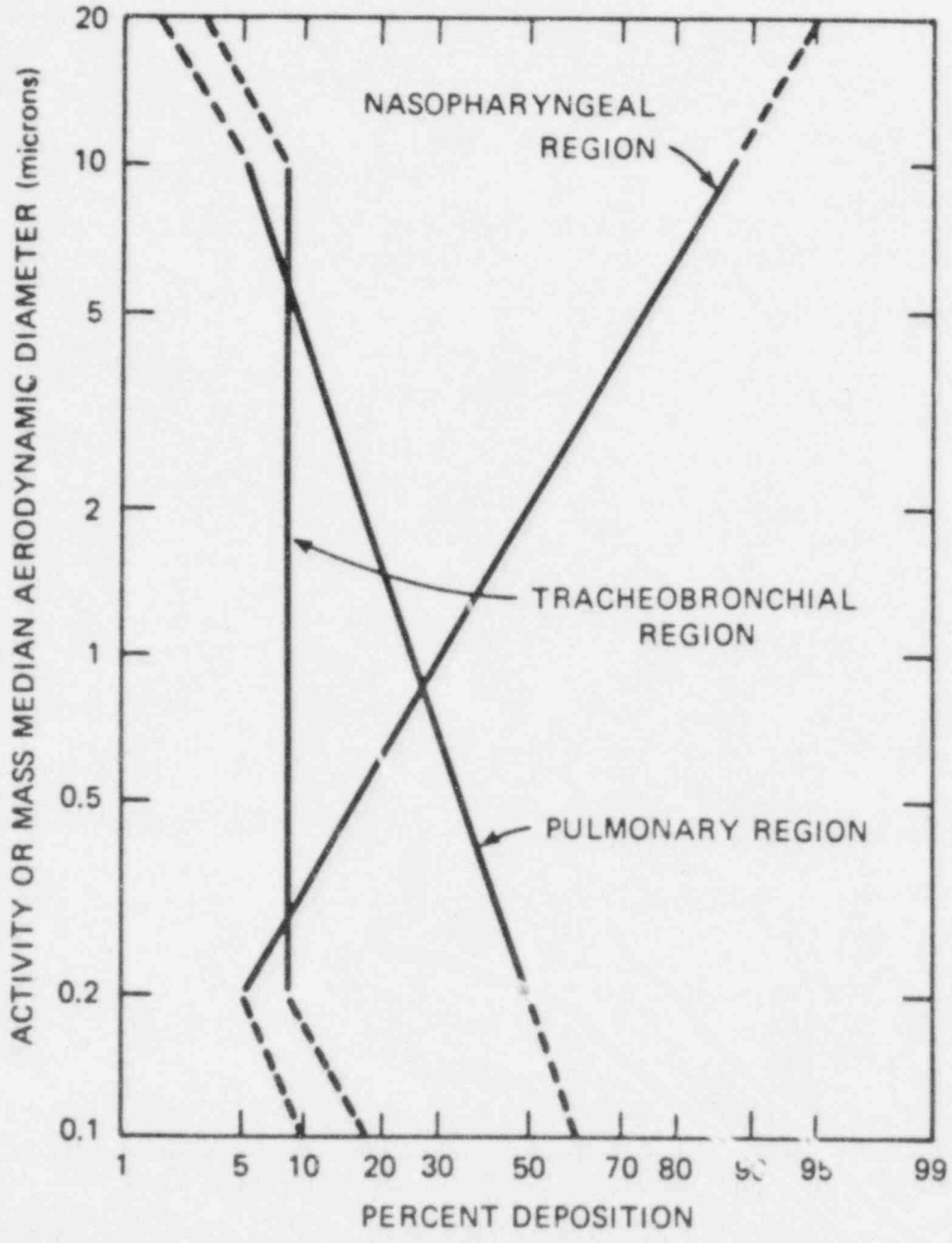


Figure 3 Lung Deposition Model. Adapted from ICRP Publication 30.

In the RSS (USNRC, 1975), the ingestion dose conversion factors were calculated using the inhalation model and assuming that all the material was transferred from the respiratory tract to the gut. The dosimetry model for the GI tract was essentially Eve's (1966) model with the same compartments and residence times.

The most recent use of Eve's model is in ICRP Publication-30 and is depicted in Figure 4. The dose equivalent for 22 body organs expressed as Sv per Bq intake via ingestion are provided in ICRP Publication 30 (1979). The factors represent the current ICRP recommendations for the gut uptake factors (f_1), the metabolic parameters and the decay data for each radionuclide. The ICRP Publication 30 dose conversion factors are adopted for use in MACCS for estimating the dose from ingested radionuclides.

4.0 UNCERTAINTY

One of the major objectives of the MELCOR program is the development of enhanced capabilities for sensitivity/uncertainty analyses (Sprung et al., 1983). This involves not only development of analysis techniques and development of a code system which has accessible parameters, but also involves assessment of model parameters to determine their potential range of variation. A reasonable estimate of parameter variation is needed to perform credible sensitivity/uncertainty analyses. Not treating para- meter variation appropriately can lead to erroneous conclusions about the contribution of that parameter to uncertainty or sensitivity in estimates of reactor accident consequences.

Uncertainty in the standard set of dose conversion factors that are recommended for use in the MACCS code results from two main sources: (1) from uncertainty in defining the physical and chemical characteristics of the released radionuclides and (2) from uncertainty inherent in the dosimetry models. For internally deposited radionuclides (i.e., inhalation and inges- tion), estimates of the dose equivalent to the body organs and tissues are highly sensitive to the properties of the released radionuclides (e.g., particle size, chemical form and solubil- ity). In most cases, these properties are not well known for reactor accidents. In addition, internal dose models are mathematical representations of complex biological processes that are based on limited biological data. Internal dose conversion factors incorporate these uncertainties. Internal dose estimates from radionuclides suspended in the air and deposited on the ground incorporate simplifying assumptions. These assumptions can, in some cases, result in significant dose factor uncertainty.

This section discusses the overall uncertainty in both the external and internal dose conversion factors and provides guidance for performing sensitivity/uncertainty analyses with

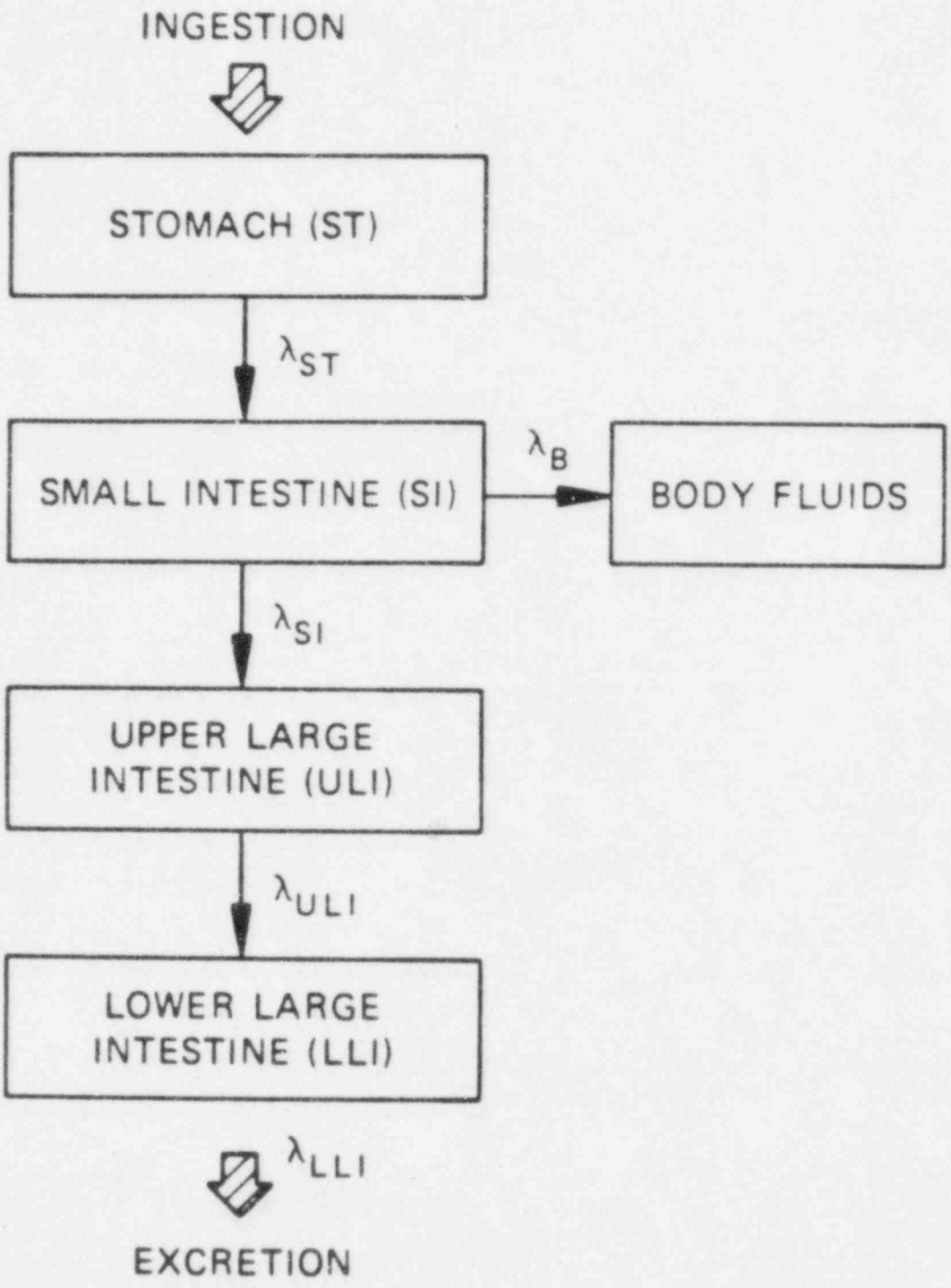


Figure 4 Mathematical model for the gastrointestinal tract. Adapted from ICRP Publication 30.

MACCS. An attempt is made to evaluate, at least qualitatively, the potential impact of uncertainty in models and data used to calculate dose conversion factors. Uncertainties for the external and internal dose factors are discussed in Sections 4.1 and 4.2, respectively. Differences between child versus adult dose estimates are discussed in Section 4.3.

4.1 Uncertainty in External Dose Estimates

The dose received by persons exposed to the contaminated plume and from radionuclides deposited on the ground depends on a number of factors which include the deposition velocity of the suspended radionuclides, radiation attenuation by ground roughness, protection afforded by structures and evacuation and protective procedures. Uncertainty in these parameters is discussed in Ostmeyer and Helton (1985) and will not be discussed in this section. This section discusses the uncertainty in both cloudshine and groundshine dose conversion factors.

4.1.1 Cloudshine

Dose-rate factors for immersion in a contaminated plume are calculated for a receptor standing at the air-ground interface. These factors assume that the receptor is located at the boundary of an infinite atmospheric cloud with uniform source concentration (Kocher, 1983). If the plume is large, the assumption of an infinite exposure medium is an accurate representation. If the plume is small in comparison to the mean-free-path of photons in air, the dose-rate factors will overestimate dose. To correct this overprediction, a semi-infinite cloud correction has been adopted to correct for the finite extent of the cloud (Ostmeyer and Helton, 1985).

At the air-ground interface, the photon dose rate is assumed to be one-half of the dose rate at any point inside an infinite cloud (Dillman, 1974). It is reasonable to assume that the dose rate is one-half of the infinite cloud value as long as the mean-free-path of photons is large when compared with the height of the receptor. (Ryman et al., 1981). When the one-half correction is applied to low energy photons (20 KeV - 50 KeV), a maximum error of $\pm$ 20% is introduced. This error is reduced to less than $\pm$ 10% for energies above 0.2 MeV (Ryman et al., 1981). The majority of the radionuclides likely to be released during a reactor accident have high energy photons (>0.2 MeV). Therefore, the one-half correction factor generally will introduce less than a few percent error in the cloudshine dose estimates.

Kocher's (1983) dose-rate factors include a ratio to correct air kerma to organ doses. The ratios take into account organ shielding by body tissues, the characteristics of the body

tissues and the energy spectrum of scattered photons. The correction ratios incorporated in Kocher (1983) were developed by Eckerman et al. (1980) and are based on the absorbed dose rate distributions from O'Brien and Sanna (1976) and the energy spectra for scattered photons from Dillman (1974). The error in the correction ratios is not specified; however, it is not likely to be large for high energy photons. Errors in the ratios will be greatest when (1) scattered photons make large contributions to dose relative to the primary photons and (2) gamma attenuation in body tissues is large. For photons with energies greater than 0.5 MeV, the scattered photon contribution to dose will generally be less than 50%. In addition, the mean-free-path of gammas in tissue ranges from about 10 cm for 0.5 MeV gammas to 10's of centimeters for higher energy gammas. Thus, errors in predicting the energy spectra of scattered photons and errors in modeling tissue attenuation would need to be large to result in more than a few tens of percent error in predictions of cloudshine for the radionu- clides likely to be important for reactor accident consequences. The correction ratio for relating organ dose to air kerma is generally greater than 0.5 for photons with energies in excess of 0.2 MeV (Kocher, 1983).

The air kerma correction factors are also sensitive to the age and sex of exposed persons. Differences in body size and mass can influence organ shielding and the resulting dose-rate. However, for the reasons noted above, differences are likely to be small for high energy photons.

Uncertainty in the cloudshine dose factors is probably less than a few 10's of percent for radionuclides that are important for reactor accident releases. The uncertainty in other parameters that influence cloudshine will dominate the uncertainty in the external cloudshine dose estimates for reactor accidents. Uncertainty about the effectiveness of structure shielding can, for example, result in more than a factor of two uncertainty in cloudshine dose estimates (Ostmeyer and Helton, 1985).

4.1.2 Groundshine

The groundshine dose-rate factors assume a smooth infinite plane with uniform concentrations of radionuclides (Kocher, 1983). The dose rate factors for groundshine are defined to be the product of the air kerma at 1 meter above the plane and an air kerma to organ dose correction factor. The 1 meter height is considered to be representative of the average height of most critical organs (Burson and Profio, 1977).

The average receptor height is sensitive to age, sex and variations within a population. Air kerma are, in turn, sensitive to the assumed receptor height. A thirty percent variation in the 1 meter height can change the estimate of air kerma by up

to ten percent (based on evaluation of relationships in Kocher (1983)).

The air kerma to organ dose correction factors used by Kocher to determine the groundshine dose factors are the ratios used for the cloudshine factors. The cloudshine ratios are inappropriate for two reasons: (1) cloud immersion results in an isotropic angular distribution of incident gammas while the angular distribution of gammas for ground exposure is anisotropic and (2) the energy spectrum for scattered photons is not the same for cloud and ground exposures. Kocher (1983) estimates that the error incorporated by using these factors is probably not greater than a few tens of percent for photon energies greater than 0.1 MeV.

Overall, the uncertainty in the groundshine dose-rate factors is probably less than a factor of 2 for the high energy photons that are important for reactor accident releases. This estimate is consistent with the uncertainty estimate presented in Lindackers and Bonnenberg (1979) for the external dose estimates. As is the case for cloudshine dose, uncertainty in exposure pathway parameters will likely dominate uncertainty in groundshine dose estimates.

4.2 Uncertainty in the Internal Dose Estimates

Uncertainty in the internal dose estimates results mainly from the poorly defined characteristics of the source term and from the uncertainty in the mathematical models and modeling parameters used to calculate the internal dose conversion factors. The parameters will also be highly variable among individuals in the population. The uncertainty resulting from these sources is discussed for the inhalation and ingestion dose factors in Sections 4.2.1 and 4.2.2, respectively.

4.2.1 Inhalation

The behavior of radionuclides within the respiratory system is governed by the particle size, solubility and chemical form of the inhaled material. The Task Group Lung Model (Morrow et al.) recommended the use of a 1 μm particle AMAD (Activity Median Aerodynamic Diameter) to estimate the dose from inhaled radionuclides for undefined particle size distributions. In ICRP Publication 30 (ICRP, 1979), the effects of various particle sizes (AMAD's of 0.1 μm to ~ 10 μm) were considered to determine their deposition patterns within the respiratory tract. Small particles (< 1 μm diameter) deposit predominantly in the pulmonary region while large particles (> 5 μm diameter) deposit predominantly in the upper respiratory regions and are rapidly cleared to the gastrointestinal tract. Aerosol size distributions for reactor accident releases are expected to range from about 0.5 to 5 μm with AMADs of a few microns and

standard deviations of a few microns (Sprung, 1985). Lower AMAD values may occur for accident sequences involving early containment failure and larger AMAD values may occur for late failure sequences (Sprung, 1985).

The ICRP Publication 30 data base includes data that can be used to calculate inhalation dose conversion factors for various particle AMADs. The fraction of the inhaled material deposited in each compartment of the respiratory tract is particle size dependent. Data are available for particle sizes from 0.01 to 10 μm AMAD. The metabolic parameters that determine the clearance and absorption of radionuclides deposited in the respiratory system are appropriate for all particle sizes. Dose equivalent factors for most organs vary by a few tens of percent to a factor of 3 for AMADs that range from 0.5 to 5 μm.

The inhalation rate can have some impact on the deposition patterns within the respiratory system. The Task Group on Lung Dynamics (Morrow et al., 1966) presented the results for three different ventilation states typified by tidal volumes of 750, 1450 and 2150 cm^3. For unit density spheres of 0.2 to 3 μm, the deposition fractions in the 3 lung regions varied by only a few percent to a few 10s of percent between the three tidal volumes. For 4 μm spheres, the pulmonary fraction decreased by a factor of 2.5 for spheres inhaled at a tidal volume of 750 cm^3 versus 2150 cm^3. For log-normal aerosol distributions with AMADs ranging from 0.5 to 5 μm, the deposition fractions varied by less than 20% between tidal volumes of 750 to 2150 cm^3. Since these tidal volumes are considered to be representative of the range of human activity (i.e., resting to heavy work), it is concluded that variations in tidal volume will have a much smaller impact on inhalation doses than will the potential variation in the particle size distribution.

The deposition fraction for each region of the lung is sensitive to variations in geometric standard deviation (σ_g) of the aerosol particle size distribution. The Task Group on Lung Dynamics compared predictions of deposition in the three respiratory regions for aerosols with σ_g ranging from 1.2 to 4.5 μm. For distributions with AMADs ranging from 0.5 to 5.0 μm, they found that the deposition fractions varied by less than a few 10's of percent over the range of σ_g. As is the case with variations in the inhalation rate, variations in the standard deviation of the aerosol distribution will likely have a small impact on variation of inhalation doses relative to that resulting from the potential variations in aerosol AMAD.

Breathing through the mouth versus nasal breathing could influence the deposition patterns of inhaled particulates. The Task Group on Lung Dynamics noted that the mouth acts as a filtering chamber similar to the nasopharyngeal region and that pulmonary deposition is unaffected by mouth breathing (Morrow et al., 1966). Pulmonary deposition is the most important

consideration for estimating the lung dose from inhaled radionuclides. The impact of differences in deposition pattern on other organ doses is not known. However, analysis of the available data suggests that these differenced are not large.

The clearance class determines the rate at which radionuclides are cleared from the respiratory system and the extent of transfer to the systemic system. For evaluating the consequences of reactor accidents, the most probable chemical forms of the inhaled radionuclides are used to assign clearance classes. Except for Cs and I isotopes, most of the important inhaled radionuclides will be in the form of insoluble compounds (principally oxides and hydroxides). Compounds of Cs and I will be soluble. However, these soluble radionuclides could be encapsulated within an insoluble particle and thus, could be considered insoluble. In this case, "particle" refers to an agglomeration of different materials and compounds. Since the in-vessel and in-containment processes that form particles are highly complex and are dependent on the accident sequence, the formation of insoluble particles cannot be ruled out entirely.

To simplify the consequence code, one inhalation clearance class must be selected for each radionuclide considered in the MACCS calculations. This selection process introduces some uncertainty, since the chemistry of the released radionuclides cannot be well defined and may change during atmospheric transport. Also, the solubility of any "carrier" material is not known. In general, the dose equivalents for a 1 μm AMAD range from a factor less than 2 up to 10 across the D, W, and Y clearance classes for radionuclides that are important for severe reactor accidents.

The ICRP Publication 30 Committee considered the metabolic behavior of various chemical forms of each radionuclide and have developed recommendations for appropriate clearance classes. In some instances, one clearance class is recommended for all chemical forms of a radionuclide (e.g., Class D for all isotopes of iodine and Class D for all isotopes of cesium). For some radionuclides the Committee recommended an appropriate clearance class for radionuclides that have interacted with the environment.

The clearance classes from ICRP Publication 30 that were adopted for use in MACCS for each element are given in Table 2. The clearance classes selected by the RSS (USNRC, 1975) and the United Kingdom NRPB (National Radiological Protection Board) (Charles and Crick, 1982) are also included in the table for compari- son. The ICRP Publication 30 clearance classes are adopted for the base case in MACCS. These clearance classes are considered appropriate for the radionuclides that are likely to be of greatest importance for reactor accident risk.

Unfortunately, radionuclide chemistry and particle solubility cannot be generically specified for all reactor accidents

TABLE 2 SUGGESTED LUNG CLEARANCE CLASSES FOR INHALED RADIONUCLIDES

	RSS Chemical Classification	RSS Clearance Class	NRPB-R-53 Clearance Class	ICRP-30 Clearance Class
Iodine	I_2, CH_3I, iodides, iodates	D	D	D - all compounds
Rubidium	Oxides, hydroxides	D	D	D - all compounds
Sodium	---	-	-	D - all compounds
Cesium	Oxides, hydroxides	D	D	D - all compounds
Tellurium	Oxides	W	W	W - oxides, hydroxides, nitrates
Antimony	Oxides	W	W	W - oxides, hydroxides, sulfides, sulfates, nitrates
Strontrium	Oxides	D	D	D - chlorides, all others ($SrTiO_3$ = y)
Barium	Oxides	D	D	D - all compounds
Ruthenium	Oxides, hydroxides	Y	Y	Y - oxides, hydroxides
Cobalt	Oxides, hydroxides	Y	-	Y - nitrates, halides, oxides, hydroxides
Molybdenum	Molybdates, (? oxides)	Y	Y	Y - oxides, hydroxides, molybdates
Technicium	Oxide, pertechnetate	D	W	W - oxide, hydroxide, halides, nitrates (pertechnetate = D)
Yittrium	Oxide	W	Y	Y - oxide, hydroxide
Lanthanium	Oxide	W	Y	W - oxides, hydroxide, chloride
Zirconium	Oxide	Y	Y	W - oxide, hydroxide, halides, nitrates (Carbide = Y)
Niobium	Oxide	Y	Y	Y - oxide, hydroxide
Cerium	Oxide	Y	Y	Y - oxide, hydroxide, Fluorides
Praseodymium	Oxide	Y	Y	Y - oxide, hydroxide, carbides, fluorides
Neodymium	Oxide	Y	Y	Y - oxide, hydroxide, carbides, fluorides
Promethium	Oxide	Y	Y	Y - oxide, hydroxide, carbides, fluorides
Neptunium	Oxide	Y	Y	W - all compounds
Americium	Oxide	Y	W	W - all compounds
Curium	Oxide	Y	W	W - all compounds
Plutonium	Oxide	Y	Y	Y - oxides

(Powers, 1985 and Sprung, 1985). This results from the large variation in containment conditions as well as in the environmental interactions following release. There is a potential for a given radionuclide to have any one or any combination of the D, W and Y clearance properties. Without a better understanding of the physical and chemical characteristics of the released radionuclides, the exact classification of a radionuclide within a given clearance class is difficult.

ICRP Publication 30 (ICRP, 1979) implements relatively complex metabolic models to treat the movement of radionuclides from the respiratory system and GI tract through the systemic system. These models are mathematical representations of complex biological processes. These processes are simulated by the use of transfer (partitioning) factors, biological retention times and other metabolic parameters. These metabolic parameters are based on the behavior of elements within the human body (when available) or on information extrapolated from animal studies. Parameter variability can range from less than a factor of 2 to greater than 10 for some radionuclides (von Kaul et al., 1981). However, the overall variation in the dose estimates resulting from parameter variations in the model is estimated to be within a factor of $\pm$ 2-3 (Lindackers and Bonnenberg, 1979; von Kaul et al., 1981; Eckerman, 1985).

Uncertainty in internal dose estimates may also arise from modeling bias. In this context, model bias results from conservatisms that are incorporated into the models due to lack of data. The bias can enter into the overall model at various steps in the modeling process. The magnitude of modeling bias will, of course, depend on the overall availability of biological data. For those radionuclides and organs that are important for reactor risk assessment, the impact of modeling bias is probably small in comparison to dose factor variability resulting from other causes (i.e., poor characterization of the aerosol and model uncertainty), (Eckerman, 1985).

4.2.2 Ingestion

The uptake of radionuclides from the gastrointestinal tract is important for direct ingestion of contaminated food and water sources and also for radionuclides cleared from the respiratory tract into the gut following inhalation. GI tract residence times and gut uptake factors are generally assumed to be the same for ingested radionuclides and radionuclides cleared from the respiratory tract.

Gut uptake fractions for radionuclides are given by f_1 factors in ICRP Publication 30. These values are assigned in accordance with the solubility of the ingested radionuclides. Generally, soluble forms of radionuclides (e.g., chlorides, nitrates, citrates) are rapidly absorbed from the gut into the

systemic system. Insoluble forms of radionuclides (e.g., oxides or hydroxides) are retained in the gut and are eliminated via excreta.

The f_1 factor may be quite uncertain for some radionuclides such as plutonium where the observed ranges in the animal data spanned several orders of magnitude (Kocher et al., 1980). For plutonium, no human data are available. However, for iodine, cesium, strontium and tellurium radionuclides, noted by Ostmeyer and Helton (1985) as being the most important for the ingestion pathway, f_1 values are much less uncertain. Iodine and cesium are assigned an $f_1 = 1$, indicating complete absorption from the gut. Tellurium and strontium are assigned f_1 values of 0.2 and 0.3, respectively. The f_1 values for radionuclides likely to be important for the inhalation pathway following severe reactor accidents show little variability and are probably accurate to within a few tens of percent.

Uncertainty in metabolic models for the systemic system was discussed in Section 4.1. Uncertainty in metabolic models and data will likely have less than a factor of two impact on estimates of dose equivalent for systemic organs.

The dose to the gut lining is sensitive to the residence times that are assumed for each region of the gastrointestinal tract. The ICRP Publication 30 residence times (discussed in Section 3.2) are those proposed by Eve, 1966. Review of Eve's discussion suggests that gut resident times could vary by about a factor of two.

The overall uncertainty in ingestion dose estimates (due to variability in gut uptake, residence times and other metabolic parameters has been defined to be within a factor of 2 to 3 (Lindackers and Bonnenberg, 1979; Eckerman, 1985). Again, uncertainty due to model bias is not known. However, dose factor bias is not considered to be large for radionuclides important for reactor risk assessment. Uncertainty in dose estimates for ingestion is expected to be dominated by uncertainty in determination of radionuclide concentrations in soil and water, and uptake and transfer factors for foodchains (Ostmeyer and Helton, 1985).

4.3 Child Versus Adult

The use of adult dose estimates has become a common practice in many risk assessments. The RSS (USNRC, 1975) noted that differences in organ masses, ingestion rates, breathing rates and metabolism between children and adults results in variation in absorbed dose with age. The intake rate for children via inhalation and ingestion will generally be lower than those for adults while the metabolism of children is higher.

The internal dosimetry models for children are easily adjusted for the changes in body masses with age. However, metabolic parameters for children are not well defined, resulting in a large uncertainty in dose estimates for many radionuclides. Adams (1981) developed approximate values for the dependence of committed dose equivalent on age at intake via ingestion and inhalation. Two critical groups at 1 year of age and 17 years of age were defined as being important within the general public. For soluble forms of ^{90}Sr, multiplicative factors of 1.2-1.4 and 1.15 were defined to adjust the adult dose to the dose for the respective age groups. For ^{239}Pu, the factors were ~ 3 and 1.2 for the respective age groups. These factors take into account differences in intake rates and organ masses. However, they do not account for changes in metabolism with age.

The RSS (USNRC, 1975) recommended factors to adjust the adult doses to those for children of various ages for ^{131}I, ^{137}Cs, ^{89}Sr and ^{90}Sr. When the ratio of the breathing rates for children versus adults was included, the final correction factors were assumed to be 1 for all age groups and radionuclides except ^{131}I. For inhaled ^{131}I, multiplicative factors of 1.9 and 1.6 were recommended for the thyroid of children ages 5 and 10, respectively.

For the base case calculations with MELCOR, adult dose models will be adopted. However, for sites with special demographic characteristics (e.g., populations with a large fraction of children) or for assessments of maximum individual risk, use of dosimetry adjusted for children should be considered.

For external dosimetry, the child would have less organ shielding than the adult and a lower effective organ height above the surface. These differences are not expected to cause differences greater than a factor of two between estimates of groundshine and cloudshine dose for children and adults

5.0 RECOMMENDATIONS

This section summarizes the recommendations for the dosimetry models to be used in the MACCS computer code. The external and internal dose estimates are discussed in Sections 5.1 and 5.2, respectively.

5.1 External Dose Estimates

The external dose factors developed by Kocher (1981; 1983) have been adopted for use in MACCS. As discussed in Section 4.1, overall uncertainty in these external factors is within a few tens of percent for cloudshine and groundshine. Uncertainties in the source term characteristics, atmospheric dispersion and

transport, and exposure pathways are much greater than that for the external dose conversion factors. Therefore, the uncertainty in the external dose factors contribute little to the uncertainty in the consequence estimates.

Estimates of beta dose due to deposits on the skin will be made with the depth-dose relationship developed by Loevinger et al. (1956). The uncertainty in these estimates are dominated by uncertainty in the exposure pathway (e.g., deposition velocity and radionuclide retention on skin).

Appendix A discusses implementation of external dose factors within MACCS.

5.2 Internal Dose Estimates

Inhalation dose conversion factors calculated with the ICRP Publication 30 models have been adopted for use in MACCS. As noted in Section 4.2.1, there is little variability in the dose estimates resulting from the particle size distribution that may result from severe degrade core reactor accidents. Therefore, a 1 μm particle size AMAD is assumed for the MACCS dose factors. The clearance classes are those recommended from ICRP Publication 30 (see Table 2).

The overall uncertainty of inhalation dose factors due to model and data uncertainty ranges from factors of less than 2 to 3. Variations in aerosol characteristics may introduce an additional uncertainty ranging from 2 to 10. The aerosol characteristics are poorly understood, therefore, it is not possible to assign a probability distribution to the uncertainty associated with the aerosol characteristics. A uniform distribution is recommended for sensitivity analysis.

The AMAD of released particle sizes may range from 0.8 to 3 μm (see Section 4.2.1) and a probability distribution cannot be defined. For sensitivity analysis a uniform distribution can be assumed.

The ICRP Publication 30 ingestion dose factors are also recommended for use in the MACCS. The following f_1 values are recommended for the ingestion factors: 1 for iodine and cesium, 0.2 for tellurium and 0.3 for strontrium. An uncertainty range of 2-3 has been defined for the dose factors for ingested radionuclides. This uncertainty is relatively unimportant when compared to the uncertainty in the atmospheric transport and the ingestion pathways models for doses via the ingestion pathway. This uncertainty can be as large as an order of magnitude.

In the RSS (USNRC, 1975), the whole body dose equivalent was calculated for external and internal exposures. Many current

guidelines and regulations are expressed in terms of the whole body dose. The ICRP (ICRP, 1977) currently recommends the use of the effective dose equivalent versus the whole body dose to evaluate compliance with radiation protection standards in the workplace. The effective dose equivalent is not appropriate for high exposures that may be encountered with reactor accidents. The whole body dose equivalent is not calculated for internally deposited radionuclides in ICRP Publication 30. Where the whole body dose has been used in previous evaluations, the red bone marrow dose equivalent could be used to replace the whole body dose for internal and external exposures.

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Appendix A: Implementation of Dose Factors

This appendix provides a brief description of how the Kocher (1981, 1983) and ICRP Publication 30 (ICRP, 1975) dose factors are implemented in the MELCOR consequence assessment code. Section A.1 discusses the external dose factors while Section A.2 discusses the internal factors.

A.1 External Dose-Factors

External exposures treated by the MELCOR consequence assessment code include cloudshine, groundshine and deposition to skin. The cloudshine and groundshine factors are discussed separately below.

Cloudshine doses to an individual are determined with an equation of the form:

$$CD = IAC*CSF*CDF \qquad a.1$$

where IAC is the integrated air concentration for the radionuclide (Bq-s/m^3), CSF is the shielding factor and CDF is the cloudshine dose conversion factor (Sv-m^3/Bq-s).

Integrated air concentrations are determined by the consequence code for each downwind spatial interval. These concentrations incorporate the impact of radioactive decay and parent daughter relationships for a standard set of radionuclides (see Table a.1). If the parent radionuclide has a short-lived radioactive daughter ($t_{1/2} \leq 1$ hr.) that is not in the set of radionuclides explicitly treated by the code (i.e., those radionuclides in Table a.1), the dose factor for the daughter is added in proportion to the daughter's branching fraction. That is,

$$CDF = CDF + \sum_{d} bf(d)*CFD(d) \qquad a.2$$

where bf(d) is the branching fraction for daughter d, CF is the cloudshine factor for the parent radionuclide and CFD(d) is the cloudshine factor for the short-lived daughter d.

The consequence assessment code makes use of both dose-rate and "integrated" dose factors for estimating groundshine doses. Rate factors are used for evaluating doses during plume passage and are also used in the long-term groundshine model. The "integrated" factors are used for time periods shortly after plume passage.

Table a.1 List of Radionuclides Treated by the Consequence Assessment Code.

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
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-127	0.391	Plutonium-239	8.9×10^6
Tellurium-127m	109	Plutonium-240	2.4×10^6
Tellurium-129	0.048	Plutonium-241	5,350
Tellurium-129m	0.340	Americium-241	1.5×10^5
Tellurium-131m	1.25	Curium-242	163
Tellurium-132	3.25	Curium-244	6,630

The groundshine rate factors are defined in the same manner as the cloud factors. Factors for short-lived daughters are summed to that for the parent if the daughters are not in the set of radionuclides explicitly treated by the dispersion model. That is,

$$GRF = GRF + \sum_{d} bf(d)*DGRF(d) \qquad a.3$$

where GRF is the dose-rate factor for the parent and DGRF(d) is the rate factor for the daughter d.

The "integrated" ground dose factors reflect dose commitments for periods of 8 hours and 7 days after deposition of radionuclides (i.e., $Sv/bq/m^2$). Contributions from radioactive daughters were added if the daughter half-lives were less than 10 days and if the daughter was not an inert gas (i.e., Xe or Kr). The integrated dose factors were defined as follows:

$$IGF(T) = \int_{0}^{T} [GRF*GC_p(t) + \sum_{d} GC_d(t)*DGRF(d)]dt \qquad a.4$$

where $GC_p(t)$ is the time dependent ground concentration of the parent and $GC_d(t)$ is the time dependent concentration of radioactive daughter d. The length of the time interval is defined by T.

A tabulation of the cloudshine and groundshine factors is contained in Table a.3.

A.2 Internal Dose Factors

This section discusses implementation of the ICRP Publication 30 factors for internal exposures. For inhalation, doses were calculated separately for activity initially deposited in the nasopharyngeal (NP), tracheobronchial (TB), and pulmonary (P) regions of the respiratory system. Estimates are tabulated for each Task Group Lung Model (TGLM) clearance category of the parent nuclide (D, W, and Y, representing rapid, intermediate and protracted clearance from the lung, respectively). Estimates of doses from inhalation of particulate material of any given activity median aerodynamic diameter (AMAD) are computed as

$$D = f_{NP}(AMAD)D_{NP} + f_{TB}(AMAD)D_{TB} + f_p(AMAD)D_p,$$

where D_{NP}, D_{TB} and D_p represent the doses from unit deposition in the NP, TB and P regions, respectively, and f_{NP}, f_{TB} and f_p represent the fraction of particulate material with a given AMAD depositing in each region (see Table a.2).

Table a.2 Respiratory Deposition Fractions as Function of Aerosol Activity Median Aerodynamic Diameter (AMAD)

AMAD (μm)	Regional deposition fractions[a]	
	NP	P
0.2	0.050	0.50
0.3	0.088	0.43
0.4	0.13	0.39
0.5	0.16	0.35
0.6	0.19	0.32
0.7	0.23	0.30
0.9	0.26	0.28
1.0	0.30	0.25
2.0	0.50	0.17
3.0	0.61	0.13
4.0	0.69	0.10
5.0	0.74	0.088
6.0	0.78	0.076
7.0	0.81	0.067
8.0	0.84	0.060
9.0	0.86	0.055
10.0	0.87	0.050

[a]The deposition fraction for the TB region, 0.08, is independent of AMAD.

The groundshine rate factors are defined in the same manner as the cloud factors. Factors for short-lived daughters are summed to that for the parent if the daughters are not in the set of radionuclides explicitly treated by the dispersion model. That is,

$$GRF = GRF + \sum_{d} bf(d)*DGRF(d) \qquad a.3$$

where GRF is the dose-rate factor for the parent and DGRF(d) is the rate factor for the daughter d.

The "integrated" ground dose factors reflect dose commitments for periods of 8 hours and 7 days after deposition of radionuclides (i.e., $Sv/bq/m^2$). Contributions from radioactive daughters were added if the daughter half-lives were less than 10 days and if the daughter was not an inert gas (i.e., Xe or Kr). The integrated dose factors were defined as follows:

$$IGF(T) = \int_{0}^{T} [GRF*GC_p(t) + \sum_{d} GC_d(t)*DGRF(d)]dt \qquad a.4$$

where $GC_p(t)$ is the time dependent ground concentration of the parent and $GC_d(t)$ is the time dependent concentration of radioactive daughter d. The length of the time interval is defined by T.

A tabulation of the cloudshine and groundshine factors is contained in Table a.3.

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$$D = f_{NP}(AMAD)D_{NP} + f_{TB}(AMAD)D_{TB} + f_{P}(AMAD)D_{P},$$

where D_{NP}, D_{TB} and D_P represent the doses from unit deposition in the NP,TB and P regions, respectively, and f_{NP}, f_{TB} and f_P represent the fraction of particulate material with a given AMAD depositing in each region (see Table a.2).

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0.7	0.23	0.30
0.9	0.26	0.28
1.0	0.30	0.25
2.0	0.50	0.17
3.0	0.61	0.13
4.0	0.69	0.10
5.0	0.74	0.088
6.0	0.78	0.076
7.0	0.81	0.067
8.0	0.84	0.060
9.0	0.86	0.055
10.0	0.87	0.050

[a]The deposition fraction for the TB region, 0.08, is independent of AMAD.

For noble gases (Kr, Xe), special respiratory clearance rates are used; deposition fractions for the three lung regions are estimated from the relative volumes of the regions: 0.02 for NP, 0.04 for TB, and 0.94 for P. The values for these gases are, of course, independent of AMAD and clearance class.

Estimates of absorbed dose (Gy/bq) were determined for a reference adult at selected time intervals following acute inhalation or ingestion of radionuclides. These time intervals are consistent with the health effect models developed by Evans et al.

The early effects models used in MACCS (Evans et al., 1985) "discount" the effectiveness of dose with time after exposure for the inhalation pathway. The models are of the form

$$R = 1-e^{-H} \qquad a.1$$

where

$$H = 0.693 \left[\frac{D_1}{\alpha_1} + \frac{D_2}{\alpha_2} + \cdots \frac{D_n}{\alpha_n} \right]^{\beta}. \qquad a.2$$

The doses in time intervals 1, 2 etc., are specified by D_1, $D_2 \ldots D_n$. The α and β variables are fitting parameters for the health effects models where α increases with each successive time interval.

The dosimetry requirement for the early effects model was simplified as follows:

$$H = 0.693 \, [D_e/\alpha_1]^{\beta} \qquad a.3$$

where

$$D_e = \left[D_1 + \frac{\alpha_1}{\alpha_2} D_2 + \frac{\alpha_1}{\alpha_3} D_3 + \ldots \frac{\alpha_1}{\alpha_n} D_n \right]. \qquad a.4$$

D_e is a special definition dose calculated for the early effects models and can be used only for these models. Early effects dose factors, D_e, were calculated for each of the early effects organs.

The inhalation and ingestion factors are given in Table a.3.

TABLE a.3 Dose Conversion Factors: Red Marrow

Radionuclide	CLOUDSHINE (Sv-m^3/Bq-sec)	GROUNDSHINE 8HR (Sv-m^2/Bq)	GROUNDSHINE 7 DAY (Sv-m^2/Bq)	GROUNDSHINE RATE (Sv-m^2/Bq-sec)	INHALATION ACUTE[A] (Sv/bq)	INHALATION CHRONIC (Sv/bq)	INGESTION (Sv/bq)
CO-58	3.9E-14	2.2E-11	4.4E-10	7.6E-16	1.1E-10	9.2E-10	2.6E-10
CO-60	1.0E-13	5.0E-11	1.1E-09	1.7E-15	2.6E-10	1.7E-08	1.3E-09
KR-85	8.6E-17	.0E+00	.0E+00	.0E+00	6.8E-14	7.0E-14	.0E+00
KR-85m	5.5E-15	.0E+00	.0E+00	.0E+00	6.4E-14	6.4E-14	.0E+00
KR-87	3.5E-14	.0E+00	.0E+00	.0E+00	2.2E-13	2.2E-13	.0E+00
KR-88	1.2E-13	.0E+00	.0E+00	.0E+00	3.7E-13	3.7E-13	.0E+00
RB-86	3.8E-15	2.0E-12	3.7E-11	6.9E-17	4.5E-10	2.4E-09	1 09
SR-89	5.5E-18	3.0E-15	6.0E-14	1.0E-19	4.9E-10	5.7E-09	3.3E-09
SR-90	.0E+00	.0E+00	.0E+00	.0E+00	6.4E-10	3.1E-07	1.8E-07
SR-91	3.9E-14	1.6E-11	3.7E-11	7.6E-16	8.5E-11	1.6E-10	1.3E-10
Y-90	.0E+00	.0E+00	.0E+00	.0E+00	7.8E-12	1.5E-11	3.7E-13
Y-91	1.4E-16	7.3E-14	1.5E-12	2.5E-18	1.2E-11	3.2E-10	6.6E-12
ZR-95	2.9E-14	1.7E-11	3.3E-10	5.7E-16	1.4E-10	3.2E-09	2.1E-10
ZR-97	6.2E-14	2.7E-11	1.1E-10	1.2E-15	1.1E-10	1.4E-10	1.3E-10
NB-95	3.1E-14	1.7E-11	3.4E-10	6.0E-16	8.5E-11	4.4E-10	2.0E-10
MO-99	6.1E-15	4.1E-12	5.7E-11	1.2E-16	2.9E-11	5.1E-11	8.0E-11
TC-99m	4.2E-15	1.8E-12	2.9E-12	9.3E-17	2.3E-12	2.4E-12	6.3E-12
RU-103	1.8E-14	1.1E-11	2.2E-10	3.8E-16	5.6E-11	3.2E-10	1.7E-10
RU-105	3.1E-14	1.0E-11	1.5E-11	6.2E-16	7.2E-12	7.7E-12	2.3E-11
RU-106	8.1E-15	4.6E-12	9.7E-11	1.6E-16	4.7E-11	1.8E-09	1.5E-09
RH-105	2.9E-15	1.7E-12	1.1E-11	6.3E-17	5.3E-12	7.7E-12	1.5E-11
TE-127	.8E-16	8.4E-14	1.9E-13	3.9E-18	3.3E-12	4.0E-12	6.4E-12
TE-127m	2.6E-17	5.6E-14	2.7E-12	1.0E-18	1.0E-10	5.3E-09	5.4E-09
TE-129	2.0E-15	2.5E-13	2.5E-13	4.2E-17	6.1E-13	6.1E-13	7.6E-13
TE-129m	1.3E-15	1.3E-12	2.9E-11	2.5E-17	2.0E-10	3.0E-09	3.4E-09
TE-131m	6.0E-14	3.0E-11	1.9E-10	1.1E-15	9.3E-11	1.4E-10	2.4E-10
TE-132	7.6E-15	3.5E-11	6.0E-10	1.7E-16	2.5E-10	4.7E-10	5.4E-10
SB-127	2.6E-14	1.5E-11	1.8E-10	5.2E-16	8.7E-11	1.5E-10	1.3E-10
SB-129	5.8E-14	1.8E-11	2.5E-11	1.1E-15	1.6E-11	1.7E-11	3.7E-11
I-131	1.4E-14	8.7E-12	1.4E-10	3.1E-16	2.8E-11	6.3E-11	9.4E-11
I-132	9.1E-14	1.9E-11	2.1E-11	1.8E-15	1.4E-11	1.4E-11	2.5E-11
I-133	2.4E-14	1.2E-11	5.1E-11	4.7E-16	2.5E-11	2.7E-11	4.3E-11
I-134	1.1E-13	9.0E-12	9.0E-12	2.0E-15	6.1E-12	6.1E-12	1.1E-11
I-135	6.4E-14	2.2E-11	3.8E-11	1.1E-15	2.2E-11	2.2E-11	3.6E-11
XE-133	7.3E-16	.0E+00	.0E+00	.0E+00	1.6E-13	1.7E-13	.0E+00
XE-135	9.2E-15	.0E+00	.0E+00	.0E+00	2.5E-13	2.6E-13	.0E+00
CS-134	6.2E-14	3.5E-11	7.3E-10	1.2E-15	4.0E-10	1.2E-08	1.9E-08
CS-136	8.6E-14	4.7E-11	8.2E-10	1.6E-15	4.2E-10	1.9E-09	3.0E-09
CS-137	2.2E-14	1.3E-11	2.7E-10	4.4E-16	2.4E-10	8.3E-09	1.3E-08
BA-140	7.1E-15	7.3E-12	6.5E-10	1.5E-16	3.0E-10	1.2E-09	4.2E-10
LA-140	9.5E-14	4.4E-11	3.2E-10	1.6E-15	1.4E-10	2.1E-10	2.8E-10
CE-141	2.4E-15	1.6E-12	3.0E-11	5.4E-17	1.7E-11	8.9E-11	3.4E-11
CE-143	9.5E-15	5.3E-12	3.3E-11	2.0E-16	2.0E-11	3.0E-11	5.1E-11
CE-144	1.9E-15	9.6E-13	2.1E-11	3.5E-17	1.9E-11	2.8E-09	8.7E-11
PR-143	3.6E-22	2.0E-19	3.5E-18	6.9E-24	2.6E-12	1.5E-11	1.0E-12
ND-147	4.5E-15	2.7E-12	4.7E-11	9.6E-17	2.7E-11	9.2E-11	5.0E-11
NP-239	5.5E-15	3.3E-12	3.1E-11	1.2E-16	5.3E-11	1.5E-10	5.7E-11
PU-238	4.5E-19	1.1E-15	2.3E-14	3.9E-20	2.0E-09	6.6E-05	1.5E-08
PU-239	1.7E-18	.0E+00	2.8E-14	4.8E-20	1.8E-09	7.6E-05	1.6E-08
PU-240	4.7E-19	1.3E-15	2.3E-14	3.8E-20	1.8E-09	7.6E-05	1.6E-08
PU-241	.0E+00	.0E+00	.0E+00	.0E+00	1.7E-13	1.7E-06	3.4E-10
AM-241	3.2E-16	2.7E-13	5.6E-12	9.2E-18	3.6E-08	2.0E-04	8.5E-07
CM-242	4.9E-19	1.3E-15	2.7E-14	4.5E-20	4.0E-08	4.0E-06	1.6E-08
CM-244	3.6E-19	1.1E-15	2.3E-14	3.8E-20	3.6E-08	1.0E-04	4.3E-07

[A] Dose factor for early effects. (see a.4)

Table a.3 Dose Conversion Factors: Bone Surface

Radionuclide	CLOUDSHINE ($Sv-m^3/Bq-sec$)	GROUNDSHINE 8HR ($Sv-m^2/Bq$)	GROUNDSHINE 7 DAY ($Sv-m^2/Bq$)	GROUNDSHINE RATE ($Sv-m^2/Bq-sec$)	INHALATION ACUTE[a] (Sv/bq)	INHALATION CHRONIC (Sv/bq)	INGESTION (Sv/bq)
CO-58	4.2E-14	2.4E-11	4.9E-10	8.3E-16	---	6.9E-10	1.3E-10
CO-60	1.1E-13	5.3E-11	1.1E-09	1.9E-15	---	1.4E-08	9.4E-10
KR-85	9.8E-17	.0E+00	.0E+00	.0E+00	---	7.0E-14	.0E+00
KR-85m	8.5E-15	.0E+00	.0E+00	.0E+00	---	6.1E-14	.0E+00
KR-87	3.7E-14	.0E+00	.0E+00	.0E+00	---	2.1E-13	.0E+00
KR-88	1.2E-13	.0E+00	.0E+00	.0E+00	---	3.5E-13	.0E+00
RB-86	4.1E-15	2.1E-12	3.9E-11	7.4E-17	---	4.3E-09	6.8E-09
SR-89	6.0E-18	3.2E-15	6.5E-14	1.1E-19	---	8.4E-09	4.8E-09
SR-90	.0E+00	.0E+00	.0E+00	.0E+00	---	6.8E-07	3.9E-07
SR-91	4.3E-14	1.7E-11	4.1E-11	8.3E-16	---	1.5E-10	1.1E-10
Y-90	.0E+00	.0E+00	.0E+00	.0E+00	---	1.5E-11	3.7E-13
Y-91	1.5E-16	7.8E-14	1.6E-12	2.7E-18	---	3.2E-10	6.1E-12
ZR-95	3.2E-14	1.8E-11	3.7E-10	6.3E-16	---	2.2E-08	4.9E-10
ZR-97	6.8E-14	3.0E-11	1.2E-10	1.3E-15	---	1.2E-10	4.5E-11
NB-95	3.3E-14	1.9E-11	3.7E-10	6.5E-16	---	5.2E-10	3.0E-10
MO-99	6.9E-15	5.2E-12	7.8E-11	1.4E-16	---	4.3E-11	6.7E-11
TC-99m	7.2E-15	3.0E-12	5.0E-12	1.6E-16	---	1.8E-12	4.1E-12
RU-103	2.1E-14	1.3E-11	2.5E-10	4.4E-16	---	2.4E-10	9.7E-11
RU-105	3.5E-14	1.2E-11	1.8E-11	7.0E-16	---	4.6E-12	8.9E-12
RU-106	9.0E-15	5.2E-12	1.1E-10	1.8E-16	---	1.6E-09	1.4E-09
RH-105	3.6E-15	2.1E-12	1.4E-11	7.8E-17	---	4.4E-12	6.7E-12
TE-127	2.2E-16	1.0E-13	2.2E-13	4.6E-18	---	4.1E-12	6.4E-12
TE-127m	1.1E-16	1.6E-13	5.1E-12	4.5E-18	---	2.1E-08	2.1E-08
TE-129	2.4E-15	3.0E-13	3.0E-13	4.9E-17	---	7.1E-13	6.0E-13
TE-129m	1.4E-15	1.6E-12	3.4E-11	3.0E-17	---	7.1E-09	8.1E-09
TE-131m	6.7E-14	3.4E-11	2.2E-10	1.3E-15	---	2.6E-10	3.7E-10
TE-132	1.1E-14	4.0E-11	6.8E-10	2.4E-16	---	8.1E-10	1.0E-09
SB-127	2.9E-14	1.6E-11	2.0E-10	5.8E-16	---	1.3E-10	5.2E-11
SB-129	6.2E-14	2.0E-11	2.8E-11	1.2E-15	---	1.5E-11	1.3E-11
I-131	1.7E-14	1.0E-11	1.7E-10	3.7E-16	---	5.7E-11	8.7E-11
I-132	1.0E-13	2.1E-11	2.3E-11	1.9E-15	---	1.2E-11	2.2E-11
I-133	2.6E-14	1.3E-11	5.7E-11	5.3E-16	---	2.5E-11	4.1E-11
I-134	1.1E-13	9.8E-12	9.8E-12	2.2E-15	---	5.3E-12	9.3E-12
I-135	6.8E-14	2.3E-11	4.1E-11	1.2E-15	---	2.0E-11	3.3E-11
XE-133	2.0E-15	.0E+00	.0E+00	.0E+00	---	1.6E-13	.0E+00
XE-135	1.2E-14	.0E+00	.0E+00	.0E+00	---	2.5E-13	.0E+00
CS-134	6.8E-14	3.8E-11	8.0E-10	1.3E-15	---	1.1E-08	1.7E-08
CS-136	9.5E-14	5.2E-11	9.2E-10	1.8E-15	---	1.7E-09	2.7E-09
CS-137	2.5E-14	1.4E-11	3.0E-10	4.9E-16	---	7.9E-09	1.3E-08
BA-140	8.3E-15	8.3E-12	7.1E-10	1.8E-16	---	2.3E-09	5.4E-10
LA-140	1.0E-13	4.7E-11	3.5E-10	1.6E-15	---	1.4E-10	9.8E-11
CE-141	4.2E-15	2.7E-12	5.3E-11	9.4E-17	---	2.7E-10	2.4E-11
CE-143	1.2E-14	6.9E-12	4.3E-11	2.6E-16	---	1.6E-11	1.6E-11
CE-144	2.4E-15	1.3E-12	2.8E-11	4.7E-17	---	4.8E-09	1.3E-10
PR-143	3.9E-22	2.2E-19	3.9E-18	7.6E-24	---	1.5E-11	1.0E-12
ND-147	6.2E-15	4.0E-12	6.9E-11	1.4E-16	---	3.3E-10	2.2E-11
NP-239	8.8E-15	5.4E-12	5.1E-11	2.0E-16	---	1.4E-09	1.5E-10
PU-238	1.8E-18	5.1E-15	1.1E-13	1.8E-19	---	8.3E-04	1.8E-07
PU-239	3.4E-18	.0E+00	7.4E-14	1.3E-19	---	9.5E-04	2.0E-07
PU-240	1.8E-18	6.1E-15	1.0E-13	1.7E-19	---	9.5E-04	2.0E-07
PU-241	.0E+00	.0E+00	.0E+00	.0E+00	---	2.1E-05	4.2E-09
AM-241	1.1E-15	9.3E-13	1.9E-11	3.2E-17	---	2.5E-03	1.1E-05
CM-242	1.9E-18	5.9E-15	1.2E-13	2.0E-19	---	5.0E-05	2.3E-07
CM-244	1.4E-18	5.1E-15	1.1E-13	1.8E-19	---	1.3E-03	5.4E-06

Table a.3 Dose Conversion Factors: Lung

Radionuclide	CLOUDSHINE ($Sv-m^3/Bq-sec$)	GROUNDSHINE 8HR ($Sv-m^2/Bq$)	GROUNDSHINE 7 DAY ($Sv-m^2/Bq$)	GROUNDSHINE PATE ($Sv-m^2/Bq-sec$)	INHALATION ACUTE[a] (Sv/bq)	INHALATION CHRONIC (Sv/bq)	INGESTION (Sv/bq)
CO-58	3.8E-14	2.1E-11	4.4E-10	7.5E-16	1.0E-09	1.6E-08	8.5E-11
CO-60	9.9E-14	5.0E-11	1.0E-09	1.7E-15	5.2E-09	3.4E-07	8.8E-10
KR-85	8.3E-17	.0E+00	.0E+00	.0E+00	4.8E-13	4.8E-13	.0E+00
KR-85m	5.8E-15	.0E+00	.0E+00	.0E+00	4.9E-13	4.9E-13	.0E+00
KR-87	3.4E-14	.0E+00	.0E+00	.0E+00	2.4E-12	2.4E-12	.0E+00
KR-88	1.1E-13	.0E+00	.0E+00	.0E+00	4.3E-12	4.3E-12	.0E+00
RB-86	3.7E-15	2.0E-12	3.6E-11	6.8E-17	1.6E-09	3.3E-09	2.1E-09
SR-89	5.4E-18	3.0E-15	5.9E-14	1.0E-19	1.3E-09	8.2E-09	2.5E-10
SR-90	.0E+00	.0E+00	.0E+00	.0E+00	7.4E-10	3.4E-09	1.3E-09
SR-91	3.9E-14	1.6E-11	3.7E-11	7.5E-16	8.7E-10	9.2E-10	3.1E-11
Y-90	.0E+00	.0E+00	.0E+00	.0E+00	3.5E-09	9.3E-09	1.3E-14
Y-91	1.4E-16	7.2E-14	1.5E-12	2.5E-18	6.9E-09	9.8E-08	2.0E-13
ZR-95	2.9E-14	1.6E-11	3.3E-10	5.6E-16	1.5E-09	1.8E-08	2.3E-11
ZR-97	6.0E-14	2.7E-11	1.0E-10	1.2E-15	2.8E-09	4.0E-09	1.8E-11
NB-95	3.0E-14	1.7E-11	3.3E-10	5.9E-16	7.4E-10	8.3E-09	2.7E-11
MO-99	6.0E-15	4.2E-12	5.9E-11	1.2E-16	1.6E-09	4.3E-09	1.5E-11
TC-99m	4.6E-15	1.9E-12	3.2E-12	1.0E-16	2.9E-11	3.1E-11	3.2E-12
RU-103	1.8E-14	1.1E-11	2.1E-10	3.7E-16	1.3E-09	1.6E-08	7.4E-11
RU-105	3.0E-14	1.0E-11	1.5E-11	6.1E-16	5.0E-10	5.7E-10	6.2E-12
RU-106	7.9E-15	4.5E-12	9.5E-11	1.6E-16	3.0E-08	1.0E-06	1.4E-09
RH-105	2.8E-15	1.6E-12	1.1E-11	6.1E-17	5.0E-10	9.5E-10	3.8E-12
TE-127	1.8E-16	8.2E-14	1.6E-13	3.8E-18	3.7E-10	4.3E-10	2.9E-12
TE-127m	6.2E-17	1.0E-13	3.6E-12	2.6E-18	2.5E-09	3.3E-08	9.6E-11
TE-129	2.0E-15	2.5E-13	2.5E-13	4.2E-17	1.5E-10	1.5E-10	4.9E-13
TE-129m	1.3E-15	1.3E-12	2.9E-11	2.6E-17	4.4E-09	4.0E-08	1.6E-10
TE-131m	6.0E-14	3.0E-11	1.9E-10	1.1E-15	1.2E-09	2.2E-09	6.0E-11
TE-132	7.7E-15	3.5E-11	5.9E-10	1.7E-16	5.6E-10	1.6E-09	2.7E-10
SB-127	2.5E-14	1.4E-11	1.8E-10	5.1E-16	1.9E-09	6.9E-09	1.6E-11
SB-129	5.7E-14	1.8E-11	2.5E-11	1.1E-15	8.4E-10	9.0E-10	9.4E-12
I-131	1.4E-14	8.4E-12	1.4E-10	3.0E-16	4.6E-10	6.6E-10	1.0E-10
I-132	9.0E-14	1.9E-11	2.1E-11	1.7E-15	2.7E-10	2.7E-10	2.6E-11
I-133	2.3E-14	1.2E-11	5.0E-11	4.6E-16	7.1E-10	8.2E-10	4.5E-11
I-134	1.0E-13	8.9E-12	8.9E-12	2.0E-15	1.4E-10	1.4E-10	1.3E-11
I-135	6.3E-14	2.2E-11	3.8E-11	1.1E-15	4.3E-10	4.4E-10	3.7E-11
XE-133	1.1E-15	.0E+00	.0E+00	.0E+00	3.6E-13	3.8E-13	.0E+00
XE-135	9.0E-15	.0E+00	.0E+00	.0E+00	7.8E-13	7.8E-13	.0E+00
CS-134	6.0E-14	3.4E-11	7.2E-10	1.2E-15	1.0E-09	1.2E-08	1.7E-08
CS-136	9.5E-14	4.6E-11	8.2E-10	1.6E-15	7.0E-10	2.3E-09	2.6E-09
CS-137	2.2E-14	1.2E-11	2.6E-10	4.4E-16	9.5E-10	8.8E-09	1.3E-08
BA-140	7.0E-15	7.2E-12	6.4E-10	1.5E-16	9.6E-10	1.7E-09	6.7E-11
LA-140	9.4E-14	4.4E-11	3.2E-10	1.6E-15	2.0E-09	4.2E-09	4.0E-11
CE-141	2.7E-15	1.7E-12	3.4E-11	6.0E-17	1.5E-09	1.7E-08	1.4E-12
CE-143	9.5E-15	5.4E-12	3.4E-11	2.0E-16	1.5E-09	3.9E-09	3.8E-12
CE-144	2.0E-15	1.0E-12	2.2E-11	3.7E-17	2.6E-08	7.9E-07	6.5E-12
PR-143	3.5E-22	1.9E-19	3.5E-18	6.8E-24	2.0E-09	1.3E-08	6.5E-15
ND-147	4.8E-15	3.0E-12	5.1E-11	1.0E-16	1.6E-09	1.1E-08	2.4E-12
NP-239	5.9E-15	3.6E-12	3.4E-11	1.3E-16	9.6E-10	2.3E-09	2.9E-12
PU-238	1.0E-18	3.0E-15	6.3E-14	1.1E-19	2.9E-06	3.2E-04	8.8E-14
PU-239	2.1E-18	.0E+00	4.5E-14	7.7E-20	2.7E-06	3.2E-04	8.0E-14
PU-240	1.0E-18	3.6E-15	6.2E-14	1.0E-19	2.7E-06	3.2E-04	8.4E-14
PU-241	.0E+00	.0E+00	.0E+00	.0E+00	1.6E-09	3.2E-06	6.5E-15
AM-241	5.9E-16	5.0E-13	1.0E-11	1.7E-17	1.3E-06	1.8E-05	2.1E-13
CM-242	1.1E-18	3.5E-15	7.3E-14	1.2E-19	1.2E-06	1.5E-05	4.4E-12
CM-244	8.3E-19	3.0E-15	6.4E-14	1.1E-19	1.3E-06	1.9E-05	4.5E-12

Table a.3 Dose Conversion Factors: Thyroid

Radionuclide	CLOUDSHINE (Sv-m^3/Bq-sec)	GROUNDSHINE 8HR (Sv-m^2/Bq)	GROUNDSHINE 7 DAY (Sv-m^2/Bq)	GROUNDSHINE RATE (Sv-m^2/Bq-sec)	INHALATION ACUTE[a] (Sv/bq)	INHALATION CHRONIC (Sv/bq)	INGESTION (Sv/bq)
CO-58	4.8E-14	2.7E-11	5.5E-10	9.4E-16	6.1E-11	8.7E-10	6.3E-11
CO-60	1.2E-13	6.3E-11	1.3E-09	2.2E-15	1.5E-10	1.6E-08	7.8E-10
KR-85	1.0E-16	.0E+00	.0E+00	.0E+00	6.7E-14	7.0E-14	.0E+00
KR-85m	7.7E-15	.0E+00	.0E+00	.0E+00	5.5E-14	5.5E-14	.0E+00
KR-87	4.1E-14	.0E+00	.0E+00	.0E+00	2.2E-13	2.2E-13	.0E+00
KR-88	1.4E-13	.0E+00	.0E+00	.0E+00	3.5E-13	3.5E-13	.0E+00
RB-86	4.7E-15	2.5E-12	4.6E-11	8.6E-17	2.5E-10	1.3E-09	2.1E-09
SR-89	6.8E-18	3.7E-15	7.5E-14	1.3E-19	8.3E-11	4.3E-10	2.5E-10
SR-90	.0E+00	.0E+00	.0E+00	.0E+00	1.1E-10	2.3E-09	1.3E-09
SR-91	4.8E-14	2.0E-11	4.6E-11	9.3E-16	3.4E-11	4.2E-11	2.5E-11
Y-90	.0E+00	.0E+00	.0E+00	.0E+00	3.2E-13	5.2E-13	1.3E-14
Y-91	1.8E-16	9.1E-14	1.8E-12	3.2E-18	6.2E-13	8.5E-12	1.3E-13
ZR-95	3.6E-14	2.0E-11	4.1E-10	7.1E-16	6.1E-11	7.6E-10	8.2E-12
ZR-97	7.6E-14	3.4E-11	1.3E-10	1.5E-15	2.6E-11	3.7E-11	2.7E-12
NB-95	3.8E-14	2.1E-11	4.2E-10	7.4E-16	4.3E-11	3.6E-10	1.2E-11
MO-99	7.6E-15	5.4E-12	7.7E-11	1.5E-16	5.9E-12	1.5E-11	1.1E-11
TC-99m	6.3E-15	2.7E-12	4.4E-12	1.4E-16	2.0E-11	2.1E-11	8.4E-11
RU-103	2.2E-14	1.3E-11	2.6E-10	4.6E-16	2.9E-11	2.6E-10	6.3E-11
RU-105	3.8E-14	1.3E-11	1.9E-11	7.7E-16	3.9E-12	4.1E-12	1.8E-12
RU-106	9.9E-15	5.7E-12	1.2E-10	2.0E-16	4.0E-11	1.7E-09	1.4E-09
RH-105	3.6E-15	2.1E-12	1.4E-11	7.8E-17	1.4E-12	2.9E-12	2.9E-12
TE-127	2.2E-16	1.0E-13	2.3E-13	4.6E-18	1.6E-12	1.8E-12	2.9E-12
TE-127m	1.2E-16	1.9E-13	5.7E-12	5.3E-18	1.3E-11	9.6E-11	9.4E-11
TE-129	2.5E-15	3.1E-13	3.2E-13	5.3E-17	5.1E-13	5.1E-13	3.4E-13
TE-129m	1.6E-15	1.7E-12	3.8E-11	3.4E-17	3.0E-11	1.6E-10	1.6E-10
TE-131m	7.5E-14	3.8E-11	2.4E-10	1.4E-15	6.4E-09	3.1E-08	3.7E-08
TE-132	1.0E-14	4.4E-11	7.5E-10	2.3E-16	7.8E-08	1.7E-07	1.5E-07
SB-127	1.2E-14	1.6E-11	2.2E-10	6.4E-16	2.4E-11	6.1E-11	4.6E-12
SB-129	7.1E-14	2.2E-11	3.1E-11	1.3E-15	9.5E-12	9.7E-12	1.5E-12
I-131	1.6E-14	1.1E-11	1.7E-10	3.7E-16	6.4E-08	2.9E-07	4.8E-07
I-132	1.1E-13	2.4E-11	2.6E-11	2.2E-15	1.7E-09	1.7E-09	3.8E-09
I-133	2.9E-14	1.5E-11	6.2E-11	5.8E-16	2.4E-08	4.9E-08	9.1E-08
I-134	1.3E-13	1.1E-11	1.1E-11	2.5E-15	2.8E-10	2.8E-10	6.2E-10
I-135	7.9E-14	2.7E-11	4.7E-11	1.4E-15	7.2E-09	8.4E-09	1.8E-08
XE-133	1.7E-15	.0E+00	.0E+00	.0E+00	1.2E-13	1.4E-13	.0E+00
XE-135	1.2E-14	.0E+00	.0E+00	.0E+00	2.3E-13	2.3E-13	.0E+00
CS-134	7.6E-14	4.3E-11	9.0E-10	1.5E-15	4.7E-10	1.1E-08	1.8E-08
CS-136	1.1E-13	5.8E-11	1.0E-09	2.1E-15	3.6E-10	1.7E-09	2.7E-09
CS-137	2.7E-14	1.6E-11	3.3E-10	5.5E-16	3.0E-10	7.9E-09	1.3E-08
BA-140	8.8E-15	9.0E-12	8.0E-10	1.8E-16	6.5E-11	2.6E-10	5.4E-11
LA-140	1.1E-13	5.4E-11	3.9E-10	2.0E-15	3.8E-11	6.9E-11	6.4E-12
CE-141	3.7E-15	2.4E-12	4.7E-11	8.4E-17	3.2E-12	2.5E-11	1.8E-13
CE-143	1.2E-14	7.1E-12	4.4E-11	2.7E-16	3.7E-12	6.2E-12	4.4E-13
CE-144	2.5E-15	1.3E-12	2.9E-11	4.8E-17	1.9E-12	2.9E-10	5.1E-12
PR-143	4.4E-22	2.5E-19	4.4E-18	8.6E-24	8.2E-14	9.4E-14	6.5E-15
ND-147	6.3E-15	4.0E-12	6.9E-11	1.4E-16	4.6E-12	1.8E-11	2.7E-13
NP-239	6.0E-15	4.9E-12	4.6E-11	1.8E-16	4.1E-12	7.3E-12	4.7E-13
PU-238	1.5E-18	3.7E-15	7.6E-14	1.3E-19	3.0E-11	3.9E-10	8.0E-14
PU-239	2.9E-18	.0E+00	5.9E-14	1.0E-19	2.8E-11	3.8E-10	7.5E-14
PU-240	1.5E-18	4.5E-15	7.7E-14	1.3E-19	2.8E-11	3.8E-10	7.5E-14
PU-241	.0E+00	.0E+00	.0E+00	.0E+00	2.2E-15	1.0E-11	1.2E-15
AM-241	9.4E-16	8.0E-13	1.6E-11	2.7E-17	5.5E-10	1.7E-09	7.0E-12
CM-242	1.6E-18	4.6E-15	9.5E-14	1.6E-19	6.1E-10	9.4E-10	4.4E-12
CM-244	1.2E-18	3.9E-15	8.2E-14	1.4E-19	5.8E-10	1.0E-09	4.2E-12

Table a.3 Dose Conversion Factors: Lower Large Intesine

Radionuclide	CLOUDSHINE ($Sv-m^3/Bq-sec$)	GROUNDSHINE 8HR ($Sv-m^2/Bq$)	GROUNDSHINE 7 DAY ($Sv-m^2/Bq$)	GROUNDSHINE RATE ($Sv-m^2/Bq-sec$)	INHALATION ACUTE* (Sv/bq)	INHALATION CHRONIC (Sv/bq)	INGESTION (Sv/bq)
CO-58	3.5E-14	1.9E-11	3.9E-10	6.8E-16	9.1E-10	2.0E-09	4.0E-09
CO-60	9.1E-14	4.6E-11	9.6E-10	1.6E-15	2.4E-09	7.9E-09	1.1E-08
KR-85	7.5E-17	.0E+00	.0E+00	.0E+00	6.8E-14	7.0E-14	.0E+00
KR-85m	5.1E-15	.0E+00	.0E+00	.0E+00	5.9E-14	5.9E-14	.0E+00
KR-87	3.1E-14	.0E+00	.0E+00	.0E+00	2.3E-13	2.3E-13	.0E+00
KR-88	1.1E-13	.0E+00	.0E+00	.0E+00	4.0E-13	4.0E-13	.0E+00
RB-86	3.4E-15	1.8E-12	3.3E-11	6.2E-17	2.0E-10	1.3E-09	2.2E-09
SR-89	4.9E-18	2.7E-15	5.4E-14	9.4E-20	2.0E-09	3.6E-09	2.1E-08
SR-90	.0E+00	.0E+00	.0E+00	.0E+00	1.6E-09	5.1E-09	1.9E-08
SR-91	3.5E-14	1.4E-11	3.3E-11	6.8E-16	5.2E-10	6.2E-10	3.9E-09
Y-90	.0E+00	.0E+00	.0E+00	.0E+00	6.5E-09	1.3E-08	3.1E-08
Y-91	1.3E-16	6.6E-14	1.3E-12	2.3E-18	6.9E-09	1.5E-08	3.0E-08
ZR-95	2.6E-14	1.5E-11	3.0E-10	5.1E-16	1.6E-09	4.2E-09	7.8E-09
ZR-97	5.5E-14	2.4E-11	9.4E-11	1.1E-15	2.6E-09	4.3E-09	1.8E-08
NB-95	2.7E-14	1.5E-11	3.0E-10	5.3E-16	9.2E-10	1.9E-09	4.0E-09
MO-99	5.4E-15	3.7E-12	5.2E-11	1.1E-16	2.9E-09	5.5E-09	1.4E-08
TC-99m	4.0E-15	1.7E-12	2.8E-12	9.0E-17	3.4E-12	3.8E-12	2.5E-11
RU-103	1.6E-14	9.7E-12	1.9E-10	3.4E-16	1.5E-09	3.1E-09	6.5E-09
RU-105	2.8E-14	9.1E-12	1.4E-11	5.5E-16	2.1E-10	3.0E-10	1.3E-09
RU-106	7.1E-15	4.1E-12	8.6E-11	1.4E-16	1.6E-08	3.7E-08	7.1E-08
RH-105	2.6E-15	1.5E-12	9.7E-12	5.5E-17	7.4E-10	1.3E-09	3.8E-09
TE-127	1.6E-16	7.4E-14	1.6E-13	3.4E-18	1.6E-10	2.3E-10	1.3E-09
TE-127m	4.1E-17	7.1E-14	2.8E-12	1.7E-18	2.3E-09	5.7E-09	1.1E-08
TE-129	1.8E-15	2.2E-13	2.2E-13	3.7E-17	1.8E-12	1.8E-12	3.7E-11
TE-129m	1.1E-15	1.2E-12	2.6E-11	2.3E-17	4.9E-09	1.1E-08	2.5E-08
TE-131m	5.4E-14	2.7E-11	1.7E-10	1.0E-15	1.3E-09	2.4E-09	8.1E-09
TE-132	6.8E-15	3.2E-11	5.4E-10	1.5E-16	7.7E-10	1.5E-09	3.7E-09
SB-127	2.3E-14	1.3E-11	1.6E-10	4.6E-16	3.7E-09	7.4E-09	2.0E-08
SB-129	5.2E-14	1.6E-11	2.3E-11	9.7E-16	2.0E-10	2.3E-10	1.9E-09
I-131	1.3E-14	7.6E-12	1.2E-10	2.7E-16	1.5E-11	2.6E-11	4.2E-11
I-132	8.1E-14	1.7E-11	1.9E-11	1.6E-15	1.1E-11	1.1E-11	2.8E-11
I-133	2.1E-14	1.1E-11	4.5E-11	4.2E-16	1.9E-11	2.0E-11	3.9E-11
I-134	9.5E-14	8.1E-12	8.1E-12	1.8E-15	4.8E-12	4.8E-12	1.3E-11
I-135	5.8E-14	2.0E-11	3.5E-11	1.0E-15	1.8E-11	1.8E-11	3.9E-11
XE-133	8.7E-16	.0E+00	.0E+00	.0E+00	1.4E-13	1.5E-13	.0E+00
XE-135	8.1E-15	.0E+00	.0E+00	.0E+00	2.5E-13	2.5E-13	.0E+00
CS-134	5.5E-14	3.1E-11	6.5E-10	1.1E-15	3.3E-10	1.4E-08	2.2E-08
CS-136	7.8E-14	4.2E-11	7.4E-10	1.5E-15	3.6E-10	2.1E-09	3.4E-09
CS-137	2.0E-14	1.1E-11	2.4E-10	3.9E-16	2.0E-10	9.1E-09	1.4E-08
BA-140	6.2E-15	6.5E-12	5.9E-10	1.3E-16	2.3E-09	4.4E-09	2.6E-08
LA-140	8.6E-14	4.0E-11	2.9E-10	1.5E-15	2.9E-09	5.5E-09	1.6E-08
CE-141	2.3E-15	1.5E-12	2.9E-11	5.2E-17	2.0E-09	4.1E-09	8.6E-09
CE-143	8.5E-15	4.8E-12	3.0E-11	1.8E-16	2.3E-09	4.3E-09	1.2E-08
CE-144	1.8E-15	9.1E-13	2.0E-11	3.3E-17	1.5E-08	3.4E-08	6.6E-08
PR-143	3.2E-22	1.8E-19	3.1E-18	6.2E-24	3.3E-09	6.8E-09	1.5E-08
ND-147	4.2E-15	2.6E-12	4.4E-11	9.0E-17	2.9E-09	5.8E-09	1.3E-08
NP-239	5.1E-15	3.1E-12	2.9E-11	1.1E-16	1.5E-09	2.9E-09	8.6E-09
PU-238	6.7E-19	1.8E-15	3.7E-14	6.2E-20	1.3E-08	3.3E-08	5.7E-08
PU-239	1.7E-18	.0E+00	3.3E-14	5.6E-20	1.2E-08	3.1E-08	5.3E-08
PU-240	6.8E-19	2.1E-15	3.7E-14	6.1E-20	1.2E-08	3.1E-08	5.3E-08
PU-241	.0E+00	.0E+00	.0E+00	.0E+00	6.2E-11	1.8E-10	2.7E-10
AM-241	4.3E-16	3.7E-13	7.5E-12	1.2E-17	1.2E-08	3.2E-08	5.8E-08
CM-242	7.1E-19	2.1E-15	4.3E-14	7.3E-20	1.3E-08	3.1E-08	6.2E-08
CM-244	5.4E-19	1.8E-15	3.8E-14	6.2E-20	1.2E-08	3.2E-08	6.0E-08

Table a.3 Dose Conversion Factors: Small Intestine

Radionuclide	CLOUDSHINE (Sv-m³/Bq-sec)	GROUNDSHINE 8HR (Sv-m²/Bq)	GROUNDSHINE 7 DAY (Sv-m²/Bq)	GROUNDSHINE RATE (Sv-m²/Bq-sec)	INHALATION ACUTE[a] (Sv/bq)	INHALATION CHRONIC (Sv/bq)	INGESTION (Sv/bq)
CO-58	3.2E-14	1.8E-11	3.7E-10	6.2E-16	3.3E-10	7.5E-10	1.1E-09
CO-60	8.5E-14	4.3E-11	9.0E-10	1.5E-15	8.1E-10	7.0E-09	3.6E-09
KR-85	6.9E-17	.0E+00	.0E+00	.0E+00	6.8E-14	7.0E-14	.0E+00
KR-85M	4.6E-15	.0E+00	.0E+00	.0E+00	6.1E-14	6.1E-14	.0E+00
KR-87	2.9E-14	.0E+00	.0E+00	.0E+00	2.2E-13	2.2E-13	.0E+00
KR-88	1.0E-13	.0E+00	.0E+00	.0E+00	3.8E-13	3.8E-13	.0E+00
RB-86	3.2E-15	1.7E-12	3.1E-11	5.8E-17	2.0E-10	1.3E-09	2.2E-09
SR-89	4.6E-18	2.5E-15	5.0E-14	8.7E-20	2.7E-10	6.1E-10	1.4E-09
SR-90	.0E+00	.0E+00	.0E+00	.0E+00	1.6E-10	2.4E-09	1.8E-09
SR-91	3.2E-14	1.3E-11	3.1E-11	6.3E-16	2.3E-10	2.4E-10	1.4E-09
Y-90	.0E+00	.0E+00	.0E+00	.0E+00	8.7E-10	1.0E-09	2.6E-09
Y-91	1.2E-16	6.2E-14	1.3E-12	2.2E-16	6.7E-10	8.4E-10	1.7E-09
ZR-95	2.4E-14	1.4E-11	2.8E-10	4.7E-16	3.3E-10	9.8E-10	1.1E-09
ZR-97	5.1E-14	2.2E-11	8.7E-11	9.9E-16	7.8E-10	8.9E-10	3.4E-09
NB-95	2.5E-14	1.4E-11	2.8E-10	4.9E-16	2.8E-10	5.2E-10	9.1E-10
MO-99	5.0E-15	3.4E-12	4.7E-11	9.9E-17	4.2E-10	5.2E-10	1.2E-09
TC-99M	3.6E-15	1.5E-12	2.5E-12	8.0E-17	3.4E-12	3.5E-12	2.2E-11
RU-103	1.5E-14	8.8E-12	1.7E-10	3.1E-16	2.7E-10	4.7E-10	8.5E-10
RU-105	2.5E-14	8.4E-12	1.2E-11	5.1E-16	1.2E-10	1.2E-10	7.9E-10
RU-106	6.6E-15	3.8E-12	7.9E-11	1.3E-16	1.6E-09	3.4E-09	5.5E-09
RH-105	2.3E-15	1.3E-12	8.8E-12	5.0E-17	1.4E-10	1.6E-10	4.4E-10
TE-127	1.5E-16	6.7E-14	1.5E-13	3.1E-18	6.8E-11	7.1E-11	3.9E-10
TE-127M	3.2E-17	5.8E-14	2.4E-12	1.3E-18	1.8E-10	3.7E-10	4.3E-10
TE-129	1.7E-15	2.0E-13	2.0E-13	3.4E-17	1.1E-11	1.1E-11	2.7E-10
TE-129M	1.0E-15	1.1E-12	2.4E-11	2.1E-17	5.1E-10	8.0E-10	1.5E-09
TE-131M	5.0E-14	2.5E-11	1.6E-10	9.5E-16	3.9E-10	4.9E-10	1.6E-09
TE-132	6.2E-15	2.9E-11	5.0E-10	1.4E-16	2.6E-10	4.2E-10	6.9E-10
SB-127	2.1E-14	1.2E-11	1.5E-10	4.2E-16	5.2E-10	7.1E-10	1.6E-09
SB-129	4.8E-14	1.5E-11	2.1E-11	9.0E-16	1.9E-10	1.9E-10	1.5E-09
I-131	1.2E-14	6.9E-12	1.1E-10	2.4E-16	1.6E-11	2.7E-11	4.5E-11
I-132	7.5E-14	1.6E-11	1.7E-11	1.5E-15	1.2E-11	1.2E-11	3.2E-11
I-133	1.9E-14	9.7E-12	4.1E-11	3.8E-16	2.0E-11	2.2E-11	4.0E-11
I-134	8.8E-14	7.5E-12	7.5E-12	1.7E-15	5.5E-12	5.5E-12	1.6E-11
I-135	5.5E-14	1.9E-11	3.3E-11	9.5E-16	1.9E-11	1.9E-11	4.1E-11
XE-133	8.0E-16	.0E+00	.0E+00	.0E+00	1.4E-13	1.5E-13	.0E+00
XE-135	7.3E-15	.0E+00	.0E+00	.0E+00	2.6E-13	2.6E-13	.0E+00
CS-134	5.0E-14	2.9E-11	6.0E-10	9.9E-16	3.4E-10	1.4E-08	2.2E-08
CS-136	7.2E-14	3.9E-11	6.9E-10	1.4E-15	3.7E-10	2.1E-09	3.4E-09
CS-137	1.8E-14	1.0E-11	2.2E-10	3.6E-16	2.0E-10	9.0E-09	1.4E-08
BA-140	5.7E-15	6.0E-12	5.5E-10	1.2E-16	2.8E-10	5.4E-10	1.7E-09
LA-140	8.1E-14	3.8E-11	2.8E-10	1.4E-15	7.5E-10	9.8E-10	3.0E-09
CE-141	2.1E-15	1.3E-12	2.6E-11	4.7E-17	2.2E-10	2.9E-10	5.9E-10
CE-143	7.8E-15	4.4E-12	2.7E-11	1.7E-16	4.2E-10	4.9E-10	1.4E-09
CE-144	1.6E-15	8.4E-13	1.8E-11	3.0E-17	1.5E-09	2.2E-09	3.7E-09
PR-143	2.9E-22	1.6E-19	2.9E-16	5.7E-24	3.4E-10	4.1E-10	8.9E-10
ND-147	3.8E-15	2.4E-12	4.0E-11	8.3E-17	3.4E-10	4.3E-10	9.4E-10
NP-239	4.6E-15	2.8E-12	2.6E-11	1.0E-16	2.4E-10	3.0E-10	8.7E-10
PU-238	4.6E-19	4.3E-16	8.9E-15	1.5E-20	1.3E-09	2.2E-09	3.2E-09
PU-239	1.5E-18	.0E+00	2.0E-14	3.4E-20	1.1E-09	2.1E-09	3.0E-09
PU-240	4.8E-19	5.6E-16	9.5E-15	1.6E-20	1.2E-09	2.1E-09	3.0E-09
PU-241	.0E+00	.0E+00	.0E+00	.0E+00	5.9E-12	2.9E-11	1.5E-11
AM-241	4.1E-16	3.4E-13	7.1E-12	1.2E-17	1.6E-09	4.7E-09	3.3E-09
CM-242	4.4E-19	4.3E-16	8.9E-15	1.5E-20	1.8E-09	2.7E-09	3.5E-09
CM-244	3.0E-19	3.1E-16	6.5E-15	1.1E-20	1.7E-09	2.7E-09	3.4E-09

Table a.3 Dose Conversion Factors: Stomach

Radionuclide	CLOUDSHINE ($Sv-m^3/Bq-sec$)	GROUNDSHINE 8HR ($Sv-m^2/Bq$)	GROUNDSHINE 7 DAY ($Sv-m^2/Bq$)	GROUNDSHINE RATE ($Sv-m^2/Bq-sec$)	INHALATION ACUTE[a] (Sv/bq)	INHALATION CHRONIC (Sv/bq)	INGESTION (Sv/bq)
CO-58	3.5E-14	2.0E-11	4.0E-10	6.9E-16	1.6E-10	1.4E-09	3.9E-10
CO-60	9.1E-14	4.6E-11	9.7E-10	1.6E-15	3.8E-10	2.7E-08	1.6E-09
KR-85	7.7E-17	.0E+00	.0E+00	.0E+00	6.8E-14	7.0E-14	.0E+00
KR-85m	5.2E-15	.0E+00	.0E+00	.0E+00	6.1E-14	6.1E-14	.0E+00
KR-87	3.2E-14	.0E+00	.0E+00	.0E+00	2.2E-13	2.2E-13	.0E+00
KR-88	1.1E-13	.0E+00	.0E+00	.0E+00	3.7E-13	3.7E-13	.0E+00
RB-86	3.5E-15	1.8E-12	3.4E-11	6.3E-17	3.0E-10	1.5E-09	2.9E-09
SR-89	5.0E-18	2.7E-15	5.5E-14	9.5E-20	1.8E-10	5.3E-10	9.2E-10
SR-90	.0E+00	.0E+00	.0E+00	.0E+00	1.1E-10	2.3E-09	1.6E-09
SR-91	3.6E-14	1.5E-11	3.4E-11	6.9E-16	1.6E-10	1.7E-10	8.6E-10
Y-90	.0E+00	.0E+00	.0E+00	.0E+00	3.7E-10	4.3E-10	1.1E-09
Y-91	1.3E-16	6.7E-14	1.4E-12	2.3E-18	2.7E-10	3.4E-10	6.9E-10
ZR-95	2.7E-14	1.5E-11	3.0E-10	5.2E-16	1.5E-10	1.1E-09	3.6E-10
ZR-97	5.6E-14	2.5E-11	9.6E-11	1.1E-15	3.8E-10	4.2E-10	1.2E-09
NB-95	2.8E-14	1.6E-11	3.1E-10	5.4E-16	1.3E-10	6.4E-10	2.8E-10
MO-99	5.5E-15	3.8E-12	5.4E-11	1.1E-16	1.9E-10	2.3E-10	5.1E-10
TC-99m	4.2E-15	1.7E-12	2.9E-12	9.2E-17	1.4E-11	1.5E-11	7.2E-11
RU-103	1.7E-14	9.8E-12	2.0E-10	3.4E-16	1.2E-10	5.0E-10	3.1E-10
RU-105	2.8E-14	9.3E-12	1.4E-11	5.6E-16	7.9E-11	8.1E-11	5.0E-10
RU-106	7.3E-15	4.2E-12	8.7E-11	1.5E-16	7.0E-10	2.9E-09	3.1E-09
RH-105	2.6E-15	1.5E-12	9.9E-12	5.6E-17	6.4E-11	7.3E-11	1.9E-10
TE-127	1.6E-16	7.5E-14	1.7E-13	3.5E-18	4.3E-11	4.5E-11	2.4E-10
TE-127m	4.6E-17	7.8E-14	3.0E-12	1.9E-18	8.9E-11	2.3E-10	2.1E-10
TE-129	1.8E-15	2.3E-13	2.3E-13	3.8E-17	1.6E-11	1.6E-11	4.0E-10
TE-129m	1.2E-15	1.2E-12	2.7E-11	2.4E-17	2.6E-10	4.8E-10	6.3E-10
TE-131m	5.5E-14	2.8E-11	1.8E-10	1.0E-15	2.2E-10	2.7E-10	6.6E-10
TE-132	7.0E-15	3.2E-11	5.5E-10	1.6E-16	1.9E-10	3.3E-10	4.2E-10
SB-127	2.3E-14	1.3E-11	1.6E-10	4.7E-16	2.3E-10	3.3E-10	5.6E-10
SB-129	5.3E-14	1.7E-11	2.3E-11	9.8E-16	1.2E-10	1.2E-10	7.2E-10
I-131	1.3E-14	7.7E-12	1.2E-10	2.7E-16	6.0E-11	7.5E-11	3.1E-10
I-132	8.3E-14	1.7E-11	1.9E-11	1.6E-15	9.9E-11	9.9E-11	6.3E-10
I-133	2.1E-14	1.1E-11	4.6E-11	4.2E-16	1.0E-10	1.0E-10	5.5E-10
I-134	9.7E-14	8.2E-12	8.2E-12	1.8E-15	7.1E-11	7.1E-11	5.5E-10
I-135	5.9E-14	2.0E-11	3.5E-11	1.0E-15	9.8E-11	9.9E-11	5.4E-10
XE-133	9.5E-16	.0E+00	.0E+00	.0E+00	1.3E-13	1.5E-13	.0E+00
XE-135	8.2E-15	.0E+00	.0E+00	.0E+00	2.5E-13	2.6E-13	.0E+00
CS-134	5.6E-14	3.2E-11	6.6E-10	1.1E-15	3.5E-10	1.3E-08	2.0E-08
CS-136	7.9E-14	4.3E-11	7.5E-10	1.5E-15	3.8E-10	2.0E-09	3.4E-09
CS-137	2.0E-14	1.1E-11	2.4E-10	4.0E-16	2.3E-10	8.6E-09	1.4E-08
BA-140	6.4E-15	6.6E-12	5.9E-10	1.3E-16	1.4E-10	3.5E-10	5.8E-10
LA-140	8.7E-14	4.0E-11	3.0E-10	1.5E-15	3.6E-10	4.7E-10	1.1E-09
CE-141	2.4E-15	1.5E-12	3.0E-11	5.4E-17	9.0E-11	1.6E-10	2.2E-10
CE-143	8.7E-15	4.9E-12	3.1E-11	1.9E-16	1.9E-10	2.1E-10	5.6E-10
CE-144	1.8E-15	9.3E-13	2.0E-11	3.3E-17	6.0E-10	1.2E-09	1.1E-09
PR-143	3.2E-22	1.8E-19	3.2E-18	6.3E-24	1.4E-10	1.7E-10	3.6E-10
ND-147	4.3E-15	2.7E-12	4.6E-11	9.4E-17	1.4E-10	2.0E-10	3.6E-10
NP-239	5.3E-15	3.2E-12	3.0E-11	1.2E-16	1.1E-10	1.3E-10	3.5E-10
PU-238	6.7E-19	1.4E-15	2.9E-14	4.9E-20	5.4E-10	1.1E-09	1.3E-09
PU-239	1.6E-18	.0E+00	3.0E-14	5.2E-20	5.0E-10	1.1E-09	1.2E-09
PU-240	7.0E-19	1.7E-15	2.9E-14	4.8E-20	5.1E-10	1.1E-09	1.2E-09
PU-241	.0E+00	.0E+00	.0E+00	.0E+00	2.4E-12	3.0E-11	6.1E-12
AM-241	4.9E-16	4.1E-13	8.5E-12	1.4E-17	1.0E-09	3.8E-09	1.3E-09
CM-242	7.0E-19	1.7E-15	3.4E-14	5.7E-20	1.1E-09	1.6E-09	1.4E-09
CM-244	5.1E-19	1.4E-15	2.9E-14	4.8E-20	1.0E-09	1.7E-09	1.4E-09

Table a.3 Dose Conversion Factors: Breast

Radionuclide	CLOUDSHINE ($Sv-m^3/Bq-sec$)	GROUNDSHINE 8HR ($Sv-m^2/Bq$)	GROUNDSHINE 7 DAY ($Sv-m^2/Bq$)	GROUNDSHINE RATE ($Sv-m^2/Bq-sec$)	INHALATION ACUTE[a] (Sv/bq)	INHALATION CHRONIC (Sv/bq)	INGESTION (Sv/bq)
CO-58	4.6E-14	2.6E-11	5.2E-10	8.9E-16	---	9.4E-10	1.8E-10
CO-60	1.2E-13	5.9E-11	1.2E-09	2.0E-15	---	1.8E-08	1.1E-09
KR-85	1.0E-16	.0E+00	.0E+00	.0E+00	---	7.0E-14	.0E+00
KR-85m	8.6E-15	.0E+00	.0E+00	.0E+00	---	5.7E-14	.0E+00
KR-87	4.1E-14	.0E+00	.0E+00	.0E+00	---	2.1E-13	.0E+00
KR-88	1.4E-13	.0E+00	.0E+00	.0E+00	---	3.6E-13	.0E+00
RB-86	4.4E-15	2.3E-12	4.3E-11	8.1E-17	---	1.3E-09	2.1E-09
SR-89	6.4E-18	3.5E-15	7.0E-14	1.2E-19	---	4.3E-10	2.5E-10
SR-90	.0E+00	.0E+00	.0E+00	.0E+00	---	2.3E-09	1.3E-09
SR-91	4.6E-14	1.9E-11	4.4E-11	9.0E-16	---	4.6E-11	5.1E-11
Y-90	.0E+00	.0E+00	.0E+00	.0E+00	---	5.2E-13	1.3E-14
Y-91	1.7E-16	8.5E-14	1.7E-12	3.0E-18	---	8.9E-12	5.5E-13
ZR-95	3.5E-14	1.9E-11	3.9E-10	6.8E-16	---	9.3E-10	1.0E-10
ZR-97	7.3E-14	3.2E-11	1.3E-10	1.4E-15	---	5.8E-11	8.1E-11
NB-95	3.6E-14	2.0E-11	4.0E-10	7.0E-16	---	4.1E-10	1.1E-10
MO-99	7.4E-15	5.5E-12	8.1E-11	1.5E-16	---	2.8E-11	3.4E-11
TC-99m	7.2E-15	3.1E-12	5.1E-12	1.6E-16	---	1.5E-12	3.6E-12
RU-103	2.3E-14	1.3E-11	2.7E-10	4.7E-16	---	3.1E-10	1.2E-10
RU-105	3.8E-14	1.3E-11	1.9E-11	7.6E-16	---	6.6E-12	1.6E-11
RU-106	9.7E-15	5.6E-12	1.2E-10	1.9E-16	---	1.8E-09	1.5E-09
RH-105	3.8E-15	2.2E-12	1.5E-11	8.2E-17	---	5.6E-12	9.0E-12
TE-127	2.3E-16	1.1E-13	2.4E-13	4.9E-18	---	1.9E-12	3.0E-12
TE-127m	3.0E-16	4.1E-13	1.0E-11	1.3E-17	---	1.1E-10	9.7E-11
TE-129	2.6E-15	3.3E-13	3.4E-13	5.6E-17	---	5.4E-13	6.1E-13
TE-129m	1.7E-15	1.9E-12	4.1E-11	3.9E-17	---	1.7E-10	1.7E-10
TE-131m	7.2E-14	3.7E-11	2.3E-10	1.4E-15	---	9.0E-11	1.3E-10
TE-132	1.2E-14	4.4E-11	7.3E-10	2.7E-16	---	3.1E-10	3.0E-10
SB-127	3.1E-14	1.7E-11	2.2E-10	6.2E-16	---	9.1E-11	7.6E-11
SB-129	6.8E-14	2.1E-11	3.0E-11	1.3E-15	---	1.3E-11	2.6E-11
I-131	1.8E-14	1.1E-11	1.8E-10	3.9E-16	---	7.9E-11	1.2E-10
I-132	1.1E-13	2.3E-11	2.5E-11	2.1E-15	---	1.4E-11	2.5E-11
I-133	2.8E-14	1.4E-11	6.1E-11	5.7E-16	---	2.9E-11	4.7E-11
I-134	1.2E-13	1.1E-11	1.1E-11	2.3E-15	---	6.2E-12	1.2E-11
I-135	7.5E-14	2.5E-11	4.5E-11	1.3E-15	---	2.3E-11	3.8E-11
XE-133	2.3E-15	.0E+00	.0E+00	.0E+00	---	1.4E-13	.0E+00
XE-135	1.3E-14	.0E+00	.0E+00	.0E+00	---	2.4E-13	.0E+00
CS-134	7.3E-14	4.1E-11	8.7E-10	1.4E-15	---	1.1E-08	1.7E-08
CS-136	1.0E-13	5.6E-11	9.9E-10	2.0E-15	---	1.7E-09	2.6E-09
CS-137	2.6E-14	1.5E-11	3.2E-10	5.3E-16	---	7.8E-09	1.2E-08
BA-140	8.9E-15	9.1E-12	7.8E-10	1.9E-16	---	2.9E-10	1.6E-10
LA-140	1.1E-13	5.2E-11	3.8E-10	1.9E-15	---	1.5E-10	1.8E-10
CE-141	4.2E-15	2.8E-12	5.5E-11	9.8E-17	---	4.5E-11	1.1E-11
CE-143	1.3E-14	7.7E-12	4.8E-11	2.9E-16	---	1.7E-11	2.3E-11
CE-144	2.7E-15	1.5E-12	3.1E-11	5.2E-17	---	3.5E-10	1.2E-11
PR-143	4.2E-22	2.3E-19	4.2E-18	8.2E-24	---	9.4E-14	6.5E-15
ND-147	6.8E-15	4.5E-12	7.7E-11	1.6E-16	---	3.5E-11	1.9E-11
NP-239	9.0E-15	6.0E-12	5.6E-11	2.2E-16	---	1.6E-11	1.7E-11
PU-238	1.5E-17	1.0E-13	2.1E-12	3.5E-18	---	4.4E-10	1.8E-13
PU-239	8.6E-18	.0E+00	8.2E-13	1.4E-18	---	4.0E-10	1.2E-13
PU-240	1.5E-17	1.2E-13	2.0E-12	3.3E-18	---	4.4E-10	1.7E-13
PU-241	.0E+00	.0E+00	.0E+00	.0E+00	---	2.6E-11	3.7E-15
AM-241	1.3E-15	1.4E-12	2.9E-11	4.8E-17	---	3.1E-09	1.7E-11
CM-242	1.7E-17	1.1E-13	2.2E-12	3.7E-18	---	9.4E-10	4.5E-12
CM-244	1.5E-17	9.5E-14	2.0E-12	3.3E-18	---	1.1E-09	4.6E-12

Table a.3 Dose Conversion Factors: Ovaries

Radionuclide	CLOUDSHINE ($Sv-m^3/Bq-sec$)	GROUNDSHINE 8HR ($Sv-m^2/Bq$)	GROUNDSHINE 7 DAY ($Sv-m^2/Bq$)	GROUNDSHINE RATE ($Sv-m^2/Bq-sec$)	INHALATION ACUTE[a] (Sv/bq)	INHALATION CHRONIC (Sv/bq)	INGESTION (Sv/bq)
CO-58	3.5E-14	1.9E-11	3.9E-10	6.8E-16	---	6.2E-10	1.0E-09
CO-60	8.9E-14	4.5E-11	9.4E-10	1.6E-15	---	4.8E-09	3.2E-09
KR-85	7.5E-17	.0E+00	.0E+00	.0E+00	---	7.0E-14	.0E+00
KR-85M	4.6E-15	.0E+00	.0E+00	.0E+00	---	6.0E-14	.0E+00
KR-87	2.9E-14	.0E+00	.0E+00	.0E+00	---	2.2E-13	.0E+00
KR-88	9.9E-14	.0E+00	.0E+00	.0E+00	---	3.9E-13	.0E+00
RB-86	3.4E-15	1.8E-12	3.3E-11	6.2E-17	---	1.3E-09	2.1E-09
SR-89	4.9E-18	2.7E-15	5.4E-14	9.4E-20	---	4.3E-10	2.5E-10
SR-90	.0E+00	.0E+00	.0E+00	.0E+00	---	2.3E-09	1.3E-09
SR-91	3.5E-14	1.4E-11	3.3E-11	6.8E-16	---	6.6E-11	2.1E-10
Y-90	.0E+00	.0E+00	.0E+00	.0E+00	---	5.2E-13	1.4E-14
Y-91	1.3E-16	6.5E-14	1.3E-12	2.3E-18	---	8.2E-12	3.5E-12
ZR-95	2.6E-14	1.5E-11	3.0E-10	5.1E-16	---	8.4E-10	8.2E-10
ZR-97	5.5E-14	2.4E-11	9.4E-11	1.1E-15	---	1.7E-10	6.2E-10
NB-95	2.7E-14	1.5E-11	3.0E-10	5.3E-16	---	4.3E-10	8.0E-10
MO-99	5.4E-15	3.6E-12	5.0E-11	1.1E-16	---	9.5E-11	2.2E-10
TC-99M	3.6E-15	1.5E-12	2.5E-12	8.0E-17	---	1.7E-12	9.7E-12
RU-103	1.6E-14	9.6E-12	1.9E-10	3.3E-16	---	3.1E-10	5.7E-10
RU-105	2.7E-14	9.1E-12	1.3E-11	5.5E-16	---	1.6E-11	9.7E-11
RU-106	7.1E-15	4.1E-12	8.5E-11	1.4E-16	---	1.3E-09	1.7E-09
RH-105	2.4E-15	1.4E-12	9.2E-12	5.2E-17	---	2.1E-11	5.8E-11
TE-127	1.6E-16	7.2E-14	1.6E-13	3.3E-18	---	2.0E-12	4.0E-12
TE-127M	4.5E-17	7.7E-14	2.9E-12	1.9E-18	---	1.1E-10	1.2E-10
TE-129	1.6E-15	2.2E-13	2.2E-13	3.7E-17	---	5.1E-13	1.6E-12
TE-129M	1.1E-15	1.2E-12	2.6E-11	2.3E-17	---	1.8E-10	2.4E-10
TE-131M	5.3E-14	2.7E-11	1.7E-10	1.0E-15	---	2.3E-10	7.3E-10
TE-132	6.2E-15	3.1E-11	5.3E-10	1.4E-16	---	3.2E-10	4.5E-10
SB-127	2.3E-14	1.3E-11	1.6E-10	4.6E-16	---	2.5E-10	6.1E-10
SB-129	5.1E-14	1.6E-11	2.3E-11	9.6E-16	---	2.1E-11	1.5E-10
I-131	1.2E-14	7.3E-12	1.2E-10	2.6E-16	---	2.5E-11	4.1E-11
I-132	8.1E-14	1.7E-11	1.9E-11	1.6E-15	---	1.0E-11	2.3E-11
I-133	2.1E-14	1.1E-11	4.5E-11	4.2E-16	---	1.9E-11	3.6E-11
I-134	9.4E-14	8.0E-12	8.0E-12	1.6E-15	---	4.2E-12	1.1E-11
I-135	5.7E-14	1.9E-11	3.4E-11	9.8E-16	---	1.7E-11	3.6E-11
XE-133	8.3E-16	.0E+00	.0E+00	.0E+00	---	1.5E-13	.0E+00
XE-135	7.5E-15	.0E+00	.0E+00	.0E+00	---	2.5E-13	.0E+00
CS-134	5.5E-14	3.1E-11	6.5E-10	1.1E-15	---	1.1E-08	1.8E-08
CS-136	7.7E-14	4.1E-11	7.3E-10	1.5E-15	---	1.7E-09	2.7E-09
CS-137	2.0E-14	1.1E-11	2.4E-10	3.9E-16	---	8.1E-09	1.3E-08
BA-140	6.2E-15	6.4E-12	5.7E-10	1.3E-16	---	4.4E-10	9.9E-10
LA-140	8.3E-14	3.9E-11	2.8E-10	1.4E-15	---	4.5E-10	1.3E-09
CE-141	2.1E-15	1.4E-12	2.7E-11	4.7E-17	---	5.5E-11	1.1E-10
CE-143	8.2E-15	4.7E-12	2.9E-11	1.8E-16	---	7.6E-11	2.1E-10
CE-144	1.7E-15	8.6E-13	1.8E-11	3.1E-17	---	2.4E-10	7.0E-11
PR-143	3.2E-22	1.8E-19	3.2E-18	6.2E-24	---	9.4E-14	6.5E-15
ND-147	4.1E-15	2.5E-12	4.4E-11	8.9E-17	---	8.4E-11	1.8E-10
NP-239	4.7E-15	2.9E-12	2.7E-11	1.1E-16	---	7.4E-11	1.6E-10
PU-238	6.7E-19	1.7E-15	3.6E-14	6.0E-20	---	1.0E-05	2.3E-09
PU-239	1.6E-18	.0E+00	3.0E-14	5.1E-20	---	1.2E-05	2.6E-09
PU-240	6.9E-19	2.1E-15	3.5E-14	5.9E-20	---	1.2E-05	2.6E-09
PU-241	.0E+00	.0E+00	.0E+00	.0E+00	---	2.8E-07	5.7E-11
AM-241	4.3E-16	3.7E-13	7.6E-12	1.3E-17	---	3.2E-05	1.4E-07
CM-242	7.0E-19	2.0E-15	4.2E-14	7.0E-20	---	5.7E-07	2.6E-09
CM-244	5.3E-19	1.7E-15	3.6E-14	6.0E-20	---	1.6E-05	6.6E-08

Table a.3 Dose Conversion Factors: Testes

Radionuclide	CLOUDSHINE ($Sv-m^3/Bq-sec$)	GROUNDSHINE 8HR ($Sv-m^2/Bq$)	GROUNDSHINE 7 DAY ($Sv-m^2/Bq$)	GROUNDSHINE RATE ($Sv-m^2/Bq-sec$)	INHALATION ACUTE[4] (Sv/bq)	INHALATION CHRONIC (Sv/bq)	INGESTION (Sv/bq)
CO-58	5.1E-14	2.8E-11	5.8E-10	9.9E-16	---	1.1E-10	1.6E-10
CO-60	1.3E-13	6.5E-11	1.4E-09	2.3E-15	---	1.7E-09	1.1E-09
KR-85	1.1E-16	.0E+00	.0E+00	.0E+00	---	7.0E-14	.0E+00
KR-85m	8.0E-15	.0E+00	.0E+00	.0E+00	---	5.5E-14	.0E+00
KR-87	4.4E-14	.0E+00	.0E+00	.0E+00	---	2.1E-13	.0E+00
KR-88	1.5E-13	.0E+00	.0E+00	.0E+00	---	3.5E-13	.0E+00
RB-86	4.9E-15	2.6E-12	4.8E-11	9.0E-17	---	1.3E-09	2.2E-09
SR-89	7.2E-18	3.9E-15	7.8E-14	1.4E-19	---	4.3E-10	2.5E-10
SR-90	.0E+00	.0E+00	.0E+00	.0E+00	---	2.3E-09	1.3E-09
SR-91	5.1E-14	2.1E-11	4.9E-11	9.9E-16	---	4.1E-11	4.0E-11
Y-90	.0E+00	.0E+00	.0E+00	.0E+00	---	5.2E-13	1.3E-14
Y-91	1.9E-16	9.6E-14	1.9E-12	3.3E-18	---	6.4E-12	4.1E-13
ZR-95	3.8E-14	2.2E-11	4.4E-10	7.5E-16	---	3.0E-10	8.0E-11
ZR-97	8.0E-14	3.5E-11	1.4E-10	1.6E-15	---	3.1E-11	5.2E-11
NB-95	4.0E-14	2.2E-11	4.4E-10	7.8E-16	---	6.5E-11	9.7E-11
MO-99	8.0E-15	5.6E-12	8.0E-11	1.6E-16	---	1.2E-11	2.7E-11
TC-99m	6.4E-15	2.7E-12	4.5E-12	1.4E-16	---	5.2E-13	2.3E-12
RU-103	2.4E-14	1.4E-11	2.9E-10	5.0E-16	---	7.0E-11	1.2E-10
RU-105	4.1E-14	1.4E-11	2.0E-11	8.2E-16	---	1.5E-12	7.6E-12
RU-106	1.1E-14	6.1E-12	1.3E-10	2.1E-16	---	1.2E-09	1.5E-09
RH-105	3.8E-15	2.2E-12	1.5E-11	8.3E-17	---	2.8E-12	7.2E-12
TE-127	2.4E-16	1.1E-13	2.5E-13	5.1E-18	---	1.8E-12	2.9E-12
TE-127m	1.9E-16	2.7E-13	7.5E-12	8.1E-18	---	9.2E-11	9.3E-11
TE-129	2.7E-15	3.4E-13	3.5E-13	5.7E-17	---	4.5E-13	3.8E-13
TE-129m	1.8E-15	1.9E-12	4.1E-11	3.8E-17	---	1.4E-10	1.6E-10
TE-131m	7.9E-14	4.0E-11	2.5E-10	1.5E-15	---	4.4E-11	9.7E-11
TE-132	1.1E-14	4.7E-11	7.9E-10	2.5E-16	---	2.6E-10	2.6E-10
SB-127	3.4E-14	1.9E-11	2.4E-10	6.8E-16	---	4.6E-11	5.9E-11
SB-129	7.5E-14	2.4E-11	3.3E-11	1.4E-15	---	5.4E-12	1.1E-11
I-131	1.9E-14	1.1E-11	1.8E-10	4.0E-16	---	2.3E-11	3.8E-11
I-132	1.2E-13	2.5E-11	2.7E-11	2.3E-15	---	9.9E-12	2.2E-11
I-133	3.1E-14	1.6E-11	6.7E-11	6.2E-16	---	1.9E-11	3.6E-11
I-134	1.4E-13	1.2E-11	1.2E-11	2.6E-15	---	4.0E-12	8.9E-12
I-135	8.3E-14	2.8E-11	5.0E-11	1.4E-15	---	1.5E-11	3.2E-11
XE-133	1.8E-15	.0E+00	.0E+00	.0E+00	---	1.4E-13	.0E+00
XE-135	1.2E-14	.0E+00	.0E+00	.0E+00	---	2.3E-13	.0E+00
CS-134	8.0E-14	4.6E-11	9.5E-10	1.6E-15	---	1.3E-08	2.1E-08
CS-136	1.1E-13	6.1E-11	1.1E-09	2.2E-15	---	1.9E-09	3.0E-09
CS-137	2.9E-14	1.7E-11	3.5E-10	5.8E-16	---	8.6E-09	1.4E-08
BA-140	9.4E-15	9.7E-12	8.5E-10	2.0E-16	---	2.8E-10	1.4E-10
LA-140	1.2E-13	5.7E-11	4.2E-10	2.1E-15	---	5.9E-11	1.2E-10
CE-141	3.8E-15	2.5E-12	4.9E-11	8.7E-17	---	5.4E-12	7.6E-12
CE-143	1.3E-14	7.6E-12	4.8E-11	2.9E-16	---	5.8E-12	1.5E-11
CE-144	2.7E-15	1.4E-12	3.1E-11	5.1E-17	---	1.9E-10	1.0E-11
PR-143	4.6E-22	2.6E-19	4.6E-18	9.1E-24	---	9.4E-14	6.5E-15
ND-147	6.7E-15	4.3E-12	7.4E-11	1.5E-16	---	6.7E-12	1.4E-11
NP-239	8.2E-15	5.1E-12	4.8E-11	1.9E-16	---	2.3E-11	1.3E-11
PU-238	3.6E-18	1.9E-14	3.9E-13	6.5E-19	---	1.0E-05	2.3E-09
PU-239	3.7E-18	.0E+00	1.7E-13	3.0E-19	---	1.2E-05	2.6E-09
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NUREG/CR-4185

2 TITLE AND SUBTITLE

An Assessment of Dosimetry Data for Accidental Radionuclide Releases from Nuclear Reactors

2 LEAVE BLANK

4 DATE REPORT COMPLETED

MONTH: March YEAR: 1985

5 AUTHOR(S)

Gene E. Runkle and Robert H. Ostmeyer

6 DATE REPORT ISSUED

MONTH: April YEAR: 1985

7 PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)

Sandia National Laboratories
P. O. Box 5800
Albuquerque, NM 87185

8 PROJECT/TASK/WORK UNIT NUMBER

9 FIN OR GRANT NUMBER

A1339
A1042

10 SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)

Division of Risk Analysis
Office of Nuclear Regulatory Research
U. S. Nuclear Regulatory Commission
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11a TYPE OF REPORT

b PERIOD COVERED (Inclusive dates)

12 SUPPLEMENTARY NOTES

13 ABSTRACT (200 words or less)

This report reviews dosimetry models for estimating the absorbed dose from external and internal exposure to radionuclides. Important modeling parameters and assumptions are described. Recommendations for the dosimetry data to be used in the MELCOR health and economic consequence model are made. For estimating the dose from cloudshine and groundshine, the models for external exposure developed by Kocher are recommended. The ICRP-30 models and metabolic parameters are recommended for estimating the dose from radionuclides deposited internally via inhalation and ingestion. Dose conversion factors calculated with these models for a variety of radionuclides, clearance classes, particle sizes and integration periods were obtained from Oak Ridge National Laboratory for use in the MELCOR health and economic consequence model. Sources and magnitude of uncertainty in dose factors were evaluated. Recommendations are made for assessing the uncertainty in estimated consequences due to uncertainty in dose conversion factors.

14 DOCUMENT ANALYSIS - a KEYWORDS/DESCRIPTORS

b IDENTIFIERS/OPEN-ENDED TERMS

15 AVAILABILITY STATEMENT

16 SECURITY CLASSIFICATION (This page) (This report)

17 NUMBER OF PAGES

18 PRICE