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Radiation And Mixed Waste Incineration

Background Information Document Volume 2: Risk Of Radiation Exposure

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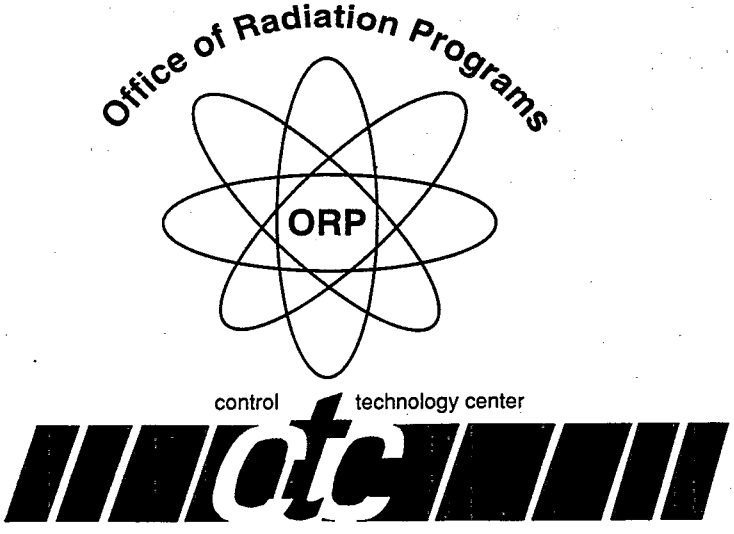

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BACKGROUND DOCUMENT ON RADIOACTIVE AND MIXED WASTE INCINERATION

VOLUME II - RISKS OF RADIATION EXPOSURE

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Preface

This document provides background information describing the major public health issues and current regulatory structure associated with radioactive materials.

The document is organized into four sections. Section 1 describes the current understanding of public health risks associated with exposure to ionizing radiation. Section 2 describes methods acceptable to the Environmental Protection Agency for calculating the doses and risks from a given level of radioactive contamination in the environment. Section 3 presents a summary of radiation protection guidelines and standards, followed by a discussion of the degree of protection afforded the public under these standards. Section 4 discusses radiological and health impacts associated with waste management and presents a sample dose estimation problem.

The report concludes with appendixes which provide formal definitions of key radiation protection terms and additional descriptive information on the types of radiation and their effects. Along with the references cited in the text, a comprehensive bibliography is also provided.

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1. Risks of Exposure to Ionizing Radiation

1.1 OVERVIEW OF THE EFFECTS OF EXPOSURE TO IONIZING RADIATION

Electromagnetic radiation and highly energetic particles are emitted from radioactive atoms during the process of radioactive decay. Because of their relatively high energy, these emissions have the ability to ionize the materials with which they interact. Ionization is the process of removing electrons from atoms and molecules, thereby producing a free negatively charged electron and a positively charged atom or molecule, referred to as an ion pair. When interacting with living tissue, ionizing radiation causes injury by breaking constituent body molecules and thereby producing chemical rearrangements that may lead to permanent cellular damage. Appendix A presents a description of the common types of ionizing radiation.

The degree of biological damage caused by the various types of radiation varies depending on the amount of energy deposited per gram of tissue and the pattern of the deposited energy. Some types of ionizing radiation (e.g., alpha particles) produce intense regions of ionization. For this reason, they are called high-LET (linear energy transfer) radiation. Other types of radiation, such as high-energy photons (i.e., x rays and gamma rays) and high energy electrons (i.e., beta particles), are called low-LET radiation because of the sparse pattern of ionization they produce. In equal doses, high-LET radiation is generally more biologically damaging than low-LET radiation.

Since the effects of radiation on living tissue, or any exposed media, results from the absorption of ionizing radiation, radiation exposure is measured and expressed in units of the amount of energy absorbed per unit mass of absorbing media. The specific unit is the rad, which is defined as 100 ergs deposited per gram of absorbing media. The rad is referred to as the unit of radiation absorbed dose, or simply the dose.

On the average, for every 32 electron volts (Ev) of energy deposited in tissue, one ion pair is produced. Since there are 1.6×10^{-12} erg per Ev, 1 rad produces about 3×10^{12} ion pairs per gram

of tissue. In addition, since a typical cell is about 10 microns, 1 rad produces about 1500 ion pairs per cell. At a dose rate of 1 rad per second (a very high dose rate), one may visualize the exposure as the continual production of 1500 ion pairs per second per cell being exposed. For low-LET radiation, the ion pairs are uniformly distributed in the cell. For high-LET radiation, the ion pairs are clustered in the cell. These ion pairs are extremely chemically reactive and rapidly interact with nearby cellular constituents, thereby causing biochemical changes in the cell that can lead to cell death or damage to important macromolecules such as DNA. Extensive radiobiological data reveals that when the ion pairs are clustered (high-LET), biological damage is greater.

Because the amount of biological damage caused by a given dose of radiation varies depending on the pattern of the distribution of the ion pairs with a cell the rad is multiplied by a unitless quality factor (QF) to account for the differences in the LET among the different types of radiation. The product of the rad with the QF yields the dose equivalent, expressed in units of rems. (Appendix B presents formal definitions of key radiation protection terms.) For x rays, gamma rays, and beta particles, the QF is 1. Accordingly, for most common types of radiation, the rad equals the rem. However, for alpha particles, the QF is 20 and 1 rad equals 20 rem. This indicates that an alpha dose to tissue is believed to be about 20 times potentially more harmful than the same dose of x rays, gamma rays, or beta particles.

The highly reactive electrons and positively charged atoms and molecules created by the ionization process in a living cell can produce, through a series of chemical reactions, permanent changes (mutations) in the cell's genetic material, the DNA. These changes may result in cell death or in an abnormally functioning cell. A mutation in a germ cell (sperm or ovum) may be transmitted to an offspring and be expressed as a genetic defect in that offspring or in an individual of a subsequent generation; such a defect is commonly referred to as a genetic effect. There is also strong evidence that the induction of a mutation by ionizing radiation in a nongerm (somatic) cell can serve as a step in the development of a cancer. Finally, mutational or other events, including possible cell killing, produced by ionizing radiation in rapidly growing and differentiating tissues of an embryo or fetus can give rise to birth defects; these are referred to

as teratological effects. At acute doses above about 25 rad, radiation induces other deleterious effects in man; however, for the low doses and dose rates of interest in this document (i.e., low-level radiation) only carcinogenic, mutagenic, and teratogenic effects are thought to be significant. Appendix C presents additional descriptions of the effects of low-level radiation.

Most important from the standpoint of the total societal risk from exposures to low-level ionizing radiation are the risks of cancer and genetic mutations. Consistent with our current understanding of their origins in terms of DNA damage, these are believed to be stochastic effects; i.e., the probability (risk) of these effects increases with the absorbed dose of radiation, but the severity of the effects is independent of dose. For neither induction of cancer nor genetic effects, moreover, is there any convincing evidence for a "threshold;" i.e., some dose level below which the risk is zero. Hence, so far as is known, any dose of ionizing radiation, no matter how small, might give rise to a cancer or to a genetic effect in future generations. Conversely, there is no way to be certain that a given dose of radiation, no matter how large, has caused an observed cancer in an individual or will cause one in the future.

At sufficiently high doses, radiation acts as a complete carcinogen, serving as both initiator and promoter. With proper choice of radiation dose and exposure schedule, cancers can be induced in nearly any tissue or organ in both humans and animals. At lower doses, radiation produces a delayed response in the form of increased incidence of cancer long after the exposure period. The risk factors provided in the next section have been documented extensively in both humans and animals. Human data are extensive and include atomic bomb survivors, many types of radiation-treated patients, underground miners, and radium dial workers. Animal data include demonstrations in many mammalian species and in mammalian tissue cultures.

Evidence of the mutagenic properties of radiation comes mostly from animal data, in which all forms of radiation-induced mutations have been demonstrated, mostly in mice. Tissue cultures of human lymphocytes have also shown radiation-induced mutations. Limited evidence that humans are not more sensitive comes from studies of the A-bomb survivors in Japan.

1.2 RISKS ASSOCIATED WITH WHOLE-BODY EXPOSURE

The likelihood of an adverse effect and the types of adverse effects associated with exposure to ionizing radiation depend on the part of the body exposed, the dose, and the type of radiation. A whole-body dose occurs if an individual is exposed in a manner that results in every gram of tissue absorbing approximately the same amount of energy. As may be expected, a whole-body dose is potentially more harmful than the same dose delivered to a localized portion of the body or limited to a specific organ.

A whole-body dose can occur if an individual is exposed to a uniform external field of penetrating radiation, such as from a large radiation source, a large area contaminated with a gamma emitter, or a large airborne plume of a gamma emitter. A whole-body dose can also occur from a uniform internal dose by both gamma and beta emitters. Certain radionuclides, such as tritium and radiocesium, are distributed fairly uniformly within the body following inhalation or ingestion and, as a result, deliver a relatively uniform dose to the entire body.

Table 1-1 summarizes EPA's estimate of the lifetime risks from whole-body exposures to high- and low-LET radiation. The nominal risk factors reflect EPA's best judgment as to the relationship between dose and risk based on a review of all relevant information available to the Agency. Likewise, the cited ranges reflect EPA's current best judgment as to the uncertainties in these risk factors.

The risk factors are expressed in terms of the probability that a given adverse effect will occur during a person's lifetime per rad delivered to the whole body.[1] The risk factors are based on the assumption that the risk is independent of the rate at which the dose is delivered. Specifically, inherent in the use of the risk factors is the assumption that the lifetime risk of a rad delivered in 1 minute or over the course of a year is the same. This assumption is used for

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[1] Table 1-1 uses the conventional approach of expressing the risks in units of risk per 10^6 rad. To obtain the risk per rad, simply divide the values by 10^6.

Table 1-1. Summary of EPA's radiation risk factors

Risk	Significant Exposure Period	Risk Factor	
		Nominal	Range
Low LET (10^{-6} rad^{-1})			
Teratological:			
Severe mental retardation	Weeks 8 to 15 of gestation	4,000	2,500 - 5,500
Genetic:			
Severe hereditary defects, all generations	30 year reproductive generation	260	60 - 1,100
Somatic:[a]			
Fatal cancers	Lifetime	390	120 - 1,200
All cancers	Lifetime	620	190 - 1,900
High LET (10^{-6} rad^{-1})			
Genetic:			
Severe hereditary defects, all generations	30 year reproductive generation	690	160 - 2,900
Somatic:			
Fatal cancers	Lifetime	3,100	960 - 9,600
All cancers	Lifetime	5,000	1,500 - 15,000

[a] The range assumes a linear, nonthreshold dose response. However, it is plausible that a threshold may exist for this effect.

rulemaking and performing risk assessments. However, it is important to recognize that a great deal of radiobiological data indicates that the risk is reduced when the dose is highly protracted or fractionated (i.e., spread out over a period of time).

Given the dose, these risk factors may be used to calculate the risk of adverse effects to individuals and populations. For example, if it is known that an individual received a single whole-body dose of 1 rad of a low-LET radiation, that individual's lifetime risk of fatal cancer attributable to this exposure is estimated to be about 0.000390 (i.e., 1 rad x 390×10^{-6} fatal cancers per rad). Similarly, if it is known that an individual is receiving a continuing dose of 1 rad per year of low-LET radiation, each year of exposure commits that person to a lifetime added risk of fatal cancer of 0.000390.

This approach to assessing the risks of exposure to radiation is an acceptable but somewhat simplified approach to assessing risk. The reason is that the risks per rad vary as a function of age of exposure, and, for most carcinogenic effects, there is a prolonged latency period between the time of exposure and the expression of the adverse effect. As a result, the risk factors may underestimate the risk for children and overestimate the risks for the elderly. For this reason, they are appropriate for estimating the risks for the average member of the population, and should be used with caution when applied to specific individuals.

The above description of dose (and risk) pertains to a single individual and, as a result, is referred to as an individual whole-body dose. When a group of individuals or a population is exposed, the dose to each individual in the exposed population is often summed. The summed value is referred to as the population dose and is expressed in units of person rads or person rems. For example, if it is known that 100,000 people each received 1 rad whole-body exposure to low-LET radiation, then the population dose is 100,000 person rads. The number of fatal cancers that are predicted to be produced in that population over the lifetime of the individuals in that population is 39 (i.e., 100,000 person rad x 390×10^{-6} fatal cancers per person rad). Because individual differences in radiosensitivity, due to age of exposure and a number of other

factors, average out when estimating population doses and risks, the risk factors are most appropriate when applied to population exposures.

The discussion and examples given above apply to radiation carcinogenesis. However, the same concepts also apply to radiation mutagenesis and teratogenesis. Accordingly, the risk factors in Table 1-1 may be used to estimate individual and population risks from all effects of low-level radiation exposure. However, for teratogenic effects, the exposures must occur during the period of gestation, and genetic effects can only occur for exposures delivered during the reproductive years. For a given individual or population dose, the carcinogenic risk dominates. As a result, estimates of the public health risks associated with radiation exposures are often limited to carcinogenic risks.

For providing a perspective on the risk of fatal radiogenic cancers due to whole-body radiation, it is instructive to calculate the risk from background radiation to the U.S. population using the risk factors summarized in Table
1-1. The absorbed dose rate from low-LET background radiation has three major components: cosmic radiation, which averages about 0.028 rad/yr (or 28 mrad/yr) in the United States; terrestrial sources, such as radium in soil, which contribute an average of 28 mrad/yr (NCRP87); and the low-LET dose resulting from internal emitters. The last differs among organs, to some extent, but for soft tissues it is about 24 mrad/yr (NCRP87). Other minor radiation sources such as fallout from nuclear weapons tests, cosmogenic radionuclides, naturally occurring radioactive materials in buildings, airline travel, and consumer products, contribute about another 7 mrad for a total low-LET whole-body dose of about 87 mrad/yr. Although extremes do occur, the distribution of this background annual dose to the U.S. population is relatively narrow. A population-weighted analysis indicates that 80 percent of the U.S. population receives annual doses that are between 75 mrad/yr and 115 mrad/yr (EPA81).

The risk of fatal cancer per person due to this dose is estimated as follows:

$$(3.9\times10^{-4}\ \text{rad}^{-1})\ (8.7\times10^{-3}\ \text{rad/yr})\ (70.7\ \text{yr}) = 2.4 \times 10^{-3}$$

or about 0.24 percent of all deaths. The vital statistics used in EPA's radiation risk analyses indicate that the probability of dying from cancer in the United States from all causes is about 0.16; i.e., 16 percent. Thus, the 0.24 percent result indicates that about 1.5 percent of all U.S. cancer is due to low-LET background radiation.

1.3 RISKS ASSOCIATED WITH INTERNAL EXPOSURES TO LOW-LET RADIATION

The preceding discussion addresses individual and population whole-body doses. However, there are many circumstances under which only individual organs are exposed. Such circumstances usually occur as a result of the inhalation or ingestion of a radionuclide that tends to accumulate in one particular organ of the body. Common examples include exposure of the lung due to the inhalation of insoluble radioactive particulates and the exposure of the thyroid gland due to the inhalation or ingestion of radioactive iodine. As may be expected, the public health concerns in these cases are lung cancer and thyroid cancer, respectively.

Tables 1-2 and 1-3 present the risk factors for exposure to low-LET radiation as function of sex, age of exposure, and exposed organ. Table 1-2 addresses fatal cancers, and Table 1-3 addresses total fatal plus nonfatal cancers. The lower right hand corners of Tables 1-2 and 1-3 present the total risk to the average individual assuming all organs are exposed to 10^6 rad (i.e., 392.14 and 622.96, respectively). Notice that these values are virtually identical to the values in Table 1-1 for low-LET somatic exposures (i.e., 390 and 620, respectively). It is convenient to think of Table 1-1 as a summary of Tables 1-2 and 1-3.

Tables 1-2 and 1-3 may be used to estimate individual and population risks of cancer for exposures to specific organs and specific age groups. The method for making these determiations is similar to that described above for whole-body exposures.

Table 1-2

Site-specific mortality risk per unit dose (1.0E-6 per rad)
for exposure to low-LET radiation

Site	Age at Exposure 0-9	10-19	20-34	35-50	50+	All
Male						
Leukemia	94.68	41.86	58.46	37.52	48.64	54.19
Bone	3.07	3.04	2.96	2.61	1.45	2.47
Thyroid	8.25	8.25	5.08	2.69	0.80	4.32
Breast	0.00	0.00	0.00	0.00	0.00	0.00
Lung	145.90	146.95	107.22	61.40	22.55	84.21
Esophagus	25.57	25.76	6.13	2.82	2.03	9.91
Stomach	110.95	111.72	40.63	16.40	9.36	6.95
Intestine	53.49	53.83	20.89	7.60	4.30	22.78
Liver	168.01	168.24	35.40	9.48	2.50	58.87
Pancreas	74.36	74.90	24.21	10.34	6.55	30.78
Urinary	40.73	40.99	13.85	5.79	2.22	16.60
Lymphoma	33.43	33.28	9.62	2.88	0.71	12.49
Other	37.48	37.23	33.72	13.09	6.93	22.66
Total	796.43	746.05	358.15	172.65	108.06	366.25
Female						
Leukemia	59.9	26.35	37.39	25.27	35.27	35.86
Bone	3.10	3.09	3.03	2.84	1.67	2.53
Thyroid	15.85	14.54	11.46	7.46	2.24	8.42
Breast	309.33	310.52	81.01	36.93	10.30	107.63
Lung	78.57	78.89	77.09	64.70	24.96	56.72
Esophagus	21.47	21.57	6.32	3.46	2.26	8.33
Stomach	102.64	103.05	51.49	22.39	10.73	45.00
Intestine	57.14	57.38	23.07	9.57	5.01	23.08
Liver	115.94	115.25	36.97	11.95	2.80	40.74
Pancreas	103.00	103.48	31.71	12.70	7.11	38.15
Urinary	46.40	46.54	19.64	9.08	3.06	18.80
Lymphoma	45.71	45.66	11.54	3.35	0.79	15.13
Other	27.69	27.65	24.48	11.27	5.80	16.20
Total	986.78	955.96	415.21	220.95	112.01	416.59
General						
Leukemia	77.69	34.26	48.06	31.39	41.20	44.76
Bone	3.09	3.06	2.99	2.72	1.58	2.50
Thyroid	12.22	11.33	8.23	5.07	1.61	6.43
Breast	151.21	52.03	39.95	18.40	5.75	55.36
Lung	112.98	113.63	92.34	63.00	23.91	70.07
Esophagus	23.56	23.71	62.22	3.14	2.16	9.09
Stomach	106.89	107.48	45.98	19.37	10.13	45.95
Intestine	55.28	55.57	21.96	8.58	4.70	2.94
Liver	142.55	142.30	36.17	10.71	2.67	49.55
Pancreas	88.36	88.89	27.90	11.51	6.87	34.57
Urinary	43.50	43.71	16.70	7.43	2.69	17.73
Lymphoma	39.44	39.34	10.56	3.11	0.76	13.85
Other	32.69	32.54	29.16	12.18	6.30	19.34
Total	889.49	847.84	386.21	196.60	110.32	392.14

Table 1-3

Site-specific incidence risk per unit dose (1.0E-6 per rad)
for exposure to low-LET radiation

Site	Age at Exposure 0-9	10-19	20-34	35-50	50	All
Male						
Leukemia	94.68	41.86	58.46	37.52	48.64	54.19
Bone	3.07	3.04	2.96	2.61	1.45	2.47
Thyroid	87.59	82.52	50.84	26.92	8.04	43.23
Breast	0.00	0.00	0.00	0.00	0.00	0.00
Lung	155.21	156.33	114.07	65.31	23.99	89.58
Esophagus	25.57	25.76	6.13	2.82	2.03	9.91
Stomach	147.94	148.97	54.18	21.87	12.48	62.61
Intestine	102.87	103.52	40.16	14.63	8.28	43.81
Liver	168.01	168.24	35.40	9.48	2.50	58.87
Pancreas	81.71	82.31	26.60	11.37	7.20	33.83
Urinary	110.08	110.79	37.44	15.65	6.01	44.87
Lymphoma	45.80	45.58	13.17	3.94	.98	17.12
Other	57.66	57.27	51.88	20.15	10.65	34.86
Total	1080.20	1026.20	491.27	232.28	132.25	495.35
Female						
Leukemia	59.93	26.35	37.39	25.27	35.27	35.86
Bone	3.10	3.09	3.03	2.84	1.67	2.53
Thyroid	158.45	145.42	114.59	74.60	22.38	84.16
Breast	793.16	796.20	207.73	94.69	26.40	275.97
Lung	83.59	83.93	82.01	68.83	26.56	60.34
Esophagus	21.47	21.57	6.32	3.46	2.26	8.33
Stomach	131.59	132.11	66.01	28.69	13.75	57.70
Intestine	103.90	104.34	41.94	17.40	9.11	41.96
Liver	115.94	115.25	36.97	11.95	2.80	40.74
Pancreas	114.44	114.98	35.23	14.11	7.91	42.39
Urinary	100.88	101.16	42.70	19.74	6.66	40.88
Lymphoma	60.95	60.88	15.38	4.47	1.06	20.18
Other	55.38	55.30	48.97	22.54	11.61	32.40
Total	1802.80	1760.60	738.28	388.58	167.42	743.44
General						
Leukemia	77.69	34.26	48.06	31.39	41.20	44.76
Bone	3.09	3.06	2.99	2.72	1.58	2.50
Thyroid	122.24	113.32	82.26	50.66	16.05	64.28
Breast	387.78	389.82	102.42	47.18	14.74	141.95
Lung	120.19	120.88	98.24	67.02	25.43	74.54
Esophagus	23.56	23.71	6.22	3.14	2.16	9.09
Stomach	139.95	140.71	60.00	25.25	13.20	60.08
Intestine	103.38	103.92	41.03	16.00	8.74	42.86
Liver	142.55	142.30	36.17	10.71	2.67	49.55
Pancreas	97.71	98.30	30.85	12.73	7.60	38.23
Urinary	105.58	106.08	40.02	17.68	6.37	42.28
Lymphoma	53.21	53.07	1426	4.20	1.02	18.69
Other	56.55	56.31	50.43	21.33	11.19	33.60
Total	1433.50	1385.70	612.96	310.01	151.96	622.96

Uncertainties in the Risks from Low-LET Radiation

The range of the risk factors presented in Table 1-1 provide an indication of the degree of uncertainty associated with the risk factors. In general, the epidemiological data upon which these risk factors are based are for exposures in excess of about 1 to 10 rads. Accordingly, most of the uncertainty is associated with extrapolation of these risks to doses well below 1 rad. Though not included in Table 1-1, zero risk at very low doses and dose rates cannot be ruled out.

The above risk factors were derived primarily from epidemiological data from the atomic bomb survivors at Hiroshima and Nagasaki. The most important uncertainties in estimating risk factors for low-LET radiation from this experience relates to (1) the extrapolation of risks observed in populations exposed to relatively high doses, delivered acutely, to populations receiving relatively low dose chronic exposures, and (2) the projection over a full lifespan; specifically, the extent to which high relative risks seen over a limited followup period among individuals exposed as children carry over into later years of life when baseline cancer incidence rates are high.

Another significant uncertainty relates to the extrapolation of risk estimates from one population to another (e.g., from the Japanese A-bomb survivors to the U.S. general population). This source of uncertainty is regarded as important for estimating the risk of radiogenic cancer in specific organs for which the baseline incidence rates differ markedly by the two populations.

In addition to uncertainties in the model, errors in dosimetry and random statistical variations also contribute to the uncertainty in the risk factors. Recent studies have shown that there were biases in the dosimetry system for the Japanese A-bomb survivors, leading to a downward bias in the estimates of risk due to low-LET radiation of about a factor of 2 to 3.

1.4 RISKS ASSOCIATED WITH INTERNAL EXPOSURES TO HIGH-LET RADIATION

In theory, Tables 1-1, 1-2, and 1-3 can be used to estimate the risk of internal doses to organs from high-LET radiation, primarily alpha exposures. This can be done by calculating the dose to the organ in rads, multiplying that value by the QF, which is 20 for alpha emitters, and then using Tables 1-1 and 1-2 to determine the risk. However, for reasons that are beyond the scope of this review, the Office of Radiation Programs has recently adopted an alternative approach to estimating the risks from internal organ exposures to both low- and high-LET radiation. For internal exposures to low- LET radiation, either the method described above or the method described in this section may be used to estimate risk. For internal exposures to high-LET radiation, the method described in this section is preferred.

The new method for estimating the risks from exposure to internal emitters was first applied in EPA88a. The methodology is now formally adopted in "Health Effects Assessment Summary Tables (HEAST)," OERR 9200 6-303, which presents tables of the risk per unit of radioactive material inhaled or ingested. Table 1-4 was taken from the most recent version of HEAST. The values in the HEAST tables are periodically updated. Accordingly, the latest version of the HEAST tables should be obtained prior to the performance of risk calculations. The HEAST helps to simplify the risk assessment calculation because risk can be estimated from calculated dose. The risk is determined by simply multiplying the radionuclide intake rate by the values in the HEAST.

Uncertainties in Risks from Alpha-Particle Emitters

The uncertainties in risk associated with internally deposited alpha emitters are often greater than for low-LET radiation. Human epidemiological data on the risks from alpha emitters are largely

Table 1-4. Slope Factor

Age-averaged lifetime excess total cancer risk per unit intake or exposure (Expressed in picocuries (pCi)*)

Nuclide	ICRP** Lung Class	GI*** Absorption Factor (f_1)	Inhalation $(pCi)^{-1}$	Ingestion $(pCi)^{-1}$
Am-241	W	1.0E-03	4.0E-08	3.1E-10
Am-243	W	1.0E-03	4.0E-08	3.0E-10
Ba-137m	D	1.0E-01	6.0E-16	2.4E-15
Bi-214	W	5.0E-02	2.2E-12	1.4E-13
C-14	g	9.5E-01	6.4E-15	9.1E-13
Ce-144	Y	3.0E-04	3.4E-10	6.1E-12
Cm-243	W	1.0E-03	3.1E-08	2.3E-10
Cm-244	W	1.0E-03	2.7E-08	2.0E-10
Co-60	Y	3.0E-01	1.6E-10	1.5E-11
Cr-51	Y	1.0E-01	3.0E-13	4.2E-14
Cs-134	D	9.5E-01	2.8E-11	4.2E-11
Cs-135	D	9.5E-01	2.7E-12	4.0E-12
Cs-137	D	9.5E-01	1.9E-11	2.8E-11
Fe-59	W	1.0E-01	9.8E-12	2.8E-12
H-3	g	9.5E-01	7.8E-14	5.5E-14
I-129	D	9.5E-01	1.2E-10	1.9E-10
I-131	D	9.5E-01	2.4E-11	3.6E-11
K-40	D	9.5E-01	7.6E-12	1.1E-11
Mn-54	W	1.0E-01	5.3E-12	1.1E-12
Mo-99	Y	8.0E-01	2.6E-12	1.7E-12
Nb-94	Y	1.0E-02	2.1E-10	2.1E-12
Np-237	W	1.0E-03	3.6E-08	2.7E-10
P-32	D	8.0E-01	3.0E-12	3.5E-12
Pb-210	D	2.0E-01	1.7E-09	6.5E-10
Pb-214	D	2.0E-01	2.9E-12	1.8E-13

Table 1-4. Slope Factor (Continued)

Age-averaged lifetime excess total cancer risk per unit intake or exposure (Expressed in picocuries (pCi)*)

Nuclide	ICRP** Lung Class	GI*** Absorption Factor (f_1)	Inhalation $(pCi)^{-1}$	Ingestion $(pCi)^{-1}$	
Po-210	W	1.0E-01	2.7E-09	2.6E-10	
Po-214	W	1.0E-01	2.8E-19	1.0E-20	
Pu-238	Y	1.0E-03	4.2E-08	2.8E-10	
Pu-239	Y	1.0E-04	4.1E-08	3.1E-11	
Pu-240	Y	1.0E-04	4.1E-08	3.1E-11	
Pu-241	Y	1.0E-03	2.9E-10	4.8E-12	
Pu-242	Y	1.0E-04	3.9E-08	3.0E-11	
Ra-226	W	2.0E-01	3.0E-09	1.2E-1	
Ra-228	W	2.0E-01	6.5E-10	1.0E-10	
Rn-222	g	--	7.2E-13	--	
Ru-106	Y	5.0E-02	4.4E-10	9.6E-12	
S-35	D	8.0E-01	1.9E-13	2.2E-13	
Sr-89	D	3.0E-01	2.9E-12	3.0E-12	
Sr-90	D	3.0E-01	5.6E-11	3.3E-11	
Tc-99	W	8.0E-01	8.3E-12	1.3E-12	
Tc-99m	W	8.0E-01	2.7E-14	5.1E-14	8.1E-12
Th-230	Y	2.0E-04	3.1E-08	2.4E-11	5.9E-14
Th-232	Y	2.0E-04	3.1E-08	2.2E-11	4.6E-14
U-234	Y	2.0E-01	2.7E-08	1.4E-10	5.7E-14
U-235	Y	2.0E-01	2.5E-08	1.3E-10	9.6E-12
U-238	Y	2.0E-01	2.4E-08	1.3E-10	4.6E-14

* A picocurie is a unit of activity equal to 3.7E-02 nuclear transformations per second: 1 pCi = 1.0E-12 curies (Ci) = 3.7E-02 becquerels (Bq).

** Lung clearance classifications recommended by the International Commission on Radiological Protection (ICRP); "D" (days), "W" (weeks), "Y" (years), "g" (gas).

***Gastrointestinal (GI) absorption factors; i.e, fractional uptake of a radionuclide from the gut into blood.

confined to: (1) lung cancer induced by radon decay products; (2) bone cancer induced by radium; and (3) liver cancer induced by injected thorothrast (thorium). Many of the risk estimates presented here for alpha irradiation were determined from high dose experiments on animals. The available evidence on cells, animals, and humans points to a linear dose response relationship for the risk from alpha emitters (NAS88). The extrapolation to low doses is therefore considered to be less important as a source of uncertainty for alpha irradiation than for low-LET irradiation.

For many alpha-emitting radionuclides, the most important source of uncertainty in the risk estimate is the uncertainty in dose to target cells. Contributing to this uncertainty is uncertainty in the location of these cells, ignorance regarding the metabolism of the radionuclide, nonuniformity of radionuclide deposition in an organ, and the short range of alpha particles in tissue.

2. Dose Assessment

The preceding discussion addresses the determination of risk given the dose to the whole body or organ. Unless the risk factors are expressed in units of risk per unit intake of a radionuclide, such as those provided in the HEAST, it is necessary to calculate dose in order to estimate the risks associated with exposure to radiation. This section describes the methods used to calculate dose.

2.1 THE CONCEPT OF THE DOSE CONVERSION FACTOR

The setting of standards for radionuclides and the determination of the risks associated with exposure to radioactive material require an assessment of the doses received by individuals who are exposed by coming into contact with radiation sources. Two forms of potential radiation exposures can occur from these sources --internal and external. Internal exposures can result from the inhalation of contaminated air or the ingestion of contaminated food or water. External exposures can occur when individuals are immersed in contaminated air or water or are standing on contaminated ground surfaces. The quantification of the doses received by individuals from these radiation exposures is called radiation dosimetry.

The term "exposure," in the context of this report, denotes the physical interaction of the radiation emitted from the radioactive material with cells and tissues of the human body. An exposure can be "acute" or "chronic" depending on how long an individual or organ is exposed to the radiation. Internal exposures occur when radionuclides, which have entered the body through the inhalation or ingestion pathway, deposit energy to organ tissues from the emitted gamma, beta, and alpha radiation. External exposures occur when radiation enters the body directly from sources located outside the body, such as radiation from material on ground surfaces, dissolved in water, or dispersed in the air.

In general, for the radiation sources of concern in this report, external exposures are from material emitting gamma radiation. Gamma rays are the most penetrating of the emitted

radiations, and external gamma ray exposure may contribute heavily to radiation doses to the internal organs. Beta and alpha particles are far less penetrating and deposit their energy primarily on the skin's outer layer. Consequently, their contribution to the absorbed dose to the total body, compared to that deposited by gamma rays, is negligible.

A vast body of research forms the basis of our understanding of internal and external radiation dosimetry. Through the use of mathematical models, the results of this research has been translated into dose conversion factors that can be used to calculate internal and external radiation exposures. The models for internal dosimetry consider the quantity of radionuclides entering the body, the factors affecting their movement or transport through the body, and the energy deposited in organs and tissues from the radiation that is emitted during spontaneous decay processes. The models for external dosimetry consider the photon doses to organs of individuals who are immersed in air or are exposed to contaminated ground.

The external dose conversion factors developed using these models relate the concentration of individual radionuclides in air and on the ground to the external radiation dose rate to individuals immersed in the airborne radioactivity or standing on the contaminated ground. The dose conversion factors for calculating doses from immersion in a contaminated plume of airborne radionuclides are expressed in units of dose rate per unit airborne concentration of individual radionuclides (e.g., rad/yr per Curie/m^3). The dose conversion factors for calculating doses from radionuclides deposited on the ground are expressed in units of dose rate per unit of area contamination of individual radionuclides (e.g., rad/yr per Curie/m^2). The Curie is the unit used to define the amount of radioactive material. It is the amount of radioactive material (i.e. the number of atoms) that decay at a rate of 3.7×10^{10} disintegrations per second. The Curie is named after Marie Curie who discovered radium, which decays at a rate of 3.7×10^{10} disintegrations per second per gram.

The internal dose conversion factors developed using these models relate the inhalation and ingestion rate of individual radionuclides to the doses to various organs. The internal dose conversion factors are expressed in units of internal dose per unit intake of individual

radionuclides (e.g., rem/Ci inhaled or ingested). The internal dose calculated in this fashion is often referred to as a dose commitment since, following inhalation or ingestion, the radionuclide is deposited in various organs and remains there for some period of time before metabolic processes or radioactive decay remove the radionuclide. Accordingly, once inhaled or ingested, the body is "committed" to a dose over a period of time that varies depending on the clearance rate of the individual radionuclides from the body. For some radionuclides, such as radioiodine, the residence time in the body is relative short, on the order of days to weeks, while for other radionuclides, such as plutonium and uranium, the residence time in the body is relatively long, on the order of years.

EPA has tabulated approved external and internal dose conversion factors for over 700 radionuclides. The values are published in "Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion and Ingestion, Federal Guidance Report No. 11" (EPA-520/1-88-020, September 1988). Given the amount of radioactive contamination in the air or on the ground, or the amount inhaled or ingested, these dose conversion factors may be used to estimate dose.

2.2 THE CONCEPT OF THE EFFECTIVE WHOLE-BODY DOSE EQUIVALENT

It is conceivable that individuals and a population can receive both external and internal exposures from a number of different radionuclides. This can result in doses to a number of different organs and also to the whole body. In order to calculate the risks associated with these exposures, the doses to each organ must be determined and then, using the risk factors in Table 1-2 or Table 1-3, the risk of fatal and nonfatal cancers can be determined. These risks are then summed to determine the total risk of fatal and nonfatal cancers.

For simplifying this process, the concept of the effective whole-body dose equivalent has been developed. During the process of calculating the organ doses associated with an exposure to a given radionuclide, a weighting factor is incorporated into the calculation so that the calculated dose is effectively the same as a dose delivered to the whole body in terms of risk. For

example, it is known that the risk of fatal cancer from a given dose to the thyroid gland is about 0.03 that of the same dose delivered to the whole body. Accordingly, when calculating the dose to the thyroid gland, a factor of 0.03 is incorporated into the calculation so that the resultant dose is expressed in units of effective whole-body dose equivalent. The benefit of calculating doses in this fashion is that, notwithstanding the organ exposed, the resulting doses are all in the same units; i.e., effective whole-body dose equivalent. In this way, all the doses may be summed and multiplied by a single risk factor. The appropriate risk factor for fatal and total cancers is 390×10^{-6} per rad and 622×10^{-6} per rad, respectively (see Table 1-1).

The weighting factors recommended by the International Committee on Radiation Protection and Measurements (ICRP) for converting the calculated organ doses to the effective whole-body equivalent doses are as follows:

Organ or Tissue	Weighting Factor
Gonads	0.25
Breast	0.15
Red Bone Marrow	0.12
Lung	0.12
Thyroid	0.03
Bone Surfaces	0.03
Remainder	0.30
Total	1.00

In addition to organ dose conversion factors, Federal Guidance Report No. 11 also provides tabulated values of effective whole-body dose equivalent for inhalation and ingestion.

2.3 UNCERTAINTIES IN DOSE CONVERSION FACTORS

A review of the uncertainty in internal and external dose conversion factors is provided in "Risk Assessment Methodology, Environmental Impact Statement, NESHAPS for Radionuclides, Background Information Document - Volume 1" (EPA 520/1-89-005, September 1989). In summary, the uncertainty in the dose conversion factors for external exposure is relatively small

for virtually all radionuclides, on the order of a factor of 1.8. The uncertainties in the internal dose conversion factors are larger, on the order of a factor of 4.4, and vary depending on the radionuclide. The greater uncertainty associated with the internal dose conversion factors is understandable because, unlike the external dose conversion factors which depend solely on physical principles, the internal dose conversion factors depend on a number of metabolic parameters which are not fully understood for all radionuclides and which vary among individuals.

3. Current Regulations and Guidelines

This section provides a brief history of the evolution of radiation protection philosophy and an outline of the current regulatory programs and strategies of the government agencies responsible for ensuring that radiation and radionuclides are used safely. The section concludes with a summary of the risks associated with current regulatory standards and guidelines.

3.1 THE INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION (ICRP) AND THE NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS (NCRP)

Throughout their existence, the ICRP and the NCRP have worked together closely to develop radiation protection recommendations that reflect the current understanding of the dangers associated with exposure to ionizing radiation. The ICRP and the NCRP function as nongovernment advisory bodies. Their recommendations are not binding on any government or user of radiation or radioactive materials. However, their recommendations establish the bases of virtually all radiation protection standards.

The ICRP and NCRP have been in existence under different names since the 1920s. In 1964 the NCRP was formally chartered by Congress to:

- Collect, analyze, develop, and disseminate in the public interest information and recommendations about radiation protection and radiation quantities, units, and measurements.
- Develop basic concepts about radiation protection and radiation quantities, units, and measurements, and the application of these concepts.
- Provide a means by which organizations concerned with radiation protection and radiation quantities, units, and measurements may cooperate to use their combined resources effectively and to stimulate the work of such organizations.
- Cooperate with the ICRP and other national and international organizations concerned with radiation protection and radiation quantities, units, and measurements.

The first exposure limits adopted by the ICRP and the NCRP (ICRP34, ICRP38, and NCRP36) established 0.2 roentgen/day[2] as the "tolerance dose" for occupational exposure to x rays and gamma radiation from radium. This limit, equivalent to an absorbed dose of approximately 25 rad/yr as measured in air, was established to guard against the known effects of ionizing radiation on superficial tissue, changes in the blood, and "derangement" of internal organs, especially the reproductive organs. At the time the recommendations were made, high doses of radiation were known to cause observable effects, but the epidemiological evidence at the time was inadequate even to imply the carcinogenic induction effects of moderate or low doses. Therefore, the aim of radiation protection was to guard against known effects, and the "tolerance dose" limits that were adopted were believed to represent the level of radiation that a person in normal health could tolerate without suffering observable effects. The concept of a tolerance dose and the recommended occupational exposure limit of 0.2 R/d for x rays and gamma radiation remained in effect until the end of the 1940's.

The recommendations of the ICRP and the NCRP made no mention of exposure of the general populace.

By the end of World War II, the widespread use of radioactive materials and scientific evidence of genetic and somatic effects at lower doses and dose rates suggested that the radiation protection recommendations of the NCRP and the ICRP would have to be revised downward.

By 1948, the NCRP had formulated its position on appropriate new limits. These limits were largely accepted by the ICRP in its recommendations of 1950 and formally issued by the NCRP in 1954 (ICRP51, NCRP54). Whereas the immediate effect was to lower the basic whole-body occupational dose limit to the equivalent of 0.3 rad/week (approximately 15 rad/yr), the revised recommendations also embodied several new and important concepts in the formulation of radiation protection criteria.

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[2] The roentgen (R) is a unit of air exposure to x radiation. For this document, it is considered to be equivalent to 1 rad of absorbed dose.

First, the recommendations recognized the difference in the effects of various types and energies of radiation; both ICRP and NCRP recommendations include discussions of the weighing factors that should be applied to radiations of differing types and energies. The NCRP advocated the use of the "rem" to express the equivalence in biological effect between radiations of differing types and energy.[3] Although the ICRP noted the shift toward the acceptance of the rem, it continued to express its recommendations in terms of the rad, with the caveat that the limit for the absorbed dose due to neutron radiation should be one-tenth the limit for x, gamma, or beta radiation.

Second, the recommendations of both organizations introduced the concept of critical organs and tissues. This concept was intended to ensure that no tissue or organ, with the exception of the skin, would receive a dose in excess of that allowed for the whole body. At the time, scientific evidence was lacking on tissues and organs. Thus, all blood-forming organs were considered critical and were limited to the same exposure as the whole body.

Third, the NCRP recommendations included the suggestion that individuals under the age of 18 receive no more than one-tenth the exposure allowed for adults. The reasoning behind this particular recommendation is interesting, as it reflects clearly the limited knowledge of the times. The scientific evidence indicated a clear relationship between accumulated dose and genetic effect. However, this evidence was obtained exclusively from animal studies that had been conducted with doses ranging from 25 to thousands of rads. There was no evidence from

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[3] Defining the exact relationship between exposure, absorbed dose, and dose equivalent is beyond the scope of this document. In simple terms, the exposure is a measure of the charge induced by x and gamma radiation in air. Absorbed dose is a measure of the energy per unit mass imparted to matter by radiation. Dose equivalent is an indicator of the effect on an organ or tissue by weighting the absorbed dose with a quality factor, Q, dependent on the radiation type and energy. The customary units for exposure, absorbed dose, and dose equivalent are the roentgen, rad and rem, respectively. Over the range of energies typically encountered, the exposure, dose and dose equivalent from x and gamma radiation have essentially the same values in these units. For beta radiation, the absorbed dose and dose equivalent are generally equal also. At the time of these recommendations, a quality factor of 10 was recommended for alpha radiation. Since 1977, a quality factor of 20 has primarily been used; i.e., for alpha radiation, the dose equivalent is 20 times the absorbed dose.

exposure less than 25 rad accumulated dose, and the interpretation of the animal data and the implications for humans were unclear and did not support a specific permissible dose. The data did suggest that genetic damage was more dependent on accumulated dose than previously believed, but experience showed that exposure for prolonged periods to the permissible exposure limit (1.0 R/week) did not result in any observable genetic effects. The NCRP decided that it was not necessary to change the occupational limit to provide additional protection beyond that provided by the reduction in the permissible exposure limit of 0.3 R/week. At the same time, it recommended limiting the exposure of individuals under the age of 10 to ensure that they did not accumulate a genetic dose that would later preclude their employment as radiation workers. The factor of 10 was rather arbitrary but was believed to be sufficient to protect the future employability of all individuals (NCRP54).

Fourth, the concept of a tolerance dose was replaced by the concept of a maximum permissible dose. The change in terminology reflected the increasing awareness that any radiation exposure might involve some risk and that repair mechanisms might be less effective than previously believed. Therefore, the concept of a maximum permissible dose (expressed as dose per unit of time) was adopted because it better reflected the uncertainty in our knowledge than did the concept of tolerance dose. The maximum permissible dose was defined as the level of exposure that entailed a small risk compared with those posed by other hazards in life (ICRP51).

Finally, in explicit recognition of the inadequacy of our knowledge regarding the effects of radiation and of the possibility that any exposure might have some potential for harm, the recommendations included an admonition that every effort should be made to reduce exposure to all kinds of ionizing radiation to the lowest possible level. This concept, known originally as ALAP (as low as practicable) and later as ALARA (as low as reasonably achievable), would become a cornerstone of radiation protection philosophy.

During the 1950's, a great deal of scientific evidence on the effects of radiation became available from studies of radium dial painters, radiologists, and survivors of the atomic bombs dropped on Japan. This evidence suggested that genetic effects and long-term somatic effects were more

important at low doses than previously considered. Thus, by the late 1950's, the ICRP and NCRP recommendations were again revised (ICRP59, NCRP59). These revisions include the following major changes: the maximum permissible occupational dose for whole-body exposure and the most critical organs (blood forming organs, gonads, and the larger lens of the eye) was lowered to 5 rem/yr, with a quarterly limit of 3 rem; the limit for exposure of other organs was set at 30 rem/yr; internal exposures were controlled by a comprehensive set of maximum permissible concentrations of radionuclides in air and water based on the most restrictive case of a young worker; and recommendations were included for some nonoccu-pational groups and for the general population (for the first time).

The lowering of the maximum permissible whole-body dose from 0.3 rad/week to 5 rem/yr, with a quarterly limit of 3 rem, reflected both the new evidence and the uncertainties of the time. Although no adverse effects had been observed among workers who had received the maximum permissible dose of 0.3 rad/week, there was concern that the lifetime accumulation of as much as 750 rad (15 rad/yr times 50 years) was too much. Lowering the maximum permissible dose by a factor of three was believed to provide a greater margin of safety. At the same time, operational experience showed that a limit of 5 rem/yr could be met in most instances, particularly with the additional operational flexibility provided by expressing the limit on an annual and quarterly basis.

The recommendations given for nonoccupational exposures were based on concerns about genetic effects. The evidence available suggested that genetic effects were primarily dependent on the total accumulated dose. Thus, having sought the opinions of respected geneticists, the ICRP and the NCRP adopted the recommenda-tion that accumulated gonadal dose to age 30 be limited to 5 rem from sources other than natural background and medical exposure. As an operational guide, the NCRP recommended that the maximum dose to any individual be limited to 0.5 rem/yr, with maximum permissible body burdens of radionuclides (to control internal exposures) set at one-tenth that allowed for radiation workers. These values were derived from consideration of the genetically significant dose to the population and were established "primarily

for the purpose of keeping the average dose to the whole population as low as reasonably possible, and not because of the likelihood of specific injury to the individual" (NCRP59).

In the late 1950's and early 1960's, the ICRP and NCRP again lowered the maximum permissible dose limits (ICRP65, NCRP71). The considerable scientific data on the effects of exposure to ionizing radiation were still inconclusive with respect to the dose response relationship at low exposure levels; thus, both organizations continued to stress the need to keep all exposures to the lowest possible level.

The NCRP and the ICRP made the following similar recommendations:

- Limit the dose to the whole body, red bone marrow, and gonads to 5 rem in any year, with a retrospective limit of 10 to 15 rem in any given year as long as total accumulated dose did not exceed 5X(N-18), where N is the age in years.
- Limit the dose to the skin, hands, and forearms to 15, 75, and 30 rem per year, respectively.
- Limit the dose to any other organ or tissue to 15 rem per year.
- Limit the average dose to the population to 0.17 rem per year.

The scientific evidence and the protection philosophy on which the above recommendations were based were set forth in detail in NCRP71. In the case of occupational exposure limits, the goal of protection was to ensure that the risks of genetic and somatic effects were small enough to be comparable to the risks experienced by workers in other safe industries. The numerical limits recommended were based on the linear, no-threshold, dose-response model and were believed to represent a level of risk that was readily acceptable to an average individual. For nonoccupational exposures, the goal of protection was to ensure that the risks of genetic or somatic effects were small compared with other risks encountered in everyday life. The derivation of specific limits was complicated by the unknown dose-response relationship at low exposure levels and the fact that the risks of radiation exposure did not necessarily accrue to the same individuals who benefited from the activity responsible for the exposure. Therefore, it was

necessary to derive limits that adequately protected each member of the public and to the gene pool of the population as a whole, while still allowing the development of beneficial uses of radiation and radionuclides.

In 1977, the ICRP made a fundamental change in its recommendations when it abandoned the critical organ concept in favor of the weighted whole-body effective dose equivalent concept for limiting occupational exposure (ICRP77). The change, made to reflect an increased understanding of the differing radiosensitivity of the various organs and tissues, did not affect the overall limit of 5 rem/yr for workers, but included a recommendation that chronic exposures of the general public from all controllable sources be limited to no more than 0.5 rem/yr to critical groups, which should result in average exposures to the public of less than 0.1 rem/yr.

Also significant, ICRP's 1977 recommendations represent the first explicit attempt to relate and justify permissible radiation exposures with quantitative levels of acceptable risk. Thus, average occupational exposures (approximately 0.5 rem/yr) are equated with risks in safe industries, given as 1.0 E-4 annually. At the maximum limit of 5 rem/yr, the risk is equated with that experienced by some workers in recognized hazardous occupations. Similarly, the risks implied by the nonoccupational limit of 0.5 rem/yr are equated to levels of risk of less than 1.0 E-2 in a lifetime; the general populace's average exposure is equivalent to a lifetime risk on the order of 1.0 E-4 to 1.0 E-3. The ICRP believed these levels of risk were in the range that most individuals find acceptable.

In June 1987, the NCRP revised its recommendations to be comparable with those of the ICRP (NCRP87). The NCRP adopted the effective dose equivalent concept and its related recommendations regarding occupational and nonoccupational exposures to acceptable levels of risk. However, the NCRP did not adopt a fully risk-based system because of the uncertainty in the risk estimates and because the details of such a system have yet to be elaborated.

The NCRP recommendations in NCRP87 for occupational exposures correspond to the ICRP recommendations. In addition, the relevant nonoccupational exposure guidelines, which the NCRP first recommended in 1984 (NCRP84a), are:

- 0.5 rem/yr effective whole-body dose equivalent, not including background or medical radiation, for individuals in the population when the exposure is not continuous.
- 0.1 rem/yr effective whole-body dose equivalent, not including background or medical radiation, for individuals in the population when the exposure is continuous.
- Continuous use of a total dose limitation system based on justification of every exposure and application of the "as low as reasonably achievable" philosophy.

The NCRP equates continuous exposure at a level of 0.1 rem/yr to a lifetime risk of developing cancer of about one in a thousand. The NCRP has not formulated exposure limits for specific organs, but it notes that the permissible limits will necessarily be higher than the whole-body limit in inverse ratio for a particular organ to the total risk for whole-body exposure.

In response to EPA's proposed national emission standards for radionuclides, the NCRP suggested that since the 0.1 rem/yr limit is the limit for all exposures from all sources (excluding natural background and medical radiation), the operator of any site responsible for more than 25 percent of the annual limit be required to ensure that the exposure of the maximally exposed individual is less than 0.1 rem/yr from all sources (NCRP84b, NCRP87).

3.2 FEDERAL GUIDANCE

The wealth of new scientific information on the effects of radiation that became available in the 1950's prompted the President to establish an official government entity with responsibility for formulating radiation protection criteria and coordinating radiation protection activities. Executive Order 10831 established the Federal Radiation Council (FRC) in 1959. The Council included representatives from all of the Federal agencies concerned with radiation protection and

2acted as a coordinating body for all of the radiation activities conducted by the Federal government. In addition to its coordinating function, the Council's major responsibility was to "...advise the President with respect to radiation matters, directly or indirectly affecting health, including guidance for all Federal agencies in the formulation of radiation standards and in the establishment and execution of programs of cooperation with States..." (FRC60).

The Council's first recommendations concerning radiation protection standards for Federal agencies were approved by the President in 1960. Based largely on the work and recommendations of the ICRP and the NCRP, the guidance established the following limits for occupational exposures:

- Whole-body head and trunk, active blood-forming organs, gonads, or lens of eye--not to exceed 3 rems in 13 weeks and total accumulated dose limited to 5 times the number of years beyond age 18.
- Skin of whole body and thyroid--not to exceed 10 rems in 13 weeks or 30 rems per year.
- Hands, forearms, feet, and ankles--not to exceed 25 rems in 13 weeks or 75 rems per year.
- Bone--not to exceed 0.1 microgram of Ra-226 or its biological equivalent.
- Any other organ--not to exceed 5 rem per 13 weeks or 15 rems per year.

Although these levels differ slightly from those recommended by NCRP and ICRP at the time, the differences did not represent any greater or lesser protection. In fact, the FRC not only accepted the levels recommended by the NCRP for occupational exposure, it adopted the NCRP's philosophy of acceptable risk for determining occupational exposure limits. Although quantitative measures of risk were not given in the guidance, the prescribed levels were not expected to cause appreciable bodily injury to an individual during his or her lifetime. Thus, while the possibility of some injury was not zero, it was expected to be so low as to be acceptable if there was any significant benefit derived from the exposure.

The guidance also established dose equivalent limits for members of the public. These were set at 0.5 rem per year (whole body) for an individual and an average of 5 rem in 30 years (2gonadal) per capita. The guidance also provided for development of a suitable sample of the population as a basis for determining compliance with the limit when doses to all individuals are unknown. Exposure of this population sample was not to exceed 0.17 rem per capita per year. The population limit of 0.5 rem to any individual per year was derived from consideration of natural background exposure. Natural background radiation varies by a factor of two to four from location to location.

In addition to the formal exposure limits, the guidance also established as Federal policy that there should be no radiation exposure without an expectation of benefit and that "every effort should be made to encourage the maintenance of radiation doses as far below this guide as practicable." The requirements to consider benefits and keep all exposure to a minimum were based on the possibility that there is no threshold dose for radiation. The linear nonthreshold dose response was assumed to place an upper limit on the estimate of radiation risk. However, the FRC explicitly recognized that it might also represent the true level of risk. If so, then any radiation exposure carried some risk, and it was necessary to avoid all unproductive exposures and to keep all productive exposures as "far below this guide as practicable."

In 1967, the Federal Radiation Council issued guidance for the control of radiation hazards in uranium mining (FRC67). The need for such guidance was clearly indicated by the epidemiological evidence that showed a higher incidence of lung cancer in adult males who worked in uranium mines compared with the incidence in adult males from the same locations who had not worked in the mines. The guidance established specific exposure limits and recommended that all exposures be kept as far below the guide limits as possible. The limits chosen represented a tradeoff between the risks incurred at various exposure levels, the technical feasibility of reducing the exposure, and the benefits of the activity responsible for the exposure.

3.3 THE ENVIRONMENTAL PROTECTION AGENCY

In 1970, the functions of the Federal Radiation Council were transferred to the Administrator of the U.S. Environmental Protection Agency. In 1971, the EPA revised the Federal guidance for the control of radiation hazards in uranium mining (EPA71). Based on the risk levels associated with the exposure limits established in 1967, the upper limit of exposure was reduced by a factor of three. The EPA also provided guidance to Federal agencies in the diagnostic use of x rays (EPA78). This guidance establishes maximum skin entrance doses for various types of routine x-ray examinations. It also establishes the requirement that all x-ray exposures be based on clinical indication and diagnostic need, and that all exposure of patients should be kept as low as reasonably achievable consistent with the diagnostic need.

In 1981, the EPA proposed new Federal guidance for occupational exposures to supersede the 1960 guidance (EPA81). The 1981 recommended guidance follows, and expands upon, the principles set forth by the ICRP in 1977. This guidance was adopted as Federal policy in 1987 (EPA87).

The Environmental Protection Agency has various statutory authorities and responsibilities regarding regulation of exposure to radiation in addition to the statutory responsibility to provide Federal guidance on radiation protection. EPA's standards and regulations for controlling radiation exposures are summarized here.

Reorganization Plan No. 3 transferred to the EPA the authority under the U.S. Atomic Energy Act of 1954, as amended, to establish generally applicable environmental standards for exposure to radionuclides. Pursuant to this authority, in 1977 the EPA issued standards limiting exposure from operations of the light-water reactor nuclear fuel cycle (EPA77). These standards cover normal operations of the uranium fuel cycle, excluding mining and spent fuel disposal. The standards limit the annual dose equivalent to any member of the public from all phases of the uranium fuel cycle (excluding radon and its daughters) to 25 mrem to the whole body, 75 mrem to the thyroid, and 25 mrem to any other organ. To protect against the buildup of long-lived

radionuclides in the environment, the standard also sets normalized emission limits for Kr-85, I-129, and Pu-239 combined with other transuranics with a half-life exceeding 1 year. The dose limits imposed by the standard cover all exposures resulting from releases to air and water from operations of fuel- cycle facilities. The development of this standard took into account both the maximum risk to an individual and the overall effect of releases from fuel- cycle operations on the population and balanced these risks against the costs of effluent control.

Under the authority of the Uranium Mill Tailings Radiation Control Act, the EPA has promulgated standards limiting public exposure to radiation from uranium tailings piles (EPA83a, (EPA83b). Whereas the standards for inactive and active tailings piles differ, a consistent basis is used for these standards. Again, the Agency sought to balance the radiation risks imposed on individuals and the population in the vicinity of the pile against the feasibility and costs of control.

Under the authority of the U.S. Atomic Energy Act of 1954, as amended, the EPA has promulgated 40 CFR 191, which establishes standards for disposal of spent fuel, high-level radioactive waste, and transuranic elements (EPA82). The standard establishes two different limits: (1) during the active waste disposal phase, operations must be conducted so that no member of the public receives a dose greater than that allowed for other phases of the uranium fuel cycle; and (2) once the repository is closed, exposure is to be controlled by limiting releases. The release limits were derived by summing, over long time periods, the estimated risks to all persons exposed to radioactive materials released into the environment. The uncertainties involved in estimating the performance of a theoretical repository led to this unusual approach, and the proposed standard admonishes the agencies responsible for constructing and operating such repositories to take steps to reduce releases below the upper bounds given in the standard to the extent reasonably achievable.

Under the authority of the Atomic Energy Act of 1954, as amended, and the Toxic Substance Control Act, the EPA is developing proposed environmental standards for the land disposal of low-level radioactive waste and certain naturally occurring and accelerator-produced radioactive

wastes. The proposed standards will establish (1) exposure limits for pre-disposal management and storage options, (2) criteria for other agencies to follow in specifying waste that is Below Regu-latory Concern (BRC), (3) post-disposal exposure limits, and (4) groundwater protection requirements (Gr88).

Under the authority of the Safe Drinking Water Act, the EPA has issued interim regulations covering the permissible levels of radium, gross alpha and manmade beta, and photon-emitting contaminants in community water systems (EPA76). The limits are expressed in picocuries/liter. The limits chosen for manmade beta and photon emitters equate to approximately 4 mrem/yr whole-body or organ dose to the most exposed individual.

Section 122 of the Clean Air Act amendments of 1977 (Public Law 95-95) directed the Administrator of the EPA to review all relevant information and determine if emissions of hazardous pollutants into air will cause or contribute to air pollution that may reasonably be expected to endanger public health. In December 1979, EPA designated radionuclides as hazardous air pollutants under Section 112 of the Act. On April 6, 1983, EPA published proposed National Emission Standards for radionuclides for selected sources in the Federal Register (48 FR 15076). Three National Emission Standards for Hazardous Air Pollutants (NESHAPS), promulgated on February 6, 1985, regulated emissions from Department of Energy (DOE) and non-DOE Federal facilities, Nuclear Regulatory Commission (NRC) licensed facilities, and elemental phosphorus plants (FR85a). Two additional NESHAPS, covering radon emission from underground uranium mines and licensed uranium mill tailings, were promulgated on April 17, 1985, and September 24, 1986, respectively (FR85b, FR86). On December 15, 1989, the EPA published its final decision on NESHAPS for emissions of radionuclides. The NESHAPS establish limits for 12 source categories. In summary, except for radon emissions from uranium tailings piles, the NESHAPS limit offsite exposures to 10 mrem per year effective whole-body dose equivalent.

3.4 NUCLEAR REGULATORY COMMISSION

Under the authority of the Atomic Energy Act of 1954, as amended, the NRC is responsible for licensing and regulating the use of byproduct, source, and special nuclear material, and for ensuring that all licensed activities are conducted in a manner that protects public health and safety. The Federal guidance on radiation protection applies to the NRC; therefore, the NRC must ensure that none of the operations of its licensees exposes a member of the public to more than 0.5 rem/yr. The dose limits imposed by the EPA's standard for uranium fuel-cycle facilities also apply to the fuel-cycle facilities licensed by the NRC. These facilities are prohibited from releasing radioactive effluents in amounts that would result in doses greater than the limits imposed by that standard.

The NRC exercises its statutory authority by imposing a combination of design criteria, operating parameters, and license conditions at the time of construction and licensing. It ensures that the license conditions are fulfilled through inspection and enforcement. The NRC licenses more than 7,000 users of radioactivity. The regulation of fuel-cycle licensees is discussed separately from the regulation of byproduct material licensees.

3.4.1 Fuel-Cycle Licensees

The NRC does not use the term "fuel-cycle facilities" to define its classes of licensees. The term is used here to coincide with EPA's use of the term in its standard for uranium fuel-cycle facilities. As a practical matter, this term includes the NRC's large source and special nuclear material and production and utilization facilities. The NRC's regulations require an analysis of probable radioactive effluents and their effects on the population near fuel-cycle facilities. The NRC also ensures that all exposures are as low as reasonably achievable by imposing design criteria and specific equipment requirements on the licensees. After a license has been issued, fuel-cycle licensees must monitor their emissions and take environmental measurements to ensure that they meet the design criteria and license conditions. For practical purposes, the NRC adopted the maximum permissible concentrations developed by the NCRP to relate effluent concentrations to exposure.

In the 1970's, the NRC formalized the implementation of as low as reasonably achievable exposure levels by issuing a regulatory guide for as low as reasonably achievable design criteria. This coincided with a decision to adopt, as a design criterion, a maximum permissible dose of 5 mrem/yr from a single nuclear electric generating station. The 5-mrem limit applies to the most exposed individual actually living in the vicinity of the reactor and refers to whole-body doses from external radiation by air pathway (NRC77).

3.4.2 Byproduct Material Licensees

The NRC's licensing and inspection procedure for byproduct material users is less uniform than that imposed on major fuel-cycle licensees for two reasons: (1) the much larger number of byproduct material licensees, and (2) their much smaller potential for releasing significant quantities of radioactive materials into the environment. The prelicensing assurance procedures of imposing design reviews, operating practices, and license conditions prior to construction and operation are similar.

The protection afforded the public from releases of radioactive materials from these facilities can vary considerably because of three factors. First, the requirements that the NRC imposes for monitoring effluents and environmental radioactivity are much less stringent for these licensees. If the quantity of materials handled is small enough, the NRC might not impose any monitoring requirements. Second, and more important, the level of protection can vary considerably because the exact point where the licensee must meet the effluent concentrations for an area of unrestricted access is not consistently defined. Depending on the particular licensee, this area has been defined as the nearest inhabited structure, as the boundary of the user's property line, as the roof of the building where the effluents are vented, or as the mouth of the stack of vent. Finally, not all users are allowed to reach 100 percent of the maximum permissible concentration in their effluents. In fact, the NRC has placed as low as reasonably achievable requirements on many of their licensees by limiting them to 10 percent of the maximum permissible concentration in their effluents.

3.5 DEPARTMENT OF ENERGY

The DOE operates a complex of national laboratories and weapons facilities. These facilities are not licensed by the NRC. The DOE is responsible, under the U.S. Atomic Energy Act of 1954, as amended, for ensuring that these facilities are operated in a manner that does not jeopardize public health and safety. The DOE is subject to the Federal guidance on radiation protection issued by EPA and its predecessor, the FRC. For practical purposes, the DOE has 2adopted the NCRP's maximum permissible concentrations in air and water as a workable way to ensure that the dose limits of 0.5 rem/yr whole-body and 1.5 rem/yr to any organ are being observed. The DOE also has a requirement that all doses be kept as low as is reasonably achievable, but the contractors who operate the various DOE sites have a great deal of latitude in implementing policies and procedures to ensure that all doses are kept to the lowest possible level.

The DOE ensures that its operations are within its operating guidelines by requiring its contractors to maintain radiation monitoring systems around each of its sites and to report the results in an annual summary report. New facilities and modifications to existing facilities are subject to extensive design criteria reviews (similar to those used by the NRC). During the mid-1970's, the DOE initiated a systematic effluent reduction program that resulted in the upgrading of many facilities and effected a corresponding reduction in the effluents (including airborne and liquid radioactive materials) released to the environment.

As a continuation of this program, DOE has issued proposed Order 5400.3 "Draft Radiation Protection of the Public and the Environment" and has issued several internal guidance documents including procedures for the calculation of internal and external doses to the public and guidance on environmental surveillance.

3.6 OTHER FEDERAL AGENCIES

3.6.1 Department of Defense

The Department of Defense operates several nuclear installations, including a fleet of nuclear-powered submarines and their shore support facilities. The DOD, like other Federal agencies, must comply with Federal radiation protection guidance. The DOD has not formally adopted any more stringent exposure limits for members of the public than the 0.5 rem/yr allowed by the Federal guidance.

3.6.2 Center for Medical Devices and Radiological Health

Under the Radiation Control Act of 1968, the major responsibility of the Center for Medical Devices and Radiological Health in the area of radiation protection is the specification of performance criteria for electronic products, including x-ray equipment and other medical devices. This group also performs environmental sampling in support of other agencies, but no regulatory authority is involved.

3.6.3 Mine Safety and Health Administration

The Mine Safety and Health Administration (MSHA) has the regulatory authority to set standards for exposures of miners to radon and its decay products and other (nonradiological) pollutants in mines. The MSHA has adopted the Federal guidance for exposure of uranium miners (EPA71). It has no authority or responsibility for protecting members of the general public from the hazards associated with radiation.

3.6.4 Occupational Safety and Health Administration

The Occupational Safety and Health Administration (OSHA) is responsible for ensuring a safe workplace for all workers. This authority, however, does not apply to radiation workers at

government-owned or NRC-licensed facilities. This group does have the authority to set exposure limits for workers at unlicensed facilities, such as particle accelerators, but it does not have any authority to regulate public exposure to radiation. OSHA has adopted the occupational exposure limits of the NRC, except it has not imposed the requirement to keep all doses as low as is reasonably achievable.

3.6.5 Department of Transportation

The Department of Transportation (DOT) has statutory responsibility for regulating the shipment and transportation of radioactive materials. This authority includes the responsibility to protect the public from exposure to radioactive materials while they are in transit. For practical purposes, the DOT has implemented its authority through the specification of performance standards for shipment containers and by setting maximum exposure rates at the surface of any package containing radioactive materials. These limits were set to ensure compliance with the Federal guidance for occupational exposure, and they are believed to be sufficient to protect the public from exposure. The DOT also controls potential public exposure by managing the routing of radioactive shipments to avoid densely populated areas.

3.7 STATE AGENCIES

States have important authority for protecting the public from the hazards associated with ionizing radiation. A total of 26 states assumed NRC's inspection, enforcement, and licensing responsibilities for users of source and byproduct materials and users of small quantities of special nuclear material. These "NRC Agreement States," which license and regulate more than 11,500 users of radiation and radioactive materials, are bound by formal agreements to adopt requirements consistent with those imposed by the NRC. The NRC continues to perform this function for all licensable uses of the source, byproduct, and special nuclear material in the 24 states that are not Agreement States.

Nonagreement states, as well as NRC Agreement States, regulate the exposures to workers from electronic sources of radiation. Also, all states retain the authority to regulate the use of naturally occurring (i.e., radium) and accelerator-produced radioactive materials (NARM).

Under the Clean Air Act (CAA), the states have the authority to regulate airborne radiological emissions. The CAA grants authority to the states to establish regulations at least as stringent as those developed by the EPA. In 1979, radionuclides were designated as hazardous air pollutants under the CAA requiring regulation, thereby effectively granting authority to the states to regulate airborne radioactive emissions. Prior to this, unless granted Agreement State status under the Atomic Energy Act, states were pre-empted under the Atomic Energy Act from regulating byproduct, source, and special nuclear material.

Under Section 3006 of the Resource Conservation and Recovery Act, states can apply for authorization to regulate hazardous waste programs. Though radionuclides regulated under the Atomic Energy Act are explicitly precluded from regulation under RCRA, in practice, radionuclides are being addressed as part of RCRA investigations for many Federal facilities because a great deal of the hazardous material at Federal facilities is mixed radioactive and hazardous material.

Under the Superfund Amendments and Reauthorization Act of 1986, the Act mandates procedures to allow state involvement in EPA selection of remedial response and negotiation with potentially responsible parties. For Federal facilities, state participation in these programs is being implemented under Interagency Agreements that include the DOE, EPA, and cognizant state authorities. These agreements are being designed to address RCRA, CERCLA, and NEPA issues in an integrated manner.

3.8 RISKS ASSOCIATED WITH RADIATION PROTECTION STANDARDS

The radiation protection standards summarized above include both prescriptive and performance based standards. Prescriptive standards are highly specific, usually establishing limits on

radionuclide release rates, concentrations of radionuclides in effluent streams, and, in some cases, specific design requirements. Performance based standards establish a dose limitation, and it is the responsibility of the licensee to demonstrate and document compliance with the dose limitations.

Because of the relationship between dose and risk, it is possible to derive the risks associated with the various dose standards. Using a risk factor of 3.9×10^{-4} fatal cancer risk per rad (or rem), the following presents an overview of the individual annual and lifetime risks of fatal cancer associated with exposures at the various radiation protection dose limits.

STANDARD	ANNUAL RISK	LIFETIME RISK
10 CFR 20		
5 rem/yr occupational limit	2×10^{-3}	1×10^{-1}
500 mrem/yr nonoccupational limit	2x10-4	1×10^{-2}
Appendix I to 10 CFR 50 (reactors)		
5 mrem/yr whole body offsite	2×10^{-6}	1×10^{-4}
15 mrem/yr organ offsite	2×10^{-7} (thyroid)	1x10-5 (thyroid)
NESHAPS		
10 mrem/yr offsite dose limit	4×10^{-6}	3×10^{-4}
40 CFR 190 (Uranium Fuel Cycle)		
25 mrem/yr whole-body offsite	1×10^{-5}	7×10^{-4}
75 mrem/yr organ offsite	1×10^{-6} (thyroid)	6×10^{-5} (thyroid)
40 CFR 141 (Drinking Water)		
4 mrem/yr	2×10^{-6}	1×10^{-4}

There are currently no radiation protection standards that establish limits on cumulative exposures to workers or the public. It is believed that such person rem limits are not needed since, by protecting the individual and implemeting ALARA programs, the cumulative exposures are properly controlled. Experience in the commercial nuclear power industry reveals that by controlling individual offsite exposures to the 5 mrem/yr limit established by Appendix I to 10 CFR 50, the cumulative offsite exposures have been limited to about 10-person rem per plant. Accordingly, over the 40-year life of a typical plant, the number of fatal cancers estimated to be caused by these exposures is less than one.

4. Radionuclide Emissions and Radiological Exposures Associated with End-Point Control Techniques

4.1 RADIOLOGICAL IMPACTS

The radiological impacts associated with the various endpoint volume reduction technologies include the impacts attributable to each step in the waste management process, from the preprocessing of the waste, to volume reduction, packaging, shipping and final disposal. Each step in the process is associated with radiation exposures to workers and members of the general public. In this section, the radionuclide emissions, radiation exposures, and potential health risks associated with these processes are estimated. In addition, a discussion is provided of how the exposures may differ among different volume reduction technologies and programs.

As discussed in Volume I, the volumetric throughput, radionuclide composition and concentration, and chemical and physical forms of waste vary widely at different facilities and as a function of time within a given facility. As a result, it would not be productive to assess the radiological impacts for a given waste stream because the results would have limited applicability. Instead, this section presents impacts in terms of normalized doses and risks. Specifically, tables of normalized doses and risks are provided, expressed in units of individual and population doses and risks per Ci/yr or per Ci/m^3 of individual radionuclides in the feed streams. These tables are designed to be used to estimate upper bound, generic default impacts for specific waste streams and endpoint volume reduction techniques, given the radionuclide throughput for a given facility over a given period of time. The results developed through the use of these tables can be used to compare radiological impacts of differing volume reduction technologies.

The normalized doses are expressed in units of effective whole-body dose commitment equivalent per year, as opposed to doses to individual organs. This greatly simplifies comparisons among different volume reduction technologies because all results are expressed in risk equivalent units. In addition, the results can be summed and readily converted to health risks.

The section concludes with an example problem using a reference low-level radioactive waste stream representing low-level radioactive waste generated by DOE facilities in the aggregate. The reference waste stream does not represent any one DOE facility. The example problem provides insight into how the normalized radiological impact assessment methodology presented in this section can be used to estimate impacts when site specific and facility specific data are not available. If specific data are available, adjustment factors, as discussed in the sample problem, will be needed to obtain more realistic values. This is especially true for occupational exposures.

An attachment to this section presents the equations and basic assumptions used to derive the normalized release rates and dose factors. A more detailed description of the methods and assumptions employed in the analysis is provided in NRC 84. It is important that the normalized dose tables be used with a complete understanding of the assumptions used in their derivation. In general, the normalized dose factors are conservative and will result in an upper bound estimate of population and occupational doses.

4.1.1 Normalized Source Terms and Doses Associated with Incineration

NRC 84 presents a generic methodology for quantifying the radiological impacts to incinerator personnel and the public at a reference incinerator; a rotary kiln with a capacity of 100 tons per day and an average annual throughput of 75 percent of capacity. The normalized impacts presented in this section are based on this reference incinerator. A more detailed description of the reference incinerator is provided in Appendix C of NRC 84.

4.1.1.1 Normalized Atmospheric Emissions and Offsite Radiological Impacts. Table 4-1 presents the estimated normalized emissions and offsite doses associated with the reference incinerator. Table 4-1 can be used to derive approximate, or upper bound, source terms and offsite doses to individuals and populations by multiplying the normalized doses by the actual throughput for individual radionuclides at a specific incinerator.

Users of Table 4-1 should fully understand the assumptions inherent in the values tabulated, especially the normalized release rate for particulate radionuclides, since these represent the greatest source of uncertainty in the methodology. For example, the normalized release rate, often referred to as the release fraction, for most particulates is assumed to be 0.0025. This is a generally conservative value representing an upper bound estimate for hazardous waste incinerators with modest controls. For any specific incinerator, the release fractions for particulates could be lower by several orders of magnitude. Accordingly, if reliable site specific release fractions are available, the values in Table 4-1 should be adjusted accordingly. For example, if the release fraction for Co-60 is actually 1.0E-06, the values for Co-60 in Table 4-1 should be multiplied by 1.0E-06/.0025.

In addition to the release fractions for particulates, the normalized individual doses may be overly conservative for some sites because they are based on the assumption that an individual is located downwind and relatively close to the plant. However, unlike the particulate release fractions, the conservatism inherent in these assumptions is likely to be less than an order of magnitude for any specific site. If site specific information is available regarding local meteorology and the location of the maximally exposed individual, the normalized individual dose factors can be adjusted by dividing out the assumed atmospheric dispersion factor (see the Attachment) and multiplying by the site specific atmospheric dispersion factor.

4.1.1.2 Normalized Occupational Exposures. Radiological exposures to incinerator workers can occur from the inhalation of airborne radionuclides and direct external radiation sources. The following table, taken from NRC 84, presents the different categories and numbers of workers at the reference incinerator and their relative potential for exposure.

Table 4-1. Normalized source terms and offsite doses due to routine atmospheric emissions from a reference radioactive waste incinerator

Radionuclide[1]	Source Term[2] (Ci/yr per Ci/yr)	Individual Dose[3] (mrem/yr per Ci/yr)	Population Dose[4] (person-mrem/yr per Ci/yr) NE	SW
H-3	O.9	3.0E-03	2.9E+01	7.5E-01
C-14	O.75	6.3E-02	6.0E+02	1.6E+01
Fe-55	O.0025	1.5E-05	1.4E-01	3.7E-03
Fe-59	0.0025	2.0E-04	1.9E+00	5.0E-02
Co-60	0.0025	5.5E-04	5.3E+00	1.4E-01
Ni-59	0.0025	3.0E-06	2.9E-02	7.4E-04
Ni-63	0.0025	6.2E-06	5.9E-02	1.5E-03
Sr-90	0.0025	1.7E-03	1.6E+01	4.2E-01
Nb-94	0.0025	1.1E-03	1.1E+01	2.7E-01
Tc-99	0.0025	1.5E-04	1.4E+00	3.7E-02
Ru-106	0.01	1.4E-02	1.3E+02	3.5E+00
Sb-125	0.0025	7.5E-05	7.2E-01	1.9E-02
I-129	0.01	1.5E-01	1.4E+03	3.7E+01
Cs-134	0.0025	1.7E-03	1.6E+01	4.2E-01
Cs-135	0.0025	1.7E-04	1.6E+00	4.2E-02
Cs-137	0.0025	1.2E-03	1.1E+01	3.0E-01
Eu-154	0.0025	4.4E-03	4.2E+01	1.1E+00
Pb-210	0.0025	9.9E-03	9.5E+01	2.5E+00
Po-210	0.0025	3.0E-02	3.1E+02	7.9E+00
Ra-226	0.0025	2.2E-02	2.1E+02	5.5E+00
Ra-228	0.0025	9.4E-03	9.0E+01	2.3E+00
Th-232	0.0025	2.9E-01	2.8E+03	7.2E+01
U-234	0.0025	1.2E-01	1.1E+03	3.0E+01
U-235	0.0025	1.1E-01	1.1E+03	2.7E+01
U-238	0.0025	1.1E-01	1.1E+03	2.7E+01
Np-237	0.0025	4.2E-01	4.0E+03	1.0E+02
Pu-238	0.0025	3.3E-01	3.2E+03	8.2E+01
Pu-239	0.0025	3.7E-01	3.5E+03	9.2E+01
Pu-241	0.0025	5.7E-03	5.4E+01	1.4E+00
Pu-242	0.0025	3.7E-01	3.5E+03	9.2E+01
Am-241	0.0025	4.1E-01	3.9E+03	1.0E+02
Am-243	0.0025	4.2E-01	4.0E+03	1.0E+02
Cm-243	0.0025	2.9E-01	2.8E+03	7.2E+01
Cm-244	0.0025	2.4E-01	2.2E+03	6.0E+01

1. The list of radionuclides is based on those included in the analyses performed by the EPA in support of its 40 CFR 193 rulemaking on low-level radioactive waste (EPA88). A more complete list can be derived from Table D-19 of NRC 84.

2. Estimated radionuclide release to the atmosphere from the stack of a reference hazardous waste incinerator per Ci/yr of radionuclide feedstream

3. Normalized dose to the hypothetical maximally exposed offsite individual from all pathways at a reference site.

4. Normalized dose to the offsite population from all pathways at a reference site in the Northeast and in the Southwest. The approximate 30-fold difference between the NE and the SW is the much higher population density assumed for the NE.

Occupation	No. Persons	Dust Level	Proximity
Manager	1	low	moderate
Foreman	1	low	moderate
Secretary	1	low	far
Office Manager	1	low	far
Engineer	1	low	far
Schedulers		low	far
Accounting	1	low	far
Occupational Health	2	moderate	moderate
Operators	2	moderate	close
Process Controllers	2	moderate	moderate
Residue Handlers	2	high	close
Maintenance	2	high	close

Unless the facility uses special enclosures and remote handling techniques, the residue handlers and maintenance personnel may at times be exposed to relatively dusty areas and come into close proximity to unshielded waste. As a result, they have the highest potential for exposure.

Table 4-2 presents estimated unshielded unit doses to the maximally exposed workers at a mixed waste incinerator. Notwithstanding these normalized dose rates, worker exposures will be limited to the occupational exposure standards set forth in 10 CFR 20. This table may be used to estimate the maximum unshielded radiation exposures to workers by multiplying the actual radionuclide throughput by the normalized values. Again it must be emphasized that the results would represent conservative values because the normalized dose factors are based on several conservative assumptions. Specifically, it is assumed that the workers are in close proximity to unshielded waste (i.e., 1 meter). In addition, it is assumed that the ash is manually handled, creating a dusty environment (i.e., 0.4 mg of dust per m^3).

These are extremely conservative assumptions which will require adjustment for the conditions at a specific incinerator. The sample problem in Section 4.4 discusses some of these adjustments. In addition, insight into the effectiveness of shielding is provided in Section 4.1.3. Further discussion of the assumptions used to derive these values is provided in the Attachment.

Table 4-2. Normalized unshielded doses to the maximally exposed worker at a reference radioactive waste incinerator

Radionuclide[1]	Individual Dose[2] (mrem/hr per Ci/m^3)	
	Inhalation	Direct Radiation
H-3	4.8E-05	0
C-14	4.1E-06	0
Fe-55	1.5E-03	0
Fe-59	3.7E-02	8.5E+02
Co-60	1.5E-01	1.9E+03
Ni-59	3.6E-04	0
Ni-63	8.5E-04	0
Sr-90	5.5E-01	2.3E-05
Nb-94	2.0E-01	1.1E+03
Tc-99	2.8E-03	5.0E-06
Ru-106	2.1E-01	1.4E+02
Sb-125	1.7E-02	3.0E+02
I-129	6.5E-02	1.9E+00
Cs-134	6.5E-02	1.1E+03
Cs-135	2.6E-03	0
Cs-137	3.5E-03	4.1E+02
Eu-154	1.4E-01	7.5E+02
Pb-210	1.0E+00	1.2E+00
Po-210	3.3E+00	1.3E-02
Ra-226	3.4E+00	3.8E+00
Ra-228	7.0E-01	5.0E-01
Th-232	1.0E+02	0
U-234	4.2E+01	6.0E-02
U-235	3.8E+01	9.0E+01
U-238	3.8E+01	8.0E+00
Np-237	1.4E+02	1.3E+02
Pu-238	1.2E+02	1.3E-02
Pu-239	1.4E+02	0
Pu-241	2.1E+00	1.7E-04
Pu-242	1.3E+02	1.6E-02
Am-241	1.4E+02	9.0E+00
Am-243	1.4E+02	1.1E+02
Cm-243	9.5E+01	6.5E+01
Cm-244	7.5E+01	7.0E-03

1. The list of radionuclides is based on those included in the analyses performed by the EPA in support of its 40 CFR 193 rulemaking on low level radioactive waste (EPA 88). A more complete list can be derived from Table D-19 of NRC 84.

2. Normalized dose to the hypothetical maximally exposed worker for a unit concentration of radionuclides in the feedstream or ash. For workers handling the ash, the radionuclide concentrations in the ash may be assumed to be about 20 times higher than in the feed streams for all radionuclides except H-3, C-14, and iodines. The content of these latter radionuclides in ash may be assumed to be zero.

4.1.2 Unit Doses Associated with Waste Handling and Volume Reduction Operations Other than Incineration

Waste management processes, such as sorting, shredding, and compaction, also result in occupational and public exposures. The maximum unit doses to workers from direct radiation are likely to be comparable to those calculated for incineration. However, there is a higher potential for inhalation exposures at an incinerator due to the generally greater dispersibility of ash as compared to solid waste. Accordingly, the occupational unit doses for incinerator personnel represent an upper bound for waste management personnel. Similarly, the potential for atmospheric emissions from routine operations for waste handling facilities and/or operations other than incinerators is smaller than that for an incinerator. It would be inappropriate, however, to assume that the emissions are zero, since shredders and compactors generate airborne particulates that need to be controlled and monitored. Due to the paucity of available operational data, it is not possible to present unit source terms and doses for these operations.

4.1.3 Unit Doses Associated with the Routine Transport of Radioactive Waste

The unshielded unit doses in Table 4-2 for external exposures may be used to estimate the external doses to workers and the general public associated with the transport of waste. However, since the values in Table 4-2 assume exposure in close proximity to the unshielded waste, the values represent only the starting point in the dose assessment. By applying appropriate correction factors, more realistic unit doses can be derived.

The following table presents correction factors that should be applied to the values in Table 4-2 for different geometries and distances from the waste shipment, as depicted in Figure 4-1.

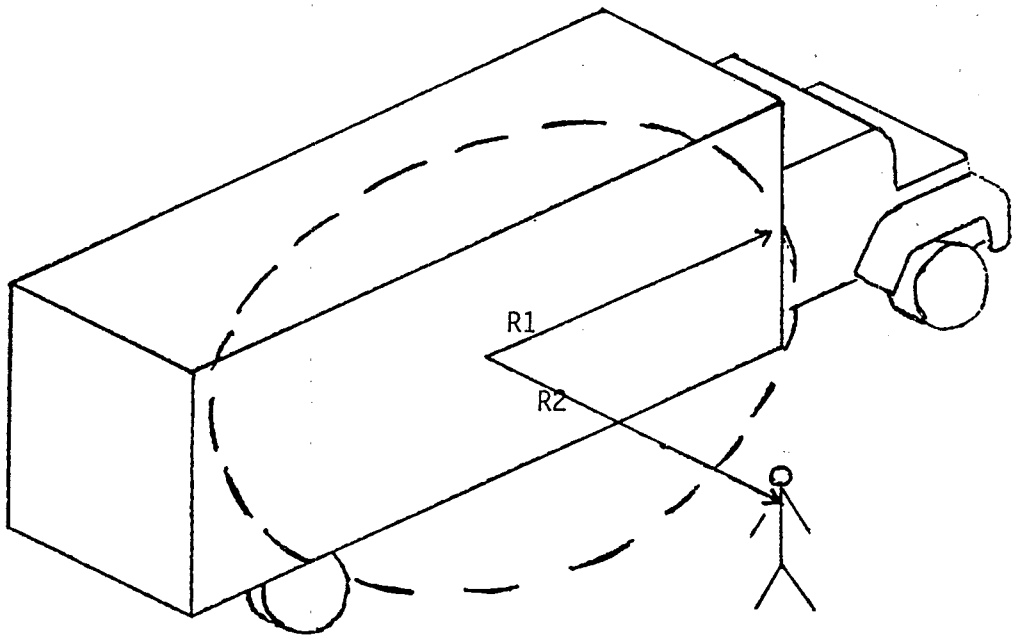

Figure 4-1. Transportation Exposure Geometry

	r1			
r2	2m	4m	10m	20m
1m	1.9E-01	3.4E-01	5.5E-01	6.9E-01
5m	2.8E-02	9.4E-02	3.0E-01	5.1E-01
10m	9.6E-03	3.6E-02	1.7E-01	3.7E-01
20m	3.3E-03	1.3E-02	7.3E-02	2.2E-01
30m	1.8E-03	7.1E-03	4.2E-02	1.4E-01
40m	1.2E-03	4.7E-03	2.8E-02	1.0E-01
50m	8.5E-04	3.4E-03	2.1E-02	7.8E-02

In addition to these correction factors, the unshielded unit doses need to be corrected for duration of exposures by multiplying by the assumed number of hours per year. By applying these corrections to the values in Table 4-2, unit doses are generated for specific geometries of the waste shipment, specific distances from the shipment, and durations of exposure.

Finally, the values in Table 4-2 need to be corrected to account for shielding of the waste. Shielding corrections are radionuclide specific and depend on the geometry of the source and the thickness and type of shielding material used. Accordingly, there are no simple correction factors that can be applied to account for shielding. However, some insight into the general effectiveness of shielding is provided in the following table of shielding factors for concrete and lead for a 0.1- and 1.0-MeV gamma emitter.

Shielding factors for gamma emitters

Thickness of Shielding (cm)	Lead		Concrete	
	0.1 MeV	1.0 MeV	0.1 MeV	1.0 MeV
1	0.7	0.94	0.98	0.99
5	0.17	0.73	0.92	0.94
10	0.029	0.54	0.85	0.88
20	8.7E-04	0.29	0.72	0.78
50	0	0.46	0.43	0.54
100	0	2.1E-03	0.19	0.29

4.2 HEALTH IMPACT ASSESSMENT

Using the methodology presented in the above sections, radiation doses to workers and the public can be estimated for a range or volume reduction technologies. For individuals, the doses are expressed in units of mrem/yr effective whole-body dose commitment equivalent, and for populations, the doses are expressed in terms of person-mrem/yr. These values can be converted to health risk by applying health risk conversion factors that relate radiation exposures to risk of fatal cancer, expressed in units of risk of fatal cancer per mrem exposure.

The health risk conversion factor used by the EPA in support of its rulemaking for radionuclide NESHAPS is 3.92 E-07 fatal cancers per mrem. Accordingly, given a derived dose commitment of 100 mrem in 1 year to an individual, the approximate lifetime risk of fatal cancer associated with that exposure is approximately 3.92E-05. Similarly, if a population is estimated to receive 1.0E+06 person-mrem in a given year, the number of fatal cancers that may eventually occur in that population due to that exposure is 0.392, or less than one.

4.3 SAMPLE PROBLEM

This section presents an example of the application of the above technique to a specific waste stream. The section is divided into two parts. The first part describes at reference waste stream and how it was derived. The second part uses the reference waste stream as input into a dose assessment using the above described normalized dose and risk assessment procedures.

4.3.1 Reference Radionuclide Source Term

For formulating a sample problem, a reference radiological source term is estimated based on published information characterizing overall waste generation and disposal practices at Department of Energy facilities. The reference waste stream developed in this section is intended to reflect overall DOE practices in an aggregate manner because waste generation practices vary over time and among facilities.

DOE program activities change due to elimination of experiments and programs, re-evaluation of production activities which routinely generate low-level and transuranic (TRU) wastes, re-definition of the waste acceptance criteria for both low-level and TRU wastes, and analyses of waste currently held in storage or destined for disposal (DOE 88, DOE 89c, DOE 89d, DOE 90). The DOE keeps track of waste generation activities and characteristics via the Solid Waste Information Management System (SWIMS). DOE Order 5820.2A defines the waste management program for all DOE facilities.

4.3.1.1 Low-Level Waste. The Department of Energy defines low-level radioactive waste as materials that contain radioactivity which is not classified as high-level waste, transuranic waste, spent-nuclear fuel, or mixed or tailing waste (DOE 88). Test specimens of fissionable material irradiated only for research and development purposes (i.e., not for the production of plutonium or power) may be classified as low-level radioactive waste, as long as the concentration of transuranic elements are less than 100 nCi/g. Accelerator produced (NARM) and naturally occurring (NORM) waste is not treated separately and are included in this category (DOE 89c).

Low-level waste is generated by all DOE facilities in varying concentrations and quantities. The waste generation rate for 1989 is estimated to range from 1,500 to nearly 32,000 m^3 among the six major DOE installations (LANL, INEL, NTS, ORNL, HANF, and SRS) (DOE 89c). The total waste volume is assumed to be nearly 100,000 m^3 per year. The total radioactivity generated by such facilities is also known to vary from 100,000 to 570,000 Ci per year. For 1989, it is estimated that these facilities will generate about 1.5 million Ci (DOE 89c).

The waste contains a number of radionuclides grouped in five categories; uranium/thorium, fission products, activation products, alpha emitters at concentrations less than 100 nCi/g, and other unspecified sources. Table 4-3 presents this breakdown by category, radionuclide distributions, and waste concentrations. The concentrations were estimated from aggregate data characterizing the typical radionuclide mix for these five categories across all DOE facilities. The concentrations are weighted to reflect fractional nuclide distributions, waste volumes, and total activity generated in each category.

A review of Table 4-3 indicates that activation products and nuclides from other unspecified sources have the highest waste concentrations. Wastes that are predominant by volume are generally characterized by nuclide concentrations which are typically one order of magnitude lower than those noted above. In summary, waste concentrations are believed to vary from about 1.3E-04 to as high as 8.1E+00 Ci/m^3. The highest concentrations, by category, are 1.6E-02 Ci/m^3 for uranium/thorium; 5.6E-01 Ci/m^3 for fission products; 8.1E+00 Ci/m^3 for activation products; 1.1E-01 Ci/m^3 for alpha emitters; and 6.0E+00 Ci/m^3 for other unspecified radionuclides.

4.3.1.2 Transuranic Waste. Transuranic waste is characterized by the presence of alpha emitting radionuclides with half-lives greater than 20 years at concentrations greater than 100 nCi/g. The predominant transuranic radionuclides are plutonium, americium, and curium (DOE 88). The DOE permits each installation, based on special consideration, to identify and include other nuclides or waste forms in this classification.

TRU waste is further classified as "contact handled" or "remote handled." Contact handled (CH) waste is characterized by surface dose rates of less than 200 mR/hr and can be handled without any specific controls. Remote handled (RH) waste requires the use of special handling equipment since their specific activity and external exposure rates are typically higher. Any waste form with exposure rates greater than 200 mR/h are classified as a RH-TRU waste. External radiation exposures are due to energetic beta, gamma, and neutron emissions. Currently, about 2.5 percent of the TRU waste which is routinely generated and/or placed in storage are considered to be RH-TRU. This waste is currently segregated, stored, and will eventually be disposed at DOE's Waste Isolation Pilot Plant (WIPP) located in Carlsbad, New Mexico. This section does not consider RH-TRU waste since the DOE plans to dispose of such waste at the WIPP facility (DOE 89c, DOE 90).

Table 4-3. Reference low-level radioactive waste source terms[a]

Category & Radionuclides	Fractional Distribution(%) Nuclide	Volume	Activity	Concentration (Ci/m^3)
Uranium/Thorium	--	17.3	0.057	--
Th-232	0.3	--	--	1.3E-4[b]
Th-234	33.2	--	--	1.6E-2
Pa-234m	33.2	--	--	1.6E-2
U-238	33.2	--	--	1.6E-2
Fission Products	--	11.5	2.5	--
Sr-90	7.8	--	--	2.5E-1
Y-90	7.8	--	--	2.5E-1
Zr-95	1.3	--	--	4.1E-2
Nb-95	2.8	--	--	9.2E-2
Sb-125	2.9	--	--	9.6E-2
Te-125m	0.7	--	--	2.4E-2
Ru-106	6.4	--	--	2.1E-1
Rh-106	6.4	--	--	2.1E-1
Cs-134	0.4	--	--	1.2E-2
Cs-137	17.3	--	--	5.6E-1
Ba-137m	16.4	--	--	5.3E-1
Ce-144	14.7	--	--	4.8E-1
Pr-144	14.7	--	--	4.8E-1
Sm-151	0.1	--	--	3.6E-3
Activation Products	--	7.8	7.6	--
Cr-51	4.9	--	--	7.2E-1
Mn-54	38.1	--	--	5.6E+0
Co-58	55.4	--	--	8.1E+0
Fe-59	0.5	--	--	7.2E-2
Co-60	0.9	--	--	1.3E-1
Zn-65	0.2	--	--	2.8E-2
Alpha (< 100 Nci/g)	--	3.8	0.029	--
Pu-238	2.6	--	--	3.0E-3
Pu-239	0.2	--	--	2.3E-4
Pu-240	0.7	--	--	8.1E-4
Pu-241	96.4	--	--	1.1E-1

(a) Calculated from DOE's 1989 Integrated Data Base, Tables A.5, A.6, and A.7 (DOE 89c). Assumes an estimated generation rate of 1.48E+6 Ci and 9.89E+4 m^3 of waste for 1989.
(b) Exponential notation, 1.3E-4 means 1.3×10^{-4}.

Table 4-3. Reference low-level radioactive waste source terms[a]
(Continued)

Category & Radionuclides	Fractional Distribution(%)			Concentration (Ci/m³)
	Nuclide	Volume	Activity	
Other Sources	--	--	--	--
H-3	1.2	0.61	18.4	5.5E+0
Mn-54	6.8	0.44	0.95	2.2E+0
Co-58	6.2	"	"	2.0E+0
Co-60	18.3	""	"	5.8E+0
Sr-90	8.5	"	"	2.8E+0
Y-90	8.5	"	"	2.8E+0
Tc-99	0.1	"	"	3.9E-2
Cs-134	14.0	"	"	4.5E+0
Cs-137	18.5	"	"	6.0E+0
Ba-137m	17.5	"	"	5.7E+0
U-238	0.7	"	"	2.4E-1

(a) Calculated from DOE's 1989 Integrated Data Base, Tables A.5, A.6, and A.7 (DOE 89c). Assumes an estimated generation rate of 1.48E+6 Ci and 9.89E+4 m^3 of waste for 1989.
(b) Exponential notation, 1.3E-4 means 1.3×10^{-4}.

The DOE has estimated that for 1989, a total of 2,500 m^3 of CH-TRU waste will be generated by all DOE installations. This waste volume comprises about 154,000 Ci and 165 Kg of TRU radionuclides (DOE 89c). Most of this waste (90 percent) has been deemed to be certifiable after processing using existing equipment and facilities. The balance is being stored while awaiting future processing capabilities (DOE 89c).

The radionuclides, and their respective concentrations, that make up CH-TRU waste are shown in Table 4-4. Radionuclide concentrations were calculated based on DOE's definition of "waste mix" which reflects the composition of six CH-TRU waste streams currently stored and generated. The "waste mix" also includes waste streams generated in support of the DOE's weapons program. Because of the classified nature of such programs, there is no additional information with which to better characterize such waste. Typically, each DOE facility generates a waste mix of different composition. Furthermore, DOE facilities do not simultaneously generate waste that comprises the "six mix." Only one DOE facility (SRS) reported having generated waste in all six "waste mixes." LANL and LLNL were reported to generate waste that represents five of the waste mixes. The calculated concentrations were weighted across the 6 CH-TRU waste "waste mix" and all 10 facilities cites by DOE (DOE 89c). The calculations ignore DOE entries given as "MFP" (mixed fission products) and "Other" since these entries do not identify specific radionuclides.

In Table 4-4, CH-TRU waste concentrations have been grouped as uranium, plutonium, and other radionuclides. Uranium and plutonium radionuclides are characterized with higher TRU concentrations than those identified as others. Only one DOE installation (Hanford) reported the presence of depleted-U, enriched-U, and normal uranium. Normal-U is assumed to mean natural uranium at its natural abundance. Waste concentrations are believed to vary from a low 1.5E-02 to as high as 4.5E+01 Ci/m^3. The highest concentrations, by category, are 4.5E+01 Ci/m^3 for depleted uranium; 3.7E+01 Ci/m^3 for plutonium; and 1.2E+01 Ci/m^3 for other unspecified radionuclides.

Table 4-4. Default transuranic waste source term[a]

Radionuclides	Fractional Distribution (Wt%)	Concentration (Ci/m^3)
Uranium		
U-233	20.3	1.3E+1[b]
U-235	3.8	2.4E+0
U-238	24.0	1.5E+1
Depleted-U	72.8	4.5E+1
Enriched-U	1.8	1.1E+0
Normal-U	20.0	1.2E+1
Plutonium		
Pu-238	59.0	3.7E+1
Pu-239	45.1	2.8E+1
Pu-240	5.8	3.6E+0
Pu-241	0.4	2.2E-1
Pu-242	0.02	1.5E-2
Others		
Am-241	2.9	1.8E+0
0Cm-244	1.2	7.5E-1
Cf-252	0.2	9.3E-2
Np-237	18.7	1.2E+1
Th-232	3.1	1.9E+0
Unspecified	0.8	5.0E-1

(a) Calculated from DOE's 1989 Integrated Data Base, Tables 3.8 and 3.10 (DOE 89c). Assumes an estimated generation rate of 1.54E+5 Ci and 2.48E+3 m^3 of waste for 1989.
(b) Exponential notation, 1.3E+1 means 1.3 x 10^{+1}.

4.3.2 Example Dose Assessment

Offsite individual, population, and worker doses are estimated based on the information given in Section 4.1 and using the unit dose conversion factors listed in Tables 4-1 and 4-2. The waste concentrations derived above are used to estimate the total yearly activity throughput for a hypothetical incinerator. The concentrations are multiplied by an effective yearly waste volume throughput. This waste volume assumes a 50-50 mix in solid and liquid wastes, 400 and 300 lbs/hr capacity for solid and liquid wastes, respectively, 4,000 operating hours per year, and effective solid and liquid waste densities of 8.0 and 52.2 lbs/ft^3, respectively. Given the above, the total waste volume throughput is estimated to be 3,157 m^3/yr.

The yearly activity throughput, airborne emissions, and doses to an offsite individual and population are shown in Table 4-5 for selected radionuclides. The yearly waste activity introduced to the incinerator is the product of the total yearly waste volume by the concentration of each respective radionuclide, based on Table 4-3 data. The source term used for this illustration does not differentiate between low-level and mixed wastes. The data tabulated for CH-TRU waste (Table 4-4) are not used here since this type of waste is typically processed by a dedicated incinerator or will be shipped for disposal at the WIPP facility. Atmospheric releases were estimated using the release fractions given in Table 4-2, corrected by a factor of 0.5 on the assumption that best available off-gas treatment technologies would further reduce airborne emissions.

Offsite doses to individuals and population groups were derived by multiplying the yearly waste input to the incinerator by the unit dose conversion factors for each radionuclide shown in Table 4-3. A review of Table 4-5 indicates that doses, given this example, are dominated by two radionuclides (H-3 and Pu-239). As was noted in Section 4.1, there are several factors which may in fact yield much lower doses than those derived above. For example, the release fractions have in fact been shown to be much lower. The data in Table 4-1 assume a release fraction of 0.0025 for most particulates while current experience indicates that release fractions ranging from 10^{-4} to 10^{-5} are readily achievable.

Table 4-5. Yearly incinerator radioactive waste throughput, releases, and offsite doses[a]

Radionuclide	Input to Incinerator (Ci/yr)	Atmospheric Releases (Ci/yr)	-- Offsite Doses -- Individual (mrem)	Population (person-mrem)
H-3	17,364	7,800	26	6,511
Fe-59	227	0.3	0.02	6
Co-60	410	0.5	0.1	29
Sr-90	789	1.0	0.7	166
Tc-99	123	0.2	0.01	2
Ru-106	663	3.0	5.0	1,160
Sb-125	303	0.4	0.01	3
Cs-134	38	0.05	0.03	8
Cs-137	1,768	2.2	1.0	265
Th-232	0.4	0.0005	0.06	15
U-238	51	0.06	2.8	682
Pu-238	9.5	0.01	1.6	389
Pu-239	726	0.9	134	33,396
Pu-241	347	0.4	1.0	243

(a) All values are rounded off. See text for details.

This information must also be used with caution since most incinerators are typically one-of-a-kind with unique design specifications. Similarly, incinerators are operated under different conditions using administrative procedures which govern the types of waste to be incinerated, require waste segregation and sorting, limit the radiological characteristics of the waste, and control waste throughput or incineration rates. Taken together, such considera-tions and practices tend to reduce airborne emissions and, consequently, offsite doses.

Finally, in actual practice, the results of risk assessment study would dictate the total amount of activity or waste concentrations which could be routinely incinerated. The radiological risk assessment takes into account the radiological properties of the waste, nuclide partitioning during the combustion process, overall effectiveness of the off-gas treatment system, meteorological conditions at the critical receptor point(s), and exposure pathways. Given that such emissions must comply with State and Federal airborne emission and dose limits, the amount of radioactivity which may be incinerated is limited to meet these regulatory requirements. Furthermore, for ensuring that these limits are never exceeded, it is common practice to impose ALARA and administrative safety factors.

Using the same approach as described above, occupational doses were estimated for inhalation and direct radiation exposures and for transportation activities. The results are shown in Table 4-6 for a selected number of radionuclides. Inhalation exposures are generally lower than exposure to direct radiation. Doses associated with waste transportation are on the same order as that due to waste handling.

Generally speaking, the higher doses are due to the conservative assumptions used in the calculations. For example, it is assumed that the worker would spend 25 percent of his time handling such waste. The correction for the source geometry and proximity factor assumes that about 10 percent of the time would be spent in close contact with waste characterized with high external exposure rates. Similarly, inhalation doses assume that exposures occur in a relatively dusty environment. In fact, current experience has shown that waste is rarely moved manually

Table 4-6. Yearly occupational inhalation, direct radiation, and transportation exposures[a]

Radionuclide	Waste Conc. (Ci/m^3)	-- Doses (mrem/yr) -- Inhalation	Direct	Transport
Fe-59	7.2E-2	1.3	367	490
Co-60	1.3E-1	9.4	1,482	1,976
Sr-90	2.5E-1	66	3.4E-5[b]	4.5E-5
Tc-99	3.9E-2	0.05	1.2E-6	1.6E-6
Ru-106	2.1E-1	21	170	227
Sb-125	9.6E-2	0.8	170	227
Cs-134	1.2E-2	0.4	79	106
Cs-137	5.6E-1	1.0	1,360	1,814
Th-232	1.3E-4	6.3	-na-	-na-
U-238	1.6E-2	289	0.8	1.0
Pu-238	3.0E-3	173	2.3E-4	3.1E-4
Pu-239	2.3E-4	15	-na-	-na-
Pu-241	1.1E-1	109	1.1E-4	1.4E-4

(a) All values are rounded off. See text for details.
(b) Exponential notation, 3.4E-5 means 3.4×10^{-5}.
-na- means "not applicable."

and that ash handling takes place in ventilated enclosures, e.g., a glove-box. These features would tend to reduce occupational exposures significantly. Transportation doses assume that a worker spends 2 hours per day (or 25 percent of the time) driving a truck or in close proximity of the waste. The combined geometry correction factor (r_1 and r_2, see Section 4.1.3) is assumed to be 0.17. Because some of the waste exhibits elevated external exposure rates, it is assumed that adequate shielding would be provided to reduce doses. A shielding factor of 0.1 is assumed for this example. Transportation doses were estimated using a combined correction factor of 0.004.

Finally, although the doses, as calculated, are within occupational limits, current radiological practices would find such doses unacceptably high. As was discussed above, the routine handling of waste containers and ashes would be controlled under administrative procedures to avoid unnecessary exposures and maintain personnel doses ALARA.

Attachment
Derivation of the Normalized Dose Factors

Normalized Atmospheric Emissions and Offsite Radiological Impacts

Table 4-2 presents the estimated normalized emissions and offsite doses associated with the reference hazardous waste incinerator. The equations and parameters used to calculate these values are as follows:

Hn/Qn = fr fs PDCF3 for individual doses

Pn/Qn = fr POP PDCF3 for cumulative population doses

where:

Hn = individual effective whole-body dose commitment equivalent (mrem/y) from the nth radionuclide.

Qn = the total throughput of the nth radionuclide in the incinerator (Ci/yr).

fr = the fraction of the nth radionuclide input into the incinerator that is discharged to the atmosphere at the plant stack. The values of fr assumed for this calculation are as follows:

Nuclide	Release Fraction (fr)
H-3	0.90
C-14	0.75
Tc-99	0.01
Iodines	0.01
Ruthenium	0.01
All Others	0.0025

fs = the average annual atmospheric dispersion factor at the location of the hypothetical maximally exposed individual. The value of fs is assumed to be 5.29E-14 yr/m^3.

PDCF3 = the pathway dose conversion factor for airborne emissions (mrem/yr per Ci/m^3) for all potentially significant pathways. The values are tabulated in Appendix D of NRC84.

Pn = the population effective whole-body dose commitment equivalent (person-mrem/yr) from the nth radionuclide.

POP = population weighted sum of the atmospheric dispersion factor as a function of radial distance from the stack. For NE sites, POP is assumed to be 5.05E-10 person-years/m^3. For SW sites, POP is assumed to be 1.33E-11 person-years/m^3.

The values selected for use in these equations are themselves derived based on a number of assumptions. A key parameter in the equation is the release fraction. The release fractions are based on data reported for pathological incinerators summarized in NRC84. The effluent processing systems employed at these incinerators differed, but typically included HEPA filters, vapor condensers and wet scrubbers. A comparison of these release fractions to those reported more recently by SEG, Inc. in Oak Ridge reveal similar results for H-3 and C-14, but 1000 fold lower values for particulates. It is clear that the actual release fractions for specific incinerators should be used if the data areavailable, and that the default values used in this report may be considered reasonable upper bound values.

The atmospheric dispersion factor for the maximally exposed individual is based on the assumption that the individual is located 300 meters from a 61- meter stack in the predominant wind direction. The values are based on the assumption that the stability classes and wind speeds are 1/3 Stability Class C with wind speed 3 m/s, 1/3 Stability Class D with wind speed 3 m/s, and 1/3 Stability Class F with wind speed 2 m/s. In addition, it is conservatively assumed that the wind blows toward the location of the critical receptor 1/3 of the time.

The POP factor is used to calculate the population doses within a 50-mile radius of the plant stack. The average annual atmospheric dispersion factor is calculated for each sector, multiplied by the population assumed in each sector, and then summed. The population distributions assumed for NE and SW sites are as follows:

Distance From Source	NE	SW
0 - 5 miles	3440	59
5 - 10 miles	20,513	180
10 - 20 miles	73,636	3,529
20 - 30 miles	121,559	9,062
30 - 40 miles	556,639	4,888
40 - 50 miles	1,012,788	27,158

The pathway dose conversion factor (PDCF3) is a derived value that relates the total annual dose commitment equivalent to an individual to the average annual airborne radionuclide concentration at the individual's residence. The pathways included in PDCF3 are inhalation of airborne and resuspended radionuclides, ingestion of food grown in soil contaminated with deposited radionuclides, and direct radiation from airborne and deposited radionuclides.

A more complete description of each parameter and how each of the values were derived is provided in NRC84.

Normalized Occupational Exposures

Table 4-3 presents estimated unit doses to the maximally exposed workers at a mixed waste incinerator. The following equations and assumptions were used to derive these values.

Hn/Cn = Twa EDF PDCF1 (for inhalation exposures)
Hn/Cn = CF DF EDF PDCF5 (for direct radiation)

where:

Hn = the effective whole body dose commitment to the worker from the nth radionuclide (mrem/h).

Cn = average annual concentration of the nth radionuclide in the feedstream or ash, depending on which end of the operation the worker is involved with (Ci/m^3).

Twa = waste to air transfer factor. For dusty environments, the dust concentration is assumed to be 0.4 mg/m^3; therefore, the value of Twa is 4.0E-10.

EDF = the exposure duration factor used to convert exposures into units of mrem/h. Accordingly, EDF is 1/8760 or about 1.0E-04.

PDCF1 = Pathway dose conversion factor for the nth radionuclide for inhalation and exposure to direct radiation from airborne radionuclides (mrem/yr per Ci/m^3). The values are tabulated in Appendix D of NRC84.

PDCF5 = Pathway dose conversion factor for external exposure at one meter away from an infinite slab at unit concentration of the nth radionuclide (mrem/yr per Ci/m^3). The values are tabulated in Appendix D of NRC84.

DF = Correction factor to account for distances other than 1 meter away from the source. For close proximity personnel, DF = 1.

CF = Correction factor to account for the finite extent of the external source of radiation. For close proximity personnel, CF = 1.

Accordingly, the two equations reduce to the following form:

Hn/Cn = 4.74E-14 PDCF1 (for inhalation exposures)

Hn/Cn = 1.19E-04 PDCF5 (for exposure to direct radiation)

For site specific conditions, adjustments will be required for (1) the actual airborne dust loading, (2) the actual time and proximity of exposure of workers, and (3) the use of remote handling and shielding to reduce worker exposure to direct radiation.

APPENDIX A

PRINCIPAL TYPES OF IONIZING RADIATION

Alpha particles are doubly charged cations, composed of two protons and two neutrons, which are ejected monoenergetically from the nucleus of an atom when the neutron to proton ratio is too low. Because of their relatively large mass and charge, alpha particles tend to ionize nearby atoms quite readily, expending their energy in short distances. Alpha particles usually will not penetrate an ordinary sheet of paper or the outer layer of skin. Consequently, alpha particles represent a significant hazard only when taken into the body, where their energy is completely absorbed by small volumes of tissues.

Beta particles are electrons ejected at high speeds from the nucleus of an unstable atom when a neutron spontaneously converts to a proton and an electron. Unlike alpha particles, beta particles are not emitted with discrete energies but are ejected from the nucleus over a continuous energy spectrum. Beta particles are smaller than alpha particles, carry a single negative charge, and possess a lower specific ionization potential. Unshielded beta sources can constitute external hazards if the beta radiation is within a few centimeters of exposed skin surfaces and if the beta energy is greater than 70 keV. Beta sources shielded with certain metallic materials may produce bremsstrahlung (low-energy x ray) radiation which may also contribute to the external radiation exposure. Internally, beta particles have a much greater range than alpha particles in tissue. However, because they cause fewer ionizations per unit path length, beta particles deposit much less energy to small volumes of tissue and, consequently, inflict much less damage than alpha particles.

Positrons are identical to beta particles except that they have a positive charge. A positron is emitted from the nucleus of a neutron-deficient atom when a proton spontaneously transforms into a neutron. Alternatively, in cases where positron emission is not energetically possible, the neutron deficiency may be overcome by electron capture, whereby one of the orbital electrons is captured by the nucleus and united with a proton to form a neutron, or by annihilation radiation, whereby the combined mass of a positron and electron is converted into photon energy. The damage inflicted by positrons to small volumes of tissue is similar to that of beta particles.

Gamma radiations are photons emitted from the nucleus of a radioactive atom. X rays, which are extra-nuclear in origin, are identical in form to gamma rays, but have slightly lower energy ranges. There are three main ways in which x and gamma rays interact with matter: the photoelectric effect, the Compton effect, and pair production. All three processes yield electrons which then ionize or excite other atoms of the substance. Because of their high penetration ability, x and gamma radiations are of most concern as external hazards.

Neutrons are emitted during nuclear fission reactions, along with two smaller nuclei, called fission fragments, and beta and gamma radiation. For radionuclides likely to be encountered in the environment, no significant neutron radiation is expected.

APPENDIX B

DEFINITIONS

Absorbed Dose (D). The mean energy imparted by ionizing radiation to matter per unit mass. The conventional unit for the absorbed dose is the rad (1 rad = 100 ergs/g). The special SI unit of absorbed dose is the gray (Gy); 1 rad = 0.01 Gy.

Airborne-Radioactivity Area. Any area or enclosure in which the airborne-radioactivity concentration exceeds the concentrations specified in 10 CFR 20, Appendix B, Table I, Column I; alternatively, any area or enclosure in which the airborne-radioactivity concentration exceeds 25 percent of the concentrations specified in the above-referenced table when averaged over the number of hours in any week an individual works in the area.

As Low As Reasonably Achievable (ALARA). A philosophy which balances costs against the benefits derived to reduce radiation exposures to the lowest levels reasonably achievable, rather than to levels minimally in compliance with regulatory limits.

Becquerel (Bq). One nuclear disintegration per second; the name for the SI unit of activity. 1 Bq = 2.7×10^{-11} Ci.

Committed Dose Equivalent ($H_{T,50}$). The total dose equivalent (averaged over tissue T) deposited over the 50-year period following the intake of a radionuclide.

Committed Effective Dose Equivalent ($H_{E,50}$). The weighted sum of committed dose equivalents to specified organs and tissues, in analogy to the effective dose equivalent.

Curie (Ci). The conventional unit of activity equal to 3.7×10^{10} nuclear disintegrations per second. 1 Ci = 3.7×10^{10}Bq. Most radiation-protection (health physics) applications involve small fractions of a curie, having the following orders of magnitude: 1 millicurie (mCi) = 10^{-3} Ci. 1 microcurie (uCi) = 10^{-6} Ci. 1 picocurie (pCi) = 10^{-12} Ci = 2.22 disintegrations per minute (dmp).

Decay Product(s). A radionuclide or a series of radionuclides formed by the nuclear transformation of another radionuclide which, in this context, is referred to as the parent. The decay product will be another element possessing chemical and physical characteristics different from those of its parent; it may also be radioactive.

Decontamination. Partial or complete removal of contaminating radioactive material from structures, equipment, vehicles, or personnel levels specified in Reg. Guide 1.86 or in appropriate PADER regulations for unrestrictive use.

Dose Commitment. The annual dose equivalent. Dose-commitment limits for various types of limit exposure are specified in 10 CFR 20.

Dose Conversion Factor (DCF). The dose equivalent per unit intake of radionuclide.

Dose Equivalent (H). The product of the absorbed dose (D), the quality factor (Q), and any other modifying factors (N). The SI unit of dose equivalent is the sievert (Sv); the conventional unit is the rem (1 rem = 0.01 Sv).

Effective Dose Equivalent (H_E). The sum over specified tissues of the products of the dose equivalent in a tissue or organ (T) and the weighing factor for that tissue.

Exempt Radioactive Source. A source having a radioactivity content lower than that specified in NRC Regulation 10 CFR 20, Appendix C, or having a concentration lower than that specified in Schedule A of 10 CFR 30.70.

External Radiation. Radiations incident upon the body from an external source.

Gray (Gy). The SI unit of absorbed dose. 1Gy = 1 Joule kg^{-1} = 100 rad.

Half-Life (physical, biological, or effective). The time for a quantity of radionuclide, i.e., its activity, to diminish by a factor of a half (because of nuclear decay events, biological elimination of the material, or both).

High-Radiation Area. Any locale in which a major portion of the body can receive a dose equivalent greater than 100 mrem in a single hour.

Internal Radiation. Any radiation emitted from radionuclides distributed within the body.

Ionizing Radiation. Any radiation (electromagnetic or particulate) capable of displacing electrons from atoms or molecules and producing ions in its passage through matter.

Linear Energy Transfer (LET). A measure of the rate of energy absorption, defined as the average energy imparted to the absorbing medium by a charged particle per unit distance (KeV per um).

Nuclear Transformation. The spontaneous transformation of one radionuclide into a different nuclide or into a different energy state of the same nuclide.

Quality Factor (QF). The principal modifying factor that is employed in deriving dose equivalent, H, from absorbed dose, D; chosen to account for the relative biological effectiveness (RBE) of the radiation in question, but to be independent of the tissue or organ under consideration, and of the biological endpoint. For radiation protection purposes, the quality factor is determined by the linear energy transfer (LET) of the radiation.

Rad. The conventional unit for absorbed dose of ionizing radiation; the corresponding SI unit is the gray (Gy); 1 rad = 0.01 Gy = 0.01 Joule/kg = 100 erg/g.

Radiation Area. Any locale in which a major portion of the body can receive a dose equivalent greater than 5 mrem in a single hour or greater than 100 mrem in five consecutive days.

Radiation Exposure Rate. The intensity of the electromagnetic ionizing radiation at any given location, expressed in roentgens (R) per unit time. Exposure rates typically encountered in the natural environment have an order of magnitude of microroentgens per hour (R/hr or 10^{-6} ur/hr).

Radiation Monitoring. Periodic or continuous determination of the concentrations of ionizing radiation or radioactive contamination present in the area or on equipment or personnel.

Radiation Source. A device or material that produces ionizing radiation.

Radioactive Contamination. The deposition of radioactive material on surfaces of structures, equipment, vehicles, or personnel in concentrations that exceed the limits established in 10 CFR 20 Appendix B for unrestricted use.

Radioactive Source. A discrete amount of radioactive material, used for example, to calibrate radiation-measurement equipment or to check responses of radiation-detection instruments. Radioactive sources having activities greater than those specified in Appendix C, 10 CFR Part 20, are designated controlled sources; those having lesser activities are exempt.

Rem. An acronym of radiation equivalent man, the conventional unit of dose equivalent (1 rem = 1 rad x QF x n); the corresponding SI unit is the Sievert; 1 Sv = 100 rem.

Removable Contamination. That fraction of contamination present on a surface that can be transferred to a smear test paper or similar material by rubbing with moderate pressure.

Restricted/Unrestricted Use. Use with/without restrictions to protect against exposure to radiation, or radioactive materials, or both.

Risk Factor. The age-averaged lifetime excess cancer incidence rate per unit intake (or unit exposure for external exposure pathways) of a radionuclide.

Roentgen. That amount of ionizing electromagnetic radiation which will produce 0.258 millicoulombs of electrical charge in one kilogram of dry air at standard temperature and pressure.

Sievert (Sv). The special name for the SI unit of dose equivalent. 1 Sv = 100 rem.

Weighting Factor (w_T). Factor indicating the relative risk of cancer induction or hereditary defects from irradiation of a given tissue or organ; used to calculate effective dose equivalent and committed effective dose equivalent.

APPENDIX C

HAZARD IDENTIFICATION

The principal adverse biological effects associated with ionizing radiation exposures from radioactive substances in the environment are carcinogenicity, mutagenicity, and teratogenicity. The following provides a more detailed description of the effects of exposure to low-level radiation.

C.1 CARCINOGENESIS

An extensive body of literature exists on radiation carcinogenesis in man and animals. This literature has been reviewed most recently by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the National Academy of Sciences Advisory Committee on the Biological Effects of Ionizing Radiations (NAS-BEIR Committee) (UNSCEAR 1977, 1982, 1988; NAS 1972, 1980, 1988). Estimates of the average risk of fatal cancer from low-LET radiation from these studies range from approximately $7x10^{-6}$ to $7x10^{-4}$ fatal cancers per rem.

An increase in cancer incidence or mortality with increasing radiation dose has been demonstrated for many types of cancer in both human populations and laboratory animals (UNSCEAR 1982, 1988; NAS 1980, 1988). Studies of humans exposed to internal or external sources of ionizing radiation have shown that the incidence of cancer increases with increased radiation exposure. This increased incidence, however, is usually associated with appreciably greater doses and exposure frequencies than those encountered in the environment. Therefore, risk estimates from small doses obtained over long periods of time are determined by extrapolating the effects observed at high, acute doses. Malignant tumors in various organs most often appear long after the radiation exposure, usually 10 to 35 years later (NAS 1980, 1988; UNSCEAR 1982, 1988). Radionuclide metabolism can result in the selective deposition of certain radionuclides in specific organs or tissues, which, in turn, can result in larger radiation doses and higher-than-normal cancer risk in these organs.

Ionizing radiation can be considered pancarcinogenic; i.e., it acts as a complete carcinogen in that it serves as both initiator and promoter, and it can induce cancers in nearly any tissue or organ. Radiation-induced cancers in humans have been reported in the thyroid, female breast, lung, bone marrow (leukemia), stomach, liver, large intestine, brain, salivary glands, bone, esophagus, small intestine, urinary bladder, pancreas, rectum, lymphatic tissues, skin, pharynx, uterus, ovary, mucosa of cranial sinuses, and kidney (UNSCEAR 1977, 1982, 1988; NAS 1972, 1980, 1988). These data are taken primarily from studies of human populations exposed to high levels of radiation, including atomic bomb survivors, underground miners, radium dial painters, patients injected with thorotrast or radium, and patients who received high x-ray doses during various treatment programs. Extrapolation of these data to much lower doses is the major source of uncertainty in determining low-level radiation risks (see EPA 1989a). It is assumed that no lower threshold exists for radiation carcinogenesis.

On average, approximately 50 percent of all of the cancers induced by radiation are lethal. The fraction of fatal cancers is different for each type of cancer, ranging from about 10 percent in the case of thyroid cancer to 100 percent in the case of liver cancer (NAS 1980, 1988). Females have approximately 2 times as many total cancers as fatal cancers following radiation exposure, and males have approximately 1.5 times as many (NAS 1980).

C.2 MUTAGENESIS

Very few quantitative data are available on radiogenic mutations in humans, particularly from low-dose exposures. Some mutations are so mild they are not noticeable, while other mutagenic effects that do occur are similar to nonmutagenic effects and are therefore not necessarily recorded as mutations. The bulk of data supporting the mutagenic character of ionizing radiation comes from extensive studies of experimental animals (UNSCEAR 1977, 1982, 1988; NAS 1972, 1980, 1988). These studies have demonstrated all forms of radiation mutagenesis, including lethal mutations, translocations, inversions, nondisjunction, and point mutations. Mutation rates calculated from these studies are extrapolated to humans and form the basis for estimating the genetic impact of ionizing radiation on humans (NAS 1980, 1988; UNSCEAR 1982, 1988). The vast majority of the demonstrated mutations in human germ cells contribute to both increased mortality and illness (NAS 1980; UNSCEAR 1982). Moreover, the radiation protection community is generally in agreement that the probability of inducing genetic changes increases linearly with dose and that no "threshold" dose is required to initiate heritable damage to germ cells.

The incidence of serious genetic disease due to mutations and chromosome aberrations induced by radiation is referred to as genetic detriment. Serious genetic disease includes inherited ill health, handicaps, or disabilities. Genetic disease may be manifest at birth or may not become evident until some time in adulthood. Radiation-induced genetic detriment includes impairment of life, shortened life span, and increased hospitalization. The frequency of radiation-induced genetic impairment is relatively small in comparison with the magnitude of detriment associated with spontaneously arising genetic diseases (UNSCEAR 1982, 1988).

C.3 TERATOGENESIS

Radiation is a well-known teratogenic agent. The developing fetus is much more sensitive to radiation than the mother. The age of the fetus at the time of exposure is the most important factor in determining the extent and type of damage from radiation. The malformations produced in the embryo depend on which cells, tissues, or organs in the fetus are most actively differentiating at the time of radiation exposure. Embryos are relatively resistant to radiation-induced teratogenic effects during the later stages of their development and are most sensitive from just after implantation until the end of organogenesis (about two weeks to eight weeks after conception) (UNSCEAR 1986; Brent 1980). Effects on nervous system, skeletal system, eyes, genitalia, and skin have been noted (Brent 1980). The brain appears to be most sensitive during development of the neuroblast (these cells eventually become the nerve cells). The greatest risk of brain damage for the human fetus occurs at 8 to 15 weeks, which is the time the nervous system is undergoing the most rapid differentiation and proliferation of cells (Otake 1984).

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16. ABSTRACT

Volume II provides background information describing the major public health issues and current regulatory structure associated with radioactive materials. The document is organized into four sections. Section 1 describes the current understanding of public health risks associated with exposure to ionizing radiation. Section 2 describes methods acceptable to the Environmental Protection Agency for calculating the doses and risks from a given level of radioactive contamination in the environment. Section 3 presents a summary of radiation protection guidelines and standards, followed by a discussion of the degree of protection afforded the public under these standards. Section 4 discusses radiological and health impacts associated with waste management and presents a sample dose estimation problem.

The report concludes with appendixes which provide formal definitions of key radiation protection terms and additional descriptive information on the types of radiation and their effects. Along with the references cited in the text, a comprehensive bibliography is also provided.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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