DRINKING WATER STANDARD FOR TRITIUM—WHAT'S THE RISK?

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Abstract—**This paper presents an assessment of lifetime risks of cancer incidence associated with the drinking water standard for tritium established by the U.S. Environmental Protection Agency (USEPA); this standard is an annual-average maximum contaminant level (MCL) of 740 Bq L^{-1}. This risk assessment has several defining characteristics: (1) an accounting of uncertainty in all parameters that relate a given concentration of tritium in drinking water to lifetime risk (except the number of days of consumption of drinking water in a year and the number of years of consumption) and an accounting of correlations of uncertain parameters to obtain probability distributions that represent uncertainty in estimated lifetime risks of cancer incidence; (2) inclusion of a radiation effectiveness factor (REF) to represent an increased biological effectiveness of low-energy electrons emitted in decay of tritium compared with high-energy photons; (3) use of recent estimates of risks of cancer incidence from exposure to high-energy photons, including the dependence of risks on an individual's gender and age, in the BEIR VII report; and (4) inclusion of risks of incidence of skin cancer, principally basal cell carcinoma. By assuming ingestion of tritium in drinking water at the MCL over an average life expectancy of 80 y in females and 75 y in males, 95% credibility intervals of lifetime risks of cancer incidence obtained in this assessment are (0.35, 12) × 10^{-4} in females and (0.30, 15) × 10^{-4} in males. Mean risks, which are considered to provide the best single measure of expected risks, are about 3 × 10^{-4} in both genders. In comparison, USEPA's point estimate of the lifetime risk of cancer incidence, assuming a daily consumption of drinking water of 2 L over an average life expectancy of 75.2 y and excluding an REF for tritium and incidence of skin cancer, is 5.6 × 10^{-5}. Probability distributions of annual equivalent doses to the whole body associated with the drinking water standard for tritium also were obtained. Means and 97.5th percentiles of maximum annual doses to females and males, which occur at age <1 y, all are less than the annual equivalent dose of 40 μSv used by USEPA to establish the MCL.**
Health Phys. 101(3):274–285; 2011

Key words: risk analysis; tritium; water, drinking; uncertainty analysis

INTRODUCTION

THE PRIMARY purpose of this paper is to present an assessment of lifetime risks of cancer incidence associated with the standard to limit concentrations of tritium in drinking water established by the U.S. Environmental Protection Agency (USEPA). An assessment of cancer risks associated with this standard is of interest when substantial amounts of tritium are released routinely to surface waters in liquid effluents from nuclear power plants (U.S. NRC 2008; Makhijani and Makhijani 2009), and there have been unplanned and unmonitored releases at several reactor sites that also could impact drinking water supplies (U.S. NRC 2009). Annual equivalent doses to the whole body associated with the drinking water standard for tritium also are calculated in this assessment.

This risk assessment has several defining characteristics. First and foremost, uncertainties in lifetime risks of cancer incidence associated with the drinking water standard for tritium are estimated on the basis of assumed uncertainties in all parameters that relate a given concentration in drinking water to lifetime risk, except the two parameters that define the frequency and duration of exposures (the number of days of consumption of drinking water in a year and the number of years of consumption) and assumed correlations of uncertain parameters. This risk assessment also takes into account (1) an increased biological effectiveness of low-energy electrons (beta particles) emitted in decay of tritium in inducing cancer in humans compared with high-energy photons; (2) recent estimates of risks of cancer incidence from exposure to high-energy photons, including the dependence of risks on an individual's gender and age; and (3) risks of incidence of skin cancer, principally basal cell carcinoma.

DRINKING WATER STANDARD FOR TRITIUM

The drinking water standard for tritium is an annual-average maximum contaminant level (MCL) of 740 Bq

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(*Manuscript accepted* 12 *January* 2011)
0017-9078/11/0

DOI: 10.1097/HP.0b013e31820ff161

L^{-1}.[†] This MCL was established by USEPA in 1976 and was retained when drinking water standards for radionuclides were revised in 2000 (USEPA 2000b). The MCL for tritium was based on a limit on annual equivalent dose to the whole body of 40 μSv, an assumed daily consumption of drinking water of 2 L, and an estimate by USEPA of the equivalent dose to the whole body per unit activity of tritium ingested in water (USEPA 1977).

When drinking water standards for radionuclides were first established, USEPA estimated that the lifetime risk of fatal cancer associated with an annual equivalent dose to the whole body of 40 μSv, assuming exposure over an average life expectancy of 70 y, was 5.6×10^{-5} (USEPA 1977, 2000a). USEPA now emphasizes that lifetime risks associated with drinking water standards should not exceed about 10^{-4} (USEPA 2000a and b). USEPA's current estimate of the lifetime risk of cancer incidence associated with the MCL for tritium is discussed later in this paper.

APPROACH TO ASSESSMENT OF LIFETIME CANCER RISK

The approach to assessing lifetime risks of cancer incidence associated with USEPA's drinking water standard for tritium presented in this paper is conceptually straightforward. First, the equivalent dose to the whole body in μSv is calculated from each year's ingestion of tritium in drinking water as the product of (1) the MCL of 740 Bq L^{-1}, (2) the consumption rate of drinking water (L d^{-1}), (3) the number of days of consumption of drinking water in a year, and (4) the equivalent dose to the whole body per unit activity of tritium ingested in water (μSv Bq^{-1}). The consumption rate of drinking water depends on an individual's age and gender, and the equivalent dose per unit activity of tritium ingested in water depends on an individual's age. Calculation of equivalent dose from each year's ingestion of tritium in drinking water is of interest when the MCL was based on a limit on annual equivalent dose of 40 μSv.

The risk of cancer incidence from each year's ingestion of tritium in drinking water at the MCL is calculated by multiplying the equivalent dose to the whole body in that year in μSv by (1) a radiation effectiveness factor (REF) for tritium (unitless) and (2) the risk of cancer incidence per unit equivalent dose to the whole body (μSv^{-1}). An REF (Kocher et al. 2005) represents an assumption that the cancer risk from exposure to low-energy tritium beta particles is higher than the risk from exposure to high-energy photons, which is estimated mainly from analyses of cancer risks in Japanese atomic bomb survivors. Use of an REF to represent an increased biological effectiveness of tritium beta particles replaces the assumption of a radiation weighting factor (w_R) of 1 in calculating equivalent dose from exposure to tritium (ICRP 2007). The risk of cancer incidence per unit equivalent dose to the whole body depends on an individual's age and gender. The risk calculated in this manner is the risk to the end of life from each year's ingestion of tritium in drinking water at the MCL.

Finally, lifetime risks of cancer incidence associated with the drinking water standard for tritium are calculated by summing the risks from each year's ingestion of tritium over an average life expectancy. Lifetime risks are calculated in females and males separately.

All parameters used in calculating lifetime cancer risks are considered to be uncertain except the two parameters that define the frequency and duration of exposures. Consumption of drinking water is assumed to occur for 365 d each year (USEPA 2000a), and the average life expectancy is assumed to be 80 y in females and 75 y in males (Arias 2007). The approach used to account for uncertainty in the other parameters is described in the following section.

APPROACH TO UNCERTAINTY ANALYSIS

Each parameter used in calculating annual equivalent doses and lifetime risks of cancer incidence that is considered to be uncertain is described by a probability distribution, which is intended to represent the current state of knowledge of possible values. Probability distributions of parameters are propagated through the model equations described in the previous section to obtain probability distributions of annual dose and lifetime risk to represent their uncertainty. These calculations were carried out using Crystal Ball® software (Decisioneering 2001).[‡]

Probability distributions of annual equivalent dose and lifetime cancer risk obtained in this assessment are described in terms of a 95% credibility interval[§] and two

[†] The MCL for tritium, which is expressed by USEPA as 20,000 pCi L^{-1} using the conventional unit of activity, is specified at 40 CFR 141.66(d)(2).

[‡] Crystal Ball® generates probability distributions of model output by repeated random sampling of probability distributions of parameters in which each iteration of a calculation produces a point estimate of the output. Probability distributions of model output were generated using 10,000 sets of parameter values that were selected using Latin hypercube sampling.

[§] The term "credibility interval" is used here, rather than "confidence interval" as often used in statistical analyses of data sets, to indicate that estimation of such an interval is based to a significant degree on subjective assessments of uncertainty, rather than a rigorous statistical analysis of outcomes that might be obtained by repeated measurement if such measurements could be made. Most parameters used in estimating dose and risk are not amenable to direct measurement. The similar term "subjective confidence interval" is used to describe uncertain estimates of cancer risk in the BEIR VII report (NRC 2006).

measures of central tendency, the 50th percentile (median) and the mean. A 95% credibility interval (range of values spanned by the 2.5th and 97.5th percentiles) represents uncertainty, and the mean is considered to provide the best single measure of an expected annual dose or lifetime risk.

A potentially important consideration in assessing uncertainties in calculated lifetime cancer risks is whether values of different uncertain parameters are correlated or the value of a single uncertain parameter is correlated at different ages of an exposed individual. Several correlations of uncertain parameters are assumed in this assessment; these correlations are specified in Crystal Ball® by correlation coefficients (Decisioneering 2001).** Consideration of parameter correlations is especially important when an uncertain lifetime risk is calculated as the sum of uncertain risks from each year's ingestion of tritium in drinking water. Failure to account for important parameter correlations over multiple years of exposure can result in substantial underestimates of uncertainties in lifetime risks.

PARAMETER UNCERTAINTIES AND CORRELATIONS

Parameters that are considered to be uncertain include consumption rates of drinking water, equivalent doses to the whole body per unit activity of tritium ingested in water, the REF for tritium, and risks of cancer incidence per unit equivalent dose to the whole body. Probability distributions to represent uncertainty in consumption rates of drinking water can be based on relevant data. However, judgment is required in developing probability distributions to represent uncertainty in the other parameters. Consequently, probability distributions of annual equivalent dose and lifetime cancer risk are subjective representations of uncertainty (NCRP 1996).

Consumption rates of drinking water

Consumption rates of drinking water in females and males of different ages assumed in this assessment are based on a recent evaluation by USEPA of survey data on direct and indirect ingestion of water by consumers of community water supplies (USEPA 2004); indirect ingestion includes water added to foods and beverages during final preparation at home or by food service establishments (e.g., school cafeterias and restaurants). The survey data exclude ingestion of purchased bottled water, water in canned or bottled beverages, and water found naturally in foods. Use of data on consumers of community water supplies is considered to be appropriate for this assessment when that type of drinking water supply is the most likely to be impacted by releases of tritium to surface waters.

Percentiles and means of assumed probability distributions of consumption rates of drinking water are given in Table 1. In all age groups except the youngest, consumption rates tend to be higher in males; mean consumption rates in males and females at any age differ by about 30% or less. The consumption rate averaged over all ages and both genders of 1.0 L d^{-1} is close to the average of 1.11 L d^{-1} used in USEPA's radiation risk assessments (Eckerman et al. 1999). Uncertainties in consumption rates are large, due mainly to the low consumption rates at the lowest percentiles that presumably reflect the much greater use of bottled water or water in canned or bottled beverages by a small fraction of consumers of community water supplies.

Percentiles of consumption rates of drinking water in Table 1 are not well represented by commonly-used probability distribution functions, such as a lognormal or normal distribution. As an alternative, the uncertain consumption rate in females or males in each age group is described by a piece-wise uniform probability distribution in which the probability of any consumption rate between specified percentiles is assumed to be constant. The piece-wise uniform probability distribution of the consumption rate in females of ages 1–10 y is shown in Fig. 1. In the portion of this distribution between the 10th and 25th percentiles, for example, it is assumed that there is an equal probability of any consumption rate between 0.059 and 0.147 L d^{-1} (see Table 1), and the probability that the consumption rate is somewhere in that interval is assumed to be 15%. This scheme is applied to all intervals between specified percentiles in the probability distributions of consumption rates for females or males in each age group.

Equivalent dose to whole body per unit activity of tritium ingested in water

Estimates of equivalent dose to the whole body per unit activity of tritium ingested in water used in this assessment are effective doses per unit activity intake calculated by the International Commission on Radiological Protection (ICRP). Since tritium is uniformly distributed in the body (ICRP 1993), the equivalent dose to the whole body and the equivalent dose to all organs or tissues including skin are the same as the effective dose. Effective doses per unit activity of tritium ingested in water by members of the public currently recommended

** Crystal Ball® uses rank correlation, which provides a method of accounting for correlations that can be applied to uncertain parameters with different types of probability distributions (Decisioneering 2001). Correlation coefficients can range from +1.0, indicating a perfect positive correlation, to −1.0, indicating a perfect negative correlation; other non-zero correlation coefficients indicate a partial correlation.

Table 1. Assumed probability distributions of direct and indirect consumption rates of drinking water by females and males of different ages.[a]

	Consumption rate of drinking water (L d^{-1})							
	Age <1 y		Ages 1–10 y		Ages 11–19 y		Ages ≥20 y	
Percentile	Females	Males	Females	Males	Females	Males	Females	Males
1st	0.003	0.007	0.005	0.004	0.007	0.007	0.011	0.015
5th	0.026	0.028	0.030	0.029	0.043	0.067	0.084	0.118
10th	0.049	0.044	0.059	0.059	0.089	0.118	0.192	0.233
25th	0.158	0.118	0.147	0.152	0.220	0.299	0.494	0.563
50th	0.503	0.459	0.323	0.355	0.459	0.595	0.943	1.038
75th	0.755	0.756	0.569	0.630	0.905	1.059	1.514	1.644
90th	0.972	0.976	0.920	0.944	1.389	1.669	2.165	2.387
95th	1.122	1.171	1.123	1.154	1.774	2.056	2.711	3.016
99th	1.617	1.488	1.736	1.705	2.600	3.985	4.268	4.939
Mean	0.515	0.488	0.417	0.445	0.640	0.827	1.116	1.242
Average over all ages			0.950	1.053				

[a] Data on consumers of drinking water from community water supplies obtained from Appendix E, Part III, Table A1 of USEPA (2004). Indirect consumption includes water added to foods and beverages during final preparation at home or by food service establishments. Consumption rates exclude ingestion of purchased bottled water, water in canned or bottled beverages, and water found naturally in foods. Assumed probability distributions of consumption rates are revisions of previous recommendations by USEPA (1997) and are largely consistent with those recommendations.

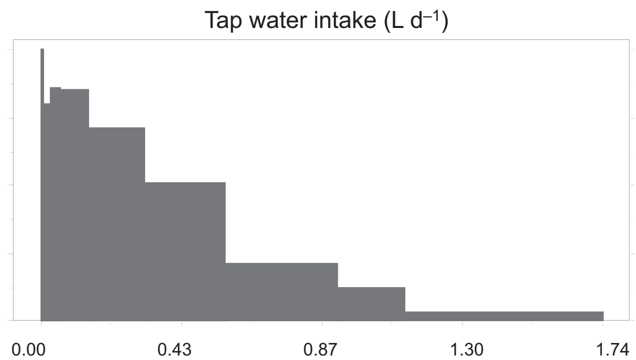

Fig. 1. Assumed piece-wise uniform probability distribution of uncertain daily consumption of drinking water by females of ages 1–10 y. Area under each step in probability distribution is proportional to difference in percentiles that define each step (see Table 1).

Table 2. Estimates by ICRP of equivalent dose to whole body per unit activity of tritium ingested in water by members of the public.[a]

Age (y)	Equivalent dose per unit activity ingested (μSv Bq^{-1})
<1	6.4×10^{-5}
1	4.8×10^{-5}
5	3.1×10^{-5}
10	2.3×10^{-5}
15	1.8×10^{-5}
Adult	1.8×10^{-5}

[a] Estimates are committed effective doses to age 70 y in females and males per unit activity of tritiated water ingested given in Table C-1.2 of ICRP (1993) and Table A.1 of ICRP (1996); due to short mean retention time of tritium in the body, dose received at any age is essentially the same as committed dose from intakes at that age. Estimates are assumed to define median values of uncertain equivalent doses per unit activity ingested.

by ICRP (1993, 1996), which apply to females and males, are given in Table 2. ICRP's estimates are assumed to define median values of uncertain equivalent doses to the whole body per unit activity of tritium ingested in water. These estimates decrease with increasing age to age 15 y and are independent of age thereafter. Values at ages between 1 and 15 y not listed in Table 2 are estimated using linear interpolation between values at the next lowest and next highest ages.

The uncertainty in effective doses per unit activity intake of tritium calculated by ICRP has been evaluated by the National Council on Radiation Protection and Measurements (NCRP 1998). Similar evaluations were reported by Harrison et al. (2002) and Melintescu et al. (2007). Consistent with the conclusion by NCRP (1998) that calculated equivalent doses to the whole body per unit activity of tritium ingested in water have an uncertainty of a factor of about two, the uncertainty in the equivalent dose to the whole body per unit activity of tritium ingested in water at any age is represented by a lognormal probability distribution with a median at the value obtained from Table 2 and a 90% credibility interval between one-half and two times the median. The 95% credibility interval of this distribution ranges from a factor of 2.3 below to a factor of 2.3 above the median, and the mean is a factor of 1.09 greater than the median.

Radiation effectiveness factor (REF) for tritium

Two sets of calculations of cancer risk are performed in this assessment, one set assuming that tritium beta particles have the same biological effectiveness as high-energy photons and the other set assuming a greater biological effectiveness of tritium beta particles, as suggested by many radiobiological studies. The first set of calculations conforms to the assumption about biological effectiveness used in most radiation risk assessments, including USEPA's current risk assessments (Eckerman et al. 1999).

The second set of calculations, which better represent the current state of knowledge of cancer risks from exposure to tritium, includes an assumption about the biological effectiveness of tritium beta particles that has been used by the National Institute for Occupational Safety and Health (NIOSH) and U.S. Department of Labor in a compensation program for energy workers who develop cancers that might have been caused by exposure to ionizing radiation (USDHHS 2002; Land et al. 2003). In these calculations, an increase in cancer risk from exposure to tritium beta particles compared with the risk from exposure to high-energy photons is represented by the probability distribution of the REF for electrons of energy $<$15 keV developed by Kocher et al. (2005). The REF for tritium is represented by a lognormal probability distribution with a 95% credibility interval of (1.2, 5.0); the median of this distribution is 2.45, and the mean is 2.6.[††]

Risks of cancer incidence per unit equivalent dose to whole body

Two sets of calculations of lifetime risks of cancer incidence were performed in this assessment, one set for incidence of all cancers excluding skin cancer, and the other set including incidence of skin cancer. Calculations that exclude incidence of skin cancer conform to the usual practice in radiation risk assessments, including USEPA's current risk assessments (Eckerman et al. 1999).[‡‡] Neglect of incidence of skin cancer has been based on two considerations: (1) basal cell carcinoma is the only type of skin cancer known to be induced by low doses of ionizing radiation (Ron et al. 1998; Preston et al. 2007), and (2) basal cell carcinoma is rarely fatal, is easily treated, and rarely causes significant disfigurement when diagnosed and treated early (i.e., this type of cancer has far less serious health consequences than other cancers). Calculations that include the risk of incidence of skin cancer, which better represent the current state of knowledge of risks of all cancers, are consistent with a policy in compensation programs for energy workers or military participants at above-ground nuclear weapons tests that basal cell carcinoma is a compensable disease if the dose to skin is sufficiently high (USDHHS 2002; U.S. DVA 2010).

Estimates of risks of cancer incidence per unit equivalent dose to the whole body for all cancers excluding skin cancer and for skin cancer only used in this assessment are given in Table 3. These estimates are assumed to define median values of uncertain cancer risks per unit equivalent dose. When skin cancer is excluded, risks of cancer incidence in males are lower than in females at all ages, and risks in males and females differ by nearly a factor of two at the youngest ages. In contrast, risks of incidence of skin cancer are about 40–60% higher in males than in females at all ages. Estimated risks in Table 3 and their uncertainties are described below.

Risks of all cancers excluding skin cancer. Estimates of risks of cancer incidence per unit equivalent dose to the whole body for all cancers excluding skin cancer in Table 3 were obtained from the recent analysis of epidemiologic data in the BEIR VII report (NRC 2006, Table 12D-1). These estimates were based primarily on data in Japanese atomic bomb survivors who were exposed mainly to high-energy photons.

Table 3. Estimates of risks of cancer incidence per unit equivalent dose to whole body in females and males exposed at different ages.[a]

Age at exposure (y)	Risk of cancer incidence per unit equivalent dose (μSv^{-1})			
	All cancers excluding skin cancer[b]		Skin cancer only[c]	
	Females	Males	Females	Males
0	4.78×10^{-7}	2.56×10^{-7}	3.06×10^{-7}	4.29×10^{-7}
5	3.38×10^{-7}	1.82×10^{-7}	3.09×10^{-7}	4.32×10^{-7}
10	2.61×10^{-7}	1.45×10^{-7}	3.09×10^{-7}	4.32×10^{-7}
15	2.06×10^{-7}	1.18×10^{-7}	1.55×10^{-7}	2.19×10^{-7}
20	1.65×10^{-7}	9.77×10^{-8}	7.85×10^{-8}	1.24×10^{-7}
30	1.07×10^{-7}	6.86×10^{-8}	1.87×10^{-8}	2.68×10^{-8}
40	8.86×10^{-8}	6.48×10^{-8}	4.23×10^{-9}	6.27×10^{-9}
50	7.40×10^{-8}	5.91×10^{-8}	3.62×10^{-9}	5.40×10^{-9}
60	5.86×10^{-8}	4.89×10^{-8}	2.73×10^{-9}	4.06×10^{-9}
70	4.09×10^{-8}	3.43×10^{-8}	1.65×10^{-9}	2.24×10^{-9}
80	2.14×10^{-8}	1.74×10^{-8}	1.65×10^{-9}	2.24×10^{-9}

[a] Estimates are assumed to define median values of uncertain risks per unit equivalent dose.
[b] Estimates obtained from Table 12D-1 of USNRC (2006).
[c] Estimates for basal cell carcinoma obtained from Land et al. (2003) and Preston et al. (2007) as described in text. Nearly constant risks at ages 0–10 y are artifact of combining data in all atomic bomb survivors in that age group in developing risk model for basal cell carcinoma in Land et al. (2003). Risks probably are underestimated at age 0 and overestimated at age 10 y.

[††] An increase in biological effectiveness of tritium beta particles by a factor of two was recently recommended for use in epidemiologic studies and retrospective risk assessments by the U.K.'s Advisory Group on Ionising Radiation (AGIR 2007). That recommendation is consistent with the REF developed by Kocher et al. (2005), except it does not account for uncertainty.

[‡‡] USEPA's current estimate of the risk of cancer incidence from uniform irradiation of the whole body in a population of all ages and both genders includes a very small contribution from fatal skin cancers of only about 0.12% of the risk of incidence of all cancers (Eckerman et al. 1999), but USEPA's risk estimate does not include the much larger contribution from incidence of skin cancer, which is about 500 times the risk of fatal skin cancers (ICRP 2007).

The assumed uncertainty in estimated risks of cancer incidence per unit equivalent dose for all cancers excluding skin cancer is based on 95% subjective confidence intervals of risks of incidence of solid cancers and leukemia separately from exposure of females or males in a population of all ages given in the BEIR VII report (NRC 2006, Table 12-13); the risk of leukemia is about 5% of the risk of all cancers excluding skin cancer in females and about 10% in males. By adding the uncertain risks per unit equivalent dose for solid cancers and leukemia given in the BEIR VII report, the 95% credibility interval of the risk excluding skin cancer in females or males ranges from a factor of about two below the central estimate to a factor of about two above. This uncertainty is assumed to apply to estimated risks at any age. The uncertainty in the risk per unit equivalent dose to the whole body for incidence of all cancers excluding skin cancer is represented by a lognormal probability distribution with a 95% credibility interval between one-half and two times the median values in Table 3. Means of these distributions are a factor of 1.06 greater than the medians.

Risks of skin cancer. The BEIR VII report (NRC 2006) does not include incidence of non-melanoma skin cancer, principally basal cell carcinoma, in its estimates of risk per unit equivalent dose for incidence of all solid cancers. Estimates of the risk of incidence of skin cancer per unit equivalent dose and their uncertainty used in this assessment are based on risks of basal cell carcinoma incorporated in the Interactive RadioEpidemiological Program (IREP) (Land et al. 2003; Kocher et al. 2008) and a more recent analysis of risks of incidence of basal cell carcinoma in Japanese atomic bomb survivors (Preston et al. 2007). IREP is used in compensation programs for energy workers or military participants in above-ground nuclear weapons tests to estimate the probability that diagnosed cancers in individuals were caused by exposure to ionizing radiation (USDHHS 2002; Mansfield 2005).

The recent analysis of risks of incidence of basal cell carcinoma in atomic bomb survivors by Preston et al. (2007) indicates that estimates of risk in IREP, which were based on a previous analysis of data in atomic bomb survivors (Ron et al. 1998), are too high at low doses by a factor of about 3.4. Therefore, estimates of risks of incidence of skin cancer per unit equivalent dose in females or males of different ages assumed in this assessment were obtained by dividing estimates for basal cell carcinoma obtained from IREP by that factor. The resulting median risks of incidence of skin cancer per unit equivalent dose are the values in Table 3.

On the basis of uncertainties in risks of basal cell carcinoma calculated in IREP (Land et al. 2003), the uncertainty in risks of incidence of skin cancer per unit equivalent dose is assumed to be a factor of 12 in females and males of all ages.[§§] This uncertainty is represented by a lognormal probability distribution with a 95% credibility interval between 1/12th and 12 times the median risks in Table 3. Means of these distributions are a factor of 2.2 greater than the medians. Given the uncertainties in other parameters used in calculating lifetime risks of cancer incidence from ingestion of tritium in drinking water described above, the large uncertainty in risks per unit equivalent dose for incidence of skin cancer is important whenever the risk of skin cancer contributes significantly to the risk of all cancers.

Dependence of risks on age. Estimates in Table 3 indicate that risks of cancer incidence per unit equivalent dose are highest in infants and decrease with increasing age at the time of exposure. The nearly constant risks of skin cancer at ages 0–10 y are an artifact of combining data in all atomic bomb survivors in that age group in developing the risk model for basal cell carcinoma incorporated in IREP (Land et al. 2003). As a result of this aggregation of data over a range of ages, risks of skin cancer probably are overestimated at ages approaching 10 y and underestimated at the youngest ages.

At younger ages, decreases in cancer risk per unit equivalent dose with increasing age are due mainly to decreases in susceptibility to radiation-induced cancer. In older adults, increases in the probability of death from all other causes also are important in reducing cancer risks with increasing age (Eckerman et al. 1999). Beyond age 10 y, risks of skin cancer per unit equivalent dose decrease more rapidly with increasing age than risks of all other cancers combined.

Cancer risks per unit equivalent dose at ages not listed in Table 3 are estimated using linear interpolation between values at the next lowest and next highest ages.

Importance of risk of incidence of skin cancer. Estimates in Table 3 indicate that the risk of incidence of skin cancer is an important contributor to the risk of incidence of all cancers at younger ages. The importance of skin cancer is indicated in Table 4, which gives the fraction of the risk of incidence of all cancers from uniform irradiation of the whole body that is attributable

[§§] This uncertainty takes into account uncertainties in estimated risks of basal cell carcinoma per unit equivalent dose in Japanese atomic bomb survivors at ages 0–10, 20 and 30 y, when risks of skin cancer are a substantial fraction of the risk of incidence of all cancers (see Table 3) and a larger uncertainty in transferring estimated risks of basal cell carcinoma in a Japanese population to a U.S. population.

Table 4. Fractions of risk of incidence of all cancers from uniform irradiation of whole body attributable to skin cancer in females and males exposed at different ages.[a]

Age at exposure (y)	Fraction of total cancer risk attributable to skin cancer[b]	
	Females	Males
0	0.39	0.63
5	0.48	0.70
10	0.54	0.75
15	0.43	0.65
20	0.32	0.56
30	0.15	0.28
40	0.046	0.088
50	0.047	0.084
60	0.045	0.077
70	0.039	0.061
80	0.072	0.11

[a] Fractions are calculated from risks of cancer incidence per unit equivalent dose for all cancers excluding skin cancer and for skin cancer only in Table 3.
[b] Contributions from skin cancer probably are underestimated at age 0 and overestimated at age 10 (see text and Table 3, footnote c).

to skin cancer at different ages. The risk of skin cancer is a substantial contributor to the risk of all cancers at ages between 0 and about 30 y but is only a minor contributor at ages 40 y and higher. In males of age about 20 y or less and females of age near 10 y or less, more than half the risk of all cancers from exposure to ionizing radiation is attributable to skin cancer.

When uncertainties in risks per unit equivalent dose for incidence of all cancers excluding skin cancer and for incidence of skin cancer only discussed previously are taken into account, estimates in Tables 3 and 4 indicate that the uncertainty in the risk of skin cancer is an important contributor to the uncertainty in the risk of all cancers from ingestion of tritium in drinking water at ages between 0 and about 30 y but is a lesser contributor to the uncertainty in estimated risks at ages beyond about 30 y.

Parameter correlations

Several uncertain parameters used in calculating lifetime cancer risks from ingestion of tritium in drinking water are assumed to be correlated:

- The equivalent dose to the whole body per unit activity of tritium ingested in water is assumed to be perfectly correlated at all ages (correlation coefficient of +1.0);
- The risk of cancer incidence, either all cancers excluding skin cancer or skin cancer only, per unit equivalent dose is assumed to be perfectly correlated at all ages; and
- The consumption rate of drinking water is assumed to be partially correlated from one age (y) to the next. A correlation coefficient of +0.9 (close to a perfect correlation) between the consumption rates at a particular age and the previous age is assumed.

The first two correlations are based on assumptions that the biokinetic behavior of tritium in the body of an individual and the susceptibility of an individual to radiation-induced cancer would differ from average conditions in a population by the same amount at all ages. A partial, rather than perfect, correlation of the consumption rate of drinking water at successive ages is justified on the grounds that it is highly unlikely that an individual's water consumption at each age would never vary relative to the average water consumption in a population. As noted previously, inclusion of these parameter correlations is important in ensuring that uncertainties in lifetime cancer risks that are calculated by summing uncertain risks from each year's ingestion of tritium in drinking water are not underestimated.

Two parameters are assumed to be uncorrelated: the risk per unit equivalent dose for incidence of all cancers excluding skin cancer and the risk of skin cancer only in females or males of a given age. The assumption that possible values of those two risks are unrelated is based on evidence that the risk of basal cell carcinoma from exposure to ionizing radiation is influenced by the risk of that cancer type from exposure to ultraviolet radiation in sunlight (NRC 1990) and the absence of such a relationship for other types of cancer. Since the uncertainty in the risk of skin cancer per unit equivalent dose is much greater than the uncertainty in the risk of all other cancers, an assumption of a positive correlation between the two risks would not have a large effect on uncertainties in risks of all cancers combined.

RESULTS OF ASSESSMENTS

Maximum annual dose equivalents and lifetime risks of cancer incidence associated with the drinking water standard for tritium obtained in this assessment are presented in the following sections. Probability distributions of doses and risks are based on assumed probability distributions of uncertain parameters and their correlations discussed above and fixed values of the two parameters that define the frequency and duration of exposures noted previously.

Maximum annual equivalent doses to whole body

Probability distributions of maximum annual equivalent doses to the whole body from consumption of drinking water containing tritium at the MCL of 740 Bq L^{-1} obtained in this assessment are summarized in Table 5. Maximum annual doses occur at age <1 y in females and males. The annual dose is lower at ages 1 y and higher when (1) the equivalent dose per unit activity of tritium ingested in water decreases with increasing age to age 15 y (see Table 2), (2) consumption rates of drinking

Table 5. Summary of probability distributions of maximum annual equivalent doses to whole body from consumption of drinking water containing tritium at MCL of 740 Bq L^{-1}.

	Maximum annual equivalent dose (μSv)[a]			
Gender	2.5th percentile	50th percentile	Mean	97.5th percentile
Females	0.18	7.7	9.4	30
Males	0.24	7.1	9.0	30

[a] Maximum occurs at age <1 y in both genders. Mean annual equivalent doses are about 30–55% lower at ages 1 y and higher.

water are slightly lower at ages 1–10 y than at age <1 y (see Table 1), and (3) increases in consumption rates of drinking water at ages 11 y and higher are less than decreases in the equivalent dose per unit activity ingested in water at ages 1–15 y. For example, mean annual equivalent doses in females at ages 1, 11 and ≥20 y are 5.8, 4.0 and 5.8 μSv, respectively, and the corresponding mean doses in males are 6.2, 5.0, and 6.4 μSv.

The uncertainty in the maximum annual equivalent dose, as represented by the ratio of the 97.5th to the 2.5th percentile, is a factor of about 170 in females and 125 in males. These uncertainties are due almost entirely to the large uncertainties in consumption rates of drinking water at age <1 y, as indicated in Table 1.

Means and 97.5th percentiles of maximum annual equivalent doses in Table 5 are less than the drinking water standard of 40 μSv used by USEPA to derive the MCL for tritium. USEPA would calculate a maximum annual dose by assuming a daily consumption of drinking water of 2 L (USEPA 2000a) and the equivalent dose per unit activity of tritium ingested in water for an adult in Table 2. The equivalent dose of 9.7 μSv so obtained is slightly higher than mean equivalent doses in Table 5 but is a factor of about three less than the 95th percentiles.***

Risks of cancer incidence from exposure over average life expectancy

Probability distributions of lifetime risks of cancer incidence in females and males from consumption of drinking water containing tritium at the MCL of 740 Bq L^{-1} obtained in this assessment, assuming exposure over an average life expectancy, are summarized in Table 6. Two sets of results are presented in which the REF for tritium and risks of incident skin cancer are excluded or included. The first set of results is consistent with assumptions used in USEPA's current radiation risk assessments (Eckerman et al. 1999). Calculations that include the REF for tritium and incidence of skin cancer are considered to provide the best representation of the current state of knowledge of lifetime risks of cancer incidence associated with USEPA's drinking water standard for tritium.

When the REF for tritium and risk of skin cancer are excluded, mean lifetime risks of cancer incidence in females and males are less than USEPA's objective of limiting lifetime risks from ingestion of radionuclides in drinking water to no more than about 10^{-4} (USEPA 2000a and b), whereas the 97.5th percentiles are slightly greater than the risk objective. USEPA considers that lifetime cancer risks somewhat greater than 1×10^{-4} (i.e., risks up to about 2×10^{-4}) from ingestion of radionuclides in drinking water are acceptable (USEPA 2000a).

When the REF for tritium and risk of incidence of skin cancer are included, 95% credibility intervals of lifetime risks of cancer incidence associated with USEPA's drinking water standard for tritium are $(0.35, 12) \times 10^{-4}$ in females and $(0.30, 15) \times 10^{-4}$ in males, and mean lifetime risks are 2.9×10^{-4} in females and 3.3×10^{-4} in males.††† The ratio of the 97.5th to the 2.5th percentile to represent uncertainty is a factor of 34 in females and 50 in males. The smaller uncertainties in lifetime cancer risks compared with uncertainties in maximum annual equivalent doses indicated in Table 5 and discussed previously are a consequence of adding uncertain risks at each age that are not perfectly correlated. Uncertainties in consumption rates of drinking water and risks of incidence of skin cancer are the most important. These results are compared with an estimate obtained on the basis of assumptions used by USEPA in a later section.

Inclusion of the REF for tritium and risks of incidence of skin cancer increases mean risks by a factor of 5.2 in females and 8.5 in males. In females, including the REF for tritium increases the risk by slightly more than including the risk of skin cancer, whereas in males,

*** The annual equivalent dose calculated on the basis of assumptions used by USEPA is a factor of about five less than the annual equivalent dose of 40 μSv that USEPA used to derive the MCL for tritium in drinking water. This reduction is a consequence of differences in internal dosimetry models for tritium currently recommended by ICRP (1993) compared with assumptions in models used by USEPA when the MCL was established (USEPA 1977).

††† Recent modifications of risk models in the BEIR VII report (NRC 2006) by Berrington de Gonzalez et al. (2009) resulted in increases in mean lifetime risks of incidence of all cancers excluding skin cancer from exposure at ages 0 to 70 y of about 20% in females and 40% in males. Modifications of the BEIR VII models included (1) use of an arithmetic-weighted averaging of multiplicative and additive models for transfer of risks from Japanese atomic bomb survivors to the U.S. population similar to the approach in IREP (Land et al. 2003; Kocher et al. 2008), rather than the geometric-weighted averaging used in the BEIR VII report; (2) an updating of baseline cancer risks in the U.S. population; (3) inclusion of risk estimates for eight additional cancer sites; and (4) calculation of risks for a redefined residual organ category. If these increases were taken into account, estimates of mean lifetime risks of incidence of all cancers including skin cancer associated with USEPA's drinking water standard for tritium would increase by about 10% in females and less than 15% in males.

Table 6. Summary of probability distributions of lifetime risks of cancer incidence from consumption of drinking water containing tritium at MCL of 740 Bq L^{-1} over average life expectancy.[a]

Case	Gender[b]	Lifetime risk of cancer incidence			
		2.5th percentile	50th percentile	Mean	97.5th percentile
All cancers excluding skin cancer;	F	1.2×10^{-5}	4.6×10^{-5}	5.6×10^{-5}	1.6×10^{-4}
REF for tritium not included	M	8.2×10^{-6}	3.1×10^{-5}	3.9×10^{-5}	1.1×10^{-4}
All cancers including skin cancer;	F	3.5×10^{-5}	1.9×10^{-4}	2.9×10^{-4}	1.2×10^{-3}
REF for tritium included[c]	M	3.0×10^{-5}	1.8×10^{-4}	3.3×10^{-4}	1.5×10^{-3}

[a] Average life expectancy is assumed to be 80 y in females and 75 y in males (Arias 2007).
[b] F = females; M = males.
[c] Preferred results of this assessment. When incidence of skin cancer and REF for tritium are included, results are considered to best represent current state of knowledge of lifetime risks of cancer incidence associated with drinking water standard for tritium.

including the risk of skin cancer has a slightly greater effect. This difference is a consequence of the greater importance of the risk of skin cancer relative to the risk of all other cancers at younger ages in males than in females (see Table 3).

Fractions of lifetime risks attributable to exposure at different ages

Estimates in Tables 1–3 indicate that cancer risks from consumption of tritium in drinking water at a constant concentration are highest at the youngest ages and decrease with increasing age. To investigate this effect, exposure at ages 0–10, 11–20, 21–30 y, etc., up to an average life expectancy was assumed and mean risks in each age group were compared. Results of these calculations are presented in Table 7 as fractions of the mean lifetime risks from ingestion of tritium in drinking water at a constant concentration over an average life expectancy that are attributable to exposure at different ages. Results of calculations that exclude and include risks of skin cancer are presented separately. All calculations include the REF for tritium, but the results in Table 7 would not change substantially if the REF were excluded, given that this factor is independent of age. Results at ages 0–10 y are not affected by the aggregation of data on incidence of basal cell carcinoma in all atomic bomb survivors in that age group noted previously.

Table 7. Fractions of mean lifetime risks of cancer incidence from ingestion of tritium in drinking water at constant concentration over average life expectancy attributable to intakes at different ages.[a]

Age (y)	Fraction excluding skin cancer		Fraction including skin cancer	
	Females	Males	Females	Males
0–10	0.35	0.29	0.48	0.47
11–20	0.14	0.15	0.19	0.23
21–30	0.15	0.14	0.13	0.13
31–40	0.11	0.12	0.067	0.055
41–50	0.089	0.11	0.049	0.041
51–60	0.072	0.095	0.040	0.035
61–70	0.054	0.073	0.030	0.026
71–80[b]	0.034	0.026	0.019	0.009

[a] Mean lifetime risks of cancer incidence from ingestion of tritium in drinking water over average life expectancy are values including REF for tritium in Table 6. Estimates are not substantially different if REF for tritium is not included.
[b] Ages in females; this group in males includes ages 71–75 y.

Results in Table 7 indicate that most of the lifetime risk from ingestion of tritium in drinking water at a constant concentration is attributable to exposures during the first few decades of life. If skin cancer is excluded, slightly less than half the lifetime risk is attributable to exposures at ages 0–20 y; but if skin cancer is included, about 60% of the lifetime risk in females and 70% of the lifetime risk in males is attributable to exposures at those ages. The higher fractions of lifetime risks that are attributable to exposures at younger ages when skin cancer is included are a consequence of the more pronounced decreases in risks of skin cancer per unit equivalent dose beyond age 10 y compared with decreases in risks of all other cancers at those ages (see Table 3). The fraction of the lifetime risk attributable to exposures beyond age 30 y ranges from 0.17 in males if skin cancer is included to 0.42 in males if skin cancer is excluded.

The age-dependence of risks indicated in Table 7 is potentially important when long-term exposure to tritium in a particular community water supply is assumed to occur and the objective of a risk assessment is to estimate lifetime risks to members of the community, most of whom would not spend their entire lives in the area covered by that supply. For example, when incidence of skin cancer is included, an assumption of exposure over an average life expectancy would not greatly overestimate risks to individuals who spend only the first 2–3 decades of life residing in an area covered by a particular community water supply.

Comparison with lifetime risk based on USEPA's assumptions

USEPA estimates lifetime cancer risks associated with drinking water standards for radionuclides on the basis of estimates of the risk per unit activity ingested in drinking water given in Federal Guidance Report No. 13 (Eckerman et al. 1999; USEPA 2000a). Those estimates are average risks in a population of all ages and both genders; average risks are the same as risks to an adult of age about 30–35 y. USEPA's estimates of cancer risks per unit activity of tritium ingested in drinking water take into account the dependence of average consumption rates of drinking water on age and gender, and they incorporate the same equivalent doses to the whole body per unit activity ingested at different ages used in this assessment (see Table 2). However, as noted previously, risks of cancer incidence per unit equivalent dose to the whole body in females and males at different ages used by USEPA do not include incidence of skin cancer. In addition, risks of incidence of all other cancers used by USEPA are somewhat less than median risks excluding skin cancer used in this assessment (see Table 3).[‡‡‡]

The risk of cancer incidence per unit activity of tritium ingested in drinking water estimated by USEPA is 1.37×10^{-12} Bq^{-1} (Eckerman et al. 1999); the risk of fatal cancer, which has been emphasized by USEPA (2000a), is 9.44×10^{-13} Bq^{-1}. Using USEPA's assumptions of a daily consumption of drinking water of 2 L for 365 d each year and an average life expectancy of 75.2 y (Eckerman et al. 1999; USEPA 2000a), the lifetime risk of cancer incidence from ingestion of tritium in drinking water at the MCL of 740 Bq L^{-1} estimated by USEPA is 5.6×10^{-5}. This estimate is intended to represent the mean risk to a reasonably maximally exposed individual, as defined by the assumed consumption rate of drinking water and duration of exposures, rather than an upper credibility limit (e.g., 97.5^{th} percentile). USEPA's estimate is about a factor of two less than its objective of limiting the lifetime risk from ingestion of radionuclides in drinking water to no more than about 10^{-4}.

Results in Table 6 that conform to assumptions used to obtain USEPA's estimate of the lifetime risk of cancer incidence given above are results that exclude the REF for tritium and incidence of skin cancer. In that case, the estimated mean risk in females is the same as USEPA's estimate, the estimated mean risk in males is about 30% less than USEPA's estimate, and the 97.5^{th} percentiles exceed USEPA's estimate by a factor of three in females and two in males. Similarities between estimates in Table 6 and USEPA's in this case are mainly a consequence of the compensating effects of the lower average daily consumption of drinking water at different ages assumed in the present assessment (see Table 1), compared with USEPA's assumption of 2 L, and the higher risks of incidence of all cancers excluding skin cancer per unit equivalent dose at any age assumed in this assessment.

When the REF for tritium and incidence of skin cancer are included, mean risks obtained in this assessment exceed USEPA's estimate by a factor of about five in females and six in males, and the 97.5^{th} percentiles exceed USEPA's estimate by a factor of about 20 in females and more than 25 in males. Mean risks are the results that are most comparable to USEPA's estimate of the risk to a reasonably maximally exposed individual.

[‡‡‡] USEPA's current estimate of the risk of cancer incidence, excluding skin cancer, per unit equivalent dose to the whole body in a U.S. population of all ages and both genders is 8.45×10^{-8} μSv^{-1} (Eckerman et al. 1999). Estimated risks in Table 3 that exclude skin cancer correspond to a median risk of cancer incidence in a U.S. population of all ages and both genders of 1.14×10^{-7} μSv^{-1} (NRC 2006; Table 12–13). The increase in risk by 35% compared with USEPA's estimate is mainly a consequence of a difference in the dose and dose-rate effectiveness factor (DDREF) used to extrapolate observed risks in Japanese atomic bomb survivors to lower doses and dose rates. A DDREF with a central estimate of 1.5 was used in the BEIR VII report, whereas USEPA used a DDREF of one for breast cancer and two for all other cancers. A small increase in the risk, excluding skin cancer, per unit equivalent dose to the whole body in atomic bomb survivors is a lesser contributor to the increase in the risk per unit equivalent dose in a U.S. population compared with USEPA's estimate.

CONCLUSION

This paper has presented an assessment of lifetime risks of cancer incidence associated with USEPA's drinking water standard for tritium that takes into account an increased biological effectiveness of beta particles emitted in decay of tritium compared with high-energy photons, as represented by an REF, and the risk of incidence of skin cancer. By accounting for uncertainties in all parameters used in calculating lifetime risks except parameters that define the frequency and duration of exposures, probability distributions that represent uncertainties in estimated lifetime risks are obtained.

The 95% credibility intervals of lifetime risks of cancer incidence, assuming exposure over an average life expectancy, from ingestion of drinking water containing tritium at the MCL of 740 Bq L^{-1} are $(0.35, 12) \times 10^{-4}$ in females and $(0.30, 15) \times 10^{-4}$ in males. These credibility intervals are intended to represent the current state of knowledge of lifetime cancer risks associated with USEPA's drinking water standard for tritium. Uncertainties in estimated risks are due primarily to the large uncertainties in consumption rates of drinking water and risks of incidence of skin cancer per unit equivalent dose. Mean risks, which are considered to provide the best single measure of expected risks, are about 3×10^{-4} in both genders. Mean risks are higher by a factor of about five in females and eight in males than mean risks obtained in this assessment by excluding the REF for tritium and risks of incidence of skin cancer.

Probability distributions of annual equivalent doses to the whole body also were obtained in this assessment. Maximum annual doses occur at age <1 y in females and males. Means and 97.5th percentiles of the maximum annual equivalent doses are less than USEPA's drinking water standard of 40 μSv that was used to establish the MCL for tritium.

Results obtained in this assessment should greatly exceed actual risks to the public from ingestion of tritium in drinking water. In many drinking water supplies that are impacted by releases from nuclear power plants, concentrations of tritium are comparable to or less than the detection limit of 37 Bq L^{-1} specified by USEPA[§§§] and rarely exceed a small fraction of the MCL (U.S. NRC 2008; Makhijani and Makhijani 2009). If long-term average concentrations were maintained at levels less than the detection limit, for example, mean lifetime risks in females and males estimated in this assessment would be less than 2×10^{-5}, and upper 97.5% credibility limits would be less than 6×10^{-5} in females and 8×10^{-5} in males. Even at an upper credibility limit, estimated lifetime risks would be less than USEPA's objective of no more than about 10^{-4}.

The approach to risk assessment of fully accounting for uncertainty and including the REF for tritium and risks of incidence of skin cancer presented in this paper differs from the usual approach in radiation risk assessment, including USEPA's assessment of risks associated with its drinking water standards. This approach can be justified on several grounds.

First, the usual assumption that tritium beta particles and high-energy photons are equally effective in inducing cancer in humans is not supported by an extensive body of radiobiological information. Although there is considerable uncertainty in an REF for tritium beta particles, and there is even some uncertainty about whether there is an increase in biological effectiveness when direct evidence obtained from epidemiologic studies is lacking, the current state of knowledge clearly includes the possibility of an increased biological effectiveness of tritium beta particles. Given the weight of evidence, it is not reasonable to assume the same biological effectiveness of tritium beta particles and high-energy photons with no uncertainty for purposes of regulatory decision making or retrospective assessments of risks to exposed individuals.

Second, full disclosure of information on risks from radiation exposure requires that, at a minimum, risks of incidence of skin cancer be included along with risk estimates that exclude incidence of skin cancer. The question of how incidence of skin cancer should be taken into account in regulatory decision making is a legitimate subject of debate when almost all skin cancers have significantly less severe health consequences for most affected individuals than other cancers. However, this question cannot be addressed in an open and transparent manner unless risks of incidence of skin cancer are included as a part of risk assessments.

Finally, full disclosure of uncertainty in risk assessments is important for purposes of regulatory decision making as well as evaluating health impacts of actual exposures. As emphasized by ICRP (2005) and Land (2009), implementation of radiation protection programs is a political process that must accommodate different interests and viewpoints of affected stakeholders. For example, stakeholders who are risk-averse may focus on an upper credibility limit of risk, whereas stakeholders who are concerned primarily with costs of controlling exposures may focus on a lower credibility limit. A fair and open process of developing and implementing radiation protection policies in a manner that achieves informed consent is greatly facilitated by full disclosure of information. Quantitative uncertainty analysis of the kind described in this paper is the only means of fully disclosing the state of knowledge of risks from exposure to ionizing radiation.

[§§§] The detection limit for tritium in drinking water, which is expressed by USEPA as 1,000 pCi L^{-1}, is specified at 40 CFR 141.25(c)(2).

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