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The Estimate of Excess Lifetime Risk of Cancer Incidence Associated with Discrete Routine Releases of Tritiated Water Vapor (HTO) from the National Tritium Labelling Facility at Lawrence Berkeley National Laboratory

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1.0 EXECUTIVE SUMMARY

This assessment evaluates the radiation dose and excess lifetime risk of cancer incidence to an individual exposed to short-term routine releases of tritiated water vapor (HTO) from the National Tritium Labelling Facility (NTLF) at the Lawrence Berkeley National Laboratory (LBNL). Estimates of risk from annual releases have been made in the past for the LBNL site; however, concerns have been raised suggesting that annual-averaged emissions may not reflect risks that occur from incidental exposures to short-term emissions.

Excess lifetime risks of cancer incidence have been estimated for three scenarios. These scenarios include typical, reasonable maximum, and hypothetical extreme exposure situations for children visiting the Lawrence Hall of Science (LHS) and for an adult exercising vigorously near the Building 75 hillside stack. In all cases, the excess lifetime cancer risks resulting from exposure to short-term routine releases of HTO are exceedingly small (fractions of one chance in one million).

The exposures from all scenarios are far below dose and risk limits established for the protection of public health and far below levels of exposure that could result in detected excess health effects in epidemiological investigations. The health risks calculated for all of the scenarios considered in this analysis would be difficult to distinguish from zero. This conclusion is based on the small magnitude of exposures and risks and the low number of individuals likely exposed. This conclusion is also influenced by the small likelihood that a visit to the LHS or surrounding area will coincide with a short-term routine release at the time winds were blowing from the direction of the Building 75 hillside stack.

The results in this report are consistent with previous Berkeley Lab reports and dose estimates (i.e. Site Environmental Report, CAP88-PC annual dose modeling) which have indicated that tritium exposures, doses, and health risks at LHS are very low.

2.0 INTRODUCTION

The purpose of this assessment is to evaluate the potential exposure and risk to an individual from short-term routine releases of tritiated water vapor (HTO) from the National Tritium Labelling Facility (NTLF) at the Lawrence Berkeley National Laboratory (LBNL) using a meteorological model (CALPUFF) that is appropriate for complex terrain and discrete release events (Scire et al., 1999).

The CALPUFF modeling system has been applied to assessing the long-term (i.e., annual) impact from ongoing routine releases from the NTLF (Radonjic et al., 2000). However, an independent contractor for the City of Berkeley has suggested in their preliminary report (Franke and Greenhouse, 2000) that in certain cases estimates made for short-term emissions could result in higher risks than for assessments based on annual-averaged exposures. This effect is due to the fact that releases only occur approximately 10% of time during the NTLF's normal operational hours (8 am to 6 pm). Therefore, when the releases from the NTLF are annually-averaged, the resulting concentrations may produce lower risks than would be possible if short-term releases were considered.

This report summarizes a risk assessment performed independently by SENES Oak Ridge, Inc. for short-term emissions of HTO from the NTLF using the CALPUFF dispersion modeling system (already calibrated for the LBNL site) and the most recent information on the uncertainty in estimating the exposure and excess lifetime risk of cancer incidence due to exposure to ionizing radiation. Risks have been estimated for various scenarios for individuals visiting the Lawrence Hall of Science (LHS) and the site boundary fence that separates the LBNL and LHS properties (Figure 1).

Risks of other deleterious effects (i.e. birth defects) have not been included because of the absence of epidemiological information from which a reliable estimate of the dose response can be obtained. At low doses, radiogenic cancer risk is believed to be the primary health issue of concern when exposures to ionizing radiation occur (ICRP, 1991).

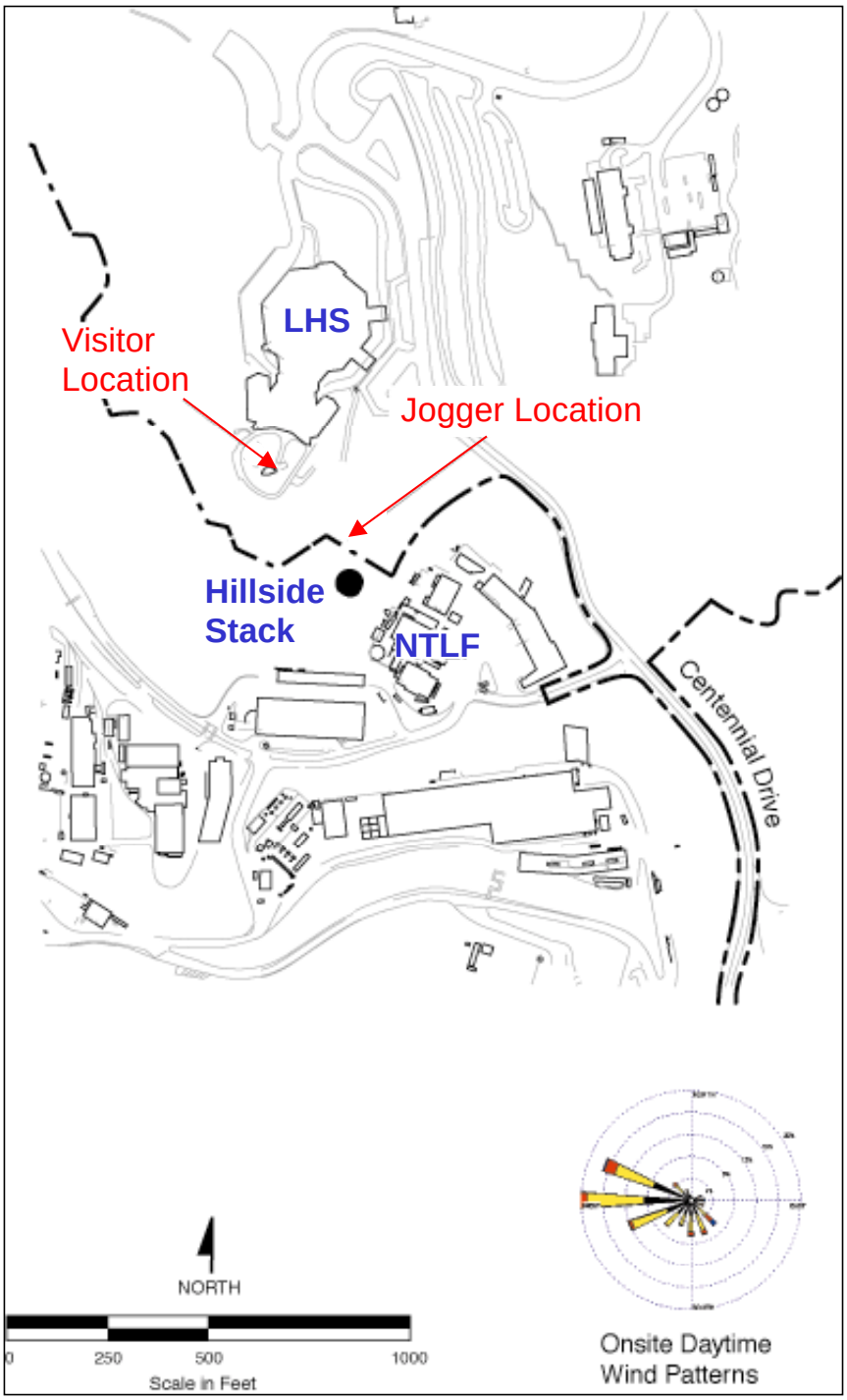

Figure 1. Location of receptors considered in this assessment. A wind rose describing onsite daytime wind patterns is also included.

3.0 SUMMARY OF SCENARIOS

This report evaluates the excess lifetime risks of cancer incidence for three different exposure scenarios. These scenarios include typical, reasonable maximum, and hypothetical extreme exposure situations, and are detail below:

3.1 Typical Exposure Scenarios

Two typical exposure situations are considered. One situation is representative of a child (ages 5 and 12) who visits the LHS one time. It is assumed that the child will spend an entire visit (2.5 hours) on the southern patio on the LHS grounds (the closest outdoor exhibit area to the Building 75 hillside stack). Another typical exposure situation was considered for a child who participates in multiple visits to the LHS. For this assessment, a large number of independent random visits (100) have been assumed, each lasting 2.5 hours.

The meteorological conditions used for these exposure situations were onsite hourly measurements of wind speed, wind direction, atmospheric stability, and mixing height taken during normal operational hours of the NTLF (8am to 6pm). These exposure situations assume that an average amount of HTO is being released from the Building 75 hillside stack for the entire visit to the LHS.

3.2 Reasonable Maximum Exposure Scenarios

Reasonable maximum exposure scenarios have been evaluated for a child who spends 2.5 hours on the southern patio of the LHS and for an adult (age 20) exercising vigorously for 15 minutes at the fence near the Building 75 hillside stack that separates the LBNL and LHS properties. The adult who exercises near the stack was assumed to be jogging on an existing fire trail, even though this trail is not routinely maintained and it dead-ends at this fence. It is unlikely that any jogger would use this trail for exercise. These scenarios assume that the highest routine release of HTO recorded during the past two years was being released coincidental with onsite meteorological conditions that existed when the wind blew in the direction (60 degree arc centered on the LHS) of these two receptors for the entire stay by either the child or the jogger. The largest 2.5 hour release over the last two years is 409 mCi while the largest 15 minute release is 218 mCi.

3.3 Hypothetical Extreme Exposure Scenarios

Although highly implausible, hypothetical extreme exposure situations have been modeled for a child visiting the LHS once and for an adult exercising vigorously near the Building 75 hillside stack. Like for the reasonable maximum exposure scenario described above, it is unlikely that any jogger would use the inadequately maintained fire trail for exercise. However, to reflect an extreme situation these scenarios assume that the worst combination of hourly meteorological conditions prevails during the time of the highest routine release of HTO recorded over the last two years. For the LHS location, the worst possible combination of meteorological conditions are: 1) wind speed = 1.3 m/s, 2) stability category = C, and 3) mixing height = 58 m For the jogger location, the worst possible combination of meteorological conditions are: 1) wind speed = 1.5 m/s, 2) stability category = C, and 3) mixing height = 245 m. The largest 15 minute release over the last two years is 218 mCi. As with the reasonable maximum exposure scenario, the largest 2.5 hour release over the last two years is 409 mCi, while the largest 15 minute release is 218 mCi.

4.0 METHODS

The CALPUFF modeling system was used to estimate air concentrations for a 2.5-hour period at the LHS southern patio and for a 15-minute period at the LBNL/LHS boundary fence that resulted from short-term routine emissions from the LBNL Building 75 hillside stack. The values of short-term routine releases used in this assessment are given in Table 1.

The release estimates used for this assessment are based on measurements taken using real-time monitoring equipment. The average amount of HTO emissions from the NTLF Hillside stack were calculated for March 3rd to July 20th. These hourly emissions were summed and grouped into continuous three-hour intervals (approximating the 2.5 hour time period that is being modeled) that did not overlap each other. 1,082 three-hour data points were generated from the original data set of 3,246 one-hour data points. The largest 2.5 hour release over the last two years is 409 mCi, while the largest 15 minute release is 218 mCi.

Estimated concentrations were then used to calculate the intake of HTO into the body through inhalation and skin absorption. The breathing rates used in this analysis (Table 1) are based on studies presented in EPA's Exposure Factors Handbook (EPA, 1997). The most recent age-dependent dose coefficients from the International Commission on Radiological Protection (ICRP, 1998), provided in Table 1, were used to estimate the committed doses. The equivalent dose to specific organ sites account specifically for the uncertainty in the enhanced relative biological effectiveness factor (RBE) for the absorption of tritium beta decay in biological tissue (Straume, 2000; Straume, 1998; Straume, 1993).

Table 1. Summary of Input Parameters used in this Assessment

Parameter	**Uncertainty distribution**	**Primary source**
Average release amount of HTO (mCi)	Lognormal (4, 2.1)[a]	measurement[b]
Maximum 15 minute release of HTO (mCi)	218	observed value[c]
Maximum 2.5 hour release of HTO (mCi)	409	observed value[c]
Breathing rate (m^3/h)		
Male , age 5 (moderate activity level)	Triangular (0.19, 0.45, 1.1)[d]	EPA, 1997
Female , age 5 (moderate activity level)	Triangular (0.19, 0.45, 1.1)	EPA, 1997
Male , age 12 (moderate activity level)	Triangular (0.34, 0.8, 1.9)	EPA, 1997
Female , age 12 (moderate activity level)	Triangular (0.27, 0.63, 1.5)	EPA, 1997
Male , age 20 (heavy activity level)	Triangular (3, 4, 5)	EPA, 1997
Female , age 20 (heavy activity level)	Triangular (3, 4, 5)	EPA, 1997
Dose conversion factor (Sv/Bq)		
Age 5	Lognormal (3.1×10^{-11}, 1.4)[e]	ICRP, 1998
Age 12	Lognormal (2.3×10^{-11}, 1.4)[e]	ICRP, 1998
Age 20	Lognormal (1.8×10^{-11}, 1.4)[e]	ICRP, 1998
Relative biological effectiveness for tritium	Logtriangular (1, 2, 5)	Straume, 1998, 1993 and personal communication

[a] Lognormal (geometric mean, geometric standard deviation)
[b] Based on 3,246 one-hour data points from real-time monitoring data
[c] Largest observed value over the past two years
[d] Triangular (minimum, median, maximum)
[e] Uncertainty assigned by authors

The values of excess lifetime risk of cancer incidence per unit dose used in this assessment have been developed by SENES Oak Ridge, Inc. and are derived from estimates of the excess relative risk per unit dose (ERR per Sv) developed with the National Cancer Institute in updating the 1985 Radioepidemiological Tables (Land, 2000). The values of excess lifetime risk of cancer incidence per unit equivalent organ dose are the product of the ERR per Sv and the background incidence rate of reported cancers for the San Francisco Bay Area (Parkin et al., 1997). The values of ERR per Sv used in this study are currently under review by a National Academy of Sciences panel.

A complete presentation of the risks per unit dose for each cancer type developed for this study is provided in Tables C1 through C.3. A comparison of these risk factors to others found in the literature is supplied in Table B.1 appended to this summary. The most significant difference between the risk estimates used in this assessment (SENES estimates) and those of other sources are:

(a) SENES estimates are for specific ages at time of exposure and gender as opposed to age-adjusted over the entire US population;

(b) SENES estimates are specific for cancer incidence, which is a more inclusive measure of health risk than mortality. The values are based on the most recent cancer incidence data from the Radiation Effects Research Foundation (RERF) on the Life Span Study (LSS) cohort of Japanese survivors from Hiroshima and Nagasaki (Land, 2000); these estimates are made for 33 individual organ sites and summed;

(c) SENES estimates include a full uncertainty analysis on all factors involved in extrapolation of risk from the Japanese to US populations and for the effects of extrapolation to low dose and low dose rates; and

(d) SENES estimates use baseline cancer incidence rates for gender and specific ages at time of diagnosis of disease specific for the San Francisco Bay Area; other studies use an average age and gender adjusted baseline for cancer mortality for the US population (EPA, NCRP), or for the global population (ICRP).

The risk estimates used for this assessment are specific for exposures at low doses and low dose rates. However, no credit is given to the likelihood of the existence of a threshold dose below which the risk is zero. This assumption is consistent with uncertainty analyses performed on the radiogenic cancer risk by NCRP (1997) and EPA (1999). The uncertainty in the biological effectiveness of the exposure to tritium is addressed explicitly in the subjective probability distribution assigned to the relative biological effectiveness factor for HTO.

5.0 SUMMARY OF RESULTS

A summary of doses for each scenario is presented in Table 2. The excess lifetime risks of cancer incidence are summarized in Table 3. The results presented in this section are for a 5-year-old female. However, a complete set of results for both genders and other age groups is provided in Appendix A (Tables A.1 through A.6). Tables A.1 through A.6 provide the 95% uncertainty range for each uncertain input, the estimated intake of HTO, the equivalent dose, and excess lifetime risk of cancer incidence. The results in Tables A.1 through A.6 show that total excess lifetime risks are not greatly influenced by age at time of exposure or gender, although the specific cancer sites contributing to the total do differ by age and gender.

Table 2. HTO-adjusted equivalent doses (mrem) for a 5-year-old female.

	HTO-adjusted equivalent dose (mrem)		
	95% uncertainty range		
Scenario	lower bound	central estimate	upper bound
Typical			
LHS visitor (1 visit)	0	0	0.000088
LHS visitor (100 visits)	0.00013	0.00058	0.0023
Reasonable Maximum			
LHS visitor (1 visit)	0.00000048	0.0023	0.018
Jogger (1 visit)[a]	0.0000017	0.010	0.11
Hypothetical Extreme[b]			
LHS visitor (1 visit)	0.0073	0.020	0.060
Jogger (1 visit)[a]	0.042	0.11	0.26

[a] The results given for the jogger scenario are for a 20-year-old female.

[b] Implausible extreme assuming that the maximum short term release, the worst hourly meteorology, and the visit by a hypothetical individual are all coincidental.

Table 3. Excess lifetime risks of cancer incidence for a 5-year-old female.

	Excess lifetime risk (given as a fraction of one chance in 1 million)		
	95% uncertainty range		
Scenario	lower bound	central estimate	upper bound
Typical			
LHS visitor (1 visit)	0	0	0.00018
LHS visitor (100 visits)	0.00031	0.0012	0.0066
Reasonable Maximum			
LHS visitor (1 visit)	0.00000076	0.0049	0.056
Jogger (1 visit)[a]	0.0000019	0.015	0.23
Hypothetical Extreme[b]			
LHS visitor (1 visit)	0.010	0.045	0.19
Jogger (1 visit)[a]	0.043	0.17	0.70

[a] The results given for the jogger scenario are for a 20-year-old female.

[b] Implausible extreme assuming that the maximum short term release, the worst hourly meteorology, and the visit by a hypothetical individual are all coincidental.

5.1 Typical Exposure Scenarios

This scenario estimates the risks to a child who visits the LHS. One visit to the LHS will more than likely result in no exposure. This is due primarily to the fact that site meteorology indicates that the wind blows from the Building 75 hillside stack toward a 60-degree arc centering on the southern patio of the LHS approximately 24% of the time between the hours of 8 am and 6 pm. When the wind is not blowing toward the LHS, the HTO released from the Building 75 hillside stack will not reach the LHS. The child who visits 100 times is more likely to be present during the time of a release while the wind is blowing toward the LHS.

The results for the one-time typical visit are representative of the fact that approximately 76% of the time no exposure will be received from a single visit to the LHS. The central estimate of the excess lifetime cancer risk for a 5-year-old female from a typical one-time visit to the LHS is zero (Table 3). The upper bound of the 95% uncertainty range is 0.00018 chances in one million.

The 95% uncertainty range for a 5-year-old female visiting the LHS 100 times is 0.00021 to 0.0066 chances in one million, with a central estimate of 0.0012 chances in one million.

5.2 Reasonable Maximum Exposure Scenarios

These scenarios are representative of the largest reasonable risks to a child who spends 2.5 hours on the southern patio of the LHS and to an adult who exercises vigorously for 15 minutes at the fence near the Building 75 hillside stack. These scenarios assume the highest routine release of HTO recorded during the past two years with the meteorogical conditions that existed when the wind was blowing in the general direction (60 degree arc centered on the LHS) of the receptor during the entire visit.

The central estimate of the excess lifetime risk for a 5-year-old female exposed at the LHS is 0.0049 chances in one million. The upper bound of the 95% uncertainty range is 0.06 chances in one million. The lower bound of the 95% uncertainty range is approximately 4 orders of magnitude less than the central estimate. This is primarily due to the fact that for a one-time exposure there is a possibility for the plume to rise above the LHS as a result of exit temperature from the stack, ambient temperature, wind speed, and atmospheric stability at the time of the release.

The central estimate of the excess lifetime risk for a 20-year-old female exposed at the fence near the Building 75 hillside stack is 0.015 chances in one million. The upper bound of the 95% uncertainty range is 0.23 chances in one million. For the same reasons as the scenario mentioned above, the lower bound of the 95% uncertainty range is approximately 4 orders of magnitude less than the central estimate.

5.3 Hypothetical Extreme Exposure Scenario

Although it is highly implausible for these conditions to occur, two hypothetical extreme situations have been assumed. These scenarios assume that the worst hourly combination of meteorological conditions prevails during the time of the highest routine release of HTO recorded over the last two years.

The central estimate of the excess lifetime risk for a 5-year-old female exposed at the LHS under hypothetical extreme conditions is 0.045 chances in one million. The 95% uncertainty interval ranges from 0.010 chances in one million to 0.19 chances in one million.

The central estimate of the excess lifetime risk for a 20-year-old female exercising vigorously near the Building 75 hillside stack under hypothetical extreme conditions is

0.17 chances in one million. The 95% uncertainty interval ranges from 0.043 chances in one million to 0.70 chances in one million.

5.4 Identification of Important Inputs and Assumptions

An analysis was done to determine which input parameters and assumptions contributed the most to the uncertainty range of the excess lifetime risk estimate for each scenario (Table 4). For the typical one-time visit to the LHS and the reasonable maximum scenarios, the primary contributor to the overall uncertainty was in the estimated air concentration of HTO at each location, which was due almost exclusively to uncertainty in meteorology. For these scenarios, the uncertainties associated with the breathing rate, the body surface area, the dose conversion factor, the relative biological effectiveness factor (RBE) for HTO, and the risk per unit dose are negligible.

For the typical 100-visit scenario to the LHS, there are two parameters that contribute equally to the variance in the excess lifetime risk: the uncertainty in the meteorology and the uncertainty in the risk per unit dose. The uncertainty for the hypothetical extreme scenarios is primarily due to the uncertainty in the risk per unit dose, but is also affected by the uncertainty in the dose conversion factor and the RBE for HTO. The contribution of uncertainty in the air concentration is zero for these scenarios because the air concentration is a fixed quantity. This single highest concentration is associated with the highest release recorded over the past two years and the worst possible combination of meteorological conditions.

Table 4. Relative contribution of input parameters to the total uncertainty in the excess lifetime risk of cancer incidence.

	Contribution to Variance (%)					
	Typical - LHS		Reasonable Max.		Hypothetical Extreme	
Uncertain Parameter	1 visit	100 visits	LHS	Jogger	LHS	Jogger
Air concentration	**99.8**	**28.8**	**84.1**	**91.8**	0.0	0.0
Breathing rate	0.0	5.3	1.8	0.5	14.0	1.1
Body surface area	0.0	0.5	0.7	0.0	0.5	0.3
Dose conversion factor	0.2	13.9	2.3	1.9	**19.5**	**24.3**
RBE for HTO	0.0	15.4	4.2	1.6	**21.2**	**21.5**
Risk per unit dose	0.0	**36.1**	7.0	4.3	**44.8**	**52.8**

6.0 CONCLUSIONS

In all cases, the organ doses and excess lifetime cancer risks are very low when compared to regulatory limits (i.e. EPA's 10 mrem per year for NESHAPS) and other risk levels of concern for the protection of public health (EPA's risk range for Superfund sites at one chance to 100 chances in one million). This conclusion holds even if one considers the upper limit of the 95% uncertainty range on the estimate of excess lifetime risk. In addition, the excess lifetime risks estimated in this assessment are far below levels (e.g. > 20 to 50% above background rates) that would need to be reached before those risks could be detected by well designed epidemiological studies involving very large numbers of exposed persons.

Because of the small exposures and risks and the small implausibility that a visit to the Lawrence Hall of Science would be coincidental with a peak short-term routine release from the Building 75 hillside stack and the unfavorable meteorological conditions assumed in this study, the small quantitative estimates of dose and risk estimated in this report would be difficult to distinguish from zero.

The modeling results estimated by this study are consistent with previous Berkeley Lab reports and dose estimates (i.e. Site Environmental Report, CAP88-PC annual dose modeling) which have indicated tritium exposure risks at LHS are very low.

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Table A.1 Results for a **Typical** scenario: an individual visiting the LHS once for a period of 2.5 hours.

		Male 5 year old			**Female 5 year old**		
		95% uncertainty range			95% uncertainty range		
	units	lower	central	upper	lower	central	upper
Location of individual receptor		--	LHS patio	--	--	LHS patio	--
Release amount (HTO)[A]	GBq (mCi)	0.035 (0.94)	0.15 (4.0)	0.63 (17)	0.035 (0.94)	0.15 (4.0)	0.63 (17)
Distance from NTLF stack	m	--	100	--	--	100	--
Direction from NTLF stack	degrees	--	145	--	--	145	--
Elevation above stacktip	m	--	10.5	--	--	10.5	--
χ / Q[B]	s/m^3	0.0E+00	0.0E+00	3.4E-04	0.0E+00	0.0E+00	3.4E-04
Time integrated air concentration[B]	Bq h/m^3	0	0	14	0	0	14
Inhalation rate	m^3/h	0.27	0.56	0.98	0.27	0.56	0.98
Intake from inhalation	Bq	0	0	7.9	0	0	7.9
Intake from skin absorption	Bq	0	0	2.4	0	0	2.4
Total intake[C]	Bq	0	0	9.3	0	0	10
Dose conversion factor (ICRP, 1998)	Sv/Bq	1.6E-11	3.1E-11	6.0E-11	1.6E-11	3.1E-11	6.0E-11
Equivalent dose (RBE=1)	mrem	0	0	0.000033	0	0	0.000034
RBE for tritium	unitless	1.3	2.6	4.4	1.3	2.6	4.4
Tritium-adjusted equivalent dose	**mrem**	**0**	**0**	**0.000079**	**0**	**0**	**0.000088**
Risk per unit dose	Risk/mrem	4.7E-07	1.4E-06	4.1E-06	8.6E-07	2.2E-06	5.6E-06
Excess Lifetime Risk		**0.0E+00**	**0.0E+00**	**9.7E-11**	**0.0E+00**	**0.0E+00**	**1.8E-10**

chances in 1 million

[A] Lognormal distribution derived from 1,082 alternative 3-hour emissions of HTO summarized from 3,246 hourly releases from the NTLF hillside stack during March 3 to July 20, 2000.

[B] CALPUFF estimates were made for all hours between 8am and 6pm for each day of the year. Zero concentrations occur when the wind does not blow toward the LHS (approximately 76% of the time).

[C] All calculations have been performed using Monte Carlo error propagation techniques; therefore, results are not directly additive.

Table A.1 (continued) Results for a **Typical** scenario: an individual visiting the LHS once for a period of 2.5 hours.

		Male 12 year old			**Female 12 year old**		
		95% uncertainty range			95% uncertainty range		
	units	lower	central	upper	lower	central	upper
Location of individual receptor		--	LHS patio	--	--	LHS patio	--
Release amount (HTO)[A]	GBq (mCi)	0.035 (0.94)	0.15 (4.0)	0.63 (17)	0.035 (0.94)	0.15 (4.0)	0.63 (17)
Distance from NTLF stack	m	--	100	--	--	100	--
Direction from NTLF stack	degrees	--	145	--	--	145	--
Elevation above stacktip	m	--	10.5	--	--	10.5	--
χ / Q[B]	s/m^3	0.0E+00	0.0E+00	3.4E-04	0.0E+00	0.0E+00	3.4E-04
Time integrated air concentration[B]	Bq h/m^3	0	0	14	0	0	14
Inhalation rate	m^3/h	0.48	0.97	1.69	0.38	0.77	1.3
Intake from inhalation	Bq	0	0	14.8	0	0	10.7
Intake from skin absorption	Bq	0	0	3.8	0	0	3.8
Total intake[C]	Bq	0	0	18	0	0	15
Dose conversion factor (ICRP, 1998)	Sv/Bq	1.2E-11	2.3E-11	4.4E-11	1.2E-11	2.3E-11	4.4E-11
Equivalent dose (RBE=1)	mrem	0	0	0.000052	0	0	0.000037
RBE for tritium	unitless	1.3	2.6	4.4	1.3	2.6	4.4
Tritium-adjusted equivalent dose	**mrem**	**0**	**0**	**0.00012**	**0**	**0**	**0.000075**
Risk per unit dose	Risk/mrem	4.1E-07	1.2E-06	3.5E-06	7.3E-07	1.9E-06	4.9E-06
Excess Lifetime Risk		**0.0E+00**	**0.0E+00**	**1.5E-10**	**0.0E+00**	**0.0E+00**	**2.1E-10**

[A] Lognormal distribution derived from 1,082 alternative 3-hour emissions of HTO summarized from 3,246 hourly releases from the NTLF hillside stack during March 3 to July 20, 2000.

[B] CALPUFF estimates were made for all hours between 8am and 6pm for each day of the year. Zero concentrations occur when the wind does not blow toward the LHS (approximately 76% of the time).

[C] All calculations have been performed using Monte Carlo error propagation techniques; therefore, results are not directly additive.

Table A.2 Results for a **Typical** scenario: an individual visiting the LHS 100 times for a period of 2.5 hours per visit.

		Male 5 year old			**Female 5 year old**		
		95% uncertainty range			95% uncertainty range		
	units	lower	central	upper	lower	central	upper
Location of receptor		--	LHS patio	--	--	LHS patio	--
Release amount (HTO) per visit[A]	GBq (mCi)	0.035 (0.94)	0.15 (4.0)	0.63 (17)	0.035 (0.94)	0.15 (4.0)	0.63 (17)
Total release (HTO) for 100 visits	GBq (mCi)	17 (460)	19 (514)	23 (622)	17 (460)	19 (514)	23 (622)
Distance from NTLF stack	m	--	100	--	--	100	--
Direction from NTLF stack	degrees	--	145	--	--	145	--
Elevation above stacktip	m	--	10.5	--	--	10.5	--
χ / Q[B]	s/m^3	7.7E-06	2.2E-05	4.8E-05	7.7E-06	2.2E-05	4.8E-05
Time integrated air concentration[B]	Bq h/m^3	42	119	259	42	119	259
Inhalation rate	m^3/h	0.27	0.45	0.75	0.27	0.45	0.75
Intake from inhalation	Bq	18	53	143	17	54	148
Intake from skin absorption	Bq	6	19	45	6	19	45
Total intake[C]	Bq	25	73	178	24	74	186
Dose conversion factor (ICRP, 1998)	Sv/Bq	1.6E-11	3.1E-11	6.0E-11	1.6E-11	3.1E-11	6.0E-11
Equivalent dose (RBE=1)	mrem	0.000065	0.00022	0.00074	0.000061	0.00022	0.00080
RBE for tritium	unitless	1.3	2.6	4.4	1.3	2.6	4.4
Tritium-adjusted equivalent dose	**mrem**	**0.00014**	**0.00057**	**0.0022**	**0.00013**	**0.00058**	**0.0023**
Risk per unit dose	Risk/mrem	4.7E-07	1.4E-06	4.1E-06	8.6E-07	2.2E-06	5.6E-06
Excess Lifetime Risk		**1.3E-10**	**7.7E-10**	**4.5E-09**	**2.1E-10**	**1.2E-09**	**6.6E-09**

[A] Lognormal distribution derived from 1,082 alternative 3-hour emissions of HTO summarized from 3,246 hourly releases from the NTLF hillside stack during March 3 to July 20, 2000.

[B] CALPUFF estimates were made for all hours between 8am and 6pm for each day of the year.

[C] All calculations have been performed using Monte Carlo error propagation techniques; therefore, results are not directly additive.

Table A.2 (continued) Results for a **Typical** scenario: an individual visiting the LHS 100 times for a period of 2.5 hours per visit.

		Male 12 year old			**Female 12 year old**		
		95% uncertainty range			95% uncertainty range		
	units	lower	central	upper	lower	central	upper
Location of receptor		--	LHS patio	--	--	LHS patio	--
Release amount (HTO) per visit[A]	GBq (mCi)	0.035 (0.94)	0.15 (4.0)	0.63 (17)	0.035 (0.94)	0.15 (4.0)	0.63 (17)
Total release (HTO) for 100 visits	GBq (mCi)	17 (460)	19 (514)	23 (622)	17 (460)	19 (514)	23 (622)
Distance from NTLF stack	m	--	100	--	--	100	--
Direction from NTLF stack	degrees	--	145	--	--	145	--
Elevation above stacktip	m	--	10.5	--	--	10.5	--
χ / Q[B]	s/m^3	7.7E-06	2.2E-05	4.8E-05	7.7E-06	2.2E-05	4.8E-05
Time integrated air concentration[B]	Bq h/m^3	42	119	259	42	119	259
Inhalation rate	m^3/h	0.48	0.80	1.3	0.38	0.63	1.1
Intake from inhalation	Bq	32	93	250	23	74	193
Intake from skin absorption	Bq	11	33	79	11	33	79
Total intake[C]	Bq	43	127	318.9	37	107	262.7
Dose conversion factor (ICRP, 1998)	Sv/Bq	1.2E-11	2.3E-11	4.4E-11	1.2E-11	2.3E-11	4.4E-11
Equivalent dose (RBE=1)	mrem	0.000084	0.00030	0.00092	0.000077	0.00025	0.00076
RBE for tritium	unitless	1.3	2.6	4.4	1.3	2.6	4.4
Tritium-adjusted equivalent dose	**mrem**	**0.00018**	**0.00074**	**0.0029**	**0.00016**	**0.00064**	**0.0024**
Risk per unit dose	Risk/mrem	4.1E-07	1.2E-06	3.5E-06	7.3E-07	1.9E-06	4.9E-06
Excess Lifetime Risk		**1.6E-10**	**9.0E-10**	**4.8E-09**	**2.1E-10**	**1.2E-09**	**6.4E-09**

[A] Lognormal distribution derived from 1,082 alternative 3-hour emissions of HTO summarized from 3,246 hourly releases from the NTLF hillside stack during March 3 to July 20, 2000.

[B] CALPUFF estimates were made for all hours between 8am and 6pm for each day of the year.

[C] All calculations have been performed using Monte Carlo error propagation techniques; therefore, results are not directly additive.

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Table A.3 Results for a **Reasonable Maximum** scenario: a one time visit to the LHS; it is assumed that a 2.5 hour visit is coincidental with the highest 2.5 hour routine release recorded over the past two years (409 mCi) and that both the visit and the release are coincidental with the wind blowing in a 60 degree arc towards the LHS.

		Male 5 year old			**Female 5 year old**		
		95% uncertainty range			95% uncertainty range		
	units	lower	central	upper	lower	central	upper
Location of receptor		--	LHS patio	--	--	LHS patio	--
Release amount (HTO)	GBq (mCi)	--	15 (409)	--	--	15 (409)	--
Distance from NTLF stack	m	--	100	--	--	100	--
Direction from NTLF stack	degrees	--	145	--	--	145	--
Elevation above stacktip	m	--	10.5	--	--	10.5	--
χ / Q[A]	s/m^3	2.0E-08	1.2E-04	5.1E-04	2.0E-08	1.2E-04	5.1E-04
Time integrated air concentration[A]	Bq h/m^3	0.084	500	2149	0.084	500	2149
Inhalation rate	m^3/h	0.27	0.56	0.98	0.27	0.56	0.98
Intake from inhalation	Bq	0.045	249	1508	0.045	245	1391
Intake from skin absorption	Bq	0.013	78	393	0.013	78	393
Total intake[B]	Bq	0.058	331	1788	0.062	328	1686
Dose conversion factor (ICRP)	Sv/Bq	1.6E-11	3.1E-11	6.0E-11	1.6E-11	3.1E-11	6.0E-11
Equivalent dose (RBE=1)	mrem	2.0E-07	0.0010	0.0062	1.9E-07	0.0010	0.0064
RBE for tritium	unitless	1.3	2.6	4.4	1.3	2.6	4.4
Tritium-adjusted equivalent dose	**mrem**	**5.0E-07**	**0.0023**	**0.017**	**4.8E-07**	**0.0023**	**0.018**
Risk per unit dose	Risk/mrem	4.7E-07	1.4E-06	4.1E-06	8.6E-07	2.2E-06	5.6E-06
Excess Lifetime Risk		**6.4E-13**	**3.1E-09**	**3.2E-08**	**7.6E-13**	**4.9E-09**	**5.6E-08**

[A] CALPUFF estimates were made for all hours when the wind is blowing in a 60 degree arc toward the LHS and meteorological conditions produce non-zero concentrations (a total of 401 hours). Each hour simulated by CALPUFF is assumed to persist for a duration of 2.5 hours.

[B] All calculations have been performed using Monte Carlo error propagation techniques; therefore, results are not directly additive.

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Table A.3 (continued) Results for a **Reasonable Maximum** scenario: a one time visit to the LHS; it is assumed that a 2.5 hour visit is coincidental with the highest 2.5 hour routine release recorded over the past two years (409 mCi) and that both the visit and the release are coincidental with the wind blowing in a 60 degree arc towards the LHS.

		Male 12 year old			**Female 12 year old**		
		95% uncertainty range			95% uncertainty range		
	units	lower	central	upper	lower	central	upper
Location of receptor		--	LHS patio	--	--	LHS patio	--
Release amount (HTO)	GBq (mCi)	--	15 (409)	--	--	15 (409)	--
Distance from NTLF stack	m	--	100	--	--	100	--
Direction from NTLF stack	degrees	--	145	--	--	145	--
Elevation above stacktip	m	--	10.5	--	--	10.5	--
χ / Q[A]	s/m^3	2.0E-08	1.2E-04	5.1E-04	2.0E-08	1.2E-04	5.1E-04
Time integrated air concentration[A]	Bq h/m^3	0.084	500	2149	0.084	500	2149
Inhalation rate	m^3/h	0.48	0.97	1.7	0.38	0.77	1.3
Intake from inhalation	Bq	0.083	397	2654	0.061	342	1947
Intake from skin absorption	Bq	0.025	129	678	0.025	129	678
Total intake[B]	Bq	0.108	532	3130	0.089	487	2584
Dose conversion factor (ICRP)	Sv/Bq	1.2E-11	2.3E-11	4.4E-11	1.2E-11	2.3E-11	4.4E-11
Equivalent dose (RBE=1)	mrem	2.5E-07	0.0012	0.0086	1.8E-07	0.0011	0.0069
RBE for tritium	unitless	1.3	2.6	4.4	1.3	2.6	4.4
Tritium-adjusted equivalent dose	**mrem**	**6.8E-07**	**0.0029**	**0.024**	**5.6E-07**	**0.0026**	**0.019**
Risk per unit dose	Risk/mrem	4.1E-07	1.2E-06	3.5E-06	7.3E-07	1.9E-06	4.9E-06
Excess Lifetime Risk		**6.1E-13**	**3.4E-09**	**3.8E-08**	**9.7E-13**	**4.7E-09**	**4.9E-08**

[A] CALPUFF estimates were made for all hours when the wind is blowing in a 60 degree arc toward the LHS and meteorological conditions produce non-zero concentrations (a total of 401 hours). Each hour simulated by CALPUFF is assumed to persist for a duration of 2.5 hours.

[B] All calculations have been performed using Monte Carlo error propagation techniques; therefore, results are not directly additive.

Table A.4 Results for a **Reasonable Maximum** scenario: 15 minute exposure by an adult exercising vigorously at the boundary fence near the NTLF hillside stack; it is assumed that this 15 minute visit is coincidental with the highest 15 minute routine release recorded over the past two years (218 mCi) and that both the visit and the release are coincidental with the wind blowing in a 60 degree arc towards the receptor.

		Male jogger			**Female jogger**		
		95% uncertainty range			95% uncertainty range		
	units	lower	central	upper	lower	central	upper
Location of receptor		--	Boundary fence	--	--	Boundary fence	--
Release amount (HTO)	GBq (mCi)	--	8.1 (218)	--	--	8.1 (218)	--
Distance from NTLF stack	m	--	41	--	--	41	--
Direction from NTLF stack	degrees	--	135	--	--	135	--
Elevation above stacktip	m	--	3.5	--	--	3.5	--
χ / Q[A]	s/m^3	1.5E-07	9.6E-04	6.9E-03	1.5E-07	9.6E-04	6.9E-03
Time integrated air concentration[A]	Bq h/m^3	0.34	2153	15400	0.34	2153	15400
		---	---	---	---	---	---
Inhalation rate	m^3/h	3.2	4.0	4.8	3.2	4.0	4.8
Intake from inhalation	Bq	0.34	2142	15720	0.38	2079	15840
Intake from skin absorption	Bq	0.040	194	2111	0.040	194	2111
Total intake[B]	Bq	0.38	2352	17450	0.42	2312	17840
		---	---	---	---	---	---
Dose conversion factor (ICRP)	Sv/Bq	9.3E-12	1.8E-11	3.5E-11	9.3E-12	1.8E-11	3.5E-11
Equivalent dose (RBE=1)	mrem	6.4E-07	0.0042	0.039	6.8E-07	0.0043	0.039
RBE for tritium	unitless	1.3	2.6	4.4	1.3	2.6	4.4
Tritium-adjusted equivalent dose	**mrem**	**1.7E-06**	**0.0103**	**0.113**	**1.7E-06**	**0.0103**	**0.114**
Risk per unit dose	Risk/mrem	3.6E-07	1.1E-06	3.3E-06	6.1E-07	1.6E-06	4.2E-06
		---	---	---	---	---	---
Excess Lifetime Risk		**1.4E-12**	**1.1E-08**	**1.7E-07**	**1.9E-12**	**1.5E-08**	**2.3E-07**

[A] CALPUFF estimates were made for all hours when the wind is blowing in a 60 degree arc towards the individual and meteorological conditions produce non-zero concentrations (a total of 236 hours). Each hour simulated by CALPUFF is assumed to persist for a duration of 15 minutes.

[B] All calculations have been performed using Monte Carlo error propagation techniques; therefore, results are not directly additive.

Table A.5 Results for a **Hypothetical Extreme** exposure situation for the LHS. It is assumed that a one time 2.5 hour visit coincides with the highest 2.5 hour routine release recorded over the past two years (409 mCi) and that both the visit and release coincide with the worst combination of daytime (8am to 6pm) meteorological conditions to occur in one hour during 1998.

		Female 5 year old		
		95% uncertainty range		
	units	lower	central	upper
Location of receptor		--	LHS patio	--
Release amount (HTO)	GBq (mCi)	--	15 (409)	--
Distance from NTLF stack	m	--	100	--
Direction from NTLF stack	degrees	--	145	--
Elevation above stacktip	m	--	10.5	--
χ / Q	s/m^3	--	8.5E-04	--
Time integrated air concentration	Bq h/m^3	--	3580	--
Inhalation rate	m^3/h	0.27	0.56	0.98
Intake from inhalation	Bq	958	1991	3499
Intake from skin absorption	Bq	401	573	818
Total intake[A]	Bq	1533	2590	4106
Dose conversion factor (ICRP)	Sv/Bq	1.6E-11	3.1E-11	6.0E-11
Equivalent dose (RBE=1)	mrem	0.0035	0.0079	0.018
RBE for tritium	unitless	1.3	2.6	4.4
Tritium-adjusted equivalent dose	**mrem**	**0.0073**	**0.020**	**0.060**
Risk per unit dose	Risk/mrem	8.6E-07	2.2E-06	5.6E-06
Excess Lifetime Risk		**1.0E-08**	**4.5E-08**	**1.9E-07**

[A] All calculations have been performed using Monte Carlo error propagation techniques; therefore, results are not directly additive.

Table A.6 Results for a **Hypothetical Extreme** exposure situation for an individual exercising vigorously at the boundary fence near the NTLF hillside stack. It is assumed that a one time 15 minute visit coincides with the highest 15 minute routine release recorded over the past two years (218 mCi) and that both the visit and release coincide with the worst combination of daytime (8am to 6pm) meteorological conditions to occur in one hour during 1998.

		Female jogger		
		95% uncertainty range		
	units	lower	central	upper
Location of receptor		--	Boundary fence	--
Release amount (HTO)	GBq (mCi)	--	8.1 (218)	--
Distance from NTLF stack	m	--	41	--
Direction from NTLF stack	degrees	--	135	--
Elevation above stacktip	m	--	3.5	--
χ / Q	s/m^3	0.0094	9.4E-03	0.0094
Time integrated air concentration	Bq h/m^3	21000	21000	21000
		---	---	---
Inhalation rate	m^3/h	3.2	4.0	4.8
Intake from inhalation	Bq	17000	21000	25000
Intake from skin absorption	Bq	1100	2200	4300
Total intake[A]	Bq	19000	23000	28000
		---	---	---
Dose conversion factor (ICRP)	Sv/Bq	9.3E-12	1.8E-11	3.5E-11
Equivalent dose (RBE=1)	mrem	0.0200	0.042	0.083
RBE for tritium	unitless	1.3	2.6	4.4
Tritium-adjusted equivalent dose	**mrem**	**0.042**	**0.110**	**0.26**
Risk per unit dose	Risk/mrem	6.1E-07	1.6E-06	4.2E-06
		---	---	---
Excess Lifetime Risk		**4.3E-08**	**1.7E-07**	**7.0E-07**

[A] All calculations have been performed using Monte Carlo error propagation techniques; therefore, results are not directly additive.

Table B.1 A Comparison of Radiation Risk Factors from this Work to Other Estimates in the Literature.

Source	Estimate	Notes
This work	90% uncertainty range (5th, 50th, 95th)	Estimates are for cancer incidence Includes the effect of DDREF Does not include the effect of RBE Includes a full uncertainty analysis on the factors involved in extrapolation of risk from the Japanese to US populations Use baseline cancer incidence rates specific for the San Francisco Bay Area
Male, age 5	(0.056, 0.14, 0.35) Sv^{-1}	
Female, age 5	(0.1, 0.22, 0.49) Sv^{-1}	
Male, age 12	(0.048, 0.12, 0.30) Sv^{-1}	
Female, age 12	(0.085, 0.19, 0.42) Sv^{-1}	
Male, age 20	(0.043, 0.11, 0.28) Sv^{-1}	
Female, age 20	(0.071, 0.16, 0.36) Sv^{-1}	
Straume, 1993	(0.038, 0.081, 0.19) Gy^{-1}	Estimates are for fatal cancers (mortality) Represents absorbed dose as opposed to equivalent dose Includes the effect of RBE for HTO
NCRP 126, 1997	(0.012, 0.034, 0.088) Sv^{-1}	Estimates are for fatal cancers (mortality) Includes the effects of DDREF
EPA, 1999		Estimates represents absorbed dose as opposed to equivalent dose Includes the effects of DDREF
Mortality	(0.02, 0.049, 0.11) Gy^{-1}	
Morbidity	(0.05, 0.14, 0.28) Gy^{-1}	
McKone, 1997	(min, median, max) (0.018, 0.080, 0.58) Sv^{-1}	Estimates are for fatal cancers (mortality) Includes an RBE of 1.8 for HTO
ICRP 60, 1991	Point estimate	Includes the effects of DDREF Detriment includes the weighting for the severity of the effect of disease incidence as well as years of life lost for a fatal cancer.
Mortality	0.05 Sv^{-1}	
Detriment	0.073 Sv^{-1}	
BIER V, 1990	Point estimate	Specific value for DDREF not assumed Estimates are for fatal cancers (mortality) No recommendations given for extrapolations below 0.1 Gy
Males	0.077 Gy^{-1}	
Females	0.081 Gy^{-1}	

* None of the above estimates explicitly include the effects of non-fatal skin cancers.

Table C.1 Excess lifetime risks per mrem dose for 5-year-old males and females.

Male	Excess Lifetime Risk/mRem				
	95% uncertainty range				
Cancer_type	lower	central	upper	Mean	Contribution
Liver	1.9E-08	1.7E-07	1.4E-06	3.2E-07	20.1%
Lung	3.1E-08	1.7E-07	9.7E-07	2.4E-07	15.0%
Colon	3.2E-08	1.7E-07	7.4E-07	2.2E-07	13.9%
Urinary organs (all)	0.0E+00	9.4E-08	7.4E-07	1.6E-07	9.8%
Thyroid	1.9E-08	9.0E-08	4.6E-07	1.3E-07	7.9%
Prostate	9.6E-09	6.2E-08	3.7E-07	9.2E-08	5.8%
Leukemia	0.0E+00	4.2E-08	4.4E-07	8.4E-08	5.3%
Male genitalia	1.3E-08	5.7E-08	2.7E-07	7.8E-08	4.9%
Bladder	0.0E+00	2.3E-08	1.9E-07	4.0E-08	2.5%
Oral Cavity and Pharynx	0.0E+00	2.4E-08	1.6E-07	3.7E-08	2.3%
Kidney	0.0E+00	2.1E-08	1.1E-07	3.0E-08	1.9%
Stomach	0.0E+00	2.1E-08	1.0E-07	2.9E-08	1.8%
Salivary gland (parotid)	0.0E+00	1.2E-08	1.2E-07	2.5E-08	1.5%
Digestive system (other)	1.7E-09	1.4E-08	8.3E-08	2.1E-08	1.3%
Rectum	2.6E-10	1.3E-08	8.1E-08	2.0E-08	1.3%
Nervous system	0.0E+00	8.8E-09	6.4E-08	1.5E-08	0.9%
Acute Myeloid Leukemia	0.0E+00	2.7E-09	6.5E-08	1.1E-08	0.7%
Non-Hodgkins Lymphoma	1.9E-09	8.3E-09	3.7E-08	1.1E-08	0.7%
Salivary gland (non-parotid)	0.0E+00	7.1E-09	4.7E-08	1.1E-08	0.7%
Pancreas	7.5E-11	6.3E-09	3.6E-08	9.4E-09	0.6%
Chronic Myeloid Leukemia	0.0E+00	4.6E-09	3.7E-08	8.4E-09	0.5%
Esophagus	1.2E-09	6.2E-09	2.9E-08	8.0E-09	0.5%
Ureter	0.0E+00	4.2E-09	2.6E-08	6.5E-09	0.4%
Multiple Myeloma	0.0E+00	1.1E-09	4.2E-08	6.4E-09	0.4%
Acute Lymphocytic Leukem	0.0E+00	2.5E-09	3.5E-08	6.0E-09	0.4%
Nasal	0.0E+00	2.0E-09	1.3E-08	3.2E-09	0.2%
Gallbladder	0.0E+00	7.5E-10	1.9E-08	2.9E-09	0.2%
Larynx and other respiratory	0.0E+00	0.0E+00	2.0E-08	2.2E-09	0.1%
Breast	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Cervix	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Female Genitalia	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Ovary	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Uterus	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Total ELR/mRem	4.7E-07	1.4E-06	4.1E-06	1.6E-06	

Female	Excess Lifetime Risk/mRem				
	95% uncertainty range				
Cancer_type	lower	central	upper	Mean	Contribution
Breast	1.4E-07	5.5E-07	2.1E-06	6.8E-07	27.4%
Lung	7.7E-08	3.5E-07	1.7E-06	4.7E-07	19.0%
Urinary organs (all)	2.4E-08	2.0E-07	1.9E-06	3.8E-07	15.4%
Thyroid	3.9E-08	2.2E-07	1.1E-06	3.1E-07	12.4%
Stomach	1.1E-08	9.3E-08	8.6E-07	1.9E-07	7.4%
Colon	2.2E-08	1.1E-07	5.3E-07	1.5E-07	6.1%
Acute Lymphocytic Leukem	5.8E-09	4.0E-08	2.4E-07	6.1E-08	2.4%
Ovary	3.7E-09	3.4E-08	1.5E-07	4.4E-08	1.8%
Leukemia	6.5E-09	3.1E-08	1.4E-07	4.2E-08	1.7%
Bladder	4.2E-09	2.9E-08	1.3E-07	3.8E-08	1.5%
Esophagus	2.9E-10	1.2E-08	7.5E-08	1.8E-08	0.7%
Digestive system (other)	2.0E-10	8.4E-09	5.8E-08	1.4E-08	0.5%
Oral Cavity and Pharynx	0.0E+00	9.2E-09	4.4E-08	1.3E-08	0.5%
Kidney	0.0E+00	9.0E-09	5.0E-08	1.3E-08	0.5%
Female Genitalia	0.0E+00	0.0E+00	1.1E-07	1.3E-08	0.5%
Salivary gland (parotid)	6.6E-10	5.9E-09	4.0E-08	9.7E-09	0.4%
Nervous system	0.0E+00	5.4E-09	3.4E-08	8.2E-09	0.3%
Acute Myeloid Leukemia	1.3E-09	6.1E-09	2.5E-08	7.9E-09	0.3%
Rectum	0.0E+00	4.5E-09	3.5E-08	7.8E-09	0.3%
Liver	0.0E+00	2.5E-09	3.7E-08	6.6E-09	0.3%
Pancreas	0.0E+00	3.1E-09	2.6E-08	5.7E-09	0.2%
Non-Hodgkins Lymphoma	0.0E+00	1.2E-09	2.8E-08	4.8E-09	0.2%
Salivary gland (non-parotid)	2.5E-11	2.7E-09	1.7E-08	4.6E-09	0.2%
Cervix	0.0E+00	0.0E+00	3.2E-08	4.2E-09	0.2%
Multiple Myeloma	0.0E+00	1.5E-09	2.2E-08	4.0E-09	0.2%
Chronic Myeloid Leukemia	1.1E-10	2.3E-09	1.6E-08	3.9E-09	0.2%
Uterus	0.0E+00	0.0E+00	3.1E-08	3.1E-09	0.1%
Gallbladder	0.0E+00	8.0E-10	1.4E-08	2.5E-09	0.1%
Ureter	0.0E+00	1.4E-09	9.8E-09	2.4E-09	0.1%
Nasal	0.0E+00	8.2E-10	4.8E-09	1.2E-09	0.0%
Larynx and other respiratory	0.0E+00	0.0E+00	3.8E-09	4.4E-10	0.0%
Male genitalia	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Prostate	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Total ELR/mRem	8.6E-07	2.2E-06	5.6E-06	2.5E-06	

Table C.2 Excess lifetime risks per mrem dose for 12-year-old males and females.

Male	Excess Lifetime Risk/mRem				
	95% uncertainty range				
Cancer_type	lower	central	upper	Mean	Contribution
Lung	3.0E-08	1.7E-07	7.9E-07	2.4E-07	17.1%
Colon	3.2E-08	1.7E-07	7.4E-07	2.2E-07	15.9%
Liver	1.3E-08	1.3E-07	9.0E-07	2.2E-07	15.9%
Urinary organs (all)	0.0E+00	8.5E-08	6.9E-07	1.5E-07	10.8%
Prostate	0.0E+00	4.2E-08	4.5E-07	8.8E-08	6.3%
Thyroid	9.2E-09	5.0E-08	2.7E-07	7.3E-08	5.2%
Acute Lymphocytic Leukem	6.2E-09	4.0E-08	2.4E-07	6.0E-08	4.3%
Leukemia	1.0E-08	4.3E-08	1.8E-07	5.6E-08	4.0%
Male genitalia	0.0E+00	2.3E-08	2.0E-07	4.0E-08	2.9%
Bladder	0.0E+00	2.4E-08	1.5E-07	3.7E-08	2.7%
Oral Cavity and Pharynx	0.0E+00	2.2E-08	1.1E-07	3.0E-08	2.2%
Kidney	0.0E+00	2.2E-08	1.1E-07	2.8E-08	2.0%
Stomach	0.0E+00	1.2E-08	1.2E-07	2.5E-08	1.8%
Salivary gland (parotid)	1.4E-09	1.3E-08	8.8E-08	2.1E-08	1.5%
Digestive system (other)	2.5E-10	1.2E-08	9.6E-08	2.1E-08	1.5%
Rectum	0.0E+00	8.7E-09	7.2E-08	1.5E-08	1.1%
Chronic Myeloid Leukemia	2.0E-09	1.0E-08	4.6E-08	1.3E-08	0.9%
Acute Myeloid Leukemia	2.2E-09	9.6E-09	4.1E-08	1.3E-08	0.9%
Non-Hodgkins Lymphoma	0.0E+00	2.7E-09	6.7E-08	1.1E-08	0.8%
Nervous system	0.0E+00	6.9E-09	4.2E-08	1.1E-08	0.8%
Salivary gland (non-parotid)	5.0E-11	6.2E-09	3.8E-08	9.5E-09	0.7%
Pancreas	0.0E+00	4.8E-09	3.8E-08	8.6E-09	0.6%
Ureter	0.0E+00	4.2E-09	2.8E-08	6.6E-09	0.5%
Esophagus	0.0E+00	1.1E-09	4.3E-08	6.4E-09	0.5%
Multiple Myeloma	0.0E+00	2.5E-09	3.3E-08	6.1E-09	0.4%
Nasal	0.0E+00	2.0E-09	1.4E-08	3.3E-09	0.2%
Gallbladder	0.0E+00	8.2E-10	2.0E-08	3.0E-09	0.2%
Larynx and other respiratory	0.0E+00	0.0E+00	2.1E-08	2.2E-09	0.2%
Breast	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Cervix	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Female Genitalia	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Ovary	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Uterus	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Total ELR/mRem	4.1E-07	1.2E-06	3.5E-06	1.4E-06	

Female Age 12

Female	Excess Lifetime Risk/mRem				
	95% uncertainty range				
Cancer_type	lower	central	upper	Mean	Contribution
Breast	1.1E-07	4.5E-07	1.6E-06	5.5E-07	26.1%
Lung	7.7E-08	3.5E-07	1.7E-06	4.7E-07	22.5%
Urinary organs (all)	2.1E-08	2.0E-07	1.8E-06	3.8E-07	18.0%
Thyroid	1.9E-08	1.3E-07	7.2E-07	1.9E-07	8.8%
Colon	2.2E-08	1.1E-07	5.3E-07	1.5E-07	7.2%
Stomach	7.3E-09	6.3E-08	5.3E-07	1.2E-07	5.8%
Ovary	3.7E-09	3.3E-08	1.4E-07	4.4E-08	2.1%
Bladder	4.7E-09	2.9E-08	1.3E-07	3.8E-08	1.8%
Leukemia	4.9E-09	2.0E-08	7.8E-08	2.6E-08	1.2%
Acute Lymphocytic Leukem	2.5E-09	1.7E-08	1.0E-07	2.6E-08	1.2%
Esophagus	4.1E-10	1.1E-08	7.8E-08	1.8E-08	0.9%
Digestive system (other)	2.5E-10	8.2E-09	5.7E-08	1.3E-08	0.6%
Oral Cavity and Pharynx	0.0E+00	8.7E-09	5.1E-08	1.3E-08	0.6%
Kidney	0.0E+00	8.9E-09	4.6E-08	1.3E-08	0.6%
Female Genitalia	0.0E+00	0.0E+00	1.1E-07	1.2E-08	0.6%
Acute Myeloid Leukemia	1.7E-09	7.6E-09	2.9E-08	9.6E-09	0.5%
Salivary gland (parotid)	6.5E-10	6.1E-09	4.0E-08	9.5E-09	0.5%
Nervous system	0.0E+00	5.1E-09	3.2E-08	7.7E-09	0.4%
Rectum	0.0E+00	4.6E-09	3.0E-08	7.4E-09	0.4%
Liver	0.0E+00	2.5E-09	4.0E-08	6.6E-09	0.3%
Pancreas	0.0E+00	3.2E-09	2.7E-08	5.7E-09	0.3%
Non-Hodgkins Lymphoma	0.0E+00	1.2E-09	2.9E-08	4.7E-09	0.2%
Salivary gland (non-parotid)	2.8E-11	2.8E-09	1.8E-08	4.4E-09	0.2%
Chronic Myeloid Leukemia	1.6E-10	2.9E-09	1.7E-08	4.3E-09	0.2%
Multiple Myeloma	0.0E+00	1.4E-09	2.5E-08	4.1E-09	0.2%
Cervix	0.0E+00	0.0E+00	3.5E-08	3.8E-09	0.2%
Uterus	0.0E+00	0.0E+00	3.4E-08	3.3E-09	0.2%
Ureter	0.0E+00	1.5E-09	9.3E-09	2.3E-09	0.1%
Gallbladder	0.0E+00	8.6E-10	1.1E-08	2.3E-09	0.1%
Nasal	0.0E+00	8.0E-10	4.8E-09	1.2E-09	0.1%
Larynx and other respiratory	0.0E+00	0.0E+00	4.6E-09	5.3E-10	0.0%
Male genitalia	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Prostate	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Total ELR/mRem	7.3E-07	1.9E-06	4.9E-06	2.1E-06	

Table C.3 Excess lifetime risks per mrem dose for 20-year-old males and females.

Male	Excess Lifetime Risk/mRem				
	95% uncertainty range				
Cancer_type	lower	central	upper	Mean	Contribution
Lung	2.7E-08	1.7E-07	9.9E-07	2.5E-07	22.3%
Colon	3.2E-08	1.6E-07	7.2E-07	2.2E-07	19.8%
Liver	1.1E-08	9.6E-08	7.4E-07	1.6E-07	14.5%
Urinary organs (all)	0.0E+00	8.6E-08	7.6E-07	1.6E-07	14.5%
Prostate	0.0E+00	4.1E-08	4.0E-07	8.2E-08	7.5%
Thyroid	3.4E-09	2.6E-08	1.6E-07	4.1E-08	3.8%
Male genitalia	0.0E+00	2.2E-08	1.9E-07	3.8E-08	3.5%
Leukemia	8.2E-09	3.0E-08	1.1E-07	3.8E-08	3.4%
Bladder	0.0E+00	2.3E-08	1.6E-07	3.6E-08	3.3%
Oral Cavity and Pharynx	0.0E+00	2.2E-08	1.1E-07	3.0E-08	2.8%
Kidney	0.0E+00	2.1E-08	1.1E-07	2.9E-08	2.6%
Stomach	0.0E+00	1.1E-08	1.4E-07	2.7E-08	2.4%
Digestive system (other)	3.1E-10	1.2E-08	9.3E-08	2.1E-08	1.9%
Salivary gland (parotid)	1.5E-09	1.3E-08	8.4E-08	2.1E-08	1.9%
Rectum	0.0E+00	9.1E-09	6.3E-08	1.5E-08	1.4%
Acute Myeloid Leukemia	2.5E-09	1.0E-08	4.2E-08	1.3E-08	1.2%
Non-Hodgkins Lymphoma	0.0E+00	2.7E-09	6.3E-08	1.1E-08	1.0%
Chronic Myeloid Leukemia	1.5E-09	8.0E-09	3.8E-08	1.0E-08	0.9%
Nervous system	0.0E+00	6.7E-09	4.2E-08	1.0E-08	0.9%
Salivary gland (non-parotid)	3.5E-11	6.1E-09	3.7E-08	9.3E-09	0.8%
Pancreas	0.0E+00	4.6E-09	4.1E-08	9.0E-09	0.8%
Acute Lymphocytic Leukem	5.3E-10	4.5E-09	2.6E-08	6.5E-09	0.6%
Ureter	0.0E+00	4.2E-09	2.6E-08	6.5E-09	0.6%
Multiple Myeloma	0.0E+00	2.5E-09	3.9E-08	6.3E-09	0.6%
Esophagus	0.0E+00	1.2E-09	4.1E-08	6.2E-09	0.6%
Gallbladder	0.0E+00	7.8E-10	2.2E-08	3.2E-09	0.3%
Nasal	0.0E+00	2.0E-09	1.3E-08	3.1E-09	0.3%
Larynx and other respiratory	0.0E+00	0.0E+00	2.2E-08	2.2E-09	0.2%
Breast	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Cervix	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Female Genitalia	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Ovary	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Uterus	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Total ELR/mRem	3.6E-07	1.1E-06	3.3E-06	1.1E-06	

Female Age 20

Female	Excess Lifetime Risk/mRem				
	95% uncertainty range				
Cancer_type	lower	central	upper	Mean	Contribution
Lung	7.3E-08	3.5E-07	1.6E-06	4.8E-07	25.0%
Breast	9.3E-08	3.4E-07	1.3E-06	4.3E-07	22.6%
Urinary organs (all)	2.5E-08	2.0E-07	1.6E-06	3.8E-07	19.8%
Colon	2.2E-08	1.1E-07	5.3E-07	1.5E-07	8.0%
Thyroid	9.2E-09	6.3E-08	4.6E-07	1.0E-07	5.3%
Stomach	5.1E-09	3.7E-08	3.3E-07	7.4E-08	3.9%
Ovary	3.1E-09	3.2E-08	1.3E-07	4.3E-08	2.3%
Bladder	4.2E-09	2.8E-08	1.3E-07	3.8E-08	2.0%
Leukemia	5.3E-09	1.9E-08	6.7E-08	2.4E-08	1.2%
Esophagus	3.5E-10	1.1E-08	7.6E-08	1.8E-08	0.9%
Digestive system (other)	1.1E-10	8.4E-09	6.0E-08	1.3E-08	0.7%
Oral Cavity and Pharynx	0.0E+00	8.4E-09	4.8E-08	1.3E-08	0.7%
Kidney	0.0E+00	9.3E-09	4.8E-08	1.3E-08	0.7%
Female Genitalia	0.0E+00	0.0E+00	1.0E-07	1.3E-08	0.7%
Acute Myeloid Leukemia	2.3E-09	9.2E-09	3.3E-08	1.1E-08	0.6%
Salivary gland (parotid)	5.1E-10	5.9E-09	4.5E-08	9.7E-09	0.5%
Rectum	0.0E+00	4.3E-09	3.3E-08	7.6E-09	0.4%
Nervous system	0.0E+00	4.7E-09	2.9E-08	7.3E-09	0.4%
Liver	0.0E+00	2.4E-09	3.4E-08	6.5E-09	0.3%
Pancreas	0.0E+00	3.2E-09	2.8E-08	5.7E-09	0.3%
Chronic Myeloid Leukemia	2.1E-10	3.5E-09	1.7E-08	4.7E-09	0.2%
Non-Hodgkins Lymphoma	0.0E+00	1.2E-09	2.5E-08	4.4E-09	0.2%
Cervix	0.0E+00	0.0E+00	4.1E-08	4.3E-09	0.2%
Salivary gland (non-parotid)	2.5E-11	2.7E-09	1.8E-08	4.3E-09	0.2%
Multiple Myeloma	0.0E+00	1.5E-09	2.0E-08	3.8E-09	0.2%
Uterus	0.0E+00	0.0E+00	3.4E-08	3.7E-09	0.2%
Acute Lymphocytic Leukem	2.8E-10	2.4E-09	1.3E-08	3.4E-09	0.2%
Gallbladder	0.0E+00	8.3E-10	1.7E-08	2.5E-09	0.1%
Ureter	0.0E+00	1.5E-09	1.0E-08	2.4E-09	0.1%
Nasal	0.0E+00	7.9E-10	5.4E-09	1.2E-09	0.1%
Larynx and other respiratory	0.0E+00	0.0E+00	4.6E-09	5.2E-10	0.0%
Male genitalia	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Prostate	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0%
Total ELR/mRem	6.1E-07	1.6E-06	4.2E-06	1.9E-06	