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Interactive Radio Epidemiological Program Use for DoD Ionizing Radiation Exposures

Steven E. Rademacher

Final

21 October 2021

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
21-10-2021	Final	August 2020 - July 2021

4. TITLE AND SUBTITLE
Interactive Radio Epidemiological Program Use for DoD Ionizing Radiation Exposures

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Steven E. Rademacher, DAF, GS-15

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Headquarters, Air Force Safety Center
Weapons Safety Division
9700 Avenue G, Southeast
Kirtland AFB, NM 87117-5670

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Headquarters, Air Force Safety Center
Weapons Safety Division
9700 Avenue G, Southeast
Kirtland AFB, NM 87117-5670

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A: Approved for Public Release.

13. SUPPLEMENTARY NOTES DISCLAIMER "The views expressed are those of the authors and do not reflect the official guidance or position of the United States Government, the Department of Defense or of the United States Air Force."

14. ABSTRACT
DoD Services have a responsibility to provide dose estimates for veterans exposed to radiation during their service to meet the needs of the Veterans Administration (VA) in health claims adjudication. The Interactive Radio Epidemiological Program (IREP) was developed as an assessment tool for probability of causation. The genesis for IREP dates back to 1985 VA work. Defense Threat Reduction Agency (DTRA) contracted development of a report with radiation dose screening levels in 2007. This report was focused on Atomic Veteran claims, where primary concern was acute exposures to external gamma radiation. In contrast, most DoD personnel with occupational radiation exposures are chronic in nature, and can include neutrons, low-energy photons, and internal exposures to alpha particles. This report provides focused examples on the latter exposure types, with details on internal doses from inhalation of weapons grade plutonium.

15. SECURITY TERMS
IREP Veterans Administration Department of Defense ionizing radiation exposure Air Force
plutonium probability of causation radiation dose cancer

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Steven E. Rademacher
Unclass	Unclass	Unclass	Unclass	101	19b. TELEPHONE NUMBER *(Include area code)*

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α	alpha
ACS	American Cancer Society
AF	Air Force
ALL	acute lymphoid leukemia
AMAD	activity median aerodynamic diameter
AML	acute myeloid leukemia
β	beta
B	baseline probability of incurring a specific cancer absent radiation exposure
BS	bone surfaces
CED	committed equivalent dose
CFR	Code of Federal Regulations
CL	credibility level
CLL	chronic lymphocytic leukemia
CML	chronic myeloid leukemia
CV	coefficient of variation
DNA	Defense Nuclear Agency
DoD	Department of Defense
DOE	Department of Energy
DOL	Department of Labor
DTRA	Defense Threat Reduction Agency
E	energy
EEOICPA	Energy Employees Occupational Illness Compensation Program
ERR	excess relative risk

GI	gastrointestinal
HHS	Department of Health and Human Services
ICRP	International Commission of Radiological Protection and Measurements
IREP	Interactive Radio Epidemiological Program
keV	kiloelectron volt
n	neutron
NCI	National Cancer Institute
NIH	National Institute for Health
NIOSH	National Institute for Occupational Safety and Health
NTPR	Nuclear Test Personnel Review
PoC	Probability of Cancer
Q	quality factor
R	probability of incurring specific cancer due to radiation exposure
RBE	relative biological effect
REF	radiation effectiveness factor
VA	Veterans Administration
w_R	radiation weighting factor

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1.0 Introduction.

Services within the Department of Defense (DoD) have responsibility to provide dose estimates for veterans exposed to radiation incurred from their service to meet the needs of the Department of Veterans Affairs (VA) in adjudicating service-related radiation exposure claims. The Interactive Radio Epidemiological Program (IREP) was developed for use by the National Institute for Occupational Safety and Health (NIOSH) and the National Institute of Health (NIH) as an assessment tool that provides estimates of probability of causation (PoC) for individuals with cancer and exposed to ionizing radiation (NIOSH 2007). The genesis for IREP was based on NIH radio epidemiological tables developed in 1985 for adjudication of claims by the VA. In 1985, tables were developed for 13 cancer sites in humans, with the current IREP code including 32 cancer sites. It is important to note that individuals with occupational exposures to radiation may have non-cancerous health conditions where concern exists for a causative link to radiation exposures. IREP was not developed as a technical aid for these types of health conditions.

Two versions of the IREP code are supported, one for use by the VA maintained by the National Cancer Institute (NCI) and one by NIOSH for Department of Labor (DoL) claims, primarily those under the Energy Employees Occupational Illness Compensation Program (EEOICPA) [HHS 2005]. The NCI is within the NIH and subsequently the Department of Health and Human Services (HHS). The codes use similar parameters, though there is a difference in modelling of PoC for lung cancer.

This report was written as a guide for Air Force (AF) individuals responsible for calculation of veteran doses for VA claims. Due to some similarities in radiation exposure cohorts among the services, it will be useful for all DoD services. For example, individuals exposed during the DoD's Operation Tomodachi response complicated by the Fukushima Daiichi Nuclear Power Station disaster, the Enewetak Atoll clean-up that was multi-service, and intrinsic radiation received by those performing nuclear weapons maintenance. For individuals completing dose estimates, it is beneficial to understand factors that are important in calculation of doses, e.g., age of exposure, period between exposure and disease diagnosis, cancer types, and radiation types. This report was prompted by a similar report completed by Kocher and Apostoaei (2007) for Defense Threat Reduction Agency (DTRA). That report provided screening doses for all 32 cancer sites covered under IREP. It was primarily focused on nine cancer sites that exist within IREP which are not presumptive for compensation under 38 CFR 3.309(d)(2), *Disease Subject to Presumptive Service Connection* (Kocher and Apostoaei 2007). The authors noted two common cancers observed in veterans, yet not deemed presumptive: skin and prostate cancers. The 2007 report modelled PoC for acute radiation exposure conditions from high-energy photons, except for the skin, where electrons with energies greater than 15 keV were modelled. The authors used this approach since most cases managed by DTRA are Atomic Veterans where important exposures supporting atmospheric testing of nuclear weapons were received in an acute manner.

This report differs from the DTRA report in a number of ways. First, most occupational exposures to ionizing radiation are received on a chronic basis. Thus, only chronic exposure

conditions are used in IREP for examples in this report. Kocher and Apostoaei (2007) should be reviewed and referenced for acute exposure scenarios, or independent calculations using IREP. Second, though all 32 cancer sites covered by IREP are modelled for high-energy photons (E > 250 keV) some examples are provided for lower energy photons (30 < E < 250 keV), neutrons of energy between 0.1 and 2 MeV, and alpha (α) particles. These four groups of radiation cover the key DoD occupational exposure conditions. Comparisons in the radiation effectiveness factor (REF) are provided to illustrate the differences for the radiation types considered. These factors can be important for exposures where dosimetry monitoring is accomplished for individuals with multiple sources of radiation exposure. A common example where a mixture of exposures can occur is in medical treatment facilities, where exposures from both high- and low-energy photons can occur.

This report will provide examples of internal dose modelling for inhalation intakes of ^{239}Pu. Internal dose modelling under IREP is different from most dose modelling where external radiation exposures are involved. For long-lived radioactive materials like ^{239}Pu and where the element has long retention periods within tissues after an intake, PoC can be considerably different than the case where all dose is assumed to be incurred at the time of exposure (i.e., time of "intake" for internal exposures). ^{239}Pu internal exposure are important for a number of DoD exposure cohorts: veterans supporting recovery operations for the 1966 Palomares and 1968 Thule nuclear weapon accidents, veterans with assignments to Johnston Atoll including those involved with weapons grade plutonium clean-up work, and veterans involved with the cleanup of Enewetak Atoll between 1977 and 1980. This report provides a comparison of key differences in PoC for key organs of exposure from ^{239}Pu in use of International Commission on Radiological Protection (ICRP) metabolism-based models and where all dose is assumed to be acquired at the time of intake. The latter is used in radiation protection management for assessment compliance with annual limits on exposures. It is not appropriate for PoC calculation for some radioactive material intakes. For this type of exposure scenario, the concept of "screening intake" is more appropriate because it incorporates the temporal basis of dose accumulation for internal emitters.

For some exposure cases from α-particles, external dose to the skin is a possible exposure route. In these cases, the α-particle exposure model is more appropriate than that for high-energy photons. Dose to the basal cells of skin from α-particles is generally negligible due to the expected absorption of most α-particle kinetic energy within the epidermal layer. However, at one location on Enewetak Atoll, ^{232}Th existed as a key residual from atmospheric tests. Alpha particles emitted by short-lived daughters of ^{220}Rn, in the ^{232}Th decay chain provide a much higher dose to the basal layer of skin than those from ^{232}Th, ^{241}Am, ^{239}Pu, and other long-lived α-particle emitters.

Many IREP calculations for VA applications have used 50% PoC at the 99% credibility level (CL). This index merges important regulatory concepts for assessments under 38 CFR 3.311 that the VA must consider:

1) "probable dose, in terms of dose type, rate, and duration," [38 CFR 3.311(e)(1)]

2) the determination if it is "at least likely as not the veteran's disease resulted from exposure in service," [38 CFR 3.311(c)(1)(i)] and

3) "taking into account any limitations in the dosimetry devices employed in its measurement or the methodologies employed in its estimation." [38 CFR 3.311(e)(1)]

For example, 50% PoC at the 50% CL meets criterion 2) above, while uncertainties in the criterion of 1), as required by 3), and uncertainties in cancer induction rates have been implied as a justification for the 99% CL criterion. Nevertheless, the 99% CL criterion and incorporation of uncertainties in cancer induction models are not detailed in 38 CFR. This report provides some example comparisons of the equivalent dose values for the 50% and 99% CL. The ratios between these criteria are commonly more than 10-fold. Under these circumstances, uncertainties in dose are dwarfed by that associated with cancer induction models. Some examples are also provided to demonstrate the variability introduced by separate factors.

Finally, it is important to understand that the DoD's involvement in VA's adjudication of claims is primarily limited to assessment of exposure potential and organ doses. Supporting details regarding the type of radiation, exposure circumstances, and/or uncertainties are also commonly provided by the DoD, as needed, and if available depending on the particular exposure. The VA is tasked with the determination of PoC for radiation exposure claims. As such, this document should not be interpreted by veterans or users as a basis for PoC assessments by the VA. Since this report has this limitation, NIOSH Version 5.8.2 of IREP was used for all calculations, except for acute lymphoid leukemia (ALL) from α-radiation were NIOSH provided an update for this cancer site in IREP. The IREP model is readily accessed through the internet at the Oak Ridge Center for Risk Analysis.

2.0 Probability of Causation.

Land *et al.* (2003) define the "probability that a cancer in an individual was caused by prior exposure to ionizing radiation" - PoC as:

$$PoC = {}^{R}/_{(R+B)},$$

where R is the probability of incurring a specific cancer due to the radiation exposure and B is the baseline (background) probability of incurring the cancer, absent the radiation exposure. IREP calculates PoC on an "estimate of the excess relative risk (ERR) associated with a given radiation dose to an organ or tissue in which a cancer occurred" (Kocher and Apostoaei 2007). ERR values are based on estimates obtained from epidemiological studies of populations exposed to radiation. The Japanese atomic bomb survivor follow-up studies have been a primary source of risk data. IREP applies a REF to the type of radiation absorbed in the organ of interest. It is important to note that equivalent dose used as an input to IREP, where radiation weighting factors from ICRP Report 60 (ICRP 1990) are used. The radiation weighting factors, w_R, for electrons, photons, and α-particles are the same in the more recent ICRP Report 103 (ICRP 2007) and ICRP Report 26 (ICRP 1977) where the term dose equivalent was used to modify dose by a radiation-specific quality factor, Q. For the purposes of this report, the units of equivalent dose and dose equivalent are interchangeable, with the former term being used. Some differences exist for neutrons among ICRP Reports 26, 60, and 103, dependent on energy. Table A-1 provides a summary of w_R and Q for various radiations. Figure A-1 illustrates the subtle difference between the continuous functions for w_R of ICRP Reports 60 and 103. An important aspect of w_R and Q are these factors were developed to

account for the relative effectiveness of different radiations to induce cancer (e.g., malignancies). Induction of malignancies is a stochastic process, as are the induction of genetic effects. Other effects of radiation are termed deterministic effects, where historically they have been attributed to a threshold dose, below which the effect is not observed. The threshold doses for these health effects may be varied, though the RBE of the varied radiation effects could be different than those attributed to cancer induction.

IREP contains eleven different radiation and energy range options for users. Table 2-1 contains a listing of the combinations along with common DoD exposure scenarios for both internal radionuclide contamination and external radiation sources. The recommendations of Ochin (2007) for the majority of Atomic Veteran cases are listed for informational purposes. The Atomic Veteran cases are commonly managed solely by the Defense Threat Reduction Agency (DTRA), while other occupational exposure cases are managed by the individual services. Withstanding unusual exposure circumstances, occupational exposure cases managed by the individual services will be for chronic exposure conditions. In contrast, most Atomic Veteran cases use an acute exposure condition for external dose, while for internal doses, chronic exposure conditions are appropriate. The matrix in Table 1 was developed for most exposure circumstances. Among historical and current exposure conditions for DoD personnel, the most common exposures are from external

TABLE 2-1. Radiation Type Matrix for Various DoD Exposure Scenarios.

IREP Radiation Category	Exposure Type	
	External	Internal
Electrons: E < 15 keV		tritium
Electrons: E > 15 keV	fission products, atomic veterans	fission products, atomic veterans
Photons: E < 30 keV	medical mammography	
Photons: 30 < E < 250 keV	ortho-voltage medical x-rays, NDI x-rays, fission products	fission products
Photons: E > 250 keV	atomic veterans, ^{137}Cs & ^{60}Co irradiators, fission products, nuclear weapon maintenance workers	fission products, atomic veterans
Neutrons: E < 10 keV	light-water reactors	unlikely exposure
Neutrons: 10 < E < 100 keV	N/A	
Neutrons: 0.1 < E < 2 MeV	atomic veterans, nuclear weapon maintenance workers, ^{252}Cf neutron sources, fast-burst reactors	
Neutrons: 2 < E < 20 MeV	^{239}Pu:Be, ^{241}Am:Be & other neutron sources (unshielded)	
Neutrons: E > 20 MeV	N/A	
Alpha Particles	skin (retained, surface-deposited contamination)	uranium & plutonium intakes [Palomares, Johnston Atoll, atomic veterans]

Atomic Veteran recommendations for most cases by Ochin (2007).

radiation sources and involve photons. Photons exposures are divided into three energy (E) ranges: < 30 keV, 30 < E < 250 keV, and > 250 keV. Although some radioisotopes may provide low-energy photons, the most common source of low-energy photons would be for medical providers supporting mammography x-ray examinations. Most other medical x-rays and fluoroscopy would fall within the 30 < E < 250 keV photon range, commonly termed orthovoltage. Most common radioisotope irradiators have historically used ^{137}Cs and ^{60}Co sources, where the energy would be > 250 keV. The photon energy ranges for fission product sources can reasonably fall within the two higher energy bins. While fission product exposures can come from discrete sources, where the energy of the photons are well known, the term fission products can be applied to a mixture of fission products, as applicable to individuals that had low-level exposures from the Fukushima Daiichi Nuclear Power Station (FDNPS) accident in March 2011 or the Chernobyl Nuclear Power Plant Disaster in April 1986. For each of these exposure cases, the majority of photon contribution to dose was from photons with E > 250 keV. This is also normally the case for Atomic Veterans that were exposed to fission products produced from atomic detonations.

For individuals exposed to electrons from an external exposure condition, the majority of exposures would fall into the higher of the two energy categories: E > 15 keV. In this case, exposures to the skin are generally of concern. With the exception of high-energy β-particles, deep tissues are not typically affected. For internal contaminants, which liberate electrons, β-particles, and/or positrons, energies will be in the > 15 keV category, with the common exception for tritium intakes. The average energy of β-particles emitted from tritium are 6 keV.

Due to wide-range in w_R for neutrons, five different energy range options are provided. For Atomic Veterans and nuclear weapon maintenance workers, the 0.1 to 2 MeV energy range is the most common, and is due to the neutrons being produced by fission. Nuclear weapons maintenance workers may also be exposed to neutrons generated by (α,n) capture reaction in light metals, e.g., beryllium. The energies would have some similarity to discrete ^{239}Pu:Be and ^{241}Am:Be sources. Sources of this type are common to nuclear density gauges. The lowest energy range for neutrons: < 10 keV should encompass the energies typically encountered by light water reactors. Within the DoD, US Navy propulsion reactors are the most common exposure source, though the AF and Army operated a small number of light water reactors. The US Army currently operates a fast-burst reactor in support of research and development programs, with one decommissioned in the latter 1990s.

The most prominent source of exposure to α-radiation sources is from inhalation and/or ingestion intakes of plutonium and uranium, which subsequently lead to internal dose. Though Atomic Veterans have some predicted intakes, dependent on their support of atmospheric tests, the more common sources of concerns are from veterans that supported clean-ups at Enewetak Atoll, Johnston Atoll, and the Palomares nuclear weapon accident site. Though α-particle emitters deposited on the skin of individuals in support of these efforts can cause irradiation of the dermal layer of skin, most α-particles provide fairly negligible skin dose, as most of the energy is deposited in the epidermal layer. One exception is described in Rademacher (2019) for daughters in the decay chain of ^{232}Th, as applicable to some exposure locations on Enewetak Atoll. Short-lived daughters in this decay chain emit α-particles with much higher kinetic energy than those emitted from ^{234}U, ^{235}U, ^{238}U, ^{239}Pu, and ^{240}Pu.

3.0 Radiation Effectiveness Factors.

REFs used by IREP are analogous to mean quality factors, ($\overline{Q}$), used in ICRP 26 or w_R, used in ICRP 60 and 103. In contrast to point values used in ICRP, as discussed above and listed in Table A-1, IREP uses distributions of potential REF, based on subjective scientific judgement of data from relevant radiobiological studies. The most abundant source of human epidemiological is from the Japanese atomic bomb survivors, where exposures were dominated by acute doses of high-energy γ rays. Hence, many radiation risk models use this data set as a foundation, with modifications for other exposure conditions based on other human epidemiological studies and animals studies. The four general equations used in IREP are listed in Table 3-1, as detailed from Kocher et al. 2002). Among the four equations, three assume a linear response, while a linear-quadratic equation is used for acute exposures to photons and electrons. Though the $DDREF_\gamma$ is not applied to α-particles and neutron exposures, enhancement factors (EF) are used for these radiation types to account for the inverse dose-rate effect.

TABLE 3-1. Cancer Risk Models Used in IREP, from (Kocher et al. 2002).

Risk Equation	Tumor Types	Conditions
$\Re = REF_L \times \frac{R_{\gamma,H}}{DDREF_\gamma} \times D$	Solid	Exposures to photons, electrons, and α-particles. $DDREF_\gamma$ not used for α-particles.
$\Re = REF_H \times R_{\gamma,H} \times D$		Neutron exposures.
$\Re = a\,(REF_L \times D) + b\,(REF_L \times D)^2$	Leukemias	Acute exposures only. Not applicable to neutrons and α-particles.
$\Re = \mathrm{a} \times REF_L \times D$		All exposures to neutrons and α-particles. Low and low dose rate exposures to photons and electrons.

Terms:

- $\Re$ is risk of a particular cancer (ERR) due to exposure to a specific radiation type.
- $R_{\gamma,H}$ is the risk coefficient (ERR per Gy) for a particular solid tumor at high acute doses of high-energy γ rays, which have a set biological effectiveness of 1.0.
- Subscripts L or H in the REF indicates that the REF is derived based on estimates of the relative biological effectiveness (RBE) at low doses and low dose rates, or at high doses and high dose rates of the reference high-energy γ rays.
- $DDREF_\gamma$ is the dose and dose-rate effectiveness factor, which takes into account that, for solid tumors, the ERR per Gy at low doses and low dose rates of photons (and electrons) may be less than the values of $R_{\gamma,H}$ at high acture does obtained from studies of exposed populations.
- a and b are the coefficients of the linear and quadratic terms, respectively, in the assumed linear-quadratic dose-response relationship for leukemias under conditions of acute exposure to high-energy γ rays.
- D is the absorbed dose of the radiation type of concern.

IREP assumes a lognormal probability distribution for the REF for fission neutrons, e.g., energies between 0.1 and 2 MeV. The distribution of REFs for solid tumors and leukemias are shown in Figure 3-1. The respective geometric means (also the medians) are 7.7 and 11 for solid tumors and leukemias. The geometric standard deviations are respectively, 2.0 and 2.4. Figure 3-1 lists the upper bound of the 95% confidence interval for each distribution, 30 and 60, respectively, for solid tumors and leukemias. Figures A-3 and A-4 show the assumed REF probability distributions for neutrons with energies between 10 and 100 keV and 2 to 20 MeV, for solid tumors and leukemias. Consistent with a lower w_R used by ICRP for neutrons of this energy range, compared to fission neutrons, the respective median values are 3.6 and 5.6 for solid tumors and leukemias. The upper bound of the 95% confidence intervals are also much lower than the respective values for fission energy neutrons. Figure A-5 and A-6 show the assumed REF probability distributions for neutrons with energies less than 10 keV and greater than 20 MeV, for solid tumors and leukemias, respectively. Similar to the lower w_R used by ICRP for neutrons of this energy range, compared to fission neutrons, the respective median values are 1.9 and 2.8 for solid tumors and leukemias. A similar characteristic also exists for the 95% confidence intervals. Figure A-7 contains the assumed probability distribution IREP uses for the neutron enhancement factors for exposures of low dose and dose rates.

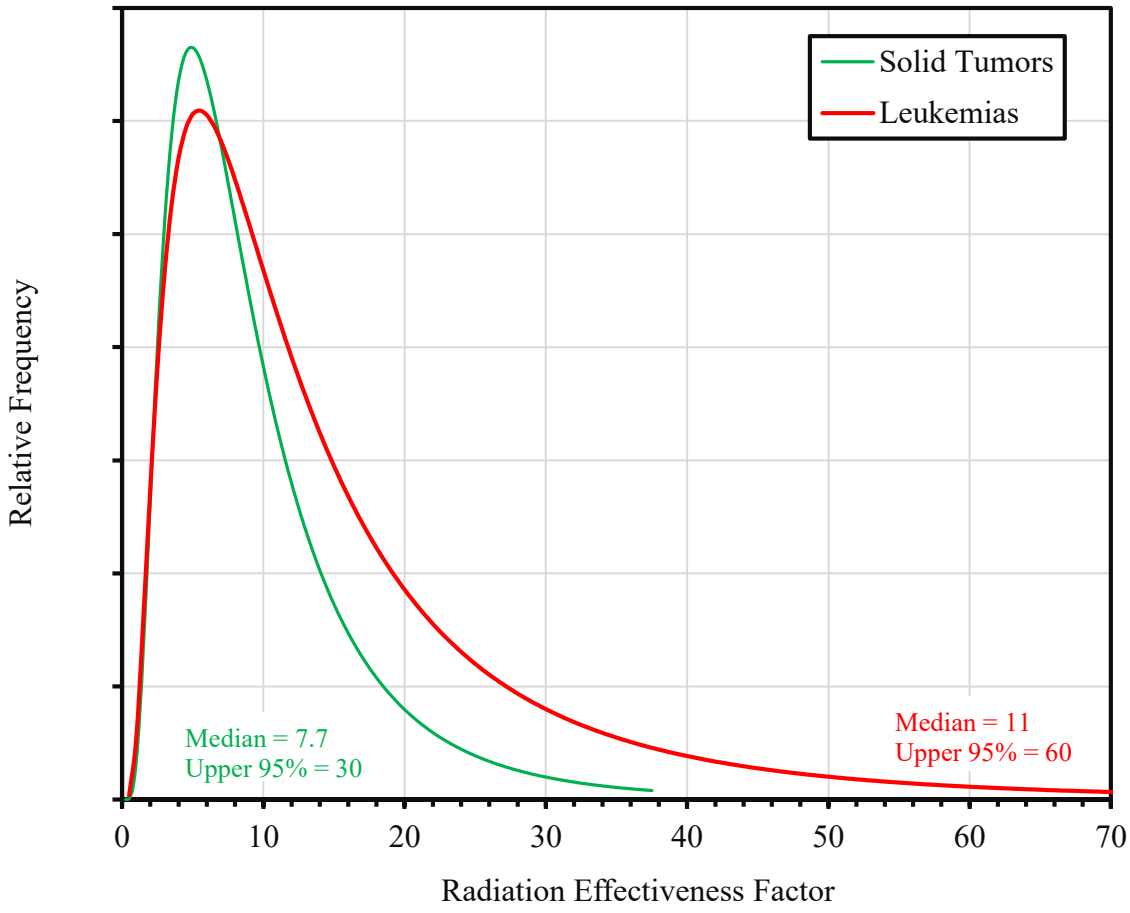

Figure 3-1. IREP Radiation Effectiveness Factors for Fission Neutrons, 0.1 – 2 MeV, Solid Tumors and Leukemias.

The mean of this distribution is 1.4. From a practical standpoint, this should cover all DoD radiation exposures cases for neutrons. Only rare potential exists for a high, acute neutron exposure, e.g., an accidental criticality. Importantly, since the EF and REF are both probabilistic distributions, the combination of these two factors are implemented in IREP, which is termed a joint probability distribution. Figure A-8 shows the combination of these two factors for solid tumors and neutrons with energies between 10 to 100 keV and 2 to 20 MeV (Figure A-3). The combination of the two factors provides for a 1.3-fold increase in the median and 1.5-fold increase in the upper 95% confidence level. The case for the combination of EF and REF for leukemias and fission neutrons are shown in Figure A-9. For the readers benefit, the distribution of REF alone, from Figure 3-1, is also shown along with a listing of minimum, mean, maximum, and median for each distribution. The Monte Carlo simulation used 2,000 events. Due to the limited number of simulations, some caution should be observed in the maximum value for each distribution, which were 251 and 502, respectively for the REF alone and the combined factors. This is a characteristic of un-bounded probability distributions – in this case the lognormal. For this 2,000 event simulation, a factor of two existed between the maximum of each distribution, while theoretically a factor of three is the highest possible. As noted for the distribution of combined factors, seven events had values in excess of 160 (0.35 %). In comparison of the REF alone to combined, the median and upper 95% confidence level are 1.35- and 1.7-fold higher, respectively. For the other neutron energy ranges, the maximum REF alone or combined in a joint probability distribution with EF will be bounded.

Figure A-10 contains the low dose and low dose rate EF distribution used by IREP for α-particles. The distribution is similar to that for neutrons, except that for the higher REF values, the probabilities are lower, with a mean of 1.225, as compared to 1.4 for neutrons. For solid tumors, IREP uses a lognormal distribution for REF from α-particles, as shown in Figure 3-2. The median is about 15, with an upper 95% confidence level at 80. For leukemias and α-particle exposures, IREP uses a hybrid distribution with 50% weight to a lognormal distribution [95% confidence interval (CI) between 1 and 15], 25% weight to a value of 1.0, and 25% to the lognormal distribution used for fission neutrons and leukemia induction. A plot of this REF distribution alone and as combined with the EF is in Figure A-11. A Monte Carlo simulation of 2,000 events was used. For the joint probability distribution, the median and upper 95% confidence level are 4.0 and 42, respectively. The addition of the low dose and dose rate EF raised each of these parameters by a modest factor of 1.14 and 1.24, respectively, for the median and upper 95% confidence level. Exposures to α-particles are always expected to be chronic for DoD exposures.

IREP uses different REF for orthovoltage photons, energies between 20 and 250 keV, and for those with energies below 30 keV. For orthovoltage photons, 75% weight is provided by a lognormal distribution with 95% confidence interval between 1.0 and 5.0, and 25% at a value of 1.0. This distribution is applied to both solid tumors and leukemias. For the case of photons with energies less than 30 keV, IREP assumes an adjustment factor (AF), which applies a triangular probability distribution. The distribution has a lower bound of 1.0, upper of 1.6, and a mode of 1.3. For leukemias. The AF is not applied to leukemias from chronic exposures. The distribution of REF's for orthovoltage photons has the prominent mode at 1.0. Similar to the other REF that incorporate a lognormal distribution, the maximum value reported is dependent on the number of Monte Carlo event simulations and varied for each data set. The median and mean parameters have much closer agreement between independent Monte Carlo simulation data sets.

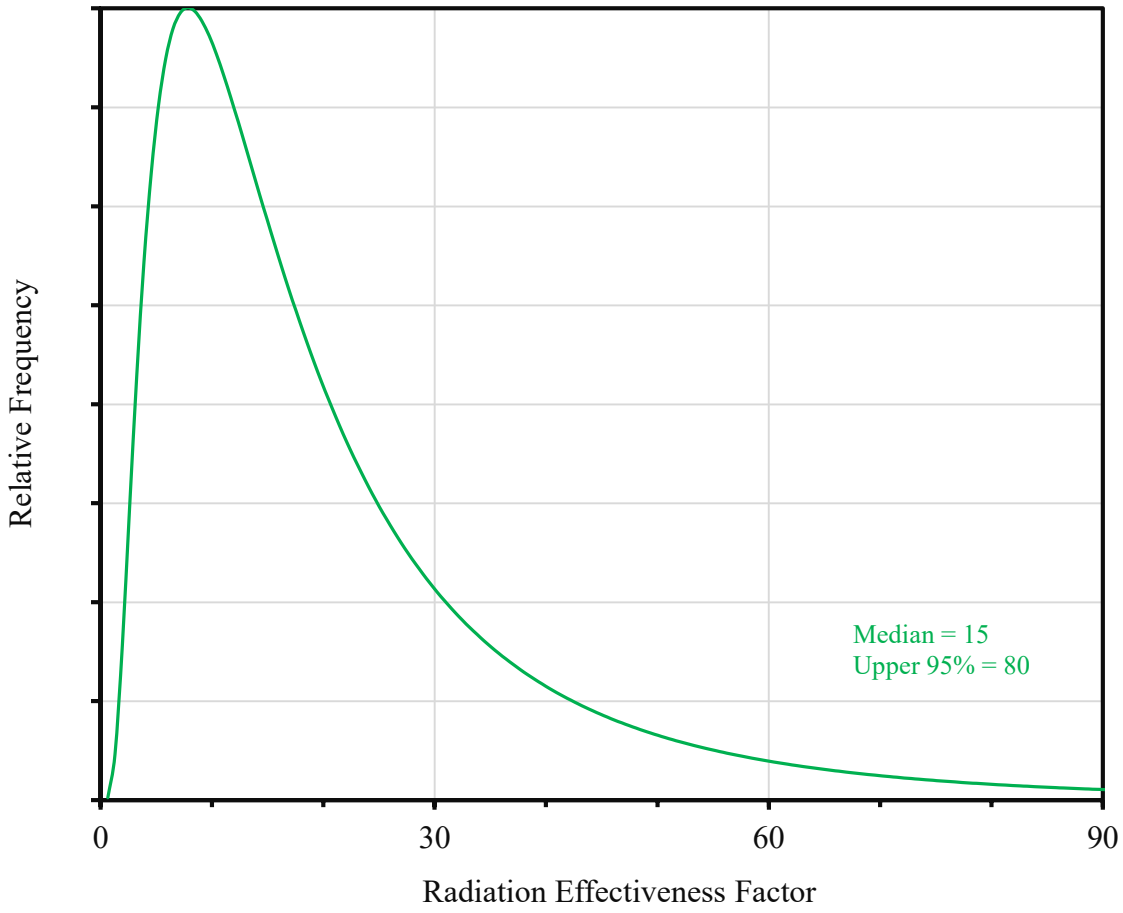

Figure 3-2. IREP Radiation Effectiveness Factors for Alpha Particles, Solid Tumors.

The probabilistic distributions of REF, EF, and AF combined provide key sources of variability in estimates of PoC. Two other important sources of variability also contribute to the variability in estimates of PoC: individual organ risk coefficients and organ dose. The variability in organ dose will be illustrate by some examples later in this report. Table A-4 contains a summary of information provided in this section.

4.0 Radiogenic Diseases, Latency Periods, Models.

Table A-2 contains a listing of radiogenic diseases recognized by the VA under 38 CFR 3.311(b)(2)(i). The majority of conditions recognized are malignancies, with exceptions being non-malignant thyroid nodular disease and posterior subcapsular cataracts. The time of disease on-set is an important consideration for most of the radiogenic diseases, as detailed in Table A-2. For most cancers, there is a minimum latency period of five years between the exposure and manifest evidence of disease. Exceptions are for induction of leukemias, which can be manifest at any time after exposure. Primary bone cancers, e.g., most commonly osteosarcomas, must become manifest within 30 years after exposure. The 30-year condition is confounding for assessment of internal

exposures to the bone for radionuclides with both long biological retention and radiological half-lives. This is a key issue for internal exposures to ^{239}Pu, where plutonium is modelled to have long-term retention in the bone and the liver, well after an inhalation and/or ingestion intake. The rules listed in 38 CFR 3.311(b)(5)(i)-(iv) were developed in response primarily to ionizing radiation exposure conditions listed 38 CFR 3.309, where doses were incurred over brief periods, and primarily from external radiation sources, e.g., Atomic Veterans. Hence, for an exposure to the bone from a long-lived internal emitter like ^{239}Pu, the latency period is an ambiguous term. Nevertheless, primary bone cancers are very uncommon[1] and have only been associated with high radiation doses, congruent with those associated with medical therapy (Boice 2005).

Concerning latency period, it is important to distinguish between the criterion in 38 CFR and provisions in IREP to account for minimum latency periods. IREP implements a probabilistic approach to incorporate this factor, among others in the calculation of PoC. The plot in Figure A-2 from Kocher and Apostoaei (2007) illustrates the PoC adjustment for latency periods for most solid tumors, based on different % CL values. For these cancers, the 1, 50, and 99th percentile are about 4, 7.5, and 11 y for the 50% CL. For 99% CL, the respective values are 1.8, 5.3, and 8.8 y. For thyroid and bone cancer, the central value is 4.5 y, while for leukemias it is 2.25 y (Kocher and Apostoaei 2007).

Table A-3 lists the tissues that are covered by IREP, with specification of the risk model used in IREP for the cancers within each group. The details provided here are summarized from Kocher and Apostoaei (2007). Group 1 cancers have ERR varied by both the age of exposure at the age at diagnosis, also referred to as attained age. For the age of exposure, the ERR decreases linearly with increasing age, up to 50, above which it remains constant. For the age of diagnosis, there is an exponential decrease between the ages of 15 and 30, and above 30, it remains constant. The cancers in Group 1 are those types with strong incidence by numbers within the Japanese atomic bomb survivor cohort. Group 2 cancers are modelled in a similar manner to Group 1, however, these cancers were not observed to the same degree as those in Group 1. Due to lower incidence, approximations of ERR were deemed more appropriate for use in IREP. As noted in Table A-3, a lung model available as an option in IREP uses Group 2 assumptions. This model is varied, dependent on the workers' smoking history. Group 3 cancers, e.g., another lung cancer model, is independent of age of exposure and age of diagnosis. Group 4 cancers, which include three skin cancer types, blood forming organs and lymphatics, and the lung based on radon exposures. Each type has a unique model. Characteristics of each can be observed by viewing the example PoC charts provided later in this report and by reviewing Kocher and Apostoaei (2007).

5.0 Examples for Chronic Exposures to Photons E > 250 keV.

Tables B-1 through B-31 provide PoC screening doses for chronic exposures to photons, $E > 250$ keV for all but two of the IREP tissue options. With exception of the ovaries and other female genitalia, the models are based on males. For all examples, the 50% PoC at the 99% CL are

[1] Primary bone cancers account for much less than 1% of all cancers. Osteosarcomas are most common for individuals between ages 10 and 19, while chondrosarcomas are more prominent in adults over the age of 40. (NCI 2008)

provided. In review of the tables, it is noteworthy that the liver, stomach, and thyroid all have relatively low screening doses for individuals exposed as young adults, provided reasonable latency periods between the exposure and disease diagnosis. These three tissues have well established higher radio sensitivity among tissues in humans. In contrast, other screening dose levels are significantly higher for tissues that have relatively low to negligible radio sensitivity to cancer induction, namely tissues in the other female genitalia, male genitalia (including prostate gland), nervous system tissues, the lymphatic system for chronic lymphocytic leukemia (CLL), the skin for squamous cell carcinomas, rectum, tissues in the other respiratory category, and the oral cavity and pharynx. Due to the relatively-high screening doses for these malignancies, it is highly unlikely that DoD exposure conditions would be sufficient within the criteria. Of note, for photons: $E > 250$ keV, the w_R is one, with dose and equivalent dose having the same value. IREP version 5.8.2 was used for all cases, except for ALL from α-particles. In December 2020, IREP version 5.9 was introduced, which had minor changes in PoC for ALL from α-particles and neutrons.

For a majority of the screening dose tables, the screening dose is constant beyond certain age of exposures and latency periods. Since many veteran claim submissions are for those advanced in years and with reasonably long latency periods, these values are more likely applicable to many exposure cases. For veterans with exposures over a broad period of service, these simplified tables will be a little different from an IREP modelling of exposures received over many years. IREP considers exposure inputs on an annual basis.

One notable characteristic for the majority of malignancies are higher dose levels for the 5-y latency period. This is most prominent for the majority of solid cancers as discussed above. Notable exceptions are for cancers of the bone and thyroid, which is due to the shorter latency period adjustment, and for leukemias, which is even lower.

In the case of ALL, the screening dose for individuals 20 and older is constant and unvaried by latency period. For AML and CML, screening doses are constant for all ages of exposure considered in ages considered in the modelling for this report, though they increase by latency period. Though both malignancy types have this characteristic, the range of screening doses for AML for a five to 40 year latency is 5.8 to 45 rem, which in the case of CML, range from 1.3 to 262 rem. Clearly, for either type of myeloid leukemia, the causative links to radiation exposure are much stronger for the shorter latency periods than later. In the case of CML and for latency periods beyond 20 years, exposures of these magnitudes would be highly unlikely for DoD veterans. Notable exceptions would be a very small group of Atomic Veterans.

Skin malignancies of melanoma and basal cell have similar screening doses for white males, as shown in Tables B-14 and B-15. Though the screening doses are reasonably low for ages of exposure up the mid-20's and latencies over five years, screening levels are much higher for exposures at older ages. Squamous cell carcinomas have the same screening dose for exposures of any age with a latency period beyond about five years. These skin cancers, nevertheless, are a negligible link to radiation exposure in comparison to basal cell and melanomas. The latter skin cancer types have low susceptibility.

6.0 Examples for Chronic Exposures to 30 – 250 keV Photons.

Example PoC screening doses for chronic exposures to photons with energies between 30 and 250 keV are provided in Appendix C for a smaller number of cancer sites than provided in the previous section for photons with energies greater than 250 keV. A smaller set was considered for brevity sake, with a primary purpose of illustrating differences in REF for the various radiations considered by IREP. Nevertheless, the examples were for cancer sites that are more commonly observed over the lifespan of males. Lifetime probabilities of developing and dying from cancer for 23 sites are listed in Table C-1, based on American Cancer Society (ACS) Surveillance Research over the period 2010 to 2012 (ACS 2016). The lifetime risk for all sites among males was 42.1 %, excluding basal and squamous cell skin cancers, and most in-situ cancers. Among males, sites with the highest probability of developing cancer were the prostate, lung (and bronchus), colorectal, and urinary bladder. All four of these had PoC calculations, with the addition of liver, thyroid, and acute leukemias. The liver was included because it is an organ with relatively-high deposition and retention of plutonium, a key concern for some AF internal exposure cases, and has a moderate incidence of 1.3% among males from the recent ACS statistics. Incidence of acute leukemias were also included since leukemias are a common malignancy studied among individuals exposed to radiation. Though the thyroid has a lower incidence in the recent ACS statistics among males, 0.6%, its induction is commonly related to intakes of radioiodines, which are released to the atmosphere from nuclear weapon detonations and nuclear reactor accidents, e.g., Chernobyl and FDNPS.

Tables C-2 through C-9 provide PoC screening doses for chronic exposures to photons: $30 < E < 250$ keV for the eight malignancies. The tables have similar distributions of equivalent dose in comparison to those for photon energies greater than 250 keV when the same malignancy is considered. Nevertheless, as shown by the plots in Figures C-1 through C-8, the fraction of equivalent dose at the 50% PoC, 99% CL is consistently lower for photons of energy: *30* - 250 keV, as compared to > 250 keV. With the exception of the acute leukemia malignancies, the higher fractions are observed for the 5-y latency period. A summary of the range of fractions are in Table 6-1. For acute leukemias, higher ratios are observed in short and long latency periods, with lower fractions at intermediate latencies. Overall, the fractions range from 0.29 to 0.50, and reflect a higher REF for the lower energy photons, compared to those with energy greater than 250 keV. It is important to note that ICRP 60 and 103 do not recommend a higher w_R for the lower energy photons. Also, the ratio of screening doses among the organs assessed are higher than the median REF of 1.9 used by IREP. This is due to evaluation of screening levels at the 99% CL.

TABLE 6-1. Fraction of Equivalent Dose for $30 < E < 250$ keV Photons Compared to Photons $E > 250$ keV, at 50% PoC at 99% Credibility Level for Select Malignancies, Ages of Exposure: 18, 21, 25, 30, 35, 40, and 45 years, with Period between Exposure and Disease Diagnosis 5 to 40 y.

Malignancy	Range of Fractions	Range of Fractions	Range of Fractions
Colon	0.32 – 0.44	Bladder	0.32 – 0.44
Liver	0.38 – 0.47	Thyroid	0.39 – 0.44
Lung	0.32 – 0.41	ALL	0.34 – 0.46
Male Genitalia*	0.36 – 0.50	AML	0.29 – 0.38

* Also prostate.

7.0 Examples for Chronic Exposures to 0.1 – 2 MeV Neutrons.

Example PoC screening doses for chronic exposures to neutrons with energies between 0.1 and 2 MeV are provided in Appendix D for a smaller number of cancer sites than provided for photons with energies greater than 250 keV. Similar to the examples of PoC for photons with energies between 30 and 250 keV, a smaller set was considered for neutrons, with the primary purpose of illustrating differences in REF for the various radiations considered by IREP. Some cancers sites were also chosen due to prevalence in the male population, e.g., colorectal, prostate, urinary bladder, and lung (and bronchus). The breast and acute myeloid leukemia (AML) were also included for neutrons. Tables D-2 through D-8 provide PoC screening doses for chronic exposures to neutrons: $0.1 < E < 2$ MeV for the seven malignancies. The tables have similar distributions of equivalent dose in comparison to those for photons when the same malignancy is considered. Nevertheless, as shown by the plots in Figures D-1 through D-7, the fraction of equivalent dose at the 50% PoC, 99% CL is consistently lower for neutrons of energy: $0.1 < E < 2$ MeV, as compared to photons of energy > 250 keV. Exceptions exist for the 18 and 21 y ages of exposure with a 5-y latency, however. With the exception of the AML, the higher fractions are observed for the 5-y latency period. For AML, higher ratios are observed in short and long latency periods, with lower fractions at intermediate latencies.

A summary of the range of fractions are summarized in Table 7-1. Overall, the fractions range from 0.27 to 0.50, and reflect a higher REF for the neutrons in this energy range, as compared to high energy photons. Overall, the fractions range from 0.27 to 1.02, and generally reflect a higher REF for the neutrons, as compared to high-energy photons. The observation of the higher fractions are mostly limited, in these examples, to the 5-y latency period. Similar to the observation of screening doses for low-energy photons, as compared those of high-energy photons, the effective REFs are greater than ICRP 60 and 103 w_R values for fission neutrons, though the mean and median of the combined REF and EF are less than the w_R of 20 for solid tumors. This is due to evaluation of screening levels at the 99% CL. The effect is even greater for AML, which is due to the higher combined REF and EF for leukemias, compared to the joint probability distribution for solid tumors.

TABLE 7-1. Fraction of Equivalent Dose for $0.1 < E < 2$ MeV Neutrons Compared to Photons $E > 250$ keV, at 50% PoC at 99% Credibility Level for Select Malignancies, Ages of Exposure: 18, 21, 25, 30, 35, 40, and 45 years, with Period between Exposure and Disease Diagnosis 5 to 40 y.

Malignancy	Range of Fractions	Range of Fractions	Range of Fractions
Colon	0.70 – 0.86	Male Genitalia (also Prostate)	0.67 – 0.86
Liver	0.65 – 1.02		
Lung	0.59 – 0.84	Bladder	0.64 – 0.86
Breast	0.51 – 0.94	AML	0.27 – 0.38

8.0 Examples for Chronic Exposures to Alpha Particles.

Example PoC screening doses for chronic exposures to α-particles are provided in Appendix E for a smaller number of cancer sites than provided for photons with energies greater than 250 keV.

Similar to the examples of PoC for photons with energies between 30 and 250 keV and neutrons, a smaller set was considered with the primary purpose of illustrating differences in REF for the various radiations considered by IREP. Some cancers sites were also chosen due to prevalence in the male population, e.g., colorectal, prostate, urinary bladder, and lung (and bronchus). The liver, bone, and acute leukemias were specifically included because they arise from dose to organs with preferential deposition and long-term retention of plutonium, whereby α-particle radiations dominate equivalent dose. In the case of bone cancer, radiation dose to the bone surfaces is used, while for leukemias, it is dose to red bone marrow. In general, even for intakes of internal emitters over brief periods, dose to the bone surfaces, red bone marrow, and liver are realized over long periods. As noted above, IREP version 5.9 was used for ALL.

In the case of the colon and skin (i.e., melanoma), internal α-particle emitters will provide some dose from systemic metabolism of these emitters, however, the doses are generally very-low in comparison to other tissues. For intakes of important α-particle emitters, dose to the colon is generally greater from radioactive material transiting the gastro-intestinal (GI) tract as its content rather than from deposition and retention from systemic circulation. In the case of inhaled plutonium, a large fraction of the initial deposit in the lungs is assumed by models to be cleared to the GI tract. On the other hand, for exposure scenarios involving the skin, it is common for cases where inhalation exposures to exist that some dose to skin is possible from direct contamination, if the skin is not covered by protective clothing. In these cases, exposures are more important for α-particles emitters with higher energies. For low-energy α-particles, large fractions of the energy are absorbed in the epidermal layer, while the stem cells in the underlying dermal layer are deemed more critical to absorbed radiation dose and cancer risk, yet only receive a small fraction of energy.

Tables E-1 through E-9 provide PoC screening doses for chronic exposures to α-particles for nine malignancies. The tables have similar distributions of equivalent dose in comparison to those for photons when the same malignancy is considered. Figures E-1 through E-9 provide the fraction of equivalent dose at the 50% PoC, 99% CL for α-particles, as compared to photons of energy > 250 keV. A summary of the range of fractions are summarized in Table 8-1. Overall, the fractions range from 0.37 to 1.77, and generally reflect a higher REF for α-particles, as compared to high-energy photons. The observation of the higher fractions are mostly limited, in these examples, to the 5-y latency period, and the longer latency periods for leukemias. Similar to fission neutrons, the effective REF and EF for α-particles, as observed for screening doses at the 99% CL are greater than the ICRP 60 and 103 w_R, with the exception of some cases of leukemia.

TABLE 8-1. Fraction of Equivalent Dose for Alpha Particles Compared to Photons $E > 250$ keV, at 50% PoC at 99% Credibility Level for Select Malignancies, Ages of Exposure: 18, 21, 25, 30, 35, 40, and 45 years, with Period between Exposure and Disease Diagnosis 5 to 40 y.

Malignancy	Range of Fractions	Range of Fractions	Range of Fractions
Colon	0.39 – 0.54	Male Genitalia (also Prostate)	0.52 – 0.64
Liver	0.41 – 0.64		
Lung	0.31 – 0.56	Bladder	0.38 – 0.54
Bone	0.37 – 0.48	ALL	0.91 – 1.77
Melanoma	0.51 – 0.65	AML	0.61 – 0.83

9.0 Example IREP for Internal Plutonium Exposures using ICRP Metabolism Models.

IREP modelling was conducted for the lung, liver, and bone cancers, and ALL using metabolic modelling of ICRP Reports 66 and 67 (ICRP 1994b, ICRP 1992) for ^{239}Pu intakes of Type S lung class compounds. Modelling was completed for inhalation intakes assuming either a 1 or 5 μm activity median aerodynamic diameter (AMAD) aerosol. To provide the reader a perspective on the temporal distribution of equivalent dose to the four key tissues for Type S lung class ^{239}Pu inhalation exposures, the plots in Figures F-1 to F-4 are provided for 5 μm AMAD aerosols. The plots provide annual and cumulative equivalent dose values for a 70-y period post, acute intake. The 70-y duration is commonly used by ICRP for general public exposures, as it includes individuals under the age of 18, while those for occupational exposures are generally limited to 50-y, a typical upper-level of a working lifetime. Notably for the lung, the vast majority of the 70-y cumulative dose is realized within about 10 y after the intake. For the other tissues, however, it takes between five to six decades to acquire a similar fraction of the 70-y cumulative dose. Additionally, the peak annual equivalent dose for the tissues is quite varied – for the lung, it is highest within the year of intake, while for the liver, red bone marrow (RBM), and bone surfaces it is 17, 5, and 17.5 y, respectively. Additionally, each plot notes the fraction of the 70-y CED acquired in 50-y. In the case of the lung, it is 99.3%, while ranging between 19 to 26% lower for the other three tissues.

Tables F-1 to F-8 provide screening doses calculated with IREP, as accumulated by the organ of interest for lung, liver, bone, and ALL at the year of diagnosis. All doses are for acute inhalation intakes of ^{239}Pu using ICRP Report 66 and 67 metabolism for 1 and 5 μm AMAD aerosols, a chronic exposure assumption for α-particles, and a PoC of 50% at the 99% CL. These tables differ somewhat from the trends in dose observed for table in Appendix E for α-particle emitters for the same malignancy. The differences are two-fold. The dose values listed in Appendix E tables assume all dose was committed in the year of intake, while for Table F-1 to F-8, the doses listed were for accumulations of dose up to the year of disease diagnosis. Second, PoC calculations are based on annual organ doses for Tables F-1 to F-8, while for tables in Appendix E PoC was based on 50-y CED to organs in the year of intake.

Tables F-9 to F-16 provide screening inhalation intake values, based on the dose values in Tables F-1 to F-16. Screening values in this format are more practical for assessment of PoC for acute intakes of internal emitters. In general, the highest screening intakes were for the short latency periods and the lower screening levels for the longer latency periods. This feature is a result of low accumulated doses in the target tissues for early periods after intakes. A summary of screening intakes are listed in Table 9-1. The values are provided for the two commonly used aerosol distribution assumptions – a 1 and 5 μm activity median aerodynamic diameter (AMAD), log-normal. For the tissues exposed, due to systemic distribution through the circulatory system, the ratios of the minimum activity for the two aerosol distributions, for the same exposed tissue closely follow the cumulative percent of inhaled activity transferred to the blood. The temporal distribution of activity from the lung to blood is shown in Figure 9-1. The ratio of the 50-y cumulative transfer to blood, Type S (1 to 5 μm AMAD) is 2.1. In comparison, the ratios of the minimum intakes for the bone (1 to 5 μm AMAD) is (122/64.4) = 1.9 and the same for the liver. Since dose to the lung is not affected to a significant degree by activity transferred to the lung, there is no expected correlation in ratios of minimum activity intake ratios between the two aerosol distributions.

TABLE 9-1. Screening Inhalation Intake Activities (nCi) for Alpha Particle Dose from ^{239}Pu. Ages of Exposure: 18, 21, 25, 30, 35, 40, and 45 years, with Period between Exposure and Disease Diagnosis of 5 to 50 y. IREP PoC of 50% at 99% CL, ICRP Reports 66 and 67 Metabolism, Type S Compounds [Tables F-9 to F-16].

Malignancy	Tissue Exposed	Aerosol Particle Distribution (AMAD)	
		1 μm	5 μm
Lung Cancer	Lung	42 – 1,060	67 – 1,610
Liver Cancer	Liver	78.5 – 87,500	148 – 152,000
Bone Cancer	Bone Surfaces	64.4 – 5,430	122 – 9,600
ALL	Red Bone Marrow	283 – 7,230	500 – 13,100

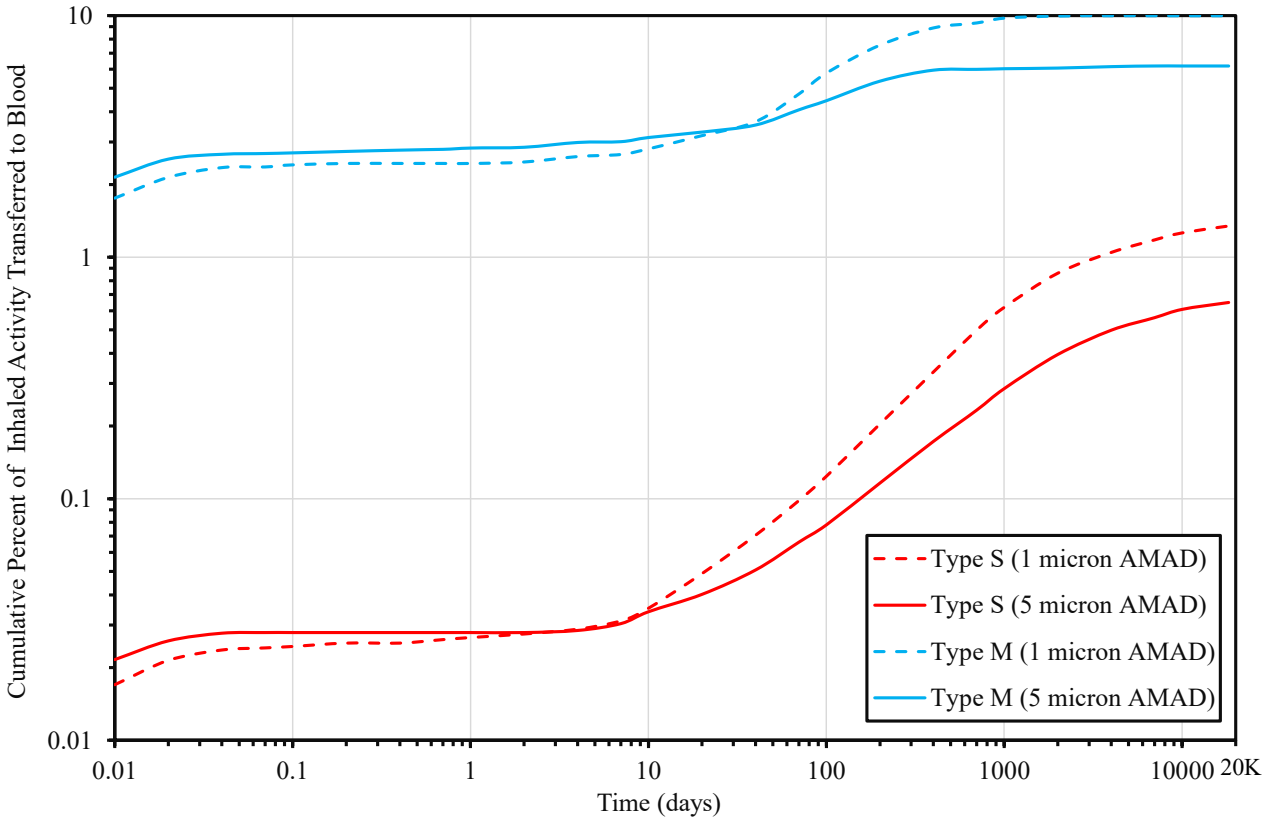

Figure 9-1. ICRP Report 66, Cumulative Percent of Inhaled Activity Transferred to Blood, Adapted from Figure 25 of ICRP Report 66 (ICRP 1994).

Figures F-5 to F-12 contain plots of the ratios of inhalation intake activities for time-integrated organ dose up to the time of disease diagnosis vs. the assumption of the 50-y CED realized in the year of the inhalation intake. The activity values are based on the calculated 50% PoC at the 99% CL. These plots use the same set of age of intakes and period between the intake and disease diagnosis, as used in Table F-9 to F-16. The data is from these same tables, however, the complementary intakes are not provided for brevity sake. The plots are in Appendix F, with the plots for each

aerosol distribution paired to the individual tissue. For the four pair of plots, there is very good agreement between the plot for the two aerosol distributions. For the internal organs, this is due to the very similar cumulative transfer of activity to the blood, though different in overall magnitude. In the case of the lung, the sets of data series are nearly identical for latency periods beyond 15 years, while the data series are somewhat similar in magnitude for shorter latency periods. The most significant aspect of these plots are the high ratios of screening activity observed for short to moderate latency periods for malignancies associated with the liver, bone surfaces, and RBM. This is due to the relatively small cumulative organ doses acquired at the time of disease diagnosis, as compared to a 50-y CED. Notably, the ratios only approach one for bone and liver cancers for very long latencies and intakes for older individuals. For individuals with an intake at 18 years of age, the ratio is near two for a 50-y latency for bone and liver cancer. These characteristics demonstrate the erroneous PoC values that can be obtained under the assumption of a 50-y CED received in the year of intake for radionuclides with long radiological and biological retention. For ALL among POC's modelled for individuals 21 and older, ratios reach one for a 50-y latency period, though they are high for short latencies. For those 18 years of age at the time of intake, the ratios are highly varied, about 30, for a 5-y latency, to 0.04 for 50-y.

Among the four tissues, the ratios shown in Figures F-5 and F-6 are no higher than 2.2, nor less than 0.8. For moderate to long latencies, the ratios are about one. This is due to the fact that doses to lung tissues are accumulated in a relatively short period, compared to the other organs illustrated here. From a practical standpoint, because many lung cancers are observed in older individuals, whom also have moderate to long latencies will have similar PoCs to the case where a 50-y CED is assumed to be incurred in the year of intake. In contrast, for the liver, the lowest screening dose is 2.1 rem for α-particles [Table E-2] for individuals 18 years of age at the time of intake, with a latency of 10 y. In the case of the bone, it is also for 18 year olds at time of intake, but for a 5-y latency, as shown in Table E-4. For ICRP Reports 66 and 67 metabolism, as shown in Figure F-4 for the BS, only 4.8% of the 70-y CED is acquired in 5-y post intake, or 6.5% for a 50-y CED.

10.0 Effect of Variability in Dose on IREP Assessments.

The IREP examples provided up to this point in this report are based on the assumption of a constant dose value. As noted above, the greatest degree of expected uncertainties in PoC values is due to uncertainties associated with cancer induction models. Appendix G contains some IREP calculations to illustrate the effect. All calculations were for α-particle dose to various tissues at age 20, with varied latency periods. Though the majority of calculations were performed to assess dose for 50% PoC at the 99% CL, numerous paired calculations were performed for the case of 50% PoC at the 50% CL. As noted above, the latter case pairs the requirements for determination of:

1) "probable dose, in terms of dose type, rate, and duration," [38 CFR 3.311(e)(1)] and

2) the determination if it is "at least likely as not the veteran's disease resulted from exposure in service," [38 CFR 3.311(c)(1)(i)].

Among the 30 cases evaluated and summarized in Table G-1, seven have paired analyses for 50% PoC at the 50% and 99% CL. All of the paired analyses are for a 50-y latency period, with a

summary in the histogram of Figure 10-1. From the plot, the relative sensitivity to induction of cancer from α-particle dose is clear, with CLL and nervous system tissues being the least sensitive among the seven examples, and the liver being the most. This comparison is based on the 50% PoC at 50% CL. The range of dose for CLL and liver cancer is a factor of 22. When compared at the 99% CL, the range of dose for nervous tissue and liver cancer is a factor of 12. It is apparent that variabilities inherent to the risk model is the dominant source of variability when high credibility levels are desirable. In the case of CLL, the ratio of dose at the 50% PoC for the 50 and 99% CL is 38.3. In the case of bone, bladder, and kidney cancer, the respective ratios are only 11.1, 11.7, and 10.6. The ratios for lung, liver, and nervous tissue cancers are between these more extreme cases, with ratios of 13.7, 18.8, and 17.4. One key provision for the seven-paired analyses considered is the 50-y latency period, where the adjustment factor for this source of uncertainty is negligible.

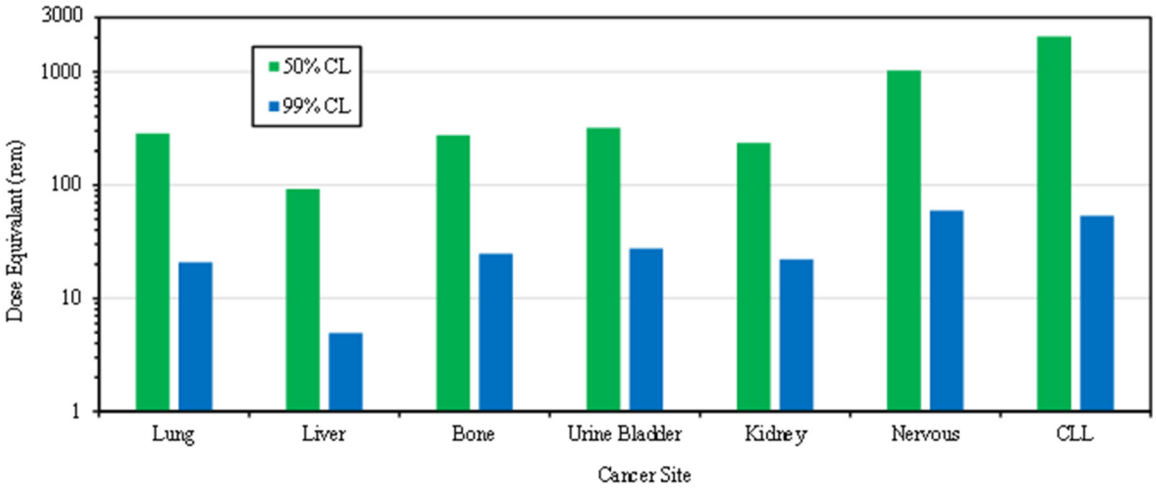

Figure 10-1. Histogram of Dose Equivalent Values for Various Cancer Sites at the 50% PoC and 99% Credibility Levels, 50-y Latency.

The IREP code offers users the ability to introduce uncertainties in the assessment of dose, whether it is from external dosimetry monitoring or a dose estimate. IREP offers numerous probability distributions for use: log-normal, normal, triangular, log-triangular, uniform, log-uniform, and Weibull. This report provides examples of PoC calculations for two organs using the normal distribution where the standard deviation is 0, 25, 50, and 75% of the mean. Tables G-2 and G-3 contain IREP calculations for the lung and liver cancer from α-particles to 20-y old males with varied latency periods. A histogram of the data from Table G-2 is contained in Figure 10-2. For each latency period, there is a general reduction in dose required as the standard deviation in the normal distribution of dose is increased from 0 to 75%, with the exception of 10 and 15-y latencies periods for the lowest coefficient of variation (CV). For latency periods of $\geq$ 30 y, the data is consistent, with 50% PoC (99% CL) for distribution of dose with 75% CV about two-thirds of the dose with 0% CV. For shorter latencies, the disparity in dose levels are lower. Overall, it is clear that despite the large variability in dose, e.g. 75% CV, there is only a modest difference in dose at the 50% PoC (99% CL). This is a result of the dominance of variabilities inherent to the risk models compared to variability introduced by uncertainties in dose.

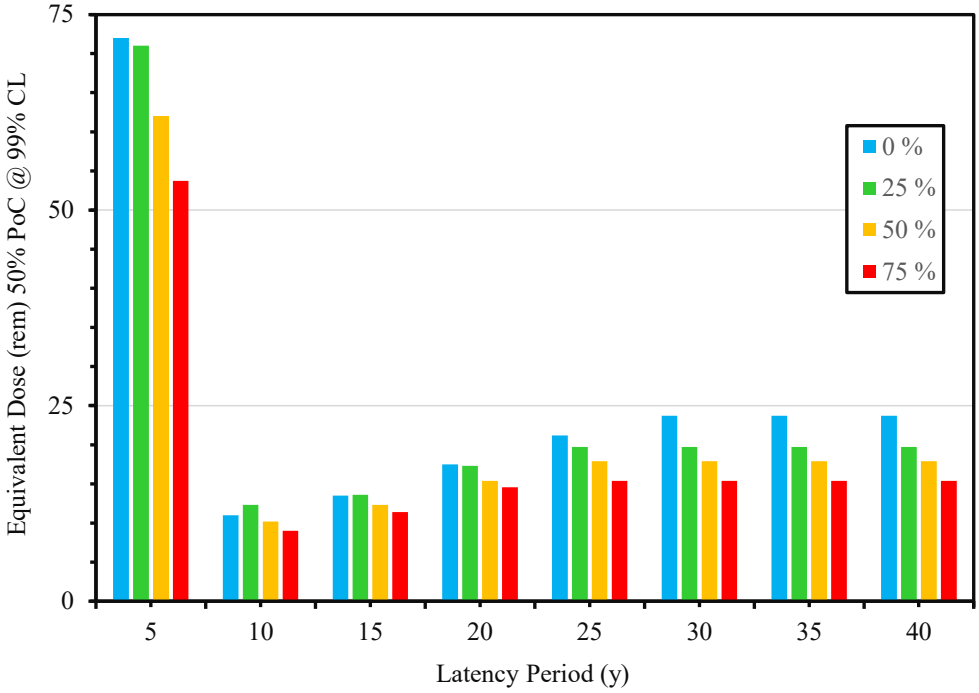

Figure 10-2. Histogram of Screening Doses (rem) Calculated with IREP, Chronic Exposures, α-Particles, Lung Cancer, 50% PoC at 99% CL for Uncertainties in Dose at 0, 25, 50, and 75% CV, Normal Distribution.

11.0 Conclusions

This report provides examples of IREP applications for dose assessments in support of VA claims for DoD components. The IREP has been used by the VA and DoL in support of adjudication of radiation exposure compensation claims, with the latter for EEOICPA. This report is an expansion upon one completed by Kocher and Apostoaei (2007) for DTRA. The report completed for DTRA was focused on exposures common to NTPR veterans, where exposures were primarily from external sources and delivered in an acute manner. In contrast, most other DoD ionizing radiation exposures are chronic, where risk models would differ. This report also provides IREP modelling examples for ^{239}Pu internal exposures to α-particles. IREP modelling of these exposures can also differ significantly from acute exposure models. The differences are most significant for tissues where dose is accumulated over long periods after an intake and there are short to moderate latency. For ^{239}Pu this is the case for liver, leukemia (dose to RBM), and bone cancer (dose to BS). This is much less pronounced for ^{239}Pu inhalation intakes and lung cancer due to much larger fractions of a 50-y accumulated dose being achieved over shorter periods. Indeed, the term latency period is somewhat ambiguous for internal emitters with long-term biological retention and relatively long radiological half-lives due to dose being accumulated over long periods and not in a discrete period, as is common to external exposures. Overall, the report provides insights into the aspects of IREP that pertain to many DoD occupational exposure cases.

12.0 References.

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Appendix A

Background Information

TABLE A-1. ICRP Radiation Weighting Factors, w_R, or Relative Biological Effectiveness (RBE) for ICRP 2 and Quality Factor for ICRP 26.

Radiation Type	RBE	Q	w_R	
	ICRP 2	ICRP 26	ICRP 60	ICRP 103
Photons	1	1	1	1
Electrons and muons	1‡	1	1*	1*
Alpha particles, fission fragments, heavy ions	-	20	20	20
Alpha particles	10	-	-	-
Recoil atoms	20	-	-	-
Neutrons	-	10	5 – 22 †	2.5 – 20.7§
Neutrons < 10 keV	-	-	5	-
Neutrons: 10 to 100 keV	-	-	10	-
Neutrons: > 100 keV to 2 MeV	-	-	20	-
Neutrons: > 2 to 20 MeV	-	-	10	-
Neutrons > 20 MeV	-	-	5	-
Protons, other than recoils, energy > 2 MeV	-	-	5	-
Protons and charged pions	-	10✦	-	2

‡ 1.7 for electrons with energy < 30 keV * Special considerations for auger electrons
† Alternate continuous function, peak of 22 at 0.5 MeV § Continuous function, peak of 20.7 at 1 MeV
✦ Other singly-charged particles of rest mass greater than one amu

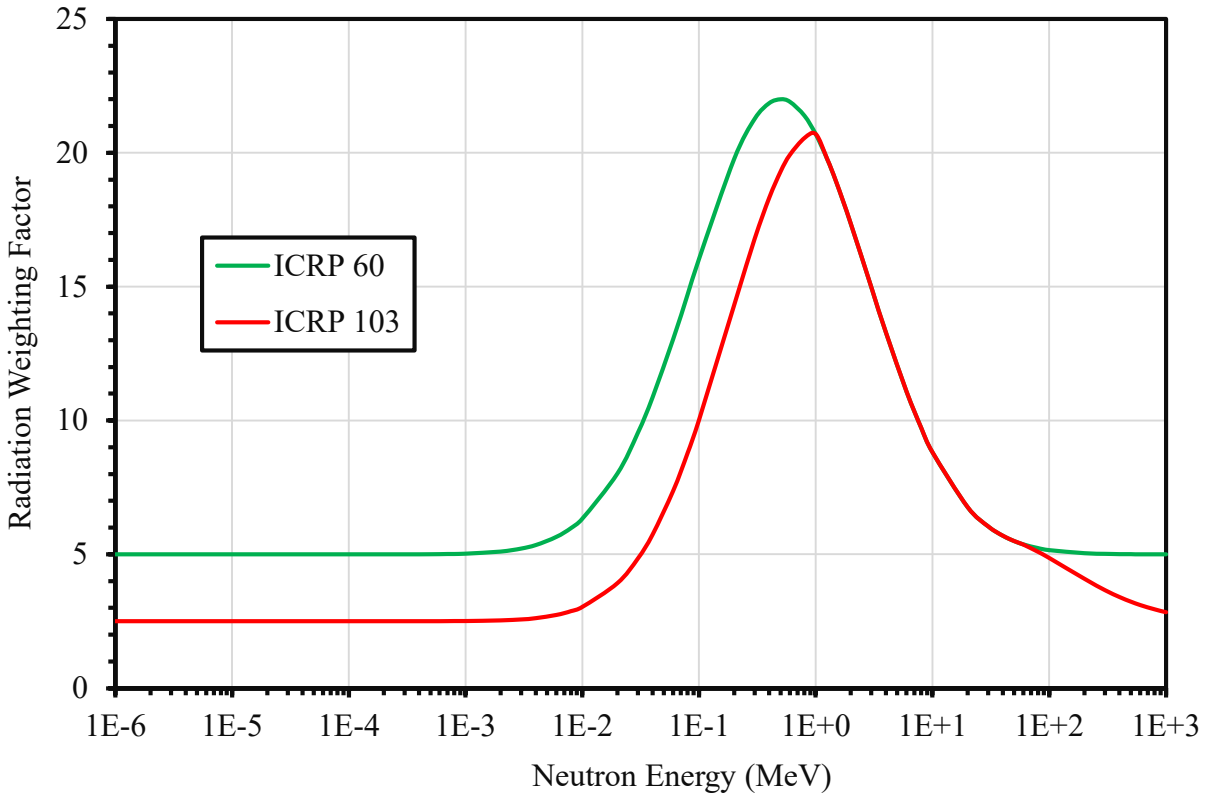

Figure A-1. Continuous Radiation Weighting Factors for ICRP Report 60 and 103.

TABLE A-2. Radiogenic Diseases, 38 CFR 3.311(b)(2)(i) and (5)(i-iv).

<table>
<tr><th>Disease</th><th>Conditions</th><th>Disease</th><th>Conditions</th></tr>
<tr><td>leukemias, except CLL</td><td>may become manifest any time after exposure</td><td>bone cancer</td><td>must become manifest within 30 years after exposure</td></tr>
<tr><td>thyroid cancer</td><td rowspan="11">must become manifest 5 years of more after exposure</td><td>pancreatic cancer</td><td rowspan="9">must become manifest 5 years of more after exposure</td></tr>
<tr><td>breast cancer</td><td>stomach cancer</td></tr>
<tr><td>lung cancer</td><td>colon cancer</td></tr>
<tr><td>liver cancer</td><td>kidney cancer</td></tr>
<tr><td>skin cancer</td><td>urinary bladder cancer</td></tr>
<tr><td>multiple myeloma</td><td>prostate cancer</td></tr>
<tr><td>salivary gland cancers</td><td>non-Hodgkin’s lymphomas*</td></tr>
<tr><td>esophageal cancer</td><td>ovarian cancer</td></tr>
<tr><td>non-malignant thyroid nodular disease</td><td>parathyroid adenoma</td></tr>
<tr><td>tumors of the brain and central nervous system</td><td>rectal cancer</td></tr>
<tr><td>any other cancer</td><td>posterior subcapsular cataracts</td><td>must become manifest 6 months or more after exposure</td></tr>
</table>

* Hodgkin’s lymphomas excluded. Due to exclusion of CLL, for practical purposes refers to ALL (non-Hodgkin’s types). VA currently considers CLL on a case-by-case basis.

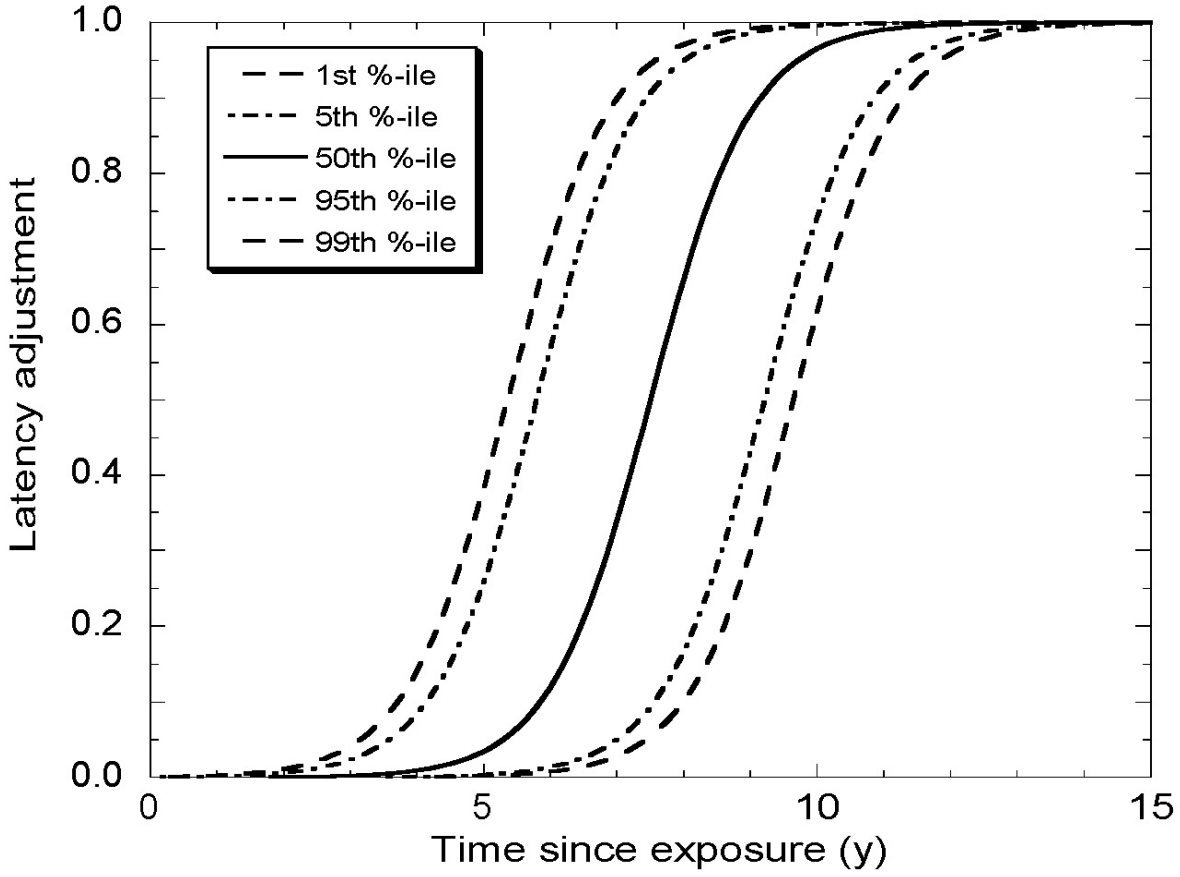

Figure A-2. S-Shaped (sigmoid) Function Assumed in IREP to Represent Effect of Minimum Latency Period on Reducing Risks of All Solid Cancers Except Thyroid and Bone Cancer at Early Times Since Exposure and its Uncertainty [Figure 3-1 from Kocher and Apostoaei (2007)].

TABLE A-3. Tissues with Probability of Causation (PoC) Modelled in IREP, with Listing of Risk Model Group (Gp).

Tissue(s)	Gp	Tissue(s)	Gp	Tissue(s)	Gp
Bone	2	Oral Cavity and Pharynx	2	Nervous System	2
Esophagus	2	Connective Tissue	2	Thyroid	2
Stomach†	1/2	Melanoma	4	Other Endocrine Glands	2
Colon	2	Basal Cell	4	Lymphoma & Multiple Myeloma	2
Rectum	2	Squamous Cell	4		
All Digestive	1	Breast	1	Leukemia, Excluding CLL	4
Liver	1	Ovaries ♀	2	Acute Lymphoid Leukemia	4
Gall Bladder	2	Other Female Genitalia ♀	3	Chronic Lymphoid Leukemia	4
Pancreas	2	All Male Genitalia ♂	2	Acute Myeloid Leukemia	4
Lung*	3/4	Bladder	2	Chronic Myeloid Leukemia	4
Other Respiratory§	2	Other Urinary Tissues	2	Eye	2

* Lung cancers evaluated against radon and its daughters in Group 4, others in Group 3. IREP has lung model option also in Group 2. † Males (2), Females (1) § Nasal cavity, larynx

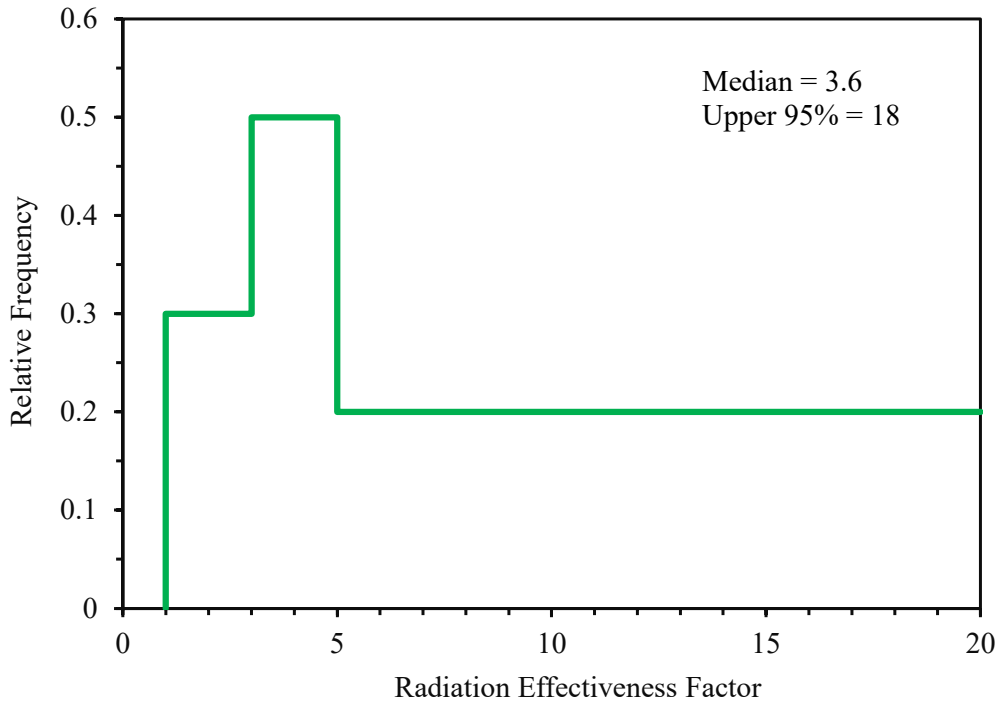

Figure A-3. IREP Radiation Effectiveness Factors for Neutrons, 10 – 100 keV and 2 – 20 MeV, Solid Tumors.

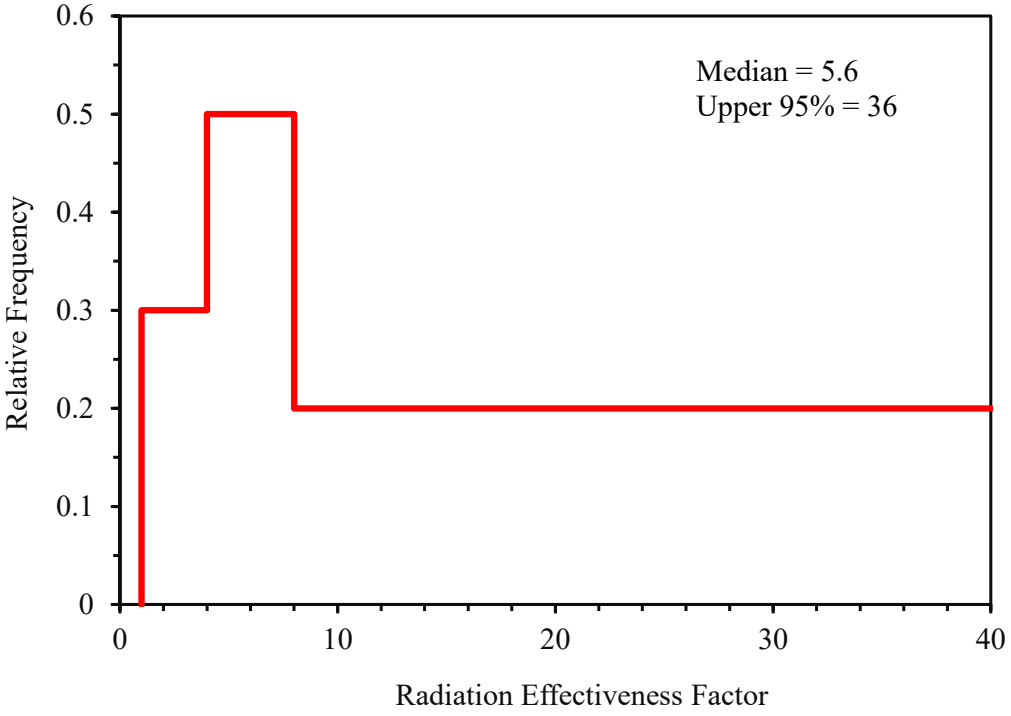

Figure A-4. IREP Radiation Effectiveness Factors for Neutrons, 10 – 100 keV and 2 – 20 MeV, Leukemias.

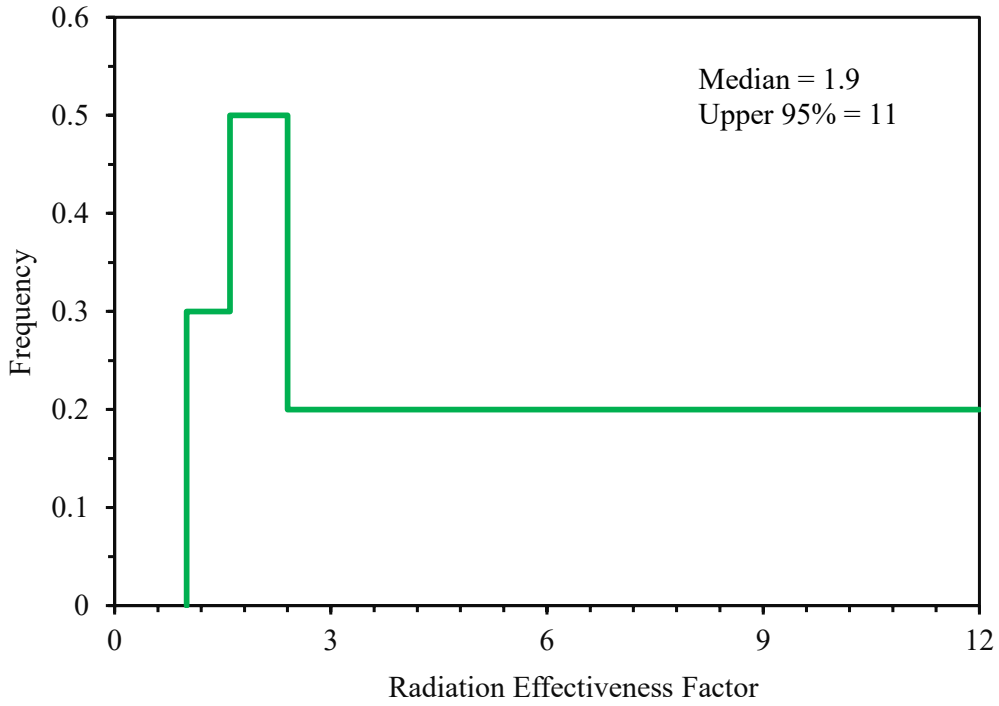

Figure A-5. IREP Radiation Effectiveness Factors for Neutrons, < 10 keV and > 20 MeV, Solid Tumors.

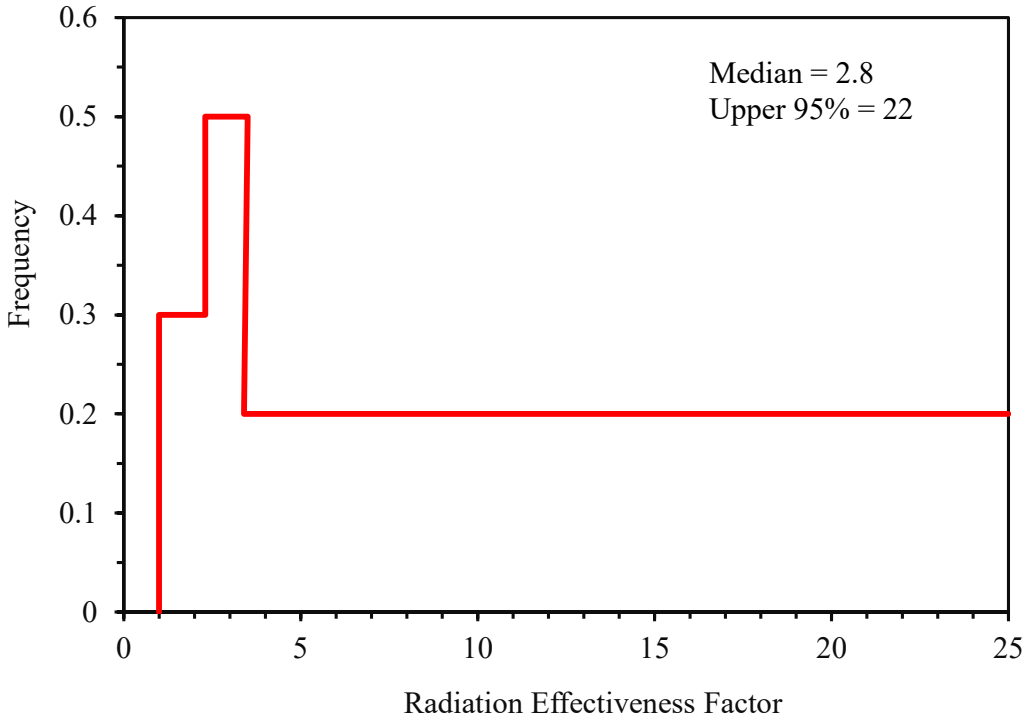

Figure A-6. IREP Radiation Effectiveness Factors for Neutrons, < 10 keV and > 20 MeV, Leukemias.

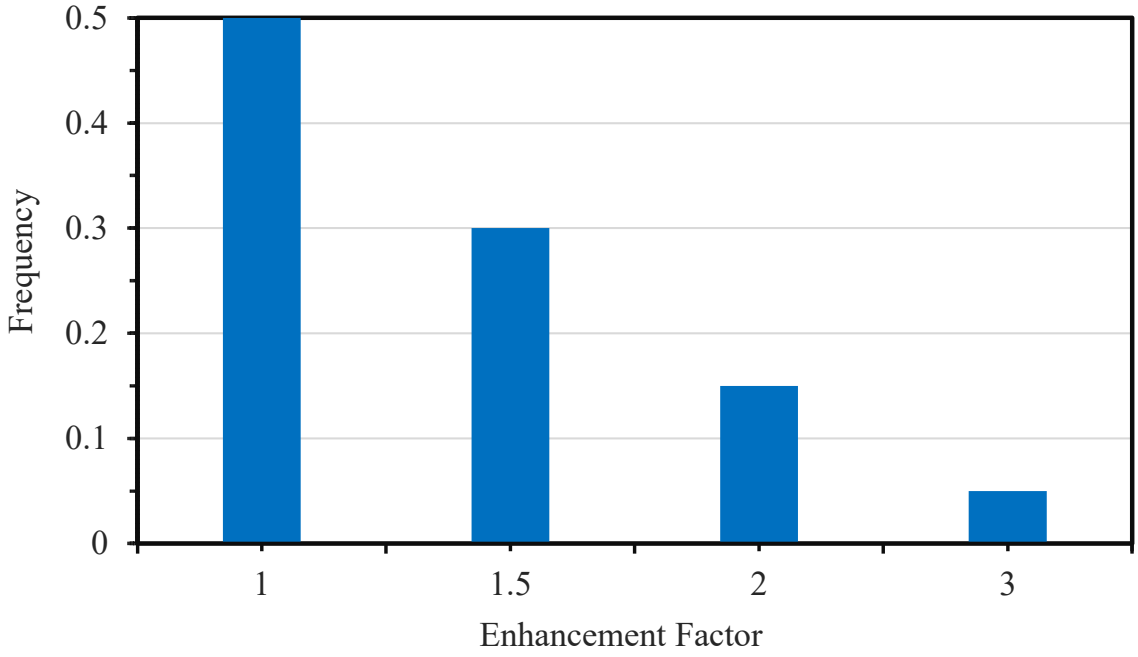

Figure A-7. IREP Enhancement Factors for Neutrons, Low Dose and Dose Rates.

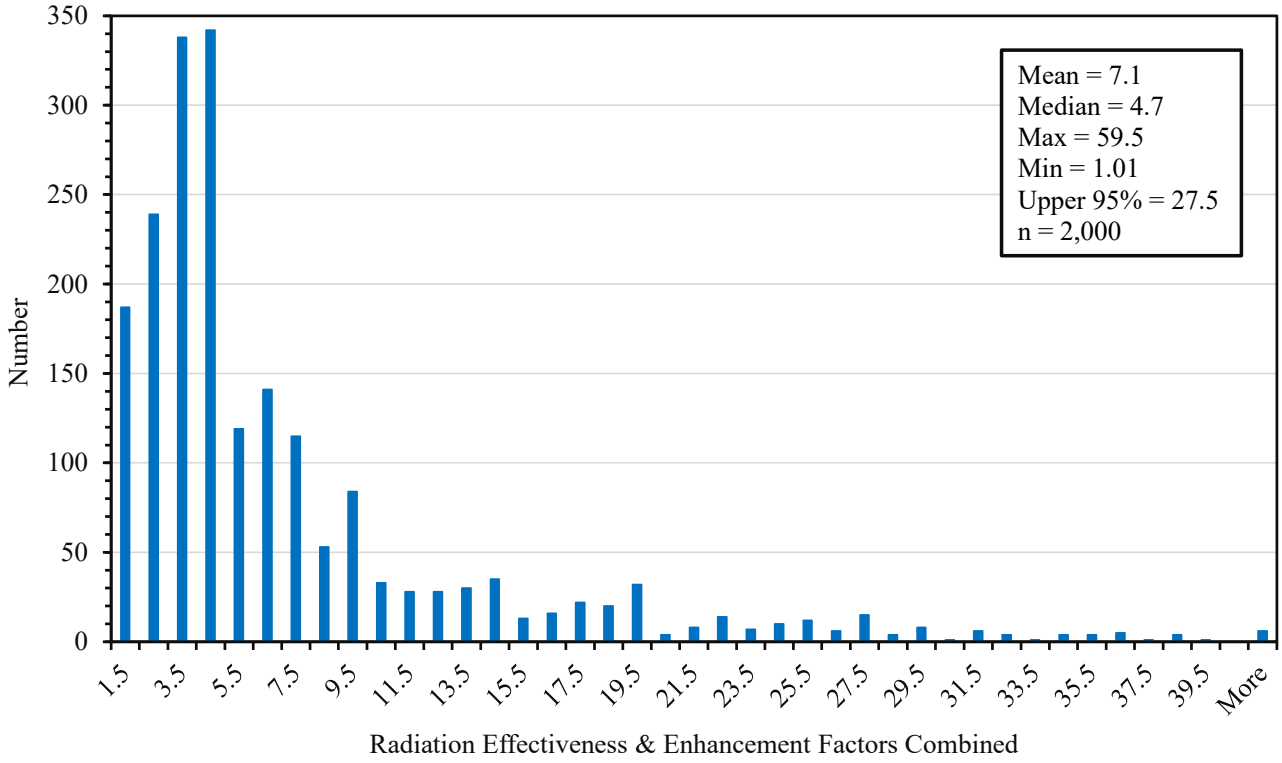

Figure A-8. IREP Radiation Effectiveness and Enhancement Factors Combined for Neutrons, 10 – 100 keV and 2 – 20 MeV, Solid Tumors.

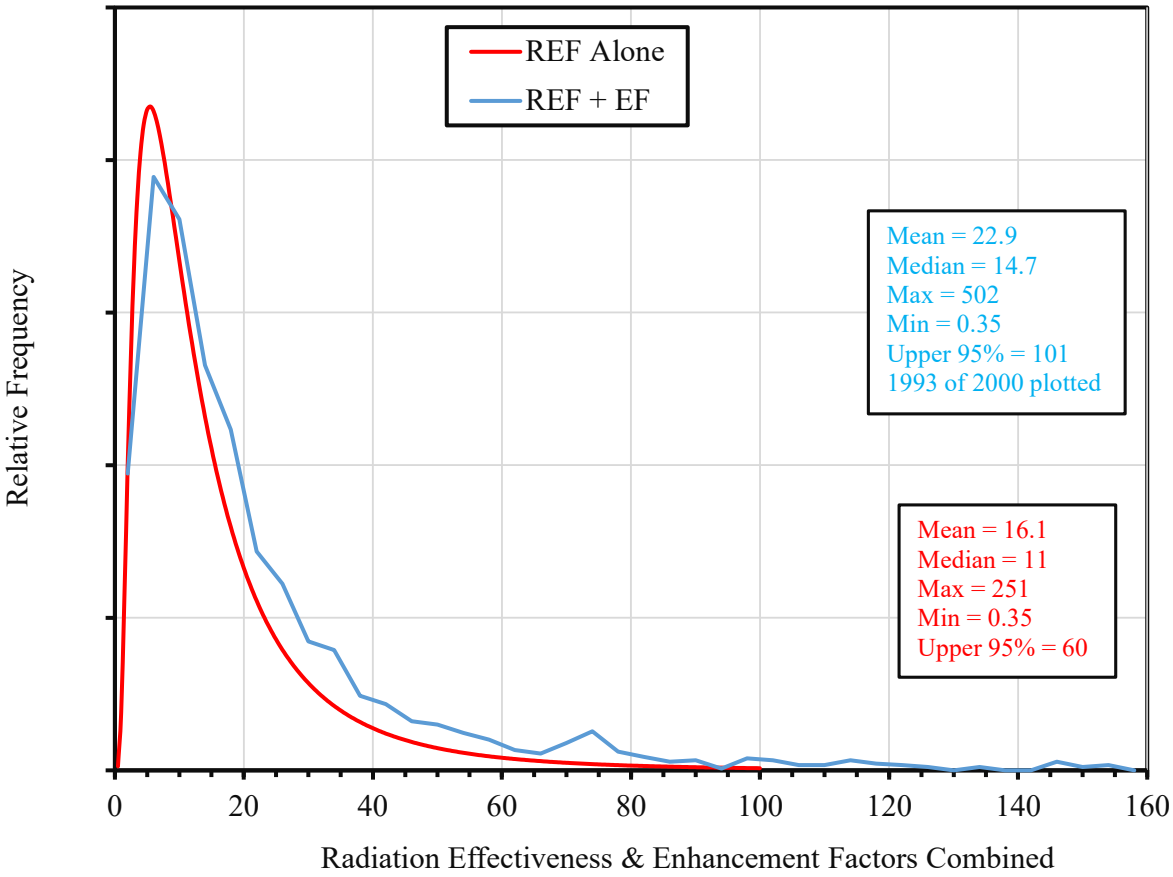

Figure A-9. IREP Radiation Effectiveness Alone and Combined with Enhancement Factor for Fission Neutrons, 0.1 – 2 MeV, Leukemias.

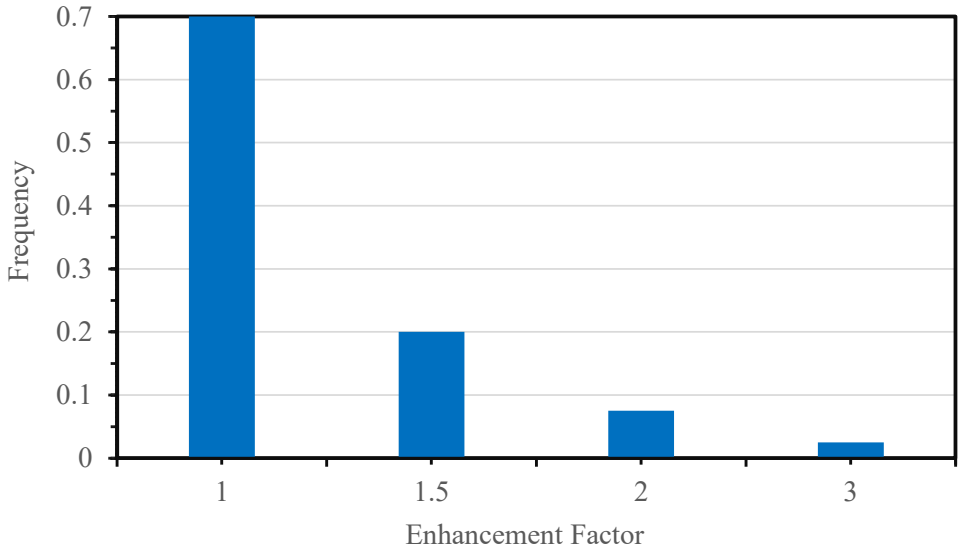

Figure A-10. IREP Enhancement Factors for Alpha Particles, Low Dose and Dose Rates.

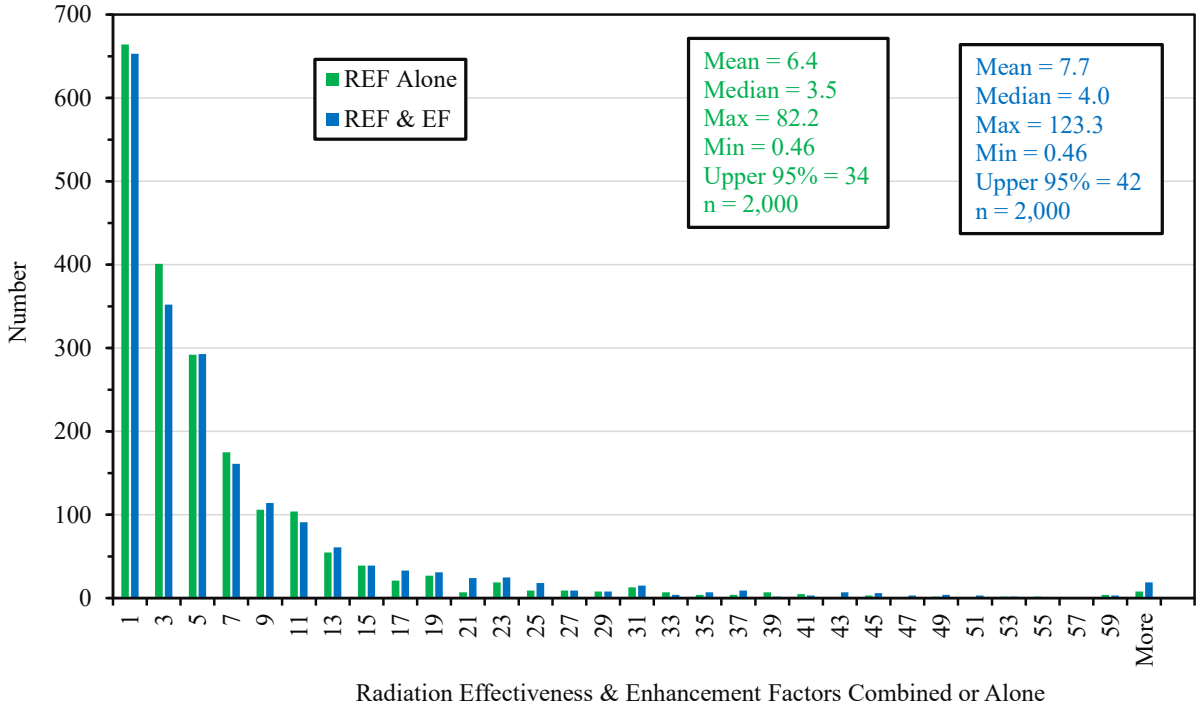

Figure A-11. IREP Radiation Effectiveness Alone and Combined with Enhancement Factor for Alpha Particles, Low Dose and Dose Rates.

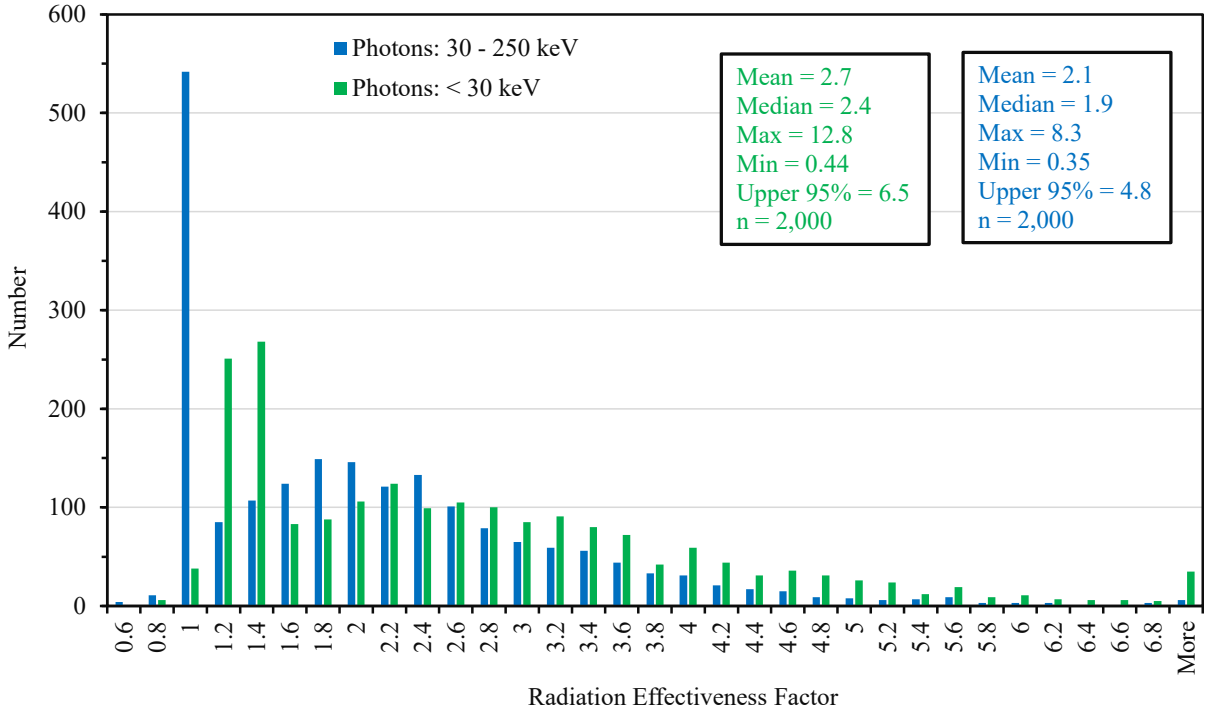

Figure A-12. IREP Radiation Effectiveness Factors for Photons: 30 – 25 keV, and Photons: < 30 keV [For Chronic Exposures to Photons: < 30 keV and Leukemia, use the REF for 30 – 250 keV].

TABLE A-4. Summary of Radiation Effectiveness and Enhancements Factors for Risk Models Used in IREP, as Noted in this Report (Kocher et al. 2002).

Radiation Type	Energy Range	Exposure Type	Cancer	Risk Equation	Parameters (REF, EF, & AF's Combined, as Applicable)*		
					Median	Mean	Upper 95% CL
Neutrons	0.1 – 2 MeV (fission)	Chronic	Solid	$\Re = REF_{n,H} \times EF_n \times R_{\gamma,H} \times D_n$	10	13.8	47
	10-100 keV & 2-20 MeV				4.7	7.1	27.5
	< 10 keV & > 20 MeV				2.4	4.0	16.5
	0.1 – 2 MeV (fission)		Leukemia	$\Re = a \times REF_{n,L} \times EF_n \times D_n$	14.7	22.9	101
	10-100 keV & 2-20 MeV				6.8	11.9	58
	< 10 keV & > 20 MeV				3.3	6.9	38
	0.1 – 2 MeV (fission)	Acute	Solid	$\Re = REF_{n,H} \times R_{\gamma,H} \times D_n$	7.7	9.8	30
			Leukemia	$\Re = a \times REF_{n,L} \times D_n$	11	15.6	60
Alpha Particles	All	Chronic	Solid	$\Re = REF_{\alpha,L} \times EF_\alpha \times \frac{R_{\gamma,H}}{DDREF_\gamma} \times D_\alpha$	18	26.2	107
			Leukemia	$\Re = a \times REF_{\alpha,L} \times EF_\alpha \times D_\alpha$	4.0	7.7	42
Tritium	< 15 keV, electrons	Any	Solid	$\Re = REF_{e,L} \times \frac{R_{\gamma,H}}{DDREF_\gamma} \times D_e$	2.4	2.6	5.0
		Acute	Leukemia	$\Re = a\,(REF_{e,L} \times D_e) + b\,(REF_{e,L} \times D_e)^2$			
		Chronic		$\Re = a \times REF_{e,L} \times D_e$			
Photons	30 – 250 keV	Chronic	Solid	$\Re = (REF_{\gamma,L} \times \frac{R_{\gamma,H}}{DDREF_\gamma} \times D_\gamma$	1.9	2.1	4.8
		Acute					
		Chronic	Leukemias	$\Re = a \times REF_{\gamma,L} \times D_\gamma$	1.9	2.1	4.8
		Acute		$\Re = a\,(REF_{\gamma,L} \times D_\gamma) + b\,(REF_{\gamma,L} \times D_\gamma)^2$	1.9	2.1	4.8
	< 30 keV	Chronic	Solid	$\Re = (REF_{\gamma,L} \times AF_\gamma \times \frac{R_{\gamma,H}}{DDREF_\gamma} \times D_\gamma$	2.4	2.7	6.5
		Acute					
		Chronic	Leukemias	$\Re = a \times REF_{\gamma,L} \times D_\gamma$	1.9	2.1	4.8
		Acute		$\Re = a\,(REF_{\gamma,L} \times AF_\gamma \times D_\gamma) + b\,(REF_{\gamma,L} \times AF_\gamma \times D_\gamma)^2$	2.4	2.7	6.5

* Values calculated by author of this report. Minor differences exist between values listed in Kocher et al. (2002), which are attributed to random variability in estimates of joint probability distributions Kocher et al. (2002) did not list mean values.

Appendix B

Example Screening Doses (rem) Calculated with NIOSH IREP, Chronic Exposures, $E > 250$ keV, Males (Unless Noted Otherwise)

TABLE B-1. Screening Doses (rem) Calculated with IREP, Chronic Exposures, $E > 250$ keV, Cancer of Oral Cavity and Pharynx, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	198	40.5	56	75	94	111	115	115
21	305	59	80	105	128	144	144	144
25	492	97	125	153	178	179	179	179
30	832	168	200	226	226	226	226	226
35	1033	213	227	227	227	227	227	227
40	1205	253	227	227	227	227	227	227
45	1450	253	227	227	227	227	227	227

TABLE B-2. Screening Doses (rem) Calculated with IREP, Chronic Exposures, $E > 250$ keV, Cancer of Esophagus, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	70	14	19	25.5	31.5	38	40	40
21	101	21	27	35	41	47	47	47
25	168	32	41	50	59	59	59	59
30	289	55	64	78	78	78	78	78
35	366	67	78	78	78	78	78	78
40	479	82	78	78	78	78	78	78
45	555	82	78	78	78	78	78	78

TABLE B-3. Screening Doses (rem) Calculated with IREP, Chronic Exposures, $E > 250$ keV, Cancer of Stomach, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	61	11.5	15	19.5	24	29	31	31
21	92	16.5	21	27	33	37	37	37
25	144	26	32	41	48	48	48	48
30	261	43	54	65	65	65	65	65
35	349	55	65	65	65	65	65	65
40	445	67	66	66	66	66	66	66
45	553	67	66	66	66	66	66	66

TABLE B-4. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer of Colon, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	65	14.7	19.3	25.5	31.5	37	39	39
21	98	21	27	35	43	48	48	48
25	162	34	42	52	62	62	62	62
30	284	58	68	81	82	82	82	82
35	353	74	82	82	82	82	82	82
40	436	87	82	82	82	82	82	82
45	548	87	82	82	82	82	82	82

TABLE B-5. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer of Rectum, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	220	48	61	83	101	121	126	126
21	322	69	87	112	136	154	154	154
25	531	109	133	162	191	191	191	191
30	940	187	213	257	257	257	257	257
35	1247	217	257	257	257	257	257	257
40	1680	272	257	257	257	257	257	257
45	1954	272	257	257	257	257	257	257

TABLE B-6. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer of All Digestive*, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	104	24	33	44	55	66	69	69
21	159	35	45	59	71	81	81	81
25	264	54	67	83	99	99	99	99
30	449	87	103	123	123	123	123	123
35	575	111	123	123	123	123	123	123
40	703	134	123	123	123	123	123	123
45	838	134	123	123	123	123	123	123

* Digestive tract, other than stomach, colon, and rectum

TABLE B-7. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer of Liver, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	20	4.6	6.0	8.0	10	12	12.5	12.5
21	30.5	6.8	8.4	10.7	13.1	15	15	15
25	51	10.5	12.5	15.5	18.5	18.5	18.5	18.5
30	88	16.5	19	23	23	23	23	23
35	118	21	23	23	23	23	23	23
40	142	25.7	23	23	23	23	23	23
45	167	25.7	23	23	23	23	23	23

TABLE B-8. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer of Gall Bladder, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	42	7.1	9.5	13	16	19	20	20
21	62	10.4	13.6	18	21	24	24	24
25	98	16	21	25	29	29	29	29
30	163	28	33	39	39	39	39	39
35	226	36	39	39	39	39	39	39
40	266	42	39	39	39	39	39	39
45	311	42	39	39	39	39	39	39

TABLE B-9. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer of Pancreas, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	199	38	51	67	84	98	102	102
21	280	59	71	91	112	127	127	127
25	444	91	110	132	157	157	157	157
30	774	148	172	212	212	212	212	212
35	1061	189	211	212	212	212	212	212
40	1285	231	212	212	212	212	212	212
45	1486	231	212	212	212	212	212	212

TABLE B-10. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer of Lung, 99% CL of PoC at 50%, Group 2 Model, Never Smokers.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	93	22	31	40	49	52	52	52
21	140	33	43	52.5	52.5	52.5	52.5	52.5
25	232	51	52	52.5	52.5	52.5	52.5	52.5
30	329	54	52.5	52.5	52.5	52.5	52.5	52.5
35	329	54	52.5	52.5	52.5	52.5	52.5	52.5
40	329	54	52.5	52.5	52.5	52.5	52.5	52.5
45	329	54	52.5	52.5	52.5	52.5	52.5	52.5

TABLE B-11. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer – Other Respiratory, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	274	47	61	82	101	120	127	127
21	399	69	87	113	137	155	155	155
25	609	106	135	167	197	197	197	197
30	993	182	218	253	253	253	253	253
35	1280	226	253	253	253	253	253	253
40	1565	266	253	253	253	253	253	253
45	1775	266	253	253	253	253	253	253

TABLE B-12. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer of Bone, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	14.7	17.3	26	34	43	51	52	52
21	23	25.5	37	46	57	64	64	64
25	39	42	55	71	83	83	83	83
30	68	71	92	108	108	108	105	105
35	90	92	105	105	105	105	105	105
40	118	108	108	108	108	108	108	108
45	140	108	108	108	108	108	108	108

TABLE B-13. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E >$ 250 keV, Cancer of Connective Tissues* (and other Soft Tissue not Listed), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	84	20	27	36	46	53	55	55
21	126	30.5	38	50	61	59	59	59
25	208	49	61	75	89	89	89	89
30	366	80	98	114	114	114	114	114
35	476	104	114	114	114	114	114	114
40	587	121	114	114	114	114	114	114
45	720	122	114	114	114	114	114	114

* Bone is a connective tissue, but is modelled separately, as listed in Table B-12.

TABLE B-14. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E >$ 250 keV, Melanoma*, 99% CL of PoC at 50%, White (Non-Hispanic).

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	58	7	6.7	6.7	6.7	6.7	6.7	6.7
21	90	11	10.5	10.5	10.5	10.5	10.5	10.5
25	153	19	18	18	18	18	18	18
30	299	37	35	35	35	35	35	35
35	537	62	60	60	60	60	60	60
40	920	103	99	99	99	99	99	99
45	920	103	99	99	99	99	99	99

* Other racial or ethnic groups covered in IREP: native Americans (and native Alaskans), Asians, Black, native Hawaiians (and other Pacific islanders), and white Hispanics.

TABLE B-15. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E >$ 250 keV, Basal Cell Carcinoma*, 99% CL of PoC at 50%, White (Non-Hispanic).

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	58	7	6.7	6.7	6.7	6.7	6.7	6.7
21	89	11.3	10.5	10.5	10.5	10.5	10.5	10.5
25	153	19	18	18	18	18	18	18
30	306	38	36	36	36	36	36	36
35	540	64	60	60	60	60	60	60
40	950	106	103	103	103	103	103	103
45	952	106	103	103	103	103	103	103

* Other racial or ethnic groups covered in IREP: native Americans (and native Alaskans), Asians, Black, native Hawaiians (and other Pacific islanders), and white Hispanics.

TABLE B-16. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Squamous Cell Carcinoma*, 99% CL of PoC at 50% White (Non-Hispanic).

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	4180	368	355	355	355	355	355	355
21	4175	368	355	355	355	355	355	355
25	4178	368	356	356	356	356	356	356
30	4178	368	356	356	356	356	356	356
35	4178	368	356	356	356	356	356	356
40	4175	368	356	356	356	356	356	356
45	4178	368	356	356	356	356	356	356

* Other racial or ethnic groups covered in IREP: native Americans (and native Alaskans), Asians, Black, native Hawaiians (and other Pacific islanders), and white Hispanics.

TABLE B-17. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer of Breast, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	48	13.8	20	28	38	47	49	49
21	89	22	33	46	58	69	69	69
25	150	34	49	65	81	81	81	81
30	191	48	60	75	75	75	75	75
35	333	76	93	93	93	93	93	93
40	440	96	93	93	93	93	93	93
45	560	96	93	93	93	93	93	93

TABLE B-18. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer of Ovary, 99% CL of PoC at 50%, Females Only.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	76	16.5	22	30	37	44	46	46
21	120	25	32	42	51	57	57	57
25	197	41	50	63	74	75	75	75
30	330	68	82	92	92	92	92	92
35	409	85	93	93	93	93	93	93
40	477	99	93	93	93	93	93	93
45	608	99	93	93	93	93	93	93

TABLE B-19. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer of Other Female Genitalia (e.g., Uterus, Vagina), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	> 6000	2650	2580	2580	2580	2580	2580	2580
21	> 6000	2650	2580	2580	2580	2580	2580	2580
25	> 6000	2650	2584	2584	2584	2584	2584	2584
30	> 6000	2650	2584	2584	2584	2584	2584	2584
35	> 10000	2650	2650	2584	2584	2584	2584	2584
40	> 10000	2650	2584	2584	2584	2584	2584	2584
45	> 10000	2650	2584	2584	2584	2584	2584	2584

TABLE B-20. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer of All Male Genitalia (also Prostate), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	147	29	37.5	50	61	72	77	77
21	224	43	53	68	84	92	93	93
25	369	67	82	101	120	120	120	120
30	607	112	131	157	157	157	157	157
35	820	138	157	157	157	157	157	157
40	995	168	157	157	157	157	157	157
45	1109	168	157	157	157	157	157	157

TABLE B-21. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer of Bladder, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	83	19	26.5	36	44	52	54	54
21	127	28.5	38	49	60	67	67	67
25	213	47	59	75	88	88	88	88
30	371	81	97	113	113	113	113	113
35	455	103	113	113	113	113	113	113
40	564	119	113	113	113	113	113	113
45	671	119	113	113	113	113	113	113

TABLE B-22. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer of Other Urinary Tissues (Primarily Kidney), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	72	17	23.5	31.5	39	46	48	48
21	109	25	33.5	43	52	59	59	59
25	173	43	52	65	77	77	77	77
30	301	71	85	101	101	101	101	101
35	386	91	101	101	101	101	101	101
40	494	109	101	101	101	101	101	101
45	564	109	101	101	101	101	101	101

TABLE B-23. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer of Nervous System Tissues (also Brain), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	227	43	58	77	94	112	119	119
21	333	66	82	104	126	142	142	142
25	520	104	124	154	182	182	182	182
30	870	171	200	236	236	236	236	236
35	1080	215	235	235	235	235	235	235
40	1310	250	235	235	235	235	235	235
45	1550	250	235	235	235	235	235	235

TABLE B-24. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer of Thyroid, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	11.5	9	9	9	9	9	9	9
21	13.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
25	18.5	14	14	14	14	14	14	14
30	28	22	22	22	22	22	22	22
35	42	32	32	32	32	32	32	32
40	49	37	37	37	37	37	37	37
45	53	41	41	41	41	41	41	41

TABLE B-25. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Cancer of Other Endocrine Glands, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	72	17	23.5	31	38	45	47	47
21	109	25	33	42	52	59	59	59
25	179	41.5	51	63	74	74	74	74
30	315	69	82	100	100	100	100	100
35	404	88	100	100	100	100	100	100
40	493	107	100	100	100	100	100	100
45	576	107	100	100	100	100	100	100

TABLE B-26. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Lymphoma and Multiple Myeloma, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	159	29	39	52	65	76	80	80
21	242	43	55	69	84	97	97	97
25	395	67	83	97	117	117	117	117
30	645	111	126	148	148	148	148	148
35	805	137	148	148	148	148	148	148
40	945	163	148	148	148	148	148	148
45	1171	163	148	148	148	148	148	148

TABLE B-27. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Leukemia (excluding Chronic Lymphocytic Leukemia), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	1.9	4.4	9.5	19	33	56	90	137
21	2.3	5.1	10.8	21	36	58	92	138
25	3	6.2	12.5	23	38	60	92	137
30	3.9	7.5	14.5	25	40	60	87	125
35	5	9.2	16.5	27	41	58	78	105
40	6.2	10.8	18.2	28	39	51	65	80
45	7.3	12.2	19.4	27.7	36	43	50	55

TABLE B-28. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Acute Lymphoid Leukemia, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	0.25	0.9	2.7	6.5	13	24	40	65
21	16	16	16	16	16	16	16	16
25	16	16	16	16	16	16	16	16
30	16	16	16	16	16	16	16	16
35	16	16	16	16	16	16	16	16
40	16	16	16	16	16	16	16	16
45	16	16	16	16	16	16	16	16

TABLE B-29. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Chronic Lymphocytic Leukemia (CLL), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	184	51	47	54	67	79	85	85
21	264	72	64	74	90	102	103	103
25	439	119	97	111	131	131	131	131
30	808	194	154	180	180	180	180	180
35	995	246	192	180	180	180	180	180
40	1230	296	192	180	180	180	180	180
45	1565	296	192	180	180	180	180	180

TABLE B-30. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Acute Myeloid Leukemia (AML), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	5.8	9.5	15	22	30	36.5	42	45
21	5.8	9.5	15	22	30	36.5	42	45
25	5.8	9.5	15	22	30	36.5	42	45
30	5.8	9.5	15	22	30	36.5	42	45
35	5.8	9.5	15	22	30	36.5	42	45
40	5.8	9.5	15	22	30	36.5	42	45
45	5.8	9.5	15	22	30	36.5	42	45

TABLE B-31. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $E > 250$ keV, Chronic Myeloid Leukemia (CML), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	1.3	5	12.4	25.5	50	89	155	262
21	1.3	5	12.4	25.5	50	89	155	262
25	1.3	5	12.4	25.5	50	89	155	262
30	1.3	5	12.4	25.5	50	89	155	262
35	1.3	5	12.4	25.5	50	89	155	262
40	1.3	5	12.4	25.5	50	89	155	262
45	1.3	5	12.4	25.5	50	89	155	262

Appendix C

Example Screening Doses (rem) Calculated with NIOSH IREP, Chronic Exposures, Photons: $30 < E < 250$ keV, Males (Unless Noted Otherwise), and American Cancer Society Statistics

TABLE C-1. Lifetime Probability (Percents) of Developing* and Dying from Cancer for 23 Sites, 2010 – 2012, American Cancer Society, Surveillance Research (ACS 2016).

Site	Males		Females	
	Developing	Dying	Developing	Dying
All Sites †	42.1	22.6	37.6	19.1
Brain & ONS	0.7	0.5	0.5	0.4
Breast	0.1	< 0.1	12.3	2.7
Colorectal	4.7	2.0	4.4	1.8
Esophagus	0.8	0.8	0.2	0.2
Hodgkin lymphoma	0.2	< 0.1	0.2	< 0.1
Kidney & renal pelvis	2.0	0.6	1.2	0.3
Larynx	0.6	0.2	0.1	< 0.1
Leukemia	1.8	1.0	1.2	0.7
Liver & intrahepatic bile duct	1.3	0.9	0.5	0.5
Lung & bronchus	7.2	6.3	6.0	4.9
Melanoma of skin‡	3.0	0.5	1.9	0.2
Myeloma	0.9	0.5	0.6	0.4
Non-Hodgkin lymphoma	2.4	0.9	1.9	0.7
Oral cavity & pharynx	1.6	0.4	0.7	0.2
Ovary	--	--	1.3	1.0
Pancreas	1.5	1.4	1.5	1.3
Prostate	14.0	2.6	--	--
Stomach	1.1	0.5	0.7	0.3
Testis	0.4	< 0.1	--	--
Thyroid	0.6	0.1	1.7	0.1
Urinary bladder§	3.8	0.9	1.1	0.3
Uterine cervix	--	--	0.6	0.2
Uterine corpus	--	--	2.8	0.6

* For those who are cancer free.

† All sites excludes basal cell and squamous cell skin cancers and in-situ cancers except urinary bladder.

‡ Statistics are for whites.

§ Includes invasive and in-situ cancer cases.

TABLE C-2. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $30 < E < 250$ keV, Cancer of Colon, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	28.5	5.1	6.6	9.1	11.2	13.4	14	14
21	42	7.2	9.7	12.1	14.6	16.6	16.6	16.6
25	69	11.6	14.3	17.5	20.6	20.6	20.6	20.6
30	28.4	28.4	28.4	149	24	28.4	28.4	28.4
35	149	24	28.4	28.4	28.4	28.4	28.4	28.4
40	186	29.7	28.4	28.4	28.4	28.4	28.4	28.4
45	208	29.7	28.4	28.4	28.4	28.4	28.4	28.4

TABLE C-3. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $30 < E < 250$ keV, Cancer of Liver, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	9.4	1.9	2.6	3.2	4	4.7	5	5
21	13.5	2.7	3.5	4.3	5.2	5.9	5.9	5.9
25	22.3	4.2	5.1	6.2	7.3	7.3	7.3	7.3
30	9.5	9.5	9.5	47	8	9.5	9.5	9.5
35	47	8	9.5	9.5	9.5	9.5	9.5	9.5
40	58	9.7	9.5	9.5	9.5	9.5	9.5	9.5
45	71	9.7	9.5	9.5	9.5	9.5	9.5	9.5

TABLE C-4. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $30 < E < 250$ keV, Cancer of Lung, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	38.5	7.6	10	13.5	16.5	18.2	18.2	18.2
21	57	11	14.4	18	18.3	18.3	18.3	18.3
25	91	17.6	18.3	18.3	18.3	18.3	18.3	18.3
30	18.2	18.2	18.2	126	19.2	18.2	18.2	18.2
35	126	19.2	18.2	18.2	18.2	18.2	18.2	18.2
40	126	19.2	18.2	18.2	18.2	18.2	18.2	18.2
45	126	19.2	18.2	18.2	18.2	18.2	18.2	18.2

TABLE C-5. Screening Doses (rem) Calculated with IREP, Chronic Exposures, $30 < E < 250$ keV, Photons: Cancer of All Male Genitalia (also Prostate), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	73	11	14	18	22.5	26.5	28	28
21	101	15.8	19.2	25	31	34	34	34
25	148	25.3	30	38	45	45	45	45
30	58	58	58	350	54	58	58	58
35	350	54	58	58	58	58	58	58
40	400	63	58	58	58	58	58	58
45	484	63	58	58	58	58	58	58

TABLE C-6. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $30 < E < 250$ keV, Cancer of Bladder, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	36.7	7	9.5	12.5	15.6	18.4	19.2	19.2
21	54	10.3	13.3	16.5	20.2	22.9	22.9	22.9
25	81	16.3	19.9	24.4	28.8	28.8	28.8	28.8
30	39	39	39	192	33.3	38.8	39	39
35	192	33.3	38.8	39	39	39	39	39
40	226	41	38.9	39	39	39	39	39
45	247	41	39	39	39	39	39	39

TABLE C-7. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $30 < E < 250$ keV, Cancer of Thyroid, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	4.8	3.5	3.5	3.5	3.5	3.5	3.5	3.5
21	5.9	4.2	4.2	4.2	4.2	4.2	4.2	4.2
25	7.9	5.8	5.8	5.8	5.8	5.8	5.8	5.8
30	8.6	8.6	8.6	18	12.9	12.9	12.9	12.9
35	18	12.9	12.9	12.9	12.9	12.9	12.9	12.9
40	20.6	14.8	14.8	14.8	14.8	14.8	14.8	14.8
45	23	17.2	17.2	17.2	17.2	17.2	17.2	17.2

TABLE C-8. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $30 < E < 250$ keV, Acute Lymphoid Leukemia, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	0.1	0.34	0.95	2.4	5	9.8	17.4	30
21	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
25	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
30	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
35	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
40	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
45	0.1	0.34	0.95	2.4	5	9.8	17.4	30

TABLE C-9. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Photons: $30 < E < 250$ keV, Acute Myeloid Leukemia, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	2.2	3.4	4.8	6.5	8.6	11.4	14.4	16.5
21	2.2	3.4	4.8	6.5	8.6	11.4	14.4	16.5
25	2.2	3.4	4.8	6.5	8.6	11.4	14.4	16.5
30	11.4	14.4	16.5	2.2	3.4	4.8	6.5	8.6
35	2.2	3.4	4.8	6.5	8.6	11.4	14.4	16.5
40	2.2	3.4	4.8	6.5	8.6	11.4	14.4	16.5
45	2.2	3.4	4.8	6.5	8.6	11.4	14.4	16.5

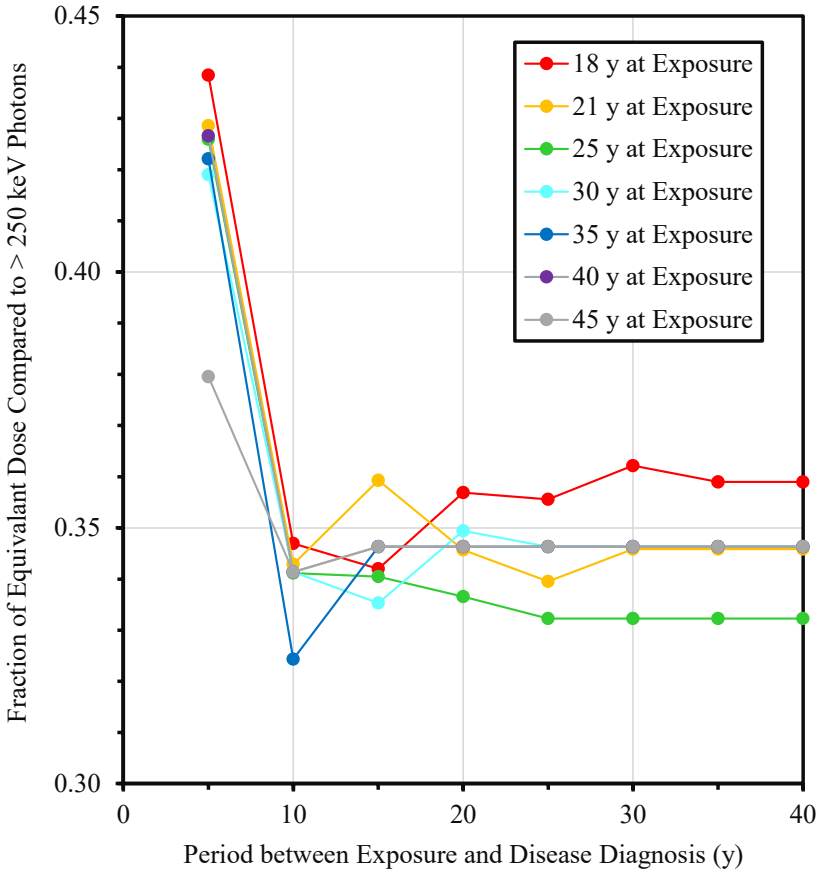

Figure C-1. Fraction of Equivalent Dose for Photons: $30 < E < 250$ keV Compared to > 250 keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Colon Cancer

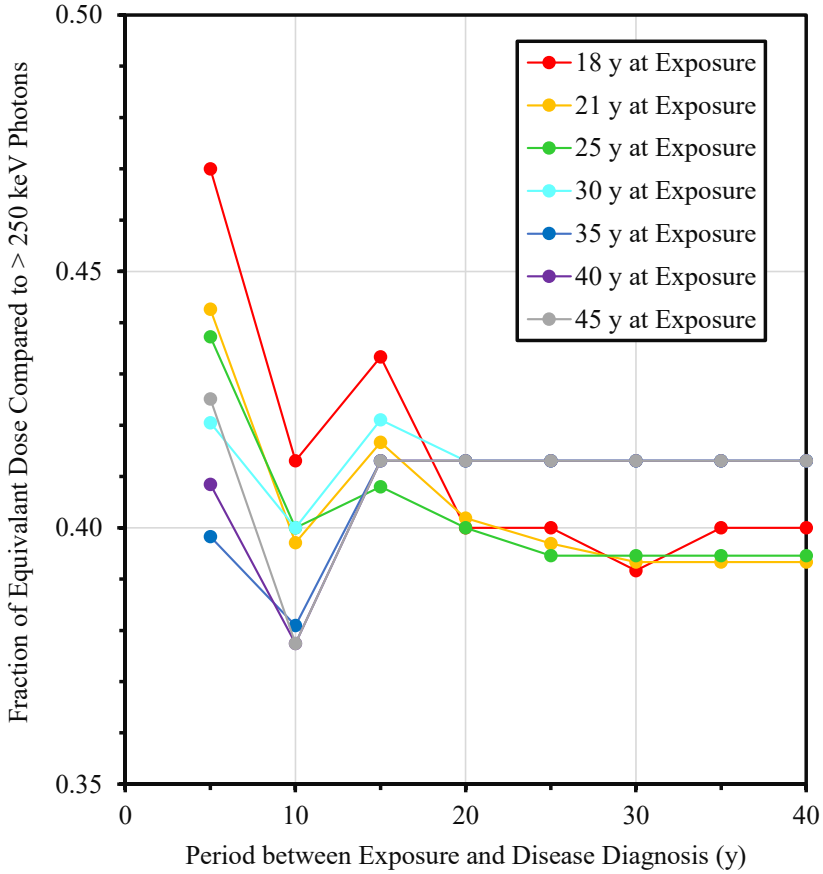

Figure C-2. Fraction of Equivalent Dose for Photons: $30 < E < 250$ keV Compared to > 250 keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Liver Cancer

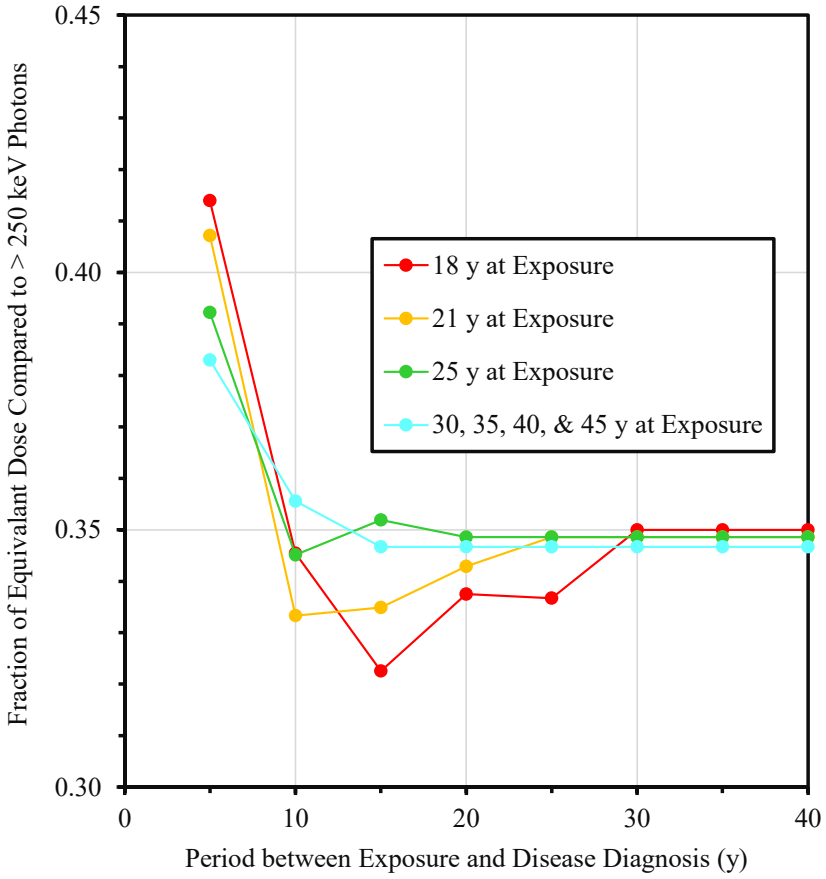

Figure C-3. Fraction of Equivalent Dose for Photons: $30 < E < 250$ keV Compared to > 250 keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Lung Cancer.

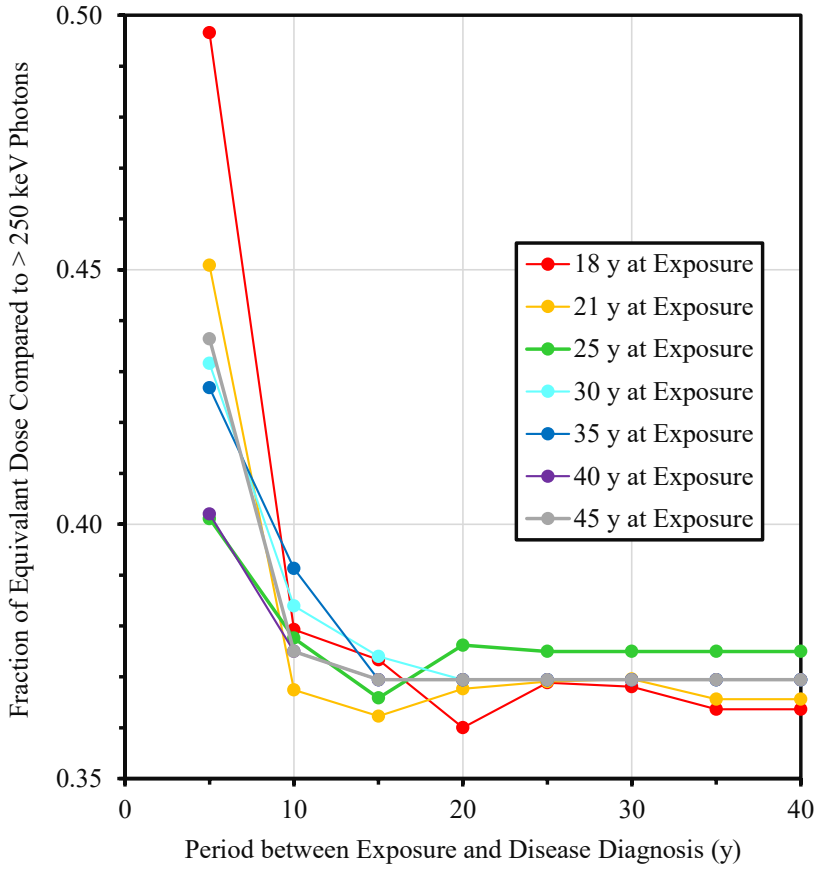

Figure C-4. Fraction of Equivalent Dose for Photons: $30 < E < 250$ keV Compared to > 250 keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Cancer of All Male Genitalia (also Prostate).

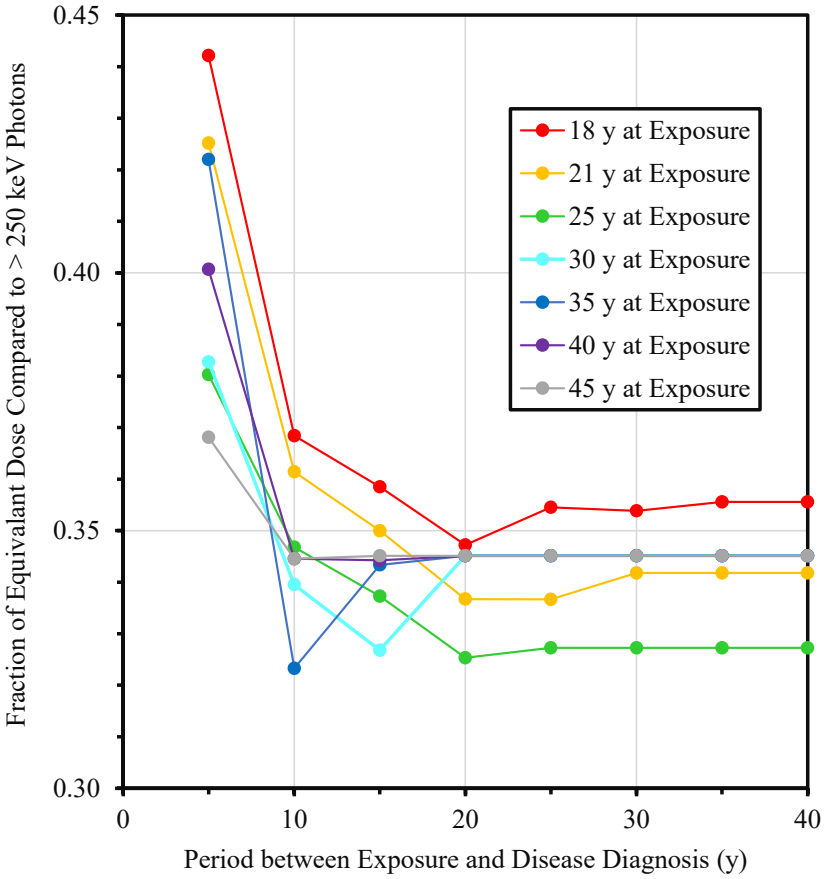

Figure C-5. Fraction of Equivalent Dose for Photons: $30 < E < 250$ keV Compared to > 250 keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Cancer of Bladder.

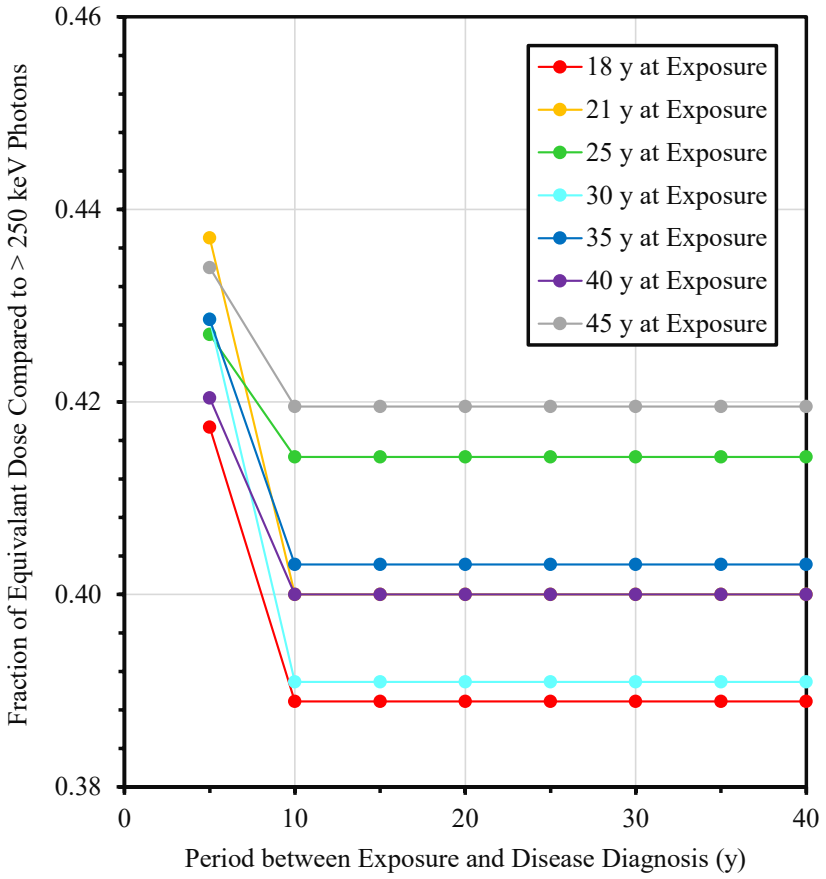

Figure C-6. Fraction of Equivalent Dose for Photons: $30 < E < 250$ keV Compared to > 250 keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Cancer of Thyroid.

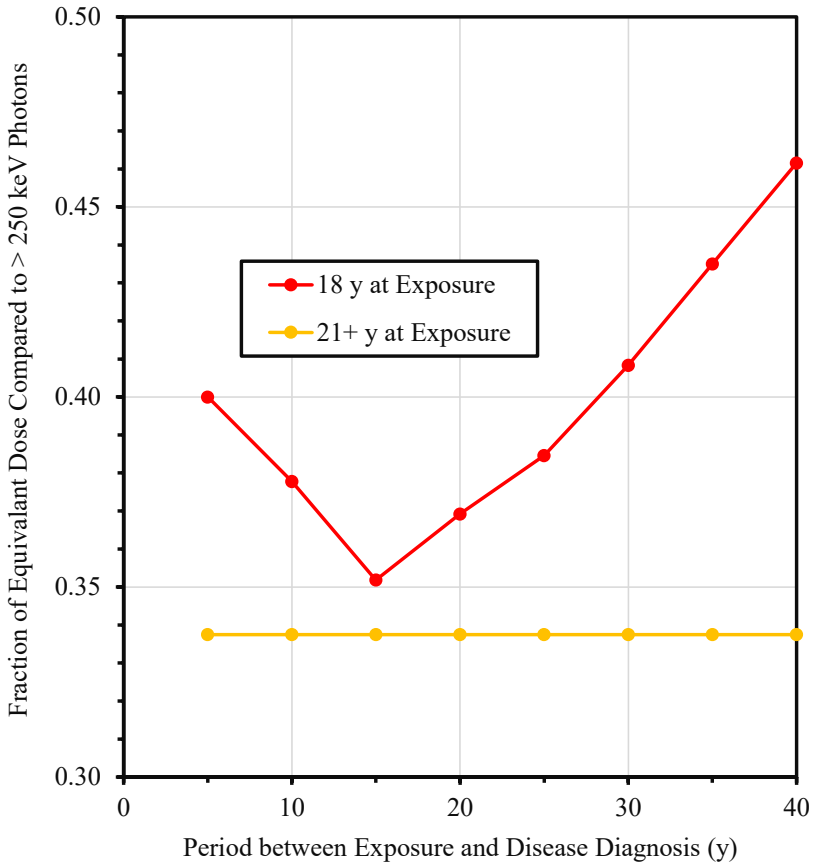

Figure C-7. Fraction of Equivalent Dose for Photons: 30 < *E* < 250 keV Compared to > 250 keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Acute Lymphoid Leukemia.

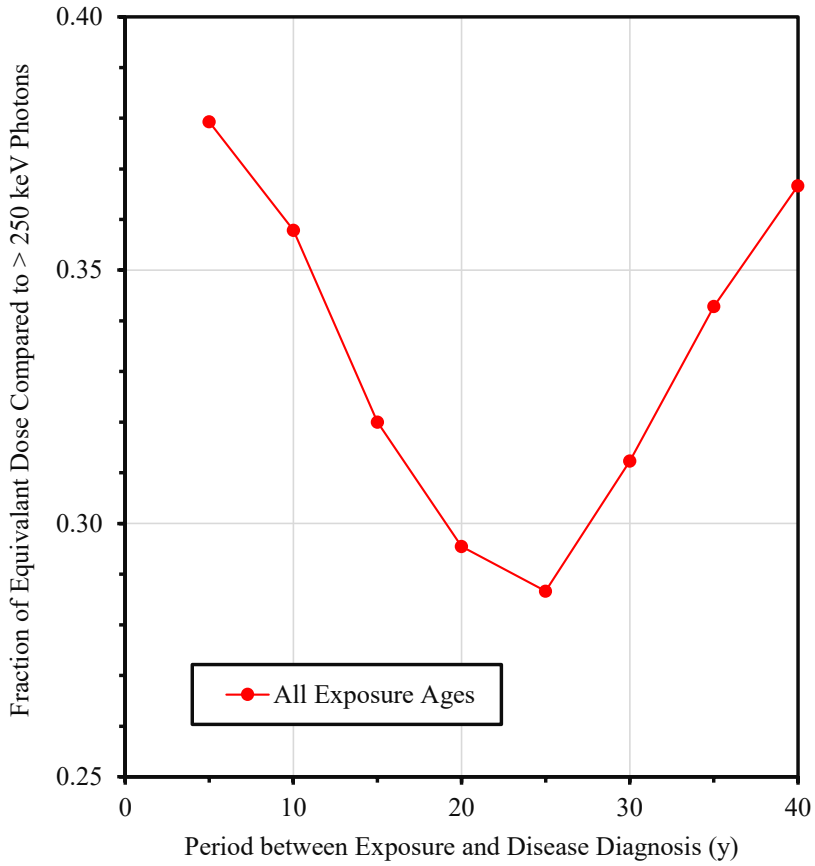

Figure C-8. Fraction of Equivalent Dose for Photons: 30 < *E* < 250 keV Compared to > 250 keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Acute Myeloid Leukemia.

Appendix D

Example Screening Doses (rem) Calculated with NIOSH IREP, Chronic Exposures, Neutrons: $0.1 < E < 2$ MeV, Males (Unless Noted Otherwise)

TABLE D-1. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Neutrons: $0.1 < E < 2$ MeV, Cancer of Colon, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	51	10.3	14.2	19	23	28	29.5	29.5
21	77	16	20	26.3	32	35.5	35.5	35.5
25	123	25	31.5	39	47	47	47	47
30	232	41.5	51	57	57	57	57	57
35	302	52	57	57	57	57	57	57
40	367	63.5	57	57	57	57	57	57
45	445	63.5	57	57	57	57	57	57

TABLE D-2. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Neutrons: $0.1 < E < 2$ MeV, Cancer of Liver, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	20.2	3	4.3	5.7	7.1	8.4	8.8	8.8
21	31	4.5	5.9	7.5	9.2	10.5	10.5	10.5
25	50	7	8.8	10.8	12.9	12.9	12.9	12.9
30	84	11.4	13.6	16.3	16.3	16.3	16.3	16.3
35	109	14.2	16.3	16.3	16.3	16.3	16.3	16.3
40	131	17	16.3	16.3	16.3	16.3	16.3	16.3
45	153	17	16.3	16.3	16.3	16.3	16.3	16.3

TABLE D-3. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Neutrons: $0.1 < E < 2$ MeV, Cancer of Lung, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	65	13.7	18.4	23.7	29.5	35	37	37
21	97	19.4	25.6	32.5	36.7	36.7	36.7	36.7
25	172	31	36.8	36.8	36.8	36.8	36.8	36.8
30	276	37.2	36.8	36.8	36.8	36.8	36.8	36.8
35	276	37.2	36.8	36.8	36.8	36.8	36.8	36.8
40	276	37.2	36.8	36.8	36.8	36.8	36.8	36.8
45	276	37.2	36.8	36.8	36.8	36.8	36.8	36.8

TABLE D-4. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Neutrons: $0.1 < E < 2$ MeV, Cancer of Breast, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	45	9.2	13	18.5	23	29	32	32
21	65	13	17.7	23.7	29.5	35.2	35.2	35.2
25	102	19.4	25.4	33.4	41	41	41	41
30	173	30.5	39	48	48	48	48	48
35	234	39	48	48	48	48	48	48
40	291	49	48	48	48	48	48	48
45	360	49	48	48	48	48	48	48

TABLE D-5. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Neutrons: $0.1 < E < 2$ MeV, Cancer of All Male Genitalia (also Prostate), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	122	20.4	26.5	35.5	44	52	55	55
21	193	28.7	38	49	60	67	67	67
25	290	46	59	71	84	84	84	84
30	493	77	92	114	114	114	114	114
35	661	97	114	114	114	114	114	114
40	705	118	114	114	114	114	114	114
45	855	118	114	114	114	114	114	114

TABLE D-6. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Neutrons: $0.1 < E < 2$ MeV, Cancer of Bladder, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	66	13.4	17.5	24	30	35.4	37	37
21	106	19.6	25.6	33.5	40	46	46	46
25	167	31	40	48	57	57	57	57
30	279	53	63	74	74	74	74	74
35	367	67	74	74	74	74	74	74
40	487	79	74	74	74	74	74	74
45	568	79	74	74	74	74	74	74

TABLE D-7. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Neutrons: $0.1 < E < 2$ MeV, Acute Myeloid Leukemia, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	2.2	3.1	4.3	6	8	10	13	17
21	2.2	3.1	4.3	6	8	10	13	17
25	2.2	3.1	4.3	6	8	10	13	17
30	2.2	3.1	4.3	6	8	10	13	17
35	2.2	3.1	4.3	6	8	10	13	17
40	2.2	3.1	4.3	6	8	10	13	17
45	2.2	3.1	4.3	6	8	10	13	17

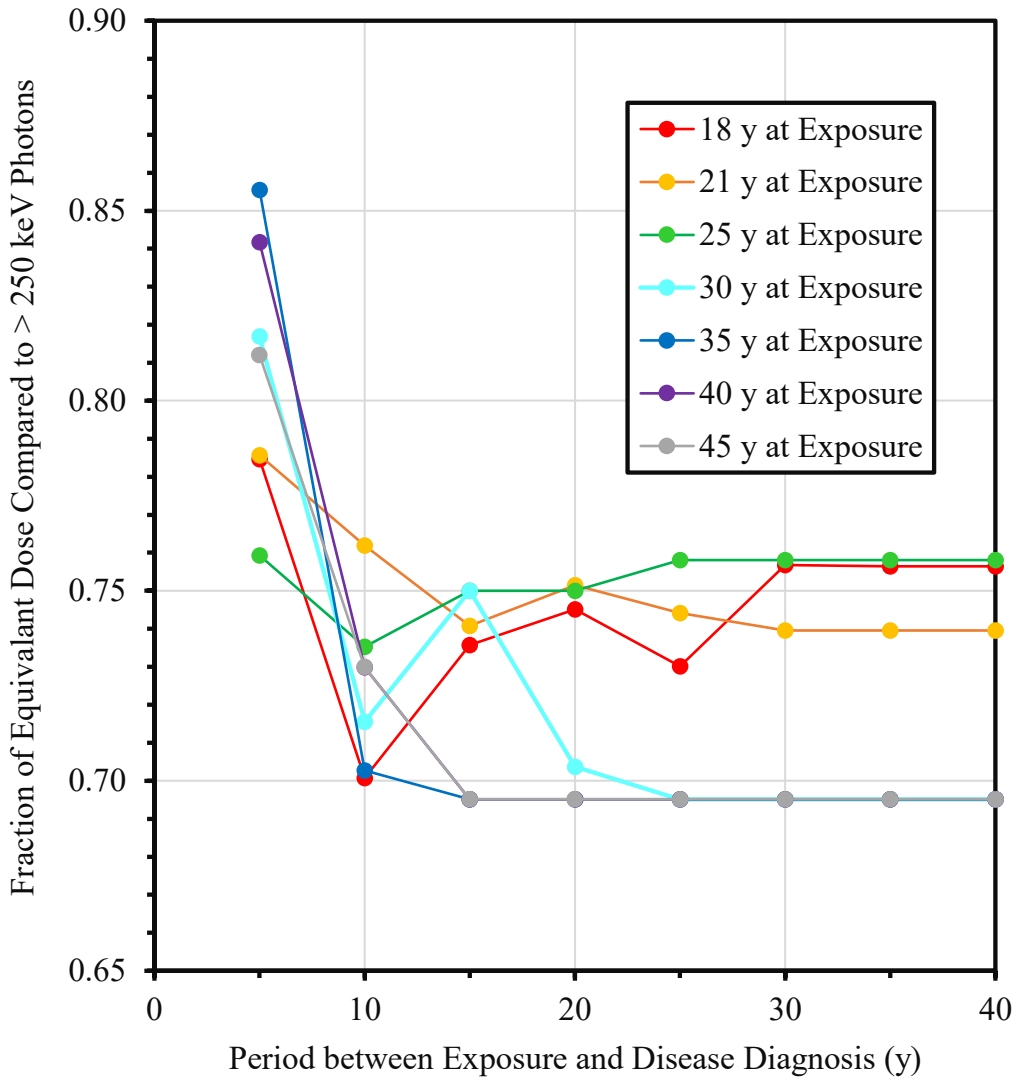

Figure D-1. Fraction of Equivalent Dose for Neutrons: $0.1 < E < 2$ MeV Compared to Photons: $E > 250$ keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Colon Cancer.

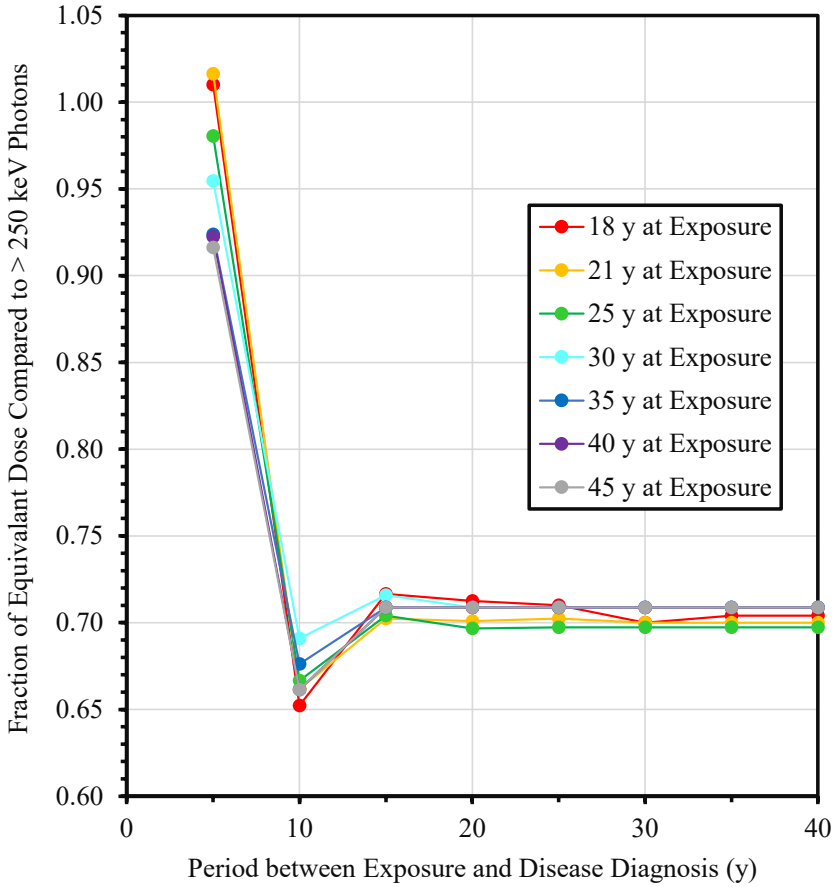

Figure D-2. Fraction of Equivalent Dose for Neutrons: $0.1 < E < 2$ MeV Compared to Photons: $E > 250$ keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Liver Cancer.

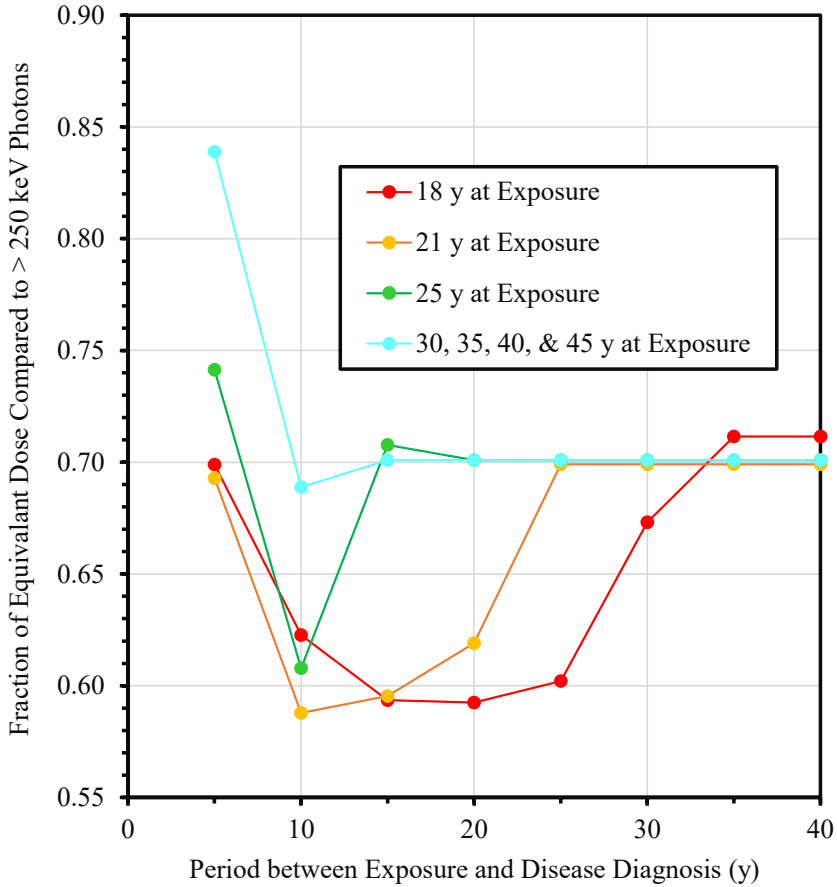

Figure D-3. Fraction of Equivalent Dose for Neutrons: $0.1 < E < 2$ MeV Compared to Photons: $E > 250$ keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Lung Cancer.

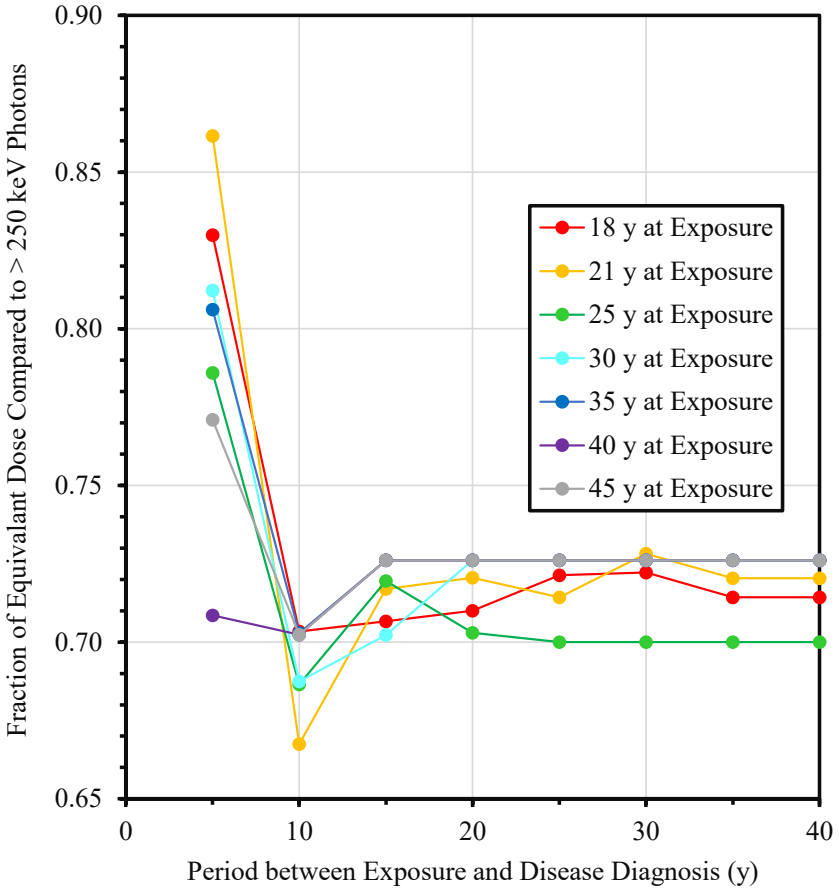

Figure D-4. Fraction of Equivalent Dose for Neutrons: $0.1 < E < 2$ MeV Compared to Photons: $E > 250$ keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Cancer to Male Genitalia (also Prostate).

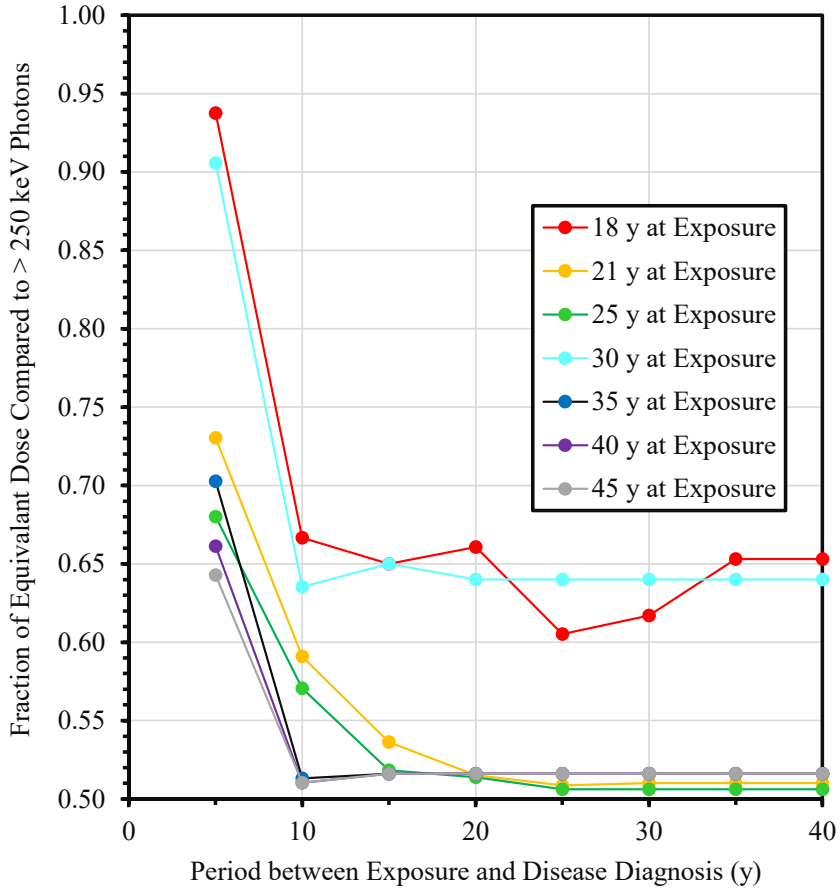

Figure D-5. Fraction of Equivalent Dose for Neutrons: $0.1 < E < 2$ MeV Compared to Photons: $E > 250$ keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Breast Cancer.

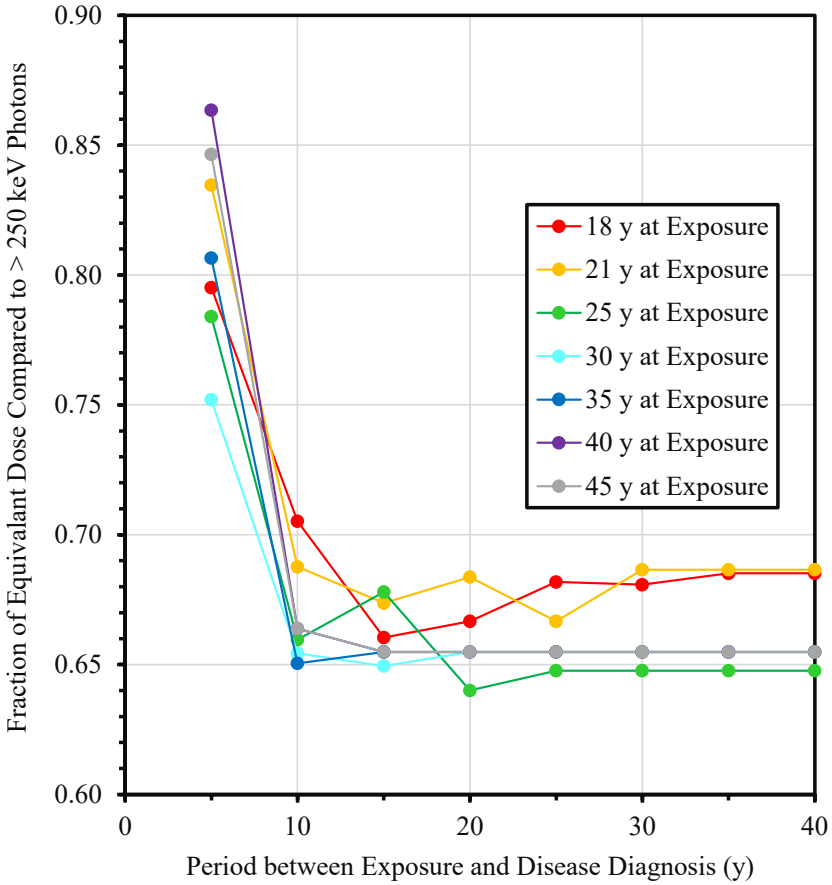

Figure D-6. Fraction of Equivalent Dose for Neutrons: $0.1 < E < 2$ MeV Compared to Photons: $E > 250$ keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Cancer to Bladder.

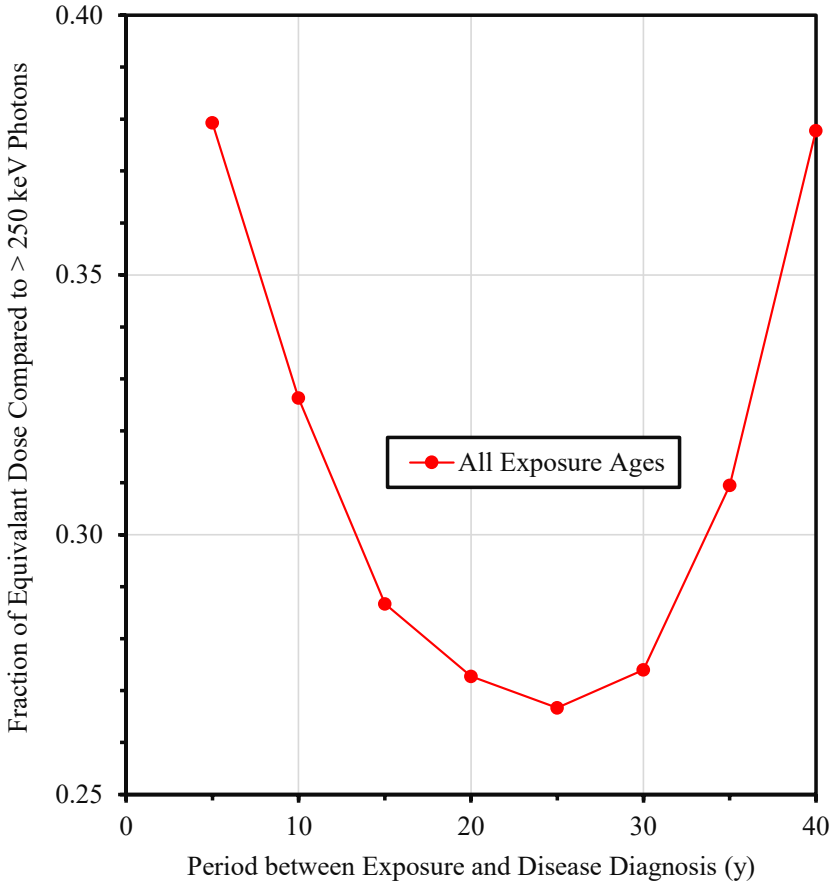

Figure D-7. Fraction of Equivalent Dose for Neutrons: $0.1 < E < 2$ MeV Compared to Photons: $E > 250$ keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Acute Myeloid Leukemia.

Appendix E

Example Screening Doses (rem) Calculated with NIOSH IREP, Chronic Exposures, Alpha Particles, Males (Unless Noted Otherwise)

TABLE E-1. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Alpha Particles, Cancer of Colon, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	35.3	7.2	9	11.3	13.9	16.6	17.5	17.5	17.5	17.5
21	51	9.8	12	14.8	17.7	20.5	20.5	20.5	20.5	20.5
25	79	14.8	17.4	21	24.8	24.8	24.8	24.8	24.8	24.8
30	137	24	27.1	32.5	32.6	32.6	32.6	32.6	32.6	32.6
35	174	29.4	32.5	32.5	32.5	32.5	32.5	32.5	32.5	32.5
40	205	33.7	32.5	32.5	32.5	32.5	32.5	32.5	32.5	32.5
45	254	33.7	32.5	32.5	32.5	32.5	32.5	32.5	32.5	32.5

TABLE E-2. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Alpha Particles, Cancer of Liver, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	12.8	2.1	2.7	3.5	4.3	5	5.4	5.4	5.4	5.4
21	19	2.9	3.7	4.6	5.6	6.3	6.3	6.3	6.3	6.3
25	31.5	4.4	5.4	6.6	7.8	7.8	7.8	7.8	7.8	7.8
30	52	7.1	8.4	10	10	10	10	10	10	10
35	65	9.9	10	10	10	10	10	10	10	10
40	82	10.5	10	10	10	10	10	10	10	10
45	96	10.5	10	10	10	10	10	10	10	10

TABLE E-3. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Alpha Particles, Cancer of Lung, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	47.4	7.6	9.8	12.6	15.8	18.6	19.7	19.7	19.7	19.7
21	72	11	13.5	17.5	21.2	23.7	23.7	23.7	23.7	23.7
25	118	16.7	20.8	23.7	23.7	23.7	23.7	23.7	23.7	23.7
30	185	25.8	23.7	23.7	23.7	23.7	23.7	23.7	23.7	23.7
35	185	25.8	23.7	23.7	23.7	23.7	23.7	23.7	23.7	23.7
40	185	25.8	23.7	23.7	23.7	23.7	23.7	23.7	23.7	23.7
45	185	25.8	23.7	23.7	23.7	23.7	23.7	23.7	23.7	23.7

TABLE E-4. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Alpha Particles, Cancer of Bone, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	7.1	8.2	11.1	14.5	17.7	21.2	22.5	22.5	22.5	22.5
21	10.8	11.5	15.5	19.5	23	26.7	26.7	26.7	26.7	26.7
25	18.2	18.2	23	27.5	32.5	32.5	32.5	32.5	32.5	32.5
30	30	30	36	42	42	42	42	42	42	42
35	39	35.5	42	42	42	42	42	42	42	42
40	46	42	42	42	42	42	42	42	42	42
45	52	42	42	42	42	42	42	42	42	42

TABLE E-5. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Alpha Particles, Melanoma, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	31	3.9	3.7	3.7	3.7	3.7	3.7	3.7
21	46	6.1	5.6	5.6	5.6	5.6	5.6	5.6
25	81	10.3	9.7	9.7	9.7	9.7	9.7	9.7
30	165	20	19	19	19	19	19	19
35	313	35.5	35	35	35	35	35	35
40	599	62	61	61	61	61	61	61
45	599	61	61	61	61	61	61	61

TABLE E-6. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Alpha Particles, Cancer of All Male Genitalia (also Prostate), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	85	16	22	30	37	44	46	46
21	125	23.5	32	40	48	55	55	55
25	220	37.5	47	56	68	68	68	68
30	358	65	73	83	83	83	83	83
35	466	76	83	83	83	83	83	83
40	581	88	83	83	83	83	83	83
45	710	88	83	83	83	83	83	83

TABLE E-7. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Alpha Particles, Cancer of Bladder, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
18	42	9.1	11.6	16.4	20.2	24	25.2	25.2
21	63	12.7	17.6	21.6	26	30	30	30
25	104	20.4	25.5	29	34.4	34.4	34.4	34.4
30	178	34.5	38	46	46	46	46	46
35	244	39	46	46	46	46	46	46
40	300	47.5	46	46	46	46	46	46
45	340	47.5	46	46	46	46	46	46

TABLE E-8. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Alpha Particles, Acute Lymphatic Leukemia, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	0.282	0.93	2.63	6.5	14.6	30.3	59.1	115.3	219	395
21	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
25	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
30	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
35	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
40	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
45	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5

TABLE E-9. Screening Doses (rem) Calculated with IREP, Chronic Exposures, Alpha Particles, Acute Myeloid Leukemia, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	4.8	7.1	10	13.8	18.4	23.7	29.8	36.5	43.7	50.2
21	4.8	7.1	10	13.8	18.4	23.7	29.8	36.5	43.7	50.2
25	4.8	7.1	10	13.8	18.4	23.7	29.8	36.5	43.7	50.2
30	4.8	7.1	10	13.8	18.4	23.7	29.8	36.5	43.7	50.2
35	4.8	7.1	10	13.8	18.4	23.7	29.8	36.5	43.7	50.2
40	4.8	7.1	10	13.8	18.4	23.7	29.8	36.5	43.7	50.2
45	4.8	7.1	10	13.8	18.4	23.7	29.8	36.5	43.7	50.2

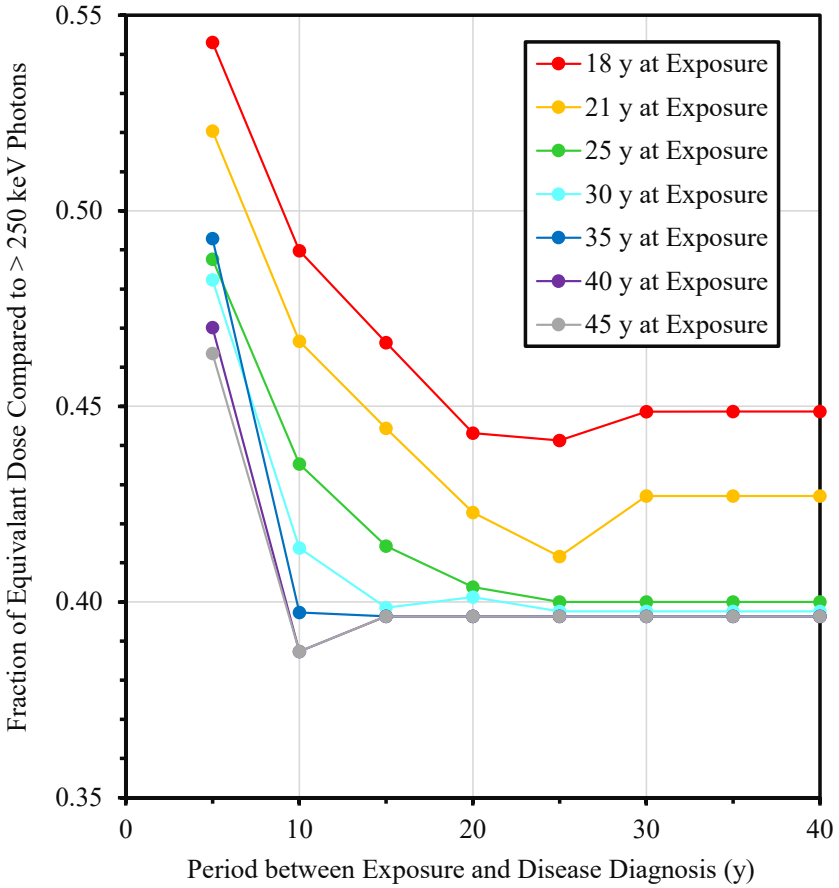

Figure E-1. Fraction of Equivalent Dose for Alpha Particles Compared to Photons: $E > 250$ keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Colon Cancer.

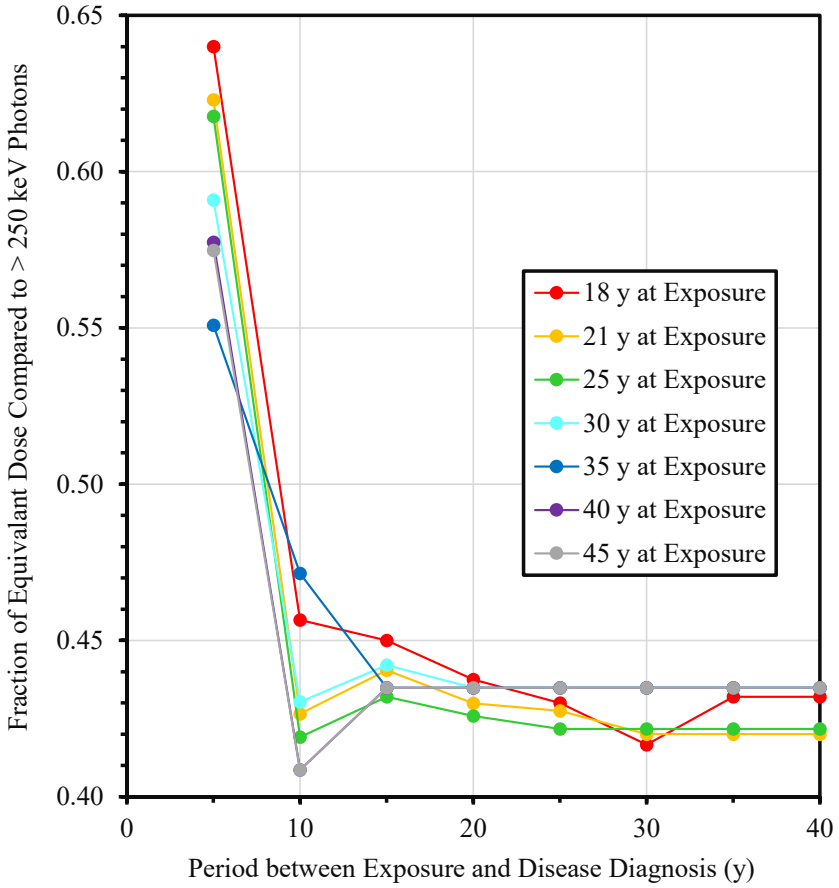

Figure E-2. Fraction of Equivalent Dose for Alpha Particles Compared to Photons: $E > 250$ keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Liver Cancer.

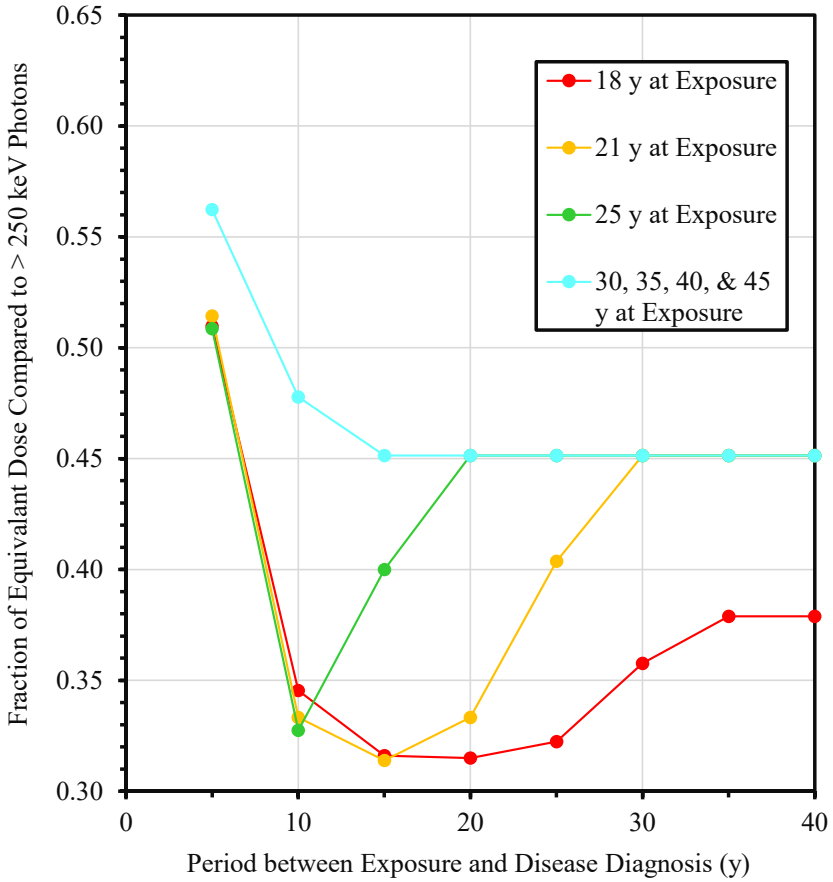

Figure E-3. Fraction of Equivalent Dose for Alpha Particles Compared to Photons: $E > 250$ keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Lung Cancer.

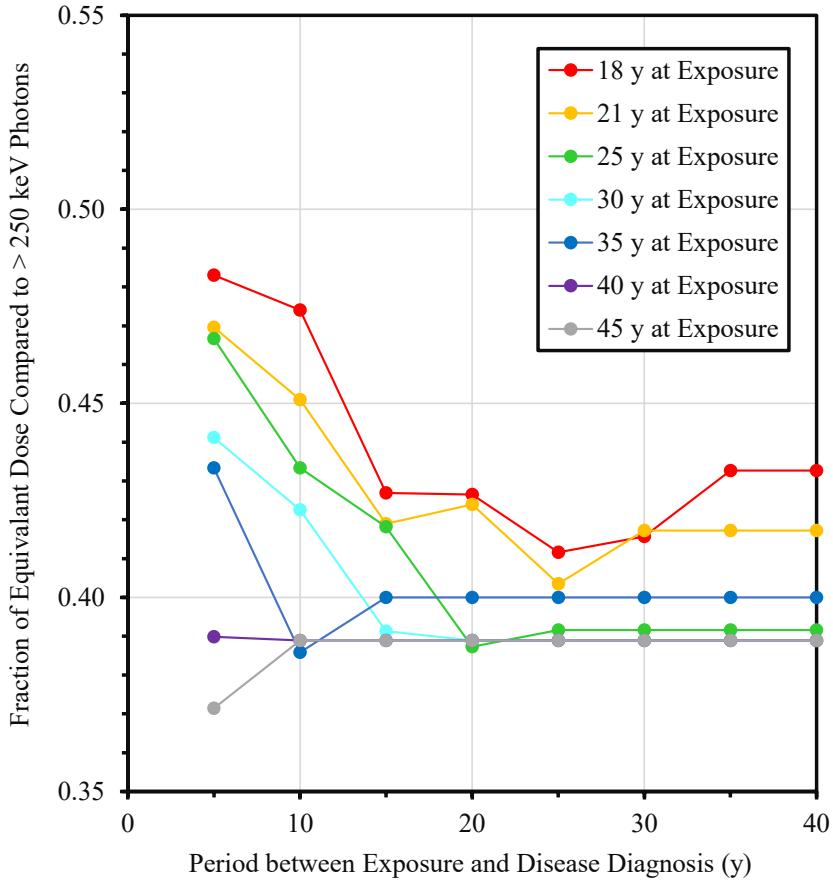

Figure E-4. Fraction of Equivalent Dose for Alpha Particles Compared to Photons: $E > 250$ keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Bone Cancer.

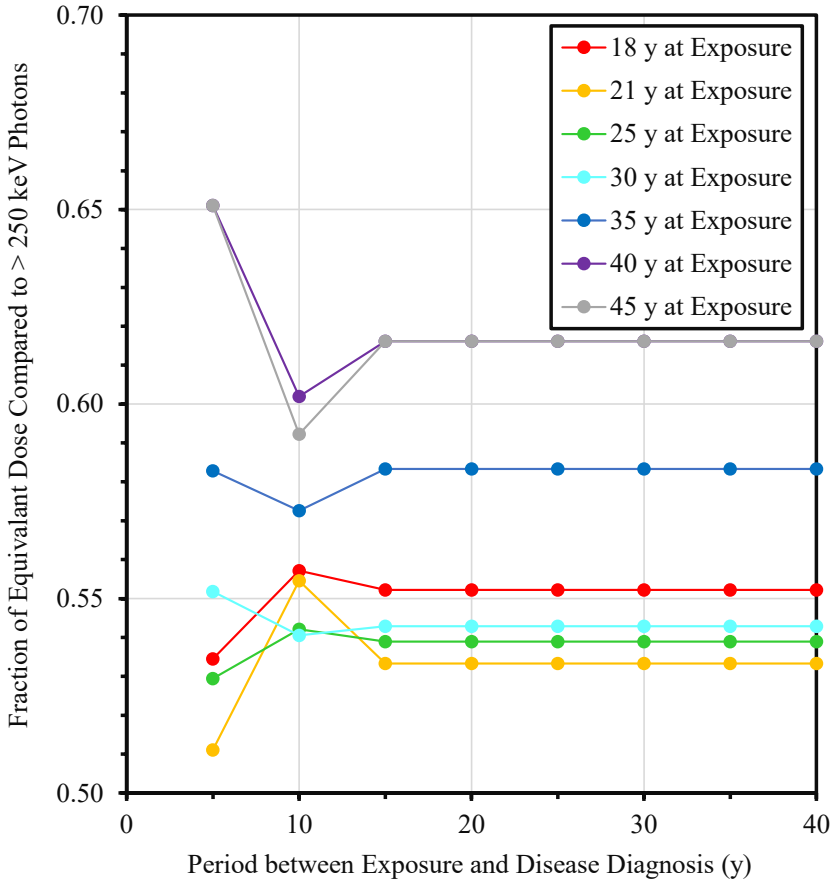

Figure E-5. Fraction of Equivalent Dose for Alpha Particles Compared to Photons: $E > 250$ keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Melanoma.

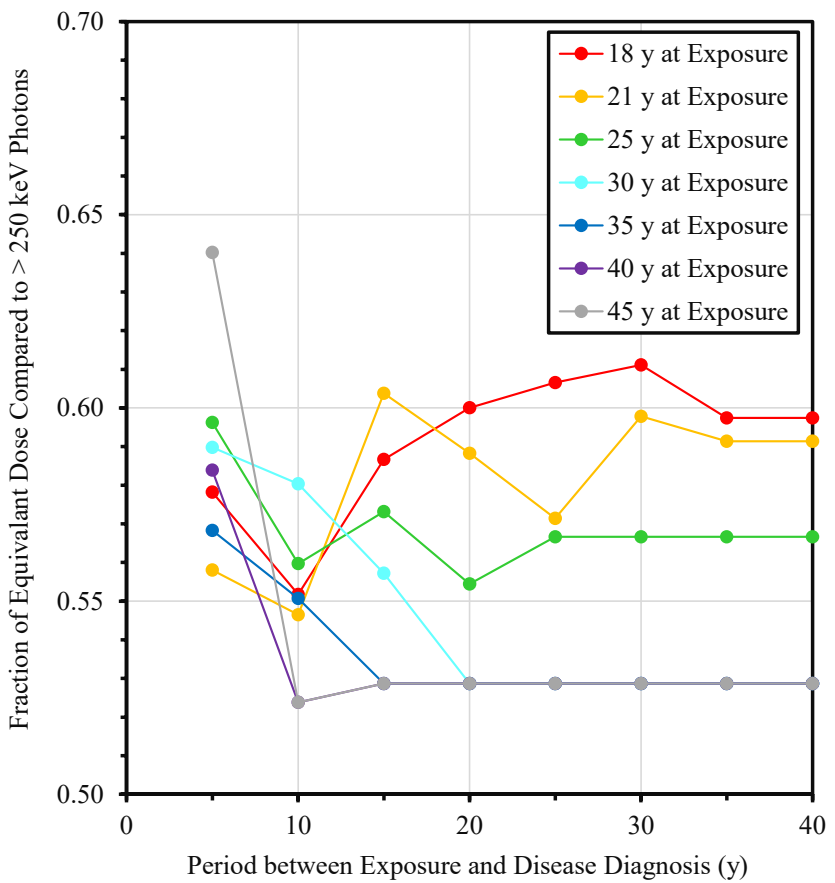

Figure E-6. Fraction of Equivalent Dose for Alpha Particles Compared to Photons: $E > 250$ keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Cancer of All Male Genitalia (also Prostate).

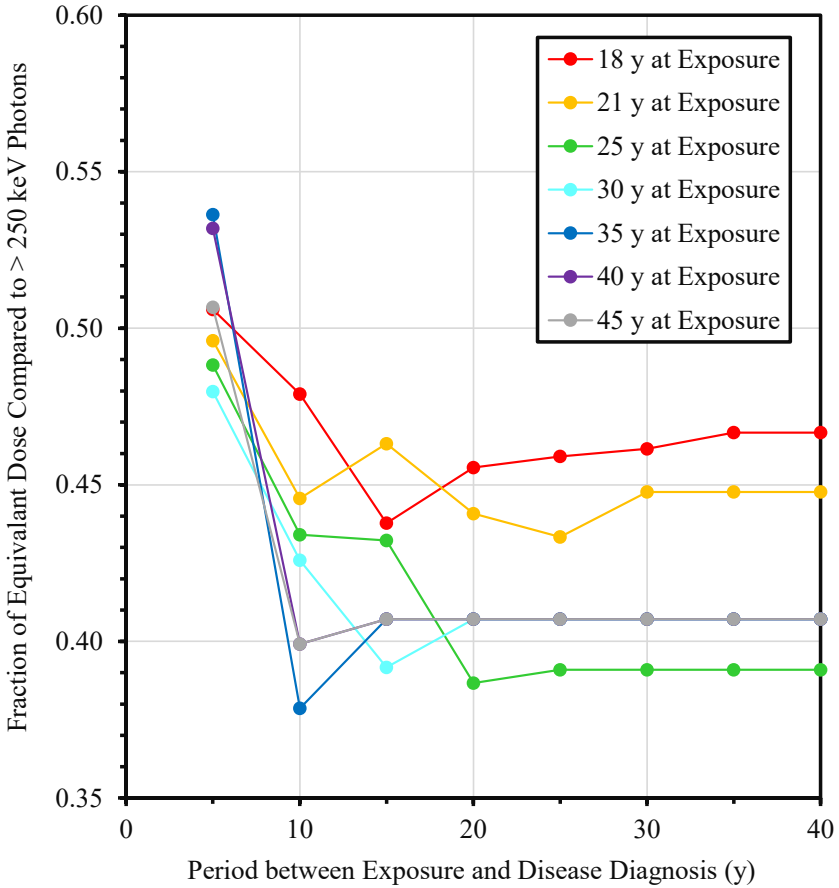

Figure E-7. Fraction of Equivalent Dose for Alpha Particles Compared to Photons: $E > 250$ keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Bladder Cancer.

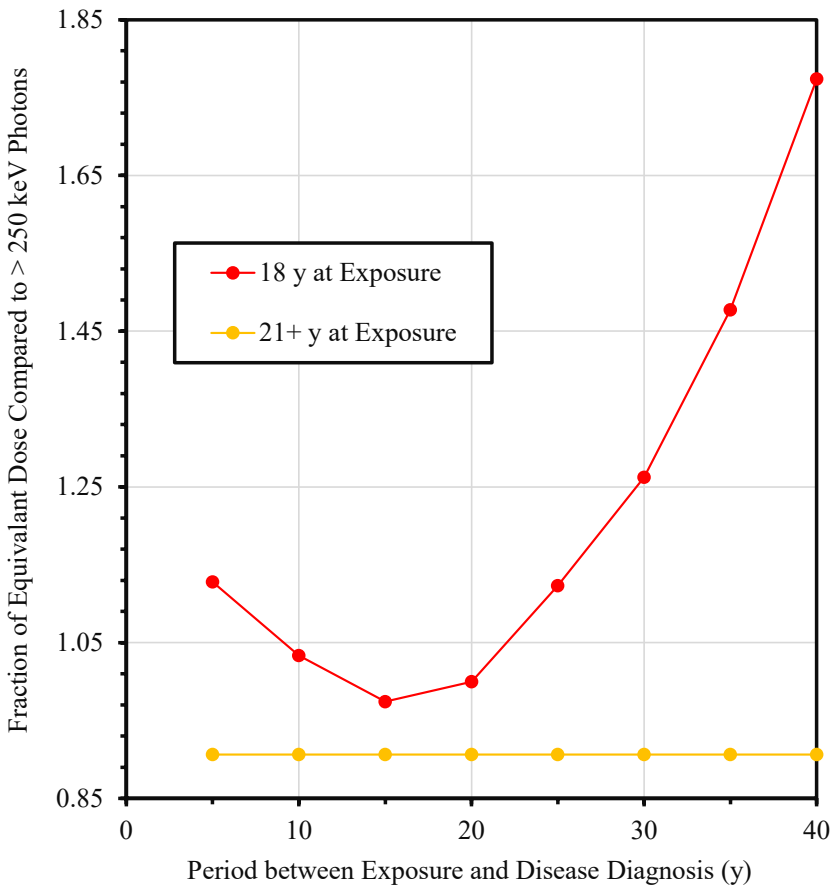

Figure E-8. Fraction of Equivalent Dose for Alpha Particles Compared to Photons: $E > 250$ keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Acute Lymphoid Leukemia.

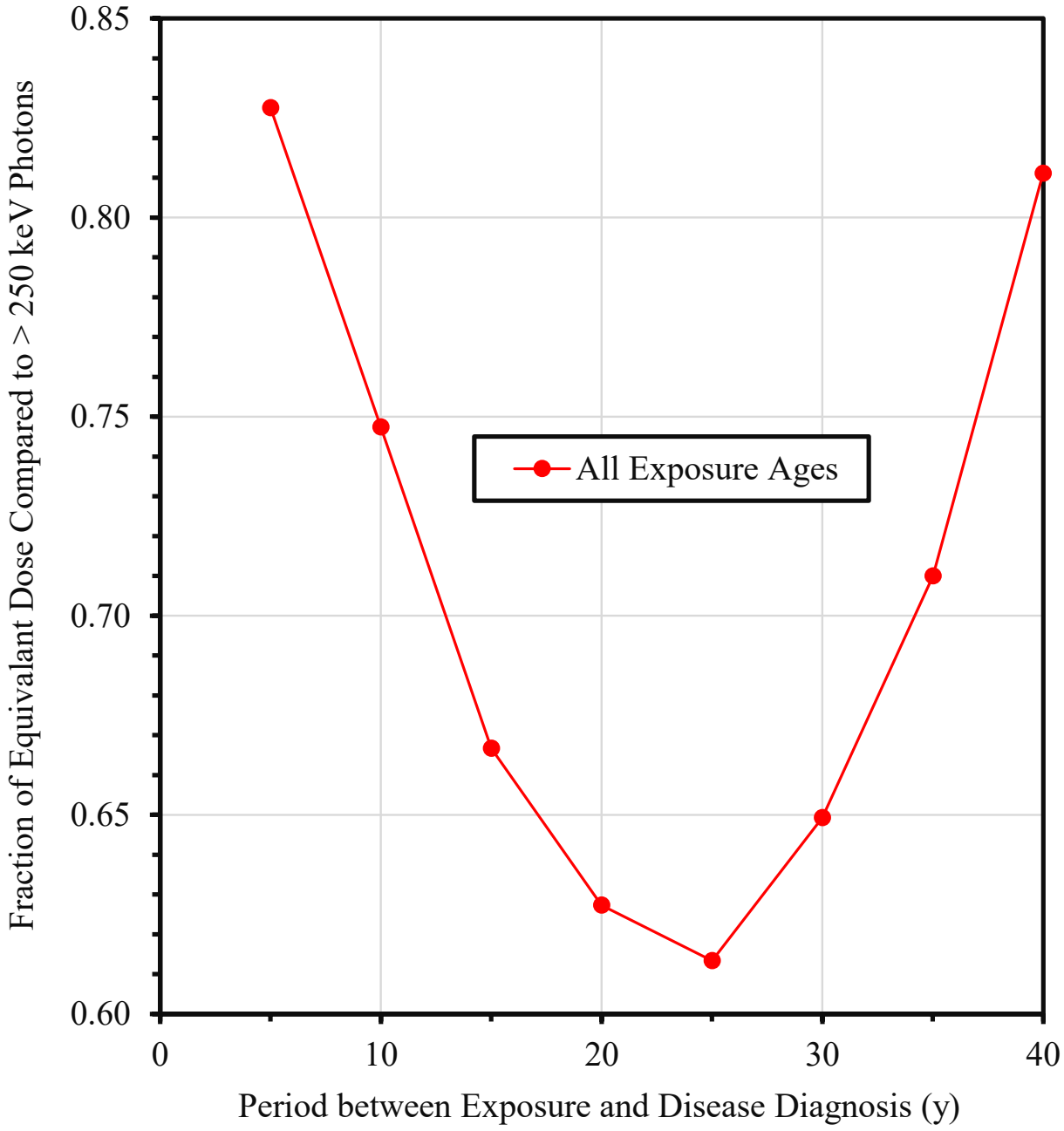

Figure E-9. Fraction of Equivalent Dose for Alpha Particles Compared to Photons: $E > 250$ keV for Various Ages of Exposure and Periods between Exposure and Disease Diagnosis, Acute Myeloid Leukemia.

Appendix F

Example Screening Doses (rem) Calculated with NIOSH IREP, Acute Inhalation Intakes of ^{239}Pu, Using ICRP Report 66 and 67 Metabolism, Chronic Exposure Assumption and Alpha Particles Dose Model, Males; Plots of Annual and Cumulative Equivalent Dose to Key Organs.

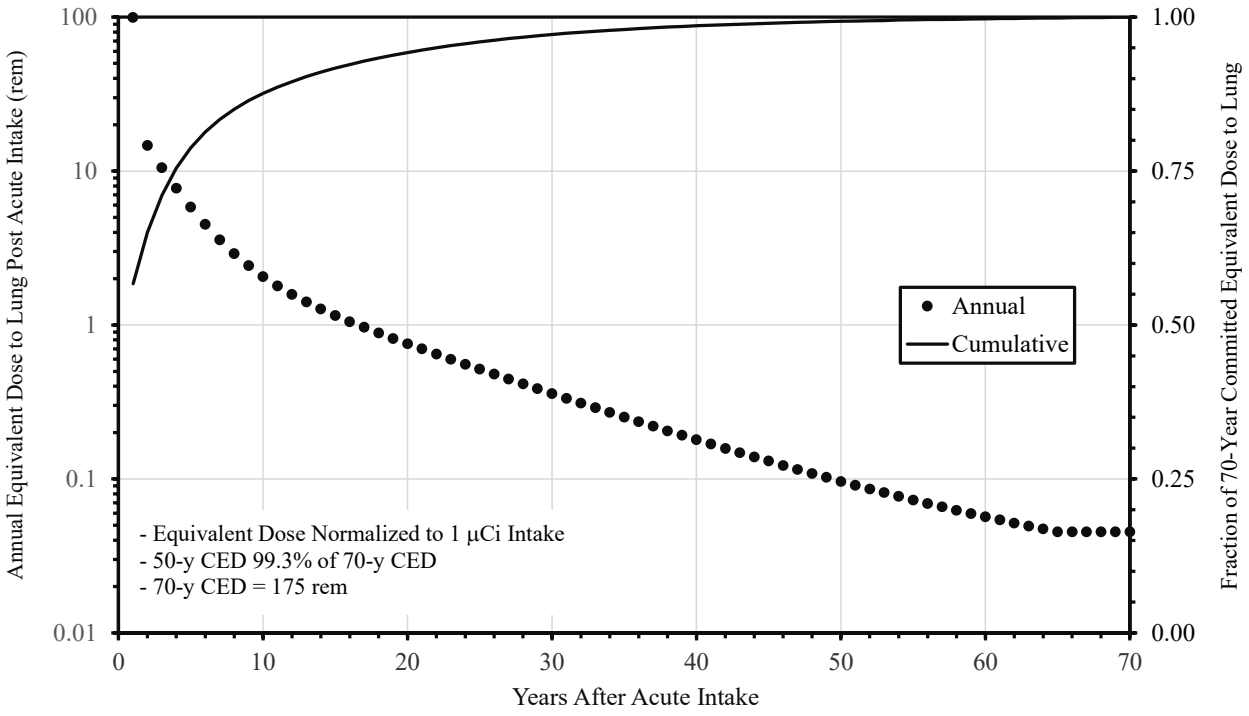

Figure F-1. Annual Equivalent Dose to Lung and Fraction of 70-y Committed Equivalent Dose using ICRP Report 66/67 for Inhalation Type S, 5 μm AMAD, 1 μCi Intake.

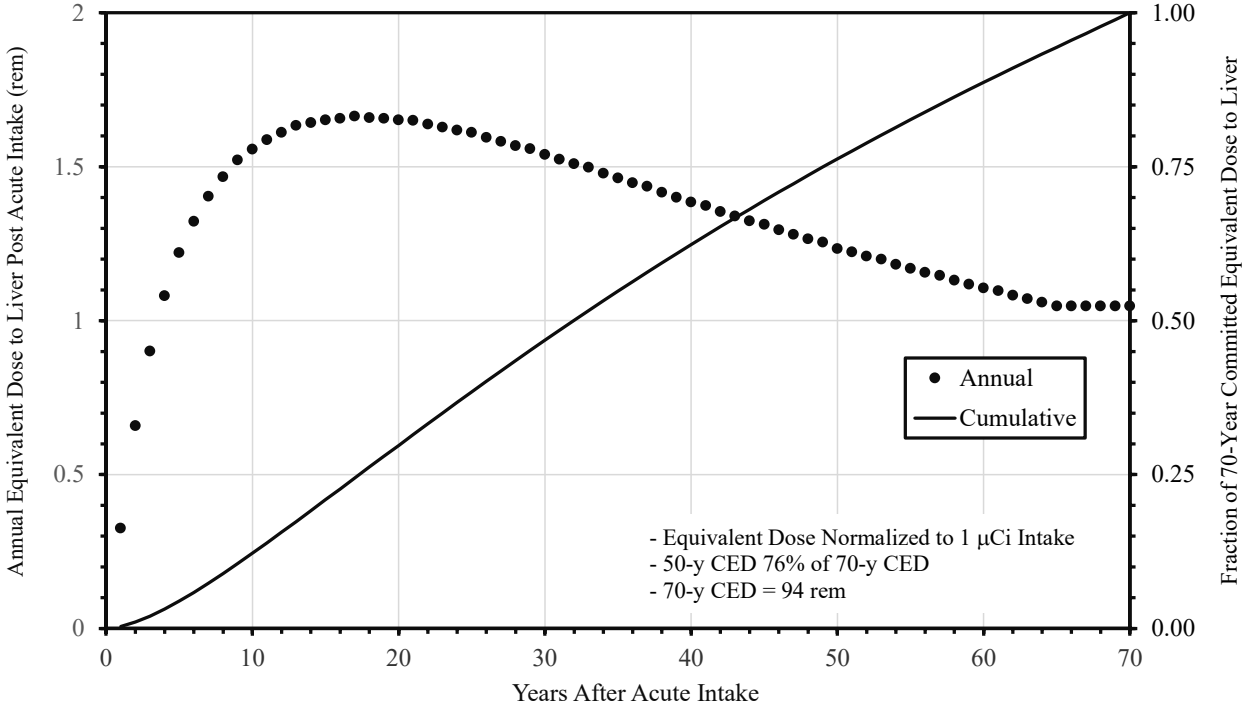

Figure F-2. Annual Equivalent Dose to Liver and Fraction of 70-y Committed Equivalent Dose using ICRP Report 66/67 for Inhalation Type S, 5 μm AMAD, 1 μCi Intake.

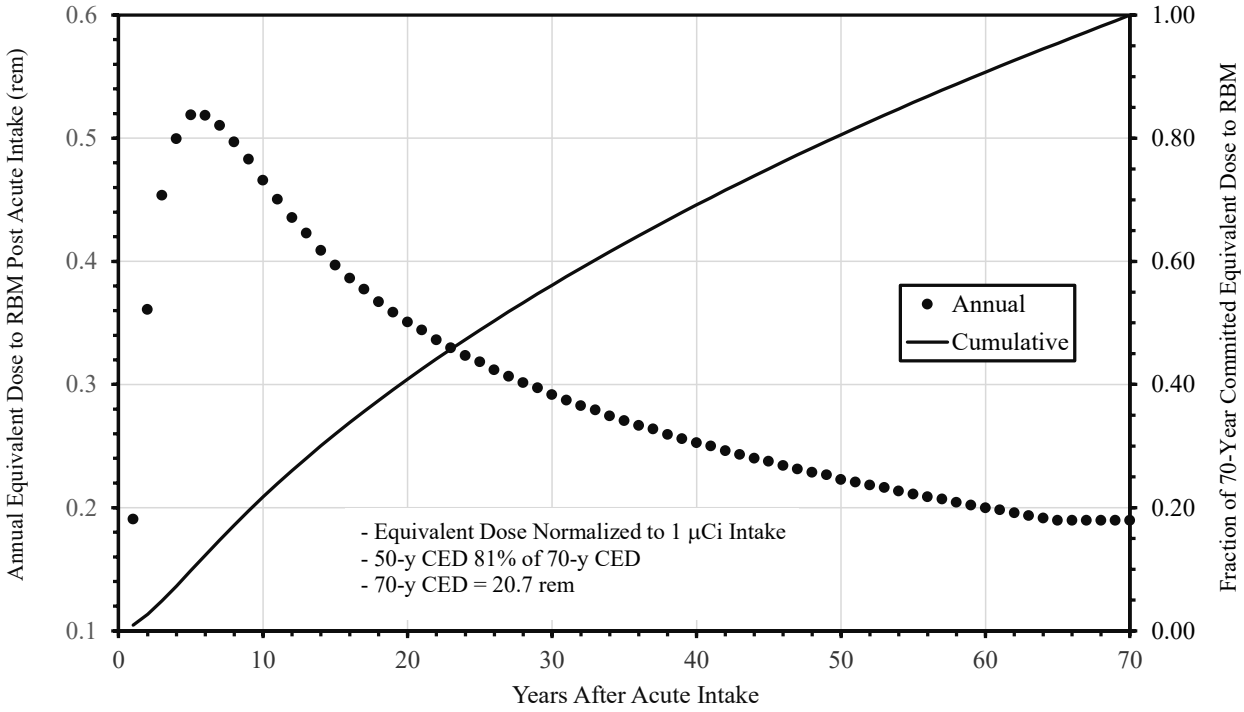

Figure F-3. Annual Equivalent Dose to RBM and Fraction of 70-y Committed Equivalent Dose using ICRP Report 66/67 for Inhalation Type S, 5 μm AMAD, 1 μCi Intake.

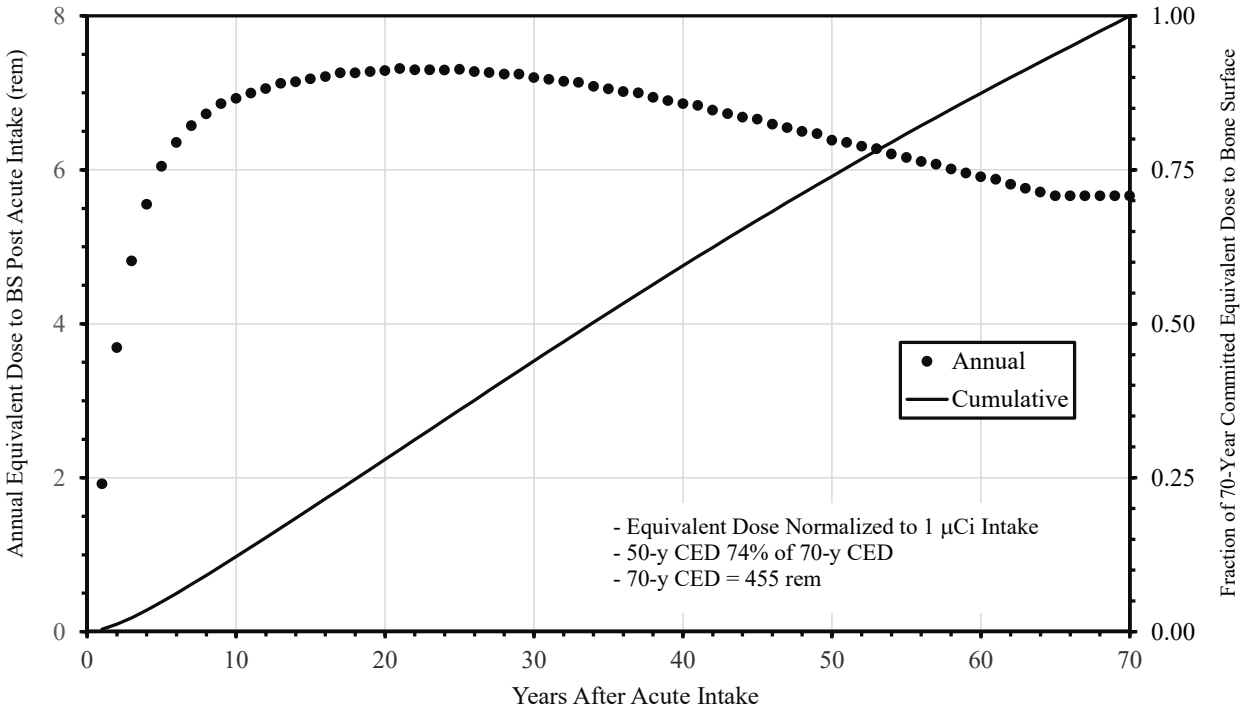

Figure F-4. Annual Equivalent Dose to BS and Fraction of 70-y Committed Equivalent Dose using ICRP Report 66/67 for Inhalation Type S, 5 μm AMAD, 1 μCi Intake.

TABLE F-1. Screening Doses (rem) Calculated with IREP up to Diagnosis, Acute Inhalation Intakes of ^{239}Pu, Using ICRP Report 66 and 67 Metabolism, 5 μm AMAD, Chronic Exposure Assumption from Alpha Particles, Cancer of Lung, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	73	10.3	12.3	19.1	19.8	22.6	20.8	21.9	18.9	21.9
21	112	14.7	17.0	21.8	22.5	22.6	20.8	22.2	18.9	21.9
25	183	22.8	22.6	21.8	22.5	22.6	20.8	20.9	18.9	21.9
30	222	26.4	22.6	21.8	22.5	22.6	20.8	22.1	18.9	21.9
35	222	26.4	22.6	21.8	22.5	22.6	20.8	22.1	18.9	21.9
40	222	26.4	22.6	21.8	22.5	22.6	20.8	22.1	18.9	21.9
45	222	26.4	22.6	21.8	22.5	22.6	20.8	22.1	18.9	21.9

TABLE F-2. Screening Doses (rem) Calculated with IREP up to Diagnosis, Acute Inhalation Intakes of ^{239}Pu, Using ICRP Report 66 and 67 Metabolism, 5 μm AMAD, Chronic Exposure Assumption from Alpha Particles, Cancer of Liver, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	88	11.5	7.5	7.3	9.3	10.5	9.8	11.3	10.5	10.6
21	132	15.7	10.3	9.4	11.3	12	10.3	11.9	10.9	10.9
25	213	23.6	14.3	12.4	14.0	15.6	10.8	12.4	11.3	11.2
30	349	34.7	18.6	15.4	14.2	12.8	10.9	12.6	11.3	11.3
35	433	41.9	22.7	15.4	14.2	12.8	10.9	12.6	11.3	11.3
40	543	49.6	22.7	15.4	14.2	12.8	10.9	12.6	11.3	11.3
45	636	49.6	22.7	15.4	14.2	12.8	10.9	12.6	11.3	11.3

TABLE F-3. Screening Doses (rem) Calculated with IREP up to Diagnosis, Acute Inhalation Intakes of ^{239}Pu, Using ICRP Report 66 and 67 Metabolism, 5 μm AMAD, Chronic Exposure Assumption from Alpha Particles, Bone Cancer (BS), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	26	15.8	21.2	24.6	30.3	42.0	40.8	38.9	37.7	41.1
21	40	22.9	29.1	33.9	36.5	48.6	43.6	42.2	39.5	42.7
25	67	34.7	39.6	43.0	46.0	53.2	47.1	43.0	41.7	42.7
30	106	47.9	51.6	50.9	47.8	52.2	49.5	45.4	42.9	43.1
35	145	61.0	61.4	50.9	47.8	52.2	49.5	45.4	42.9	43.1
40	177	71.0	61.6	50.9	47.8	52.2	49.5	45.4	42.9	43.1
45	212	71.6	61.6	50.9	47.8	52.2	49.5	45.4	42.9	43.1

TABLE F-4. Screening Doses (rem) Calculated with IREP up to Diagnosis, Acute Inhalation Intakes of ^{239}Pu, Using ICRP Report 66 and 67 Metabolism, 5 μm AMAD, Chronic Exposure Assumption from Alpha Particles, Acute Lymphoid Leukemia (RBM), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	1.0	5.4	11.3	14.2	16.1	17.9	16.1	17.1	15.3	14.8
21	27	19.3	17.1	15.7	16.2	17.4	15.7	16.5	14.9	14.4
25	27	19.3	17.1	15.7	16.2	17.4	15.7	16.5	14.9	14.4
30	27	19.3	17.1	15.7	16.2	17.4	15.7	16.5	14.9	14.4
35	27	19.3	17.1	15.7	16.2	17.4	15.7	16.5	14.9	14.4
40	27	19.3	17.1	15.7	16.2	17.4	15.7	16.5	14.9	14.4
45	27	19.3	17.1	15.7	16.2	17.4	15.7	16.5	14.9	14.4

TABLE F-5. Screening Doses (rem) Calculated with IREP up to Diagnosis, Acute Inhalation Intakes of ^{239}Pu, Using ICRP Report 66 and 67 Metabolism, 1 μm AMAD, Chronic Exposure Assumption from Alpha Particles, Cancer of Lung, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	79	10.8	12.5	19.5	20.3	22.6	20.7	22.1	18.9	21.8
21	121	15.4	17.3	21.9	22.5	22.6	20.8	22.1	18.9	21.9
25	196	24.1	23.0	21.9	22.5	22.6	20.8	22.1	18.9	21.9
30	239	26.9	23.0	21.9	23.0	22.7	20.7	22.1	18.9	21.9
35	239	27.4	23.0	21.9	22.5	22.6	20.8	22.1	18.9	21.8
40	239	27.4	23.0	21.9	22.5	22.6	20.8	22.1	18.9	21.8
45	239	27.4	23.0	21.9	22.5	22.6	20.8	22.1	18.9	21.8

TABLE F-6. Screening Doses (rem) Calculated with IREP up to Diagnosis, Acute Inhalation Intakes of ^{239}Pu, Using ICRP Report 66 and 67 Metabolism, 1 μm AMAD, Chronic Exposure Assumption from Alpha Particles, Cancer of Liver, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	94	11.8	7.6	7.3	9.3	10.5	9.8	11.3	10.5	10.6
21	139	16.2	10.5	9.5	11.4	12	10.3	11.9	10.9	10.9
25	228	24.4	14.4	12.5	14.0	12.6	10.8	12.4	11.3	11.2
30	370	35.3	18.7	15.5	14.2	12.8	10.9	12.6	11.4	11.3
35	458	42.6	22.8	15.4	14.2	12.8	10.9	12.6	11.4	11.3
40	574	50.5	22.8	15.4	14.2	12.8	10.9	12.6	11.4	11.3
45	676	50.5	22.8	15.4	14.2	12.8	10.9	12.6	11.4	11.3

TABLE F-7. Screening Doses (rem) Calculated with IREP up to Diagnosis, Acute Inhalation Intakes of ^{239}Pu, Using ICRP Report 66 and 67 Metabolism, 1 μm AMAD, Chronic Exposure Assumption from Alpha Particles, Bone Cancer (BS), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	28	15.8	21.2	24.6	30.3	42.0	40.8	38.9	37.7	41.1
21	40	22.9	29.1	33.9	36.5	48.6	43.6	42.2	39.5	42.7
25	67	34.7	39.6	43.0	46.0	53.2	47.1	43.0	41.7	42.7
30	106	47.9	51.6	50.9	47.8	52.2	49.5	45.4	42.9	43.1
35	145	61.0	61.4	50.9	47.8	52.2	49.5	45.4	42.9	43.1
40	177	71.0	61.6	50.9	47.8	52.2	49.5	45.4	42.9	43.1
45	212	71.6	61.6	50.9	47.8	52.2	49.5	45.4	42.9	43.1

TABLE F-8. Screening Doses (rem) Calculated with IREP up to Diagnosis, Acute Inhalation Intakes of ^{239}Pu, Using ICRP Report 66 and 67 Metabolism, 1 μm AMAD, Chronic Exposure Assumption from Alpha Particles, Acute Lymphoid Leukemia (RBM), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	1.0	5.4	11.3	14.2	16.1	17.9	16.1	17.1	15.3	14.8
21	27	19.3	17.1	15.7	16.2	17.4	15.7	16.5	14.9	14.4
25	27	19.3	17.1	15.7	16.2	17.4	15.7	16.5	14.9	14.4
30	27	19.3	17.1	15.7	16.2	17.4	15.7	16.5	14.9	14.4
35	27	19.3	17.1	15.7	16.2	17.4	15.7	16.5	14.9	14.4
40	27	19.3	17.1	15.7	16.2	17.4	15.7	16.5	14.9	14.4
45	27	19.3	17.1	15.7	16.2	17.4	15.7	16.5	14.9	14.4

TABLE F-9. Screening Intakes (nCi) Calculated with IREP, Acute Inhalation Intakes of ^{239}Pu, Using ICRP Report 66 and 67 Metabolism, 5 μm AMAD, Chronic Exposure Assumption from Alpha Particles, Cancer of Lung, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	530	67	76.3	116	118	133	121	127	109	126
21	810	96	106	132	134	133	121	128	109	126
25	1330	149	141	132	134	133	121	128	109	126
30	1610	172	141	132	134	133	121	128	109	126
35	1610	172	141	132	134	133	121	128	109	126
40	1610	172	141	132	134	133	121	128	109	126
45	1610	172	141	132	134	133	121	128	109	126

TABLE F-10. Screening Intakes (nCi) Calculated with IREP, Acute Inhalation Intakes of ^{239}Pu, Using ICRP Report 66 and 67 Metabolism, 1 μm AMAD, Chronic Exposure Assumption from Alpha Particles, Cancer of Lung, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	272	44	56	72	91	107	113	113	113	113
21	414	63	78	101	122	136	136	136	136	136
25	678	96	120	136	136	136	136	136	136	136
30	1063	148	136	136	136	136	136	136	136	136
35	1063	148	136	136	136	136	136	136	136	136
40	1063	148	136	136	136	136	136	136	136	136
45	1063	148	136	136	136	136	136	136	136	136

TABLE F-11. Screening Intakes (nCi) Calculated with IREP, Acute Inhalation Intakes of ^{239}Pu, Using ICRP Report 66 and 67 Metabolism, 5 μm AMAD, Chronic Exposure Assumption from Alpha Particles, Cancer of Liver, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	21000	1000	382	262	257	239	190	193	161	148
21	31500	1370	525	338	315	273	201	204	167	153
25	50900	2060	730	445	389	287	210	213	173	157
30	83400	3030	952	552	395	291	213	215	174	158
35	103500	3660	1160	552	395	291	213	215	174	158
40	129600	4330	1160	552	395	291	213	215	174	158
45	152000	4330	1160	552	395	291	213	215	174	158

TABLE F-12. Screening Intakes (nCi) Calculated with IREP, Acute Inhalation Intakes of ^{239}Pu, Using ICRP Report 66 and 67 Metabolism, 1 μm AMAD, Chronic Exposure Assumption from Alpha Particles, Cancer of Liver, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	12150	547	205	139	136	127	101	102.5	85	78.5
21	18000	755	283	180	167	145	106	108	88.8	81
25	29500	1135	391	237	205	152	111	112	91.5	83
30	47900	1635	507	294	209	154	112.5	113.8	92.5	84
35	59300	1980	617	293	209	154	112.5	113.8	92.5	84
40	74300	2350	617	293	209	154	112.5	113.8	92.5	84
45	87500	2350	617	293	209	154	112.5	113.8	92.5	84

TABLE F-13. Screening Intakes (nCi) Calculated with IREP, Acute Inhalation Intakes of ^{239}Pu, Using ICRP Report 66 and 67 Metabolism, 5 μm AMAD, Chronic Exposure Assumption from Alpha Particles, Cancer of Bone, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	1200	285	233	193	185	210	173	144	124	122
21	1830	413	320	266	223	243	185	156	130	127
25	3030	626	435	338	281	266	200	159	137	127
30	4810	864	567	400	292	261	210	168	141	128
35	6580	1100	675	400	292	261	210	168	141	128
40	8050	1280	677	400	292	261	210	168	141	128
45	9600	1290	677	400	292	261	210	168	141	128

TABLE F-14. Screening Intakes (nCi) Calculated with IREP, Acute Inhalation Intakes of ^{239}Pu, Using ICRP Report 66 and 67 Metabolism, 1 μm AMAD, Chronic Exposure Assumption from Alpha Particles, Cancer of Bone, 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	680	153	124.5	102.5	98	111.5	91.9	76.3	65.8	64.6
21	1035	223	172	141	118	128.6	98	81	68.7	67.3
25	1690	336	230.8	179	148.7	140.8	105.8	84.2	72.7	67.3
30	2720	462	300.7	211.7	154.5	138.1	111.3	89	74.7	67.9
35	3700	586	359	211.7	154.5	138.1	111.3	89	74.7	67.9
40	4570	689	359	211.7	154.5	138.1	111.3	89	74.7	67.9
45	5430	689	359	211.7	154.5	138.1	111.3	89	74.7	67.9

TABLE F-15. Screening Intakes (nCi) Calculated with IREP, Acute Inhalation Intakes of ^{239}Pu, Using ICRP Report 66 and 67 Metabolism, 5 μm AMAD, Chronic Exposure Assumption from Alpha Particles, Acute Lymphoid Leukemia (RBM), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	228	452	710	690	650	550	510	470	433	401
21	5350	1670	1080	760	650	535	494	452	419	388
25	5350	1670	1080	760	650	535	494	452	419	388
30	5350	1670	1080	760	650	535	494	452	419	388
35	5350	1670	1080	760	650	535	494	452	419	388
40	5350	1670	1080	760	650	535	494	452	419	388
45	5350	1670	1080	760	650	535	494	452	419	388

TABLE F-16. Screening Intakes (nCi) Calculated with IREP, Acute Inhalation Intakes of ^{239}Pu, Using ICRP Report 66 and 67 Metabolism, 1 μm AMAD, Chronic Exposure Assumption from Alpha Particles, Acute Lymphoid Leukemia (RBM), 99% CL of PoC at 50%.

Age at Time of Exposure (y)	Period Between Exposure and Disease Diagnoses									
	5	10	15	20	25	30	35	40	45	50
18	283	667	920	890	840	813	655	630	522	470
21	7230	2280	1360	980	845	790	638	610	510	460
25	7230	2280	1360	980	845	790	638	610	510	460
30	7230	2280	1360	980	845	790	638	610	510	460
35	7230	2280	1360	980	845	790	638	610	510	460
40	7230	2280	1360	980	845	790	638	610	510	460
45	7230	2280	1360	980	845	790	638	610	510	460

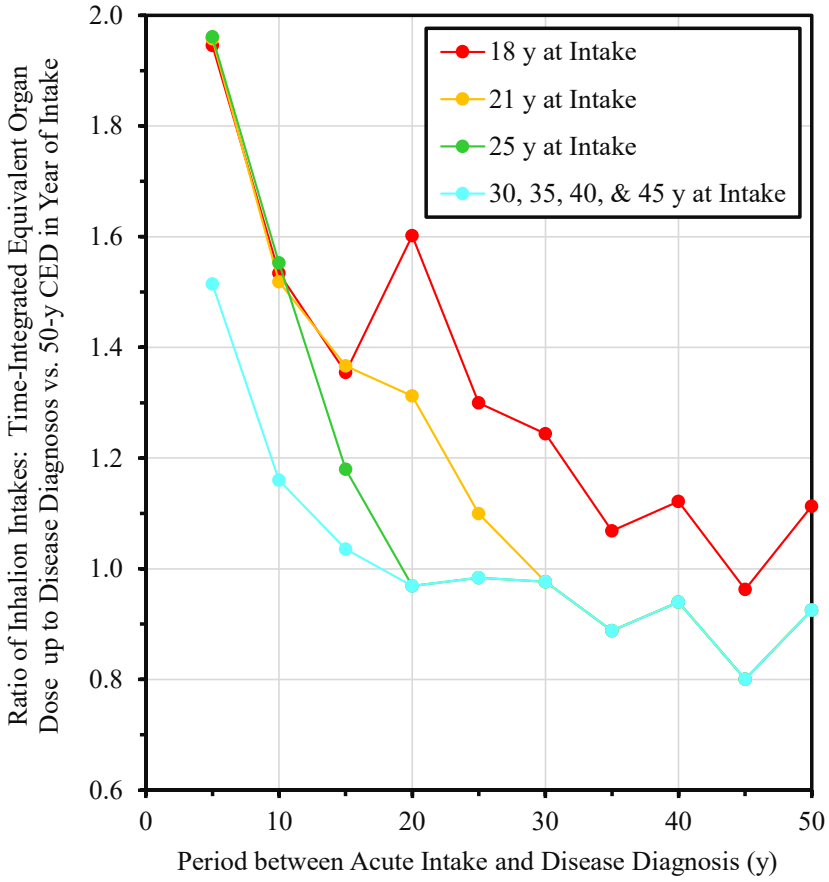

Figure F-5. Ratio of Inhalation Intakes: Time-Integrated Equivalent Dose to Lung up to Disease Diagnosis Versus 50-y Committed Effective Dose to Lung in Year of Inhalation Intake, 5 μm AMAD, ICRP Report 66 Type S Compounds [50% PoC at 99% CL].

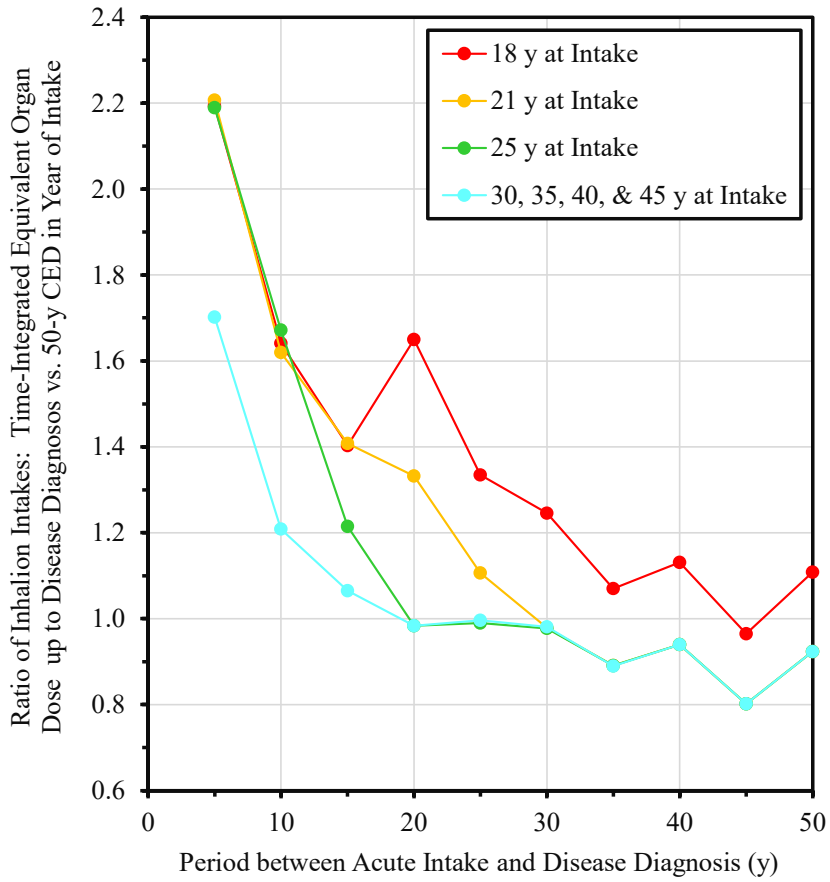

Figure F-6. Ratio of Inhalation Intakes: Time-Integrated Equivalent Dose to Lung up to Disease Diagnosis Versus 50-y Committed Effective Dose to Lung in Year of Inhalation Intake, 1 μm AMAD, ICRP Report 66 Type S Compounds [50% PoC at 99% CL].

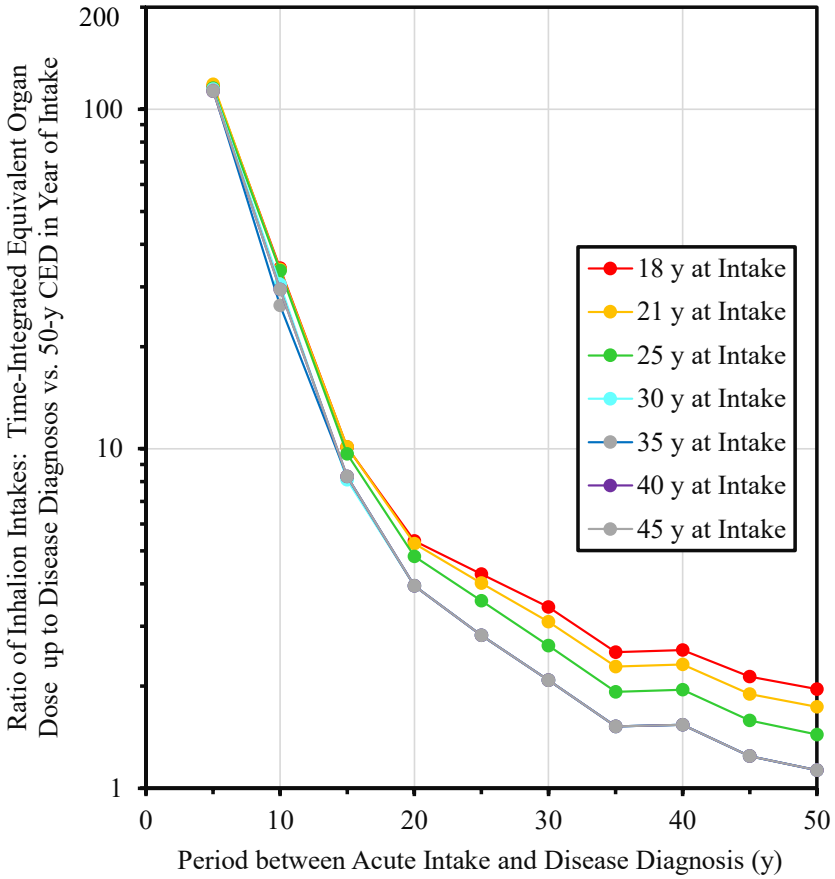

Figure F-7. Ratio of Inhalation Intakes: Time-Integrated Equivalent Dose to Liver up to Disease Diagnosis Versus 50-y Committed Effective Dose to Liver in Year of Inhalation Intake, 5 µm AMAD, ICRP Report 66 Type S Compounds, ICRP 67 Systemic Metabolism [50% PoC at 99% CL].

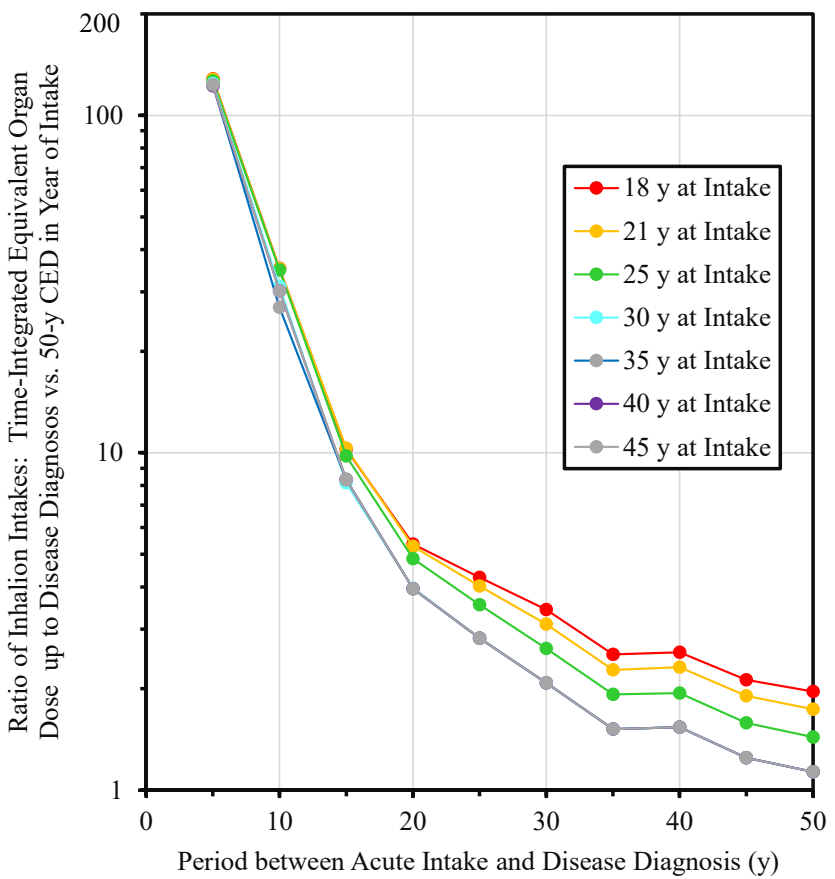

Figure F-8. Ratio of Inhalation Intakes: Time-Integrated Equivalent Dose to Liver up to Disease Diagnosis Versus 50-y Committed Effective Dose to Liver in Year of Inhalation Intake, 1 µm AMAD, ICRP Report 66 Type S Compounds, ICRP 67 Systemic Metabolism [50% PoC at 99% CL].

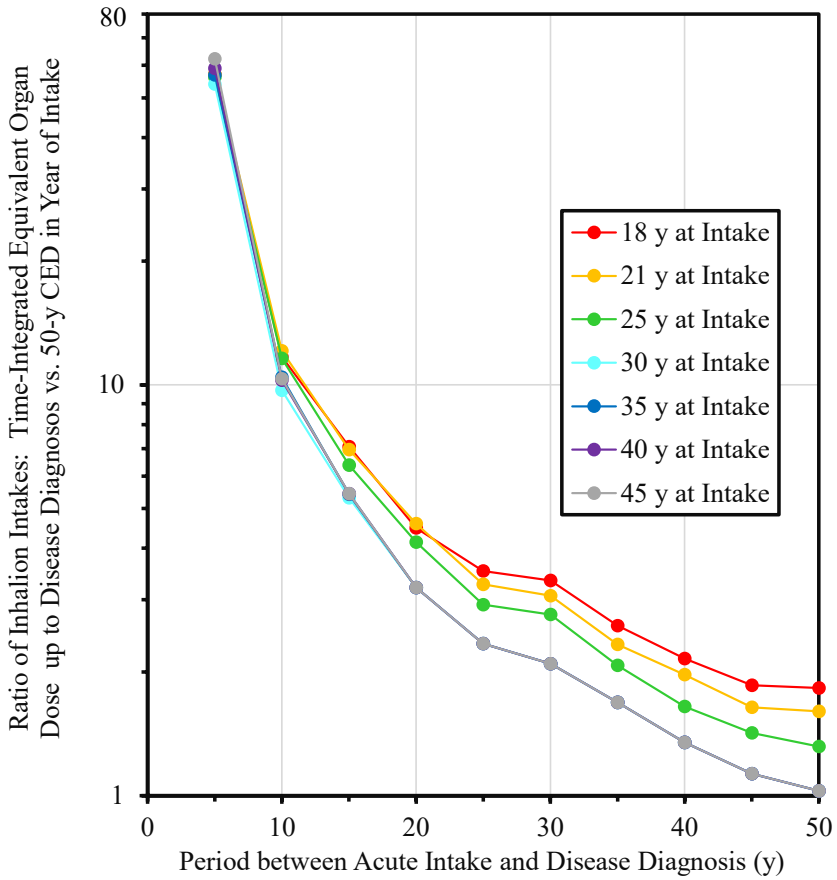

Figure F-9. Ratio of Inhalation Intakes: Time-Integrated Equivalent Dose to Bone Surfaces up to Disease Diagnosis Versus 50-y Committed Effective Dose to Bone Surfaces for Bone Cancer in Year of Inhalation Intake, 5 µm AMAD, ICRP Report 66 Type S Compounds, ICRP 67 Systemic Metabolism [50% PoC at 99% CL].

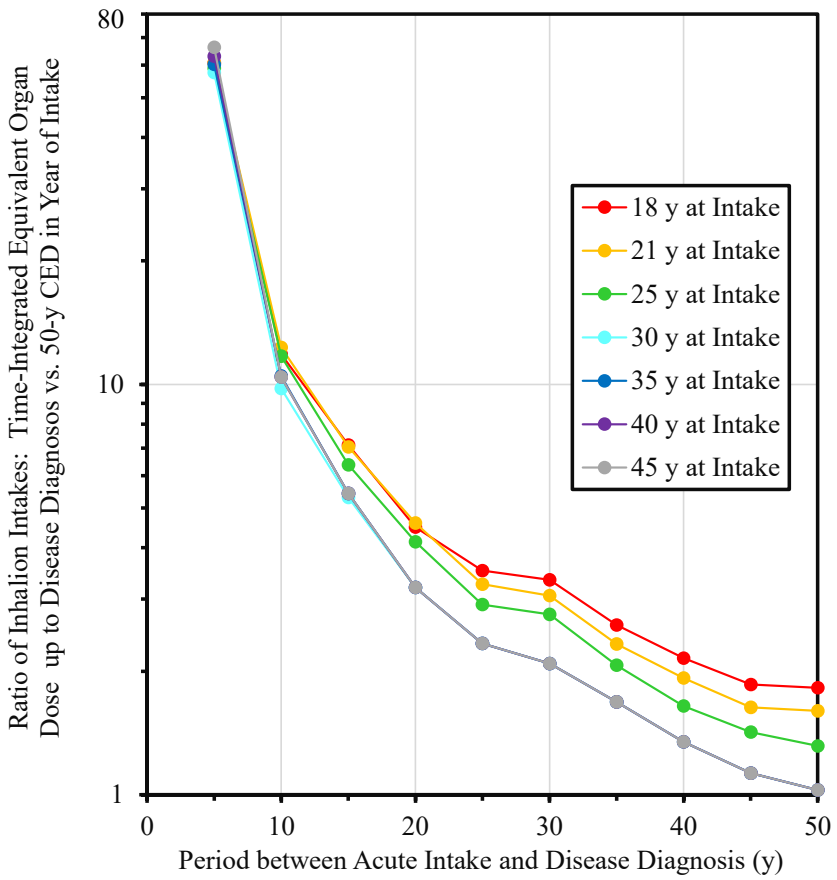

Figure F-10. Ratio of Inhalation Intakes: Time-Integrated Equivalent Dose to Bone Surfaces up to Disease Diagnosis Versus 50-y Committed Effective Dose to Bone Surfaces for Bone Cancer in Year of Inhalation Intake, 1 µm AMAD, ICRP Report 66 Type S Compounds, ICRP 67 Systemic Metabolism [50% PoC at 99% CL].

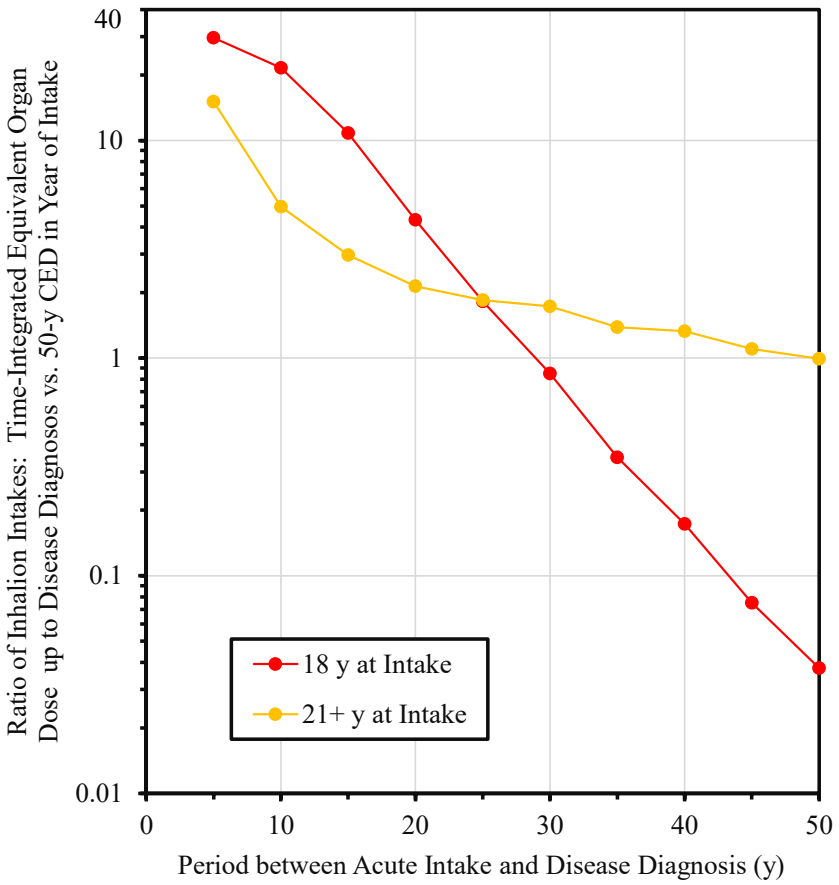

Figure F-11. Ratio of Inhalation Intakes: Time-Integrated Equivalent Dose to Red Bone Marrow up to Disease Diagnosis Versus 50-y Committed Effective Dose to Red Bone Marrow for ALL in Year of Inhalation Intake, 5 µm AMAD, ICRP Report 66 Type S Compounds, ICRP 67 Systemic Metabolism [50% PoC at 99% CL].

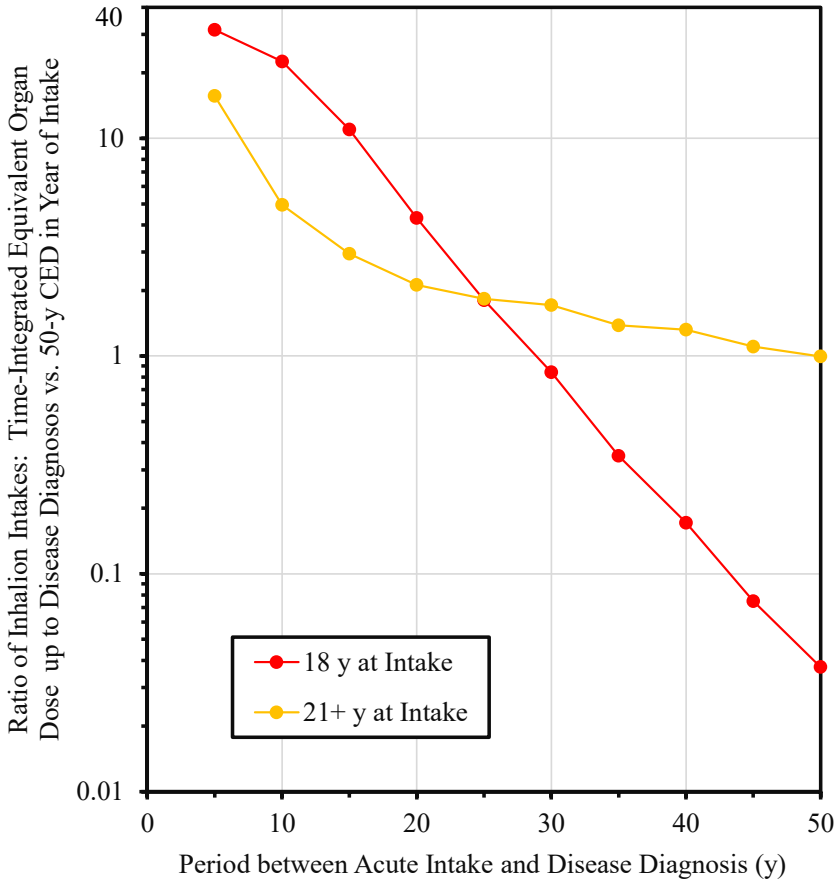

Figure F-12. Ratio of Inhalation Intakes: Time-Integrated Equivalent Dose to Red Bone Marrow up to Disease Diagnosis Versus 50-y Committed Effective Dose to Red Bone Marrow for ALL in Year of Inhalation Intake, 1 µm AMAD, ICRP Report 66 Type S Compounds, ICRP 67 Systemic Metabolism [50% PoC at 99% CL].

Appendix G

Example Screening Doses (rem) Calculated with NIOSH IREP, for α-Particle Radiations to Various Cancer Sites, Latency Periods, and 50% PoC CL Endpoints to Illustrate the Influence of Uncertainties in PoC Models on Statistical Decision Points

TABLE G-1. Example IREP Version 5.8.2 PC Calculations for α-Particle Radiation, Year of Exposure – 1966, Year of Birth – 1946, 10% Standard Deviation in Dose (Normal Distribution).

Factor	Example Cases								
	1	2	3	4	5	6	7	8	9
Diagnosis Year	2008	2008	2018	1998	1988	1978	2008	2008	2008
Latency (years)	42	42	52	32	22	12	42	42	42
Dose (rem)	285	20.8	20.8	20.8	18	10.8	30.8	33.5	34
Cancer Site	lung	lung	lung	lung	lung	lung	lung	lung	lung
Smoking	never	never	never	never	never	never	former	10-19 cig/d	20-39 cig/d
CL (1 %)	4.3%	0.32%	0.32%	0.32%	0.65%	0.57%	0.55%	0.48%	0.44%
CL (5 %)	11.4%	0.93%	0.93%	0.93%	1.4%	1.2%	1.24%	1.19%	1.11%
CL (50 %)	50%	6.8%	6.8%	6.8%	7.4%	7.0%	7.1%	7.1%	7.2%
CL (95 %)	86.6%	32.0%	32.0%	32.0%	31.2%	30.3%	31.4%	32.5%	32.6%
CL (99 %)	93.2%	50 %	50 %	50 %	50 %	50 %	50 %	50 %	50 %

Factor	Example Cases								
	10	11	12	13	14	15	16	17	18
Diagnosis Year	2008	2008	2018	1998	1988	2008	2008	2016	2016
Latency (years)	42	42	52	32	22	42	42	50	50
Dose (rem)	92	4.9	4.9	4.9	4.9	277	24.9	1030	59.3
Cancer Site	liver	liver	liver	liver	liver	bone	bone	nervous	nervous
Smoking	NA	NA	NA	NA	NA	NA	NA	NA	NA
CL (1 %)	4.40%	0.24%	0.24%	0.24%	0.24%	6.12%	0.58%	0.00%	0%
CL (5 %)	9.9%	0.6%	0.6%	0.6%	0.6%	13.8%	1.4%	5.1%	0%
CL (50 %)	50%	5.1%	5.1%	5.1%	5.1%	50%	8.3%	50.0%	5.5%
CL (95 %)	87.9%	27.9%	27.9%	27.9%	27.9%	85.6%	34.9%	88.8%	31.3%
CL (99 %)	94.9%	50%	50%	50%	50%	91.8%	50%	94.5%	50.0%

TABLE G-1. Example IREP Version 5.8.2 PC Calculations for α-Particle Radiation, Year of Exposure – 1966, Year of Birth – 1946, 10% Standard Deviation in Dose (Normal Distribution), continued.

Factor	Example Cases									
	19	20	21	22	23	24	25	26	27	28
Diagnosis Year	2016	2016	2016	2016	2016	2016	2016	2006	1996	1986
Latency (years)	50	50	40	30	20	50	50	40	30	20
Dose (rem)	320	27.4	27.4	27.4	18.8	236	22.2	22.2	22.2	15.5
Cancer Site	urine bladder	urine bladder	urine bladder	urine bladder	urine bladder	kidney	kidney	kidney	kidney	kidney
Smoking	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
CL (1 %)	4.89%	0.44%	0.44%	0.44%	0.44	7.0%	0.70%	0.70%	0.70%	0.70%
CL (5 %)	12.0%	1.16%	1.16%	1.16%	1.2%	14.2%	1.5%	1.5%	1.5%	1.6%
CL (50 %)	50.0%	7.9%	7.9%	7.9%	7.8%	50.0%	8.6%	8.6%	8.6%	8.6%
CL (95 %)	86.3%	35.0%	35.0%	35.0%	34.7%	85.0%	34.7%	34.7%	34.7%	34.7%
CL (99 %)	92.1%	50.0%	50.0%	50.0%	50.0%	91.4%	50.0%	50.0%	50.0%	50.0%

Factor	Example Cases	
	29	30
Diagnosis Year	2016	2016
Latency (years)	50	50
Dose (rem)	2050	53.5
Cancer Site	CLL	CLL
Smoking	NA	NA
CL (1 %)	0.0%	0.0%
CL (5 %)	0.0%	0.0%
CL (50 %)	50.0%	2.5%
CL (95 %)	93.9%	28.5%
CL (99 %)	97.5%	50.0%

TABLE G-2. Screening Doses (rem) Calculated with IREP, Chronic Exposures, α-Particles, Lung Cancer, 50% PoC at 99% CL for Uncertainties in Dose at 0, 25, 50, and 75% CV, Normal Distribution.

Normal Distribution (%CV)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
0	72	11	13.5	17.5	21.2	23.7	23.7	23.7
25	71	12.3	13.6	17.3	19.7	19.7	19.7	19.7
50	62	10.2	12.3	15.4	17.9	17.9	17.9	17.9
75	53.8	9	11.4	14.6	15.4	15.4	15.4	15.4

TABLE G-3. Screening Doses (rem) Calculated with IREP, Chronic Exposures, α-Particles, Liver Cancer, 50% PoC at 99% CL for Uncertainties in Dose at 0, 25, 50, and 75% CV, Normal Distribution.

Normal Distribution (%CV)	Period Between Exposure and Disease Diagnoses							
	5	10	15	20	25	30	35	40
0	19	2.92	3.7	4.6	5.57	6.35	6.35	6.35
25	16.9	2.34	3.1	3.8	4.55	5.18	5.18	5.18
50	17.8	2.21	2.65	3.35	4.08	4.65	4.65	4.65
75	18.2	1.96	2.51	3.22	3.93	4.3	4.3	4.3