NASA Space Cancer Risk Model: 2020 Operational Implementation

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# Acronyms and Nomenclature

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| --- | --- |
| A | Mass number |
| ALARA | As Low As Reasonably Achievable |
| AML  BEIR | Acute myeloid leukemia  Biological Effects of Ionizing Radiation |
| CDC  CLL  CFR | Centers for Disease Control  Chronic lymphocytic leukemia  Code of Federal Regulations |
| DDREF  FAX | Dose and dose-rate effectiveness factor  Female adult voxel |
| GCR | Galactic cosmic rays |
| GUI  HG | Graphical user interface  Harderian gland |
| HZE | High energy and charge |
| HZETRN  ICRP | High-charge-and-energy transport computer program  International Commission on Radiological Protection |
| JSC | Johnson Space Center |
| LaRC | Langley Research Center |
| LAR | Lifetime attributable risk |
| LEO | Low-Earth orbit |
| LET | Linear energy transfer |
| LSS  MAX  NASA | Life Span Study of Japanese atomic bomb survivors  Male adult voxel  National Aeronautics and Space Administration |
| NCI | National Cancer Institute |
| NCRP | National Council on Radiation Protection and Measurements |
| NIOSH | National Institute for Occupational Safety and Health |
| NSCR | NASA Space Cancer Risk model |
| NSRL | NASA Space Radiation Lab |
| NTE | Non-targeted effects |
| ORRISK | Oak Ridge Center for Risk Analysis, Inc. |
| OSHA | Occupational Safety and Health Administration |
| PDF | Probability distribution function |
| R0 | Low-LET risk coefficient per unit dose (derived from atomic bomb survivors) |
| RAE | Risk Analysis Environment |
| RBE | Relative biological effectiveness |
| REIC | Risk of exposure-induced cancer (incidence) |
| REID  RERF  SMR | Risk of exposure-induced death  Radiation Effects Research Foundation  Standardized mortality rate |
| SPE | Solar particle event |
| SPEL  SRAG | Space permissible exposure limit  Space Radiation Analysis Group |
| QF  UNSCEAR | Quality factor  United Nations Scientific Committee on the Effects of Atomic Radiation |
| Z | Charge number |
| Z\* | Effective charge number |
| (Z\*/𝛃)2 | Effective charge number scaled to the speed of light |

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# Preface Dedication Haiku

Space radiation

Particles whipping through hulls

Human risk is low...

**放射線**

**宇宙戦割って、**

**大丈夫**

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# Executive Summary

## Introduction

Astronauts are exposed to increased radiation from the space environment and from biomedical research studies conducted in the workplace. Federal requirements mandate that these exposures be limited to provide adequate radiation protection1. This report summarizes the National Aeronautics and Space Administration (NASA) Space Cancer Risk (NSCR) model as implemented in 2020 for calculation of risk of exposure-induced death (REID) and risk of exposure-induced cancer (REIC) following occupational radiation exposures for astronauts.

## NASA Space Cancer Risk Model Framework

The 2020 operationalization of NSCR integrates the core risk components of the model first implemented in 2010 into a new analytical platform2,3. An element of this platform is the Risk Analysis Environment (RAE), which performs Monte Carlo simulation for individual astronaut risk calculation. RAE combines all NASA occupational exposures for a given astronaut, providing a full risk distribution across multiple exposures.

## Available Evidence

The risk model was developed using evidence from human epidemiology, animal biology, and cellular physiology. Human epidemiology is primarily informed by the Life Span Study (LSS) of Japanese atomic bomb survivors4–12. This cohort was exposed to a single, acute dose of low-linear energy transfer (LET) radiation, which is constitutionally different from the chronic, low dose-rates of high-LET radiation experienced in the space environment3. Animal studies and cellular studies of chronic doses to high-LET radiation are used to inform translations of this risk to an astronaut setting3.

## Overall Implementation of the NASA Space Cancer Risk Model

The primary outputs of NSCR are REID and REIC, which require a set of necessary inputs. Major components include physics, background mortality, excess radiation-induced cancer risk estimates, astronaut population transfer, radiation quality, low dose-rate scaling, and risk accumulation over multiple exposures. Each of these elements is implemented with inputs for uncertainty that enable the calculation of a full distribution for REID and REIC. Physics includes information regarding local environments, shielding, and mission-specific fluences, which are used to calculate organ doses. Background mortality is a baseline for mortality in an astronaut-like US-based population, derived from the Centers for Disease Control and the National Cancer Institute13–18. Excess cancer risk estimates are primarily derived from the LSS cohort and are used to inform cancer risk estimates for a given dose of low-LET radiation. Transfer is used to translate LSS risk estimates to an astronaut-like US-based population so that REID and REIC calculations are appropriate to the individuals being protected. Radiation quality translates radiation-induced cancer risk estimates from the low-LET terrestrial environment to the high-LET space environment. Low dose-rate scaling adjusts LSS estimates received at acute doses to chronically received doses experienced in space. The ability to account for multiple missions and biomedical exposures allows full distributions for REID and REIC to be calculated.

## Other Aspects of Implementation

RAE is a tool used to implement all components of NSCR that incorporates uncertainty directly into the calculation of REID and REIC distributions using Monte Carlo simulation across all exposures. RAE conducts risk calculations through a graphical user interface that allows even individuals unfamiliar with coding languages to operate the tool. RAE was built using Analytica Decision Engine software, which operationalizes arrays for an efficient, modularized workflow19.

## Future Improvements

Since the elements of NSCR are coded modularly, individual modules can be replicated for development and testing for potential adoption ensuring new information can be integrated in a timely manner19. Ongoing research from human cohorts including those from radiation-exposed human population studies and cancer incidence and mortality data in the United States can be used to update radiation risk estimates and background cancer rates. Further, the NASA Empirical Data-driven Radiation (NEDRad) model uses an empirical approach to incorporate information from human, animal, and cellular studies into the overall risk model. NSCR enables sensitivity analyses, which can be run quickly by utilizing a replicated version of a module in place of the original module19. Thus, new modules can be efficiently tested and replaced as the knowledge base grows.

# Introduction

Compared to the terrestrial environment, the space environment exposes astronauts to increased levels and different types and energies of ionizing radiation (hereafter referred to as “radiation”). Three major sources contribute to the space radiation environment relevant to human space exploration. Galactic cosmic rays (GCR) are theorized to be the result of massive stellar energy releases such as supernovae that accelerate particles throughout the universe. GCR consists of high energy protons (~87%), helium particles (~12%), and high-charge and high-energy (HZE) particles (~1%). In interplanetary space, GCR is constantly present at a low dose-rate20,21. The Earth’s magnetic field also traps energetic protons and electrons in toroidal regions surrounding the planet called the Van Allen Belts (Figure 1). The inner belt consists primarily of protons, and the outer belt is almost exclusively electrons22. Exposure to this source of radiation occurs during a trajectory through the belts or through a portion of the belts. Solar activity is the largest contributor to changes in the radiation environment. Solar energy releases can result in interplanetary particles or solar mass being accelerated toward Earth or elsewhere in the solar system23. Earth’s magnetic field (or magnetosphere) and atmosphere protect most of the planet from both GCR and particles accelerated by solar energy releases. However, in the polar regions, Earth’s open magnetic field lines channel particles toward the planet resulting in exposures in these regions at high altitudes such as low-Earth orbit (LEO)24.

A planet in space

Description automatically generated with low confidence

Figure 1: Van Allen Belts. Image credit: NASA/Van Allen Probes/Goddard Space Flight Center25

Epidemiological studies of radiation-exposed cohorts on Earth have demonstrated dose-related increases in cancer mortality and incidence6,11. Because exposure to space radiation for astronauts is unavoidable, assessment of the health outcomes associated with radiation exposure is important for appropriate radiation protection and risk communication. The National Aeronautics and Space Administration (NASA) acknowledged the potential health hazards due to space radiation early on and initially set dose limits in 1961 to reduce health risks associated with radiation exposure. This self-regulation was driven by early recommendations by authorities such as the National Academy of Sciences and the National Research Council, though there was no expectation of mandatory compliance26. In 1980, Executive Order 12196, "Occupational Safety and Health Programs for Federal Employees," identified ionizing radiation as a workplace hazard due to known health risks and mandated compliance to radiation limits established by the Occupational Safety and Health Administration (OSHA), as listed in the Code of Federal Regulations (CFR)1. The established radiation dose limits would have made spaceflight impractical: the annual limits for terrestrial workers were below anticipated exposures for astronauts. This restriction prompted NASA to request special dispensation for supplemental standards under 29 CFR 1960.27. The new standards were based on recommendations and guidance from the National Council on Radiation Protection and Measurements (NCRP)28. The aim of these recommendations has been to balance space exploration’s benefit to society while considering the potential health impacts to individual crewmembers. A major shift for space radiation protection was that the recommended career limit for fatal cancer became risk-based rather than dose-based29. This transition necessitated methodologies for individual risk calculation because unlike dose, risk is a quantity that cannot be measured and must be estimated. Current NASA limits related to radiation and other spaceflight exposures can be found in the NASA Space Flight Human-System Standard Volume 1: Crew Health29.

Here, we describe the general framework of how radiation-induced cancer risk estimates are calculated from radiation measurements, available evidence, and overall implementation of the risk model. Additionally, potential future improvements to risk calculation and implementation are discussed. The 2020 operational implementation of the NASA Space Cancer Risk (NSCR) model is broadly based on the original NSCR model first released in 20102,3, with updates and improvements made in coordination with the Space Radiation Analysis Group (SRAG) at Johnson Space Center (JSC), the Space Radiation Group (SRG) at Langley Research Center (LaRC), and the Oak Ridge Center for Risk Analysis, Inc (ORRISK).

# NASA Space Cancer Risk Model

NSCR uses an established basic methodology utilized by other agencies including the National Institute for Occupational Safety and Health (NIOSH) and the National Cancer Institute (NCI) that can be used to assess radiation-induced cancer risk based on measured or projected crew exposures3,6,11,30–32. Typically, lifetime attributable risk (LAR) is used to estimate radiation-associated excess cancer risk in worker populations, since LAR is a relatively simple calculation that approximates lifetime excess cancer risk well in terrestrial settings with total cumulative exposures less than 1 Sv6,11. However, LAR does not account for the excess mortality due to radiation exposure in the background survival function30,33. Therefore, it tends to overestimate risks at higher doses where radiation contributes more substantially to excess mortality. Since cumulative career doses in an astronaut population can in theory exceed 1 Sv, and accurate risk estimation is essential, NSCR estimates lifetime probability of excess cancer mortality and incidence from radiation exposure as the risk of exposure-induced death (REID) and the risk of exposure-induced cancer (REIC), respectively. As REID and REIC account for radiation-associated excess mortality in the survival function, these measures provide a more accurate assessment of risk compared to LAR3.

Similar to other radiation-induced cancer risk assessment tools, the basis for NSCR is epidemiological data from human cohorts exposed to terrestrial radiation6,11,30–32,34. However, adjustments can be made to available terrestrial excess cancer risk models to make risk estimates more appropriate to the unique nature of the astronaut cohort, as well as to the radiation experienced in the space environment. The 2020 operational version of NSCR integrates the core risk components of the NSCR 2012 model into a new analytical platform3. The calculations of REID and REIC for astronauts exposed to the space radiation environment are principally informed by six core risk components: space radiation physics, terrestrial radiation risk models, background rates adjusted to a never smoker (“astronaut-like”) population, tissue-specific transfer from epidemiological models to an astronaut-like population, radiation quality, and dose and dose-rate effects. Each of these components can be parameterized by likeliest values and corresponding distributions.

ORRISK designed the Risk Analysis Environment (RAE) to perform Monte Carlo simulations for individual astronaut risk calculation using the Analytica Decision Engine platform through a graphical user interface (GUI)19. REID and REIC are calculated as statistical distributions using Monte Carlo simulation techniques to combine the core risk components and control for the inherent mathematical and scientific uncertainty and variability therein. This risk assessment framework enables incorporation of human radiation epidemiology data as well as animal and cellular data that can be improved as the state of knowledge evolves. The upgrade to the Analytica Decision Engine platform allows individual uncertainty and multiple exposure analyses19, providing a full risk distribution across multiple exposures.

Each of the six major risk components and their implementation in NSCR will be described in more detail in the *Overall Implementation of NSCR* section. Briefly, NSCR translates astronaut radiation exposures to REID and REIC. Normalized sex-specific organ doses are based on measured (or estimated) crew dose, local environmental radiation measurements, and modeled vehicle and body shielding, with vehicle shielding based on the vehicle of interest in the analysis or a mission-specific vehicle projection35. The quality factor function is used to address differences between the radiation in the terrestrial and space environments, enabling translation of sex-specific absorbed tissue doses to dose equivalents. A dose and dose-rate effectiveness factor (DDREF) is applied to dose equivalents to account for estimated doses outside the range used to inform terrestrial models as well as the protracted exposures experienced in spaceflight. Tissue- and sex-specific terrestrial radiation-induced cancer risk models are used to calculate tissue- and sex-specific excess cancer risk based on these estimated weighted organ doses for a specific age of exposure and attained age. These tissue-, age-, and sex-specific excess cancer risk values are then applied to a US never smoker population which is assumed to approximate an astronaut population. The result is tissue-specific excess cancer risks relevant to the astronauts. For each astronaut, the sex-appropriate tissue-specific excess cancer risks are summed, and this total cancer risk estimate is summed over expected astronaut lifetimes (Figure 2).

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\*Sex-specific weighted organ doses do not represent an individual model step, but rather are folded into the hazard rate calculations. They are represented individually in the flow chart for clarity.

Figure 2: Mermaid diagram representing NSCR and applied uncertainties in REID and REIC calculations

# Available Evidence

NSCR relies on evidence from human epidemiology, animal biology, and cellular physiology. Although the underlying radiation-induced cancer risk model is primarily based on human evidence, both animal and cellular studies have informed model parameters.

## Human Epidemiology

The evidence that has most directly influenced understanding of the human response to low-LET radiation exposures has been derived from human cohorts. The most impactful of these cohorts is the Life Span Study (LSS) of Japanese atomic bomb survivors, a cohort of 120,321 individuals who were either within three km of the bomb epicenters in Hiroshima or Nagasaki, were on the outskirts of the city, or who lived in either city but were not present at the time of the bombing (zero dose)36. Reports of both incidence and mortality from various outcomes among survivors have been published iteratively since 19614,5,7–10,12,36,37. Follow-up questionnaires and advancements in dosimetry, spatial mapping, and statistical computing have contributed to a robust description of radiation-induced cancer and non-cancer outcomes following acute, low-LET exposures in this cohort38. Strengths of this study are the long follow-up time, inclusion of a large number of individuals who were close to the epicenters at the time of the bombing, a robust nationwide mortality reporting system, virtually complete prefecture-wide cancer reporting systems that began in 1958, and survivor-reported confounder measurements from questionnaires. Limitations are unreported outcomes due to migration and outcomes that occurred before study start (i.e., 1950, or 1958 for cancer incidence outcomes), bias in self-reported location at the time of the bombing and confounder measurements, and uncertainty in the estimation of quality for the high-LET neutron component of the atomic bomb exposures.

Several other human cohorts have informed the radiation protection field, though not to the same extent. Nuclear worker cohorts include first responders to the Chernobyl incident, US nuclear workers at various plants around the nation, and nuclear workers from plants using radioactive materials in other countries6,11. Medical workers include radiologists and radiation technicians employed at various facilities over time6,11. Residents of the Techa River delta and the areas surrounding Chernobyl were exposed following releases of radioactive material into the surrounding environments6,11. Finally, nuclear medicine and radiation therapy patients have been followed-up for late effects of irradiation6,11. These studies carry their own strengths and limitations that make them more or less appropriate to construct a radiation-induced cancer risk model for astronauts. Nuclear medicine and radiation therapy cohorts represent individuals with potential underlying health conditions irradiated at high dose-rates, making these cohorts dissimilar to astronauts on multiple levels. During a nuclear incident, some exposure data may be missing or inaccurate, and follow-up of exposed individuals is likely to be incomplete11,39. Nuclear and medical worker cohorts, while not as healthy as the astronaut cohort, are more representative populations with relatively complete follow-up. However, these populations tend to be small, and it can be difficult to see any significant effects of their exposures. These populations are currently under further investigation for a combined analysis that will likely increase the power to see an effect and increase the precision of effect estimates in a US workforce40–43.

Few terrestrial human cohorts have received high-LET exposures. Some radiotherapy patients have received external exposures to carbon ions and high-energy protons that may inform high-LET risk estimates; however, these patients do not adequately represent a healthy astronaut population44–51. Individuals exposed internally to radon occupationally and environmentally have provided some information on lung cancer induction following high-LET exposures. Some nuclear worker cohorts have received internal plutonium and polonium exposures that may provide further information when pooled analyses are conducted42,52–54. However, the difference in effect between external and internal exposure to high-LET radiation may not be trivial. Thus, a majority of the evidence for the health effects of high-LET radiation has been provided from animal and cellular studies.

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## Animal Studies

Early animal studies focused primarily on heritable effects and life shortening. These studies revealed that cancer was the main contributor to observed life shortening following doses of radiation that are not acutely fatal55–59. Subsequent experiments concentrated on estimating cancer risks and dose-rate effects57,60–64. Historically, these animal studies have provided much of the basis for dose-rate assumptions used to adjust acute, low-LET radiation cancer risk estimates from human cohorts such as the atomic bomb survivors to chronically irradiated populations. A majority of animal studies use photon irradiation (i.e., gamma-rays, x-rays) similar to the predominant types of exposures experienced by the LSS and other documented radiation-exposed cohorts.

A variety of animal models, including rodents, rabbits, beagle dogs, and rhesus monkeys have been used in neutron studies conducted at low and high dose-rates65–69. However, even though neutrons are a component of the space radiation environment, particularly internal to spacecraft, it is unclear if the effects observed following neutron irradiation are reflective of those that will be observed following space radiation as a whole due to the unique nature of neutron interactions with matter35. While limited, there are a number of studies using the same animal models that investigate the carcinogenic effects of high energy particle irradiation, including not only neutrons, but also protons, HZE particles, and other relevant high energy radiation types. Generally, studies indicate that irradiating animals with high energy particles results in an increased number of animals developing cancer in a dose-dependent manner. Furthermore, emerging evidence indicates that latency periods may be shortened and cancers may be more aggressive70. A brief description of animal studies relevant to assessing high energy particle carcinogenesis as of January 2020 is available in Appendix Y.

Although not directly relevant to the assessment of radiation-induced cancer risk following exposure to the space radiation environment, these studies can be used to assess the radiation quality differences of the types of particles in the space environment to induce or promote carcinogenesis. High-LET animal studies with a low-LET component help inform how acute, low-LET human epidemiological data can be translated to the space radiation setting for more relevant radiation-induced cancer risk modeling for astronauts.

## Cellular Studies

It is difficult to directly translate cellular studies to radiation-induced cancer risk because the relationship between cellular outcomes and cancer risk is not well-characterized. However, cellular studies provide convenient and accessible model systems to test the effects of radiation on cellular outcomes theoretically related to carcinogenesis and investigate the mechanistic response to low-dose and low dose-rate exposures6. Additionally, human cellular models can be used to study surrogate endpoints for carcinogenesis where animal studies are inefficient or costly. Cellular models have been used to investigate the effects on a variety of endpoints theorized to be related to carcinogenic processes following high energy particle irradiation71. Similar to observations in animal studies, cellular models show that particle radiation is generally more efficient at causing damage compared to photon radiation, and the extent of damage tends to correlate with particle energy and charge. Further, results from chromosome aberration studies demonstrate that both the amount and the types of aberrations observed are different following particle irradiation compared to photons72–77. Outcomes are highly dependent on both particle type and measured endpoint. Additionally, it is clear that some endpoints are more closely related to carcinogenesis (e.g., neoplastic transformation) compared to other endpoints (e.g., cell death)71. Because these endpoints are only surrogates for carcinogenesis and their correlations to cancer risk are unclear, it is difficult to assess if and how observed differences translate to human cancer risk. Nonetheless, the quality of high energy particles observed in some cellular models is similar to animal tumor studies, which indicates these systems may help to substantiate animal models of human responses. Similar to the results from animal studies, those from cellular studies can improve the understanding of radiation quality and DDREF3,71.

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# Overall Implementation of the NASA Space Cancer Risk Model

Lifetime excess cancer risk is quantified using REID and REIC in NSCR. Respectively, these metrics represent the probability that a person exposed to radiation will die from or be diagnosed with cancer over their lifetime caused by the radiation exposure11. The calculation of lifetime risk metrics is based on a formulism described in NCRP Report 12678. In this report, individual components of lifetime risk are each defined by a “likeliest value” multiplied by corresponding uncertainty factors, where uncertainty factors are each specified by a subjectively characterized uncertainty distribution78. In NSCR, the major components necessary to calculate REID and REIC are space radiation physics, background rates adjusted to a never smoker (“astronaut-like”) population, excess radiation-induced cancer risk estimates, tissue-specific transfer from epidemiological models to an “astronaut-like” population, radiation quality, dose and dose-rate effect scaling, and risk accumulation over multiple exposures. These elements will be presented individually and the overall model implementation will be discussed at the end of this section.

## Space Radiation Physics: Local Environments, Shielding, and Mission-Specific Fluences

Environmental monitoring takes place on all crewed missions. Active dosimeters record total mission absorbed dose to individual crew members (prior to 2020, passive thermoluminescent dosimeters were used). Additionally, the radiation environment internal to the vehicle is monitored using active radiation detectors. Along with these measurements, mission-specific organ fluences are calculated using models for the ambient environment79,80, physical interactions and particle transport35, vehicle mass shielding, and human tissue shielding81–83. Normalization procedures (similar to Cucinotta et al 200884) are then used to ensure model calculations are in agreement with area dosimeter measurements.

*Uncertainty*

The process of calculating mission-specific organ fluences from radiation measurements carries aspects of uncertainty related to each of the components included in the transport calculations. The uncertainty in these physics calculations is represented by an uncertainty factor that is normal with a mean of 1 and a standard deviation of 1/4 for ions with Z > 2, and is normal with a mean of 1.05 and a standard deviation of 1/3 for ions with Z ≤ 2, truncated at 0. These uncertainties are only applicable to model outputs after they have been normalized to available dosimetry.

## Background Mortality in an Astronaut-Like Population

There are two background statistics from a representative population necessary to estimate excess cancer risk in the astronaut cohort:

1. Background cancer mortality and incidence rates;
2. Background survival function.

Background cancer mortality and incidence rates in a US astronaut-like population must be estimated to translate excess cancer risk from a Japanese to a US population. An overall US astronaut-like survival function is also necessary to adjust for competing risks when modeling cancer mortality-free survival in this population.

Cancer mortality and incidence rates relevant to an astronaut cohort are necessary to extrapolate risk in an astronaut-like cohort from risk observed in the LSS cohort. Robust databases of US background cancer rates are maintained by the Centers for Disease Control (CDC) and the NCI85–87. However, due to the exceptional health status of astronauts88–90, a modeled never smoker population is used as a more relevant reference US background. The Surgeon General has identified the following cancers as smoking sensitive: stomach, colon, liver, bladder, lung, esophagus, oral cavity, kidney, pancreas, breast, acute myeloid leukemia (AML), larynx, and cervix uteri18. Table 1 contains a list of tissue-specific models included in NSCR. The background rates of these cancers must be estimated because the national background cancer databases do not separate data based on smoking status. It is difficult to separate some cancers from their more generic types: AML (leukemia), cervix uteri (uterine), and pancreas (other tissues). The background rates for these cancers are currently only derived for the larger category (see Future Improvements section). These background cancer rates are estimated based on two types of statistics: relative risk of cancer for never smokers compared to former and current smokers15–18, and smoking prevalences for never, former, and current smokers18. Data for smoking prevalences are available up to 2011 in the 2014 Surgeon General report18. The central estimates for the US never smoker cancer rates are based on these data; however, the uncertainty distributions associated with these estimates are based on subjective expert opinion. Background rates for cancers considered non-smoking sensitive included in NSCR (brain, thyroid, prostate, and ovary) reflect the general US background population from 2011 and do not include uncertainty. Updates to these rates can be made as new data become available from the CDC and NCI.

US life tables, which report annual age- and period-specific mortality statistics, are necessary to estimate the background survival function implemented in NSCR. These life tables are abstracted from the US National Vital Statistics Reports which are published yearly and updated with census data as it becomes available. The 2011 rates implemented at the time of this publication are from Volume 64 Number 1191. To model all-cause survival in a background population similar to astronauts, all-cause survival in a never smoking US population is estimated. Updates to the life tables implemented in NSCR can be made as new data become available from these reports (See Future Improvements).

*Uncertainty*

No uncertainty factor is applied for background cancer rates and background survival; the rates are abstracted from general US background rates and smoothed from five- to one-year intervals. Since never smoker cancer rates are estimated values, an uncertainty factor is applied to background cancer mortality and incidence rates for smoking-related cancers. The uncertainty factor is a normal distribution with a mean of 1 and a standard deviation of 0.15. The same uncertainty factor is applied for every smoking-related cancer; therefore, never smoker background rates are correlated across type and tissue. Although the general US background rates are applied to leukemia, uterine cancers, and cancers of other tissues, the never smoker uncertainty factor is applied to these cancers to account for the subtypes potentially linked to smoking. Although a never smoker correction is applied to background survival, no uncertainty factor is included in this estimate.

## Excess Cancer Risk Estimates

Available radiation-induced cancer risk models are estimated based on human epidemiological evidence. These are commonly referred to as “low-LET models” because they are based on human cohorts exposed to low-LET radiation. NSCR uses excess cancer risk models based on quantified excess cancer incidence derived by the National Research Council (in the Biological Effects of Ionizing Radiation (BEIR) VII Report), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and the Radiation Effects Research Foundation (RERF)6,7,11,92. Excess cancer risk estimates are expressed in terms of multiplicative and additive risk models. A multiplicative risk model assumes risk of cancer increases proportionately to the background risk in unexposed cohort members; as exposure increases, the risk becomes multiplicatively greater relative to the background. The multiplicative model is known as the excess relative risk (ERR) model, since the increase in risk is relative to the background rate. Conversely, an additive risk model assumes risk of cancer increases incrementally compared to the background risk in unexposed cohort members; as exposure increases, the risk becomes additively greater relative to the background. The additive model is known as the excess absolute risk (EAR) model, since the risk increases by an absolute amount over the background. The individual parameters for the ERR and EAR models with their specific sources are included in Appendix X.

*Uncertainty*

The uncertainty in the ERR and EAR are broken up into three components as identified in NCRP Report 126 and adapted into NSCR to characterize uncertainty in the LSS risk estimates3,78. The uncertainty distributions associated with these components can be further updated to represent more recent LSS evaluations (see Future Improvements). The first component is tissue-specific statistical error, represented by an uncertainty factor that has a normal distribution with a mean of 1 and a tissue-specific standard deviation defined in Table 1. The second component is incidence data uncertainty or reporting bias, represented by an uncertainty factor that has a normal distribution with a mean of 1 and a standard deviation of 0.05. The third component is dosimetry error, represented by an uncertainty factor that has a log-normal distribution with a geometric mean of 0.9 and a geometric standard deviation of 1.3. The distributions associated with these components consider multiple LSS data analyses as well as subjective expert opinion3,78,93. Each of these uncertainty factors is multiplied by the estimated excess cancer risk, regardless of whether risk is considered ERR or EAR. New LSS analyses progressively account for more of the uncertainty than in previous analyses; newer technologies and more powerful computing software enable uncertainty reduction in LSS estimates5,38,94. Therefore, as new LSS estimates are released, we update our implemented ERRs and EARs accordingly (see Future Improvements).

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## Transfer to an Astronaut Population

NSCR estimates excess cancer risk in the astronaut population using the low-LET models described in Excess Cancer Risk Estimates. To determine the astronaut ERR, US never smoker background cancer mortality is multiplied by the LSS-derived ERR of cancer incidence. This application assumes that the excess risk of cancer incidence following radiation exposure is proportional to the excess risk of cancer mortality in both the Japanese and US populations. Thus, the model based on ERR is directly related to the cancer mortality observed in the background (unexposed) population of interest. The cancer incidence-based EAR is not directly related to background cancer mortality; rather, the excess risk represents an absolute increase in cancer incidence and must be converted to cancer mortality before it can be added to the US never smoker background cancer mortality6. EAR of cancer incidence is translated to a cancer mortality risk in an astronaut-like population using the ratio of the background incidence rates to background mortality rates. For each cancer type, the astronaut tissue-specific ERR () and EAR () values are weighted based on the expected contribution of a multiplicative (ERR) versus an additive (EAR) excess cancer mortality mechanism31. This weighting factor is known as the “transfer weight” (). weights the ERR contribution, while 1- weights the EAR contribution. The calculation for REID is as follows:

where

* is the age of exposure for mission ;
* is the attained age;
* is the dose equivalent for tissue and mission ;
* is the background cancer mortality rate by age for tissue ;
* is an uncertainty factor for tissue-specific never smoker background rates defined as a normal distribution and applied to the following smoking sensitive cancers: leukemia, stomach, colon, liver, bladder, lung, esophagus, oral cavity, other tissues, and uterus;
* is an uncertain Bernoulli parameter with equal to the tissue-specific multiplicative transfer weight for tissues with non-integer weights. For tissues with integer weights, is simply the integer weight [Table 1];
* is the ratio of the background cancer mortality to incidence rates by age for tissue with an upper bound set at 1.0.

This same calculation can be modified to calculate REIC which will be further described in Model Implementation.

*Uncertainty*

To account for uncertainty in the relative weights of the ERR and EAR models, the parameter is directly defined by a Bernoulli distribution with tissue-specific probabilities (Table 1). The Bernoulli distribution selects a single model (ERR or EAR) for each Monte Carlo run; overall, the number of times the ERR or EAR model is selected averages out to a tissue-specific binomial distribution that differs by Monte Carlo simulation specifics. This method relies on the assumption that only the ERR or EAR mechanism is acting at one time.

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## Radiation Quality

Radiation quality refers to the difference in dose necessary to achieve a particular effect size based on the type of radiation. Logistically, it is easiest to compare particles to photon radiation, since a majority of human data involves photon exposures. NSCR follows this paradigm, using a combination of LET and to characterize the quality of the different particles expected in space compared to that of photons. The form of the quality function is based on the biophysical Katz model95 and uses experimental animal and cellular data to subjectively inform the different model parameters3. The following equation is implemented to assess the quality of any given ion at any given energy:

where:

;

and:

* Z is ion charge;
* E is ion kinetic energy in MeV/n;
* is a high energy proton correction factor applied to all ions that is a normal distribution ;
* is a parameter to translate the maximum Q value () to the fluence scale and is defined as 7000 for solid cancer and 1750 for leukemia ;
* is a parameter to convert dose to fluence using LET and is predefined as 6.24;
* is a correlation function between and that is defined as = for and for ;
* is a parameter that sets the slope of Q before on the scale and is defined as a discrete distribution over with weights of 0.2, 0.2, 0.35, 0.2, 0.05;
* is an uncertainty factor for defined as a log normal distribution for solid cancers and for leukemia;
* LET is linear energy transfer in units of keV/um;
* Z\* is the Barkas form for ion effective charge;
* is ion velocity relative to the speed of light;
* is a parameter that sets the location of along the axis and is defined as for and for ;
* is a correlation function between and *m* and is defined as for and for ;
* is an uncertainty factor for defined as a log normal distribution ;
* is a thindown correction for low energy particles and is defined as .

*Uncertainty*

Three uncertainty factors (, , and ) and one uncertainty parameter (*m*) are included in the quality equation. The first two uncertainty factors are associated with the model parameters and , and the third is a high-energy proton correction factor. is a location parameter for the maximum value of quality for a given ion over all possible energies. Its uncertainty factor is log-normal with a geometric mean of 0.9 and a geometric standard deviation of 1.4 for solid cancers, and a geometric mean of 1 and a geometric standard deviation of 1.5 for leukemia. is the location for a given ion on the axis where the highest quality occurs. Its uncertainty factor is log-normal with a geometric mean of 0.95 and a geometric standard deviation of 1.4. The slope parameter *m* represents the rate of increased quality over the axis. Its uncertainty is represented by a discrete distribution with values of 2, 2.5, 3, 3.5, and 4 with weights of 0.2, 0.2, 0.35, 0.2, and 0.05, respectively. is correlated with both and . The correlation of *m* and is implemented to ensure the *maximum estimate* of quality remains unchanged regardless of the slope parameter. The correlation of and is implemented to ensure the *location* of the maximum estimate of quality on the axis remains unchanged regardless of the slope parameter. These methods concentrate uncertainty in the densely ionizing portion of the equation. A high energy proton correction factor is applied to better model the uncertainty in the sparsely ionizing portion of the equation. This correction is an uncertainty factor with a mean of 1 and a standard deviation of 0.15. These uncertainty distributions are based on subjective expert opinion3.

*Upgrades from the 2012 implementation*

Several upgrades to the quality equation have been made since the original implementation in 2012. The distribution for was changed from normal (mean = 1, standard deviation = 1/3) to log normal (geometric mean = 0.95, geometric standard deviation = 1.4). A normal distribution is a poor choice for for three reasons. First, a normal distribution does not naturally limit values to positive numbers; however, 𝜅 values below zero will result in non-real values for quality. Therefore, truncation of the distribution to values greater than zero is required when using a normal distribution. Second, dividing by a normal distribution results in the Cauchy distribution, which has several undesirable properties including lack of a mean and standard deviation96. Third, when the distribution approaches zero, P(Z, E) approaches 1, and the model inaccurately reports energy being deposited entirely as densely ionizing for all values and all ions. Modifying to a log-normal distribution naturally constrains values to real numbers and is consistent with standard mathematical practice. This change reduces bias in REID estimates by allowing replacement of the current distribution shape while maintaining the current mean and standard deviation.

The correlations between , , and discussed above were also modified from the 2012 implementation. Complexity was added to the correlation function to ensure that the location of is fixed for all values of . Correlation was added between and to ensure that the magnitude of is fixed for each .

## 

## Scaling to Low Doses and Low Dose-Rates

Just as the atomic bomb survivor population must be transferred to an astronaut-like background, the high dose-rates received by the atomic bomb survivors must be scaled to the low dose-rates expected in space. Furthermore, many missions have substantially lower doses than the relatively high doses (1-4 Gy-equivalent) that drive LSS risk estimates38. While dose scaling is handled using a linear dose-response in all models, dose-rate effects are built into NSCR separately from ERR and EAR constructs. These effects are treated differently for leukemias and solid cancers.

*Leukemias*

LSS models for leukemia use a linear-quadratic dose response (except chronic lymphocytic leukemia, or CLL, which is not considered radiogenic and is excluded from the model)92. It is assumed that when exposure is not acute, the quadratic portion of the model does not apply, and leukemia will be adequately characterized by a linear dose-response6. Since NSCR assumes a linear model for leukemia, a separate DDREF is not applied to the risk estimates for leukemia.

*Solid Cancers*

While excess risk of solid cancer is modeled linearly, it is still assumed that lower dose-rates will result in decreased excess risk compared to higher dose-rates. Since this assumption is not inherent in a linear model, a scaling factor must be applied before this assumption is integrated into NSCR6. A DDREF scales high doses and acute dose-rates to low doses and chronic dose-rates for all solid cancers included in the model. A central estimate for the DDREF of 1.5 was selected based on the BEIR VII report which assessed low-LET human epidemiology data and animal data6. For all solid cancers, is divided by the DDREF to adjust for the low doses and chronic dose-rates observed in space.

*Uncertainty*

Since leukemia is scaled by removing the quadratic component of a defined model, no additional uncertainty is considered beyond what is already incorporated into the model. Because a scaling factor is applied for solid cancers to account for the assumed dose-rate effects, uncertainty is included in the form of a distribution for DDREF. The DDREF distribution is based on low-LET human epidemiological data, animal data, and cellular data3. The central estimate used in NSCR is 1.5 based on the BEIR VII report6. Unlike BEIR VII, which uses a log-normal distribution, NSCR implements a log-Student T distribution with 5 degrees of freedom. This distribution is then truncated so the lower bound remains above 0.2 due to lack of evidence for a lower DDREF97. The combination of the central estimate with the truncated log-Student T distribution results in a DDREF distribution with a median of 1.5 and a 95% CI of 0.84 to 2.65.

## Multiple Exposures

Many astronauts participate in multiple missions with different mission parameters. In the NSCR 2012 model implementation, REID and REIC were calculated separately for each mission and totaled following these calculations. Using this method, uncertainty intervals could not be directly calculated for combined multiple exposures; rather, the REID and REIC point estimates were calculated, and the REID could be multiplied by “fold factors” to approximate upper limits of the uncertainty interval3. Due to improvements in technology and computing power, the cumulative dose from these missions is now considered together when calculating REID and REIC, which enables direct calculation of uncertainty intervals. This method assumes near-perfect correlation of uncertainty across missions (i.e., uncertainty factors and uncertainty parameters are considered identical regardless of mission), with the exception of physics uncertainty. Physics uncertainty is unique to each mission and is folded in when mission doses are totaled.

## 

## Model Implementation

Using survival analysis techniques, the REID and REIC are calculated for each tissue type by multiplying the appropriate hazard function for the radiation exposure () by the overall survival function for an astronaut-like population adjusted for deaths caused by radiation exposure (). Ideally, the probability would be integrated over all ages in an expected lifetime (age at exposure to 101 years of age). However, since background survival probabilities, incidence rates, and mortality rates are typically provided in one year intervals, it is reasonable to approximate this integral by summing over all ages in an expected lifetime in one year intervals. A period life-table methodology is applied such that background cancer mortality and incidence rates are allowed to change by age, but are held constant over time period. That is, only the most recent set of background rates are applied, which models age but not cohort effects. For instance, an astronaut born in 1945 would have different background rate estimates at age 30 and age 35; however, two astronauts born in 1945 and 1960, respectively, would have the same background rate estimates for age 30. Since each tissue is modeled separately, a total REID or REIC is calculated as the sum of tissue-specific REIDs or REICs over all modeled tissues (T). Because many astronauts fly on multiple missions, radiation exposure is summed over all mission exposures (). Thus, REID and REIC are estimated as follows:

where:

* is an estimation of ;
* is the hazard function for radiation exposure based on mortality (REID) or incidence (REIC) for tissue ;
* is the age of exposure for mission ;
* is the attained age;
* is the dose equivalent for tissue and mission ;
* is the overall survival function adjusted for deaths caused by radiation exposure.

The radiation risk hazard function can be estimated using the appropriate tissue-specific ERR and EAR models from radiation exposed cohorts transferred to an astronaut-like population as described above. The atomic bomb survivor populations have indicated a latency period between irradiation and cancer incidence that differs by cancer type (i.e., solid cancer vs leukemia)11. NSCR uses a solid cancer latency of 5 years and a leukemia latency of 2 years. The hazard functions are estimated as follows:

for REID calculations:

for REIC calculations:

where:

* is the age of exposure for mission ;
* is the attained age;
* is the dose equivalent for tissue and mission ;
* is the background cancer mortality rate by age for tissue ;
* is the background cancer incidence rate by age for tissue ;
* is an uncertainty factor for never smoker background rate defined as a normal distribution and applied to the following smoking sensitive cancers: leukemia, stomach, colon, liver, bladder, lung, esophagus, oral cavity, other tissues, and uterus;
* is an uncertain Bernoulli parameter with p equal to the tissue-specific multiplicative transfer weight for tissues with non-integer weights. For tissues with integer weights, is simply the integer weight (Table 1);
* is the ratio of the background cancer mortality to incidence rates by age for tissue that is defined as:
  + The calculated ratio for solid cancers and 1 for leukemia when estimating REID;
  + The calculated ratio for leukemia and 1 for solid cancers when estimating REIC;
* is an uncertainty factor for the statistical uncertainties in the ERR and EAR models for tissue (Table 1);
* is a latency function that equals 1 for all ages attained greater than the age of exposure plus 2 years for leukemia or plus 5 years for solid cancer; for attained ages less than these values equals 0;
* is 1 for leukemia and a log Student T distribution truncated at 0.2 for solid cancers.

The overall survival function for an astronaut-like population adjusted for deaths caused by radiation exposure can be defined as:

where:

* is the background survival function for a representative astronaut population;
* is the attained age;
* is the age of exposure for mission ;
* is calculated as defined in the hazard function above.

Mission-specific tissue dose equivalents are estimated to incorporate radiation quality and low dose-rate scaling. Due to limited computing power, the NSCR 2012 model implementation used an “approximate solution” to calculate tissue dose equivalents which split ions into two categories: light ions (Z ≤ 4) and heavy ions (Z > 4)3. Currently, an “exact solution” is implemented to calculate tissue dose equivalents, where each ion has a uniquely defined quality within a discrete set of energies. The exact solution enables more granularity in the overall REID calculation. NSCR calculates the exact solution for tissue dose equivalents as:

where:

* Z is ion charge;
* E is ion kinetic energy in MeV/n;
* uses the trapezoidal rule to approximate , which represents the mission differential fluence for tissue T in units of particles/cm2/(MeV/n);
  + is the differential fluence for tissue T in units of particles/cm2/(MeV/n) for each energy bin;
* LET is the linear energy transfer in units of keV/um;
* is the NASA quality factor function as defined above;
* is an uncertainty factor for physics that is defined as a normal distribution for and truncated at 0 for .

Mission differential fluence is calculated for 59 ions and mesons (mu+, mu-, pi+, pi-) across 100 energy bins with non-uniform widths (a 125 energy bin option is in development as of January 2021). Although each ion is unique, each energy bin represents multiple energies; the trapezoidal rule is used to integrate over the bins. A table identifying the value representing each ion and energy combination is listed in Appendix Z. By extension, this table selects the quality factor representative of the energy bin to calculate tissue dose equivalent. Electromagnetic particles (e-, photon, e+) are also included in the model with a quality factor of 1.

Table 1: Statistical uncertainty distribution and weights for individual tissues

|  |  |  |  |
| --- | --- | --- | --- |
| **Tissue** | **Normal Distribution Properties for** | | **(a)(b)** |
| **Mean** | **Standard Deviation** |
| Leukemia | 1 | 0.2 | 0.5 |
| Stomach | 1 | 0.2 | 0.7 |
| Colon | 1 | 0.3 | 0.7 |
| Liver | 1 | 0.2 | 0.7 |
| Bladder | 1 | 0.2 | 0.7 |
| Lung | 1 | 0.6 | 0.5 |
| Esophagus | 1 | 1 | 0.7 |
| Oral Cavity | 1 | 0.5 | 0.7 |
| Brain | 1 | 0.3 | 0.7 |
| Thyroid | 1 | 0.4 | 1 |
| Other tissues(c) | 1 | 0.4 | 0.7 |
| Prostate | 1 | 0.2 | 0.7 |
| Breast | 1 | 0.2 | 0 |
| Ovary | 1 | 0.2 | 0.7 |
| Uterus | 1 | 0.2 | 0.7 |

# *Footnote for Table 1:*

# *Values based on BEIR VII with the exception of Leukemia and Lung.*

# *Thyroid and breast are based on a pooled analysis that determined which model applies. No uncertainty is applied to these tissues for .*

# *Other tissues includes: Small intestine, retroperitoneum, peritoneum, omentum and mesentery, other digestive organs, larynx, pleura, trachea, mediastinum, other respiratory organs, nose, nasal cavity, middle ear, bones and joints, soft tissues including heart, melanoma, vagina, vulva, other female genital organs, testis, penis, other urinary organs, eye and orbit, other endocrine including thymus.*

# 

# Other Aspects of Implementation

## Upgrade to the Analytica Decision Engine

Previously, both transport and risk calculations were performed using Fortran. In NSCR, transport is still performed using Fortran, and risk calculations have been migrated to the Analytica Decision Engine software through the Risk Analysis Environment (RAE) designed in collaboration with ORRISK19. The separate environments for transport and risk calculations are advantageous in a number of ways. The Analytica environment was specifically designed for uncertainty quantification, which enables uncertainty propagation to be easily applied and summary statistics to be readily calculated. Analytica provides advanced uncertainty distribution sampling using random number generation through Latin hypercube technology instead of simple Monte Carlo techniques. Analytica contains a library of simple and complex functions commonly used in uncertainty analysis and therefore provides error checking on a wide array of operations. For instance, the Analytica environment has natively coded random number generators tied to specific distributions, and it performs error checking on these processes. Furthermore, Analytica is also used by other government agencies such as NCI and NIOSH for similar calculations, allowing for consistency in risk calculation between government agencies30,34. Analytica’s graphical interface creates a more transparent coding environment, where coded modules are easy to interpret, verify, and maintain (Figure 3)19.

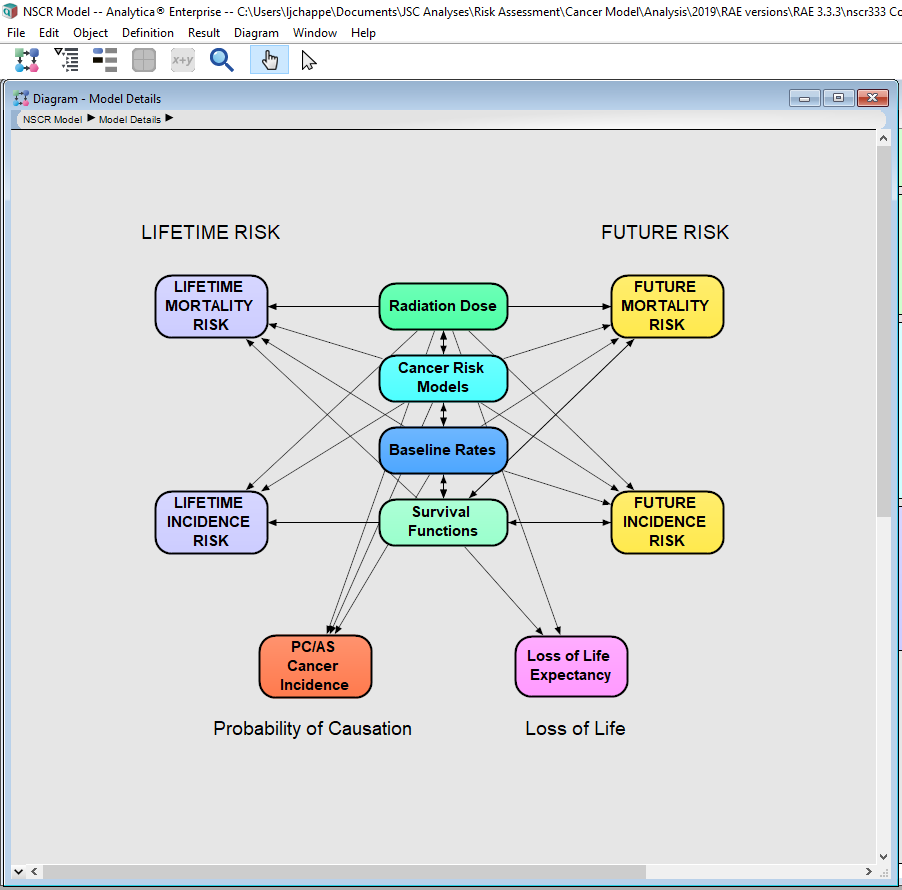


Figure 3: Image of Analytica graphical user interface for RAE

## Risk Analysis Environment Graphical User Interface

RAE is used to implement all components of NSCR. ORRISK defines RAE in three parts: the risk assessment code; the MySQL-based RAE database; and the RAE GUI, which is a web-based interface that ties together transport, risk, and results output. Users interact with RAE via the RAE GUI that makes analyses easily navigable and user-friendly and does not require users to be fluent in Analytica coding. The four main RAE GUI options are *Data*, *Transport, Risk,* and *Reporting* which takes a user to the respective environments for interacting with the data, running the transport code, running the risk model for individual astronauts, and generating reports from previously existing *Risk* output.

The *Data* option allows users to add and edit information in the database. It contains four sub-options, called *Database, Space, Medical,* and *Other*. The *Database* option presents a GUI version of the data stored in the MySQL database, and users can add and edit these data. Since using *Database* requires users to be moderately well-versed in the data storage system used by RAE, the other *Data* sub-options provide an easier interface for adding data. The *Space, Medical*, and *Other* sub-options contain collated sets of required variables necessary for creating new database records specific to these respective categories. Each set also contains variables for additional, potentially relevant information. In this way, new astronauts, missions, exposures, and radiation monitoring data can be created and tied correctly together in the database without a user needing to explicitly access *Database.*

The *Transport* option allows users to run the transport code for an individual astronaut on an individual mission to calculate a fluence file. The data from each successful *Transport* run is stored in the MySQL database so it can be used for risk analyses.

The *Risk* option allows users to run the risk assessment for an individual astronaut on zero, one, or multiple missions. If missions are included in the assessment, a fluence file must already have been generated using *Transport.* Astronauts may have no missions but still require a risk profile; astronaut candidates and astronauts with no spaceflight record can use the option to run *Risk* with no existing missions. Mission projections may also be used, though these do require fluence files. *Risk* generates a results summary page that can be submitted to the database. These results can also be used to generate Astronaut Radiation Reports.

The *Reporting* option completes the Astronaut Radiation Report generation process. The following sub-options are available on the *Reporting* page: *Astronaut Annual Report, Upload, Retrieve, RHO Monthly Reports,* and *Additional Queries.* *Astronaut Annual Report* is used to generate and edit reports from existing *Risk* output. *Upload* allows users to save relevant files to the RAE database, and *Retrieve* allows users to view these files and past Astronaut Radiation Reports. *RHO Monthly Reports* displays lists of astronauts by birth month. By selecting an astronaut, a user is taken to *Astronaut Annual Reports* to select which *Risk* run they would like to use to generate a report. A PDF may also be available next to the listed astronaut; this PDF will be the most recent saved Astronaut Radiation Report. *RHO Monthly Reports* shows color codes for whether a signed report is available for the astronaut in question in the designated month and year. Finally, *Additional Queries* allows users to interrogate the results stored in the database to answer questions that arise frequently for astronaut radiation-related risks.

# 

# Future Improvements

To ensure that the cancer risk due to radiation exposure is well-characterized and reflects the most recent state of knowledge, NSCR must be updated as new evidence emerges. Human cohort evidence evolves through both epidemiological advances and updated understanding of cancer incidence and mortality metrics. Further, experimental cancer research is a constantly advancing field. Implementing changes to the state of knowledge using a data-driven approach allows the integrity of these advances to be maintained. The Analytica platform allows modular development of code to integrate these data-driven approaches and updates.

## Human Cohorts

NSCR has the flexibility to accommodate changes in knowledge stemming from new human information. Human cohorts that can advance NSCR come primarily in two forms: publications from radiation-exposed human population studies, and cancer incidence and mortality data in the United States.

As of 2020, NSCR only considers data from atomic bomb survivors for a majority of site-specific ERR and EAR estimates, since atomic bomb survivors are historically the only population with enough high-quality data to inform effect estimates (breast and thyroid cancer risk estimates also leverage data from radiation therapy cohorts6). The LSS updates cohort risk estimates approximately every decade, incorporating improvements to dosimetry, increased follow-up, and state-of-the-art modeling techniques7,36,38. Following these improvements, RERF publishes combined and site-specific solid cancer and leukemia/lymphoma incidence and mortality reports which incorporate these changes4,5,7–10,12,36. Several more updates are anticipated before the LSS cohort can no longer provide data with enough power to modify risk estimates. ERR and EAR estimates in NSCR will continue to be updated periodically as new information from the LSS becomes available.

As of December 2020, RERF has published the first of a new series of cancer incidence updates4,5,8–10,12,36. These publications include revised dosimetry which incorporates improved location mapping for survivors, better understanding of free in-air kerma given local topography, and newer human phantoms38. Epicure, the statistical software RERF uses for Poisson regression, is used to model ERRs and EARs98. These Poisson models better incorporate smoking data for smoking-related cancers, and where appropriate, report separate risks for males and females. SRAG is working with ORRISK to replace the previous estimates with these updated ERRs and EARs. More specific cancers are reported (for instance, proximal and distal colon cancers are reported individually), which enables distinct etiologic factors to be assessed for each cancer subtype10. This more granular analysis requires further sub-categorization of some cancers in NSCR. Including these more specific cancer rates provides flexibility to implement new RERF models as they become available. To properly integrate these more granular estimates, both the modeled cancers and their background rates must be updated. To implement these changes, updates must also be made to the background cancer methods.

Cancer incidence and mortality statistics were discussed previously in the *Background Mortality in an Astronaut Population* section. Briefly, models are informed by CDC WONDER, a series of databases which collate information from multiple data sources99,100. Background cancer incidence and mortality in NSCR are updated periodically with new information available through CDC WONDER. Consistency has been reviewed between the International Classification of Diseases for Oncology (ICD-O-3) codes for cancers in the recent RERF reports and for background cancers in NSCR. As of 2020, NSCR includes 15 cancer subtypes and with the additional updates, it will include 37 distinct cancer subtypes. With these changes to the background rates, new strategies for modeling cancer rate uncertainty are being developed including data-driven approaches for smoothing rates for each one-year increase in age and applying updated never smoker cancer rates.

As of 2020, NSCR calculates REID and REIC propagated over an astronaut’s lifetime; that is, the time of first exposure to predicted end of life (See Model Implementation Section). NSCR utilizes background rates updated for a modern population, which means that these rates are most relevant to astronauts only over the most recent portion of their lifetime. Rates become less relevant when applied to years further from those used to define the background rates. In other words, there is an uncertainty gradient, where uncertainty is least pronounced for the years used to define the background rates, and more pronounced for both years previous to that date and years used for risk projection at later dates.

Other methods to predict background rates into the future have been considered by groups such as the Potomac Institute101. With these methods, handling uncertainty needs to be considered carefully. There are also considerations that need to be made for using current rates to represent rates that occurred in the past. These rates have been observed but are not being utilized in our current methodology. Incorporating cohort effects into the model could be a complex process. An alternative to lifetime risk calculation would be to calculate future risk over an astronaut's remaining lifetime which would address this concern of using the incorrect cohort for past rates. Future risk leverages the empirical data that the astronaut has survived to the time of present calculation, and begins age-specific risk summation at the astronaut’s age at time of calculation rather than age at first exposure. Since the cohort is constructed from astronaut current age, both age and cohort effects are represented. Risk calculations using this methodology only consider risk from the date of calculation to year of expected death. The 2020 operational implementation of NSCR contains a module capable of calculating future risk (Figure 3). Both lifetime and future risk use the most recent set of estimates to represent rates in the future. Another possible improvement to the present methodology would be to predict future cancer incidence and mortality rates rather than using present rates to represent those in the future. While this type of prediction is possible with regression analysis, it would require the addition of considerable uncertainty, particularly due to the possibility of unprecedented changes in population health outcomes102. Changes in common causes of death over time would require extrapolation, which would also increase uncertainty surrounding these rate estimates. As healthcare science and technology is expected to improve, the current rates can be assumed to be an upper limit to what would be anticipated in the future. Since these rates are expected to be an upper limit, no additional uncertainty is applied. Due to the vast uncertainties involved in predicting future rates, the current assumption may be more appropriate. Sensitivity analyses can provide further insights into the relative uncertainties involved in each of these potential methods.

The Million Person Study (MPS; also referred to as the Million Worker Study) is an ongoing project to analyze and report results for over one million healthy US citizens exposed to low dose-rates of ionizing radiation in multiple cohorts40–42. These cohorts include nuclear workers from various facilities, radiation-exposed medical workers, and atomic veterans. Since several of these cohorts include both males and females, the MPS is expected to assess whether the dose-response relationship between ionizing radiation and lung cancer differs by sex, which may enable a reassessment of sex-specific REID estimates40. Multiple MPS cohorts also include internal exposures to alpha-emitters such as plutonium and polonium as well as external exposures to neutrons that can help assess the effects of high-LET radiation in human cohorts52–54,103. Although these exposures to high-LET radiation are predominantly internal and differ greatly from the radiation profile found in space, they can provide a link between the heavy ion exposures in animals and the primarily low-LET exposures studied thus far in humans.

There are several benefits of MPS data compared to LSS data. These include the low dose-rates experienced by workers, the US population involved in these studies, and the experience of high-LET radiation by multiple MPS cohorts40,103. The one major drawback is that MPS cohorts are split into sub-groups that, due to differences in potential confounding variables, may not always be pooled for increased power to determine effect sizes. While meta-analyses can account for this limitation in some circumstances, the LSS is useful since it is a single, high-powered cohort.

Once a larger volume of MPS data is published, future work will be needed to combine and weight risk estimates from both the MPS and the LSS. Expert opinion and sensitivity analyses will be required to adequately weight the information provided from each cohort.

## NASA Empirical Data-driven Radiation (NEDRad) model

Ideally, ongoing improvements to the state of knowledge should be applied to the risk model using an empirical, data-driven approach which can be implemented using the following strategies:

* Perform analyses using rigorous, state-of-the-art statistical techniques;
* Incorporate new data as they become available;
* Reanalyze historical data with improved techniques to gain new insights;
* Derive central estimates and associated uncertainty from empirical data where possible;
* Clearly document all analyses and provide the code that produced the results;
* Ensure all analyses are repeatable and verifiable;
* Seek expert guidance where gaps in data remain;
* Define and document all assumptions and decisions.

This empirical data-driven approach can be applied to each area of model uncertainty to improve overall risk estimates and communication. The NASA Empirical Data-driven Radiation (NEDRad) model uses this approach to incorporate information and empirical data into the overall risk model. Areas of uncertainty described in *Overall Implementation of the Model* are explored using the NEDRad approach.

*Background rates*

In addition to updating to the most recent CDC and NCI background rates99,100, further data involving a healthy, never smoker population must be incorporated to better characterize background cancer incidence and mortality for an astronaut-like population. The relative risk of cancer following exposure to smoking is leveraged to estimate population never smoker cancer rates. Published confidence intervals for smoking relative risks used to estimate these rates can be incorporated into the model to more directly approximate the uncertainty distribution associated with cancer rates in an astronaut-like population13,16–18. The US never smoker population used to represent astronaut background cancer risk in the 2020 implementation of NSCR can be expanded to develop a background risk model more comparable to astronauts based on healthy workers and never smokers. The astronaut population is considered a healthy worker cohort by virtue of being a working population. Further, the astronaut population is healthy beyond what is expected in a healthy worker population due to the rigorous selection process undergone by all cohort members. Data are available for aircrew cohorts and military cohorts that have some similarities to an astronaut population104–106. A meta-analysis could be performed on published standardized mortality rates (SMRs) from these studies with the goal of adjusting the US average cancer rates with methods similar to those used for the US never smoking population107. This type of methodology is described for the healthy worker effect in UNSCEAR 2012108.

*DDREF*

ORRISK recently published an extensive review of the data available to estimate DDREF and its empirical distribution97,109. The ICRP is publishing a series of papers reanalyzing DDREF110. For instance, Shore et al. 2017 published a meta-analysis of DDREF among low dose-rate cohorts111. These published distributions represent the current state of knowledge surrounding DDREF and should be more thoroughly investigated for application to NSCR in a data-driven manner.

*Quality factor function*

Animal tumor data are particularly valuable for informing the quality factor function due to similarities between tumorigenesis and analogous endpoints across species112. Tumor data are considered to be the most relevant outcome to human carcinogenesis for cancer risk modeling113. Multiple ions and energies are needed to estimate a quality factor function covering the full fluence spectra found in the space radiation environment3. With limited HZE animal tumor data, it is important to efficiently leverage the available data (Appendix Y). An empirical data-driven approach is in development to incorporate HZE animal tumor data into an updated quality factor function. The goal is to reanalyze raw animal tumor data to directly estimate parameters that can be incorporated into the current risk framework.

A re-evaluation of the Harderian gland (HG) tumorigenesis data explored different model shapes to evaluate assumptions underlying dose-response shape for varying ions and energies. In this study, each ion-energy combination was analyzed as a separate parameter in the model to determine the shape for each combination separately114. A second analysis is ongoing using the parameter to allow ion-energy combinations to be modeled continuously rather than categorically. This modeling methodology allows extrapolation to ion-energy combinations not included in the initial data. Furthermore, the use of Bayesian methods will provide data-driven posterior uncertainty distributions for estimated parameters that can be incorporated directly into NSCR.

Future analyses will focus on validating the initial models based on the HG data using other HZE animal tumor data sets. These analyses may also need to extend to neutron animal tumor data and other cancer related endpoints. Since cellular endpoints related to cancer may have larger ranges of ions and energies, they could be useful in estimating the shape of the quality factor function especially for values greater than 3000 where HZE animal tumor data are lacking3.

*Quality and DDREF correlation*

Currently, dose-rate effects and quality have been studied and implemented into models separately. However, there is a possibility that dose-rate effects are a function of quality. This possible relationship has only been characterized minimally in the past but has the potential to impact REID estimates115,116. Data sources with different dose-rates, ions, and energies should be identified to study this potential correlation.

## Model Development and Sensitivity Analyses

Analytica provides a convenient platform to develop and explore updates to NSCR and perform sensitivity analyses. Sensitivity analysis libraries are available to help investigate the relative contribution of each uncertain variable included in the model. Different candidate distributions for uncertain variables can easily be swapped into the code using drop-down menus for exploratory analyses. Analytica also has built-in functions for natively creating user-friendly interfaces to change model parameters across multiple modules (Figure 4)19.

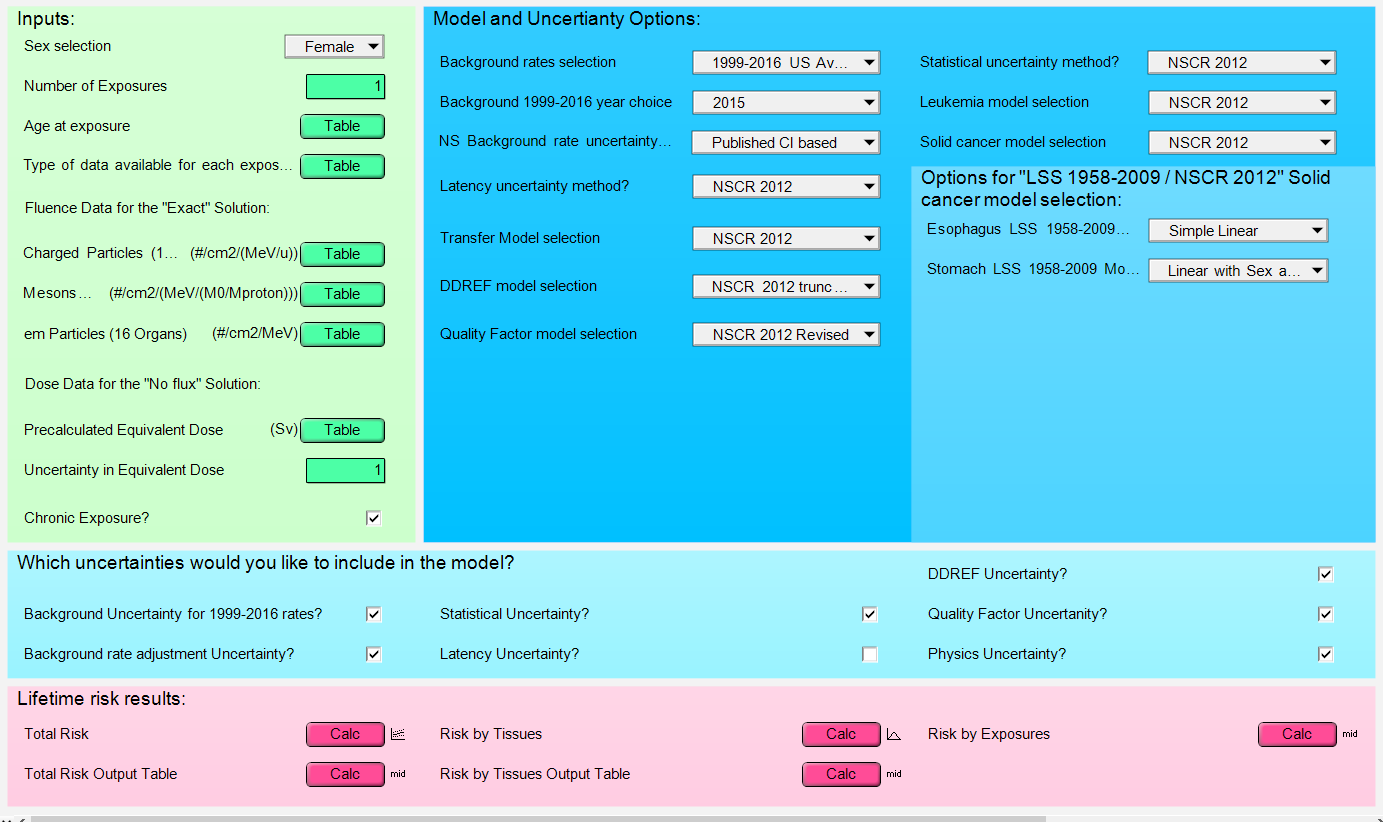


Figure 4: Analytica graphical user interface for model development and sensitivity analyses

An independent, version controlled development risk code (Radiation Cancer Risk Development Model) has been used for sensitivity analyses since 2015 and tracked using Gitlab since 2018. The code is continually used to explore many aspects of uncertainty in the REID calculation. Areas that have been considered or are in development as of 2020 are shown in Table 2. This process highlights how changes to different aspects of the model might alter REID estimates; combined with the data-driven approach described in the NASA Empirical Data-Driven Radiation Model and expert knowledge where necessary, the best candidates for model improvement can be tested for operational use.

Table 2: Radiation Cancer Risk Development Model options, where Implemented models are those currently available for use in the Radiation Cancer Risk Development, and Development models are those being researched.

|  |  |  |
| --- | --- | --- |
| **Background Rates** | | |
| **Description** | **Status in Radiation Cancer Risk Development Model** | **Citation** |
| US Average Rates 2007 | Implemented | 117–120 |
| US Average Rates 2009 | Implemented | 121–127 |
| US Average Rates 2011 | Implemented | 85–87,91,128–132 |
| US Average Rates 2013 | Implemented | 133–138 |
| US Average Rates 1999-2016: uncertainty methodology, greater fidelity of tissue subtypes, and cohort trends | Implemented | 91,99,100,117,121,133,139–152 |
| NS methodology and uncertainty | Implemented | 14 |
| Healthy worker methodology | Implemented | 107,108 |
| **Solid Cancer Models** | | |
| RadRAT/BEIR VII | Implemented | 6,30 |
| UNSCEAR | Implemented | 11 |
| RERF Incidence | Implemented | 7 |
| RERF Mortality | Implemented | 37 |
| Walsh | Implemented | 153 |
| RERF Histology Incidence | Implemented | 7 |
| Methods to weight different cancer incidence and mortality risk models | Implemented | Internal research |
| RERF Incidence update | Development | 4,5,8–10,12 |
| **Leukemia models** | | |
| RadRAT/BEIR VII | Implemented | 6,30 |
| UNSCEAR | Implemented | 92 |
| RERF | Implemented | 154 |
| **Latency models** | | |
| RadRAT with uncertainty | Implemented | 30 |
| **Transfer models** | | |
| Multiplicative | Implemented | Internal research |
| Additive | Implemented | Internal research |
| Point Estimate | Implemented | Internal research |
| RadRAT | Implemented | 30 |
| **DDREF models** | | |
| Historical DDREF distributions | Implemented | 3,30,32,108,155–157 |
| Methods to weight different models | Implemented | Internal research |
| NIOSH 2017 | Implemented | 97,109 |
| ICRP review | Implemented | 111 |
| **Quality factor models** | | |
| New approach | Implemented | 115 |
| Results from NEDRad analyses | Development | Internal research (publication pending) |

In addition to the development risk code, a new version of the RAE system is maintained by ORRISK that supports the transition of model updates into the operational risk analysis framework. This system is known as the Modeling And Development Risk Analysis Environment (MADRAE). MADRAE utilizes the already developed structure of RAE, but allows the testing of new models before they are implemented operationally. Modules can be created in Analytica to incorporate new evidence and models into both MADRAE and Radiation Cancer Risk Development Model.

# Conclusions

The 2020 operational version of NSCR enables estimation of long-term excess risk of cancer mortality and incidence in astronauts from occupational radiation exposures received at NASA. Figure 2 illustrates the process of translating dose measurements (or predictions) to risk using models informed by human, animal, and cellular data. NSCR includes the RAE platform, which uses Monte Carlo simulation to generate a probability distribution from which uncertainty can be assessed and communicated. The modular nature of NSCR allows new model innovations to be tested and incorporated without concern for total model integrity. As more data becomes available, the model structure itself may need to be updated. Other model frameworks that could be implemented in the future are currently being researched158–160.

# Appendix X: Excess risk model details

The following equation can generalize the excess risk models:

where

* ER = ERR or EAR per 10,000 person years
* = the tissue specific risk coefficient for males or females
* = the tissue specific dose equivalent in Sv
* = the age at exposure parameter
* = a transformation of the age at exposure that depends on the model source
* = the attained age parameter
* = a transformation of the attained age that depends on the model source
* = the years since exposure parameter
* = a transformation of the years since exposure that depends on the model source

Table X.1: ERR Transformations and Parameter Estimates:

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  |  | Source |
| Leukemia |  |  |  | 1.599 | 1.599 | 0.233 | -1.98 | 0 | (Little et al., 2008)92 |
| Stomach |  |  |  | 4025 | 4025 | 0 | -2.253 | 0 | (UNSCEAR, 2008)11 |
| Colon |  |  |  | 1.481e6 | 1.481e6 | 0 | -3.526 | 0 | (UNSCEAR, 2008)11 |
| Liver |  |  |  | 0.3951 | 0.3951 | 0 | 0 | 0 | (UNSCEAR, 2008)11 |
| Bladder |  |  |  | 0.8989 | 0.8989 | 0 | 0 | 0 | (UNSCEAR, 2008)11 |
| Lung |  |  |  | 0.3182 | 1.399 | 0 | 0 | 0 | (UNSCEAR, 2008)11 |
| Esophagus |  |  |  | 0.5278 | 0.5278 | 0 | 0 | 0 | (UNSCEAR, 2008)11 |
| Oral Cavity |  |  |  | 0.39 | 0.39 | 0 | -1.65 | 0 | (Preston et al., 2007)7 |
| Brain |  |  |  | 7.431 | 7.431 | -0.9897 | 0 | 0 | (UNSCEAR, 2008)11 |
| Thyroid |  |  |  | 0.53 | 1.05 | -0.83 | 0 | 0 | (BEIR VII, 2006)6 |
| Other Tissues |  |  |  | 143.2 | 143.2 | 0 | -2.939 | 1.645 | (UNSCEAR, 2008)11 |
| Prostate |  |  |  | 0.11 | - | 0 | -1.65 | 0 | (Preston et al., 2007)7 |
| Breast |  |  |  | - | 0 | 0 | 0 | 0 | (BEIR VII, 2006)6 |
| Ovary |  |  |  | - | 0.61 | 0 | -1.65 | 0 | (Preston et al., 2007)7 |
| Uterus |  |  |  | - | 0.10 | 0 | -1.65 | 0 | (Preston et al., 2007)7 |

Table X.2: EAR Transformations and Parameter Estimates

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  |  | Source |
| Leukemia |  |  |  | 1.187 | 1.187\*exp(-0.594) | 0 | 0 | -0.574 | (Little et al., 2008)92 |
| Stomach |  |  |  | 3.969e-3 | 3.969e-3 | 0 | 1.828 | 0 | (UNSCEAR, 2008)11 |
| Colon |  |  |  | 2.875e-5 | 2.875e-5 | 0 | 0 | 3.204 | (UNSCEAR, 2008)11 |
| Liver |  |  |  | 1.037e-6 | 1.037e-6 | 0 | 3.479 | 0 | (UNSCEAR, 2008)11 |
| Bladder |  |  |  | 6.135e-11 | 6.135e-11 | 0 | 5.748 | 0 | (UNSCEAR, 2008)11 |
| Lung |  |  |  | 1.008e-7 | 1.505e-7 | 0 | 4.211 | 0 | (UNSCEAR, 2008)11 |
| Esophagus |  |  |  | 0.1453 | 0.1453 | 0 | 0 | 0 | (UNSCEAR, 2008)11 |
| Oral Cavity |  |  |  | 0.56 | 0.56 | 0 | 2.38 | 0 | (Preston et al., 2007)7 |
| Brain |  |  |  | 0.4924 | 0.4924 | 0 | 0 | 0 | (UNSCEAR, 2008)11 |
| Thyroid |  |  |  | 0 | 0 | 0 | 0 | 0 | (BEIR VII, 2006)6 |
| Other Tissues |  |  |  | 2.208e-3 | 2.208e-3 | 0 | 0 | 2.161 | (UNSCEAR, 2008)11 |
| Prostate |  |  |  | 0.34 | - | 0 | 2.38 | 0 | (Preston et al., 2007)7 |
| Breast |  |  |  | - | 10 | -0.5 | 3.5, 1[[1]](#footnote-1) | 0 | (BEIR VII, 2006)6 |
| Ovary |  |  |  | - | 0.56 | 0 | 2.38 | 0 | (Preston et al., 2007)7 |
| Uterus |  |  |  | - | 0.56 | 0 | 2.38 | 0 | (Preston et al., 2007)7 |

If then 3.5 else 1

# Appendix Y: Table describing radiation animal experiments (excluding neutrons)

| **Source** | **Particle** | **Z** | **Energy** | **LET** | **Fract.** | **Dose rate (cGy/min)** | **Doses (Gy)** | **n** | **Strain** | **Sex** | **Tissues Exposed** | **Age at Exposure** | **Age sacrificed** | **Reason Sacrificed** | **Cancers Studied** | **Additional experimental conditions** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| (Chernyavskiy et al., 2017)161 | Silicon | 14 | 240 |  | 1 |  | 0.4 | 308 | HS/Npt | Both | Whole Body | 49 to 84 | 800 | lifespan | All tumors |  |
| Iron | 26 | 600 |  | 1 |  | 0.4 | 314 |  |
| Gamma |  | 0.667 |  | 1 |  | 3 | 615 |  |
| (Watanabe et al., 1998)162 | Carbon | 6 | 290 |  | 1 | 40 | 0.462 | 60 | B6C3F1 | Both | Whole Body | 42 | 405 | timepoint | All tumors |  |
| X-ray |  | 0.25 |  | 1 | 10 | 0.5 | 60 |  |
| X-ray |  | 0.25 |  | 1 | 100 | 5 | 64 |  |
| (Weil et al., 2009)163 | Iron | 26 | 1000 | 150 | 1 |  | 0.1 | 293 | CBA/CaJ | Male | Whole Body | 56 to 98 | 800 | lifespan | Hepatocellular Carcinoma and Acute Myeloid Leukemia |  |
| Iron | 26 | 1000 | 150 | 1 |  | 0.2 | 286 |  |
| Iron | 26 | 1000 | 150 | 1 |  | 0.4 | 189 |  |
| Iron | 26 | 1000 | 150 | 1 |  | 1 | 192 |  |
| Gamma |  | 0.667 |  | 1 |  | 1 | 390 |  |
| Gamma |  | 0.667 |  | 1 |  | 2 | 275 |  |
| Gamma |  | 0.667 |  | 1 |  | 3 | 101 |  |
| (Weil et al., 2014)164 | Proton | 1 |  |  | 1 |  | 1 | 400 | C3H/HeNCrl | Male | Whole Body | 56 to 70 | 800 | lifespan | Hepatocellular Carcinoma and Acute Myeloid Leukemia |  |
| Proton | 1 |  |  | 1 |  | 2 | 300 |  |
| Silicon | 14 | 300 | 64 | 1 |  | 0.1 | 300 |  |
| Silicon | 14 | 300 | 64 | 1 |  | 0.2 | 300 |  |
| Silicon | 14 | 300 | 64 | 1 |  | 0.4 | 200 |  |
| Silicon | 14 | 300 | 64 | 1 |  | 1 | 200 |  |
| Iron | 26 | 600 | 181 | 1 |  | 0.1 | 300 |  |
| Iron | 26 | 600 | 181 | 1 |  | 0.2 | 300 |  |
| Iron | 26 | 600 | 181 | 1 |  | 0.4 | 200 |  |
| Iron | 26 | 600 | 181 | 1 |  | 1 | 200 |  |
| Gamma |  | 0.667 |  | 1 |  | 1 | 400 |  |
| Gamma |  | 0.667 |  | 1 |  | 2 | 300 |  |
| Gamma |  | 0.667 |  | 1 |  | 3 | 100 |  |
| (Bielefeldt-Ohmann et al., 2012)112 | Iron | 26 | 1000 | 150 | 1 |  | 0.2 | 99 | BALB/cByJ | Female | Whole Body | 84 | 800 | lifespan | Hepatocellular Carcinoma and Acute Myeloid Leukemia |  |
| Gamma |  | 0.667 |  | 1 |  | 0.5 | 100 |  |
| (Yamamoto et al., 2011)165 | Iron | 26 | 1000 | 148 | 1 | 100 | 1 | 47 | 129SvJ:C57BL/65 AtmΔSRI homozygous^ | Both | Whole body | 35 to 105 | 730 | lifespan | Hepatocellular Carcinoma, Lymphoma, and All tumors |  |
| Iron | 26 | 1000 | 148 | 1 | 100 | 1 | 100 | 129SvJ:C57BL/65 |  |
| Iron | 26 | 1000 | 148 | 1 | 100 | 1 | 152 | 129SvJ:C57BL/65 AtmΔSRI heterozygous^ |  |
| Iron | 26 | 1000 | 148 | 1 | 100 | 2 | 47 | 129SvJ:C57BL/65 AtmΔSRI homozygous^ |  |
| Iron | 26 | 1000 | 148 | 1 | 100 | 2 | 100 | 129SvJ:C57BL/65 |  |
| Iron | 26 | 1000 | 148 | 1 | 100 | 2 | 152 | 129SvJ:C57BL/65 AtmΔSRI heterozygous^ |  |
| (Alpen et al., 1993)166 | Hydrogen | 1 | 245 | 0 | 1 |  | 0.4 | 43 | B6CF1/Anl | Female | Head and Thorax | 100 to 120 | 590 | timepoint | Harderian gland | pituitary isographs |
| Hydrogen | 1 | 245 | 0 | 1 |  | 0.8 | 41 |
| Hydrogen | 1 | 245 | 0 | 1 |  | 1.6 | 43 |
| Hydrogen | 1 | 245 | 0 | 1 |  | 3.2 | 24 |
| Helium | 2 | 244 | 2 | 1 |  | 0.2 | 44 |
| Helium | 2 | 244 | 2 | 1 |  | 0.4 | 89 |
| Helium | 2 | 244 | 2 | 1 |  | 0.6 | 105 |
| Helium | 2 | 244 | 2 | 1 |  | 1.2 | 83 |
| Helium | 2 | 244 | 2 | 1 |  | 2.4 | 72 |
| Helium | 2 | 244 | 2 | 1 |  | 3.2 | 58 |
| Helium | 2 | 244 | 2 | 1 |  | 5.1 | 66 |
| Helium | 2 | 244 | 2 | 1 |  | 7 | 53 |
| Neon | 10 | 620 | 25 | 1 |  | 0.1 | 64 |
| Neon | 10 | 620 | 25 | 1 |  | 0.1 | 95 |
| Neon | 10 | 620 | 25 | 1 |  | 0.2 | 61 |
| Neon | 10 | 620 | 25 | 1 |  | 0.4 | 94 |
| Neon | 10 | 620 | 25 | 1 |  | 0.8 | 42 |
| Iron | 26 | 262 | 253 | 1 |  | 0.1 | 81 |
| Iron | 26 | 262 | 253 | 1 |  | 0.1 | 83 |
| Iron | 26 | 262 | 253 | 1 |  | 0.2 | 58 |
| Iron | 26 | 262 | 253 | 1 |  | 0.4 | 29 |
| Iron | 26 | 448 | 193 | 1 |  | 0.1 | 154 |
| Iron | 26 | 448 | 193 | 1 |  | 0.1 | 149 |
| Iron | 26 | 448 | 193 | 1 |  | 0.2 | 82 |
| Iron | 26 | 448 | 193 | 1 |  | 0.2 | 88 |
| Iron | 26 | 448 | 193 | 1 |  | 0.4 | 83 |
| Iron | 26 | 448 | 193 | 1 |  | 0.8 | 56 |
| Iron | 26 | 448 | 193 | 1 |  | 1.6 | 74 |
| Niobium | 41 | 484 | 464 | 1 |  | 0.1 | 71 |
| Niobium | 41 | 484 | 464 | 1 |  | 0.2 | 54 |
| Niobium | 41 | 484 | 464 | 1 |  | 0.4 | 48 |
| Niobium | 41 | 484 | 464 | 1 |  | 0.8 | 28 |
| Gamma |  | 1.17 | 0 | 1 |  | 0.4 | 229 |
| Gamma |  | 1.17 | 0 | 1 |  | 0.8 | 161 |
| Gamma |  | 1.17 | 0 | 1 |  | 1.6 | 117 |
| Gamma |  | 1.17 | 0 | 1 |  | 3.2 | 115 |
| Gamma |  | 1.17 | 0 | 1 |  | 7 | 52 |
| (Alpen et al., 1993)166 | Iron | 26 | 448 | 193 | 1 |  | 0.10 | 84 | B6CF1/Anl | Female | Head and Thorax | 100 to 120 | 590 | timepoint | Harderian gland |  |
| Iron | 26 | 448 | 193 | 1 |  | 0.20 | 48 |  |
| Iron | 26 | 448 | 193 | 1 |  | 0.40 | 59 |  |
| Iron | 26 | 448 | 193 | 1 |  | 0.80 | 48 |  |
| Iron | 26 | 448 | 193 | 1 |  | 1.60 | 33 |  |
| (Alpen et al., 1994)167 | Lanthanum | 57 | 426 | 953 | 1 |  | 0.20 | 26 | B6CF1/Anl | Female | Head and Thorax | 100 to 120 | 590 | timepoint | Harderian gland | pituitary isographs |
| Lanthanum | 57 | 426 | 953 | 1 |  | 0.40 | 38 |
| Lanthanum | 57 | 426 | 953 | 1 |  | 0.80 | 15 |
| (Chang et al., 2016)168 | Silicon | 14 | 296 | 70 | 1 |  | 0.04 | 141 | CB6F1/Hsd | Female | Whole Body | 100 to 120 | 590 | timepoint | Harderian gland |  |
| Silicon | 14 | 296 | 70 | 1 |  | 0.08 | 122 |  |
| Silicon | 14 | 296 | 70 | 1 |  | 0.16 | 97 |  |
| Silicon | 14 | 296 | 70 | 1 |  | 0.32 | 74 |  |
| Titanium | 22 | 936 | 107 | 1 |  | 0.03 | 134 |  |
| Titanium | 22 | 936 | 107 | 1 |  | 0.07 | 114 |  |
| Titanium | 22 | 936 | 107 | 1 |  | 0.13 | 110 |  |
| Titanium | 22 | 936 | 107 | 1 |  | 0.26 | 55 |  |
| Titanium | 22 | 936 | 107 | 1 |  | 0.52 | 62 |  |
| Titanium | 22 | 939 | 107 | 5 |  | 0.13 | 105 |  |
| Titanium | 22 | 939 | 107 | 5 |  | 0.26 | 109 |  |
| Iron | 26 | 559 | 175 | 1 |  | 0.1 | 78 |  |
| Iron | 26 | 559 | 175 | 1 |  | 0.2 | 47 |  |
| Iron | 26 | 559 | 175 | 1 |  | 0.4 | 41 |  |
| Gamma |  | 0.667 | 0 | 1 |  | 0.4 | 148 |  |
| Gamma |  | 0.667 | 0 | 1 |  | 0.8 | 90 |  |
| Gamma |  | 0.667 | 0 | 1 |  | 1.2 | 78 |  |
| Gamma |  | 0.667 | 0 | 1 |  | 1.6 | 84 |  |
| (Kennedy et al., 2008)169 | Proton | 1 | 1000 | 0 | 1 | 20 | 3 | 60 | CBA/JCR HSD | Male | Whole Body | 56 to 63 | 790 | lifespan | All tumors |  |
| Proton | 1 | 1000 | 0 | 1 | 20 | 3 | 60 | added BBIC\* diet |
| Proton | 1 | 1000 | 0 | 1 | 20 | 3 | 60 | added antioxidant diet |
| Iron | 26 | 1000 | 150 | 1 | 100 | 0.5 | 72 |  |
| Iron | 26 | 1000 | 150 | 1 | 100 | 0.5 | 72 | added BBIC\* diet |
| Iron | 26 | 1000 | 150 | 1 | 100 | 0.5 | 60 | added antioxidant diet |
| (Kennedy et al., 2011)170 | Proton | 1 | 1000 | 0 | 1 | 20 | 3 | 60 | CBA/JCR HSD | Male | Whole Body | 56 to 63 | 790 | lifespan | Harderian gland |  |
| Proton | 1 | 1000 | 0 | 1 | 20 | 3 | 60 | added BBIC\* diet |
| Proton | 1 | 1000 | 0 | 1 | 20 | 3 | 60 | added antioxidant diet |
| Iron | 26 | 1000 | 150 | 1 | 100 | 0.5 | 72 |  |
| Iron | 26 | 1000 | 150 | 1 | 100 | 0.5 | 72 | added BBIC\* diet |
| Iron | 26 | 1000 | 150 | 1 | 100 | 0.5 | 60 | added antioxidant diet |
| (Suman et al., 2017)171 | Silicon | 14 | 300 | 69 | 1 | 50 | 0.1 | 40 | APC^1638N/+ | Both | Whole Body | 42 to 56 | 200 | timepoint | Intestinal |  |
| Silicon | 14 | 300 | 69 | 1 | 0.33 | 0.1 | 40 |  |
| Silicon | 14 | 300 | 69 | 1 | 0.33 | 0.5 | 40 |  |
| Silicon | 14 | 300 | 69 | 1 | 50 | 0.5 | 40 |  |
| Iron | 26 | 1000 | 148 | 1 | 50 | 0.1 | 40 |  |
| Iron | 26 | 1000 | 148 | 1 | 0.33 | 0.1 | 40 |  |
| Iron | 26 | 1000 | 148 | 1 | 0.33 | 0.5 | 40 |  |
| Iron | 26 | 1000 | 148 | 1 | 50 | 0.5 | 40 |  |
| (Suman et al., 2016)172 | Carbon | 6 | 290 | 13 | 1 |  | 0.1 | 40 | APC^1638N/+ | Both | Whole Body | 42 to 56 | 200 | timepoint | Intestinal |  |
| Carbon | 6 | 290 | 13 | 1 |  | 0.5 | 40 |  |
| Carbon | 6 | 290 | 13 | 1 |  | 2 | 40 |  |
| Silicon | 14 | 300 | 69 | 1 |  | 0.1 | 40 |  |
| Silicon | 14 | 300 | 69 | 1 |  | 0.5 | 40 |  |
| Silicon | 14 | 300 | 69 | 1 |  | 1.4 | 40 |  |
| Iron | 26 | 1000 | 148 | 1 |  | 0.1 | 40 |  |
| Iron | 26 | 1000 | 148 | 1 |  | 0.5 | 40 |  |
| Iron | 26 | 1000 | 148 | 1 |  | 1.6 | 40 |  |
| Gamma |  | 0.667 | 0 | 1 |  | 0.1 | 40 |  |
| Gamma |  | 0.667 | 0 | 1 |  | 0.5 | 40 |  |
| Gamma |  | 0.667 | 0 | 1 |  | 2 | 40 |  |
| (Kim et al., 2016)173 | Proton | 1 | 50 |  | 1 | 20 | 2 |  | CDX2P APCflox/+ (CPC;Apc)15 | Both | Whole Body | 42 to 63 | 105 | timepoint | Intestinal |  |
| Proton | 1 | 50 |  | 1 | 20 | 2 |  | CDX2P APCflox/+ (CPC;Apc)15 | 155 | timepoint |  |
| Proton | 1 | 50 |  | 1 | 20 | 2 |  | CDX2P APCflox/+ (CPC;Apc)15 |  | lifespan |  |
| Proton | 1 | 50 |  | 1 | 20 | 2 |  | C57BL/6J |  | lifespan |  |
| Proton | 1 |  |  | 1 | 2 | 2 |  | C57BL/6J |  | lifespan |  |
| Proton | 1 |  |  | 1 | 2 | 2 |  | CDX2P APCflox/+ (CPC;Apc)15 |  | lifespan |  |
| Proton | 1 |  |  | 1 | 2 | 2 |  | CDX2P APCflox/+ (CPC;Apc)15 | 105 | timepoint |  |
| Proton | 1 |  |  | 1 | 2 | 2 |  | CDX2P APCflox/+ (CPC;Apc)15 | 155 | timepoint |  |
| Proton | 1 |  |  | 1 | 2 | 2 |  | CDX2P APCflox/+ (CPC;Apc)15 | 105 | timepoint | CDDO-EA\* diet 3 days pre-radiation |
| Proton | 1 |  |  | 1 | 2 | 2 |  | CDX2P APCflox/+ (CPC;Apc)15 | 155 | timepoint | CDDO-EA\* diet 3 days pre-radiation |
| Proton | 1 |  |  | 1 | 2 | 2 |  | CDX2P APCflox/+ (CPC;Apc)15 |  | lifespan | CDDO-EA\* diet 3 days pre-radiation |
| X-ray |  |  |  | 1 | 20 | 2 |  | CDX2P APCflox/+ (CPC;Apc)15 |  | lifespan |  |
| X-ray |  |  |  | 1 | 20 | 2 |  | CDX2P APCflox/+ (CPC;Apc)15 | 105 | timepoint |  |
| X-ray |  |  |  | 1 | 20 | 2 |  | CDX2P APCflox/+ (CPC;Apc)15 | 155 | timepoint |  |
| (X. Wang et al., 2015)174 | Oxygen | 8 | 600 | 17 | 1 | 75 | 1 | 40 | C57BL/6 | Both | Whole Body | 42 | 590 | lifespan | Lung |  |
| Oxygen | 8 | 600 | 17 | 5 | 75 | 1 | 40 |  |
| Silicon | 14 | 300 | 70 | 1 | 75 | 1 | 40 |  |
| Silicon | 14 | 300 | 70 | 5 | 75 | 1 | 40 |  |
| Iron | 26 | 600 | 175 | 1 | 75 | 1 | 40 |  |
| Iron | 26 | 600 | 175 | 5 | 75 | 1 | 40 |  |
| X-ray |  | 0.32 |  | 1 | 75 | 1 | 40 |  |
| X-ray |  | 0.32 |  | 5 | 75 | 1 | 40 |  |
| (J. Wang et al., 2016)175 | Oxygen | 8 | 600 | 17 | 1 | 75 | 1 | 40 | C57BL/6 Gprc5a-/- | Both | Whole Body | 42 | 590 | timepoint | Lung | . |
| Oxygen | 8 | 600 | 17 | 5 | 75 | 1 | 40 | C57BL/6 Gprc5a-/- | . |
| Silicon | 14 | 300 | 70 | 1 | 75 | 1 | 40 | C57BL/6 Gprc5a-/- | . |
| Silicon | 14 | 300 | 70 | 5 | 75 | 1 | 40 | C57BL/6 Gprc5a-/- | . |
| Iron | 26 | 600 | 175 | 1 | 75 | 1 | 40 | C57BL/6 miR-21 knock-in | . |
| Iron | 26 | 600 | 175 | 1 | 75 | 1 | 40 | C57BL/6 Gprc5a-/- | . |
| Iron | 26 | 600 | 175 | 1 | 75 | 1 | 40 | C57BL/6 miR-21 knock-in/Gprc5a-/- | . |
| Iron | 26 | 600 | 175 | 1 | 75 | 1 | 40 | C57BL/6 miR-21-/- | . |
| Iron | 26 | 600 | 175 | 5 | 75 | 1 | 40 | C57BL/6 miR-21-/- | . |
| Iron | 26 | 600 | 175 | 5 | 75 | 1 | 40 | C57BL/6 miR-21 knock-in | . |
| Iron | 26 | 600 | 175 | 5 | 75 | 1 | 40 | C57BL/6 Gprc5a-/- | . |
| Iron | 26 | 600 | 175 | 5 | 75 | 1 | 40 | C57BL/6 miR-21 knock-in/Gprc5a-/- | . |
| X-ray |  | 0.32 |  | 1 | 75 | 1 | 40 | C57BL/6 Gprc5a-/- | . |
| X-ray |  | 0.32 |  | 1 | 75 | 1 | 40 | C57BL/6 miR-21-/- | . |
| X-ray |  | 0.32 |  | 1 | 75 | 1 | 40 | C57BL/6 miR-21 knock-in/Gprc5a-/- | . |
| X-ray |  | 0.32 |  | 1 | 75 | 1 | 40 | C57BL/6 miR-21 knock-in | . |
| X-ray |  | 0.32 |  | 5 | 75 | 1 | 40 | C57BL/6 Gprc5a-/- | . |
| X-ray |  | 0.32 |  | 5 | 75 | 1 | 40 | mC57BL/6 iR-21 knock-in | . |
| X-ray |  | 0.32 |  | 5 | 75 | 1 | 40 | C57BL/6 miR-21 knock-in/Gprc5a-/- | . |
| X-ray |  | 0.32 |  | 5 | 75 | 1 | 40 | C57BL/6 miR-21-/- | . |
| (Asselin-Labat et al., 2017)176 | Silicon | 14 | 300 |  | 1 | 20 | 0.1 | 58 | Scgb1a1-creER/K-RasLSL-G12D/þ | Unknown | Whole Body | 70 to 112 | 150 | timepoint | Lung | Injected with tamoxifen 4 weeks before irradiation |
| Iron | 26 | 600 |  | 1 | 20 | 0.1 | 72 |
| Iron | 26 | 600 |  | 5 | 20 | 1 | 49 |
| X-ray |  | 0.32 |  | 5 | 20 | 2 | 10 |
| X-ray |  | 0.32 |  | 5 | 20 | 6 | 6 |
| (Moding et al., 2016)177 | Iron | 26 | 600 |  | 5 | 20 | 1 | 53 | LA-1 KrasG12D with wild-type p53 | Both | Whole Body | 42 to 84 | 250 | lifespan | Lung |  |
| Iron | 26 | 600 |  | 5 | 20 | 1 | 40 | LA-1 KrasG12D with an extra copy of p53 |  |
| X-ray |  | 0.32 |  | 1 | 200 | 6 | 12 | LA-1 KrasG12D with an extra copy of p53 |  |
| X-ray |  | 0.32 |  | 1 | 200 | 6 | 11 | LA-1 KrasG12D with wild-type p53 |  |
| X-ray |  | 0.32 |  | 5 | 200 | 6 | 42 | LA-1 KrasG12D with wild-type p53 |  |
| X-ray |  | 0.32 |  | 5 | 200 | 6 | 42 | LA-1 KrasG12D with an extra copy of p53 |  |
| (Delgado et al., 2014)178 | Iron | 26 | 1000 |  | 1 | 20 | 0.1 |  | K-rasLA1 | Both | Whole Body | 35 to 105 |  | lifespan | Lung |  |
| Iron | 26 | 1000 |  | 1 | 20 | 0.2 |  |  |  |
| Iron | 26 | 1000 |  | 5 | 20 | 0.2 |  |  |  |
| Iron | 26 | 1000 |  | 5 | 20 | 1 |  |  |  |
| X-ray |  | 0.25 |  | 1 | 14 | 1 |  |  |  |
| X-ray |  | 0.25 |  | 5 | 14 | 1 |  |  |  |
| X-ray |  | 0.25 |  | 5 | 14 | 2 |  |  |  |
| (Luitel et al., 2018)179 | Proton | 1 | 50 |  | 1 | 20 | 2 |  | K-rasLA1 | Both | Whole Body | 56 to 105 |  | lifespan | Lung |  |
| Proton | 1 | 50 |  | 1 | 20 | 2 |  | 180 | timepoint |  |
| Proton | 1 | 150 |  | 1 | 20 | 2 |  |  | lifespan |  |
| Proton | 1 | 150 |  | 1 | 20 | 2 |  | 180 | timepoint |  |
| X-ray |  |  |  | 1 | 20 | 2 |  |  | lifespan |  |
| X-ray |  |  |  | 1 | 20 | 2 |  | 180 | timepoint |  |
| (Patel et al., 2019)180 | Iron | 26 | 600 |  | 1 | 5 | 0.1 | 40 | B6.129-Mlh1tm1Rak Mlh1+/+ | Both | Whole Body | 84 |  | lifespan | Lymphoma |  |
| Iron | 26 | 600 |  | 1 | 5 | 0.1 | 40 | B6.129-Mlh1tm1Rak Mlh1+/- |  |  |
| Iron | 26 | 600 |  | 1 | 50 | 1 | 40 | B6.129-Mlh1tm1Rak Mlh1+/+ |  |  |
| Iron | 26 | 600 |  | 1 | 50 | 1 | 40 | B6.129-Mlh1tm1Rak Mlh1+/- |  |  |
| Gamma |  | 0.667 |  | 1 | 220 | 1 | 40 | B6.129-Mlh1tm1Rak Mlh1+/- |  |  |
| Gamma |  | 0.667 |  | 1 | 220 | 1 | 40 | B6.129-Mlh1tm1Rak Mlh1+/+ |  |  |
| Gamma |  | 0.667 |  | 1 | 220 | 2.5 | 40 | B6.129-Mlh1tm1Rak Mlh1+/+ |  |  |
| Gamma |  | 0.667 |  | 1 | 220 | 2.5 | 40 | B6.129-Mlh1tm1Rak Mlh1+/- |  |  |
| (Imaoka et al., 2007)181 | Carbon | 6 | 290 | 40 to 90 | 1 |  | 0.05 to 2 |  | Sprague-Dawley | Female | Whole Body | 49 to 56 | 414 to 421 | lifespan | Mammary |  |
| Carbon | 6 | 290 | 40 to 90 | 1 |  | 0.05 to 2 |  | ACI |  |
| Carbon | 6 | 290 | 40 to 90 | 1 |  | 0.05 to 2 |  | F344 |  |
| Carbon | 6 | 290 | 40 to 90 | 1 |  | 0.05 to 2 |  | Wistar |  |
| Gamma |  | 0.667 |  | 1 |  | 0.05 to 2 |  | Sprague-Dawley |  |
| Gamma |  | 0.667 |  | 1 |  | 0.05 to 2 |  | ACI |  |
| Gamma |  | 0.667 |  | 1 |  | 0.05 to 2 |  | F344 |  |
| Gamma |  | 0.667 |  | 1 |  | 0.05 to 2 |  | Wistar |  |
| (Imaoka et al., 2013)182 | Carbon | 6 | 250 | 13 | 1 |  | 0.2 to 2 |  | Sprague-Dawley | Female | Whole Body | 7 | 630 | lifespan | Mammary |  |
| Carbon | 6 | 250 | 13 | 1 |  | 0.2 to 2 |  | 21 |  |
| Carbon | 6 | 250 | 13 | 1 |  | 0.2 to 2 |  | 49 |  |
| Carbon | 6 | 250 | 13 | 1 |  | 0.2 to 2 |  | 105 |  |
| Gamma |  | 0.667 |  | 1 |  | 0.2 to 2 |  | 7 |  |
| Gamma |  | 0.667 |  | 1 |  | 0.2 to 2 |  | 21 |  |
| Gamma |  | 0.667 |  | 1 |  | 0.2 to 2 |  | 49 |  |
| Gamma |  | 0.667 |  | 1 |  | 0.2 to 2 |  | 105 |  |
| (Dicello et al., 2004)183 | Proton | 1 | 250 |  | 1 | 75 | 0.5 | 36 | Sprague-Dawley | Female | Whole Body | 60 |  | lifespan | Mammary |  |
| Proton | 1 | 250 |  | 1 | 75 | 1.6 | 36 |  |
| Proton | 1 | 250 |  | 1 | 75 | 5 | 36 |  |
| Iron | 26 | 1000 |  | 1 | 50 | 0.05 | 70 |  |
| Iron | 26 | 1000 |  | 1 | 50 | 0.16 | 71 |  |
| Iron | 26 | 1000 |  | 1 | 50 | 0.5 | 69 |  |
| Iron | 26 | 1000 |  | 1 | 50 | 2 | 18 |  |
| Gamma |  | 0.667 |  | 1 |  | 0.5 | 54 |  |
| Gamma |  | 0.667 |  | 1 |  | 1.6 | 53 |  |
| Gamma |  | 0.667 |  | 1 |  | 5 | 66 |  |
| Gamma |  | 1.17 |  | 1 |  | 0.5 | 18 |  |
| Gamma |  | 1.17 |  | 1 |  | 1.6 | 18 |  |
| Gamma |  | 1.17 |  | 1 |  | 5 | 18 |  |
| (Illa-Bochaca et al., 2014)184 | Silicon | 14 | 350 | 64 | 1 |  | 0.11 | 14 | BALB/c | Female | Whole Body | 70 | 600 | lifespan | Mammary | transplanted with syngeneic Trp53 null mammary fragments 3 days after irradiation |
| Silicon | 14 | 350 | 64 | 1 |  | 0.3 | 12 |
| Silicon | 14 | 350 | 64 | 1 |  | 0.81 | 9 |
| Gamma |  | 0.667 |  | 1 |  | 1 | 12 |
| (Mishra et al., 2018)185 | Iron | 26 | 600 | 179 | 1 |  | 0.5 | 15 | C57BL/6J | Female | Whole Body | 84 | 534 | lifespan | Ovary |  |
| (Fredric J. Burns et al., 1991)186 | Neon | 10 |  | 45 | 1 |  | 2 |  |  |  | 6.0 cm2 of skin | NA |  | lifespan | Skin |  |
| Neon | 10 |  | 45 | 1 |  | 2.8 |  |  |
| Neon | 10 |  | 45 | 1 |  | 4 |  |  |
| Neon | 10 |  | 45 | 1 |  | 5.6 |  |  |
| Neon | 10 |  | 45 | 1 |  | 6 |  |  |
| Neon | 10 |  | 45 | 1 |  | 11.3 |  |  |
| Neon | 10 |  | 45 | 1 |  | 16 |  |  |
| Argon | 18 |  | 125 | 1 |  | 0.5 |  |  |
| Argon | 18 |  | 125 | 1 |  | 1.6 |  |  |
| Argon | 18 |  | 125 | 1 |  | 2.9 |  |  |
| Argon | 18 |  | 125 | 1 |  | 4.8 |  |  |
| Argon | 18 |  | 125 | 1 |  | 6.3 |  |  |
| Argon | 18 |  | 125 | 1 |  | 9.5 |  |  |
| Electron |  |  | 0.34 | 1 |  | 5 |  |  |
| Electron |  |  | 0.34 | 1 |  | 7 |  |  |
| Electron |  |  | 0.34 | 1 |  | 9.8 |  |  |
| Electron |  |  | 0.34 | 1 |  | 13.7 |  |  |
| Electron |  |  | 0.34 | 1 |  | 19.2 |  |  |
| Electron |  |  | 0.34 | 1 |  | 26.9 |  |  |
| (Fredric J. Burns et al., 1993)187 | Argon | 18 | 640 |  | 1 |  | 0.5 |  | Sprague-Dawley | Male | 8.0 cm2 of skin | 28 |  | lifespan | Skin |  |
| Argon | 18 | 640 |  | 1 |  | 1.6 |  | 8.0 cm2 of skin | 28 |  |
| Argon | 18 | 640 |  | 1 |  | 3.2 |  | 8.0 cm2 of skin | 28 |  |
| Argon | 18 | 640 |  | 1 |  | 4.8 |  | 8.0 cm2 of skin | 28 |  |
| Argon | 18 | 640 |  | 1 |  | 5 |  | 8.0 cm2 of skin | 28 |  |
| Argon | 18 | 640 |  | 1 |  | 6.3 |  | 8.0 cm2 of skin | 28 |  |
| Argon | 18 | 640 |  | 1 |  | 9 |  | 8.0 cm2 of skin | 28 |  |
| Electron |  | 0.8 |  | 1 |  | 8 |  | 24.0 cm2 of skin | 182 |  |
| Electron |  | 0.8 |  | 1 |  | 8 |  | 24.0 cm2 of skin | 113 |  |
| Electron |  | 0.8 |  | 1 |  | 8 |  | 24.0 cm2 of skin | 28 |  |
| Electron |  | 0.8 |  | 1 |  | 12 |  | 24.0 cm2 of skin | 28 |  |
| Electron |  | 0.8 |  | 1 |  | 12 |  | 24.0 cm2 of skin | 182 |  |
| Electron |  | 0.8 |  | 1 |  | 12 |  | 24.0 cm2 of skin | 113 |  |
| Electron |  | 0.8 |  | 1 |  | 16 |  | 24.0 cm2 of skin | 182 |  |
| Electron |  | 0.8 |  | 1 |  | 16 |  | 24.0 cm2 of skin | 113 |  |
| Electron |  | 0.8 |  | 1 |  | 16 |  | 24.0 cm2 of skin | 28 |  |
| Electron |  | 0.8 |  | 1 |  | 19.5 |  | 24.0 cm2 of skin | 28 |  |
| Electron |  | 0.8 |  | 3 |  | 19.5 |  | 24.0 cm2 of skin | 28 |  |
| Electron |  | 0.8 |  | 5 |  | 19.5 |  | 24.0 cm2 of skin | 28 |  |
| Electron |  | 1.8 |  | 1 | 500 | 5 |  | 8.0 cm2 of skin | 28 |  |
| Electron |  | 1.8 |  | 1 | 500 | 7 |  | 8.0 cm2 of skin | 28 |  |
| Electron |  | 1.8 |  | 1 | 500 | 9.8 |  | 8.0 cm2 of skin | 28 |  |
| Electron |  | 1.8 |  | 1 | 500 | 13.7 |  | 8.0 cm2 of skin | 28 |  |
| Electron |  | 1.8 |  | 1 | 500 | 19.2 |  | 8.0 cm2 of skin | 28 |  |
| Electron |  | 1.8 |  | 1 | 500 | 26.9 |  | 8.0 cm2 of skin | 28 |  |
| (F. J. Burns et al., 1994)188 | Neon | 10 |  | 45 | 1 |  | 2 |  |  |  | 6.0 cm2 of skin | NA |  | lifespan | Skin |  |
| Neon | 10 |  | 45 | 1 |  | 2.8 |  |  |
| Neon | 10 |  | 45 | 1 |  | 4 |  |  |
| Neon | 10 |  | 45 | 1 |  | 5.6 |  |  |
| Neon | 10 |  | 45 | 1 |  | 6 |  |  |
| Neon | 10 |  | 45 | 1 |  | 11.3 |  |  |
| Neon | 10 |  | 45 | 1 |  | 16 |  |  |
| Argon | 18 |  | 125 | 1 |  | 0.5 |  |  |
| Argon | 18 |  | 125 | 1 |  | 1.6 |  |  |
| Argon | 18 |  | 125 | 1 |  | 2.9 |  |  |
| Argon | 18 |  | 125 | 1 |  | 4.8 |  |  |
| Argon | 18 |  | 125 | 1 |  | 6.3 |  |  |
| Argon | 18 |  | 125 | 1 |  | 9.5 |  |  |
| Electron |  |  | 0.34 | 1 |  | 5 |  |  |
| Electron |  |  | 0.34 | 1 |  | 7 |  |  |
| Electron |  |  | 0.34 | 1 |  | 9.8 |  |  |
| Electron |  |  | 0.34 | 1 |  | 13.7 |  |  |
| Electron |  |  | 0.34 | 1 |  | 19.2 |  |  |
| Electron |  |  | 0.34 | 1 |  | 26.9 |  |  |
| (Ando et al., 2005)189 | Carbon | 6 |  |  | 1 | 300 | 65 |  | C3H/HeMsNrsf | Both | Right hind leg | 84 to 126 |  | lifespan | Hind leg | Many doses and fractionation schema combined |
| Gamma |  | 0.667 |  | 1 | 160 | 95 |  | Both |

# Appendix Z: Table identifying the single value representing each ion and energy combination

| Upper limit of energy bins (MeV/u) | Protons, Deuterium, Tritium (Z=1;  A=1, 2, 3) | Helium (Z=2;  A=3, 4) | Lithium (Z=3;  A=6, 7) | Beryllium (Z=4;  A=8, 9) | Boron (Z=5;  A=10, 11) | Carbon (Z=6;  A=12, 13) | Nitrogen (Z=7;  A=14, 15) | Oxygen (Z=8;  A=16, 17) | Fluorine (Z=9;  A=18, 19) | Neon (Z=10;  A=20, 21, 22) | Sodium (Z=11; A=23) | Magnesium (Z=12;  A=24, 25, 26) | Aluminium (Z=13; A=27) | Silicon (Z=14; A=28) |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 0.01 | 9002.92 | 17412.32 | 24761.4 | 31425.29 | 37600.42 | 43403 | 48908.49 | 54169.23 | 59223.37 | 64099.79 | 68820.98 | 73404.9 | 77866.17 | 82216.9 |
| 0.014081 | 8172.54 | 16339.64 | 23569.4 | 30159.73 | 36284.05 | 42048.99 | 47525.24 | 52762.48 | 57797.24 | 62657.33 | 67364.54 | 71936.34 | 76386.97 | 80728.27 |
| 0.019828 | 7303.98 | 15167.22 | 22242.06 | 28735.33 | 34791.92 | 40506.35 | 45943.16 | 51148.58 | 56157 | 60994.86 | 65683.01 | 70238.23 | 74674.3 | 79002.67 |
| 0.02781 | 6424.64 | 13919.11 | 20798.27 | 27166.59 | 33134.98 | 38783.09 | 44167.83 | 49331.03 | 54304.4 | 59112.58 | 63775.2 | 68308.19 | 72724.67 | 77035.65 |
| 0.038755 | 5561.44 | 12622.72 | 19261.44 | 25472.82 | 31328.94 | 36891.87 | 42209.27 | 47317.61 | 52245.21 | 57014.51 | 61643.6 | 66147.3 | 70537.95 | 74825.91 |
| 0.053325 | 4750.85 | 11327.56 | 17683.54 | 23705.84 | 29424.65 | 34882.32 | 40115.86 | 45155.46 | 50025.46 | 54745.64 | 59332.22 | 63798.69 | 68156.4 | 72414.97 |
| 0.072012 | 4023.1 | 10085.85 | 16125.5 | 21930.55 | 27488.99 | 32822.31 | 37955.96 | 42913.15 | 47713.72 | 52374.42 | 56909.35 | 61330.45 | 65647.91 | 69870.48 |
| 0.095042 | 3395.07 | 8939.85 | 14642.56 | 20209.66 | 25589.37 | 30782.41 | 35802.36 | 40665.08 | 45385.62 | 49977.44 | 54452.33 | 58820.51 | 63090.89 | 67271.24 |
| 0.122257 | 2870.85 | 7917.78 | 13278.15 | 18596.48 | 23785.95 | 28827.83 | 33724.11 | 38483.33 | 43115.68 | 47631.25 | 52039.37 | 56348.51 | 60566.2 | 64699.19 |
| 0.153549 | 2439.11 | 7020.74 | 12043.32 | 17109.11 | 22101.98 | 26985.64 | 31751.26 | 36400.34 | 40938.29 | 45371.81 | 49707.82 | 53952.95 | 58113.36 | 62194.7 |
| 0.188764 | 2085.5 | 6240.6 | 10936.92 | 15751.9 | 20545.99 | 25267.68 | 29898.29 | 34432.71 | 38871.79 | 43218.99 | 47478.8 | 51656.06 | 55755.53 | 59781.78 |
| 0.227671 | 1796.38 | 5566.1 | 9952.6 | 14522.83 | 19119.52 | 23678.39 | 28172.01 | 32589.25 | 36926.7 | 41184.71 | 45365.48 | 49472.08 | 53507.93 | 57476.5 |
| 0.271437 | 1552.68 | 4967.07 | 9053.93 | 13381.05 | 17778.29 | 22170.6 | 26522.78 | 30818.16 | 35049.3 | 39213.57 | 43310.91 | 47342.68 | 51310.92 | 55218.05 |
| 0.319916 | 1348.54 | 4440.07 | 8241.78 | 12331.44 | 16530.46 | 20755.21 | 24963.79 | 29134.53 | 33256.29 | 37323.63 | 41334.36 | 45288.15 | 49185.73 | 53028.46 |
| 0.373716 | 1175.69 | 3972.94 | 7502.96 | 11360.43 | 15362.32 | 19418.37 | 23481.03 | 27524.2 | 31533.34 | 35500.38 | 39421.11 | 43293.57 | 47117.22 | 50892.4 |
| 0.433654 | 1027.82 | 3555.82 | 6826.37 | 10456.36 | 14261.82 | 18147.69 | 22061.77 | 25974.08 | 29866.99 | 33730.01 | 37556.98 | 41344.42 | 45090.55 | 48794.66 |
| 0.500671 | 900.3 | 3181.42 | 6203.92 | 9610.87 | 13220.4 | 16934.43 | 20697.04 | 24474.94 | 28247.74 | 32002.71 | 35731.87 | 39430.29 | 43094.96 | 46724.2 |
| 0.575455 | 790.18 | 2845.77 | 5632.34 | 8821.72 | 12236.81 | 15778.16 | 19387.1 | 23027.59 | 26676.82 | 30320.04 | 33947.6 | 37553.17 | 41132.62 | 44683.29 |
| 0.659489 | 694.19 | 2542.86 | 5104.28 | 8080.76 | 11302.28 | 14669.51 | 18121.97 | 21621.43 | 25143.02 | 28670.2 | 32191.77 | 35700.1 | 39189.96 | 42657.8 |
| 0.753842 | 610.49 | 2270.06 | 4617.73 | 7386.97 | 10416.74 | 13609.24 | 16903.08 | 20258.45 | 23648.76 | 27055.92 | 30467.34 | 33874.21 | 37270.27 | 40651.09 |
| 0.859868 | 537.35 | 2024.55 | 4170.05 | 6738.33 | 9578.84 | 12596.6 | 15730.19 | 18938.76 | 22194.44 | 25477.79 | 28775.05 | 32076.29 | 35374.35 | 38663.95 |
| 0.979108 | 473.34 | 1803.8 | 3758.83 | 6133.02 | 8787.48 | 11631.15 | 14603.39 | 17662.92 | 20780.93 | 23936.96 | 27116.19 | 30307.78 | 33503.69 | 36697.9 |
| 1.111958 | 417.73 | 1607.34 | 3385.31 | 5574.62 | 8048.66 | 10721.21 | 13533.19 | 16443.38 | 19422.46 | 22449.21 | 25508 | 28587.18 | 31677.95 | 34773.63 |
| 1.262183 | 368.64 | 1430.16 | 3041.83 | 5053.27 | 7350.63 | 9853.3 | 12504.42 | 15263.4 | 18100.79 | 20994.86 | 23929.37 | 26892.02 | 29873.36 | 32866.11 |
| 1.43026 | 325.75 | 1272.36 | 2730.24 | 4573.26 | 6700.31 | 9036.96 | 11529.14 | 14137.36 | 16832.4 | 19592.34 | 22400.51 | 25244.11 | 28113.2 | 30999.96 |
| 1.619384 | 287.99 | 1131.2 | 2446.66 | 4130.09 | 6092.88 | 8267.15 | 10602.15 | 13059.91 | 15611.77 | 18235.91 | 20915.45 | 23637.25 | 26390.96 | 29168.38 |
| 1.831895 | 254.79 | 1005.31 | 2189.67 | 3722.88 | 5528.32 | 7544.86 | 9725.43 | 12033.97 | 14442.75 | 16930.23 | 19479.58 | 22077.47 | 24713.29 | 27378.51 |
| 2.070313 | 225.61 | 893.33 | 1957.71 | 3350.44 | 5006.15 | 6870.52 | 8900.39 | 11061.94 | 13328.61 | 15679.45 | 18097.84 | 20570.43 | 23086.49 | 25637.25 |
| 2.337882 | 199.91 | 793.78 | 1748.72 | 3010.68 | 4524.62 | 6242.88 | 8126.41 | 10143.83 | 12270.03 | 14484.86 | 16772.08 | 19118.51 | 21513.38 | 23947.84 |
| 2.638686 | 177.23 | 705.21 | 1560.55 | 2701.13 | 4081.31 | 5659.82 | 7401.75 | 9278.37 | 11266.2 | 13346.09 | 15502.36 | 17722.13 | 19994.76 | 22311.38 |
| 2.976327 | 157.22 | 626.59 | 1391.74 | 2420.39 | 3675.21 | 5120.96 | 6726.85 | 8466.87 | 10319.33 | 12266.25 | 14292.67 | 16386.13 | 18536.22 | 20734.18 |
| 3.354537 | 139.59 | 556.95 | 1240.85 | 2166.9 | 3305.06 | 4625.61 | 6101.74 | 7710.19 | 9431.19 | 11248.01 | 13146.55 | 15114.91 | 17143.01 | 19222.32 |
| 3.779 | 123.99 | 495.15 | 1105.88 | 1938.11 | 2967.99 | 4170.83 | 5523.6 | 7005.77 | 8599.51 | 10289.46 | 12062.48 | 13907.33 | 15814.36 | 17775.33 |
| 4.255003 | 110.21 | 440.35 | 985.42 | 1732.22 | 2662.14 | 3754.98 | 4991.18 | 6352.88 | 7824.18 | 9391.17 | 11041.73 | 12765.36 | 14552.94 | 16396.59 |
| 4.788643 | 98.01 | 391.77 | 878.04 | 1547.35 | 2385.43 | 3375.97 | 4502.63 | 5750.04 | 7104.22 | 8552.69 | 10084.44 | 11689.75 | 13360.12 | 15088.08 |
| 5.386816 | 87.21 | 348.7 | 782.39 | 1381.66 | 2135.7 | 3031.58 | 4055.81 | 5195.37 | 6438.11 | 7772.99 | 9190.09 | 10680.55 | 12236.51 | 13850.99 |
| 6.057149 | 77.64 | 310.49 | 697.27 | 1233.39 | 1910.86 | 2719.54 | 3648.5 | 4686.83 | 5824.11 | 7050.71 | 8357.8 | 9737.39 | 11182.3 | 12686.08 |
| 6.808107 | 69.16 | 276.61 | 621.55 | 1100.92 | 1708.86 | 2437.6 | 3278.37 | 4222.17 | 5260.21 | 6384.16 | 7586.28 | 8859.44 | 10197.16 | 11593.55 |
| 7.649509 | 61.64 | 246.53 | 554.21 | 982.64 | 1527.66 | 2183.36 | 2942.84 | 3798.8 | 4743.89 | 5771.03 | 6873.49 | 8045.01 | 9279.8 | 10572.54 |
| 8.591997 | 54.96 | 219.82 | 494.33 | 877.16 | 1365.37 | 1954.61 | 2639.52 | 3414.23 | 4272.72 | 5209.02 | 6217.39 | 7292.37 | 8428.88 | 9622.14 |
| 9.64756 | 49.03 | 196.11 | 441.08 | 783.13 | 1220.23 | 1749.2 | 2365.94 | 3065.85 | 3844.03 | 4695.54 | 5615.53 | 6599.32 | 7642.46 | 8740.78 |
| 10.82961 | 43.76 | 175.03 | 393.74 | 699.36 | 1090.55 | 1565.02 | 2119.71 | 2751.04 | 3455.09 | 4227.84 | 5065.23 | 5963.31 | 6918.26 | 7926.42 |
| 12.15322 | 39.07 | 156.3 | 351.63 | 624.75 | 974.78 | 1400.11 | 1898.49 | 2467.17 | 3103.1 | 3803.01 | 4563.59 | 5381.53 | 6253.57 | 7176.59 |
| 13.63491 | 34.91 | 139.64 | 314.17 | 558.32 | 871.5 | 1252.63 | 1700.08 | 2211.77 | 2785.35 | 3418.23 | 4107.72 | 4851.08 | 5645.61 | 6488.62 |
| 15.29532 | 31.2 | 124.81 | 280.81 | 499.1 | 779.32 | 1120.73 | 1522.18 | 1982.14 | 2498.81 | 3070.17 | 3694.08 | 4368.32 | 5090.63 | 5858.79 |
| 17.15376 | 27.9 | 111.61 | 251.13 | 446.39 | 697.17 | 1002.99 | 1363.04 | 1776.22 | 2241.19 | 2756.39 | 3320.14 | 3930.65 | 4586.09 | 5284.62 |
| 19.23466 | 24.97 | 99.87 | 224.7 | 399.43 | 623.93 | 897.88 | 1220.74 | 1591.73 | 2009.85 | 2473.93 | 2982.67 | 3534.65 | 4128.41 | 4762.45 |
| 21.5643 | 22.35 | 89.4 | 201.16 | 357.6 | 558.64 | 804.1 | 1093.61 | 1426.62 | 1802.41 | 2220.12 | 2678.74 | 3177.2 | 3714.31 | 4288.87 |
| 24.17442 | 20.02 | 80.08 | 180.17 | 320.3 | 500.41 | 720.39 | 980 | 1278.87 | 1616.49 | 1992.22 | 2405.31 | 2854.94 | 3340.19 | 3860.1 |
| 27.0974 | 17.94 | 71.77 | 161.47 | 287.06 | 448.5 | 645.73 | 878.58 | 1146.83 | 1450.1 | 1787.94 | 2159.82 | 2565.08 | 3003.05 | 3472.96 |
| 30.37216 | 16.09 | 64.36 | 144.8 | 257.42 | 402.2 | 579.1 | 788.03 | 1028.83 | 1301.25 | 1604.97 | 1939.6 | 2304.67 | 2699.65 | 3123.97 |
| 34.0407 | 14.44 | 57.75 | 129.93 | 230.99 | 360.91 | 519.67 | 707.22 | 923.45 | 1168.2 | 1441.25 | 1742.32 | 2071.07 | 2427.1 | 2809.98 |
| 38.15234 | 12.96 | 51.85 | 116.66 | 207.4 | 324.06 | 466.63 | 635.07 | 829.33 | 1049.29 | 1294.8 | 1565.68 | 1861.67 | 2182.49 | 2527.81 |
| 42.76254 | 11.65 | 46.59 | 104.82 | 186.35 | 291.18 | 419.28 | 570.66 | 745.26 | 943.02 | 1163.84 | 1407.59 | 1674.1 | 1963.15 | 2274.51 |
| 47.93135 | 10.47 | 41.89 | 94.26 | 167.57 | 261.83 | 377.03 | 513.16 | 670.2 | 848.11 | 1046.82 | 1266.24 | 1506.25 | 1766.72 | 2047.45 |
| 53.73154 | 9.43 | 37.7 | 84.83 | 150.8 | 235.63 | 339.3 | 461.82 | 603.16 | 763.31 | 942.22 | 1139.83 | 1356.07 | 1590.82 | 1843.98 |
| 60.23854 | 8.49 | 33.96 | 76.41 | 135.83 | 212.24 | 305.62 | 415.98 | 543.31 | 687.59 | 848.79 | 1026.89 | 1221.82 | 1433.52 | 1661.9 |
| 67.55091 | 7.65 | 30.61 | 68.88 | 122.46 | 191.34 | 275.53 | 375.02 | 489.81 | 619.9 | 765.26 | 925.88 | 1101.71 | 1292.72 | 1498.84 |
| 75.76738 | 6.91 | 27.63 | 62.16 | 110.51 | 172.67 | 248.65 | 338.44 | 442.03 | 559.44 | 690.64 | 835.62 | 994.36 | 1166.83 | 1352.99 |
| 85.0071 | 6.24 | 24.96 | 56.16 | 99.84 | 156 | 224.63 | 305.75 | 399.35 | 505.42 | 623.96 | 754.96 | 898.41 | 1054.29 | 1222.57 |
| 95.4071 | 5.64 | 22.58 | 50.8 | 90.3 | 141.1 | 203.18 | 276.55 | 361.21 | 457.15 | 564.38 | 682.88 | 812.65 | 953.68 | 1105.95 |
| 107.1423 | 5.11 | 20.44 | 46 | 81.77 | 127.77 | 183.98 | 250.42 | 327.08 | 413.96 | 511.05 | 618.37 | 735.89 | 863.62 | 1001.53 |
| 120.3541 | 4.64 | 18.54 | 41.72 | 74.16 | 115.88 | 166.86 | 227.12 | 296.64 | 375.43 | 463.5 | 560.83 | 667.42 | 783.27 | 908.38 |
| 135.2905 | 4.21 | 16.84 | 37.89 | 67.35 | 105.24 | 151.54 | 206.27 | 269.41 | 340.97 | 420.95 | 509.35 | 606.16 | 711.39 | 825.02 |
| 152.1613 | 3.83 | 15.32 | 34.47 | 61.28 | 95.74 | 137.87 | 187.66 | 245.11 | 310.21 | 382.98 | 463.4 | 551.48 | 647.22 | 750.61 |
| 171.3748 | 3.49 | 13.96 | 31.4 | 55.82 | 87.22 | 125.6 | 170.95 | 223.28 | 282.59 | 348.88 | 422.14 | 502.38 | 589.6 | 683.79 |
| 193.0143 | 3.19 | 12.75 | 28.68 | 50.98 | 79.66 | 114.71 | 156.14 | 203.94 | 258.11 | 318.65 | 385.57 | 458.86 | 538.52 | 624.55 |
| 217.8676 | 2.91 | 11.66 | 26.23 | 46.62 | 72.85 | 104.9 | 142.78 | 186.49 | 236.03 | 291.39 | 352.59 | 419.61 | 492.45 | 571.13 |
| 246.1532 | 2.67 | 10.69 | 24.04 | 42.74 | 66.78 | 96.17 | 130.89 | 170.96 | 216.37 | 267.13 | 323.23 | 384.67 | 451.45 | 523.57 |
| 278.111 | 2.46 | 9.83 | 22.11 | 39.31 | 61.43 | 88.46 | 120.4 | 157.26 | 199.03 | 245.72 | 297.32 | 353.83 | 415.26 | 481.6 |
| 314.7252 | 2.27 | 9.06 | 20.39 | 36.26 | 56.65 | 81.58 | 111.03 | 145.02 | 183.55 | 226.6 | 274.19 | 326.3 | 382.95 | 444.13 |
| 357.101 | 2.09 | 8.38 | 18.85 | 33.51 | 52.36 | 75.4 | 102.63 | 134.05 | 169.65 | 209.45 | 253.43 | 301.6 | 353.96 | 410.51 |
| 405.3476 | 1.94 | 7.77 | 17.49 | 31.1 | 48.59 | 69.97 | 95.24 | 124.4 | 157.44 | 194.37 | 235.19 | 279.89 | 328.48 | 380.96 |
| 461.7689 | 1.81 | 7.23 | 16.27 | 28.93 | 45.21 | 65.1 | 88.61 | 115.73 | 146.47 | 180.83 | 218.8 | 260.39 | 305.6 | 354.42 |
| 526.8134 | 1.69 | 6.76 | 15.2 | 27.03 | 42.23 | 60.81 | 82.77 | 108.11 | 136.83 | 168.92 | 204.39 | 243.24 | 285.47 | 331.08 |
| 602.4618 | 1.58 | 6.34 | 14.26 | 25.35 | 39.6 | 57.03 | 77.62 | 101.39 | 128.32 | 158.42 | 191.68 | 228.12 | 267.72 | 310.5 |
| 691.328 | 1.49 | 5.97 | 13.42 | 23.86 | 37.28 | 53.69 | 73.08 | 95.45 | 120.8 | 149.14 | 180.46 | 214.76 | 252.04 | 292.31 |
| 795.6862 | 1.41 | 5.64 | 12.69 | 22.56 | 35.25 | 50.77 | 69.1 | 90.25 | 114.22 | 141.02 | 170.63 | 203.06 | 238.32 | 276.39 |
| 919.1872 | 1.34 | 5.36 | 12.05 | 21.43 | 33.48 | 48.21 | 65.63 | 85.71 | 108.48 | 133.93 | 162.05 | 192.86 | 226.34 | 262.5 |
| 1067.888 | 1.28 | 5.11 | 11.5 | 20.44 | 31.93 | 45.98 | 62.58 | 81.74 | 103.46 | 127.72 | 154.54 | 183.92 | 215.85 | 250.34 |
| 1245.753 | 1.22 | 4.9 | 11.02 | 19.58 | 30.6 | 44.07 | 59.98 | 78.34 | 99.15 | 122.41 | 148.11 | 176.26 | 206.86 | 239.91 |
| 1453.242 | 1.18 | 4.72 | 10.62 | 18.88 | 29.5 | 42.48 | 57.82 | 75.52 | 95.58 | 118 | 142.79 | 169.93 | 199.43 | 231.29 |
| 1709.641 | 1.14 | 4.57 | 10.28 | 18.27 | 28.55 | 41.11 | 55.96 | 73.09 | 92.51 | 114.21 | 138.19 | 164.46 | 193.01 | 223.84 |
| 2016.451 | 1.11 | 4.44 | 10 | 17.77 | 27.77 | 39.99 | 54.44 | 71.1 | 89.98 | 111.09 | 134.42 | 159.97 | 187.75 | 217.74 |
| 2396.919 | 1.08 | 4.34 | 9.76 | 17.36 | 27.12 | 39.06 | 53.16 | 69.44 | 87.88 | 108.5 | 131.28 | 156.24 | 183.36 | 212.66 |
| 2863.224 | 1.06 | 4.26 | 9.58 | 17.03 | 26.6 | 38.31 | 52.14 | 68.1 | 86.19 | 106.41 | 128.76 | 153.23 | 179.84 | 208.57 |
| 3444.241 | 1.05 | 4.19 | 9.43 | 16.76 | 26.19 | 37.71 | 51.33 | 67.04 | 84.84 | 104.75 | 126.74 | 150.84 | 177.02 | 205.3 |
| 4156.085 | 1.03 | 4.14 | 9.31 | 16.55 | 25.87 | 37.25 | 50.7 | 66.22 | 83.81 | 103.47 | 125.2 | 148.99 | 174.86 | 202.8 |
| 5040.332 | 1.02 | 4.1 | 9.22 | 16.4 | 25.62 | 36.9 | 50.22 | 65.6 | 83.02 | 102.49 | 124.02 | 147.59 | 173.21 | 200.89 |
| 6133.931 | 1.02 | 4.07 | 9.16 | 16.28 | 25.44 | 36.64 | 49.87 | 65.13 | 82.43 | 101.77 | 123.14 | 146.55 | 171.99 | 199.47 |
| 7488.086 | 1.01 | 4.05 | 9.11 | 16.2 | 25.31 | 36.45 | 49.61 | 64.79 | 82 | 101.24 | 122.5 | 145.78 | 171.09 | 198.43 |
| 9166.967 | 1.01 | 4.03 | 9.08 | 16.14 | 25.21 | 36.31 | 49.42 | 64.55 | 81.7 | 100.86 | 122.04 | 145.24 | 170.45 | 197.68 |
| 11264.86 | 1.01 | 4.02 | 9.05 | 16.09 | 25.15 | 36.21 | 49.29 | 64.38 | 81.48 | 100.59 | 121.71 | 144.84 | 169.99 | 197.15 |
| 13861.32 | 1 | 4.02 | 9.04 | 16.06 | 25.1 | 36.14 | 49.2 | 64.25 | 81.32 | 100.4 | 121.48 | 144.57 | 169.67 | 196.78 |
| 17094.41 | 1 | 4.01 | 9.02 | 16.04 | 25.07 | 36.1 | 49.13 | 64.17 | 81.22 | 100.27 | 121.32 | 144.39 | 169.45 | 196.52 |
| 21122.06 | 1 | 4.01 | 9.02 | 16.03 | 25.04 | 36.06 | 49.09 | 64.11 | 81.14 | 100.18 | 121.22 | 144.26 | 169.3 | 196.35 |
| 26151.97 | 1 | 4 | 9.01 | 16.02 | 25.03 | 36.04 | 49.06 | 64.08 | 81.1 | 100.12 | 121.14 | 144.17 | 169.2 | 196.23 |
| 32436.14 | 1 | 4 | 9.01 | 16.01 | 25.02 | 36.03 | 49.04 | 64.05 | 81.06 | 100.08 | 121.09 | 144.11 | 169.13 | 196.15 |
| 40232.51 | 1 | 4 | 9 | 16.01 | 25.01 | 36.02 | 49.03 | 64.03 | 81.04 | 100.05 | 121.06 | 144.07 | 169.09 | 196.1 |
| 50000 | 1 | 4 | 9 | 16.01 | 25.01 | 36.01 | 49.02 | 64.02 | 81.03 | 100.03 | 121.04 | 144.05 | 169.06 | 196.07 |

| Upper limit of energy bins (MeV/u) | Phosphorus (Z=15; A=29) | Sulfur (Z=16; A=30, 31, 32) | Chlorine (Z=17; A=33, 35) | Argon (Z=18; A=34, 36) | Potassium (Z=19; A=37, 39) | Calcium (Z=20; A=40, 41, 42) | Scandium (Z=21; A=43) | Titanium (Z=22; A=44, 45, 46, 47) | Vanadium (Z=23; A=48, 49) | Chromium (Z=24; A=50, 51, 52) | Manganese (Z=25;  A=53, 54) | Iron  (Z=26; A=55, 56) | Cobalt (Z=27; A=57) | Nickel (Z=28; A=58) |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 0.01 | 86467.24 | 90625.84 | 94700.12 | 98696.49 | 102620.6 | 106477.3 | 110271.2 | 114005.9 | 117685.2 | 121312 | 124889.3 | 128419.7 | 131905.6 | 135349 |
| 0.014081 | 84970.19 | 89121.21 | 93188.62 | 97178.73 | 101097.1 | 104948.6 | 108737.5 | 112467.8 | 116142.8 | 119765.8 | 123339.5 | 126866.4 | 130349 | 133789.4 |
| 0.019828 | 83233.03 | 87373.63 | 91431.58 | 95413.09 | 99323.56 | 103167.8 | 106950 | 110674.1 | 114343.3 | 117960.9 | 121529.5 | 125051.7 | 128529.8 | 131966 |
| 0.02781 | 81250.41 | 85376.95 | 89422.14 | 93391.99 | 97291.78 | 101126.2 | 104899.3 | 108614.9 | 112276.3 | 115886.5 | 119448.2 | 122964 | 126436 | 129866.5 |
| 0.038755 | 79020.03 | 83127.9 | 87156.14 | 91110.49 | 94996.06 | 98817.33 | 102578.3 | 106282.6 | 109933.5 | 113533.9 | 117086.4 | 120593.5 | 124057.5 | 127480.2 |
| 0.053325 | 76582.67 | 80666.63 | 84673.09 | 88607.53 | 92474.78 | 96279.15 | 100024.5 | 103714.2 | 107351.5 | 110939.2 | 114479.8 | 117975.8 | 121429.1 | 124842 |
| 0.072012 | 74005.74 | 78060.3 | 82039.94 | 85949.81 | 89794.44 | 93577.9 | 97303.84 | 100975.5 | 104596 | 108167.9 | 111693.7 | 115175.7 | 118615.9 | 122016.3 |
| 0.095042 | 71368.37 | 75388.29 | 79336.3 | 83217.12 | 87034.97 | 90793.66 | 94496.58 | 98146.84 | 101747.2 | 105300.4 | 108808.5 | 112273.9 | 115698.5 | 119084 |
| 0.122257 | 68753.45 | 72734.33 | 76646.61 | 80494.58 | 84282.11 | 88012.68 | 91689.46 | 95315.33 | 98892.91 | 102424.6 | 105912.7 | 109359.1 | 112765.7 | 116134.3 |
| 0.153549 | 66202.1 | 70140.23 | 74013.3 | 77825.17 | 81579.3 | 85278.88 | 88926.79 | 92525.7 | 96078.03 | 99586.02 | 103051.7 | 106477.1 | 109863.8 | 113213.6 |
| 0.188764 | 63739.08 | 67631.4 | 71462.4 | 75235.43 | 78953.59 | 82619.73 | 86236.47 | 89806.22 | 93331.21 | 96813.49 | 100255 | 103657.4 | 107022.5 | 110351.8 |
| 0.227671 | 61381.23 | 65225.37 | 69012.01 | 72744.05 | 76424.19 | 80054.93 | 83638.61 | 87177.4 | 90673.32 | 94128.25 | 97543.94 | 100922 | 104264 | 107571.4 |
| 0.271437 | 59066.62 | 62859.2 | 66598.28 | 70286.29 | 73925.5 | 77518.09 | 81066.11 | 84571.45 | 88035.94 | 91461.26 | 94848.99 | 98200.62 | 101517.5 | 104801.1 |
| 0.319916 | 56818.04 | 60556.32 | 64245.23 | 67886.7 | 71482.59 | 75034.74 | 78544.89 | 82014.68 | 85445.72 | 88839.48 | 92197.39 | 95520.78 | 98810.91 | 102069 |
| 0.373716 | 54619.93 | 58300.99 | 61936.91 | 65529.14 | 69079.12 | 72588.35 | 76058.24 | 79490.2 | 82885.59 | 86245.7 | 89571.76 | 92864.96 | 96126.44 | 99357.25 |
| 0.433654 | 52456.78 | 56077.36 | 59657.17 | 63197.16 | 66698.36 | 70161.9 | 73588.89 | 76980.48 | 80337.78 | 83661.88 | 86953.84 | 90214.69 | 93445.41 | 96646.94 |
| 0.500671 | 50317.21 | 53873.76 | 57394.04 | 60878.49 | 64327.74 | 67742.55 | 71123.72 | 74472.12 | 77788.63 | 81074.13 | 84329.49 | 87555.57 | 90753.21 | 93923.24 |
| 0.575455 | 48203.58 | 51692.6 | 55149.94 | 58575.58 | 61969.73 | 65332.75 | 68665.15 | 71967.53 | 75240.5 | 78484.75 | 81700.96 | 84889.82 | 88052.02 | 91188.23 |
| 0.659489 | 46101.22 | 49518.67 | 52909.18 | 56272.24 | 59607.61 | 62915.33 | 66195.58 | 69448.65 | 72674.93 | 75874.88 | 79048.99 | 82197.78 | 85321.78 | 88421.54 |
| 0.753842 | 44013.53 | 47355.39 | 50675.15 | 53971.81 | 57244.73 | 60493.57 | 63718.18 | 66918.59 | 70094.94 | 73247.45 | 76376.42 | 79482.2 | 82565.15 | 85625.68 |
| 0.859868 | 41941.25 | 45203.43 | 48448.44 | 51674.79 | 54881.44 | 58067.69 | 61233.07 | 64377.32 | 67500.33 | 70602.11 | 73682.75 | 76742.41 | 79781.31 | 82799.7 |
| 0.979108 | 39885.89 | 43064.26 | 46230.44 | 49382.48 | 52518.96 | 55638.79 | 58741.21 | 61825.68 | 64891.82 | 67939.43 | 70968.39 | 73978.68 | 76970.37 | 79943.55 |
| 1.111958 | 37869.09 | 40960.38 | 44044.44 | 47118.9 | 50181.94 | 53232.14 | 56268.43 | 59289.98 | 62296.2 | 65286.64 | 68260.99 | 71219.05 | 74160.71 | 77085.93 |
| 1.262183 | 35864.59 | 38864.34 | 41861.85 | 44854.34 | 47839.62 | 50815.94 | 53781.92 | 56736.49 | 59678.78 | 62608.14 | 65524.06 | 68426.16 | 71314.17 | 74187.9 |
| 1.43026 | 33898.24 | 36803.12 | 39710.68 | 42617.77 | 45521.84 | 48420.84 | 51313.1 | 54197.29 | 57072.32 | 59937.3 | 62791.55 | 65634.51 | 68465.73 | 71284.87 |
| 1.619384 | 31962.91 | 34769.26 | 37583.14 | 40401.04 | 43220.1 | 46037.98 | 48852.75 | 51662.81 | 54466.85 | 57263.8 | 60052.76 | 62833.01 | 65603.94 | 68365.08 |
| 1.831895 | 30066.22 | 32770.78 | 35487.57 | 38212.8 | 40943.32 | 43676.51 | 46410.18 | 49142.53 | 51872.03 | 54597.39 | 57317.56 | 60031.62 | 62738.84 | 65438.57 |
| 2.070313 | 28215.56 | 30815.54 | 33432.28 | 36061.73 | 38700.5 | 41345.71 | 43994.98 | 46646.26 | 49297.84 | 51948.25 | 54596.26 | 57240.8 | 59880.98 | 62516.03 |
| 2.337882 | 26414.57 | 28907.49 | 31421.49 | 33952.31 | 36496.32 | 39050.46 | 41612.14 | 44179.13 | 46749.52 | 49321.69 | 51894.25 | 54465.97 | 57035.82 | 59602.91 |
| 2.638686 | 24664.6 | 27048.22 | 29456.98 | 31886.45 | 34332.84 | 36792.92 | 39263.9 | 41743.41 | 44229.39 | 46720.04 | 49213.84 | 51709.42 | 54205.63 | 56701.43 |
| 2.976327 | 22972.65 | 25245.35 | 27546.95 | 29872.91 | 32219.3 | 34582.75 | 36960.36 | 39349.59 | 41748.25 | 44154.43 | 46566.44 | 48982.83 | 51402.3 | 53823.72 |
| 3.354537 | 21345.52 | 23506.4 | 25699.59 | 27920.48 | 30165.07 | 32429.9 | 34711.94 | 37008.56 | 39317.46 | 41636.59 | 43964.19 | 46298.66 | 48638.63 | 50982.86 |
| 3.779 | 19783.11 | 21831.56 | 23915.36 | 26029.88 | 28171.09 | 30335.48 | 32519.95 | 34721.77 | 36938.57 | 39168.22 | 41408.83 | 43658.76 | 45916.52 | 48180.78 |
| 4.255003 | 18289.43 | 20225.47 | 22199.49 | 24206.91 | 26243.71 | 28306.35 | 30391.7 | 32496.99 | 34619.77 | 36757.86 | 38909.31 | 41072.38 | 43245.53 | 45427.34 |
| 4.788643 | 16867.06 | 18691.31 | 20555.74 | 22455.86 | 24387.72 | 26347.78 | 28332.93 | 30340.38 | 32367.64 | 34412.49 | 36472.93 | 38547.18 | 40633.62 | 42730.8 |
| 5.386816 | 15517.79 | 17231.41 | 18986.98 | 20780.15 | 22607.05 | 24464.22 | 26348.56 | 28257.3 | 30187.96 | 32138.28 | 34106.26 | 36090.06 | 38088.05 | 40098.72 |
| 6.057149 | 14242.93 | 15847.69 | 17495.71 | 19182.82 | 20905.29 | 22659.75 | 24443.18 | 26252.84 | 28086.27 | 29941.23 | 31815.71 | 33707.86 | 35616.02 | 37538.66 |
| 6.808107 | 13043.25 | 14541.45 | 16083.78 | 17666.29 | 19285.4 | 20937.89 | 22620.82 | 24331.53 | 26067.61 | 27826.84 | 29607.23 | 31406.95 | 33224.32 | 35057.83 |
| 7.649509 | 11918.35 | 13312.78 | 14751.77 | 16231.62 | 17748.96 | 19300.69 | 20884.02 | 22496.38 | 24135.43 | 25799.01 | 27485.17 | 29192.1 | 30918.13 | 32661.76 |
| 8.591997 | 10867.77 | 12161.71 | 13500.22 | 14879.88 | 16297.51 | 17750.24 | 19235.39 | 20750.51 | 22293.36 | 23861.87 | 25454.12 | 27068.36 | 28702.97 | 30356.44 |
| 9.64756 | 9890.34 | 11087.49 | 12328.83 | 13611.21 | 14931.73 | 16287.67 | 17676.54 | 19096.04 | 20544.01 | 22018.5 | 23517.65 | 25039.79 | 26583.32 | 28146.8 |
| 10.82961 | 8984.34 | 10088.77 | 11236.65 | 12425.12 | 13651.52 | 14913.37 | 16208.33 | 17534.27 | 18889.17 | 20271.16 | 21678.5 | 23109.57 | 24562.86 | 26036.96 |
| 12.15322 | 8147.56 | 9163.64 | 10222.1 | 11320.38 | 12456.07 | 13626.92 | 14830.78 | 16065.68 | 17329.74 | 18621.22 | 19938.47 | 21279.97 | 22644.28 | 24030.06 |
| 13.63491 | 7377.55 | 8309.9 | 9283.28 | 10295.42 | 11344.18 | 12427.51 | 13543.48 | 14690.27 | 15866.17 | 17069.55 | 18298.9 | 19552.79 | 20829.85 | 22128.83 |
| 15.29532 | 6670.6 | 7523.93 | 8416.7 | 9346.93 | 10312.71 | 11312.23 | 12343.76 | 13405.66 | 14496.35 | 15614.37 | 16758.31 | 17926.84 | 19118.72 | 20332.74 |
| 17.15376 | 6024.4 | 6803.61 | 7620.49 | 8473.31 | 9360.42 | 10280.21 | 11231.15 | 12211.76 | 13220.66 | 14256.49 | 15317.98 | 16403.91 | 17513.14 | 18644.55 |
| 19.23466 | 5435.23 | 6145.25 | 6891 | 7671.02 | 8483.87 | 9328.17 | 10202.56 | 11105.74 | 12036.48 | 12993.56 | 13975.85 | 14982.24 | 16011.68 | 17063.16 |
| 21.5643 | 4899.64 | 5545.36 | 6224.79 | 6936.69 | 7679.83 | 8453.01 | 9255.07 | 10084.89 | 10941.35 | 11823.4 | 12730.02 | 13660.21 | 14613.04 | 15587.59 |
| 24.17442 | 4413.67 | 4999.89 | 5617.72 | 6266.12 | 6944.08 | 7650.57 | 8384.6 | 9145.19 | 9931.39 | 10742.26 | 11576.91 | 12434.46 | 13314.07 | 14214.92 |
| 27.0974 | 3974.02 | 4505.43 | 5066.33 | 5655.87 | 6273.21 | 6917.49 | 7587.87 | 8283.52 | 9003.61 | 9747.34 | 10513.93 | 11302.61 | 12112.64 | 12943.3 |
| 30.37216 | 3577 | 4058.1 | 4566.59 | 5101.79 | 5662.99 | 6249.49 | 6860.58 | 7495.57 | 8153.75 | 8834.45 | 9536.98 | 10260.69 | 11004.92 | 11769.04 |
| 34.0407 | 3219.23 | 3654.35 | 4114.8 | 4600.03 | 5109.47 | 5642.55 | 6198.69 | 6777.3 | 7377.8 | 7999.61 | 8642.16 | 9304.88 | 9987.21 | 10688.6 |
| 38.15234 | 2897.27 | 3290.49 | 3707.04 | 4146.5 | 4608.4 | 5092.29 | 5597.69 | 6124.12 | 6671.1 | 7238.15 | 7824.78 | 8430.51 | 9054.87 | 9697.39 |
| 42.76254 | 2607.92 | 2963.07 | 3339.64 | 3737.31 | 4155.7 | 4594.46 | 5053.19 | 5531.52 | 6029.05 | 6545.38 | 7080.11 | 7632.83 | 8203.15 | 8790.67 |
| 47.93135 | 2348.27 | 2668.94 | 3009.24 | 3368.88 | 3747.61 | 4145.12 | 4561.13 | 4995.31 | 5447.34 | 5916.92 | 6403.69 | 6907.34 | 7427.53 | 7963.93 |
| 53.73154 | 2115.4 | 2404.91 | 2712.34 | 3037.49 | 3380.14 | 3740.08 | 4117.06 | 4510.84 | 4921.17 | 5347.79 | 5790.43 | 6248.81 | 6722.67 | 7211.74 |
| 60.23854 | 1906.86 | 2168.28 | 2446.04 | 2739.98 | 3049.94 | 3375.76 | 3717.25 | 4074.22 | 4446.47 | 4833.8 | 5235.98 | 5652.81 | 6084.05 | 6529.49 |
| 67.55091 | 1720 | 1956.13 | 2207.12 | 2472.86 | 2753.24 | 3048.14 | 3357.4 | 3680.89 | 4018.44 | 4369.9 | 4735.1 | 5113.86 | 5506.01 | 5911.36 |
| 75.76738 | 1552.8 | 1766.19 | 1993.09 | 2233.43 | 2487.12 | 2754.07 | 3034.17 | 3327.3 | 3633.36 | 3952.21 | 4283.73 | 4627.77 | 4984.2 | 5352.87 |
| 85.0071 | 1403.22 | 1596.2 | 1801.46 | 2018.95 | 2248.6 | 2490.34 | 2744.1 | 3009.8 | 3287.33 | 3576.62 | 3877.55 | 4190.02 | 4513.92 | 4849.13 |
| 95.4071 | 1269.43 | 1444.11 | 1629.94 | 1826.9 | 2034.93 | 2253.98 | 2484 | 2724.93 | 2976.7 | 3239.23 | 3512.46 | 3796.29 | 4090.64 | 4395.43 |
| 107.1423 | 1149.63 | 1307.89 | 1476.28 | 1654.78 | 1843.37 | 2042 | 2250.63 | 2469.22 | 2697.72 | 2936.07 | 3184.22 | 3442.1 | 3709.66 | 3986.82 |
| 120.3541 | 1042.73 | 1186.31 | 1339.1 | 1501.1 | 1672.27 | 1852.6 | 2042.05 | 2240.59 | 2448.18 | 2664.79 | 2890.37 | 3124.87 | 3368.26 | 3620.46 |
| 135.2905 | 947.06 | 1077.49 | 1216.31 | 1363.5 | 1519.05 | 1682.94 | 1855.16 | 2035.67 | 2224.45 | 2421.48 | 2626.72 | 2840.14 | 3061.69 | 3291.35 |
| 152.1613 | 861.65 | 980.34 | 1106.66 | 1240.62 | 1382.2 | 1531.38 | 1688.16 | 1852.52 | 2024.44 | 2203.91 | 2390.88 | 2585.35 | 2787.29 | 2996.66 |
| 171.3748 | 784.95 | 893.08 | 1008.18 | 1130.23 | 1259.24 | 1395.2 | 1538.09 | 1687.9 | 1844.63 | 2008.25 | 2178.75 | 2356.12 | 2540.33 | 2731.36 |
| 193.0143 | 716.95 | 815.72 | 920.85 | 1032.35 | 1150.2 | 1274.41 | 1404.96 | 1541.85 | 1685.07 | 1834.61 | 1990.46 | 2152.6 | 2321.02 | 2495.7 |
| 217.8676 | 655.63 | 745.95 | 842.1 | 944.07 | 1051.86 | 1165.46 | 1284.88 | 1410.1 | 1541.11 | 1677.92 | 1820.52 | 1968.89 | 2123.02 | 2282.91 |
| 246.1532 | 601.04 | 683.84 | 771.99 | 865.47 | 964.29 | 1068.45 | 1177.94 | 1292.75 | 1412.89 | 1538.35 | 1669.12 | 1805.2 | 1946.58 | 2093.25 |
| 278.111 | 552.86 | 629.03 | 710.11 | 796.11 | 887.01 | 982.83 | 1083.55 | 1189.17 | 1299.7 | 1415.13 | 1535.45 | 1660.67 | 1790.76 | 1925.74 |
| 314.7252 | 509.85 | 580.09 | 654.87 | 734.17 | 818.01 | 906.37 | 999.27 | 1096.68 | 1198.63 | 1305.09 | 1416.07 | 1531.57 | 1651.58 | 1776.1 |
| 357.101 | 471.25 | 536.18 | 605.3 | 678.6 | 756.09 | 837.77 | 923.64 | 1013.69 | 1107.92 | 1206.34 | 1308.93 | 1415.71 | 1526.66 | 1641.78 |
| 405.3476 | 437.33 | 497.58 | 561.72 | 629.75 | 701.67 | 777.47 | 857.15 | 940.72 | 1028.18 | 1119.52 | 1214.74 | 1313.84 | 1416.82 | 1523.67 |
| 461.7689 | 406.86 | 462.92 | 522.59 | 585.88 | 652.79 | 723.31 | 797.44 | 875.19 | 956.56 | 1041.54 | 1130.13 | 1222.34 | 1318.15 | 1417.57 |
| 526.8134 | 380.07 | 432.43 | 488.18 | 547.3 | 609.8 | 675.68 | 744.93 | 817.56 | 893.57 | 972.96 | 1055.72 | 1141.86 | 1231.37 | 1324.25 |
| 602.4618 | 356.44 | 405.55 | 457.82 | 513.27 | 571.88 | 633.67 | 698.62 | 766.73 | 838.02 | 912.47 | 990.09 | 1070.87 | 1154.82 | 1241.94 |
| 691.328 | 335.56 | 381.79 | 431 | 483.2 | 538.38 | 596.55 | 657.69 | 721.82 | 788.93 | 859.02 | 932.09 | 1008.15 | 1087.18 | 1169.2 |
| 795.6862 | 317.29 | 361 | 407.54 | 456.89 | 509.07 | 564.06 | 621.88 | 682.52 | 745.97 | 812.25 | 881.34 | 953.26 | 1027.99 | 1105.54 |
| 919.1872 | 301.34 | 342.86 | 387.06 | 433.93 | 483.48 | 535.72 | 590.63 | 648.22 | 708.48 | 771.43 | 837.05 | 905.35 | 976.33 | 1049.99 |
| 1067.888 | 287.38 | 326.97 | 369.12 | 413.82 | 461.08 | 510.89 | 563.26 | 618.18 | 675.65 | 735.68 | 798.27 | 863.4 | 931.09 | 1001.34 |
| 1245.753 | 275.41 | 313.36 | 353.75 | 396.59 | 441.88 | 489.62 | 539.81 | 592.44 | 647.52 | 705.05 | 765.03 | 827.45 | 892.33 | 959.65 |
| 1453.242 | 265.51 | 302.09 | 341.03 | 382.33 | 426 | 472.02 | 520.4 | 571.14 | 624.24 | 679.7 | 737.53 | 797.71 | 860.25 | 925.15 |
| 1709.641 | 256.96 | 292.37 | 330.06 | 370.03 | 412.28 | 456.82 | 503.65 | 552.76 | 604.15 | 657.83 | 713.79 | 772.03 | 832.56 | 895.37 |
| 2016.451 | 249.96 | 284.4 | 321.06 | 359.94 | 401.04 | 444.37 | 489.92 | 537.68 | 587.68 | 639.89 | 694.32 | 750.98 | 809.86 | 870.96 |
| 2396.919 | 244.12 | 277.75 | 313.56 | 351.53 | 391.68 | 433.99 | 478.48 | 525.13 | 573.95 | 624.95 | 678.11 | 733.44 | 790.95 | 850.62 |
| 2863.224 | 239.43 | 272.41 | 307.53 | 344.77 | 384.15 | 425.65 | 469.28 | 515.03 | 562.92 | 612.93 | 665.07 | 719.34 | 775.74 | 834.27 |
| 3444.241 | 235.68 | 268.15 | 302.72 | 339.38 | 378.14 | 418.99 | 461.93 | 506.97 | 554.11 | 603.34 | 654.67 | 708.09 | 763.6 | 821.21 |
| 4156.085 | 232.8 | 264.88 | 299.02 | 335.24 | 373.52 | 413.87 | 456.3 | 500.79 | 547.35 | 595.98 | 646.68 | 699.45 | 754.28 | 811.19 |
| 5040.332 | 230.61 | 262.38 | 296.21 | 332.08 | 370 | 409.97 | 452 | 496.07 | 542.19 | 590.36 | 640.59 | 692.86 | 747.18 | 803.55 |
| 6133.931 | 228.98 | 260.53 | 294.11 | 329.73 | 367.39 | 407.08 | 448.8 | 492.56 | 538.36 | 586.19 | 636.05 | 687.96 | 741.89 | 797.87 |
| 7488.086 | 227.79 | 259.17 | 292.58 | 328.01 | 365.47 | 404.96 | 446.46 | 490 | 535.56 | 583.14 | 632.74 | 684.38 | 738.03 | 793.71 |
| 9166.967 | 226.93 | 258.2 | 291.48 | 326.78 | 364.1 | 403.43 | 444.78 | 488.15 | 533.54 | 580.94 | 630.36 | 681.8 | 735.25 | 790.73 |
| 11264.86 | 226.32 | 257.5 | 290.7 | 325.9 | 363.12 | 402.35 | 443.59 | 486.84 | 532.1 | 579.38 | 628.67 | 679.97 | 733.28 | 788.6 |
| 13861.32 | 225.9 | 257.02 | 290.15 | 325.29 | 362.44 | 401.59 | 442.76 | 485.93 | 531.11 | 578.29 | 627.49 | 678.69 | 731.9 | 787.12 |
| 17094.41 | 225.6 | 256.69 | 289.77 | 324.87 | 361.97 | 401.07 | 442.18 | 485.3 | 530.42 | 577.54 | 626.67 | 677.81 | 730.95 | 786.1 |
| 21122.06 | 225.4 | 256.46 | 289.52 | 324.58 | 361.65 | 400.71 | 441.79 | 484.86 | 529.95 | 577.03 | 626.12 | 677.21 | 730.3 | 785.4 |
| 26151.97 | 225.27 | 256.3 | 289.34 | 324.38 | 361.43 | 400.47 | 441.52 | 484.57 | 529.63 | 576.68 | 625.74 | 676.8 | 729.86 | 784.93 |
| 32436.14 | 225.18 | 256.2 | 289.23 | 324.25 | 361.28 | 400.31 | 441.34 | 484.38 | 529.41 | 576.45 | 625.49 | 676.53 | 729.57 | 784.61 |
| 40232.51 | 225.12 | 256.13 | 289.15 | 324.17 | 361.18 | 400.2 | 441.23 | 484.25 | 529.27 | 576.29 | 625.32 | 676.35 | 729.37 | 784.4 |
| 50000 | 225.08 | 256.09 | 289.1 | 324.11 | 361.12 | 400.13 | 441.15 | 484.16 | 529.18 | 576.19 | 625.21 | 676.23 | 729.24 | 784.26 |

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