Space radiation risk limits and Earth-Moon-Mars environmental models

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[1] We review NASA's short-term and career radiation limits for astronauts and methods for their application to future exploration missions outside of low Earth orbit. Career limits are intended to restrict late occurring health effects and include a 3% risk of exposure-induced death from cancer and new limits for central nervous system and heart disease risks. Short-term dose limits are used to prevent in-flight radiation sickness or death through restriction of the doses to the blood forming organs and to prevent clinically significant cataracts or skin damage through lens and skin dose limits, respectively. Large uncertainties exist in estimating the health risks of space radiation, chiefly the understanding of the radiobiology of heavy ions and dose rate and dose protraction effects, and the limitations in human epidemiology data. To protect against these uncertainties NASA estimates the 95% confidence in the cancer risk projection intervals as part of astronaut flight readiness assessments and mission design. Accurate organ dose and particle spectra models are needed to ensure astronauts stay below radiation limits and to support the goal of narrowing the uncertainties in risk projections. Methodologies for evaluation of space environments, radiation quality, and organ doses to evaluate limits are discussed, and current projections for lunar and Mars missions are described.

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1. Introduction

[2] Mars exploration continues to be the primary goal for human exploration with missions returning to the moon or nearby Earth objects as possible intermediate steps toward this goal [*NASA*, 2009]. As missions progress outside of low Earth orbit and away from the protection of Earth's magnetic shielding, the radiation exposures that astronauts face change to include higher exposure to the full galactic cosmic ray (GCR) spectrum and solar particle events (SPE). The large uncertainties in projecting the risks from space radiation and the potential for unacceptable risks for long-term exposures GCR are major scientific challenges to achieving the exploration goal [*Cucinotta et al.*, 2001; *Cucinotta and Durante*, 2006; *Durante and Cucinotta*, 2008]. Heavy ions produce distinct types of biological damage to biomolecules, cells and tissues compared to X-rays or gamma rays complicating risks assessments based on human data. Responding to large SPEs presents a distinct challenge that must rely on knowledge of the space environment and the development of operational procedures for effective real-time responses [*National Council on Research Protection and Measurements* (*NCRP*), 2006; *National Research Council* (*NRC*), 2008]. An objective of the Earth-Moon-Mars Radiation Environment Module (EMMREM) is to provide a framework to overcome the SPE safety challenges [*Schwadron et al.*, 2010]. Our review discusses radiation safety issues and limits for the protection of astronauts that can be supported by the EMMREM framework.

[3] NASA has recognized the importance of the uncertainties in risk projection models for radiation exposures, and uncertainty assessments are requirements for mission design optimization and operational radiation protection methods. Mission safety can only be predicted within a defined confidence level, corresponding to the statistical nature of such a calculation. Large uncertainties limit the value of a median projection or so-called point estimate. Permissible exposure limits (PELs) for exploration missions have been implemented at NASA based on the NCRP recommendations [*NCRP*, 2000, 2003] for organ dose methodologies and point estimates for cancer risks, however NASA applies these with an ancillary requirement to protect against the upper bound of the 95% confi-

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dence level of risk projection. In support of the principle of as low as reasonably achievable (ALARA), mission design and operations must include cost versus benefit analyses of approaches to improve crew safety with higher confidence. Such analyses are often limited by the uncertainties in risk projections because the benefit of mitigation measures cannot be adequately stated if uncertainties are large.

[4] Estimates of the uncertainties for cancer risk from low linear energy transfer (LET) radiation, such as X-rays and gamma rays, have been reviewed several times in recent years, and indicate that the major uncertainty is the extrapolation of cancer effects data from high to low dose rates [*NCRP*, 1997a; *Committee on the Biological Effects of Radiation*, 2006]. Other projection model uncertainties include the transfer of risk across populations, and sources of error in epidemiology data including dosimetry, bias, and statistical ones. Additional uncertainties contribute to protecting against the cancer risks from the protons and heavy ions and secondary radiation in space, and in space dosimetry [*Cucinotta et al.*, 2001]. The limited understanding of heavy ion radiobiology has been estimated to be the largest contributor to the uncertainty for space radiation effects [*National Academy of Sciences* (*NAS*), 1996; *Cucinotta and Durante*, 2006; *Durante and Cucinotta*, 2008]. Understanding heavy ion risk is difficult because of the absence of epidemiology data for humans exposed to heavy ions, and has been impeded by the lack of a dedicated facility to perform experiments with heavy ions on biological models until 2003 [*Cucinotta and Durante*, 2006]. SPEs present distinct challenges since their time of onset, size and spectral characteristics cannot be predicted reliably [*NRC*, 2008]. SPE challenges include specifying mission design criteria based on a well defined worse case [*Kim et al.*, 2009a, 2009b], and the development of real-time response models [*Schwadron et al.*, 2010].

[5] In this paper we review the basis for radiation limits for astronauts and the recently revised limits implemented at NASA for planning toward exploration missions returning humans to the moon or voyaging beyond. The historical bases for acceptable levels of risks and astronauts radiation limits are first described, and changes in radiation epidemiology data in recent years summarized. We then outline methodologies appropriate for the application of space radiation environment and transport models to exploration missions. Example risks and organ specific and effective dose (E) projections for lunar and Mars GCR and SPE exposures are then described.

2. Acceptable Levels of Risks: Historical Perspective

[6] Permissible exposure limits (PEL) for radiation exposure of astronauts have the primary functions of preventing in-flight risks that would jeopardize mission success, and limiting chronic risks to acceptable levels based on legal, ethical or moral, and financial considerations. Early radiation effects usually are related to a significant fraction of cell loss, exceeding the threshold for impairment of function in a tissue. These are "deterministic" effects, so called because the statistical fluctuations in the number of affected cells are very small compared to the number of cells required to reach the threshold [*International Commission on Radiological Protection* (*ICRP*), 1991]. Maintaining dose limits can ensure that no occurrence of early effects occurs. Late effects can result from changes in a very small number of cells, so that statistical fluctuations can be large and some level of risk is incurred even at low doses. Referring to them as a "stochastic" effect recognizes the predominance of statistical effects in their manifestation.

[7] NASA has followed several distinct recommendations on radiation limits since the Apollo era until the Constellation program of today due to the evolving understanding of space radiation environments inside spacecraft and tissue, new epidemiology data, and the age and gender makeup of astronauts. Recommendations by *NAS* [1967] noted that radiation protection in manned space flight is philosophically distinct from protection practices of terrestrial workers because of the high-risk nature of space missions. The *NAS* [1967] report did not recommend "permissible doses" for space operations, noting the possibility that such limits may place the mission in jeopardy and instead made estimates of what the likely effects would be for a given dose of radiation.

[8] In 1970, the NAS Space Science Board made recommendations of guidelines for career doses to be used by NASA for long-term mission design and manned operations. At that time, NASA employed only male astronauts and the typical age of astronauts was 30–40 years. A "primary reference risk" was proposed equal to the natural probability of cancer over a period of 20 years following the radiation exposure (using the period from 35 to 55 years of age) and was essentially a doubling dose. The estimated doubling dose of 382 rem (3.82 Sv), which ignored a dose rate reduction factor, was rounded to 400 rem (4 Sv). The NAS panel noted that their recommendations were not risk limits, but rather a reference risk and that higher risk could be considered for planetary missions or a lower level of risk for a possible space station [*NAS*, 1970]. Ancillary reference risks were described to consider monthly, annual, and career exposure patterns. However, the *NAS* [1970] recommendations were implemented by NASA as dose limits used operationally for all missions until 1989.

[9] At the time of the *NAS* [1970] report the major risk from radiation was believed to be leukemia. Since that time the maturation of the data from the Japanese atomic bomb (AB) survivors has led to estimates of higher levels of cancer risk for a given dose of radiation including the observation that the risk of solid tumors following radiation exposure occurs with a higher probability than leukemia's although with a longer latency period before expression. Along with the maturation of the AB data, reevaluation of the dosimetry of the AB survivors, and inclusion of data from other exposure cohorts, scientific assessments of the dose response models and dose rate dependencies have contributed to the large increase in the risk estimate over this time period (1970–2009), and these continue to be modified [*Committee on*

the Biological Effects of Radiation, 2006; *United Nations Scientific Committee on the Effects of Atomic Radiation* (*UNSCEAR*), 2008]. A newer finding is the large risk of heart disease death from radiation that appears in many exposed cohorts [*Little et al.*, 2010], albeit data for low dose rate exposures is inconsistent. The mortality risk for heart disease may approach that of solid cancers at least at older ages [*Preston et al.*, 2003] and research in this area will be important in the future.

[10] By the early 1980s several major changes in epidemiology data had occurred leading to the need for a new approach to define dose limits for astronauts. At that time NASA requested the U.S. National Council on Radiation Protection and Measurements (NCRP) to reevaluate dose limits to be used for low Earth orbit (LEO) operations. Considerations included the increases in estimates of radiation-induced cancer risks in the Japanese A-bomb survivors, the criteria for risk limits, and the role of the evolving makeup of the astronaut population from male test pilots to a larger diverse population (~100) of astronauts including mission specialists, female astronauts, and career astronauts of older ages that often participate in several missions. *NCRP* [1989] Report 98 recommended age- and gender-dependent career dose limits using as a common risk limit of a 3% increase in cancer mortality. The limiting level of 3% excess cancer fatality risk was based on several criteria including comparison to dose limits for ground radiation workers and to rates of occupational death in the less safe industries. It was noted that astronauts face many other risks, and adding an overly large radiation risk was not justified. It also is noted that the average years of life loss from radiation-induced cancer death, about 15 years for workers over age 40 years, and 20 years for workers between 20 and 40 years, is less than that of other occupational injuries. A comparison of radiation-induced cancer deaths to cancer fatalities in the U.S. population is also complex because of the smaller years of life loss from cancers in the general population where most cancer deaths occur above age 70 years.

[11] In the 1990s, the additional follow-up and evaluation of the AB survivor data led to further increases in the estimated cancer risk for a given dose of radiation. Recommendations from *NCRP* [2000], while keeping the basic philosophy of risk limitation in their earlier report, advocated significantly lower limits than those recommended by *NCRP* [1989]. *NCRP* [2000] Report 132 notes that the use of comparisons to fatalities in the less safe industries advocated by the *NCRP* [1989] was no longer viable because of the large improvements made in ground-based occupational safety; indeed the decreased rate of fatalities in the so-called less safe industries, such as mining and agriculture would suggest a limit well below the 3% fatality level estimated in 1989. The most recent reviews of the acceptable levels of radiation risk for LEO, including a 1996 NCRP symposium [*NCRP*, 1997b] and the report on LEO dose limits from *NCRP* [2000], instead advocate that comparisons to career dose limits for ground-based workers should be used. On one hand it is widely held that the social and scientific benefits of space flight continue to provide justification for the 3% risk level for astronauts participating in exploration missions. On the other hand improvements in other aspects of space safety [*NASA*, 2009] place pressure on radiation protection to also improve. The recent report from *NRC* [2008] reinforces the need to uphold radiation limits at NASA for safe mission design and astronaut health.

[12] In comparison to NASA limits, the U.S. nuclear industry has adopted age-specific limits that neglect any gender dependence. Limits are set at an effective dose equal to the individuals Age × 0.01 Sv. It is estimated by the NCRP that ground workers that reach their dose limits would have a lifetime risk of about 3%, but note the differences in dose values corresponding to the limit due to differences in how the radiation doses are accumulated over the worker's career. NASA's short-term LEO dose limits are several times higher than that of terrestrial workers because they are intended to prevent acute risks while annual dose limits of 50 mSv (5 rem) followed by U.S. terrestrial radiation workers intended to control the accumulation of career doses. The exposures received by radiation workers in reactors, accelerators, hospitals, etc. rarely approach dose limits with the average annual exposure of 1 to 2 mSv, which is a factor of 25 below the annual exposure limit, and significantly less than the average effective dose for 6 month ISS missions of 80 mSv [*Cucinotta et al.*, 2008]. Similarly, transcontinental pilots, although not characterized as radiation workers in the United States, receive annual exposures of about 1 to 5 mSv and enjoy long careers without approaching exposure limits recommended for terrestrial workers in the U.S. Under these conditions, ground-based radiation workers are estimated to be well below the career limits, even if a 95% confidence level is applied. Because space missions have been relatively short in the past requiring minimal mitigation consideration, the impact of dose limits when space programs approach such boundaries including the application of the ALARA principle have been unexplored.

[13] Late occurring morbidity risks associated with space radiation are difficult to compare to other occupational risks, and traditionally radiation mortality risks have been used as the primary criteria for setting career risk limits. For example, basal cell carcinomas of the skin and thyroid cancers are more easily treated than leukemias, or lung and breast cancers, which involve a larger degree of suffering and costs. *NCRP* [1989] has used the quantity of excess risk of cancer mortality to estimate age- and gender-dependent dose limits, which differs from the risk of exposure-induced death (REID). The excess risk is a calculation of the increased risk above the background level of cancer deaths in a population not exposed to radiation, and does not account for cancer deaths that would occur anyway but are shifted to an earlier age due to radiation exposure. The REID quantity accounts for these deaths and when supplemented with estimates of years of life loss for deaths occurring is a more meaningful comparison to other mortality risks of astronauts.

Table 1. Example Career Effective Doses Limits for Up to 1 Year Missions for a 3% REID and Estimates of Average Life Loss if Death Occurs

Age at Exposure (years)	E (mSv) for a 3% REID[a]	
	Males	Females
30	620 (15.7)	470 (15.7)
35	720 (15.4)	550 (15.3)
40	800 (15.0)	620 (14.7)
45	950 (14.2)	750 (14.0)
50	1150 (12.5)	920 (13.2)
55	1470 (11.5)	1120 (12.2)

[a]Values in parentheses are average life loss per death (years).

[14] The various approaches to setting acceptable levels of radiation risks and limitations of each are summarized here.

[15] 1. The first approach is unlimited radiation risk. NASA management and the families or loved ones of astronauts would find this approach unacceptable.

[16] 2. Another approach is the comparison to occupational fatalities in less safe industries. The life loss from attributable radiation cancer death is less than from most other occupational deaths. Also, at this time this comparison would be very restrictive on ISS operations or lunar and Mars mission because of continued improvements in ground based occupational safety over the last 20 years.

[17] 3. We can also compare to cancer rates in general population. The life loss from radiation-induced cancer deaths can be significantly larger than from cancer deaths in general population, which often occur late in life, >70 years.

[18] 4. Doubling dose for 20 years following exposure provides a roughly equivalent comparison base of life loss from other occupational risks or background cancer fatalities during the workers career but negates the role of mortality later in life.

[19] 5. Use of ground-based worker limit of ~3% or a similar approach provides a reference point equivalent to a standard set on Earth and recognizes that astronauts face other risks. However, ground workers remain well below dose limits and are largely exposed to low-LET radiation where uncertainties of biological effects are much smaller than for space radiation.

[20] The possibility of future changes in radiation risk estimates can of course not be safely predicted today, and it is possible that such changes could potentially impact exploration missions. New risks of heart disease and central nervous system effects [*NCRP*, 2006] could have a large impact since they would contribute to the overall mortality risks. Current radiation protection methods assume risk varies in proportion to doses, however new science findings in the area of nontargeted effects [*Barcellos-Hoff et al.*, 2005; *Cucinotta and Chappell*, 2010] suggest a shallower (nonlinear) dose response model, and would have large implications on how mission length is evaluated. NASA's approach to consider the upper 95% confidence level in risk estimates in a conservative approach however should protect against the changing nature of radiation risk projections. In the future individual based risk assessments using genetic and epigenetic factors may become feasible, however a recent review suggests the scientific basis to perform such assessments does not exist at this time [*NCRP*, 2010].

3. NASA's Permissible Exposure Limits

3.1. Limits

[21] We next summarize the system of radiation limits at NASA to be used for exploration missions.

3.1.1. Cancer Risk Limits

[22] Career exposure to radiation is limited to not exceed 3% risk of exposure-induced death (REID) from fatal cancers. An ancillary requirement assures that this risk limit is not exceeded at a 95% confidence level using a statistical assessment of the uncertainties in the risk projection calculations to limit the cumulative effective dose (in units of sievert) received by an astronaut throughout his or her career.

3.1.2. Cancer Risk to Dose Relationship

[23] The relationship between radiation exposure or dose and risk is age and gender specific due to latency effects, and differences in tissue types and sensitivities, and differences in average life spans between genders. These relationships are estimated using the double detriment life table methodologies recommended by *NCRP* [2000] and more recent radiation epidemiology information [*Preston et al.*, 2003; *Cucinotta et al.*, 2006]. Table 1 lists examples of career effective dose (E) limits for a REID = 3% for missions of 1 year duration or less. Limits for other mission lengths will vary and should be calculated using the appropriate life table formalism. Note the values in Table 1 differ from the values typically quoted for 10 year careers [*NCRP*, 1989, 2000] since cancer risk will decrease with age at exposure. Estimates of average life loss for a radiation attributable death based on low-LET radiation are also listed in Table 1, however higher values should be expected for high LET exposures such as GCR.

3.1.3. Dose Limits for Noncancer Effects

[24] Short-term dose limits are imposed to prevent clinically significant noncancer health effects including performance degradation, sickness, or death in flight. For risks that occur above a threshold dose, a probability of $<10^{-3}$ is a practical limit. However, radiobiology data rarely determines risk probability $<10^{-2}$. The dose limits for the blood forming organs (BFO) should be adequate to project against the risks of prodromal effects such as nausea, vomiting, and fatigue. Dose limits for cataracts, skin, heart disease, and damage to the central nervous system (CNS) are imposed to limit or prevent risks of degenerative tissue diseases (e.g., stroke, coronary heart disease, striatum aging or dementia, etc.) that could occur postmission. Career limits for the heart are intended to limit the REID for heart disease to be below a few percent, and are expected to be largely age- and gender-independent. Average life loss

Table 2. Dose Limits for Short-Term or Career Noncancer Effects (in mGy-Eq or mGy)[a]

Organ	30 Day Limit	1 Year Limit	Career Limit
Lens[b]	1000 mGy-Eq	2000 mGy-Eq	4000 mGy-Eq
Skin	1500	3000	6000
BFO	250	500	Not applicable
Heart[c]	250	500	1000
CNS[d]	500	1000	1500
CNS[d] ($Z \geq 10$)	-	100 mGy	250 mGy

[a]The lens, skin, and BFO limits are from *NCRP* [2000] Report 132. The heart and CNS limits are from a NASA assessment of human studies and radiobiology.
[b]Lens limits are intended to prevent early (<5 years) severe cataracts (e.g., from a solar particle event). An additional cataract risk exists at lower doses from cosmic rays for subclinical cataracts, which may progress to severe types after long latency (>5 years) and are not preventable by existing mitigation measures but are deemed an acceptable risk by NASA.
[c]Heart doses calculated as average over heart muscle and adjacent arteries.
[d]CNS limits should be calculated at the hippocampus.

from gamma ray induced heart disease death is approximately 9 years [*Preston et al.*, 2003] less than that observed for radiation-induced cancers. Dose limits for noncancer effects (units of milli-gray equivalent (mGy-Eq)) are listed in Table 2. Distinct relative biological effectiveness (RBE) factors for converting organ average dose to organ Gy-equivalent dose occur for each noncancer risk as defined below. CNS risks are expressed as mGy-equivalent dose, however with a separate limit for heavy ions with elemental charge >10 absorbed dose (in mGy).

3.1.4. Principle of as Low as Reasonably Achievable

[25] The ALARA principle is a NASA requirement intended to ensure astronauts' safety. An important function of ALARA is to ensure that astronauts do not approach radiation limits and that such limits are not considered as "tolerance values." Mission programs and terrestrial occupational procedures resulting in radiation exposures to astronauts are required to find cost-effective approaches to implement ALARA.

3.2. Method of Evaluation

3.2.1. Cancer Risk Evaluation

[26] Cancer risk is not measured directly, but is calculated utilizing radiation dosimetry, physics methods, and dose to risk conversion formula. The absorbed dose D (in units of gray) is calculated using measurements of radiation levels provided by dosimeters (e.g., film badges, thermoluminescent dosimeters (TLDs), spectrometers such as the tissue equivalent proportional counter (TEPC), area radiation monitors, biodosimetry or biological markers) and corrections for instrument limitations. The limiting risk is calculated using the effective dose, E (in units of mSv) and risk conversion life table methodologies. For the purpose of determining radiation exposure limits at NASA, the probability of fatal cancer is calculated as follows.

[27] 1. The body is divided into a set of sensitive tissues, and each tissue T is assigned a weight w_T according to its estimated contribution to cancer risk as described by the ICRP (Table 3).

[28] 2. The absorbed dose, D_T (in units of gray (Gy) or mGy where 1 Gy = 100 rad) delivered to each tissue is determined from measured dosimetry or estimated from radiation transport models. Different types of radiation have different biological effectiveness, dependent on the ionization density left behind locally (e.g., in a cell or a cell nucleus) by their passage through matter. For the purpose of estimating radiation risk to an organ, the quantity characterizing this ionization density is the linear energy transfer (LET) (in units of keV/μm) in water.

[29] 3. For a given interval of LET, denoted L, between L and $L + \Delta L$, the dose equivalent risk (units of sievert (Sv) or mSv, where 1 Sv = 100 rem) to a tissue T, $H_T(L)$ is calculated as

$$H_T(L) = Q(L)D_T(L), \quad (1)$$

where the quality factor, $Q(L)$, is obtained according to the International Commission on Radiological Protection (ICRP) prescription. This way of calculating $H_T(L)$ differs from the method used by ICRP, where a tabulated set of weighting factors is given instead of the quality factor [*NCRP*, 2003]. The method used here is considered to yield a better approximation by using the quality factor as the weight most representative of cancer risk, while the ICRP method may overestimate the risk, especially for high-energy protons, He, and other light to medium mass ions.

Table 3. Tissue Weighting Factors as Defined By *ICRP* [1991, 2007]

	ICRP w_T	
	ICRP [1991] Report 60	*ICRP* [2007] Report 103
Skin	0.01	0.01
Bone marrow	0.12	0.12
Bone surface	0.01	0.01
Stomach	0.12	0.12
Colon	0.12	0.12
Liver	0.05	0.04
Lung	0.12	0.12
Esophagus	0.05	0.04
Bladder	0.05	0.04
Thyroid	0.05	0.04
Breast or prostate	0.05	0.12
Ovary+uterus or testis	0.2	0.08
Brain		0.01
Lens		
Salivary gland		0.01
Remainder	0.05[a]	0.12[b]
Sum	1	1

[a]Remainder organ/tissue defined in *ICRP* [1991] Report 60: adrenals, brain, trachea, small intestine, kidneys, muscle, pancreas, spleen, thymus and uterus.
[b]Remainder organ/tissue defined in *ICRP* [2007] Report 103: adrenals, extrathoracic (ET) region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus, and uterus/cervix.

Table 4. *NCRP* [2000] Report 132 Recommendations on RBE Values for Noncancer Radiation Effects to Be Used for Skin and Blood Forming Organ (BFO) Risks[a]

Radiation Type	Recommended RBE[b]	Range
1 to 5 MeV neutrons	6.0	4–8
5 to 50 MeV neutrons	3.5	2–5
Heavy ions	2.5[c]	1–4
Proton > 2 MeV	1.5	-

[a]RBE values for late deterministic effects are higher than for early effects in some tissues and are influenced by the doses used to determine the RBE.
[b]There are not sufficient data on which to base RBE values for early or late effects by neutrons of energies <1 MeV or greater than about 25 MeV.
[c]There are few data for the tissue effects of ions with a Z > 18, but the RBE values for iron ions (Z = 26) are comparable to those of argon (Z = 18). One possible exception is cataract of the lens of the eye because high RBE values for cataracts in mice have been reported.

Neutron contributions are evaluated by their contribution to $D_T(L)$.

[30] 4. The average risk to a tissue T, due to all types of radiation contributing to the dose, can be found by integrating the differential fluence spectra in LET.

[31] Denoting $F_T(L)$ as the differential fluence spectra of particles with LET = L, traversing the organ, we evaluate the organ dose equivalent as

$$H_T = \int dLLQ(L)F_T(L). \quad (2)$$

[32] 5. The effective dose (E in units of Sv) is used as a summation over radiation type and tissue using the tissue weighting factors, w_T,

$$E = \sum_T w_T H_T. \quad (3)$$

[33] 6. For a mission of duration t, the effective dose will be a function of time, $E(t)$, and the effective dose for mission i is found by integration of the effective dose rate over the time of the mission:

$$E_i = \int \frac{dE(t)}{dt} dt \quad (4)$$

and in applying the associated risk factor $R_0(age_i, gender)$, age_i is the average age during the mission.

[34] 7. The effective dose is used to scale the mortality rate for radiation-induced death from the Japanese survivor data using the average of the multiplicative and additive transfer models for solid cancers and the additive transfer model for leukemias and applying life table methodologies based on the U.S. population data for background cancer and all causes of death mortality rates. A dose and dose rate effectiveness factor (DDREF) of 2 is assumed to reduce cancer risks at low dose and dose rates compared to acute radiation cancer risk.

3.2.2. Evaluation of Cumulative Cancer Risk

[35] The cumulative cancer fatality risk (%REID) to an astronaut for N occupational radiation exposures is found by applying life table methodologies, which can be approximated at small values of %REID by summing over the tissue-weighted effective dose, E_i, as

$$Risk = \sum_{i=1}^{N} E_i R_0(age_i, gender), \quad (5)$$

where R_0 are the age and gender specific radiation mortality rates per unit effective dose. The effective dose limits given in the Table 1 illustrate the effective dose that corresponds to a 3% REID for missions of duration up to 1 year. Values for multiple missions or other occupational exposure can be estimated using equation (5) or directly from life table calculations [*Cucinotta et al.*, 2006]. For organ dose calculations, NASA uses the model of *Billings et al.* [1973] to represent the self-shielding of the human body in a water equivalent mass approximation. Consideration of the orientation of the human body relative to vehicle shielding should be made if known, especially for solar particle events [*Wilson et al.*, 1995].

3.2.3. Noncancer Risk Limits

[36] The method used for evaluating the equivalent dose for noncancer effects is similar to equation (2), however it uses the "Gy-equivalent" to distinguish effective doses based on relative biological effectiveness factors (RBE) for noncancer effects from those based on Q values to be used for estimating cancer risks. Tissue specific Gy-equivalents are denoted G_T. Because RBEs for noncancer effects may depend on dose, the RBE used for specifying the Gy-equivalent are the values determined at the threshold dose for the noncancer effect being evaluated. ICRP and NCRP recommendations for RBE values for short-term noncancer effects are listed in Table 4 and are generally smaller than the Q values. These values are not dependent on LET and are defined by radiation type and energy. Based on available radiobiology data for noncancer late effects, organ dose-Eq estimates for cataracts, heart and CNS risks are expected to be highly uncertain.

3.2.4. Confidence Levels for Career Cancer Risks

[37] Confidence levels are evaluated using the methods specified by *NCRP* [1997a] in their Report 126 modified to account for the uncertainty in quality factors and space dosimetry [*Cucinotta et al.*, 2001, 2006]. The uncertainties considered in the evaluation of the 95% confidence levels are (1) the uncertainties in human epidemiology data including uncertainties in statistics limitations of epidemiology data, dosimetry of exposed cohorts, bias including misclassification of cancer deaths, and the transfer of risk across populations; (2) the uncertainties in the dose and dose rate effectiveness reduction (DDREF) factor used to scale acute radiation exposure data to low dose and dose rate radiation exposures; (3) the uncertainties in the radiation quality factor (Q) as a function of LET; and (4) the uncertainties in space dosimetry.

Table 5. Approximate Fold Uncertainty Defined as Ratio of Upper 95% Confidence Level to Point Risk Projection

Type of Exposure	Approximate Ratio of Upper 95% Confidence Interval to Mean Projection
Medical diagnostic	2.0
ISS environment	3.1
Solar particle event	2.5
Deep space or planetary surface GCR	4.0

[38] The so-called "unknown uncertainties" included by *NCRP* [1997a] are ignored. The statistical distribution for the estimated probability of fatal cancer is evaluated in order to project the most likely values and the lower and upper 95% confidence intervals (CI) reported within brackets. For example, for the average adult exposed to 100 mSv (10 rem) of gamma rays, the estimated cancer risk is 0.4% and the 95% CIs estimated by the NCRP are written as [0.11%, 0.82%] where 0.11% is the lower 95% level and 0.82% is the upper 95% confidence level. In order to assure that the career risk limit is not exceeded with a safety margin corresponding to a 95% confidence level, the upper confidence level (worse case) is considered in the developing mission constraints and for crew selection. Table 5 lists approximate fold uncertainties defined as the ratio of the upper 95% confidence level to the median project. These results summarize Monte Carlo propagation of errors based on subjective evaluation of uncertainties in physical, biological and epidemiological factors that enter into risk projections [*NCRP*, 1997a; *Cucinotta et al.*, 2006].

3.2.5. Confidence Levels or Uncertainty Factors for Acute Risks

[39] Confidence levels or uncertainty factors such as radiation sickness or mortality are manifested in the models of RBEs as function of ion type, and in the dose rate reduction and repopulation effects that modify threshold doses. The dose limit values shown in Table 2 are expected to be conservative, however the actual margin between the limit and a significant probability of effect ($>10^{-3}$) should be considered in determining uncertainty bounds. The shape of the dose response function for acute risks near the threshold dose is poorly understood and will likely dependent on individual responses.

4. Applications to Lunar and Mars Mission Assessments

[40] We next discuss several applications of the above methodology for lunar and Mars missions. For the calculations described space environments are evaluated using the HZETRN code [*Wilson et al.*, 1994] with the QMSFRG cross sections as described previously [*Cucinotta et al.*, 2006], and the Badhwar and O'Neill GCR environment models [*Badhwar et al.*, 1994]. For an example SPE we consider the historical large August 1972 event using the fluence spectra for the event estimated by *King* [1974]. The models described agree with spaceflight data on organ doses measured with phantom torsos or spacecraft area detectors measuring dose or dose equivalent to within ±15% [*Cucinotta et al.*, 2008]. *ICRP* [2007] has recently made new recommendations on tissue weighting factors as shown in Table 3. We compare effective doses using the old and new values in some of the examples below. NASA will adopt new gender specific tissue weighting factors (w_T) (M.-H. Y. Kim and F. A. Cucinotta, manuscript in preparation) appropriate for typical astronaut ages in the near future.

[41] Figure 1 (left) shows predictions of integral LET spectra of effective dose for the GCR at different shielding depths, and Figure 1 (right) is for the 1972 event. The GCR contains higher LET contributions and modest attenuation with increasing shielding amounts compared to SPEs. In Table 6 we show the organ doses for GCR at solar mini-

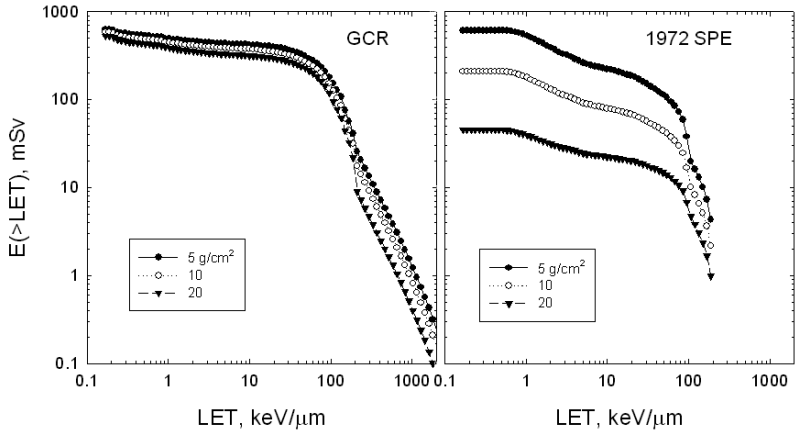

Figure 1. Integral LET distribution of (left) effective dose for annual GCR at solar minimum and (right) the 1972 SPE behind several thicknesses of aluminum shielding.

Table 6. Organ Doses and Effective Doses of a Male Inside Aluminum Shields for the August 1972 SPE and Annual GCR at Solar Minimum

	August 1972 SPE			Annual GCR at Solar Minimum		
	D (mGy)	G (mGy-Eq)	H (mSv)	D (mGy)	G (mGy-Eq)	H (mSv)
			5 g/cm^2 Aluminum			
Avg. skin	2692.3	4052.1	4259.7	198.8	375.8	832.3
Avg. BFO	306.9	462.5	442.1	185.7	337.2	614.0
Stomach	112.3	169.6	168.0	182.2	324.4	547.6
Colon	251.4	379.0	363.8	185.6	336.4	606.2
Liver	174.1	262.7	255.0	183.1	327.9	566.6
Lung	205.6	310.1	299.4	184.5	332.9	590.9
Esophagus	195.4	294.8	285.0	184.0	331.3	584.4
Bladder	118.7	179.2	176.8	181.6	322.5	540.8
Thyroid	333.2	502.1	479.0	186.8	341.1	632.7
Chest/breast	1615.9	2430.6	2323.9	194.1	365.6	770.2
Gonads/ovarian	748.1	1125.7	1072.2	186.5	339.7	640.9
Front brain	571.7	860.9	816.4	190.6	354.4	696.9
Midbrain	279.6	421.5	403.9	187.7	344.1	640.2
Rear brain	557.5	839.6	796.2	190.5	354.0	695.2
Lens	1959.0	2946.2	2829.4	196.2	372.4	806.3
Heart[a]	205.6	310.1	299.4	184.5	332.9	590.9
Gallbladder	118.7	179.2	176.8	181.6	322.5	540.8
Remainder	406.3	611.9	585.9	186.1	338.2	619.5
Point dose	5389.0	8125.0	8663.0	218.2	434.4	1140.7
E (mSv)						
w_T [*ICRP*, 1991]			612.3			611.1
w_T [*ICRP*, 2007]			676.2			620.7
			20 g/cm^2 Aluminum			
Avg. skin	87.8	132.8	144.0	193.5	342.3	599.8
Avg. BFO	23.4	35.7	42.9	182.0	314.9	494.2
Stomach	12.1	18.6	25.5	179.1	306.4	465.5
Colon	21.0	32.1	39.4	181.9	314.6	491.3
Liver	15.6	23.8	30.7	179.8	308.6	473.6
Lung	18.3	28.0	35.2	180.9	312.0	484.4
Esophagus	17.5	26.8	34.0	180.5	310.9	481.4
Bladder	12.0	18.4	25.0	178.6	305.0	462.2
Thyroid	25.7	39.1	46.5	182.9	317.5	502.5
Chest/breast	67.2	101.9	107.0	189.0	333.8	558.7
Gonads/ovarian	37.5	57.0	62.5	182.5	316.1	503.3
Front brain	37.6	57.1	64.8	186.1	326.6	530.5
Midbrain	24.0	36.7	44.8	183.7	319.8	506.9
Rear brain	37.0	56.4	64.0	186.0	326.4	529.8
Lens	76.7	116.1	120.9	190.8	338.4	574.0
Heart[a]	18.3	28.0	35.2	180.9	312.0	484.4
Gallbladder	12.0	18.4	25.0	178.6	305.0	462.2
Remainder	26.0	39.6	46.5	182.3	315.6	496.3
Point dose	164.7	248.9	267.8	210.7	384.3	751.4
E (mSv)						
w_T [*ICRP*, 1991]			45.83			492.48
w_T [*ICRP*, 2007]			48.45			496.74

[a]Heart tissue shielding files were not available, and lung distributions are used.

mum and the 1972 SPE for 5 and 20 g/cm^2 diameter aluminum spheres. The 1972 solar event is represented by the protons fluence spectrum derived by *King* [1974]. SPE spectra are greatly attenuated with shielding and show important variations in doses between tissue types, while GCR produces only modest variation between the organs. The point dose shown is the dose without tissue shielding. Values of point doses are well above organ doses for SPEs and similar to organ doses for GCR. Doses to the skin can be several times higher than that of the internal organs for SPEs [*Kim et al.*, 2006]. An average skin dose may not properly describe the risk to specific skin areas, which are highly variable. A critical factor is the real-time assessment of organ doses at specific tissue locations is the accurate characterization of the energy distribution of protons. Such real-time assessments are an important goal of the EMMREM module.

[42] Up to 15% of crew time may be in extravehicular activities (EVAs) on lunar missions. The major constraint for lunar surface mission is time to return to shelter by short-term warning of SPE onset, and a rover may be the only shelter in the worst case of being far away from a

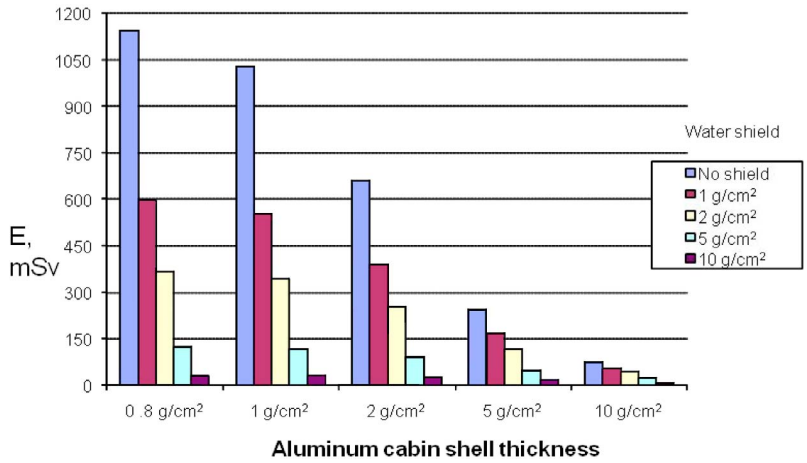

Figure 2. Effective dose analysis of lunar rover concept with water shield augmentation for optimization of shield mass and effective dose reduction.

habitat. Figure 2 shows the radiation analysis of a conceptual lunar rover from the August 1972 SPE. It shows the reduction of effective dose (E in mSv) by increasing cabin shell thickness to above 5 g/cm^2 from the initial 0.8 g/cm^2 of aluminum for the configuration of 2 astronauts sitting in vertical orientation inside a rover. Significant reduction is achieved by adding 5 g/cm^2 of water augmentation shielding inside a rover of 1 g/cm^2 thickness. For the best optimization and protection, parametric optimization analysis should be made for the astronauts' sitting orientation, multifunctional shielding materials, and lunar topology consideration of lunar basin and cliff.

[43] Dose rate is an important factor in risk assessments. The current projection models assume cancer risk is reduced by a factor of 2 when comparing a chronic (low dose rate) exposure to an acute exposure [*NCRP*, 2000]. Acute risks such as prodromal effects are also significantly reduced as the dose rate is decreased [*Hu et al.*, 2009]. All GCR exposures occur at low dose rate, loosely defined by the NCRP as dose rates <50 mSv/h. SPEs occur with highly variable dose rates, however the majority of events will still be classified as low dose rate. An exception is the 1972 SPE, which occurred with a rapid onset and included BFO dose-equivalent rates (Figure 3) above 200 mSv/h at the peak of the event. These higher dose rates could lead to prodromal effects if astronauts do not seek shelter in radiation shielding within a few hours [*Hu et al.*, 2009].

[44] Annual GCR effective doses are calculated in Figure 4 for various charge groups inside a spacecraft of 5 g/cm^2 aluminum from GCR at solar minimum in interplanetary space (blue bars). These heavy nuclei are a concern for radiation risks, because they have the highest biological effectiveness and leave columns of damage at the molecular level as they traverse a biological system, and because a plausible mitigation measure by shielding is impossible due to the high penetration power of energetic particles of GCR.

[45] On the Martian surface, the interplanetary GCR fluxes at solar minimum were propagated through its atmosphere of 16 g/cm^2 carbon dioxide. Annual effective doses are shown in Figure 4 on Martian surface (red bars) from GCR at solar minimum, where radiation protection by Martian atmospheric shielding and shadow effect of Mars itself was estimated [*Saganti et al.*, 2004]. Also shown in Figure 4 is the estimate of effective dose for males during the 30 month Mars mission (green bars), which is composed of interplanetary transit to/from Mars for 6 months each way and Mars surface stay for 1.5 years. Organ doses for males and females show small differences due to the variations in body shielding of the various organs. Total effective dose was estimated about 1 Sv for male crew member inside 5 g/cm^2 of aluminum sphere at solar minimum.

[46] In Table 7 cancer risks for males and females of different ages are shown for 180 day lunar surface missions. These results are for the GCR at solar minimum or at solar maximum where the large 1972 SPE is added to the GCR. Cancer risks are similar for these two scenarios; however the uncertainties are larger for GCR compared to SPEs [*Cucinotta et al.*, 2006]. Cancer risks are below a 3% REID for the 180 day lunar surface missions, however the 95% confidence level exceeds these values for some crew variables. Because astronauts often participate in more than one spaceflight, mission length on the moon could be even more constraining than Table 7 suggests. In contrast median REID values for Mars mission scenarios exceed the NASA limits in most scenarios and the upper 95% confidence level often exceeds 10% REID [*Cucinotta et al.*, 2006]. The recent *Committee on the Biological Effects of Radiation* [2006] and *UNSCEAR* [2008] reports provide new analysis of cancer risk coefficients and DDREF values for low-LET radiation exposure based on the most recent epidemiology studies. NASA is currently reassessing values to be used in determining risk to dose conversion factors

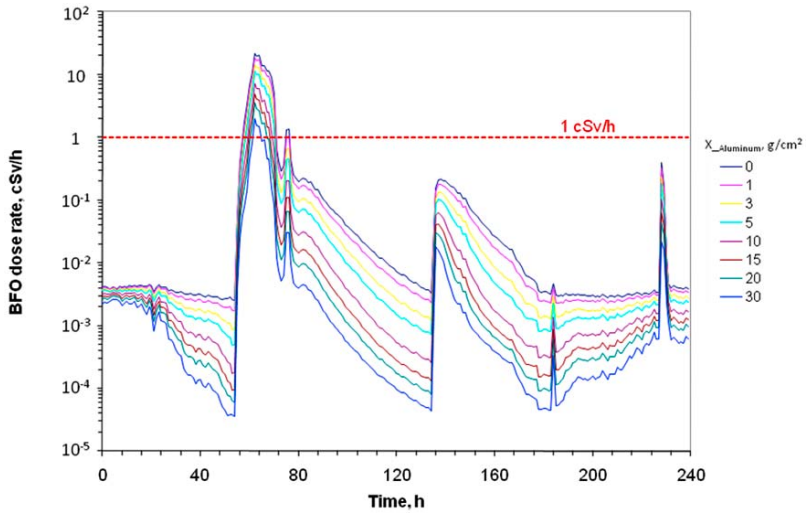

Figure 3. Calculations for the 1972 SPE of the BFO dose equivalent rate versus time for increasing amounts of aluminum shielding. The calculations show that intermediate dose equivalents rates are reached if only thin shields are available.

and performing related updates to cancer projection uncertainty assessments.

5. Conclusions

[47] Astronaut health risks from space radiation are a primary concern for space exploration. A system of Risk limits from ionizing radiation has been implemented at NASA to prevent clinically significant acute health effects and limit late effects such as cancer death. Risk limits for heart disease and central nervous system effects are a more recent concern, and the dose limits and RBE factors for these risks should be considered preliminary at this time. The GCR organ exposures inside spacecraft or on planetary surfaces have been adequately characterized and can be predicted by existing methodologies to a sig-

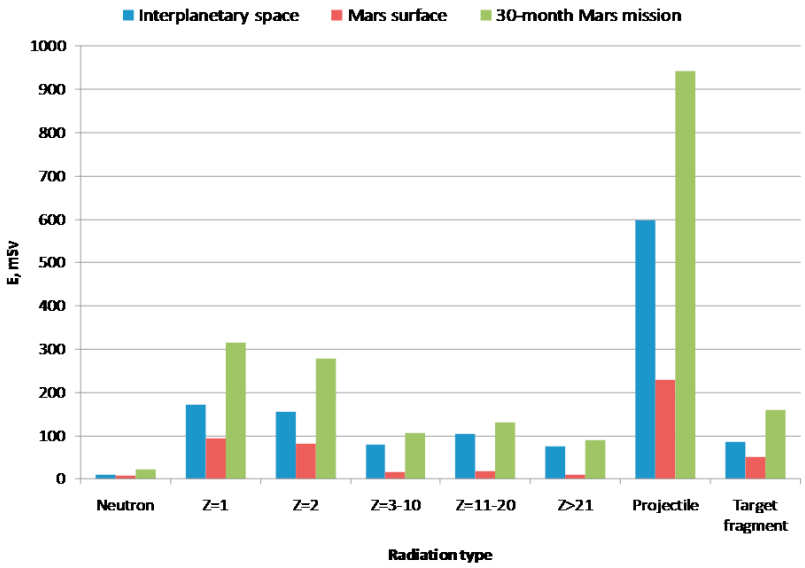

Figure 4. Effective doses for GCR charge groups, the overall projectile-like effective dose (primaries and projectile fragments), and of target fragments inside a spherical spacecraft of 5 g/cm^2 aluminum shield thickness: annual exposure in interplanetary space and on Mars surface and that for 30 month Mars mission.

Table 7. Predictions of the %REID and 95% Confidence Intervals for All Cancers for 180 Day Lunar Surface Missions at Solar Minimum or at Solar Maximum Including the 1972 SPE[a]

Age (years)	Solar Minimum	Solar Maximum With Large SPE
	Females	
35	0.86 (0.25, 3.2)	0.89 (0.31, 2.6)
45	0.64 (0.19, 2.4)	0.68 (0.23, 2.0)
55	0.43 (0.13, 1.6)	0.45 (0.15, 1.3)
	Males	
35	0.71 (0.21, 2.6)	0.75 (0.26, 2.2)
45	0.53 (0.16, 2.0)	0.57 (0.19, 1.6)
55	0.36 (0.11, 1.35)	0.39 (0.14, 1.1)

[a]Calculations assume a 5 g/cm^2 aluminum spherical habitat with a 10 cm water shield. Shown are values for males and females at different ages of exposure using the methods of *Cucinotta et al.* [2006]. Values in parentheses are the 95% confidence intervals (lower, upper).

nificant degree of accuracy. SPEs are highly variable with most leading to small organ doses [*Kim et al.*, 2009b], however the few that lead to high effective doses and the potential mission disruption due to the inability to distinguish in real time a small event from a large event are major problems for exploration missions. To protect against uncertainties in the biological effects of space radiation, NASA uses an ancillary condition of the upper 95% percent confidence level in cancer risk projections. Further research on the biological effects of space radiation and improved approaches to real-time response to SPEs are vital to overcome these major challenges to human space exploration missions. New research findings in these areas could have major impacts on mission design parameters such as mission length, shielding requirements or the need for biological countermeasures and genetic selection of crew members.

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