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Quality factors for space radiation: A new approach

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ABSTRACT

NASA has derived new models for radiological risk assessment based on epidemiological data and radiation biology including differences in Relative Biological Effectiveness for leukemia and solid tumors. Comprehensive approaches were used to develop new risk cross sections and the extension of these into recommendations for risk assessment during space missions. The methodology relies on published data generated and the extensive research initiative managed by the NASA Human Research Program (HRP) and reviewed by the National Academy of Sciences. This resulted in recommendations for revised specifications of quality factors, $Q_{NASA}(Z,\beta)$ in terms of track structure concepts that extend beyond LET alone. The new paradigm for quality factors placed demands on radiation monitoring procedures that are not satisfied by existing dosimetry systems or particle spectrometers that are practical for space exploration where mass, volume, band width and power consumption are highly constrained. We have proposed a new definition of quality factors that relaxes the requirements for identifying charge, Z, and velocity, β, of the incident radiation while still preserving the functional form of the inherent risk functions. The departure from the exact description of $Q_{NASA}(Z,\beta)$ is that the revised values are new functions of LET for solid cancers and leukemia. We present the motivation and process for developing the revised quality factors. We describe results of extensive simulations using GCR distributions in free space as well as the resulting spectra of primary and secondary particles behind aluminum shields and penetration through water. In all cases the revised dose averaged quality factors agreed with those based on the values obtained using $Q_{NASA}(Z,\beta)$. This provides confidence that emerging technologies for space radiation dosimetry can provide real time measurements of dose and dose equivalent while satisfying constraints on size, mass, power and bandwidth. The revised quality factors are sufficiently generalized to be applicable to radiation protection practices beyond space exploration.

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1. Introduction

Systems for radiation protection from occupational exposure to ionizing radiation must include a methodology to optimize constraints that keep individual exposures as low as reasonably achievable (ALARA) and insure that the combination of all efforts will not result in radiation risks that are judged to be unacceptable (International Commission on Radiological Protection, 1977). The ICRP has recognized that the general systems of radiation protection of workers on earth are not appropriate for astronauts exposed to environmental radiations during manned space missions (International Commission on Radiological Protection, 2007; International Commission on Radiological Protection, 2013). One significant issue is the large contribution of high energy, heavy charged particles (HZE) which necessitates the determination of radiation quality factors rather than radiation weighting factors, w_R. NASA has established guidance for both acute effects that might cause performance degradation or sickness resulting from high intensity solar particle events (SPE) and late effects related to the incidence and possible mortality of cancer from continuous long term exposure to galactic cosmic rays (GCR). The current permissible exposure limit (PEL) for astronauts corresponds to a 3% risk of exposure-induced death (REID) evaluated at the 95% confidence level (NASA, 2007; National Council on Radiation Protection and Measurements, 2000).

New models for radiological risk assessment have been proposed that include significant revisions based on new epidemiological data and radiation biology results that indicate RBE differs for leukemia and solid tumors. Extensive computational approaches were used to develop new risk cross sections and the extension

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of these into recommendations for risk assessment during space missions (Cucinotta et al., 2013). The methodology is based on published results generated by the comprehensive research program that was managed by the NASA Human Research Program (HRP) which conducts research and develops technologies that allow humans to travel safely and productively in the environment of space.

In 2011, the National Research Council (NRC) Space Science Board of the National Academy of Sciences began a review of the NASA Model by a panel of experts in the areas of space physics, radiobiology, epidemiology, and risk assessment. The technical evaluation of the NASA model for cancer risks to astronauts due to space radiation was published in 2012 (National Research Council, 2012).

This resulted in recommendations for revised specifications of quality factors, Q, in terms of track structure concepts that extend beyond LET alone and revised estimates of DDREF. The new paradigm for determining quality factors places demands on radiation monitoring procedures that are not satisfied by existing dosimetry systems or particle spectrometers suitable for space exploration. In effect, instrumentation would be required to measure the charge, Z, and velocity, β, of the complete fluence spectrum of heavy charged particles in the galactic cosmic ray continuum $\Phi(Z,\beta)$ generally specified as $\frac{dN(Z,E)}{dE\,d\Omega\,dt}$ where $dN(Z,E)$ is the multiplicity of particle with charge Z and energy E (MeV/n) per cm^2 specified for intervals of energy dE, solid angle $d\Omega$, and time dt.

We have proposed a new definition of quality factors that relaxes the constraint of differentiating charge and velocity while still preserving the functional form of the inherent risk functions that are influenced by relative biological effectiveness and track structure. The departure from the exact description of Q is that the revised values are new functions of LET for solid cancers and leukemia.

We present the motivation and process for developing the new quality factors and the results of extensive tests using GCR distributions in free space as well as the resulting spectrum of primary and secondary particles behind aluminum shields and penetration through water. In all cases the revised dose averaged quality factors agreed with those based on the values originally proposed by NASA. This provides confidence that emerging technologies for space radiation dosimetry can provide real time measurements of dose and dose equivalent while satisfying constraints on size, mass, power and bandwidth.

2. Background

To the first approximation, there is a phenomenological relationship between radiation quality and RBE, which is defined in terms of absorbed dose.

$$RBE = \frac{D_\gamma}{D_L} \propto \frac{\alpha_L}{\alpha_\gamma} \tag{1}$$

where α represents the slope of the linear portion of the dose response curve for reference photons (γ) and heavy charged particles (L).

For convenience in radiation protection, the concept of RBE was introduced through the quantity of dose equivalent, H, that correlates to the detrimental effects of stochastic late effects. H is defined as the dose at the point of interest, D, multiplied by an RBE based Quality Factor, Q (International Commission on Radiological Protection, 1977). This was later modified to form an equivalent dose, $H_{T,R}$, which is the dose averaged over a tissue or organ, D_T, multiplied by a radiation weighting factor, w_R for radiation of type, R (International Commission on Radiological Protection, 1990). The ICRP provided a table for recommended radiation weighting factors for common types of radiation but concluded that for applications in space, where high energy charged particles contribute significantly to the total dose in the human body, a more realistic approach may have to be used (International Commission on Radiological Protection, 1990). For mission planning and operations, NASA uses the model recommended by the NCRP to estimate cancer risks from space LET-dependent radiation quality factors, $Q(LET)$ to estimate organ dose equivalents.

Another approach for characterizing radiation quality for penetrating charged particles is to introduce risk or action cross sections, σ, which express the risk per unit fluence (Curtis et al., 1992; National Council on Radiation Protection and Measurements, 2001). Biophysical models applied to these cross sections provided a more consistent and accurate description of risks for a large variety of radiations and biological end points (Curtis et al., 1992).

NASA has adopted the biophysical approach and developed a risk cross section for carcinogenesis, $\Sigma(Z,E)$, for GCR radiations with atomic number, Z, and energy per nucleon, E (Cucinotta et al., 2013).

$$\Sigma(Z,E) = \Sigma_0 \cdot P(Z,E) + \frac{\alpha_\gamma \cdot LET}{6.24} \cdot \big(1 - P(Z,E)\big), \tag{2}$$

where

$$P(Z,E) = \Big(1 - e^{\frac{-(Z^*/\beta)^2}{\kappa}}\Big)^m \cdot P_{\mathrm{TD}} \tag{3}$$

$$Z^* = Z\Big(1 - e^{-\left(\frac{1.25\cdot\beta}{Z^{2/3}}\right)}\Big) \tag{4}$$

$$P_{\mathrm{TD}} = \Big(1 - e^{-\left(\frac{E}{E_{\mathrm{TD}}}\right)}\Big) \tag{5}$$

The parameter m is the slope of the cross section representing the increase in RBE as the ionization density increases. κ determines the location of the maximum value of RBE and then begins to decline due to saturation effects of increasing ionization density. The quantity Z^* in Eq. (4) represents the reduced charge of the positive ions as they reach low velocities. P_{TD} takes into consideration the decrease in the radial dimensions, "thinning down", of a track as it nears termination (Katz et al., 1971). E_{TD} (MeV/n) in Eq. (5) is set at 0.2 based on experimental data for H and He (Cucinotta et al., 2013).

Ideally, a dosimetric approach and fluence based approach should provide similar estimates of risk, and thus:

$$D \cdot Q = \Sigma \cdot \Phi \tag{6}$$

Considering that:

$$D = \frac{LET}{\rho} \cdot \Phi \tag{7}$$

and

$$RBE = \frac{6.24}{\alpha_\gamma \cdot LET} \tag{8}$$

where the units are expressed as D (Gy), LET (keV/μm) and ρ (g/cm^3). One then obtains the following expression for the proposed NASA quality factor:

$$Q_{\mathrm{NASA}} = \big(1 - P(Z,E)\big) + \frac{6.24(\Sigma_0/\alpha_\gamma)}{LET} \cdot P(Z,E) \tag{9}$$

This constitutes a hybrid approach where absorbed dose is modified by a fluence-based biophysical model for Q_{NASA}.

Implementation of this approach using Eqs. (3), (4), (5) and (9) will introduce significant challenges to the development of instrumentation and data processing. Table 1 is a summary of the parameters that need to be included either by derivation from the model or real-time measurements in space. The coefficients can be applied off line and include values for solid tumors and leukemia,

Table 1
Model parameters for Q_{NASA}.

Model coefficients		Measured quantities	
Parameter	Units	Parameter	Units
Σ_0/α_γ	Gy · μm^2	D	Gy
m	–	LET	keV/μm
κ	Z/β	E, β	MeV/n
E_{TD}	MeV/n	Z	–
DDREF	–		

Table 2
Parameters for Q_{NASA}.

Parameter	Solid cancer		Leukemia	
	$Z \leqslant 4$	$Z > 4$	$Z \leqslant 4$	$Z > 4$
m	3	3	3	3
κ $(Z/\beta)^2$	1000	550	1000	550
Σ_0 (μm^2)	7000	7000	1750	1750
α_γ (Gy^{-1})	6.24	6.24	6.24	6.24
E_{TD} (MeV/n)	0.2	0.2	0.2	0.2

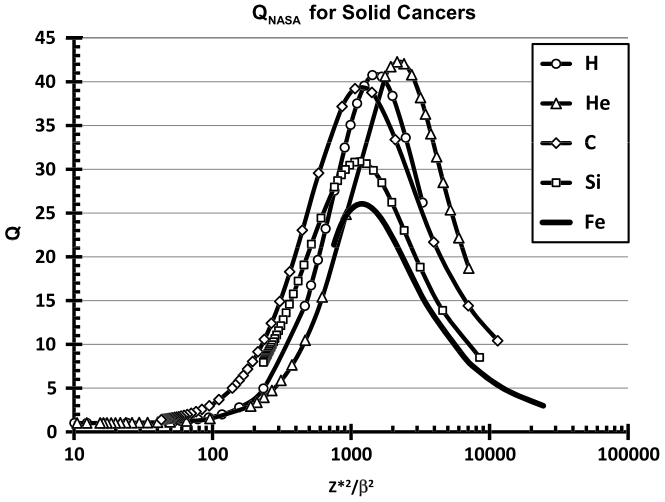

Fig. 1. Q_{NASA} for Solid Cancers as a function of Z^{*2}/β^2 for H, He, C, Si, and Fe.

whereas the onboard dosimetry system must supply the measured parameters for incident charged particles.

Model coefficients were selected to provide quality factors for solid cancers and leukemia as well as for charged particles with $Z > 4$ and $Z \leqslant 4$ (Cucinotta et al., 2013). These are summarized in Table 2.

Fig. 1 shows the values of Q_{NASA} for solid cancers as a function of Z^{*2}/β^2 for H, He, C, Si and Fe. The coefficients Σ_0/α_γ, m, κ and E_{TD} are nominal values shown in Table 2. Q_{NASA} has a maximum value near 40 for ions with $Z < 6$ and a peak value near 25 for Fe. This is a reflection of the track structure model where heavy particles have a larger velocity for a fixed value of Z^{*2}/β^2. This illustrates the complex nature of Q_{NASA} since the estimation of Q requires identification of Z and β (e.g., MeV/n).

Fig. 2 shows values of Q_{NASA} for solid cancers as a function of energy per nucleon, E. This illustrates the large dynamic spread in energies where Q_{NASA} is maximum and therefore must be within the window of sensitivity of the instrumentation.

3. Methodology

We have developed a process to evaluate the implications of implementing Q_{NASA} for typical distributions of GCR, $\Phi(Z, \beta)$, with using energy per nucleon, E (MeV/n), as the measure of β. Our

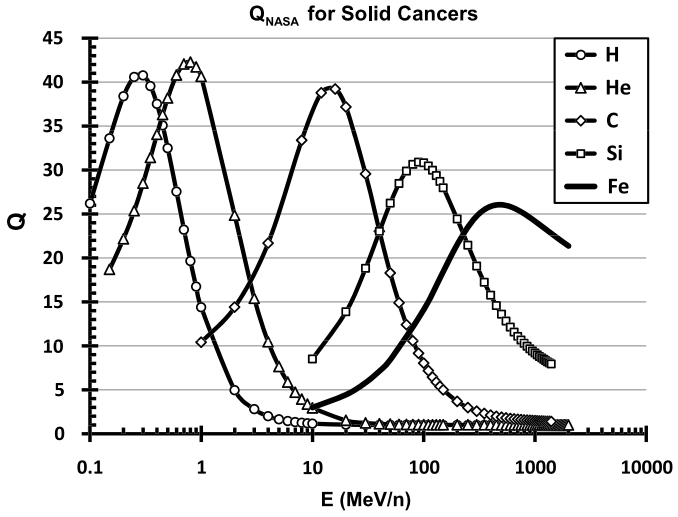

Fig. 2. Q_{NASA} for Solid Cancers as a function of Energy per nucleon (MeV/n) for H, He, C, Si, and Fe.

approach has been to combine the expected GCR fluence, $\Phi(Z, E)$, with $Q_{NASA}(Z, E)$ to approximate the profile of dose equivalent, $H(Z, E)$ with the objective of identifying regions where it would be possible to relax or compress specifications for detector requirements while focusing on other regions of the spectrum without compromising risk assessment. This is summarized in the following steps:

1) Compute $Q_{NASA}(Z, E)$ for the range Z (1 to 26) and MeV/n (25, 2000).
2) Select a distribution of GCR fluence, $\Phi(Z, E)$, for the same range (GCR O'Neill, 2010; Wilson et al., 1995).
3) Compute the dose delivered from charged particles, $D(Z, E) \sim \Phi(Z, E) \cdot LET(Z, E)$.
4) Compute the dose equivalent from charged particles $H(Z, E) \sim D(Z, E) \cdot Q_{NASA}(Z, E)$.
5) Compute the dose averaged quality factor $\overline{Q}_{NASA}$ for these conditions.
   Where

$$\overline{Q}_{NASA} = \frac{\sum_Z \int_E Q(Z, E) \cdot D(Z, E)\, dE}{\sum_Z \int_E D(Z, E)\, dE} \tag{10}$$

6) Evaluate regions of (Z, E) that have the greatest influence on $\overline{Q}_{NASA}$.
7) Repeat for additional fluence distributions.

Fig. 3 shows a 3-dimensional surface profile of Q_{NASA} for solid tumors as a function of Z and E. There is no apparent portion of this profile that vanishes or remains relatively constant.

Results of the computations for Φ, D, H, and $\overline{Q}_{NASA}$ using GCR fluence in free space at solar minimum, solar maximum and penetration of solar minimum through 2 cm of aluminum are summarized in Table 3. Although 99% of the fluence for GCR in free space and penetrating a thin layer of aluminum consists of charged particles with $Z \leqslant 4$, they only contribute to about 50% of the dose and 10% of the dose equivalent for solid cancers. The dose averaged quality factors are similar for both solar minimum and maximum, but are reduced by 20% after penetration through the 2 cm of aluminum. The values of $\overline{Q}_{NASA}$ for leukemia are more than a factor of two less than the values for solid tumors. Light particles contribute more than 20% of the dose equivalent for leukemia compared with about 10% for solid cancers.

Fig. 4 shows a surface profile of $H(Z, E)$ for solid cancers from the GCR spectrum at solar minimum. There is an observable

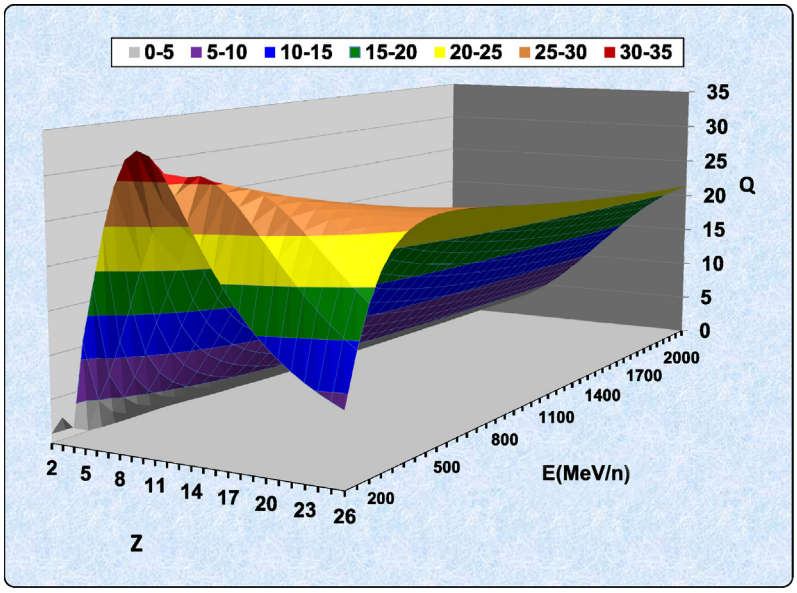

Fig. 3. Surface profile of Q_{NASA} as a function of atomic number (Z) and energy per nucleon E (MeV/n).

Table 3
Results of computations for $\Phi(Z, \text{MeV/n})$, $D(Z, \text{MeV/}n)$, $H(Z, \text{MeV/n})$ and $\overline{Q}_{NASA}$.

GCR	Φ		D		Q_{NASA}	H		$\overline{Q}_{NASA}$
	$Z \leqslant 4$	$Z > 4$	$Z \leqslant 4$	$Z > 4$		$Z \leqslant 4$	$Z > 4$	
Solar max.	99%	1%	50%	50%	Solid cancers	7%	93%	7.0
Solar min.	99%	1%	60%	40%		8%	92%	7.0
2 cm Al	99%	1%	70%	30%		14%	86%	5.0
10 cm Al + 20 cm water	99.9%	0.1%	96%	4%		86%	14%	2.2
Solar max.	99%	1%	50%	50%	Leukemia	21%	79%	2.4
Solar min.	99%	1%	60%	40%		24%	76%	2.4
2 cm Al	99%	1%	70%	30%		36%	64%	2.0
10 cm Al + 20 cm water	99.9%	0.1%	96%	4%		92%	8%	1.3

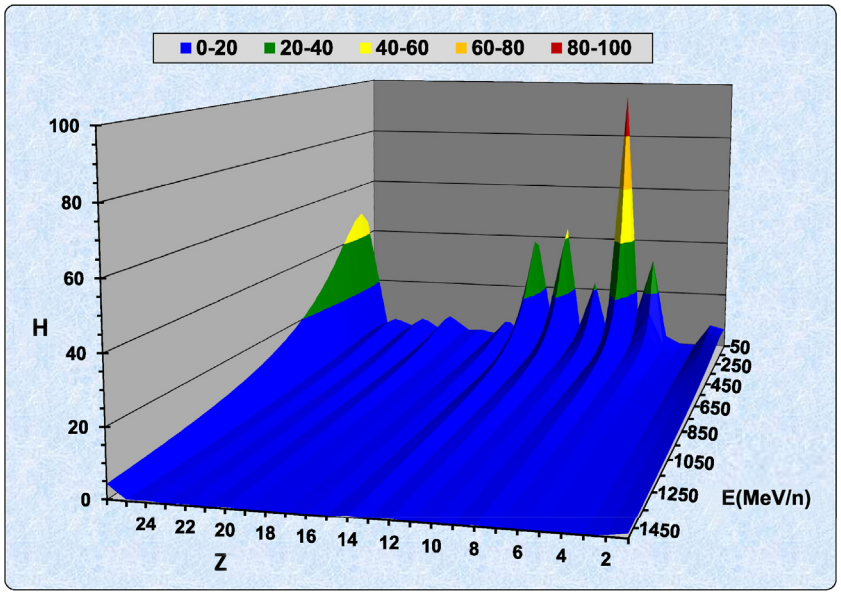

Fig. 4. Surface profile of dose equivalent ($D \cdot Q_{NASA}$) in free space for an incident fluence of GCR at solar minimum, $\Phi_{min}(Z, \text{MeV/n})$.

increase of H below 100 MeV/n with specific enhancements for C, O, Ne, Mg, Si and Fe. However, there are contributions to H throughout the entire distribution of Z and MeV/n. Integration of the distributions show that 70% to 80% $H(Z, E)$ is delivered by particles with energies greater than 100 MeV/n. There did not appear to be any region where charge or velocity could be grouped to relax demands on detector systems.

We have explored another approach to forming a quality factor suitable for space radiations that eases the demands on dosimetry systems. The objective was to preserve the functional form of

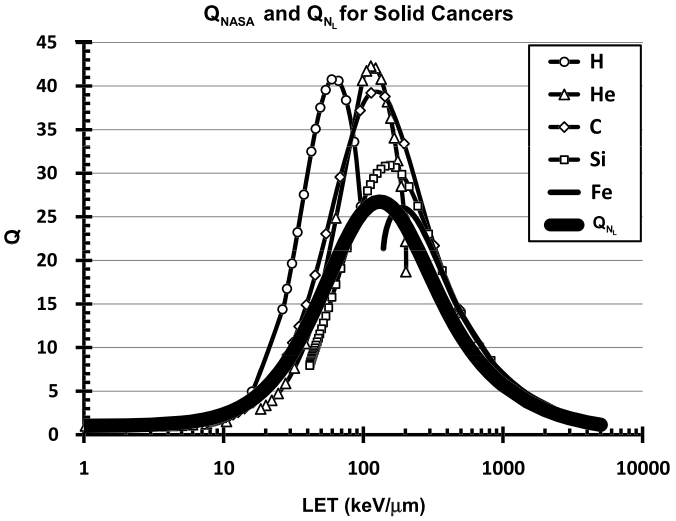

Fig. 5. Q_{NASA} for H, He, C, Si, Fe and Q_{N_L} for solid cancers as a function of LET.

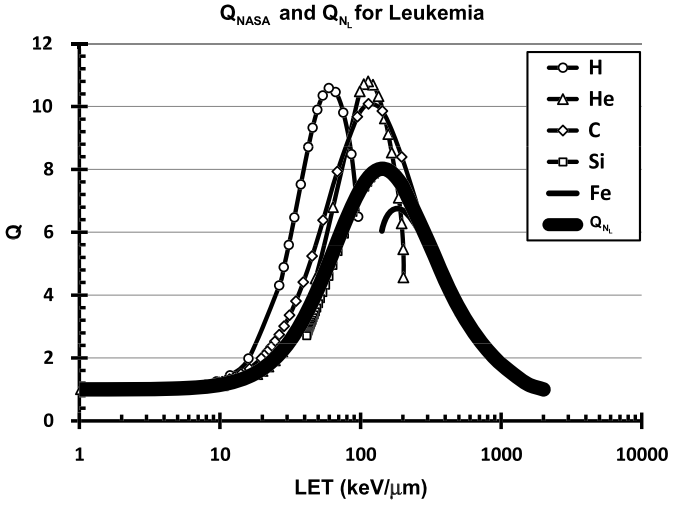

Fig. 6. Q_{NASA} for H, He, C, Si, Fe and Q_{N_L} for leukemia as a function of LET.

Table 4
Coefficients for Q_{N_L}.

	Solid cancers	Leukemia
Σ_L (keV/μm)	5700	1800
Λ (keV/μm)	70	71
m	3.0	3.5

Q_{NASA} but replace (Z^{*2}/β^2) in Eq. (9) and Eq. (3) with LET in units of keV/μm:

$$Q_{N_L}(LET) = \left(1 - P(LET)\right) + \frac{\Sigma_L}{LET} \cdot P(LET) \tag{11}$$

$$P(LET) = \left(1 - e^{-\frac{LET}{\Lambda}}\right)^m \tag{12}$$

The coefficients, Σ_L, Λ, and m are new model parameters for Q_{N_L} having values shown in Table 4.

Fig. 5 shows a comparison of Q_{NASA} and Q_{N_L} for solid cancers and Fig. 6 shows the comparison for leukemia. Fig. 7 shows the surface profile of Q_{N_L} as a function of Z and MeV/n. This surface profile for Q_{N_L} preserves the same general shape as that for Q_{NASA} in Fig. 3. However as illustrated in Figs. 5 and 6, Q_{N_L} has a smaller peak value at a fixed value of LET for all particles but broader width compared with Q_{NASA} for individual values of Z.

We have performed an evaluation of the dose averaged values of $\overline{Q}_{NASA}$ and $\overline{Q}_{N_L}$ from charged particles similar to that outlined above. For this we have used the code HZETRN (Wilson et al., 1995; Slaba et al., 2010) to transport the GCR fluence distribution, $\Phi(Z, E)$, at solar minimum through thick aluminum shields followed by volumes of water. The computations include fragmentation and slowing down as a function of depth in water at the surface, 1 cm, 5 cm, 10 cm and 20 cm, downstream from 2 cm, 5 cm and 10 cm of aluminum. The computation includes elements from $Z = 1$ to $Z = 26$ and corresponding velocities from E = 1 MeV/n to E = 50 000 MeV/n.

Fig. 8 shows the results for solid cancers and Fig. 9 shows results for leukemia. In all cases $\overline{Q}_{N_L}$ was within 5% of the values obtained for $\overline{Q}_{NASA}$. These data show that for penetration through 48 g/cm^2 of aluminum and water, both $\overline{Q}_{N_L}$ and $\overline{Q}_{NASA}$ converge to similar values. In this situation the fluence is strongly dominated by H and He as shown in Table 3. Beyond 50 g/cm^2, the majority of the heavy particles have either stopped or fragmented

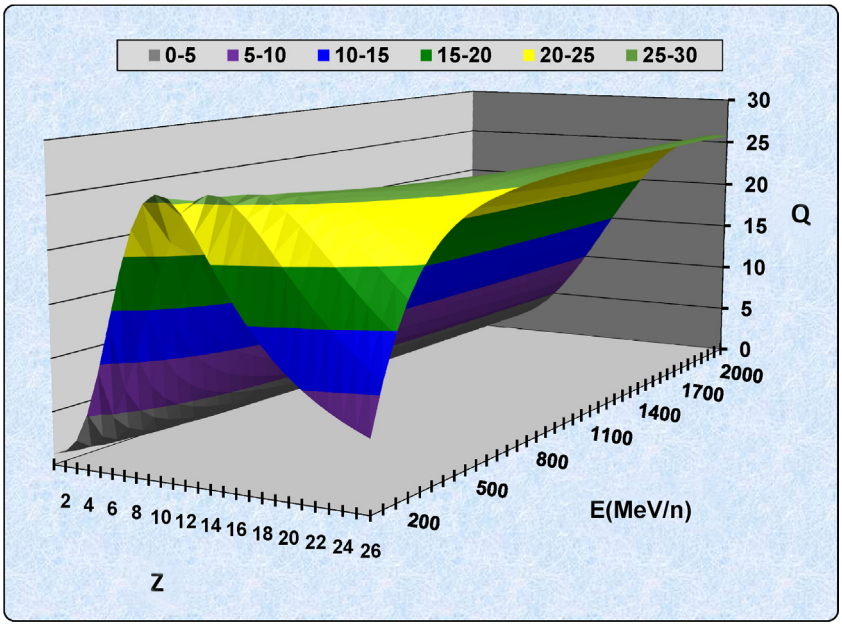

Fig. 7. Surface profile of Q_{N_L} for solid cancers as a function of atomic number (Z) and energy per nucleon E (MeV/n).

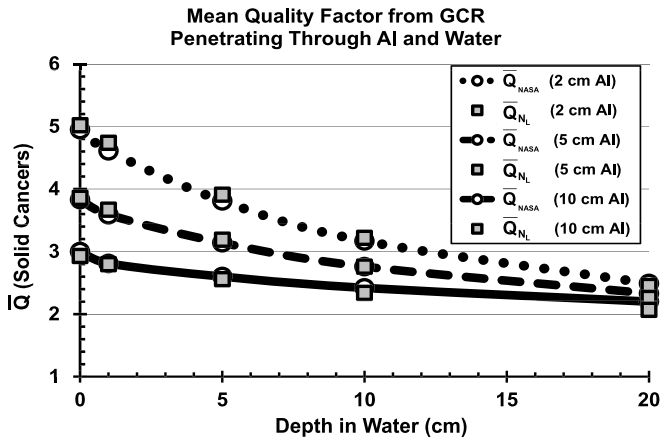

Fig. 8. Dose mean Quality Factors ($\overline{Q}_{NASA}$ and $\overline{Q}_{N_L}$) for solid cancers resulting from the solar minimum GCR spectrum penetrating various depths in water downstream from aluminum shields.

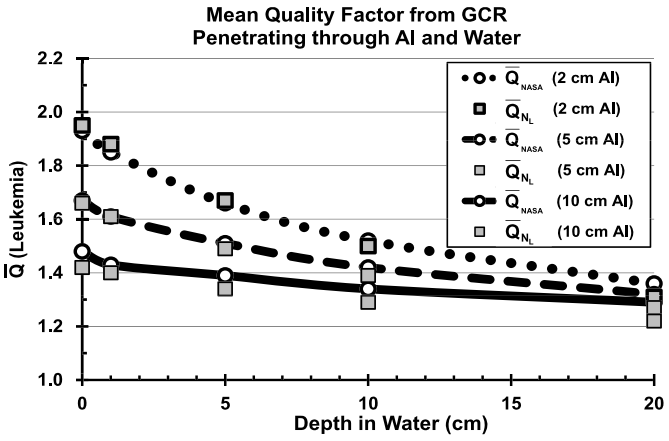

Fig. 9. Dose mean Quality Factors ($\overline{Q}_{NASA}$ and $\overline{Q}_{N_L}$) for leukemia resulting from the solar minimum GCR spectrum penetrating various depths in water downstream from aluminum shields.

into light particles. The composition is almost exclusively H and He and the quality factors for charged particles remain stable as the shields become thicker. However, in this regime, the dose and dose equivalent from directly ionizing charged particles will be diminished and be dominated by secondary neutrons.

4. Summary

New paradigms for assessing REID for space radiation place demands on radiation monitoring procedures that are not satisfied by existing space flight dosimetry systems or compact particle spectrometers. The derivation of the proposed quality factors for the composition of HZE particles in the GCR is based on extensive ground based research over several decades. The amount of information relating to the physical behavior and biological response of heavy high energy particles with a large range of LET is unprecedented. The results of these efforts have been published in conference proceedings, peer reviewed literature and vetted in over 20 annual workshops. The process of consolidating this vast reservoir of information into risk models and radiation quality factors has been thorough and reviewed by the National Academy of Sciences.

However the routine implementation of the recommended quantities, in particular, radiation quality factors, places severe demands of radiation dosimetry systems that are necessary for providing measurements for assessing both dose and dose equivalent.

We have presented an alternate approach to defining quality factors that does not require identification of the charge (Z) and E (MeV/n) of the incident radiation. It is based on redefining the new quality factors as a function of LET, independent of charge and energy. It certainly can be argued that LET alone is insufficient to describe the complex nature of biological response to ionizing radiation. But the process attempts to preserve the functional form of the new quality factors and differences between risk estimates for solid cancers and leukemia.

We are also aware that defining quality factors based on LET is not an original approach. The International Commission of Radiological Protection (ICRP) recommended a function for $Q(L)$ in Publication 26 (International Commission on Radiological Protection, 1977) and revised this in Publication 60 (International Commission on Radiological Protection, 1990). Fig. 10 shows these relationships along with the one suggested here. There is no theoretical foundation or phenomenological evidence to suggest that risk coefficients remain constant for high LET or reach a maximum point value and transform immediately from a linear relationship

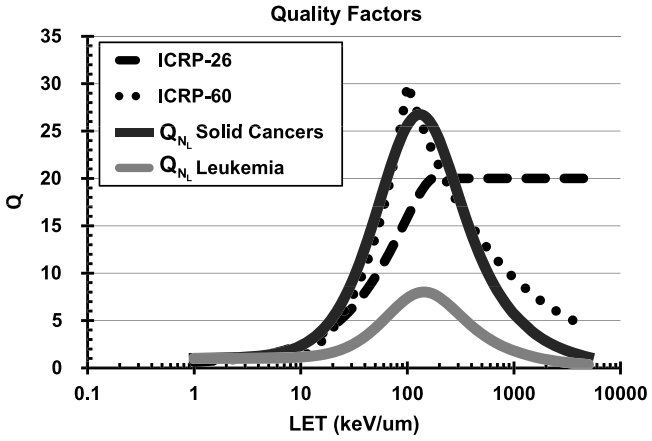

Fig. 10. Quality factors defined by ICRP 26, ICRP 60 and Q_{N_L} for solid cancers and leukemia as a function of LET.

into a power function proportional to $LET^{-1/2}$. As can be seen, Q_{N_L} preserves the increase in values from low LET to a maximum value of 27 at 130 keV/μm followed by a decrease as LET continues to increase. The departure from ICRP 60 is the symmetrical shape of the distribution as opposed to an instantaneous change in slope. The mathematical form is a continuous differentiable function for all meaningful values of LET. It is argued that this is a more representative reflection of the biophysical processes based on long standing models and improved scientific data. The ICRP quality factors do not distinguish between solid cancers and leukemia.

Recommendations for radiation protection often need to balance between fidelity to biophysical processes that control risk and operational constraints. The goal is to accommodate both ends of this spectrum without sacrificing reasonable expectations for demonstrating compliance with optimization and limitation. It is suggested that this formulation of Q_{N_L} satisfies this goal for astronauts during manned space exploration missions and could be considered as a revision for quality factors in general.

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