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ON THE POTENTIAL IMPACT OF THE NEWLY PROPOSED QUALITY FACTORS ON SPACE RADIATION PROTECTION

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Abstract

The recently proposed changes in the defined quality factor hold great potential of easing some of the protection requirements in protection from the electron and proton environments of the near earth environment. At the same time the high Linear Energy Transfer (LET) components play an even more important role which must be further evaluated. Several recommendations are made which need to be addressed before these new quality factors can be implemented into space radiation protection practice.

Introduction

With the advent of proposed new recommendations on the quality factor Q to be used in risk assessment (ref. 1), it seems prudent to evaluate its impact on radiation protection practice in the space program. The most significant features of the new recommendations are the increased importance of high LET radiations (particles with a large linear energy transfer, LET) and the question of the standard reference radiation. These are both critical issues in space radiation risk assessment.

Although the new recommendations on high LET values of Q are of great importance, the question of low LET values of Q is also of current critical interest. In all previous recommendations, although there has been a lingering question about possible differences due to the choice of low LET reference radiation, it was assumed that Q was assumed to be unity for LET less than 35 keV/μm. However, the present experimental data base now confirms that significant differences between 100 keV x-rays and cobalt (60) gamma rays exist (ref. 1). This fact holds important potential consequences for risk assessment in the space program since a sizeable fraction of exposure comes from near minimum ionizing charged particle exposure (~ 0.2 keV/μm) which may carry a smaller risk than presently assumed under the previous Q recommendations.

In the present report, we make a preliminary evaluation of the potential impact of these proposed new recommendations on space radiation risk assessment. There are several questions which NASA needs to consider concerning the methods used in risk assessment, and it is recommended that NASA requirements be clarified.

The Quality Factor

Although ionizing radiation interaction occurs primarily through the formation of ions in materials, the spatial distribution of the ions on a microscopic scale is found to be a contributing factor in determining biological response. The term radiation quality is applied to denote these differences in the spatial distribution, and the quality factor is introduced in risk assessment schemes to account for the quality of the radiation. The term equivalent dose, H, is taken as an indicator of predicted biological response and is related to the absorbed energy per unit mass, the physical dose D, through the quality factor Q as

$$H = Q\,D \tag{1}$$

Exposure limits are expressed in terms of exposures to some reference radiation for which Q is assumed to be unity. All previous recommendations assumed Q to be unity for LET values less than 35 keV/μm. The current values given in the International Commission on Radiation Units and Measure report number 16 (ICRU 16, see ref.2) for Q are given in table I and shown in figure 1 in comparison to the function

$$Q_p(S) = \begin{cases} 12.5\ \ell n(1 + S/437.5) & S > 40\ \text{MeV/cm} \\ 1 & S > 40\ \text{MeV/cm} \end{cases} \tag{2}$$

where S is the charged particle stopping power in water (MeV/cm). This is related to LET (keV/μm) as

$$LET_\infty \equiv L = S/10 \tag{3}$$

New recommendations of quality factors are expressed in units of lineal energy given in International Commission on Radiation Units and Measure report number 40 (ICRU 40, see ref. 1) which have been expressed as an average quality factor for fixed LET and found to have the following relation (ref. 3):

$$\overline{Q}(L) = \frac{60,000}{L} (1 - e^{-4.6\mathrm{x}10^{-5} L^{2.03}}) \qquad (4)$$

Values of $\overline{Q}$ are shown in figure 1. The average quality factors for electrons and protons are shown in figures 2 and 3 as a function of particle energy over the range most important to space applications. It is clear from these figures that Q is less than unity over broad regions important to space radiation protection. This has the potential for great impact on current protection practices as applied in the space program.

Some Effects on Space Station Dose Assessment

To begin the evaluation of the impact on the current space station shield design, the space station proton environment is approximately

$$\phi(E) = 3.63 \times 10^4 e^{-E/243}, \text{ p/cm}^2\text{-MeV-day} \qquad (5)$$

The physical dose and equivalent dose for the two quality factors have been calculated using

$$D(x) = \int_0^\infty S(E_o)\, \phi(E_o)\, dE, \qquad E_o = \xi[x + R(e)] \qquad (6)$$

where $\xi(x)$ denotes the energy vs. range relation in water. The equivalent dose is evaluated using

$$H(x) = \int_0^\infty Q_p(E)\ S(E_0)\ \phi(E_0)\ dE \tag{7}$$

where $Q_p(E)$ is shown in figure 2. The average space quality factor is given as

$$\langle Q \rangle = H(x)/D(x) \tag{8}$$

The reduction in dose equivalent expected by the new recommendation is given by

$$r = \frac{\langle Q \rangle\ (\text{ICRU40})}{\langle Q \rangle\ (\text{ICRU16})}$$

and is seen in figure 4 to be on the order of 50-70 percent. The potential effects on easing current space radiation practices are enormous. A correspondingly larger reduction is expected in the case of electron exposure. But, these reductions may prove illusory.

A Note of Caution

Although the newly recommended values for Q could ease protection requirements from low LET radiations, the high LET components of high charge and energy (HZE) particles, nuclear reaction produced components (stars and neutrons), and secondary electrons all have relatively higher quality factors under the new recommendations. Clearly a program to evaluate the relative importance of various components is required to place methods used by NASA on a sound foundation (see Appendix for further detail).

Furthermore, the limits of maximum permissible doses now in effect were based on previous reference exposures for which Q is assumed to be unity below 35 keV/µm. Hence, the old limits may not generally be applicable with the new quality factors. This situation requires clarification.

Recommendations

There are several points which need to be clarified and some associated tasks are proposed:

1. NASA needs to seek clarification on the relation between the newly recommended quality factors and the presently recommended exposure limits used in the space program.
2. NASA needs to seek clarification on the use of the newly proposed quality factor in calculations of low LET components (See Appendix).
3. An evaluation of the variation of Q at low LET on electron shield design and dose assessment needs to be made for typical space environments.
4. A re-evaluation of nuclear star effects in energetic proton exposures needs to be made. A careful re-evaluation of the recoil energy in formation of nuclear stars is a critical issue.
5. The role of neutrons in space shielding needs to be re-evaluated.
6. New dose kernels for protons and electrons need to be derived for use in space shield analysis.
7. The impact on dosimetry requirements needs to be assessed.

References

1. ICRP/ICRU Joint Task Group: The Quality Factor in Radiation Protection. ICRU Report 40, April 1986.
2. International Commission on Radiation Units and Measurements: Linear Energy Transfer. ICRU Report 16, 1970.
3. Townsend, L. W.; Wilson, J. W.; and Cucinotta, F. A.: A Simple Parameterization for Quality Factors From ICRU Report 40. Health Physics. (To be Published).

Table I - Current Recommended Values of Quality Factor (ICRU16)

LET_∞, keV/μm	Q
3.5 or less	1
3.5 - 7.0	1-2
7.0 - 23	2-5
23 - 53	5-10
53 - 175	10-20

Appendix

Calcuational Methods

One's first impression of the new Q in ref. 1 is that there is some mistake since such low values of Q for minimum ionizing radiation (LET~2.2 MeV/cm or 0.22 KeV/μm are contrary to our previous understanding at low LET. However, further reading of the report would imply that the proposed Q is in fact correct but must be properly understood. For example, the effective Q of photons was calculated with the results of figure 3 and are in accord with the experimental observations of RBE. We must, however, obtain further understanding of the means by which figure 3 is obtained since this could have a great potential impact on the actual use of the newly proposed Q. I would mention that we have some doubts about the veracity of figure 3, but must admit that we have not done the calculations.

The procedure for calculating their photon effective Q is as follows: Consider the exposure of a tissue sample sufficiently small so that photon attenuation may be neglected. The photons give rise to a volume source of electrons with the spectrum characteristics of the Compton and photoelectric processes by which they were formed. This electron source spectrum is used to calculate the slowing down spectrum of electrons in the tissue assuming the tissue sample is large enough to keep the electrons in equilibrum. This final electron spectrum $\phi_\gamma(E)$ is used to calculate the effective Q_γ

$$Q_\gamma(E_\gamma) = \frac{\int Q[S_e(E)]\, S_e(E)\, \phi_\gamma(E)\, dE}{\int S_e(E)\, \phi_\gamma(E)\, dE}$$

where E_γ is the photon energy and $S_e(E)$ is the electron stopping power in tissue and $\bar{Q}$ is the LET dependent stopping power (see ref. 3).

If this procedure in fact produces the results of figure 3 of reference 1, then we must consider what procedures to apply to calculate the effective Q for exposures with minimum ionizing radiation.

One could propose that the energy deposite from high energy protons (neglect high LET secondaries in the present discussion which would be treated by the customs of the past) be partitioned into secondary electron components, $S_k(E_p)$, where the total proton stopping power is

$$S_p(E_p) = S_d(Ep) + S_k(E_p)$$

Letting the equilibruim secondary electron spectrum be $\phi_p(E)$, then

$$S_k(E_p) = \int S_e(E)\phi_p(E)\, dE$$

The corresponing effective Q for protons would then be

$$Q_p(E_p) = [Q(S_p)\ S_d(E_p) + \int Q(S_e)\ S_e(E)\ \phi_p(E)\ dE]/S_p(E_p)$$

If the resultant photon calculation of reference 1 is correct, then we expect the main contribution to $Q_p(E_p)$ to come from the electron term. It is obvious that $Q_p(E_p)$ is probobly less than unity. Perhaps about 0.75 as has been proposed in the past.

The real question is this: Is this the intended use of Q as proposed by reference 1? It is not clear from the document itself.

Do note that such a $Q_p(E_p)$ would be model dependent since $S_d(E_p)$ and $S_k(E_p)$ are not precisely known and the secondary electron spectra for proton impact are uncertain.

Assuming that the photon Q valves of reference 1 are correct, we cannot avoid the question on how to utilize the new recommendations for minimum ionizing radiations. Similar to photons, minimum ionizing radiation mediate a large fraction of their energy through secondary low-energy electrons. Should we expect the low LET valves of Q to use such detailed descriptions of track structure in dose estimates? Has the ICRU made such calculations for high energy electrons and protons?

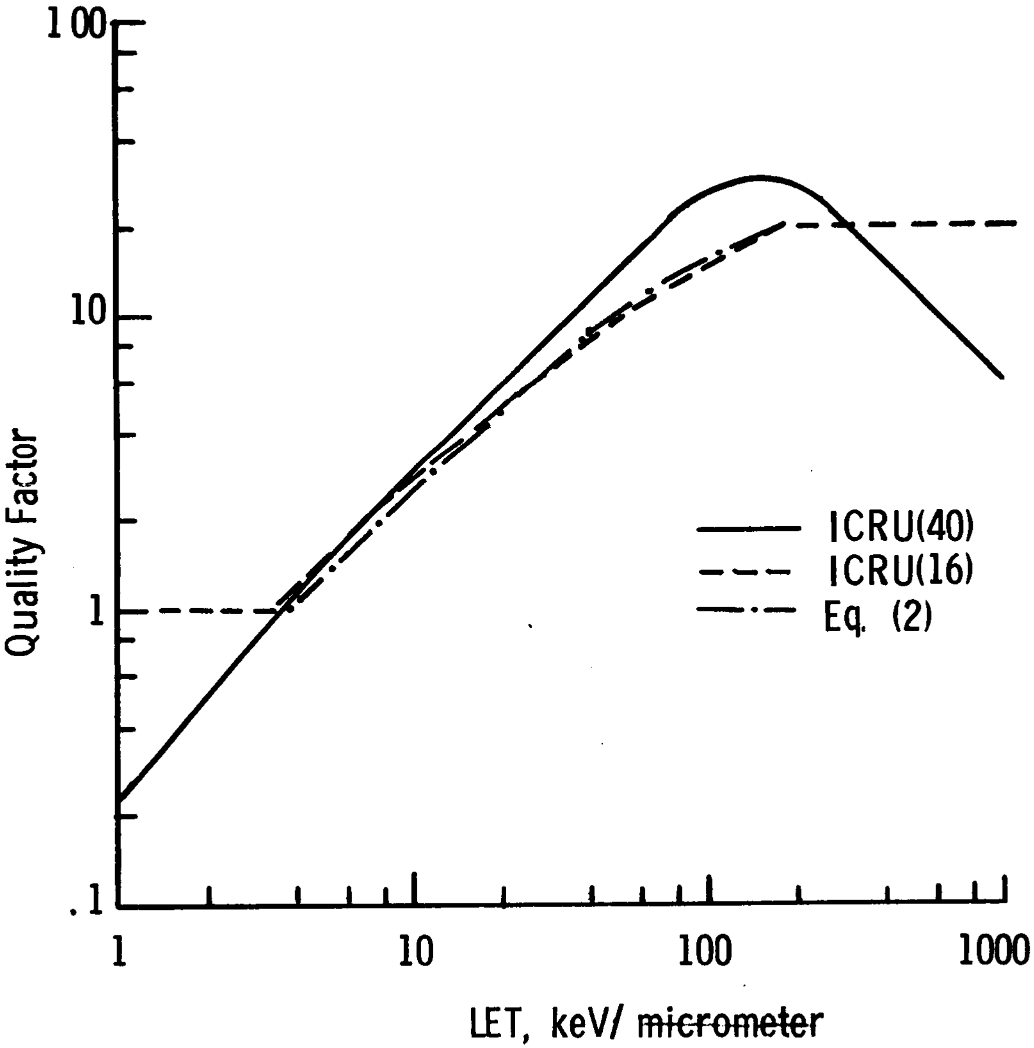

Figure 1. Quality factors relevant to the present discussion.

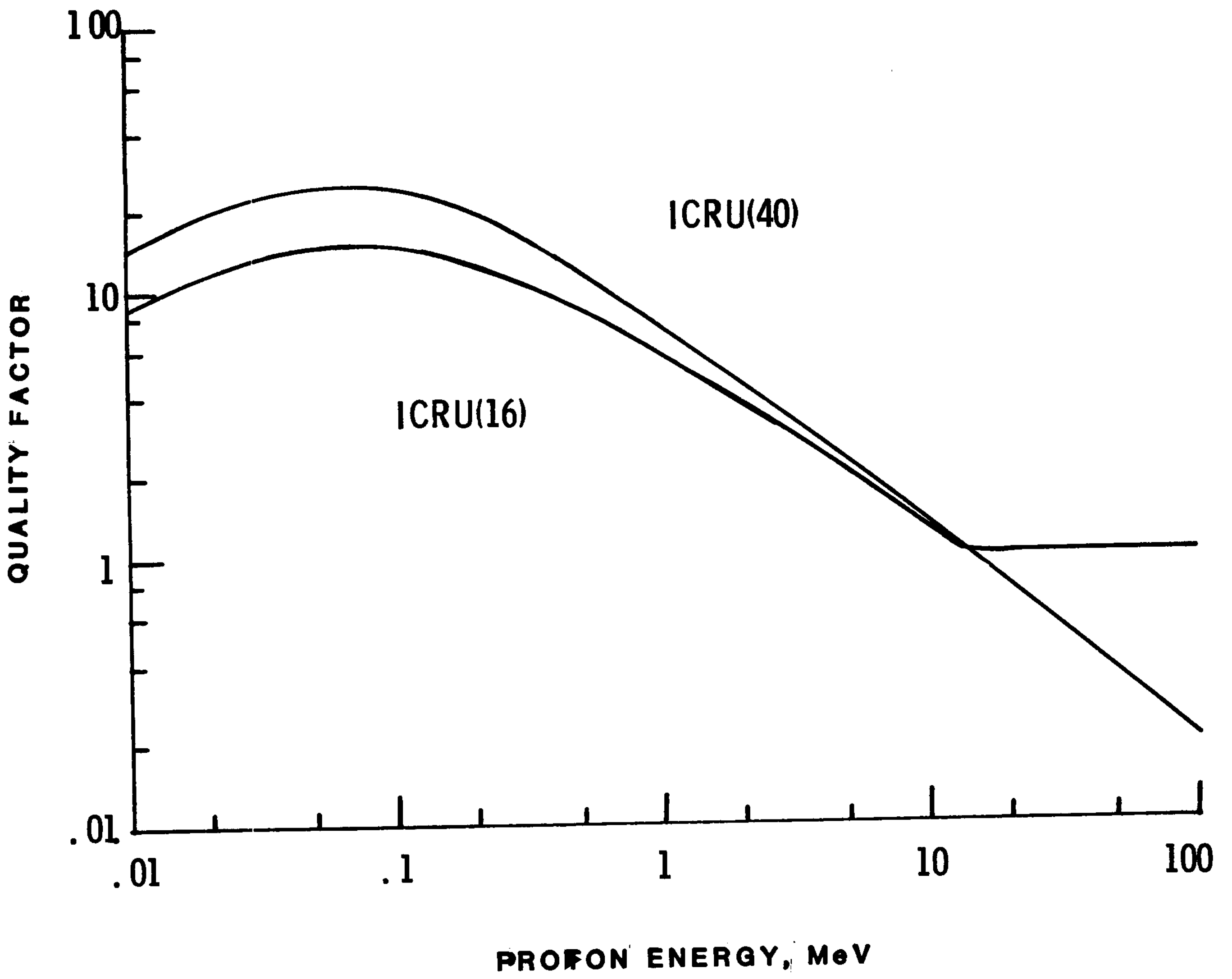

Figure 2. Quality factor for protons as a function of proton energy.

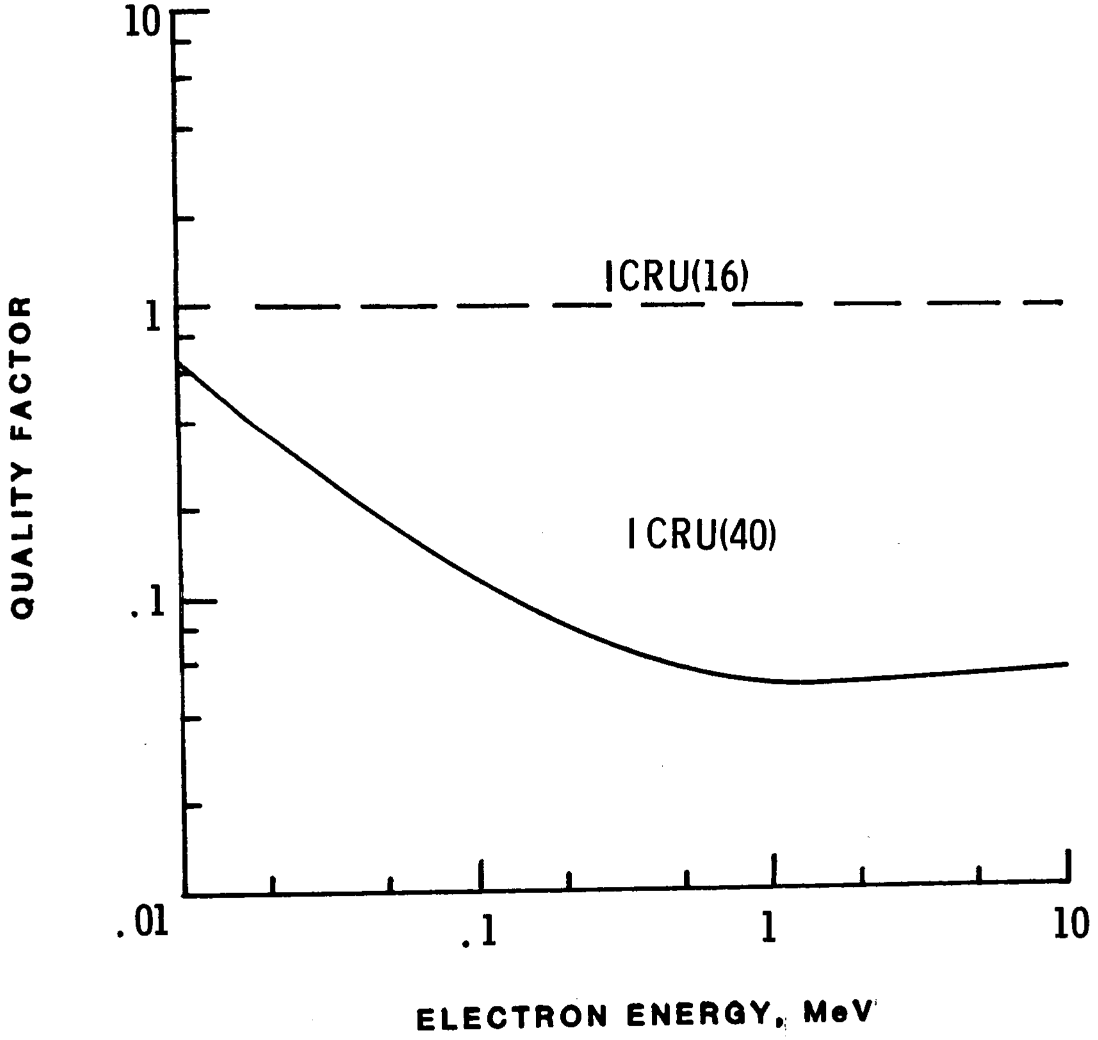

Figure 3. Electron quality factor as a function of electron energy.

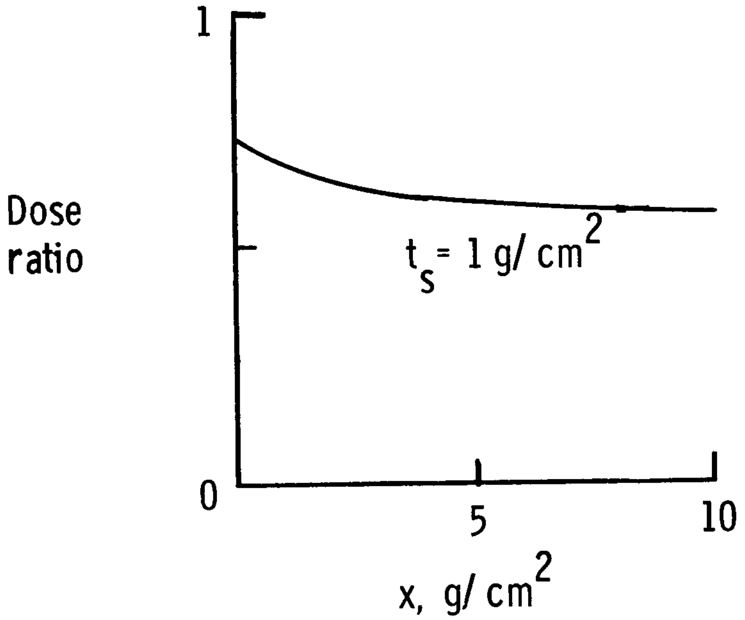

Figure 4. Estimated reduction in equivalent dose of protons in a space station as a function of depth in tissue. Assumed shield thickness is 1 g/cm^2.

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