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Memo

Date: February 3, 2010 (**Revised February 16, 2010**)

To: D. Beavis (RSC Chair)

From: R. Karol

Subject: Chipmunk Quality Factor (QF) Settings Using the New 10CFR835 Neutron Radiation Weighting Factors (w_R) - **Revised**

Purpose

This memorandum reviews the information in References 1 through 3 and documents justification to keep Chipmunk QF settings at their current value of 2.5 at C-AD facilities.

Details of the Analysis

The correct QF-setting is a function of the neutron energy spectrum and the neutron/photon dose ratio at the Chipmunk location. Thus to have accurate Chipmunk QF-settings, these parameters must be precisely known at every Chipmunk location. This is neither practical nor necessary for the intended purpose of the Chipmunks.

The energy spectrum of neutrons at a particular location defines the neutron equivalent dose to an individual at that location. The energy spectrum of neutrons can vary from the full beam energy down to thermal energies depending upon the shielding materials, structures and geometry between the source of the first generation of secondary particles and the dose point in question. Examples of various conditions include:

a) Thick shielding which results in a large source contribution of higher energy neutrons of about 2 MeV
b) Trenches which can result in a source of almost all low energy neutrons less than ~0.5 MeV
c) Labyrinths which can result in a source having a high fraction of lower energy neutrons less 0.1 MeV
d) Labyrinth punch-through or other penetrations which increases the contribution of higher energy neutrons to the source

The Chipmunk QF-setting considers the low-energy neutrons coming from trenches and labyrinths. For example, for the Chipmunk response for EBIS with deuterons, we plan to make adjustment for neutron risk weighting factor and for the fraction of the absorbed dose due to

gamma. Thus there would be a correction-factor of about 6 if we used a Chipmunk with a QF-setting at 2.5. This will be presented to the Radiation Safety Committee in the future. We normally look on a case basis for Chipmunks at our lower energy machines such as EBIS, Tandem and Linac realizing that the Chipmunks are used only as an operational aid.

The 2.5 used for the QF-setting in Chipmunks at high energy machines (>1 GeV) was based on all measurements made near trenches, gates (labyrinths) and thick shield walls. It represents the "average" of different radiation fields at high energy machines realizing that individuals do not spend time exclusively at one type of location.

It is noted that some C-AD Chipmunks have the QF set to 1 if only photons less than about 10 MeV are present; higher energy photons tend to produce neutrons in photonuclear reactions. An example of this would be an RF cavity being tested in a concrete block house.

It is important to note that Chipmunk readings are not used as a legal record for personnel dose. Chipmunks are used as an operational aid to interlock or alarm to alert operators and workers to a change in the area radiation level. Controls for area radiation levels are specified for a wide range of dose rate; for example, a posted Radiation Area is an area greater than 5 mrem/h but less than 100 mrem/h. That is, radiological controls are the same for a range of 20 in equivalent dose rate. The QF settings in the Chipmunk could be off a bit and still give the correct information for intended use, e.g., an operating aid to alert and locate machine tuning issues. Thus, the "ballpark" approach at high energy machines with more attention to QF-settings in the Chipmunk at low energy machines is practicable. The best thing to do from a Human Performance perspective is to minimize the variation in the Chipmunk QF-setting so that errors in Chipmunk locations are minimized.

The following discussion summarizes the justification that the Chipmunk QF-setting of 2.5 is acceptable for high energy machines.

1. Attachment 1 summarizes the new definitions applicable to this review described in Reference 1, paragraph 835.2(b). Attachment 2 graphically shows the new radiation weighting factors for neutrons which have replaced the old concept of quality factor.
2. Reference 2 reviewed a set of typical Fermilab accelerator neutron energy spectra and reassessed the effect on effective dose using the new neutron weighting factors. This spectrum is similar to all accelerators that have adequate shielding to maintain doses ALARA. The conclusion of this analysis was that the average increase in the neutron quality factor, or the neutron radiation weighting factor was 29±9%. Thus the neutron equivalent dose could increase no more than an average factor of 1.38 over the previous measured values.
3. Reference 4, derived from Reference 3, reviewed the measured neutron dose equivalent[1] (1.69 mrem/h average) and added this to the photon dose equivalent (1.89 mrem/h average) based on measurements at many locations in B912 outside the beam line shields during the FY96 high intensity proton run. The average neutron quality factor was determined to be 5.63 and the quality factor for photons is 1.0. The average split between measured neutron and photon dose equivalent rates in the mixed radiation field was 47% for neutrons and 53% for photons. The average neutron plus photon dose equivalent rate was 3.58 mrem/h and the average Chipmunk response with a QF-setting of 2.5 was 5.49 mrem/h. Thus the Chipmunk response, which is a measure of both neutron and photon equivalent dose rate, was conservatively high. Reference 4 concluded that a Chipmunk

[1] Dose equivalent was the term used by the previous versions of 10CFR835.

QF-setting of 2.5 provided enough of a safety factor to maintain compliance with regulations, should the regulatory neutron quality factors, now called neutron weighting factors, increase in the future.

4. Using the above information and the values from the table in Reference 4, the following calculation shows that the current QF-setting of 2.5 remains acceptable under the new 10CFR835 rule:
    a. The average neutron QF of 5.63 is multiplied by 1.38 (see step 2 above) to give an average radiation weighting factor value of 7.77.
    b. This results in an increased average neutron equivalent dose rate of 2.33 mrem/h if one goes back to the FY96 study.
    c. Adding the photon equivalent dose rate of 1.89 mrem/h to this updated neutron equivalent dose rate results in a total measured equivalent dose rate of 4.22 mrem/h.
    d. The average Chipmunk response, with the QF-setting remaining at 2.5, is 5.49 mrem/h. Thus, even if the weighting factor (w_R) is used instead of the QF, the Chipmunk QF-setting of 2.5 is still more conservative in measuring equivalent dose rates at the C-AD high-energy accelerators by a factor of 1.3.

References

1. 10CFR835, Occupational Radiation Protection, 2007 Amended Text dated April 21, 2009.
2. FERMILAB-PUB-08-244-ESH, J. Donald Cossairt and Kamran Vaziri, Neutron Dose per Fluence and Weighting Factors for Use at High Energy Accelerators
3. J. R. Preisig, 1995 Alternating Gradient Synchrotron (AGS) Bonner Multisphere Spectrometry and Carbon-11 Detector Results, July 24, 1995.
4. E. Lessard, Summary of Neutron and Gamma Measurements for FY96, Friday, October 11, 1996.

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Attachment 1

Equivalent dose (H_T) means the product of average absorbed dose ($D_{T,R}$) in rad (or gray) in a tissue or organ (T) and a radiation (R) weighting factor (w_R). For external dose, the equivalent dose to the whole body is assessed at a depth of 1 cm in tissue; the equivalent dose to the lens of the eye is assessed at a depth of 0.3 cm in tissue, and the equivalent dose to the extremity and skin is assessed at a depth of 0.007 cm in tissue. Equivalent dose is expressed in units of rems (or Sv).

Radiation weighting factor (w_R) means the modifying factor used to calculate the equivalent dose from the average tissue or organ absorbed dose; the absorbed dose (expressed in rad or gray) is multiplied by the appropriate radiation weighting factor. The radiation weighting factors to be used for determining equivalent dose in rems are as follow:

RADIATION WEIGHTING FACTORS[1], w_R

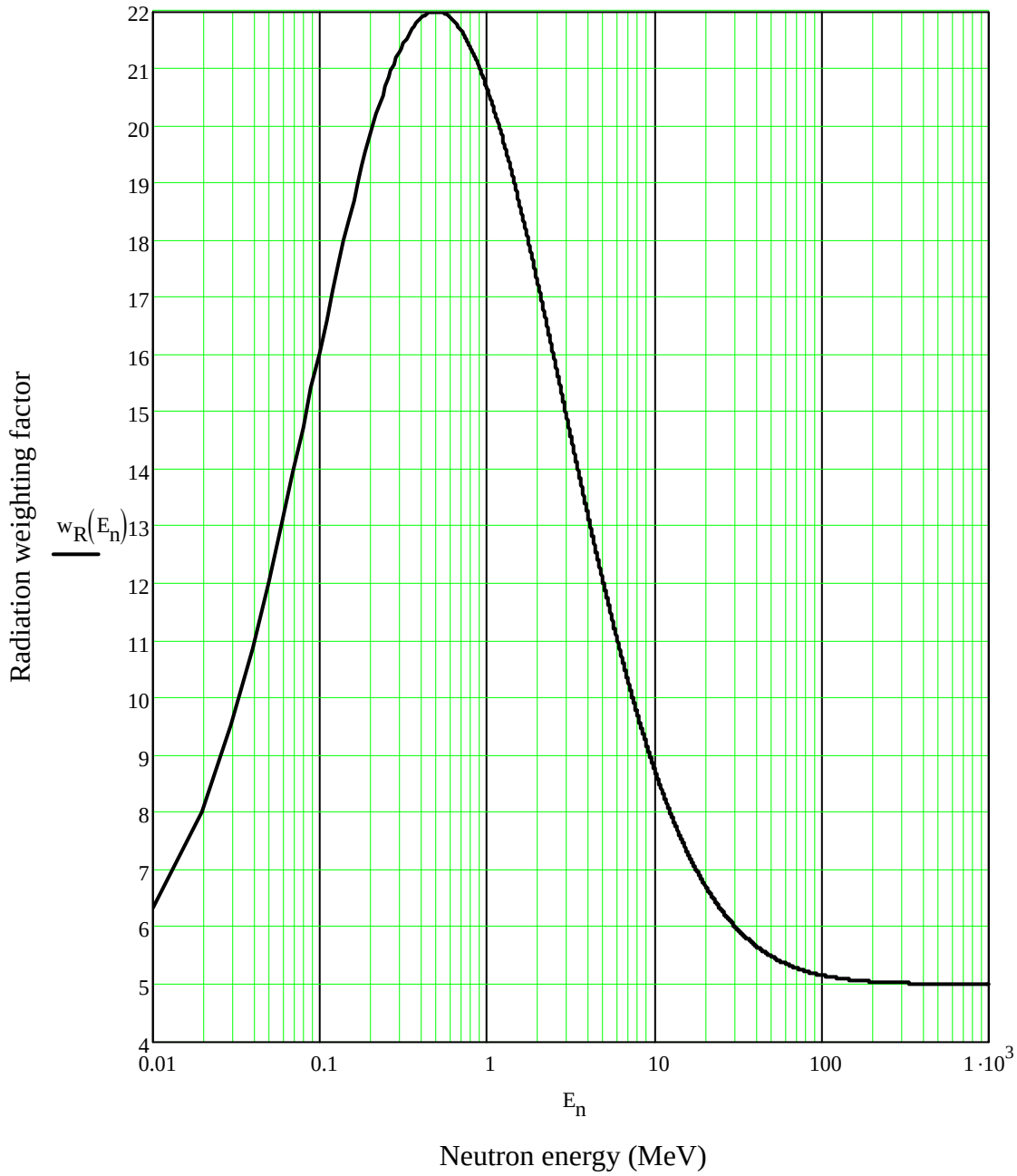
Type and energy range	Radiation weighting factor
Photons, electrons and muons, all energies	1
Neutrons, energy < 10 keV[2, 3]	**5**
Neutrons, energy 10 keV to 100 keV[2, 3]	**10**
Neutrons, energy > 100 keV to 2 MeV[2, 3]	**20**
Neutrons, energy > 2 MeV to 20 MeV[2, 3]	**10**
Neutrons, energy > 20 MeV[2, 3]	**5**
Protons, other than recoil protons, energy > 2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

1. All values relate to the radiation incident on the body or, for internal sources, emitted from the source.
2. When spectral data are insufficient to identify the energy of the neutrons, a radiation weighting factor of 20 shall be used.
3. When spectral data are sufficient to identify the energy of the neutrons, the following equation may be used to determine a neutron radiation weighting factor value:

$$w_R = 5 + 17 \exp\left[\frac{-(\ln(2E_n))^2}{6}\right]$$ Where E_n is the neutron energy in MeV.

Attachment 2

New 10CFR835 Neutron Radiation Weighting Factors

$E_n := 0.01, 0.02 .. 1000$ MeV

$$w_R(E_n) := 5 + 17 \cdot \exp\left[\frac{-(\ln(2 \cdot E_n))^2}{6}\right]$$