Document Title:	
Technical Basis for Conversion from NCRP Report 38 Neutron Quality Factors to ICRP Publication 60 Radiation Weighting Factors for Respective IREP Input Neutron Energy Ranges	Document Number: ORAUT-OTIB-0055 Revision: 00 Effective Date: 06/05/2006 Type of Document: OTIB Supersedes: None

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☒ New ☐ Total Rewrite ☐ Revision ☐ Page Change

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
06/05/2006	00	New document for Conversion from NCRP Report 38 Neutron Quality Factors to ICRP Publication 60 Radiation Weighting Factors for Respective IREP Input Neutron Energy Ranges. First approved issue. Training required: As determined by the Task Manager. Initiated by George D. Kerr and Jack J. Fix.

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ACRONYMS AND ABBREVIATIONS

DOE	U.S. Department of Energy
E	neutron energy
EEOICPA	Energy Employees Occupational Illness Compensation Program Act
hr	hour
ICRP	International Commission on Radiological Protection
IREP	Interactive RadioEpidemiological Program (a computer program)
keV	thousand electron-volts (a unit of energy)
LET	linear energy transfer (along a charged particle track)
MeV	million electron-volts (a unit of energy)
mrem	millirem
NCRP	National Council on Radiation Protection and Measurements
PNL	Pacific Northwest Laboratory
POC	probability of causation
Q	neutron quality factor
$\overline{Q}$	average neutron quality factor (for the energy groups used in dose reconstruction)
Q_s	site-specific neutron quality factor
RBE	relative biological effectiveness (compared to X or gamma radiation)
TBD	technical basis document
TIB	technical information bulletin
U.S.C.	United States Code
Y-12	Y-12 National Security Complex
w_R	radiation weighting factor
§	section

1.0 INTRODUCTION

Technical information bulletins (TIBs) are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather working documents that provide historical background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained. TIBs may be used to assist the NIOSH staff in the completion of individual work required for each dose reconstruction.

In this document the word “facility” is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an “atomic weapons employer facility” or a “Department of Energy [DOE] facility” as defined in the Energy Employees Occupational Illness Compensation Program Act [EEOICPA; 42 U.S.C. § 7384l(5) and (12)]. EEOICPA defines a DOE facility as “any building, structure, or premise, including the grounds upon which such building, structure, or premise is located … in which operations are, or have been, conducted by, or on behalf of, the Department of Energy (except for buildings, structures, premises, grounds, or operations … pertaining to the Naval Nuclear Propulsion Program)” [42 U.S.C. § 73841(12)]. Accordingly, except for the exclusion for the Naval Nuclear Propulsion Program noted above, any facility that performs or performed DOE operations of any nature whatsoever is a DOE facility encompassed by EEOICPA.

For employees of DOE or its contractors with cancer, the DOE facility definition only determines eligibility for a dose reconstruction, which is a prerequisite to a compensation decision (except for members of the Special Exposure Cohort). The compensation decision for cancer claimants is based on a section of the statute entitled “Exposure in the Performance of Duty.” That provision [42 U.S.C. § 7384n(b)] says that an individual with cancer “shall be determined to have sustained that cancer in the performance of duty for purposes of the compensation program if, and only if, the cancer … was at least as likely as not related to employment at the facility [where the employee worked], as determined in accordance with the POC [probability of causation[1]] guidelines established under subsection (c) ….” [42 U.S.C. § 7384n(b)]. Neither the statute nor the probability of causation guidelines (nor the dose reconstruction regulation) define “performance of duty” for DOE employees with a covered cancer or restrict the “duty” to nuclear weapons work.

As noted above, the statute includes a definition of a DOE facility that excludes “buildings, structures, premises, grounds, or operations covered by Executive Order No. 12344, dated February 1, 1982 (42 U.S.C. 7158 note), pertaining to the Naval Nuclear Propulsion Program” [42 U.S.C. § 7384l(12)]. While this definition contains an exclusion with respect to the Naval Nuclear Propulsion Program, the section of EEOICPA that deals with the compensation decision for covered employees with cancer [i.e., 42 U.S.C. § 7384n(b), entitled “Exposure in the Performance of Duty”] does not contain such an exclusion. Therefore, the statute requires NIOSH to include all occupationally derived radiation exposures at the facility in its dose reconstructions for employees at DOE facilities, including radiation exposures related to the Naval Nuclear Propulsion Program. As a result, all internal and external dosimetry monitoring results are considered valid for use in dose reconstruction. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction. NIOSH, however, does not consider the following exposures to be occupationally derived:

- Radiation from naturally occurring radon present in conventional structures

[1] The U.S. Department of Labor is ultimately responsible under the EEOICPA for determining the POC.

- Radiation from diagnostic X-rays received in the treatment of work-related injuries

The purpose of this TIB is to provide a broader technical basis to convert from recorded neutron dose to dose equivalent using the ICRP Publication 60 radiation weighting factors (ICRP 1991). The respective site Technical Basis Documents (TBDs) often present this approach without a clear basis. For example, the Savannah River and Pantex site dosimetry representatives have expressed concern over the origin of the tables in these TBDs that are similar to Table 3.1 of this TIB. The guidance in this TIB states under the Discussion section that the neutron dose equivalent fractions are obtained from the respective TBDs and the methodology of this TIB is applied in the process of conversion to dose equivalent using the ICRP Publication 60 radiation weighting factors.

2.0 BACKGROUND

When routine personal monitoring or radiation survey data are reported, the site-specific neutron quality factor (Q_s) must be removed such that absorbed dose is the fundamental unit and the ICRP Publication 60 (ICRP 1991) radiation weighting factor (w_R) must be applied before the conversion to organ dose for use in IREP (NIOSH 2003). The ICRP selected the value of the radiation weighting factor for a specific type and energy of radiation to be representative of the relative biological effectiveness (RBE) of that radiation in inducing stochastic effects such as cancer due to low radiation doses. Table 2-1 summarizes the radiation weighting factors recommended by ICRP (1991). The values of w_R are broadly compatible with values of neutron quality factors (Q), which are related to the quantity of linear energy transfer (LET). The LET is a measure of the density of ionization along the track of an ionizing particle such as an electron, proton, alpha particle, or heavier nucleus. The value of w_R is set equal to unity for all radiations of low LET, including X and gamma radiation of all energies. The choice for other radiations is based on values of the RBE, regardless of whether the reference radiation is X or gamma.

Table 2-1. Radiation weighting factors from ICRP Publication 60 (ICRP 1991).

Type of radiation and energy range[a]	Radiation weighting factor, w_R
Photons, all energies	1
Electrons and muons, all energies[b]	1
Neutrons, energies less than 10 keV	5
10 keV to 100 keV	10
100 keV to 2 MeV	20
2 MeV to 20 MeV	10
Energies greater than 20 MeV	5
Protons, other than recoil protons with energies greater than 2 Mev	5
Alpha particles, fission fragments, and heavy nuclei	20

a. All values relate to the energy of the radiation incident on the body or, for internal sources, the energy of the radiation emitted from the source.
b. Excluding Auger electrons emitted from nuclei bound to DNA.

In general, since the 1950s a quality factor of 10 has been applied to fast neutron exposures, but this value has changed from 5 to 20 across facilities and time frames (NIOSH 2002). This TIB presents a technique that dose reconstructors can use to remove the site-specific quality factor (Q_s) from personal monitoring or radiation survey data at a facility of interest. Figure 2-1 shows the two most widely used sets of neutron quality factors (Q) in the United States. The first set, from NCRP Report 20 (NCRP 1957), was obtained from neutron transport calculations of both the absorbed dose and dose equivalent in a slab phantom. The second set, from NCRP Report 38 (NCRP 1973), was obtained from neutron transport calculations of both the absorbed dose and dose equivalent in a cylindrical phantom. The two sets of data for the neutron quality factor are in close agreement despite differences in the shapes of the tissue-equivalent phantoms used to represent the human torso. The Q(E) values are the ratio of the dose equivalent to the absorbed dose nearest the surface of the phantom being irradiated by a normally incident plane, parallel beam of monoenergetic neutrons having an energy, E. The results in the following sections are based on the newer, more extensive set of data on Q(E) from NCRP Report 38.

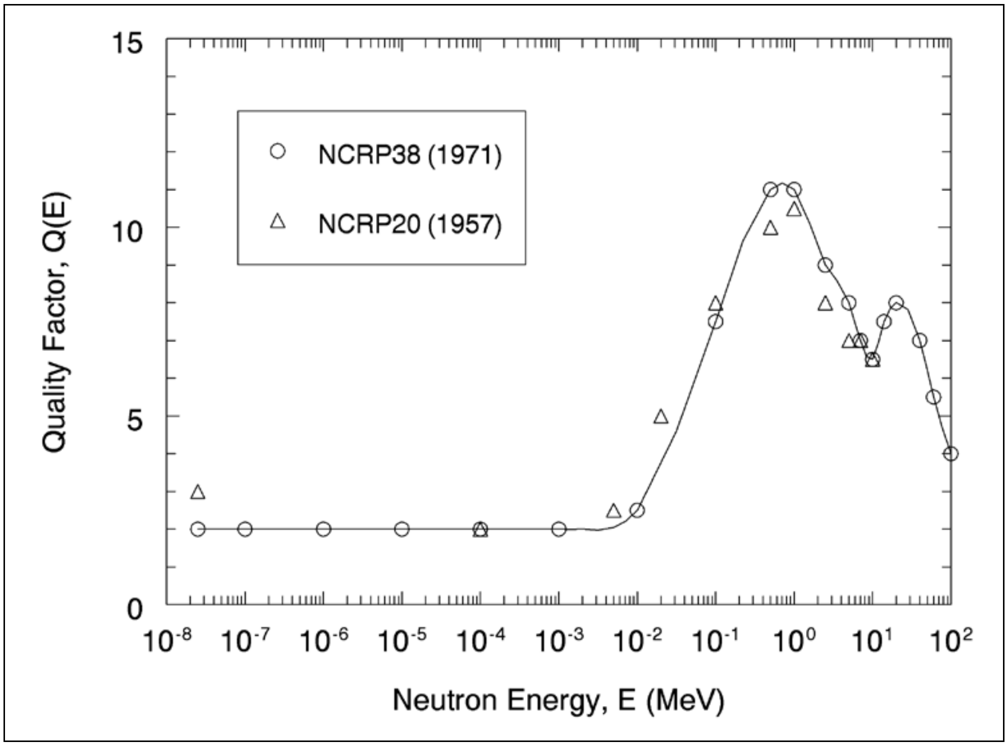

Figure 2-1. Comparison of neutron quality factors from NCRP Report 20 (NCRP 1957) and NCRP Report 38 (NCRP 1971).

3.0 NEUTRON DOSE EQUIVALENT ADJUSTMENTS

An adjustment to the dose equivalent from neutrons is necessary to account for the change in neutron quality factors between historical and current scientific guidance, as discussed in NIOSH (2003). To make such an adjustment, a curve was fit that described the NCRP 38 (NCRP 1971) neutron quality factor as a function of neutron energy (see Figure 2-1). An average quality factor, $\overline{Q}(E_1,E_2)$, for each neutron energy group was developed by integrating to find the area under the curve ($E_2 > E_1$) and then dividing the area under the curve by the width of the neutron energy group, $E_2 - E_1$, as shown in equation (1).

$$\overline{Q}(E_1,E_2) = \frac{\int_{E_1}^{E_2} Q(E)dE}{E_2 - E_1} \tag{1}$$

Figure 3-1 shows the point-wise neutron quality factors from NCRP Report 38 (NCRP 1971) and average quality factors calculated for each of the neutron energy groups used to define the neutron weighting factors in ICRP Publication 60 (ICRP 1991). Table 3-1 summarizes these group averaged quality factors and the radiation weighting factors used in dose reconstruction. In addition, this table compares the group averaged NCRP 38 quality factors with other historical dosimetry guidelines for neutrons from the First Tripartite Conference at Chalk River in 1949 (Warren et al. 1949; Fix, Gilbert, and Baumgartner 1994) and NCRP Report 17 (NCRP 1954; Taylor 1971).

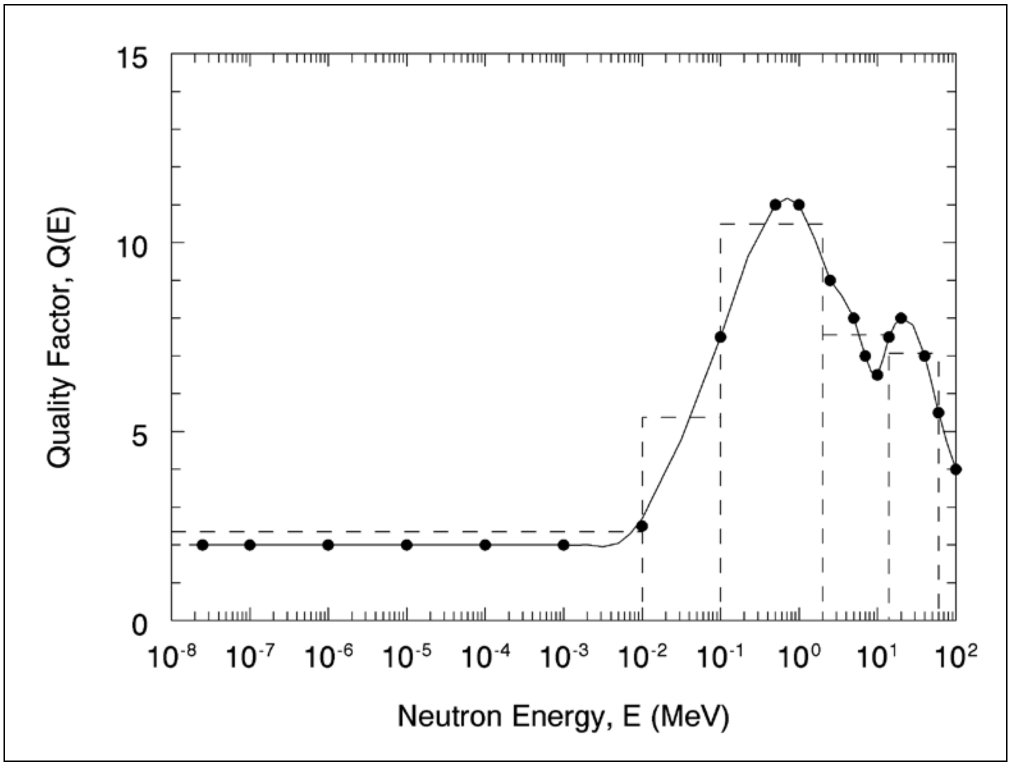

Figure 3-1. Comparison of point-wise data on the neutron quality factor from NCRP Report 38 (solid line) and group averaged neutron quality factors used in dose reconstruction (dashed lines).

Table 3-1. Neutron quality factor, Q, or weighting factor, w_R.

Neutron energy (MeV)	Historical dosimetry guidelines[a]	NCRP Report 38 group averaged quality factor[b]	ICRP Publication 60 neutron weighting factor	Ratio[c]
Thermal	3	2.35	5	2.13
0.5 eV - 10 keV	10			
10 keV - 100 keV		5.38	10	1.86
100 keV - 2 MeV		10.49	20	1.91
2 MeV – 20 MeV		7.56	10	1.32
20 MeV - 60 MeV		6.96[d]	5	1.00[e]

a. First Tripartite Conference at Chalk River in 1949 (Warren et al. 1949; Fix, Gilbert, and Baumgartner 1994) and NCRP Report 17 (NCRP 1954; Taylor 1971).
b. See Figure 3-1.
c. Ratio of the ICRP 60 weighting factor to the group averaged NCRP38 quality factor each neutron energy group.
d. “Not applicable” is usually inserted here rather than the NCRP group averaged value of 6.96, which is larger than the ICRP 60 weighting factor of 5 for 20-to-60-MeV neutrons and results in a non-claimant-favorable reduction in the corrected dose for this neutron energy group.
e. Ratio for adjusting neutron dose from NCRP 38 quality factor to ICRP 60 weighting factor is arbitrarily set equal to unity to avoid a non-claimant-favorable reduction in the corrected dose for this neutron energy group.

A corrected neutron dose equivalent, $C_f(E_1,E_2)$, for each of the five neutron energy groups used in dose reconstruction (see Table 2-1) can be calculated by dividing the dose equivalent fraction, $D_f(E_1,E_2)$, for each energy group by the corresponding energy specific averaged NCRP 38 (NCRP 1971) quality factor, $\overline{Q}(E_1,E_2)$, and then multiplying by the ICRP 60 (ICRP 1991) weighting factor, $w_R(E_1,E_2)$, as shown in equation (2). The total corrected dose equivalent is then the sum of the corrected energy group dose equivalents. Note that the D_f values are unique to each facility and are discussed in the site specific TBDs. These corrections, based on the values of $\overline{Q}(E_1,E_2)$ and $w_R(E_1,E_2)$ as listed in Table 3-1, should be applied to measured dose, missed dose, and dose determined based on neutron-to-photon ratio (ORAU 2005a). It is recommended to use the value of 1.00 for the ratio of wR to $\overline{Q}$ noted in Table 3.1 for the energy range from 20-60 MeV because this results in a claimant favorable dose equivalent fraction.

$$C_f(E_1,E_2) = \frac{D_f(E_1,E_2)}{\overline{Q}(E_1,E_2)} \times w_R(E_1,E_2) \qquad (2)$$

The following example, based on results of neutron spectra and dose equivalent measurements by the Pacific Northwest Laboratory (PNL) in a highly enriched UF_4 storage area at the Y-12 facility in Oak Ridge, Tennessee, illustrates the application of equation (2) (PNL 1990; McMahan 1991; BWXT Y-12 2001). The interaction of alpha particles from uranium with the nuclei of fluorine and other low-Z atoms generates neutrons with energies of approximately 2 MeV (DOE 2004). In general, the exposure potential of workers to neutrons generated by (alpha,neutron) reactions is low, but dose reconstructors should evaluate their exposures to neutrons if their work assignments required them to spend time near storage or process areas for large quantities of uranium fluoride compounds (DOE 2004). The solid line in Figure 3-2 shows the PNL measurements of exposure to neutrons from (alpha,neutron) reactions in highly enriched UF_4 at the Y-12 storage area, and Table 3-2 lists the dose fractions for the neutron energy groups shown by the dashed line in the figure. Suppose that a recorded neutron dose for a Y-12 worker in this storage area is 500 mrem. The corrected dose equivalent fractions as calculated using equation (2) and the data in Tables 3-1 and 3-2 are 13, 3, 926, and 10 mrem for the less-than-10 keV, 10-to-100-keV, 0.1-to-2-MeV, and 2-to-20-MeV neutron energy groups, respectively, and the total corrected neutron dose equivalent is 952 mrem (see Table 3-3). The dose fractions for the lower energy (less than 10 keV), intermediate-energy (10 to 100 keV), and high-energy (2 to 20 MeV) neutron groups are only 3% of the recorded dose equivalent for neutrons. Combining these three neutron energy groups with the 0.1-to-2-MeV fast neutron group provides a reasonable and claimant-favorable simplification of the neutron dose reconstruction for a Y-12 worker (see Table 3-2). The calculated corrected dose equivalent based on this simplifying assumption is 955 mrem (i.e., 1.91 × 1.00 × 500 mrem).

The use of only one dose fraction for neutrons with energies between 10 keV and 20 MeV as discussed above is unusual unless sufficiently detailed information of the neutron energy spectrum is not available. In this situation, the NCRP recommends the use of an average neutron quality factor for fast neutrons of 10 (NCRP 1973; also see NCRP 1957). Thus, dose reconstructors should use the following claimant-favorable recommendations in the absence of detailed information on the neutron energies involved in a worker's exposure: (1) assume the corrected neutron dose equivalent to be twice the measured dose, missed dose, or dose based on a neutron-to-photon ratio, and (2) assume the neutron energies to be in the energy range from 0.1 to 2 MeV. These recommendations should apply mainly to neutron doses measured prior to 1957 and the publication of NCRP Report 20.

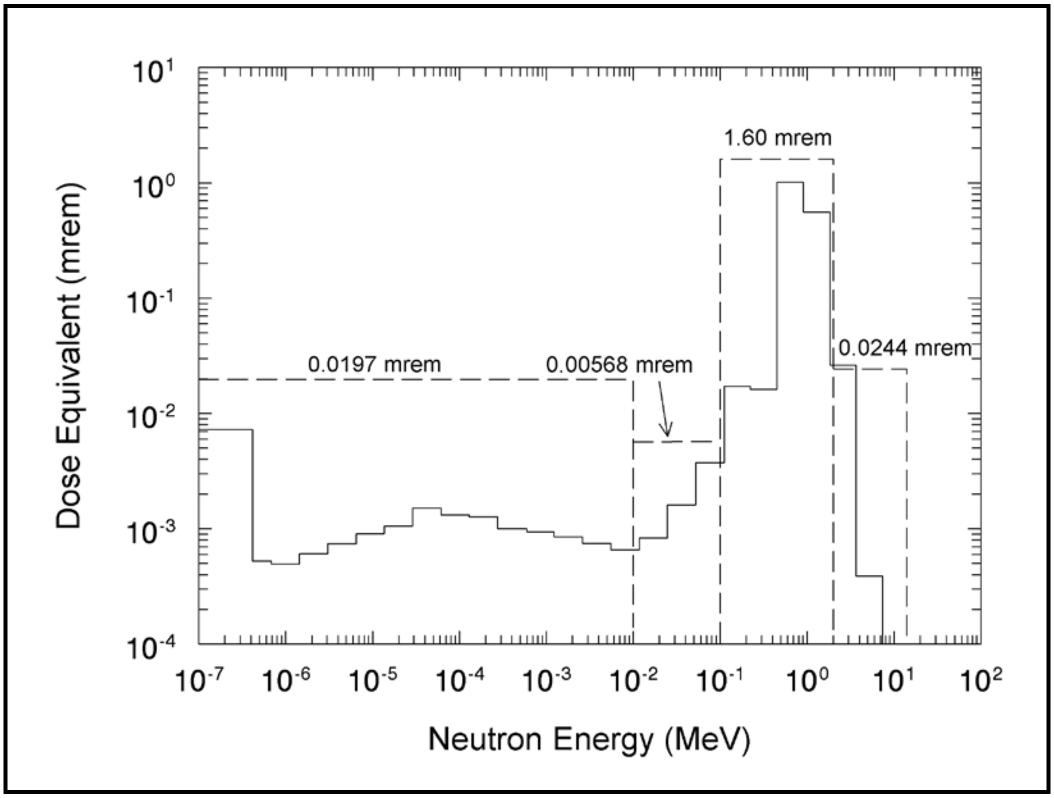

Figure 3-2. Dose equivalent fractions for an exposure to neutrons from (alpha,neutron) reactions in highly enriched UF_4 storage containers at the Y-12 facility. The solid line shows PNL measured results and the dashed line shows dose fractions for neutron energy groups used in dose reconstruction. The dose equivalent values in the figure are for a 1-hr exposure near the center of a large rack containing multiple UF_4 storage containers.

Table 3-2. Dose equivalent fractions for exposure to neutrons from (alpha,neutron) reactions in highly enriched UF_4 storage containers at the Y-12 facility.

Neutron energy group	Dose fraction
< 10 keV	0.012
10 - 100 keV	0.003
0.1 - 2 MeV	0.970
2 - 20 MeV	0.015
Claimant-favorable dose fractions	
0.1 - 2 MeV	1.00

Table 3-3. Example calculation of the corrected dose equivalent for exposure of a worker to neutrons from (alpha,neutron) reactions in highly enriched UF_4 storage containers at the Y-12 facility.

Neutron energy group[a]	NCRP 38 quality factor[a]	ICRP weighting factor[a]	Ratio[a]	Recorded dose equivalent	Dose fraction[b]	Corrected dose equivalent
<10 keV	2.35	5	2.13	500	0.012	12.78
10 - 100 keV	5.38	10	1.86	500	0.003	2.79
0.1 - 2 MeV	10.49	20	1.91	500	0.970	926.35
2 - 20 MeV	7.56	10	1.32	500	0.015	9.90
20 - 60 MeV	6.69	5	1.00	500	0.	0
Total						951.82

a. See Table 3-1.
b. See Table 3-2.

4.0 DISCUSSION

Adjustment to the neutron dose for each worker is necessary to account for the change in neutron quality factors between historical and current scientific guidance (see Table 3-1). A corrected neutron dose equivalent for each of the five energy groups used in dose reconstruction can be calculated using equation (2), the data in Table 3-1, and dose fractions listed in tables of the TBD for DOE facility of interest (see Tables 3-2 and 3-3). These corrections should be applied to measured dose, missed dose, and dose determined based on neutron-to-photon ratios. It is recommended to use the value of 1.00 for the ratio of w_R to $\overline{Q}$ noted in Table 3.1 for the energy group from 20-60 MeV because this results in a claimant favorable dose equivalent fraction. If sufficiently detailed information on neutron energies is not available, dose reconstructors should use the following claimant-favorable recommendations: (1) assume the corrected dose equivalent to be twice the measured dose, missed dose, or dose based on neutron-to-photon ratios; and (2) assume the neutron energies are in the range from 0.1 to 2 MeV. These recommendations should apply mainly to neutron doses measured prior to 1957 and the publication of NCRP Report 20 (NCRP 1957).

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