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TECHNICAL REPORT

Considerations on Estimating Upper Bounds of Neutron Doses to Military Participants at Atmospheric Nuclear Tests

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14. ABSTRACT
This report discusses how the Defense Threat Reduction Agency should estimate upper bounds of neutron doses to military service members who participated in the atmospheric nuclear weapons testing program.

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CONVERSION TABLE

Conversion Factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY → BY → TO GET		
TO GET ← BY ← DIVIDE		
angstrom	1.000 000 x E -10	meters (m)
atmosphere (normal)	1.013 25 x E +2	kilo pascal (kPa)
bar	1.000 000 x E +2	kilo pascal (kPa)
barn	1.000 000 x E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 x E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical/cm^2)	4.184 000 x E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 x E +1	*giga bacquerel (GBq)
degree (angle)	1.745 329 x E -2	radian (rad)
degree Fahrenheit	$t_k = (t°f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 x E -19	joule (J)
erg	1.000 000 x E -7	joule (J)
erg/second	1.000 000 x E -7	watt (W)
foot	3.048 000 x E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 x E -3	meter^3 (m^3)
inch	2.540 000 x E -2	meter (m)
jerk	1.000 000 x E +9	joule (J)
joule/kilogram (J/kg) radiation dose absorbed	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 x E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 x E +3	kilo pascal (kPa)
ktap	1.000 000 x E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000 x E -6	meter (m)
mil	2.540 000 x E -5	meter (m)
mile (international)	1.609 344 x E +3	meter (m)
ounce	2.834 952 x E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 x E -1	newton-meter (N-m)
pound-force/inch	1.751 268 x E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 x E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 x E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 x E -2	kilogram-meter^2 (kg-m^2)
pound-mass/foot^3	1.601 846 x E +1	kilogram-meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 x E -2	**Gray (Gy)
roentgen	2.579 760 x E -4	coulomb/kilogram (C/kg)
shake	1.000 000 x E -8	second (s)
slug	1.459 390 x E +1	kilogram (kg)
torr (mm Hg, 0° C)	1.333 22 x E -1	kilo pascal (kPa)

*The bacquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (GY) is the SI unit of absorbed radiation.

ABSTRACT

This report addresses a provision in the 2004 Report to Congress by the Departments of Defense (DoD) and Veterans Affairs (VA) that the Defense Threat Reduction Agency (DTRA) will investigate the proper degree of uncertainty that should be incorporated in estimated upper bounds of neutron doses to military participants in the atmospheric nuclear-weapons testing program to account for uncertainty in the biological effectiveness of neutrons. Analyses presented in this report led to two main conclusions. First, application of an adjustment factor of 6 to mean neutron doses that had been calculated by Science Applications International Corporation (SAIC), as specified in DTRA's 2003 Interim Guidance, is more than sufficient to ensure that the resulting upper bounds are at least upper 95% credibility limits of doses to any organ or tissue, in accordance with DoD regulations in 32 CFR Part 218. Second, now that VA uses the Interactive RadioEpidemiological Program (IREP) exclusively to evaluate causation of cancers for the purpose of adjudicating claims for compensation and no longer uses a table of screening doses for specific cancers that were calculated by the Committee on Interagency Radiation Research and Policy Coordination (CIRRPC), an adjustment factor that incorporates an uncertainty in the biological effectiveness of neutrons is no longer needed because that uncertainty is taken into account in IREP. Rather, to provide neutron equivalent doses to organs or tissues that are suitable for input to IREP, all mean doses and upper bounds calculated previously by SAIC should be increased by a factor of 2 to account for the difference between the radiation weighting factor (w_R) of 20 for fission neutrons recommended by the International Commission on Radiological Protection (ICRP) and the factor of 13 that SAIC used in most cases to modify estimates of tissue kerma free-in-air to obtain estimates of organ dose. Mean

neutron doses and upper bounds calculated previously in the case of exposure of certain participants at Operation PLUMBBOB, Shot DOPPLER at the Nevada Test Site also should be increased by another factor of 13/11 to correct the modifying factor that SAIC used in that case. Thus, now that IREP is used to evaluate causation of cancers, upper bounds of neutron equivalent doses reported by DTRA should account for uncertainty in tissue kerma only, and an uncertainty in the biological effectiveness of neutrons should not be included.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

TABLE **PAGE**

SECTION 1

INTRODUCTION

This report considers the issue of how the Defense Threat Reduction Agency (DTRA) should estimate upper bounds of neutron doses to members of military services who participated in the atmospheric nuclear-weapons testing program when radiation dose assessments include an assumption that external exposure to neutrons occurred. The need to consider this issue arose as a consequence of three developments:

[1] A finding by a committee of the National Research Council (NRC, 2003), which reviewed the dose reconstruction program of DTRA, that upper bounds of doses to military participants from external exposure to neutrons are always underestimated because of neglect of the substantial uncertainty in the biological effectiveness of neutrons relative to high-energy gamma rays (photons);

[2] A provision in DTRA's Interim Guidance (Benavides, 2003), which was issued in response to findings by the NRC committee on deficiencies in the dose reconstruction program, that upper bounds of neutron doses should be obtained by increasing calculated mean doses by a factor of 6;

[3] A provision in the Report to Congress by the Department of Defense (DoD) and Department of Veterans Affairs (VA) (Cooper and Klein, 2004) that DTRA will investigate the proper degree of uncertainty that should be incorporated in estimated upper bounds of neutron doses to account for uncertainty in the biological effectiveness of those radiations.

DoD regulations in 32 CFR Part 218 specify that upper bounds of neutron doses reported by DTRA, as well as upper bounds of doses from all other radiation types and routes of external and internal exposure, should be at least upper 95% credibility limits (i.e., upper bounds of 90% credibility intervals of uncertain doses), meaning that upper bounds of doses should exceed

actual doses in at least 95% of all cases. Methods of estimating upper bounds of doses are important because VA uses upper bounds reported by DTRA in adjudicating claims for compensation for cancer or other radiogenic diseases when an evaluation of causation of a participant's disease is required.

The purpose of this report is to address the provision in the Report to Congress (Cooper and Klein, 2004) that DTRA will investigate the proper degree of uncertainty that should be incorporated in estimated upper bounds of doses from external exposure to neutrons to account for uncertainty in the biological effectiveness of those radiations. An important focus of this investigation is a consideration of the adjustment factor of 6 specified in the Interim Guidance (Benavides, 2003). This report considers whether use of that adjustment factor provided credible upper bounds of neutron doses, and whether that adjustment factor should continue to be used or an alternative approach to estimating upper bounds of neutron doses should be adopted.

Topics discussed in this report include the following:

- A review of methods and assumptions that were used by Science Applications International Corporation (SAIC) to estimate mean values and upper bounds of neutron doses to military participants in the atmospheric testing program;
- The basis for the finding by the NRC committee (NRC, 2003) that upper bounds of neutron doses to participants are always underestimated;
- The rationale for the adjustment factor of 6 specified in the Interim Guidance (Benavides, 2003) for use in obtaining upper bounds of neutron doses;
- How use of the adjustment factor of 6 by DTRA has affected VA's evaluations of causation of cancers in adjudicating claims for compensation for those diseases;
- An evaluation of whether use of the adjustment factor of 6 provided credible upper bounds (at least upper 95% credibility limits) of neutron doses to specific organs or tissues of exposed individuals;
- An assessment of how mean doses and upper bounds from external exposure to neutrons can be calculated by DTRA to provide consistency and compatibility with VA's current approach to evaluating causation of cancers;

- A summary of the results of this investigation and recommendations on how mean neutron doses and upper bounds should be calculated by DTRA.

Diseases other than cancer that may be caused by exposure to ionizing radiation (e.g., cataract of the lens of the eye) are not considered in this report. Thus, discussions about the biological effectiveness of neutrons and approaches used by VA to evaluate causation of diseases apply only to cancer and not to any other radiogenic disease.

This report is concerned with calculations of biologically significant doses to specific organs or tissues from exposure to neutrons. It is DTRA's current policy to calculate *equivalent doses* (DTRA, 2007) to conform to a recommendation in Publication 60 of the International Commission on Radiological Protection (ICRP, 1991). In cases of external exposure to neutrons, an equivalent dose is the product of an average absorbed dose to an organ or tissue due to neutrons incident on the body surface modified by a radiation weighting factor (w_R) to represent the biological effectiveness of the incident neutrons. For example, a w_R of 20 is generally appropriate in cases of exposure to spectra of fission neutrons.

However, use of the term "equivalent dose" is appropriate only in cases where an average absorbed dose to an organ or tissue is modified by a w_R recommended by ICRP (1991). Thus, it does not apply to biologically significant doses to organs or tissues from exposure to neutrons that were calculated by SAIC and reported by DTRA up to the time DTRA's Interim Guidance (Benavides, 2003) and the Report to Congress (Cooper and Klein, 2004) were issued, in part because those doses were calculated using modifying factors that differ from a w_R that would apply to fission neutrons.

Therefore, in this report, the term "dose equivalent" is used to describe biologically significant doses to organs or tissues from exposure to neutrons that were calculated by SAIC. This terminology conforms to a recommendation by ICRP (1977) at the time SAIC's calculations were performed. The term "equivalent dose" is used in this report only in cases where a w_R recommended by ICRP (1991) is used to calculate a biologically significant dose to an organ or tissue.

The more general term "dose" also is used in some discussions in this report. This term

is used, for example, in introductory discussions in this section, and it also is used in the Report to Congress (Cooper and Klein, 2004). Whenever the term "dose" by itself is used, reference to a biologically significant dose to an organ or tissue is implied.

SECTION 2

METHODS OF ESTIMATING NEUTRON DOSES

Methods that were developed by SAIC to estimate doses from external exposure to neutrons are described by Goetz et al. (1979; 1981; 1985). The last of those reports contains summary tables of mean neutron dose equivalents that SAIC assigned to participants in particular military units at specific shots at the Nevada Test Site (NTS) and in the Pacific.

In all calculations, SAIC first estimated a quantity referred to as tissue kerma free-in-air at assumed locations of exposure to neutrons. Kerma is defined as the quotient of dE_{tr} by dm, where dE_{tr} is the sum of the initial kinetic energies of all charged particles that are liberated by uncharged ionizing particles (neutrons in this case) in a material of mass dm (an infinitesimal mass of tissue in air in this case); e.g., see ICRU (1998). Kerma thus has units of absorbed dose and is given in rads by SAIC.[2] Tissue kerma free-in-air at assumed locations of exposure was estimated on the basis of calculations of neutron fluence (i.e., the number of neutrons per unit cross sectional area) as a function of energy at those locations, cross sections for interactions of neutrons with constituents of tissue that liberate charged ionizing particles as a function of energy, and the energy transferred to each charged ionizing particle in each neutron interaction. Tissue kerma for monoenergetic neutrons of energy up to 14 MeV and contributions from different interactions that produce charged ionizing particles are shown in Figure 2-1 (NCRP, 1971; Figure 3). Values of tissue kerma free-in-air used by SAIC were nearly the same as, but not identical to, those in Figure 2-1 (S.D. Egbert, SAIC, personal communication).

SAIC then calculated a neutron dose equivalent (in rem) at assumed locations of exposure by modifying an estimated tissue kerma free-in-air by a dimensionless quantity that represents the greater biological effectiveness of neutrons, relative to high-energy photons, in inducing stochastic health effects, primarily cancers. This modifying factor was referred to as an

[2]Tissue kerma free-in-air is not equal to the absorbed dose in an infinitesimal mass of tissue in air because charged-particle equilibrium is not achieved—i.e., the energy spectrum of charged particles produced by neutron interactions in air that enter the infinitesimal volume of tissue is not the same as the energy spectrum of charged particles that are liberated from that volume of tissue by incident neutrons (e.g., see Shultis and Faw, 1996).

average or effective quality factor or a "rad-rem conversion factor" (Goetz et al., 1979; 1981; 1985). A neutron dose equivalent was initially referred to as a "dose (rem) free-in-air" (Goetz et al., 1979) and later as an "equivalent tissue dose" or an "in-trench dose equivalent" in cases of exposure in trenches at NTS (Goetz et al., 1981) or, more generally, as a "neutron dose (rem)" (Goetz et al., 1985). For exposure to spectra of fission neutrons that occurred in detonations of nuclear weapons, SAIC applied a modifying factor of 13 to tissue kerma free-in-air to account for the biological effectiveness of neutrons (Goetz et al., 1981; 1985), except in the case of exposure of certain participants at Operation PLUMBBOB, Shot DOPPLER at NTS, where a lower modifying factor of 11 discussed later in this section was used (Goetz et al., 1979).

Neutron dose equivalents calculated by SAIC, as described above, were used by VA in adjudicating claims for compensation for cancers in specific organs or tissues. Thus, neutron dose equivalents that were calculated by modifying estimates of tissue kerma free-in-air by a factor that represents the biological effectiveness of neutrons were assumed to represent average dose equivalents to any organ or tissue of an exposed individual.

It is important to emphasize that the quantity used by SAIC to modify an estimate of tissue kerma free-in-air to obtain an estimate of neutron dose equivalent is not the same as a neutron quality factor, because the latter is defined as a quantity that modifies an absorbed dose from neutrons in tissue of humans to obtain a dose equivalent (NCRP, 1971; ICRP, 1977); i.e., a quality factor is not a quantity that modifies tissue kerma.[3] Because the quantity used by SAIC to modify estimates of tissue kerma free-in-air from neutrons is not strictly a quality factor, we refer to it as a modifying factor in this report. However, even though the biologically significant dose obtained by applying a modifying factor to tissue kerma free-in-air is not strictly a dose equivalent, we refer to it as a dose equivalent to be consistent with the terminology that was used by DTRA in reporting neutron doses to VA.

For neutrons, differences between tissue kerma free-in-air and absorbed dose in tissues of the body are illustrated by comparing estimates of tissue kerma in Figure 2-1 with estimates of

[3]SAIC clearly was aware of this distinction, as evidenced, for example, by the occasional use of the term "rad-rem conversion factor" rather than "quality factor" (Goetz et al., 1981) and avoidance of the term "dose equivalent" to describe biologically significant doses from exposure to neutrons that were calculated on the basis of estimates of tissue kerma free-in-air (Goetz et al., 1979; 1981; 1985).

absorbed dose from mono-directional neutrons incident on a 30-cm diameter cylindrical phantom from a direction perpendicular to the axis of the cylinder (NCRP, 1971). For example, at an energy of 1 MeV, which is near the peak of energy spectra of fission neutrons (Shleien et al., 1998; Table 7.1), the tissue kerma per neutron fluence in Figure 2-1 is about 2.3×10^{-9} rad cm^2, and the absorbed dose in the central region of the cylindrical phantom is given by the curve for all interactions along the traverse in the beam direction in Figure 2-2 (NCRP, 1971; Figure 15). At this energy, the absorbed dose is greater than tissue kerma free-in-air at depths in the phantom less than about 3 cm, but is less than tissue kerma at greater depths. Absorbed doses in the phantom at other energies between 0.025 eV and 14 MeV (NCRP, 1971; Appendix B) give similar comparisons. At all energies, the maximum absorbed dose from neutrons and secondary photons produced by neutron interactions in the phantom, which occurs at a depth of about 5 cm or less and most often at a depth of about 1 cm, is greater than tissue kerma free-in-air, and the absorbed dose is less than tissue kerma at greater depths.[4]

As noted previously, except in the case of exposure of certain participants at Operation PLUMBBOB, Shot DOPPLER, SAIC assumed that neutron dose equivalents can be calculated by applying a modifying factor of 13 to estimates of tissue kerma free-in-air. This modifying factor was based on comparisons of maximum dose equivalents in a 30-cm diameter cylindrical phantom (NCRP, 1971) with tissue kerma free-in-air over a range of neutron energies of concern at locations of exposure (S.D. Egbert, SAIC, personal communication). An example calculation of dose equivalents in the central region of the phantom at an incident neutron energy of 1 MeV is given in Figure 2-3 (NCRP, 1971; Figure 16). The dose equivalent at any depth in the phantom was calculated from (a) the absorbed dose from all neutron interactions that produce charged particles, as given in Figure 2-2, (b) an assumed relationship between the quality factor

[4]Increases in absorbed dose at depths close to the surface of the phantom compared with tissue kerma free-in-air are due in part to the low attenuation of incident neutrons in transport to those depths and the multiple collisions of neutrons in finite volumes of tissue that result in a greater average energy of all liberated charged particles per incident neutron compared with the average energy of charged particles liberated by a single interaction in an infinitesimal mass of tissue. At greater depths in the phantom, attenuation of the incident neutron fluence is more important than increases in the average energy of all liberated charged particles per incident neutron, and absorbed dose is less than tissue kerma free-in-air. The relationship between absorbed dose at any depth and tissue kerma free-in-air also is influenced by contributions to absorbed dose from secondary photons, which depend on neutron energy.

(Q) for charged ionizing particles and linear energy transfer (L) given by the dashed curve in Figure 2-4 (ICRP, 1996; Figure 2), (c) the absorbed dose from interactions of secondary photons, as given in Figure 2-2, and (d) an assumed quality factor for photons of 1.0. The maximum dose equivalent per neutron fluence at 1 MeV shown in Figure 2-3 is about 3.2×10^{-8} rem cm^2. Given the tissue kerma at 1 MeV shown in Figure 2-1, the ratio of the maximum dose equivalent in the phantom to tissue kerma free-in-air then is about $(3.2 \times 10^{-8})/(2.3 \times 10^{-9}) = 14$. By examining ratios of maximum dose equivalent in the phantom to tissue kerma free-in-air as a function of energy and averaging those ratios over energy spectra of fission neutrons at locations of exposure,[5] SAIC concluded that the value 13 was a reasonable representation of that ratio.

SAIC's modifying factor of 13 described above can be compared with mean quality factors recommended by the National Council on Radiation Protection and Measurements (NCRP, 1971) and given in Table 2-1; NCRP's mean quality factors are maximum ratios of dose equivalent to absorbed dose in a 30-cm diameter cylindrical phantom and were obtained from calculations such as those shown in Figures 2-2 and 2-3 (NCRP, 1971; Appendix B). Mean quality factors calculated by NCRP are less than 13 at all energies.[6] However, this difference does not indicate that the modifying factor of 13 used by SAIC in most cases is inconsistent with mean quality factors recommended by NCRP because, as discussed above, SAIC applied its modifying factor to a tissue kerma free-in-air from neutrons, whereas NCRP's mean quality factors are intended to be applied to an absorbed dose in tissues of the body. Indeed, SAIC's modifying factor of 13 is consistent with NCRP's mean quality factors in Table 2-1, because both were derived using the same maximum dose equivalent from neutrons and secondary photons in a 30-cm diameter cylindrical phantom. As indicated in Table 2-1, NCRP also recommended that a mean quality factor of 10 was generally suitable for use in radiation protection when detailed information on energy spectra of neutrons was not available.

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[5]For example, in a case of exposure in a trench at a ground distance of about 2.85 km from a detonation at NTS, contributions to the calculated fluence were about 10% from thermal (< 0.3 eV) neutrons, 50% from epithermal (0.3 eV-10 keV) neutrons, 15% from 0.01-0.63 MeV neutrons, and 25% from the highest energy (> 0.63 MeV) neutrons (Goetz et al., 1979).

[6]The highest mean quality factor that would be obtained from values in Table 2-1 would not exceed about 12, and an average over spectra of fission neutrons at locations of exposure would be less than 11.

A modifying factor less than 13 was used by SAIC to calculate neutron dose equivalents to members of Task Force WARRIOR at Operation PLUMBBOB, Shot DOPPLER (Goetz et al., 1979); this was the first calculation of neutron doses performed by SAIC. The modifying factor in that case was derived on the basis of calculations of neutron fluence in different energy groups at the location of exposure, an estimated tissue kerma free-in-air per neutron fluence for each energy group obtained from calculations for monoenergetic neutrons similar to calculations in Figure 2-1, and the energy dependence of the mean quality factor given in Table 2-1 (NCRP, 1971). Goetz et al. (1979) state that a modifying factor of 8.6 applied to the neutron field immediately above a trench in which members of Task Force WARRIOR were located, and that the modifying factor is "close to the maximum" at the assumed location of exposure at a depth of 2.33 ft in a trench. However, the assumed modifying factor at that depth in a trench was not stated. On the basis of the ratio of neutron dose equivalent free-in-air of 0.227 rem to tissue kerma free-in-air of 0.020 rad at a depth of 2.33 ft in a trench given by Goetz et al. (1979), it can be inferred that the modifying factor used by SAIC in that case is about 11.[7] This inference is supported by inclusion of a neutron dose equivalent of 0.227 rem to members of Task Force WARRIOR in a summary of doses at all shots at NTS and in the Pacific (Goetz et al., 1985).

There is a slight inconsistency between the modifying factor of 11 used by SAIC in the case of exposure of members of Task Force WARRIOR at Operation PLUMBBOB, Shot DOPPLER and the modifying factor of 13 used by SAIC in all other cases. As discussed above, the value 13 was derived on the basis of ratios of maximum dose equivalent in a 30-cm diameter cylindrical phantom (NCRP, 1971) to tissue kerma free-in-air. However, the value 11, which also was used by SAIC to modify tissue kerma free-in-air, was derived using mean quality factors that were calculated by NCRP (1971) as ratios of maximum dose equivalent to absorbed dose in the phantom. Thus, when a modifying factor of 11 is applied to estimates of tissue kerma free-in-air, the resulting dose equivalent is not the same as the maximum dose equivalent in the phantom that would be calculated by NCRP at the same tissue kerma. Since the maximum

[7]A modifying factor of 11 was used only in the case of exposure of members of Task Force WARRIOR at Shot DOPPLER. A modifying factor of 13 apparently was used in cases of exposure of other participants at that shot.

absorbed dose in the phantom is greater than tissue kerma free-in-air at neutron energies of interest, as discussed above, SAIC's use of a modifying factor of 11 resulted in a slight underestimate of maximum dose equivalent in the phantom.[8]

The inconsistency between SAIC's modifying factor of 11 that was used to estimate neutron dose equivalents to members of Task Force WARRIOR at Operation PLUMBBOB, Shot DOPPLER and NCRP's mean quality factors could be addressed by applying a modifying factor of 13 to the estimated tissue kerma free-in-air of 0.020 rad at the assumed location of exposure in a trench (Goetz et al., 1979). Thus, the reported neutron dose equivalent of 0.227 rem in that case (Goetz et al., 1979; 1985) could be increased to 0.26 rem. If this change were made, all neutron dose equivalents calculated by SAIC would correspond to the maximum dose equivalent in a 30-cm diameter phantom, and SAIC's modifying factor would be consistent with mean quality factors recommended by NCRP (1971) and given in Table 2-1 in all cases.

The discussions in this section may be summarized as follows:

- Dose equivalents from external exposure to neutrons were calculated by SAIC by modifying estimates of tissue kerma free-in-air at assumed locations of exposure by a factor (either 13 or 11) to represent the biological effectiveness of neutrons. Neutron dose equivalents so estimated are assumed to represent average dose equivalents to any organ or tissue of an exposed individual.
- The modifying factor of 13 that was used in most cases is consistent with mean quality factors recommended by NCRP (1971) and given in Table 2-1, because both were derived on the basis of the same maximum dose equivalent in a 30-cm diameter phantom.
- The modifying factor of 11 that was used in one case results in a slight underestimate of the maximum dose equivalent in a 30-cm diameter phantom. This inconsistency could be

[8]SAIC's derivation of a modifying factor of 11 in this case was based on the incorrect assumptions that (a) an average quality factor could be obtained by weighting the energy-dependent quality factor recommended by NCRP (1971) by the energy distribution of neutrons in air at the assumed location of exposure and (b) the maximum dose equivalent in a phantom could be obtained by modifying tissue kerma free-in-air by an average quality factor (S.D. Egbert, SAIC, personal communication). These assumptions were not incorporated in SAIC's subsequent calculations of neutron dose equivalent in which a modifying factor of 13 was applied to estimates of tissue kerma free-in-air.

removed by applying a modifying factor of 13, rather than 11, to the estimated tissue kerma free-in-air at the location of exposure in that case.

When neutron doses to military participants in the atmospheric testing program are estimated, DTRA reports mean doses and upper bounds to VA. Prior to the Interim Guidance (Benavides, 2003), SAIC estimated uncertainties in mean dose equivalents calculated as described above by taking into account uncertainties in estimates of tissue kerma free-in-air only; an uncertainty in the biological effectiveness of neutrons was not taken into account.[9] For example, in estimating neutron dose equivalents from exposure in trenches at NTS, sources of uncertainty in estimating tissue kerma that were taken into account include (a) uncertainties in neutron output of a weapon, including uncertainties in the number of neutrons, their energy spectrum, and their angular distribution as it deviates from radial symmetry, (b) uncertainty in calculations of neutron transport from the burst point to a location above a trench, (c) uncertainty in the downward-directed fraction of the neutron field above a trench, and (d) uncertainty in the location of an individual in a trench (Goetz et al., 1979; 1981). In cases of exposure in trenches at NTS, estimated upper 95% credibility limits of tissue kerma at specific shots exceed mean values by a factor between 1.5 and 2.2 (Goetz et al., 1979; 1981); i.e., estimated uncertainties in mean neutron dose equivalents in those cases were about a factor of 2 on average.[10]

[9]SAIC did recognize, however, that there is substantial uncertainty in radiobiological data that were used by NCRP (1971) in developing recommended mean quality factors (Goetz et al., 1979).

[10]Goetz et al. (1985) does not give estimated uncertainties in calculated mean neutron dose equivalents in the Pacific. However, neutron doses in the Pacific generally were low compared with doses at NTS.

Table 1. Mean quality factors for neutrons recommended in NCRP Report No. 38[a]

Neutron energy (MeV)	Mean quality factor[b]	Neutron energy (MeV)	Mean quality factor[b]
2.5×10^{-8} (thermal)	2	5	8
1×10^{-7}	2	7	7
1×10^{-6}	2	10	6.5
1×10^{-5}	2	14	7.5
1×10^{-4}	2	20	8
1×10^{-3}	2	40	7
1×10^{-2}	2.5	60	5.5
1×10^{-1}	7.5	1×10^{2}	4
5×10^{-1}	11	2×10^{2}	3.5
1	11	3×10^{2}	3.5
2.5	9	4×10^{2}	3.5

[a]See NCRP (1971), Table 2.

[b]Maximum values of mean quality factor—i.e., ratios of dose equivalent to absorbed dose—at any depth in central region of a 30-cm diameter cylindrical phantom. When sufficiently detailed information on neutron energies at locations where absorbed dose is delivered is not available, mean quality factor of 10 should be assumed for purposes of radiation protection.

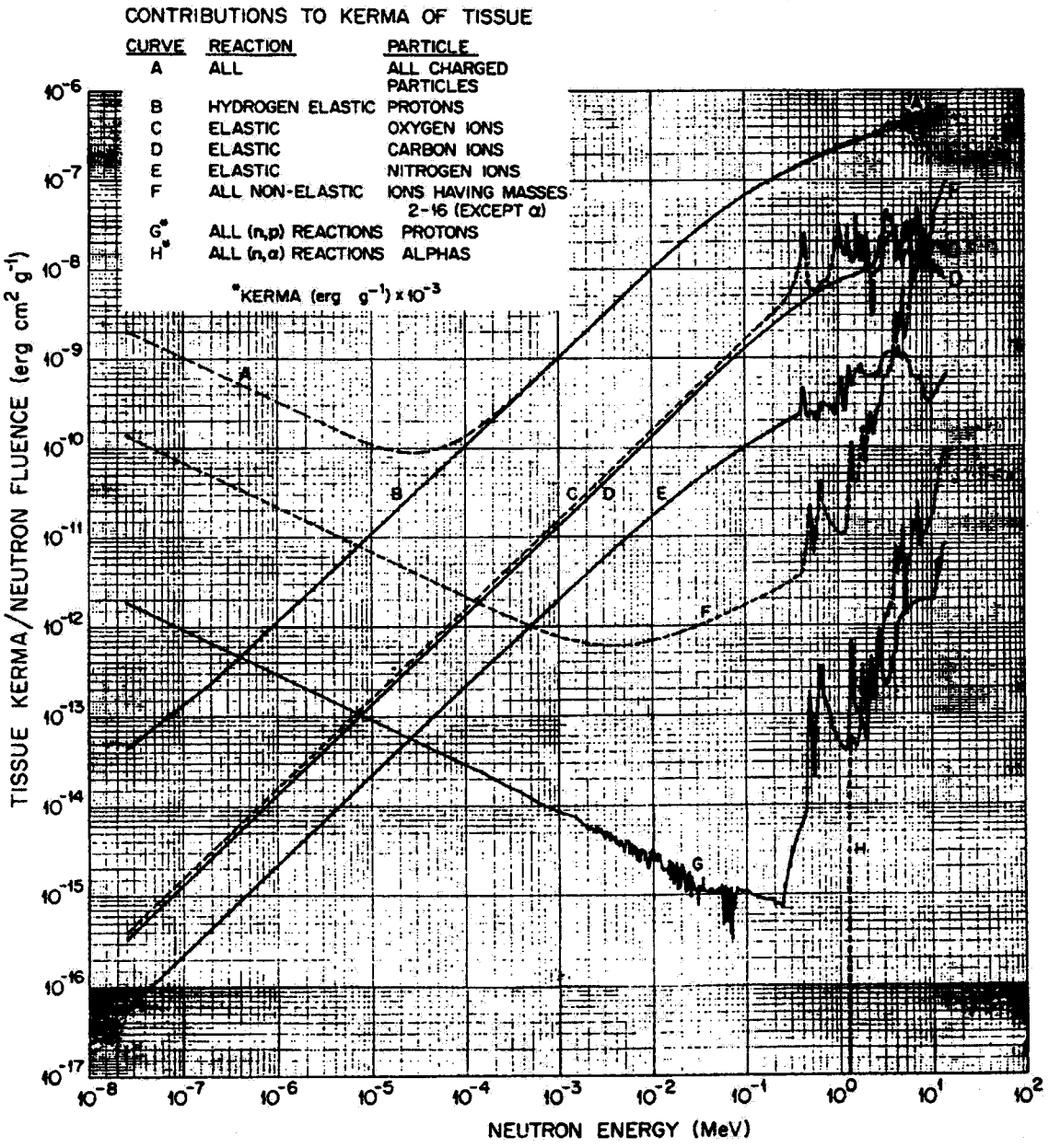

Figure 1. Tissue kerma free-in-air per neutron fluence and contributions from different reactions of neutrons with constituents of tissue vs. neutron energy (NCRP, 1971; Figure 3). To obtain kerma per neutron fluence in units of rad cm^2, divide values in units of erg cm^2 g^{-1} by 100.

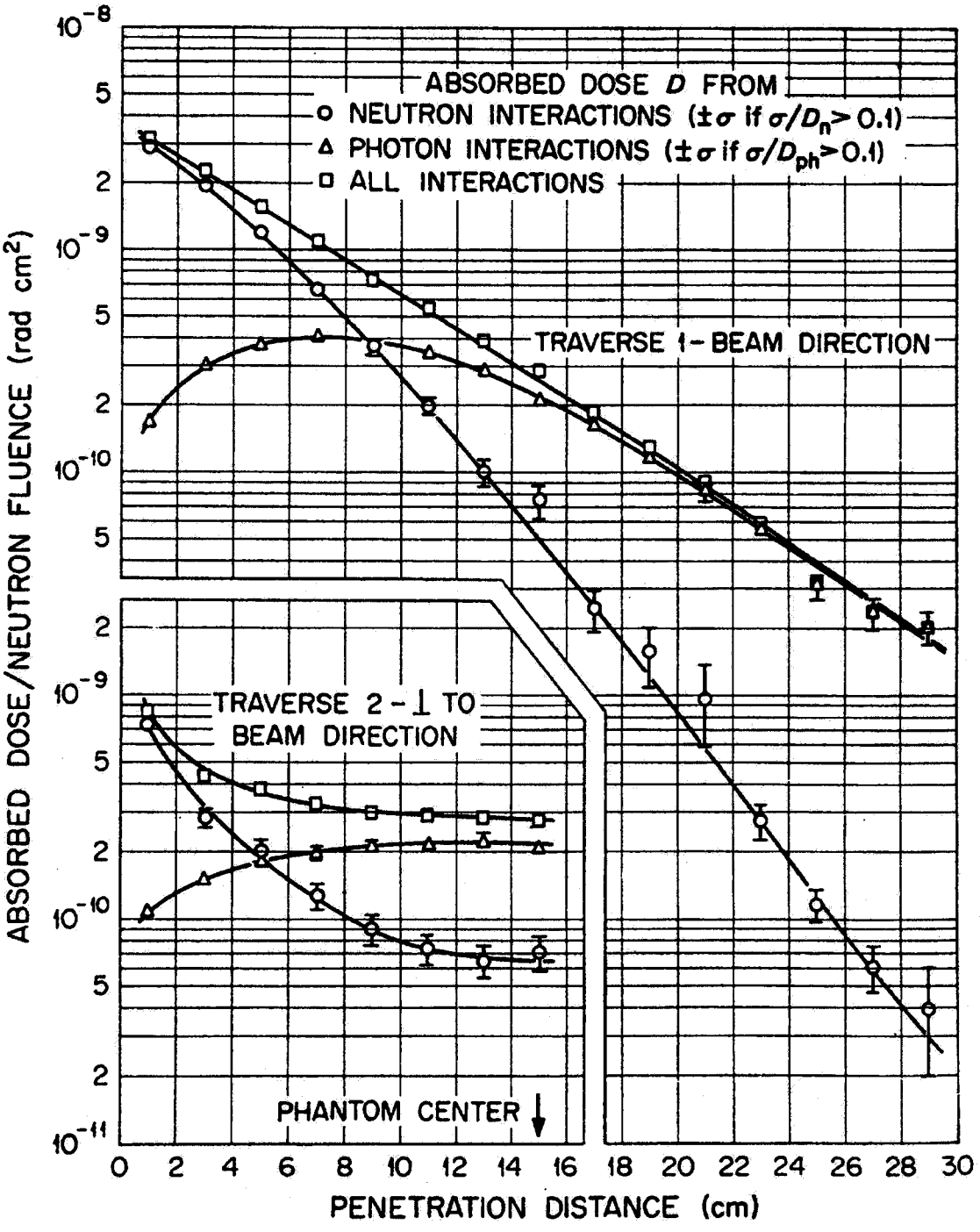

Figure 2. Absorbed dose per neutron fluence vs. depth in central region of 30-cm diameter cylindrical phantom of tissue-equivalent material at incident neutron energy of 1 MeV (NCRP, 1971; Figure 15).

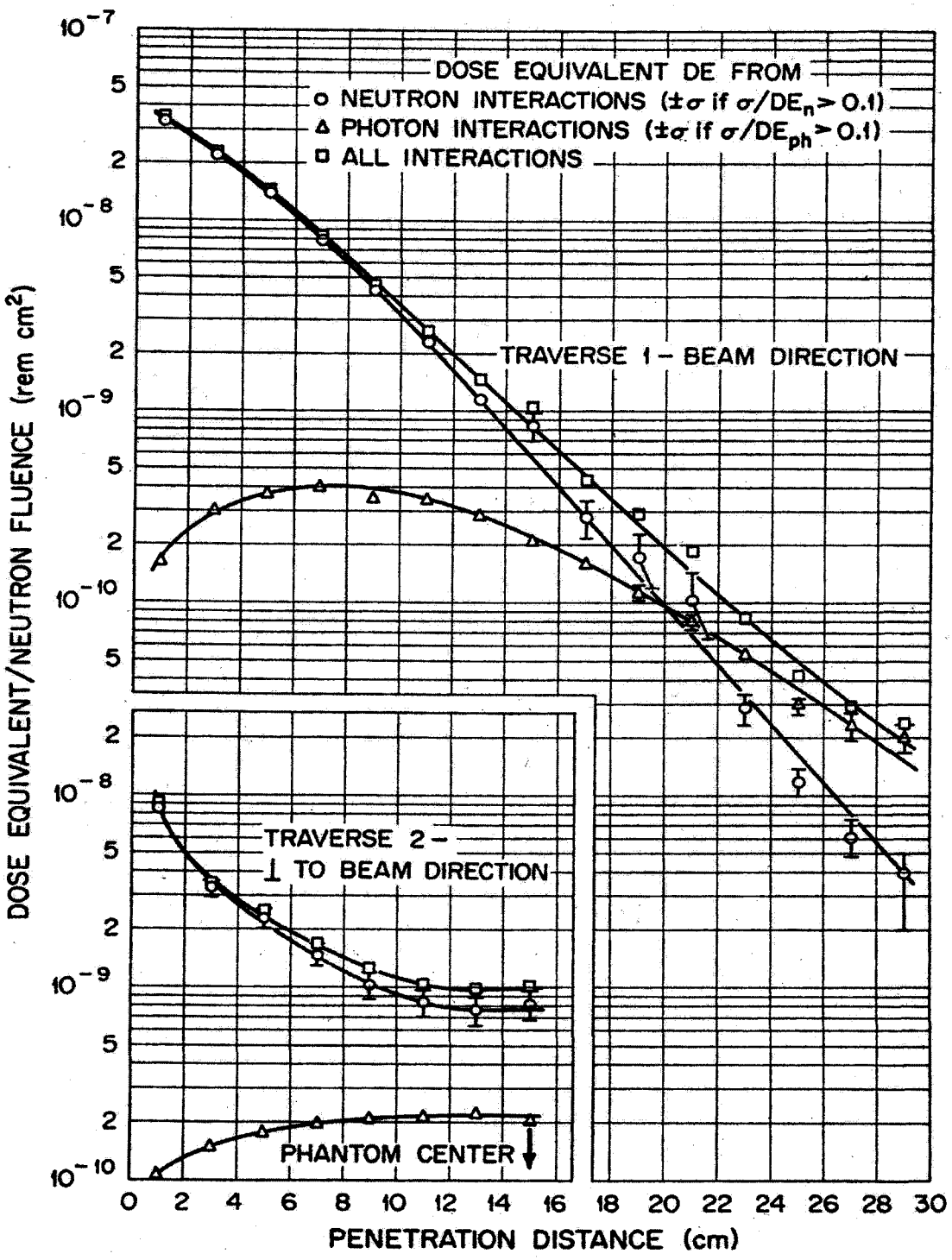

Figure 3. Dose equivalent per neutron fluence vs. depth in central region of 30-cm diameter cylindrical phantom of tissue-equivalent material at incident neutron energy of 1 MeV (NCRP, 1971; Figure 16).

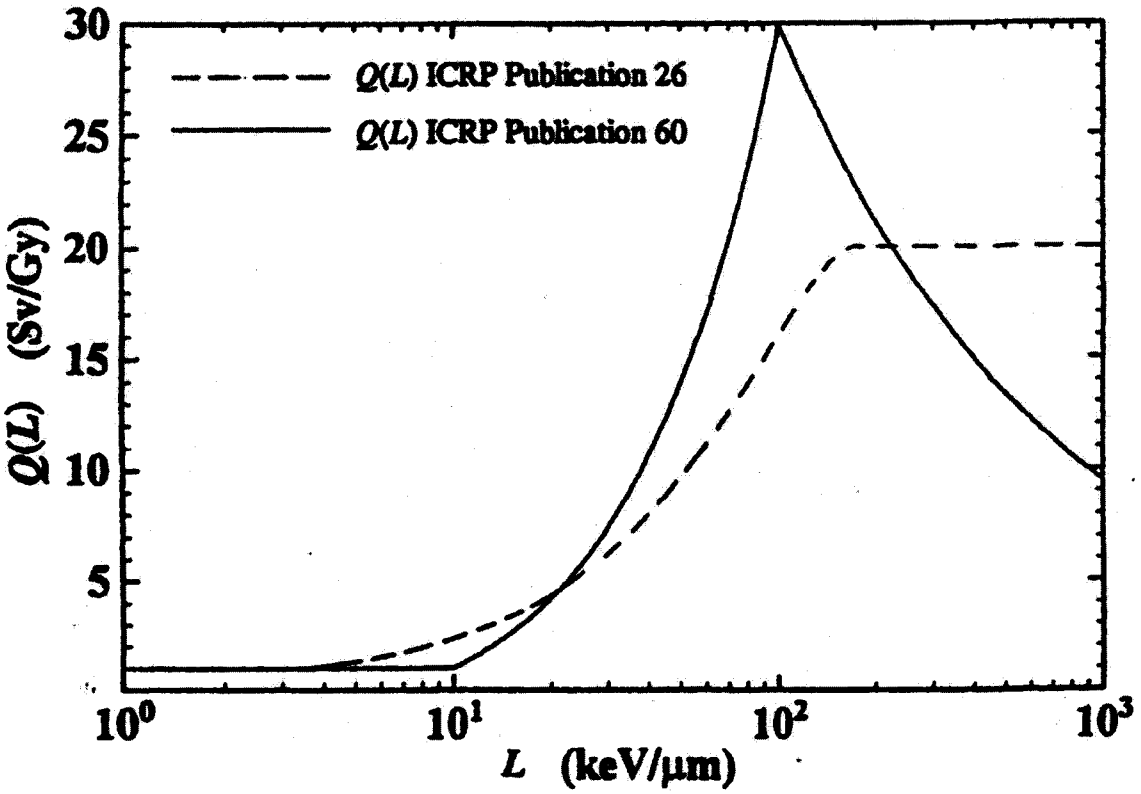

Figure 4. Quality factor (Q) for charged ionizing particles vs. linear energy transfer (L) recommended in ICRP Publication 60 (ICRP, 1991) and recommended previously in ICRP Publication 26 (ICRP, 1977); see also ICRP (1996; 2003).

SECTION 3

FINDING BY NRC COMMITTEE ON UPPER BOUNDS OF NEUTRON DOSES

As noted in Section 1, an NRC committee found that upper bounds of neutron doses to military participants in the atmospheric testing program reported by DTRA are always underestimated because of neglect of uncertainty in the biological effectiveness of neutrons relative to high-energy photons (NRC, 2003). The committee found that the degree of underestimation of credible upper bounds of neutron doses was a factor of about 3-5, depending on the neutron quality factor (i.e., modifying factor) that had been used by SAIC.

In considering the NRC committee's finding, it is important to note that the committee assumed that the factor used by SAIC to modify estimates of tissue kerma free-in-air to obtain estimates of dose equivalent was either 13 or 8.5 (NRC, 2003). The higher value is as stated by Goetz et al. (1981; 1985), and it applies in most cases. However, as discussed in the previous section, the lower value (which should have been 8.6) applied above a trench in which members of Task Force WARRIOR at Operation PLUMBBOB, Shot DOPPLER were located, but the modifying factor at locations of exposure in the trench used by SAIC in that case is about 11 (Goetz et al., 1979). Thus, the committee erred in its assumption about the modifying factor used by SAIC in that case.

The NRC committee's finding was based mainly on an evaluation of data on the relative biological effectiveness (RBE) of fission neutrons and their uncertainties by Kocher et al. (2002); see also Kocher et al. (2005). On the basis of estimates of RBE in studies of life-shortening, which was due primarily to cancers, and induction of specific cancers in mice, Kocher et al. (2002) developed a probability distribution of an uncertain radiation effectiveness factor (REF)[11] for induction of solid tumors in humans by fission neutrons at high doses and high dose rates.

[11]The term "radiation effectiveness factor" (REF) was introduced to distinguish a quantity that represents biological effectiveness for purposes of estimating cancer risks and probability of causation of cancers in identified individuals from (a) the quality factor and radiation weighting factor used in radiation protection and (b) an RBE, which strictly applies only to results of a specific radiobiological study under controlled conditions (Kocher et al., 2002).

That probability distribution has an upper 95% credibility limit of about 25, which is about a factor of 3 above the median REF at high acute doses of 7.7. By applying a dose and dose-rate effectiveness factor (DDREF) for photons of 2 (ICRP, 1991) to the REF at high acute doses, the committee considered that the median and upper 95% credibility limit of REF for induction of solid tumors by fission neutrons at low doses are about 15 and 50, respectively. The committee thus assumed that an upper 95% credibility limit of REF for fission neutrons is a factor of about 4 or 6 higher than the modifying factor of 13 or 8.5, respectively, that the committee assumed was used by SAIC. The probability distribution of REF for fission neutrons developed by Kocher et al. (2002) is assumed to apply at energies of 0.1-2 MeV. By considering that military participants at atmospheric tests also were exposed to substantial fluences of neutrons of lower energies (see footnote 4) that have substantially lower REFs than 0.1-2 MeV neutrons (Kocher et al., 2002), consistent with the energy dependence of the mean quality factor in Table 2-1, the NRC committee reduced the assumed degree of underestimation of upper bounds of neutron dose equivalents calculated by SAIC to a factor of about 3-5 (NRC, 2003). The lower end of this range applied when a modifying factor of 13 was used by SAIC, and the upper end applied to the presumed modifying factor of 8.5 in the case of exposure of certain participants at Operation PLUMBBOB, Shot DOPPLER.

The following points about the NRC committee's evaluation should be noted. First, the committee assumed that the degree of underestimation of credible upper bounds of neutron dose equivalents of 3-5 applies to all organs or tissues of an exposed individual. This assumption is consistent with VA's use of neutron dose equivalents calculated by SAIC and reported by DTRA in adjudicating claims for compensation for cancers in specific organs or tissues.

Second, the committee's finding that upper bounds of neutron dose equivalents are always underestimated by a factor of about 3-5 was based only on a consideration of uncertainty in the biological effectiveness of neutrons (i.e., an upper 95% credibility limit of an REF for neutrons compared with modifying factors used by SAIC), and uncertainties in tissue kerma estimated by SAIC were not taken into account. Thus, in effect, the committee assumed that uncertainties in estimates of tissue kerma are small compared with the uncertainty in biological effectiveness. As noted in the previous section, SAIC's estimates of upper 95% credibility limits

of tissue kerma in trenches at NTS exceed mean values by a factor between 1.5 and 2.2. The effect of combining the two uncertainties is considered in Section 4.

Third, the committee's finding was based on its evaluation of REFs for solid tumors only, and REFs for leukemia were not considered. Although REFs for induction of leukemia by fission neutrons tend to be less than REFs for solid tumors, the upper 95% credibility limit of REF for fission neutrons and leukemia at low doses developed by Kocher et al. (2002) differs from the upper 95% credibility limit of REF for solid tumors at low doses of about 50 noted above by less than 10%. Thus, the committee's finding could be applied to all cancer types.

Fourth, the committee's estimate of an upper 95% credibility limit of REF for fission neutrons and solid tumors at low doses, which was obtained from a probability distribution of REF at high acute doses (Kocher et al., 2002) by assuming a DDREF for photons of 2 (ICRP, 1991), incorporates an assumption that there is no uncertainty in DDREF. However, DDREF also is uncertain. For most solid tumors, DDREF has been described by a probability distribution that ranges from 0.5 to 5.0 and has a mean value of 1.8 (Land et al., 2003). When that probability distribution is used to adjust the REF for fission neutrons and solid tumors at high acute doses, the median REF at low doses is reduced by about 20% compared with the value obtained by assuming a DDREF of 2, but the upper 95% credibility limit is reduced by less than 2%. A similar result is obtained when a somewhat different probability distribution of DDREF for breast and thyroid cancer (Land et al., 2003) is assumed. Thus, neglect of an uncertainty in DDREF does not have a significant effect on the committee's finding.

Finally, as noted earlier in this section, the NRC committee erred in assuming that SAIC used a modifying factor of 8.5 in the case of exposure of certain participants at Operation PLUMBBOB, Shot DOPPLER. If the modifying factor of 11 that was actually used by SAIC had been assumed instead, the NRC committee probably would have concluded that the degree of underestimation of upper bounds of neutron dose equivalents that results from neglect of an uncertainty in biological effectiveness should be no more than a factor of 50/11 = 4.5 in that

case, and should not exceed a factor of about 4 when the neutron spectrum at locations of exposure and the energy dependence of REF are taken into account.[12]

The NRC committee's consideration of credible upper bounds of neutron doses also was influenced by recommendations in Publication 60 of the International Commission on Radiological Protection (ICRP, 1991) on radiation weighting factors (w_Rs) for neutrons, which also represent their biological effectiveness and are given in Table 3-1 and Figure 3-1. Those recommendations are consistent with previous recommendations, which were developed subsequent to SAIC's calculations of neutron dose equivalents, that mean quality factors for neutrons in Table 2-1 should be increased by a factor of 2 (ICRP, 1985; NCRP, 1987).[13] For example, the w_R of 20 at energies of 0.1-2 MeV recommended by ICRP (1991), which is generally appropriate for fission neutrons, is a factor of 2 higher than the mean quality factor of 10 that had been recommended previously for general use in radiation protection (see Table 2-1). Thus, since the modifying factor of 13 used by SAIC in most cases is consistent with mean quality factors in Table 2-1, as discussed in Section 2, ICRP's recommendation on a w_R for fission neutrons implies that mean neutron dose equivalents calculated by SAIC should be increased by a factor of 2. Recommended increases in the biological effectiveness of neutrons were based mainly on estimates of RBE at low doses in studies of various stochastic endpoints that were reviewed by expert groups (ICRU, 1986; NCRP, 1990), including RBEs that were used by Kocher et al. (2002) to develop probability distributions of REFs.

In response to data on RBE which indicated that the biological effectiveness of neutrons at low doses should be increased by a factor of 2, ICRP (1991) also modified the relationship between the quality factor (Q) for charged ionizing particles and linear energy transfer (L) given by the dashed curve in Figure 2-4. That relationship had been used by NCRP (1971) to calculate

[12]We also note that the NRC committee apparently did not recognize that modifying factors used by SAIC are not the same as mean quality factors recommended by NCRP (1971), and that the modifying factor of 11 that was used by SAIC in one case resulted from an incorrect application of NCRP's mean quality factors to an estimate of tissue kerma free-in-air.

[13]Radiation weighting factors replace mean quality factors used previously for purposes of radiation protection. Radiation weighting factors also modify estimates of average absorbed dose in specific organs or tissues (ICRP, 1991). However, radiation weighting factors for any radiation type differ from mean quality factors in that the former are determined by the energies of radiations incident on the body or emitted by radionuclides in the body, whereas the latter are determined by the energies of radiations at locations in the body where absorbed dose is delivered.

neutron dose equivalents in a 30-cm diameter cylindrical phantom and, thus, is incorporated in modifying factors used by SAIC. The *Q–L* relationship currently recommended by ICRP (1991; 1996; 2003) is given by the solid curve in Figure 2-4. As indicated in Figure 3-1 (ICRP, 1996; Figure 3), use of the revised *Q–L* relationship, as well as newer data on stopping powers of charged particles, results in a higher maximum biological effectiveness of neutrons at energies near 0.5 MeV and a more pronounced energy dependence than were obtained by using the previous *Q–L* relationship and previous stopping-power data.

Table 2. Radiation weighting factors (w_R) for neutrons recommended in ICRP Publication 60 (ICRP, 1991)

Neutron energy	Radiation weighting factor (w_R)
< 10 keV	5
10-100 keV	10
0.1-2 MeV	20
2-20 MeV	10
> 20 MeV	5

Note: When calculation of radiation weighting factors for neutrons requires a continuous function, the following approximation can be used (ICRP, 1991):

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

where E_n is the neutron energy in MeV. There is no intent to imply any biological meaning to this relationship; it is simply a tool for calculation.

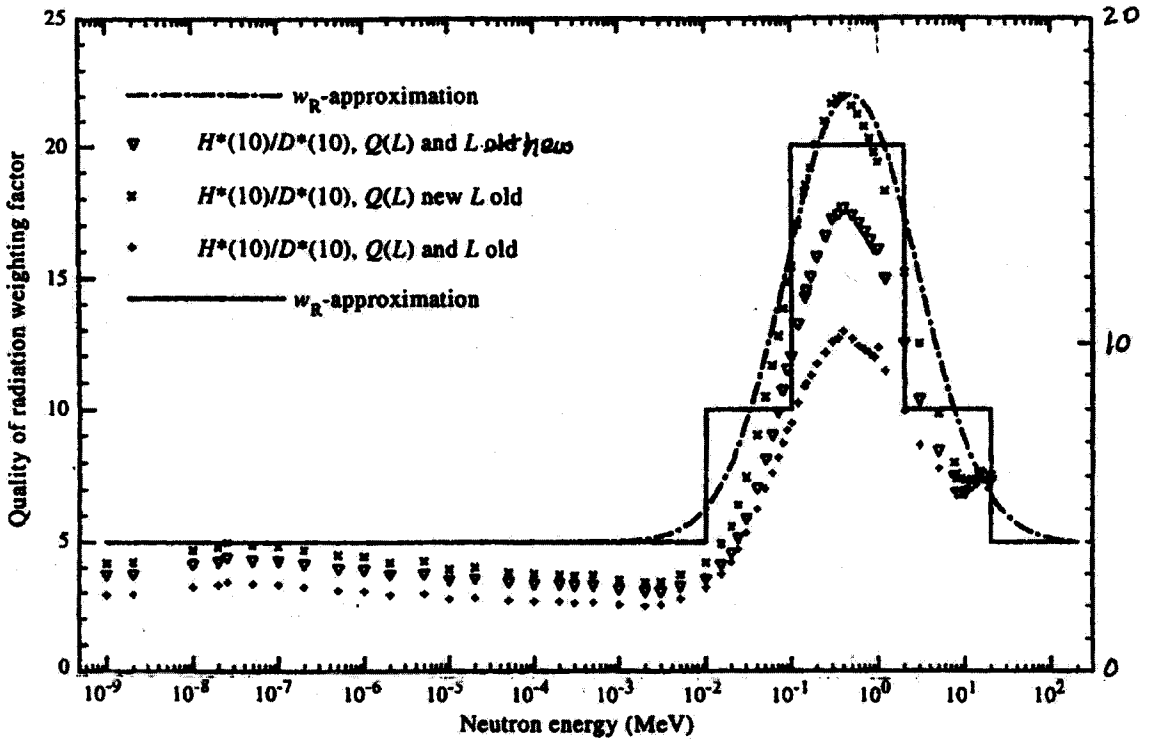

Figure 5. Summary of influence of relationship between quality factor (Q) and linear energy transfer (L) and stopping powers of charged particles on quality factor for neutrons (ICRP, 1996; Figure 3); new and old Q–L relationships are given in Figure 2-4. Data points are ratios of ambient dose equivalent and absorbed dose at depth of 1 cm in tissue, and solid and broken curves are recommendations on radiation weighting factors (w_Rs) for neutrons given in Table 3-1 (ICRP, 1991). Scale on left vertical axis applies to all data points and curves, except scale on right vertical axis applies to data points obtained using old Q–L relationship and stopping-power data.

SECTION 4

ADJUSTMENT FACTOR IN INTERIM GUIDANCE

Following the NRC committee's review of the dose reconstruction program of DTRA (NRC, 2003), DTRA issued Interim Guidance (Benavides, 2003) on changes to be made in methods of dose reconstruction to address various findings by the committee. In response to the finding that upper bounds of neutron doses are always underestimated by a factor of about 3-5, the Interim Guidance specified that mean values of neutron dose equivalents that had been calculated by SAIC, as described in Section 2, should be increased by a factor of 6 to obtain upper bounds (i.e., at least upper 95% credibility limits) in all cases.

A basis for the adjustment factor of 6 is not discussed in the Interim Guidance. However, we believe it is reasonable to presume that it was obtained by combining the higher uncertainty factor of 5 to represent uncertainty in the biological effectiveness (REF) of fission neutrons, which applied when the modifying factor used by SAIC was assumed by the NRC committee to be 8.5, with a factor that represents uncertainty in estimates of tissue kerma free-in-air. As noted in Section 2, the uncertainty in tissue kerma estimated by SAIC is a factor of about 1.5 to 2.2 in cases of exposure in trenches at NTS. By combining uncertainty factors (i.e., ratios of upper 95% credibility limits to median values) of 5 and 2.2, an overall uncertainty factor of about 6 is obtained,[14] in agreement with the adjustment factor in the Interim Guidance.

Given the presumption that the adjustment factor of 6 specified in the Interim Guidance was based on an erroneous assumption by the NRC committee (NRC, 2003) that SAIC used a modifying factor of 8.5 in the case of exposure of certain participants at Operation PLUMBBOB, Shot DOPPLER, use of that adjustment factor should have been more than sufficient to provide upper bounds of neutron doses that are at least upper 95% credibility limits. An analysis to address this issue in more detail is presented in Section 6.

[14]In this report, an uncertainty in the product of two uncertain parameters is estimated by assuming that the parameters are uncorrelated and are described by lognormal probability distributions that are defined by assumed ratios of upper 95% credibility limits to median values.

SECTION 5

EFFECT OF ADJUSTMENT FACTOR ON VA's EVALUATIONS OF CAUSATION OF CANCERS

When an evaluation of causation is required in adjudicating claims for compensation for cancers experienced by military participants in the atmospheric testing program, VA uses upper bounds of dose equivalents from all radiation types and routes of exposure reported by DTRA in those evaluations; VA does not use reported mean doses. Use of upper bounds of doses in evaluating causation of cancers is in accordance with VA regulations in 38 CFR 3.311(a), which specify that whenever a range of doses is reported, the highest level of the reported dose range will be presumed.

When the Interim Guidance (Benavides, 2003) and Report to Congress (Cooper and Klein, 2004) were issued, VA was evaluating causation of cancers in two different ways. This section discusses how use of the adjustment factor of 6 to estimate upper bounds of neutron doses, as specified in the Interim Guidance, affected the two ways of evaluating causation of cancers when a neutron dose was reported by DTRA.

In the approach to evaluating causation of certain cancers that VA had been using for many years, an estimated upper bound of the total dose equivalent from all radiation types and routes of exposure combined was compared with a so-called screening dose for the cancer type of concern in a claim for compensation. Screening doses for various cancer types were given in a table that was developed by the Committee on Interagency Radiation Research and Policy Coordination (CIRRPC, 1988; Table 3); the CIRRPC table is reproduced in Table III.E.3 of the NRC (2003) report. Screening doses corresponded to an estimated probability of causation (PC) of cancer of 50% at the upper 99% credibility limit. They were calculated by taking into account various sources of uncertainty in estimating cancer risk and PC, including uncertainties in epidemiological data on risks of specific types of cancer associated with given doses of low-LET radiation and assumed extrapolations of observed risks to lower doses (CIRRPC, 1988). If an estimated upper bound of the total dose equivalent to a participant equaled or exceeded the

screening dose that applied to the participant's cancer type, age at time of exposure, and time since exposure when cancer was diagnosed in cases of leukemia, VA normally concluded that it is at least as likely as not that the participant's cancer was caused by radiation exposure and compensation was awarded.

When VA used the CIRRPC table to evaluate causation of cancers, estimated upper bounds of neutron dose equivalents needed to take into account an uncertainty in the biological effectiveness of those radiations, as well as an uncertainty in the estimated tissue kerma, because uncertainties in the biological effectiveness of different radiation types were not incorporated in screening doses in the CIRRPC table.[15] Thus, since uncertainties in neutron doses estimated by SAIC represented uncertainties in tissue kerma only, use of an adjustment factor that accounts for an uncertainty in biological effectiveness, as specified in the 2003 Interim Guidance, was required when the CIRRPC table was used, in order to ensure that credible upper bounds (at least upper 95% credibility limits) of neutron doses would be used in evaluating causation of cancers.

In late 2003, VA began to use software called the Interactive RadioEpidemiological Program (IREP) (Land et al., 2003) as an alternative to screening doses in the CIRRPC table in evaluating causation of cancers (VHA/OPHEH, 2003; Mather and Otchin, 2004).[16] In contrast to VA's use of the CIRRPC table, which did not involve an estimation of PC, IREP calculates a probability distribution of an uncertain PC for a cancer type of concern that is associated with given doses, ages at times of exposure, and age at the time of diagnosis of cancer by taking into account several sources of uncertainty. VA then used the upper 99% credibility limit of PC for the cancer type of concern that was calculated by IREP in adjudicating claims for compensation, to be consistent with the assumption used in developing screening doses in the CIRRPC table. When a cancer type of concern in a claim was included in the CIRRPC table, VA based its

[15]Screening doses in the CIRRPC table were based on estimates of cancer risks and PC associated with given doses of low-LET radiation, principally high-energy photons (NIH, 1985). Thus, use of those screening doses in cases of exposure to high-LET radiations (e.g., neutrons and alpha particles) required assumptions about the biological effectiveness of those radiations.

[16]Versions of IREP that have been used by VA were developed for use by The National Institute for Occupational Safety and Health (NIOSH, 2002) in the compensation program for energy workers. The current version of NIOSH-IREP is available at http://www.niosh-irep.com/irep_niosh.

medical opinion on causation on the approach (the CIRRPC table or IREP) that was more favorable to the claimant.[17]

An important difference between IREP and the CIRRPC table is that, instead of using a total dose from all radiation types and routes of exposure combined as required by the CIRRPC table, it is intended that doses will be entered into IREP by radiation type. Specifically, *equivalent doses* from photons, electrons, neutrons, and alpha particles that are calculated using radiation weighting factors (w_Rs) recommended by ICRP (1991) should be entered separately.[18] IREP accounts for uncertainties in the biological effectiveness of different radiation types relative to high-energy (> 250 keV) photons by incorporating probability distributions of REFs developed by Kocher et al. (2002), including the probability distributions of REF for fission neutrons discussed in Section 3. When a neutron equivalent dose and the associated energy range of neutrons are entered into IREP, the equivalent dose is divided by the w_R that IREP assumes was used to estimate equivalent dose to obtain the corresponding absorbed dose. IREP then modifies the absorbed dose by the probability distribution of REF that applies to the specified neutron energy range and cancer type of concern (either solid tumors or leukemia).[19] The result is a probability distribution of a biologically significant dose that is used in IREP to calculate a probability distribution of PC. In cases of exposure to fission neutrons or neutrons of unspecified energy, an energy range of 0.1-2 MeV should be assumed, in which case IREP assumes that a w_R of 20 was used to calculate equivalent doses (see Table 3-1).

[17]Use of screening doses in the CIRRPC table usually was more favorable, except possibly in cases of cancer of the colon or female breast. However, only 12 cancers were included in the CIRRPC table, whereas IREP calculates PC for 32 cancers, including cancers of the skin and prostate, which are the most common in claims for compensation by military participants but are not included in the CIRRPC table. Therefore, in practice, VA used IREP to evaluate causation of cancer in most cases.

[18]In calculating PC for cancers in military participants at atmospheric tests, equivalent doses from photons and electrons can be combined and entered into IREP as the equivalent dose from high-energy (> 250 keV) photons or higher-energy (>15 keV) electrons. However, equivalent doses from neutrons and alpha particles should always be entered separately into IREP to ensure that uncertainties in the biological effectiveness of those radiations are taken into account properly in estimating PC.

[19]IREP incorporates probability distributions of REFs for neutrons that apply to energy ranges used by ICRP (1991) to specify the step-function representation of w_R given in Table 3-1.

When VA evaluated causation of cancers using IREP, upper bounds of doses from each radiation type reported by DTRA were entered as point (constant) values without uncertainty. This way of using IREP, which is in accordance with VA regulations, as noted above, should result in a higher estimate of an upper 99% credibility limit of PC than would be obtained by using probability distributions of uncertain doses and, thus, is favorable to claimants.[20]

The foregoing discussions indicate that the effect of using the adjustment factor of 6 specified in the 2003 Interim Guidance to estimate upper bounds of neutron doses differed depending on whether VA used the CIRRPC table or IREP to evaluate causation of cancers. When the CIRRPC table was used, application of an adjustment factor to mean neutron doses that had been calculated by SAIC was necessary to ensure that credible upper bounds of doses were used in evaluating causation of cancers, because an adjustment factor was the only means of accounting for an uncertainty in the biological effectiveness (REF) of neutrons.

When VA used IREP, however, an uncertainty in REF for neutrons was taken into account twice, once by means of the adjustment factor specified in the 2003 Interim Guidance, which takes into account the upper 95% credibility limit of an REF for fission neutrons relative to modifying factors used by SAIC, and again by means of the probability distribution of REF for fission neutrons incorporated in IREP. This double-counting of uncertainty in REF, which was favorable to claimants, resulted in an upper 95% credibility limit of a biologically significant dose from exposure to neutrons that is higher than needed by a factor given by the ratio of the upper 95% credibility limit of REF for fission neutrons at low doses of about 50 incorporated in IREP to the w_R of 20 that IREP assumes was used to estimate equivalent doses from fission neutrons, or a factor of about 2.5.[21]

In April 2005, VA discontinued use of the CIRRPC table and adopted a policy of using IREP exclusively to evaluate causation of cancers (Mansfield, 2005). With that change in policy, the adjustment factor that should be applied to mean neutron doses calculated by SAIC to

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[20]In addition to constant doses, various probability distributions of doses (lognormal, normal, triangular, logtriangular, uniform, or loguniform) can be entered into IREP.

[21]It is important to emphasize that an overestimation of dose by a some factor does not result in an overestimation of PC by the same factor, because PC is a nonlinear function of dose (D, rem) given by $[\text{ERR/rem} \times D]/[(\text{ERR/rem} \times D) + 1]$, where ERR/rem is the excess relative risk per rem for a participant's cancer type, ages at times of exposure, and age at the time of diagnosis.

obtain credible upper bounds should take into account (a) an uncertainty in tissue kerma only and (b) an increase in mean doses by a factor of 2 to represent the ratio of the w_R of 20 that IREP assumes was used to estimate equivalent doses from fission neutrons to the modifying factor of 11 or 13 used by SAIC. The adjustment factor should no longer include an uncertainty in the biological effectiveness of fission neutrons, because that uncertainty is incorporated in IREP. For example, if the uncertainty in tissue kerma is a factor of 2.2, as assumed in the previous section, the adjustment factor that should be applied to mean doses calculated by SAIC would be 2.2×2, or about 4, rather than 6 as specified in the 2003 Interim Guidance.

SECTION 6

EVALUATION OF ADEQUACY OF UPPER BOUNDS OF NEUTRON DOSES

An important concern in this investigation is whether upper bounds of neutron doses that were obtained by applying the adjustment factor of 6 specified in the Interim Guidance (Benavides, 2003) to mean doses that had been calculated by SAIC were adequate for the purpose of evaluating causation of cancers. As discussed in the previous section, this issue is particularly important in cases where VA evaluated causation of cancers using screening doses in the CIRRPC table. Upper bounds obtained by using the adjustment factor of 6 would be adequate if they are at least upper 95% credibility limits of doses to any organ or tissue from external exposure to neutrons. In addressing this issue, it is important to recognize that mean quality factors and radiation weighting factors for neutrons recommended by NCRP and ICRP and given in Tables 2-1 and 3-1, respectively, are intended to be used for purposes of radiation protection (control of exposures), rather than for purposes of estimating risks and PC of specific cancers in identified individuals. That is, it is intended that use of radiation protection quantities would not result in substantial underestimates of dose to specific organs or tissues of concern.

In evaluating the adequacy of upper bounds of neutron doses that were obtained using the adjustment factor of 6, we consider doses to skin separately from doses to internal organs. The latter lie well below the body surface, whereas radiosensitive tissues of the skin lie at an average depth of about 0.07 mm (ICRP, 1977). We also consider the potential importance of recent changes in evaluated cross sections for interactions of neutrons with constituents of air as they affect estimates of neutron fluences at assumed locations of exposure of military participants in the atmospheric testing program.

6.1 Doses to Internal Organs

A comparison of doses to internal organs from exposure to fission neutrons with doses calculated by SAIC can be made on the basis of organ-specific transmission factors in an adult (55-kg) Japanese phantom from exposure to prompt neutrons produced in the detonations at Hiroshima and Nagasaki (Kaul et al., 1987) and an assumed quality factor for neutrons. A transmission factor is defined as the ratio of an organ kerma to tissue kerma free-in-air from neutrons. Transmission factors were calculated for neutrons and secondary photons produced by interactions of neutrons in tissues of the body. Calculated transmission factors essentially give absorbed doses to specific organs from neutrons or secondary photons relative to tissue kerma free-in-air for an assumed spectrum of incident neutrons.

Organ-specific transmission factors at a ground distance of 1.5 km from the detonation at Nagasaki that were calculated by assuming a standing phantom facing the detonation (Kaul et al., 1987; Tables 74 and 78) are given in the middle two columns of Table 6-1. Transmission factors in the last column were calculated by weighting the transmission factor for neutrons by a quality factor of 11 and adding the transmission factor for secondary photons; a quality factor of 11 is the maximum value in Table 2-1 and is the same as the lower value of the modifying factor that SAIC applied to tissue kerma free-in-air. Weighted transmission factors in Table 6-1 thus provide dose equivalents from neutrons and secondary photons combined that can be compared with the dose equivalent that was calculated by SAIC by applying a modifying factor of 11 to an estimate of tissue kerma free-in-air.[22]

We find that the neutron dose equivalent that was calculated by SAIC using a modifying factor of 11 exceeds dose equivalents to specific organs in the adult phantom by a factor that ranges from 11/8.6 = 1.3 in the female breast to 11/2.5 = 4.4 in the pancreas. The average of these ratios in all organs listed in Table 6-1 is 2.2. All such ratios are 18% higher when dose equivalents were calculated by SAIC using a modifying factor of 13, as has most often been the case, and the same quality factor of 11 is used to calculate weighted transmission factors in the

[22]In estimating dose equivalents to specific organs of Japanese atomic-bomb survivors, a quality factor of 10 for neutrons has often been used; e.g., see Roesch (1987).

adult phantom. Similar results would be obtained if transmission factors that apply to prompt neutrons produced in the detonation at Hiroshima (Kaul et al., 1987) were used.

If an upper 95% credibility limit of an REF for induction of solid tumors at low doses of 50 discussed in Section 3 were used to represent the biological effectiveness of neutrons, rather than the lower modifying factor of 11 used by SAIC and the quality factor of 11 used to calculate weighted transmission factors in Table 6-1, ratios of dose equivalents calculated by SAIC to organ-specific dose equivalents in the adult phantom would differ little from the ratios summarized above, mainly because weighted transmission factors in Table 6-1 are dominated by the contribution from neutrons in all cases and, thus, would be nearly proportional to an assumed biological effectiveness of neutrons. That is, the ratios summarized above also apply reasonably well at upper 95% credibility limits of the two dose equivalents. The biggest change would occur in the ratio of dose equivalents in the pancreas, which would increase from 4.4 to 4.8.

Our analysis of neutron dose equivalents calculated by SAIC compared with weighted transmission factors in specific organs in an adult phantom, as described above, is subject to several limitations. For example: (a) energy and angular distributions of neutrons above ground at a ground distance of 1.5 km from the detonation at Nagasaki differ from distributions at greater distances in trenches at NTS;[23] (b) transmission factors in Table 6-1 apply to a standing phantom facing the detonation and, thus, differ from values that would apply to an individual crouching in a trench; and (c) transmission factors in most participants at atmospheric tests would be lower than values in a 55-kg phantom, due to their greater body mass. Nonetheless, we believe it is reasonable to conclude that estimates of tissue kerma free-in-air modified by an appropriate factor to account for the biological effectiveness of neutrons should provide overestimates of doses to internal organs of participants in all cases. However, our analysis also suggests that the degree of overestimation of doses to internal organs that lie relatively close to the body surface could be less than a factor of 2.

[23]The closest ground distance of observers at NTS was about 1.8 km, and other exposures on the ground at NTS occurred at distances greater than 2 km (Goetz et al., 1981).

6.2 Doses to Skin

In contrast to doses to internal organs discussed above, neutron dose equivalents calculated by SAIC probably do not overestimate doses to skin by a substantial amount. This conclusion is based on the following considerations. First, at an average depth of skin below the body surface of 0.07 mm (ICRP, 1977), the transmission factor for spectra of fission neutrons should be close to 1.0; i.e., kerma at that depth should differ little from tissue kerma free-in-air.[24] Second, when the variable angles of incidence of neutrons at the body surface and ranges of recoil protons that are produced by scattering of neutrons by nuclei of hydrogen atoms, which are less than about 0.4 mm (Shleien et al., 1998; Figure 5.8.1), are taken into account, the absorbed dose to skin from neutron interactions should be only slightly less than tissue kerma free-in-air, perhaps by about 10%.[25] Third, as illustrated by calculations in Figure 2-2, the absorbed dose to skin from interactions of secondary photons should be insignificant at incident neutron energies above about 10 keV (NCRP, 1971; Appendix B).

Thus, estimates of tissue kerma free-in-air modified by an appropriate factor to account for the biological effectiveness of neutrons should provide a reasonable representation of doses to skin. Discussions on the NRC committee's evaluation of SAIC's calculations of neutron doses (see Section 3) and uncertainties in tissue kerma free-in-air estimated by SAIC (see Section 2) indicate that when an adjustment factor of 6 was applied to mean doses, as specified in the 2003 Interim Guidance, the resulting upper bounds probably were about 50% higher than needed to represent upper 95% credibility limits of doses to skin when a modifying factor of 13

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[24]An implicit assumption in these discussions is that neutrons are incident on the body at locations of skin cancers, rather than transported through a substantial thickness of tissue prior to irradiating skin at those locations. Attenuation of incident neutrons by transport through the body could greatly reduce dose equivalents to skin relative to tissue kerma free-in-air (e.g., see Figure 2-3).

[25]Recoil protons from elastic scattering by hydrogen nuclei are the most important charged particles produced by neutron interactions in tissue at energies above 50 eV (see Figure 2-1), and the maximum range of recoil protons of about 0.4 mm applies to backscattering of 6 MeV neutrons, which is about the highest energy of neutrons to which military participants at atmospheric tests were exposed (S.D. Egbert, SAIC, personal communication). Absorbed dose from neutron interactions would be the same as tissue kerma free-in-air if charged-particle equilibrium were achieved at a depth of 0.07 mm below the body surface, but absorbed dose is less than tissue kerma free-in-air when charged-particle equilibrium is not achieved; e.g., see Shultis and Faw (1996).

was used by SAIC. However, the upper bound probably was no more than about 20% higher than needed in the one case where a modifying factor of 11 was used.

6.3 Effect of Revised Estimates of Neutron Fluences

Neutron fluences at assumed locations of exposure of military participants at atmospheric tests that were calculated by SAIC incorporate assumptions about cross sections for interactions of neutrons with constituents of air during transport from a burst point. Subsequent to SAIC's calculations, evaluated cross sections for inelastic scattering of neutrons from nuclei of nitrogen and oxygen atoms at energies greater than about 2 MeV were increased (S.D. Egbert, SAIC, personal communication). As a result, SAIC probably overestimated fluences of higher-energy neutrons at locations of exposure and, thus, neutron doses to participants.

The potential importance of increases in cross sections for inelastic scattering of neutrons in air is suggested by recent revisions of dosimetry data at Hiroshima and Nagasaki. As shown in Figure 6-1, tissue kerma free-in-air from neutrons is reduced at ground distances from the detonation at Hiroshima greater than 2 km and is reduced at all distances from the detonation at Nagasaki compared with previous calculations (Cullings and Fujita, 2003); the reduction in tissue kerma at Nagasaki is about 30% at 2 km. Similarly, as shown in Figure 6-2, absorbed doses to the colon from neutrons are reduced at all distances at both sites (Preston et al., 2004); the reductions at 2 km are about 20% at Hiroshima and 40% at Nagasaki. Reductions in tissue kerma free-in-air and absorbed dose to the colon from neutrons increase as the ground distance increases beyond 2 km at both sites, due to the more rapid attenuation of lower-energy neutrons and, thus, the greater proportion of higher-energy neutrons in fluences at greater distances.

If we assume that reductions in tissue kerma free-in-air and absorbed dose to the colon at Nagasaki are representative of reductions that would apply to detonations at NTS and in the

Pacific,[26] we would conclude that neutron doses calculated by SAIC probably overestimate doses to all organs and tissues, including skin, by at least 30% in all cases, and that larger reductions could apply at distances from a detonation greater than 2 km. However, reductions in dosimetry data at Nagasaki indicated in Figures 6-1 and 6-2 should be interpreted with caution when factors other than increases in cross sections for neutron interactions in air also contributed to the reductions (Cullings and Fujita, 2003) and the importance of higher-energy neutrons produced in detonations at NTS and in the Pacific could be different than in the detonation at Nagasaki. In addition, reductions in neutron fluences due to increases in cross sections for inelastic scattering from nitrogen and oxygen nuclei could have been less at NTS than in Japan, due to the lower density of the atmosphere at higher elevations and the lower absolute humidity. Therefore, definitive conclusions about the effect of increased cross sections on calculated neutron doses to military participants at atmospheric tests would require further consideration of the applicability of revised dosimetry data at Nagasaki to detonations at NTS and in the Pacific.

A more rigorous approach to addressing the importance of increases in neutron cross sections in air and resulting reductions in fluences of higher-energy neutrons would require additional calculations of neutron transport in air to assumed locations of exposure of military participants at each atmospheric test. In this approach, mean neutron doses and upper bounds calculated previously by SAIC could be reduced by the same factor at any location, but the reductions would depend on distance from a detonation and the neutron spectrum in each case.

6.4 Conclusions on Adequacy of Adjustment Factor in Interim Guidance

The foregoing discussions indicate that use of the adjustment factor of 6 specified in the Interim Guidance (Benavides, 2003) to obtain upper bounds of neutron doses from mean doses that were calculated by SAIC is more than sufficient to ensure that those upper bounds are at least upper 95% credibility limits of neutron doses to any organ or tissue of military participants at atmospheric tests. This conclusion is based on several considerations, including: (a) the

[26]This assumption takes into account that the Hiroshima bomb did not resemble weapons detonated in the atmospheric testing program.

erroneous assumption by the NRC committee (NRC, 2003) about the modifying factor that SAIC applied to an estimate of tissue kerma free-in-air from neutrons to estimate dose equivalent in a particular case of exposure at Operation PLUMBBOB, Shot DOPPLER; (b) the conclusions that doses to all internal organs should be overestimated and that doses to skin should not be underestimated; and (c) the conclusion that tissue kerma free-in-air and neutron dose equivalents at locations of exposure of military participants at atmospheric tests were always overestimated by SAIC as a result of an overestimation of fluences of higher-energy neutrons in all cases.

The conclusion that use of the adjustment factor of 6 specified in the 2003 Interim Guidance is more than sufficient to given credible upper bounds (at least upper 95% credibility limits) of neutron doses is important mainly in cases where VA used screening doses in the CIRRPC table (CIRRPC, 1988) to evaluate causation of cancers. In those cases, upper bounds of neutron doses reported by DTRA needed to account for uncertainty in the biological effectiveness of neutrons. However, now that VA no longer uses the CIRRPC table but uses IREP exclusively to evaluate causation of cancers (Mansfield, 2005), an adjustment factor that includes an uncertainty in the biological effectiveness of neutrons is no longer needed, because an uncertainty in REF for fission neutrons is incorporated in IREP.

Table 3. Transmission factors for kerma in organs of adult (55-kg) adult Japanese phantom relative to neutron kerma free-in-air from prompt neutrons produced in detonation at Nagasaki and transmission factors weighted by assumed quality factor for neutrons[a]

Organ	Transmission factor (organ kerma/tissue kerma free-in-air)[b]		Transmission factor weighted by $Q = 11$ for neutrons[c]
	Neutrons	Secondary photons	
Active marrow	0.34	0.18	3.9
Bladder	0.30	0.21	3.5
Bone	0.40	0.18	4.6
Brain	0.42	0.15	4.8
Breasts (female)	0.77	0.13	8.6
Eyes	0.75	0.12	8.4
Intestinal tract	0.23	0.24	2.8
Liver	0.34	0.19	3.9
Lungs	0.36	0.17	4.1
Pancreas	0.21	0.22	2.5
Stomach	0.37	0.20	4.3
Testes	0.51	0.18	5.8
Thyroid	0.57	0.18	6.5

[a]Transmission factors for kerma obtained from Tables 74 and 78 of Kaul et al. (1987) apply to standing phantom facing detonation at ground distance of 1.5 km.

[b]Organ kerma for neutrons and secondary photons produced by neutron interactions in tissue is essentially the same as absorbed dose from those radiations.

[b]Calculated as $TF_n \times Q_n + TF_\gamma$, where TF is transmission factor for neutrons or photons and quality factor for neutrons (Q_n) of 11 is lower of two values used by SAIC to modify estimates of tissue kerma free-in-air to obtain dose equivalents.

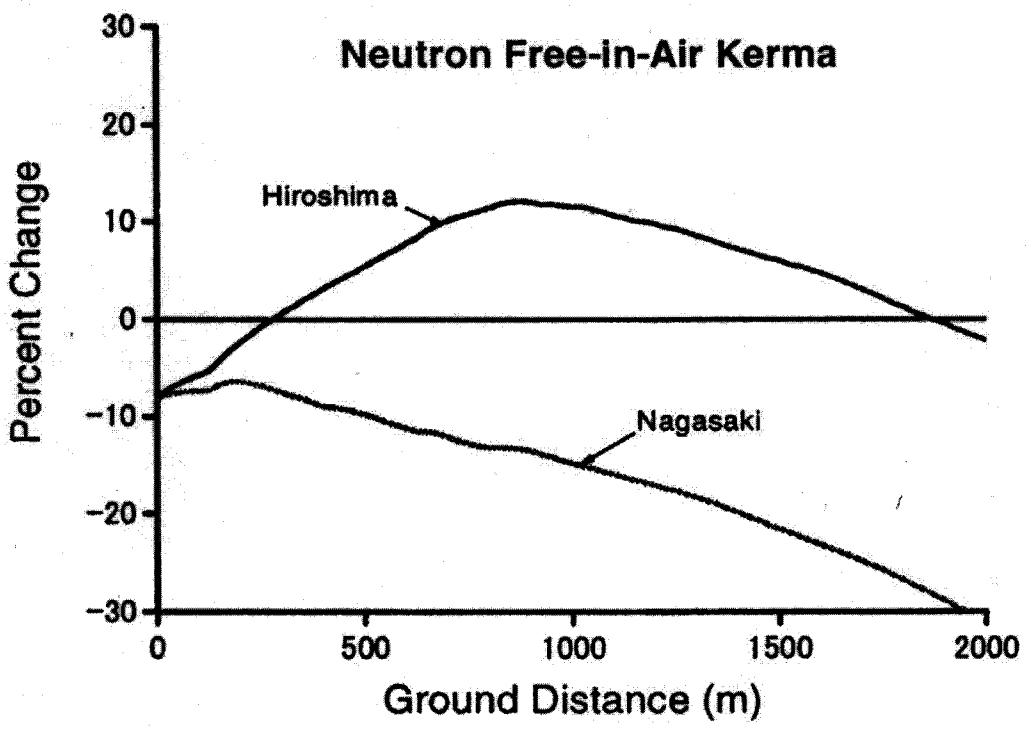

Figure 6. Changes in estimates of neutron kerma free-in-air vs. ground distance from detonations at Hiroshima and Nagasaki due to change in dosimetry system from DS86 to DS02 (Cullings and Fujita, 2003).

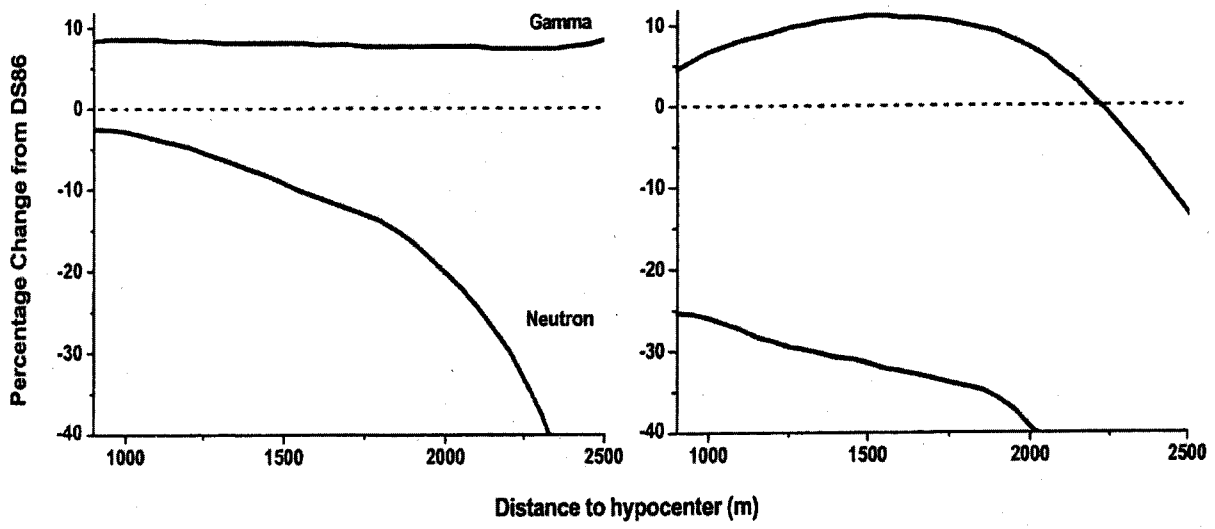

Figure 7. Changes in estimates of absorbed dose to colon from gamma rays and neutrons vs. ground distance from detonations at Hiroshima (left panel) and Nagasaki (right panel) due to change in dosimetry system from DS86 to DS02 (Preston et al., 2004).

SECTION 7

ESTIMATION OF UPPER BOUNDS OF NEUTRON DOSES FOR USE IN IREP

Now that VA uses IREP exclusively to evaluate causation of cancers in military participants at atmospheric tests and it is no longer necessary to account for an uncertainty in the biological effectiveness of neutrons in applying an adjustment factor to mean neutron doses calculated by SAIC, DTRA could use one of two approaches to estimate upper bounds of neutron doses to be reported to VA. As noted in Section 5, upper bounds of neutron doses should be entered into IREP separately from upper bounds of doses from other radiation types.

The first approach is based on an assumption that mean neutron doses that were calculated previously by SAIC, as described in Section 2, would not be revised; i.e., DTRA would continue to report neutron doses that were calculated using a modifying factor of 11 or 13, except we also assume that the dose that was calculated using a modifying factor of 11 in one case would be increased to a value that corresponds to a modifying factor of 13 to correct an inconsistency between the modifying factor of 11 and NCRP's mean quality factors. On the basis of these assumptions, upper bounds of neutron doses estimated by SAIC would need to incorporate (a) an uncertainty in tissue kerma only and (b) an increase that accounts for the difference between the radiation weighting factor (w_R) of 20 that IREP assumes was used to calculate equivalent doses from fission neutrons and the modifying factor of 13 used by SAIC. Since the modifying factor of 13 is consistent with NCRP's mean quality factors in Table 2-1, upper bounds of neutron doses estimated by SAIC that take into account uncertainties in tissue kerma only would need to be increased by a factor of 2 to obtain upper bounds of equivalent doses suitable for input to IREP.

In the second approach, neutron doses calculated previously by SAIC would need to be revised to incorporate a w_R of 20, rather than a modifying factor of 11 or 13, to be consistent with the recommendation on the biological effectiveness of fission neutrons (ICRP, 1991) and the assumption in IREP. If we assume that the neutron dose that was calculated using a

modifying factor of 11 would be increased to give a value that corresponds to a modifying factor of 13, SAIC would need to increase mean neutron doses calculated previously (Goetz et al., 1985) by a factor of 2. The resulting doses would be mean equivalent doses. With these increases in mean neutron doses, SAIC could revert to the approach that was used to estimate upper bounds of neutron doses prior to implementation of the provision in the 2003 Interim Guidance on use of an adjustment factor of 6. That is, upper bounds of neutron equivalent doses could be estimated by accounting for uncertainties in estimates of tissue kerma only, and no further adjustment would be needed. Thus, in this approach, means and upper bounds of neutron doses calculated previously by SAIC both would be increased by a factor of 2 to obtain means and upper bounds of equivalent doses.

Thus, in either approach, upper bounds of neutron doses calculated previously by SAIC would be increased by a factor of 2, but only in the second approach would mean neutron doses calculated previously also be increased. Again, an uncertainty in biological effectiveness (REF) of fission neutrons would not need to be taken into account in estimating upper bounds, because that uncertainty is incorporated in IREP.

Of the two approaches to revising neutron doses calculated previously by SAIC, we believe that the second approach is preferable because means and upper bounds both would be calculated using a w_R of 20 for fission neutrons, as recommended by ICRP and assumed in IREP. Thus, both would be equivalent doses. This approach would be particularly advantageous if VA revised its regulations to allow the use of ranges of doses in evaluating causation of cancers. With this change, neutron doses could be entered into IREP as probability distributions (see footnote 19), but only if means and upper bounds both were calculated using a w_R of 20. In addition, the interpretation of upper bounds of neutron doses would be more transparent when they represent uncertainties in tissue kerma only and do not incorporate an additional adjustment to account for an increase in biological effectiveness compared with the modifying factors used previously by SAIC. Finally, an approach of estimating means and upper bounds of neutron equivalent doses using a w_R of 20 is preferable if additional calculations for participants whose neutron doses were not estimated previously were needed.

SECTION 8

SUMMARY AND CONCLUSIONS

This report has considered approaches to estimating upper bounds of neutron doses to veterans of military services who participated in the atmospheric nuclear-weapons testing program. An important focus of this report is an investigation of the adequacy of the adjustment factor of 6 that was specified in the Interim Guidance (Benavides, 2003) for use in estimating upper bounds of neutron doses from mean doses calculated by SAIC (Goetz et al., 1979; 1981; 1985). That adjustment factor was developed to take into account an uncertainty in the biological effectiveness of fission neutrons that was not incorporated in upper bounds of neutron doses calculated previously by SAIC. An investigation of the adequacy of the adjustment factor of 6 involves an assessment of whether upper bounds of neutron doses obtained using that adjustment factor are at least upper 95% credibility limits of doses to any organ or tissue.

On the basis of an evaluation of the adjustment factor specified in the 2003 Interim Guidance and assumptions that were used by SAIC to calculate mean neutron doses and upper bounds, we concluded that applying an adjustment factor of 6 should be more than sufficient to ensure that the resulting upper bounds would be at least upper 95% credibility limits of doses to any organ or tissue, including skin. This conclusion is particularly important in cases where VA evaluated causation of cancers in participants at atmospheric tests using screening doses in the CIRRPC table (CIRRPC, 1988).

However, now that VA no longer uses the CIRRPC table but uses IREP exclusively to evaluate causation of cancers (Mansfield, 2005), an adjustment of mean neutron doses calculated by SAIC by a factor that accounts for an uncertainty in biological effectiveness, as specified in the 2003 Interim Guidance, is no longer needed, because an uncertainty in the biological effectiveness (REF) of fission neutrons is incorporated in IREP. Therefore, a different approach can be used to estimate upper bounds of neutron doses to be reported to VA.

On the basis of analyses presented in this report, we recommend that mean neutron doses and upper bounds calculated previously by SAIC (Goetz et al., 1979; 1981; 1985) both should be

revised as summarized below to provide doses suitable for input to IREP.

- The mean dose equivalent and upper bound that were calculated by applying a modifying factor of 11 to an estimate of tissue kerma free-in-air in the case of exposure of certain participants at Operation PLUMBBOB, Shot DOPPLER (Goetz et al., 1979) both should be increased to give values that are consistent with the use of a modifying factor of 13 in all other cases (Goetz et al., 1981; 1985). The modifying factor of 11 was based on an incorrect application of mean quality factors recommended by NCRP (1971) and given in Table 2-1 to an estimate of tissue kerma.

- All mean dose equivalents and upper bounds that were calculated by applying a modifying factor of 13 to an estimate of tissue kerma free-in-air, including revised estimates in the case of exposure of certain participants at Operation PLUMBBOB, Shot DOPPLER as recommended above, should be increased by a factor of 2 to account for the difference between the radiation weighting factor (w_R) of 20 recommended by ICRP (1991) and the modifying factor of 13 used by SAIC. The resulting doses would be means and upper bounds of neutron equivalent doses that are suitable for input to IREP. These upper bounds would take into account an uncertainty in tissue kerma only, as was the case prior to use of the adjustment factor specified in the 2003 Interim Guidance. The recommended increase in means and upper bounds calculated previously by a factor of 2 is based on the consideration that SAIC's modifying factor of 13 is consistent with the mean quality factor of 10 for neutrons that was used in radiation protection (NCRP, 1971; ICRP, 1977) prior to its replacement by a w_R of 20.

We also recommend that any additional calculations of neutron doses to participants that might be performed should use a w_R of 20 to obtain means and upper bounds of equivalent doses.

At the present time, VA uses only the upper bounds of neutron doses reported by DTRA in evaluating causation of cancers. We have shown that an increase in upper bounds calculated previously by SAIC by a factor of 2, as recommended above, should provide appropriate upper bounds of equivalent doses for input to IREP, meaning that upper bounds of biologically

significant doses from neutrons that are calculated in IREP by taking into account the uncertainty in biological effectiveness (REF) incorporated in IREP should exceed upper 95% credibility limits of doses to any organ or tissue of exposed individuals, including skin. This conclusion is based on data and analyses which indicate that (a) doses to internal organs should be overestimated due to neglect of the attenuation of incident neutrons in transport through tissues of the body and (b) fluences of important higher-energy neutrons and, therefore, tissue kerma at locations of exposure of military participants were overestimated by SAIC in all cases.

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SECTION 9

REFERENCES

Benavides, C., 2003. Letter to S. Powell, Titan Corporation (Defense Threat Reduction Agency, Fort Belvoir, Virginia) (July 16).

CIRRPC (Committee on Interagency Radiation Research and Policy Coordination), 1988. *Use of Probability of Causation by the Veterans Administration in the Adjudication of Claims of Injury Due to Exposure to Ionizing Radiation*, Report ORAU 88/F-4 (Office of Science and Technology Policy, Washington, D.C.).

Cooper, D.L., and Klein, D., 2004. *Radiation Dose Reconstruction Program of the Department of Defense (DoD) Report to Congress* (Department of Defense and Department of Veterans Affairs, Washington, D.C.) (June 3).

Cullings, H.M., and Fujita, S., 2003. "The Way to DS02: Resolving the Neutron Discrepancy," *RERF Update* 14 (Issue 1), 17-23.

DTRA (Defense Threat Reduction Agency), 2007. *Policy & Guidance Manual, Nuclear Test Personnel Review Program*, draft report (Defense Threat Reduction Agency, Fort Belvoir, Virginia) (March).

Goetz, J., Kaul, D., Klemm, J., and McGahan, J.T., 1979. *Analysis of Radiation Exposure for Task Force Warrior-Shot SMOKY-Exercise Desert Rock VII-VIII, Operation PLUMBBOB*, Report DNA 4747F (Science Applications, Inc., McLean, Virginia).

Goetz, J., Kaul, D., Klemm, J., McGahan, J., and Weitz, R., 1981. *Analysis of Radiation Exposure for Troop Observers, Exercise Desert Rock V, Operation UPSHOT-KNOTHOLE*, Report DNA 5742F (Science Applications, Inc., McLean, Virginia).

Goetz, J., Klemm, J., Thomas, C., and Weitz, R., 1985. *Neutron Exposure for DoD Nuclear Test Personnel*, Report DNA-TR-84-405 (Science Applications International Corporation, McLean, Virginia).

ICRP (International Commission on Radiological Protection), 1977. *Recommendations of the International Commission on Radiological Protection*, ICRP Publication 26, *Ann. ICRP* 1(3) (Pergamon Press, New York).

ICRP (International Commission on Radiological Protection), 1985. "Statement from the 1985 Paris Meeting of the ICRP," Health Phys. 48, 828.

ICRP (International Commission on Radiological Protection), 1991. *1990 Recommendations of the International Commission on Radiological Protection*, ICRP Publication 60, *Ann. ICRP* 21(1-3) (Pergamon Press, New York).

ICRP (International Commission on Radiological Protection), 1996. *Conversion Coefficients for Use in Radiological Protection Against External Radiation*, ICRP Publication 74, *Ann. ICRP* 26(3/4) (Elsevier Science, New York).

ICRP (International Commission on Radiological Protection), 2003. *Relative Biological Effectiveness (RBE), Quality Factor (Q), and Radiation Weighting Factor (w_R)*, ICRP Publication 92, *Ann. ICRP* 33(4) (Elsevier Science, New York).

ICRU (International Commission on Radiation Units and Measurements), 1986. *The Quality Factor in Radiation Protection*, ICRU Report 40 (International Commission on Radiation Units and Measurements, Bethesda, Maryland).

ICRU (International Commission on Radiation Units and Measurements), 1998. *Fundamental Quantities and Units for Ionizing Radiation*, ICRU Report 60 (International Commission on Radiation Units and Measurements, Bethesda, Maryland).

Kaul, D.C., Egbert, S.D., Otis, M.D., Kuhn, T., Kerr, G.D., Eckerman, K.F., Cristy, M., Maruyama, T., Ryman, J.C., and Tang, J.S., 1987. "Organ Dosimetry," Chapter 8 in *US-Japan Joint Reassessment of Atomic Bomb Radiation Dosimetry in Hiroshima and Nagasaki*, Volume 1, Roesch, W.C. (Ed.) (The Radiation Effects Research Foundation, Hiroshima, Japan).

Kocher, D.C., Apostoaei, A.I., and Hoffman, F.O., 2002. *Radiation Effectiveness Factors (REFs) for Use in Calculating Probability of Causation of Radiogenic Cancers* (*SENES* Oak Ridge, Inc., Oak Ridge, Tennessee); available at http://www.cdc.gov/niosh/ocas/pdfs/irep/irepref/pdf.

Kocher, D.C., Apostoaei, A.I., and Hoffman, F.O., 2005. "Radiation Effectiveness Factors for Use in Calculating Probability of Causation of Radiogenic Cancers," *Health Phys.* 89, 3-32.

Land, C., Gilbert, E., Smith, J.M., Hoffman, F.O., Apostoaei, I., Thomas, B., and Kocher, D.C., 2003. *Report of the NCI-CDC Working Group to Revise the 1985 NIH Radioepidemiological Tables*, NIH Publication No. 03-5387 (National Cancer Institute, U.S. Department of Health and Human Services, Washington, D.C.).

Mansfield, G.H., 2005. Letter to M. Strehlow and H.D. Royal, Veterans Advisory Committee on Environmental Hazards (The Deputy Secretary of Veterans Affairs, Washington, D.C.) (April 22).

Mather, S.H., and Otchin, N.S., 2004. Letter to M. Strehlow and H.D. Royal, Veterans Advisory Committee on Environmental Hazards (Office of Public Health and Environmental Hazards, Department of Veterans Affairs, Washington, D.C.) (February 2).

NCRP (National Council on Radiation Protection and Measurements), 1971. *Protection Against Neutron Radiation*, NCRP Report No. 38 (National Council on Radiation Protection and Measurements, Bethesda, Maryland); second reprinting 1992.

NCRP (National Council on Radiation Protection and Measurements), 1987. *Recommendations on Limits for Exposure to Ionizing Radiation*, NCRP Report No. 91 (National Council on Radiation Protection and Measurements, Bethesda, Maryland).

NCRP (National Council on Radiation Protection and Measurements), 1990. *The Relative Biological Effectiveness of Radiations of Different Quality*, NCRP Report No. 104 (National Council on Radiation Protection and Measurements, Bethesda, Maryland).

NIH (National Institutes of Health), 1985. *Report of the National Institutes of Health Ad Hoc Working Group to Develop Radioepidemiological Tables*, NIH Publication No. 85-2748 (National Institutes of Health, Bethesda, Maryland).

NIOSH (National Institute for Occupational Safety and Health), 2002. *NIOSH-Interactive RadioEpidemiological Program (IREP) Technical Documentation; Final Report*. Available at: http://www.cdc.gov/niosh/ocas/pdfs/irep/irepfnl.pdf.

NRC (National Research Council), 2003. *A Review of the Dose Reconstruction Program of the Defense Threat Reduction Agency* (The National Academies Press, Washington, D.C.).

Preston, D.L., Pierce, D.A., Shimizu, Y., Cullings, H.M., Fujita, S., Funamoto, S., and Kodama, K., 2004. "Effect of Recent Changes in Atomic Bomb Survivor Dosimetry on Cancer Mortality Risk Estimates," *Radiat. Res.* 162, 377-389.

Roesch, W.C. (Ed.), 1987. *Final Report on the Reassessment of Atomic Bomb Radiation Dosimetry in Hiroshima and Nagasaki* (The Radiation Effects Research Foundation, Hiroshima, Japan).

Shleien, B., Slayback, L.A., Jr., and Kirby, B.K. (Eds.), 1998. *Handbook of Health Physics and Radiological Health*, third edition (Williams & Wilkins, Baltimore, Maryland).

Shultis, J.K., and Faw, R.E., 1996. *Radiation Shielding* (Prentice-Hall, Upper Saddle River, New Jersey).

VHA/OPHEH (Veterans Health Administration ,Office of Public Health and Environmental Hazards), 2003. "Standard Operating Procedures---Use of the 'Interactive RadioEpidemiological Program' (IREP) for Formulating Medical Opinions to Assist in Adjudication of Some VA Radiation Compensation Claims" (Office of Public Health and Environmental Hazards, Department of Veterans Affairs, Washington D.C.) (December 17).

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