The Three Bs: Before, Berkeley, and Beyond

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Abstract

Accelerator radiological protection was born with the discovery of x-rays in 1895. For the next sixty years its focus for protection against external radiation exposure was largely concerned with photons. Events which led to today’s much broader interest in radiations, energies, and stopping powers are the

- Annus mirabilis of 1932,
- Manhattan Project (1941-1946),
- Postwar period (1945-1965) to which the Berkeley campus of the University of California contributed significantly under the leadership of Burton Moyer, and
- Sophisticated understanding of high-energy accelerator radiation environments brought about during the 1960s and 1970s by experimental studies and computer simulations for the design of high-energy particle accelerators.

In the future accelerators will be increasingly used, inevitably leading to increased exposures to neutrons that generate high linear energy transfer (LET) radiations within body tissues. Much work remains to provide a logical basis for protection standards for high-LET radiations in general and for neutrons in particular.

Key Words: Accelerator Radiological Protection; Berkeley; High-LET Radiations; History; Radiation Weighting

Introduction

“So long, it’s been good to know ya!” Woody Guthrie (1912-1967)

This 2008 meeting in Oakland convened by the Health Physics Society is devoted to the future of all radiation-generating devices. Because “the past is prologue” it is helpful to begin by briefly reviewing our history while remaining mindful of Burke’s stern stricture that “you can never plan the future from the past” (Shakespeare 1611; Burke 1791).
The development of our profession has truly been an international team effort (see, for example, Patterson and Thomas 1994 in reference data base*). At the campus of the University of California at Berkeley important and definitive contributions both to the sources of high-energy ionizing radiations and to the protection against them were made. In the first part of this paper some examples will be given of the work at Berkeley during the formative days of accelerator radiological protection.

**Before Berkeley—The Birth of Radiological Protection**

It is arguable whether accelerator radiological protection can rightly claim to be the founder of the entire and diverse profession we know today—but the major discoveries that led to the need for our profession resulted from the discoveries of atomic and nuclear physicists. X-ray tubes are electron accelerators and the “x-rays” discovered by Roentgen in 1895 were rapidly applied in medicine with almost unbridled enthusiasm—leading to an immediate need for protection from external irradiation by low-energy photons. The events of the thirties and forties set in motion the interest in radiations, energies, and charged-particle stopping powers that typify our profession today. The protection system that evolved over the past century and is greatly influenced by its focus on photons may need to change to accommodate other radiations and higher energies.

**Berkeley**

1932, the *annus mirabilis*, witnessed the splitting of the atom, the discoveries of the neutron and the positron, and the first particle accelerators. Fig. 1 shows the apparatus of Cockcroft and Walton while Fig. 2 shows the first cyclotron—this is so small that it fitted in the palm of the human hand. A year later the production of “artificial radioactivity” was reported by Joliot-Curie and Fermi et al. With the means of producing new radionuclides in relatively large quantities progress at Berkeley was extraordinarily rapid. (For an excellent summary of this era see the history by Heilbron and Seidel [1989 in reference data base].) 1935 saw the birth of nuclear medicine with the use of radio-sodium and radio-phosphorous (Fig. 3). In the same year a neutron protection limit of 0.01 R/day had been established by the Lawrence

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*Throughout this paper, references marked as being in the reference data base can be found in Thomas 2003 (online at http://www.hps.org/iarpe/thomas).
brothers. In 1936 Aebersold and his colleagues began systematic neutron radiobiology studies and Stone first used neutrons in radiotherapy (see reference data base). By 1939 Alvarez and Cornog had established that tritium was radioactive (see reference data base). By 1941 McMillan had identified element 93, subsequently named neptunium (see reference data base). By the end of 1941 the concerns that have since occupied health physics had been identified, and the United States had joined the war that was already waging in Europe and Asia.

The Manhattan Project, 1941–1946

By the end of 1942 Seaborg had isolated plutonium, the first sizeable quantities of $^{235}\text{U}$ had been isolated by the accelerator-like “Calutron,” and Fermi and his colleagues achieved the first self-sustaining neutron chain reaction (Marshall-Libby 1979 in reference data base). Accelerators designed for nuclear physics research were now diverted to the war effort and the secrecy of the Manhattan Project meant that little of the subsequent work done at Berkeley was to be published until the cessation of hostilities.

Berkeley during the Postwar Period

Ernest Lawrence asked Burton Moyer to establish a health physics group at Berkeley. With his creation of an independent health physics group, with which accelerator designers could consult on matters of radiation safety, Moyer set a pattern followed by accelerator laboratories around the world.

Moyer is remembered for the “Moyer Model,” developed to design the shielding for the Bevatron (Moyer 1961, 1962 in reference data base); for his studies of neutron skyshine (Moyer 1962 in reference data base); but most importantly for his philosophy of radiation dosimetry (Moyer 1952, 1954 in reference data base). By comparison with low-energy photon fields, dosimetry is considerably more complex when neutrons or high-energy, high-LET radiations are produced. This was understood by Moyer who noted that efforts to determine the physical aspects of the radiation field would lead to definite and permanent data but by contrast the biological basis for radiation protection was ephemeral. Instead of attempting to directly determine absorbed dose and obtain the required modified absorbed dose quantity by arithmetic, the necessary components and characteristics of the “high-energy” radiation fields
were systematically identified. These components include integrated particle fluence, $\Phi$; energy spectra, $d\phi/dE$; and to a limited extent the angular distributions of particles in the field. Such physical data provide permanent records of the irradiation conditions and may immediately or retroactively be used to provide any physical quantities needed by radiobiologists to interpret their data or to determine exposures in terms of the protection quantities then in vogue. This is done by conversion coefficients, $g(E)$, values of which depend upon neutron energy and irradiation geometry. If the differential energy neutron spectrum, $d\phi/dE$, is determined and a conversion function, $g(E)$, is available, the relevant dose equivalent quantity, $H$, may then be calculated from

$$H = \int_{E_{\text{min}}}^{E_{\text{max}}} g(E)(d\phi/dE)dE$$

where $E_{\text{min}}$ and $E_{\text{max}}$ are the energy bounds of the spectrum.

Moyer’s system of dosimetry is based on fluence rather than absorbed dose (preferred by the International Commission on Radiological Protection [ICRP]). Conversion coefficients for neutrons have been available since the late 1950s with increasing accuracy, in various phantoms, and over an ever-increasing range of energy. It is a philosophy that has been adopted at most accelerator laboratories and seems all the wiser with the passage of time.

*Nuclear Cascade Studies—Shielding.* The successful operation of the early weak-focusing proton synchrotrons led to an appetite for improving their performance, as at the Bevatron; to designing higher intensity weak-focusing synchrotrons, as at the Rutherford and Argonne National Laboratories; or to venturing to higher energies with strong-focusing proton synchrotrons as at Brookhaven National Laboratory (BNL) and at CERN. By the mid-1960s designs were underway for synchrotrons in the 250 GeV energy region.
The design of efficient and economic accelerator shielding demanded an understanding of the physical processes of high-energy radiation transport. The data needed were obtained by performing several “shielding experiments” throughout the 1960s. Two geometries were used: either in the line of, or transverse to, the high-energy proton beam, known colloquially as “beamstop” or “overhead shielding.” Measurements were made with a wide variety of radiation detectors in concrete, earth, or steel and with incident proton energies ranging from 2–30 GeV. These experiments were costly and required collaborative efforts. Various groups from BNL, CERN, DESY, Berkeley Lab, Daresbury, Oak Ridge National Laboratory, Rutherford High Energy Laboratory, and Stanford Linear Accelerator Center (SLAC) collaborated to make measurements at the Alternating Gradient Synchrotron, Bevatron, CERN Proton Synchrotron, Nimrod, Nina, and SLAC (see reference data base). It is a tribute to the accelerator community that these opportunities were afforded radiation physicists, particularly at the front-rank accelerators, where there was fierce competition for accelerator time.

**The Bevatron and The Moyer Model.** Moyer’s Bevatron roof-shielding was installed in 1962 (see Fig. 4). In the course of his design work Moyer developed a simple formula now named in his honor (Moyer 1961, 1962 in reference data base). In annular cylindrical geometry the dose equivalent, \( H(r, \theta) \), at a point on the surface of the shield is given by

\[
H(r, \theta) = \frac{1}{(a+d)^2 \csc^2 \theta} BN \cdot f(E) \cdot g(\theta) \cdot \exp(-d \csc \theta / \lambda)
\]

where \( a \) is the internal radius, \( d \) is the transverse shield thickness, \( \theta \) is the angle subtended to the beam, \( B \) is the neutron build-up factor, \( N \) is the number of protons incident on the target, \( f(E) \) is the fluence-to-dose-equivalent conversion coefficient, \( g(\theta) \) is the angular distribution of high-energy neutrons from the target, and \( \lambda \) is the neutron attenuation length (see Fig. 5).

Approximations in this simple model were made possible by understanding that neutrons with energies greater than about 150 MeV controlled the development of the nuclear cascade in the shield,
resulting in an attenuation length inversely proportional to the inelastic cross-sections at high energies, essentially constant in value. Moyer also derived an angular distribution for these high-energy neutrons, $g(\theta)$, at angles close to $90^\circ$ to the target, later shown to be exponential in character (Routti and Thomas 1969 in reference data base). A later refinement to the Moyer model was made in the 1980s by examining the variation of neutron yield with proton energy, $E_p$. Hitherto it had been assumed that neutron production was proportional to proton energy; analysis of available data showed that in fact neutron production varied as $E_p^{0.8}$ (Thomas RH and Thomas SV 1984 in reference data base).

Moyer’s shield design was intended to reduce radiation levels by a factor of 100, and subsequent measurements determined a reduction by a factor of 95 (Smith 2003 in reference data base). This good result was obtained by setting the attenuation length to 130 g cm$^{-2}$—a felicitous choice. At that time there was considerable uncertainty in the value of this parameter and values then in use ranged from 110–170 g cm$^{-2}$. For a 1000 g cm$^{-2}$ thick shield this uncertainty would correspond to a variation in attenuation by a factor of 25. Subsequently the interpretation of shielding data using the Moyer point source model was improved by adapting it to account for the finite dimensions typical of accelerator radiation sources.

A Typical Beamstop Shielding Experiment: The Bevatron 1964. A typical beamstop experiment consisted of a large array of blocks assembled so that radiation detectors could be inserted to explore the spatial distribution and composition of the radiation field in the assembly. The concrete beamstop assembly used at Berkeley measured 8.5-m long by 6.7-m wide by 5.5-m high and weighed 755 tonnes (see Fig. 6). Data obtained from this experiment are shown in Fig. 7 and 8. Fig. 7 reveals an increase in the attenuation length from 99 to 114 g cm$^{-2}$ as the energy of the incident proton increased from 2.2 to 6.2 GeV. Fig. 8 shows that the attenuation length is almost independent of angle to the beam axis, confirming the assumption of Moyer.

Shielding experiments of the type described here are part of history. At the time the experiments importantly provided empirical data that could be put to immediate use in shield design but perhaps even more importantly also provided an understanding of radiation transport mechanisms. The studies also revealed sources of avoidable error—some as simple as determining the density of the shield material;
agreeing to consistent definitions of terms (e.g., “attenuation length”); or taking care not to make unwarranted assumptions as to the mathematical function describing the attenuation (e.g., not all transmission curves are exponential in character). With the great advances in radiation transport theory and calculations over the past twenty years it seems unlikely that such heroic experiments will ever again be needed.

**The Future**

“Order and simplification are the first steps to the mastery of a subject—the actual enemy is the unknown.” Thomas Mann (1924)

The world is moving towards an energy crisis. At the highest levels in government, financial, and even “green” circles there is increasing interest in the adoption of nuclear energy programs to meet this crisis (Economist 2007). Whatever nuclear programs may be adopted it is certain that accelerators will play prominent roles.

An obligation of our profession must surely be to provide appropriate authorities with clear, practical, and authoritative advice based only upon our scientific expertise that will permit the development and maintenance of safe operating conditions at such nuclear facilities. Members of our profession have the necessary expertise to offer authoritative advice to National Council on Radiation Protection and Measurements (NCRP), ICRP, and International Commission on Radiation Units and Measurements (ICRU) with respect to protection against high-LET radiations.

Time is not on our side. We already know that some of the highest individual doses observed in the workforce are from neutron exposures. Aircrew exposures to a complex radiation field are among the highest to any quasi-occupational group and have a significant component contributed by neutrons. For radiation workers high-LET (neutron) exposures make up 10–20% of the total (comparable with the percentage of exposures due to “internal emitters”). Any increase in nuclear power programs carries with it the potential to expose an increased number of workers, and possibly also the general public, to neutrons and other high-LET radiations. Perhaps because of their small contribution to population dose, exposure to neutrons has been of rather low priority to standards-setting organizations leading to the
suggestion that neutrons are the stepchild of the recommendations (of ICRP) (Thomas and McDonald 2007).

An ideal system of dosimetry for radiological protection should be

- Universal, applying to all radiations whatever their energy;
- Integrated, independent of the origin of the radiation (outside or inside the human body);
- Rational and rigorous, consistent with mathematical logic and physical laws;
- Stable, avoiding frequent changes in names and symbols of dosimetric concepts; and
- Unambiguous, with standards set in determinable (physical) quantities (i.e., making no distinction between “protection” and “operational” quantities).

It is both remarkable and admirable that within only three years of the discovery of the neutron protection standards were in place at Berkeley but arguable that, while we have made great advances in technical issues, over the past 20 years we have made little progress in establishing a rational, stable, and practical basis for radiological protection against high-LET, high-energy radiations. To the contrary recommendations of the advisory bodies in this domain seem increasingly confusing and need urgent clarification.

Space does not permit a comprehensive discussion of the issues related to high-energy, high-LET radiological protection and so in the remainder of this paper emphasis must be given to the most troubling and confusing issue which is that of radiation weighting from both theoretical and practical considerations.

**Radiation Weighting**

*Relative Biological Effectiveness (RBE).* The major difficulty in setting protection standards for neutron and other high-LET radiations is, as Thomas Mann says, “the unknown.” No adequate human epidemiological data exist for neutron exposure. M. P. Little has concluded that no useful information on neutron risks may be obtained from the study of Hiroshima survivors because neutrons contributed only 1%–2% of their total absorbed dose (Little 2003 in reference data base).
As early as 1933, John Lawrence suggested neutrons were about ten times more harmful than photons. Such differences in biological response per unit “dose” were accommodated by the application of the first “radiation weighting factor” (the “RBE”) and the “RBE dose” was the first “modified absorbed dose.” In the mid-1950s values of RBEs for human protection were estimated by extrapolation from mammalian cell data. Experiments suggested that there was a loose relationship between RBE and the LET of the incident radiation (see for example Fig. 9) and led to ICRP making recommendations as a function of LET. By 1964 RBE was called “quality factor” and RBE dose called “dose equivalent” (ICRU 1962, ICRP 1964 [see reference database]).

Quality Factors: Q, Q, Q(L). Confusion began almost immediately with the interpretation of the new term “quality factor.” Some took it to be a single number, usually the default value to be used when little is known of the neutron energy. Others took it to be a specific value of the function Q(L) at a given value of linear energy transfer, L. Yet others saw it as a number, Q, averaged over a volume of tissue or a spectrum of L, or both.

To facilitate measurement and calculation, ICRP recommended values of Q in some detail and provided a method of interpolation with respect to LET (ICRP 1964, 1973 in reference data base) (see Fig. 10). This latter step was the birth of a Q(L)-L relationship which is vital for the calculation of average quality factors, Q; neutron fluence-to-dose conversion coefficients; and calculations of absorbed dose and LET distributions in anthropoid and other phantoms including the ICRU sphere. Clearly the detail inherent in using a formal Q(L)-L relationship to modify absorbed dose was only for arithmetical convenience and never attempted to “reflect the higher probability of detriment from exposure to radiation components with high LET” (Paragraph A8, ICRP 60 [ICRP 1991 in reference data base]).

By the mid-1980s a sea-change in ICRP policy was visible on the horizon. The commission was increasingly persuaded that there were new neutron RBE data suggesting that the values for the quality factor for fission neutrons had been underestimated. In its Paris Statement ICRP recommended “an increase in Q by a factor of 2. The permitted approximation [emphasis added] for neutrons thus changes
from 10 to 20. These changes relate only to neutrons and no other changes in $Q$ are recommended at this time” (ICRP 1985 in reference data base). The subsequent interpretation and implementation of this policy in ICRP Publication 51 was that all values of $\bar{Q}$ and conversion coefficients be doubled whatever the neutron energy. This interpretation did a serious disservice for three reasons. The writers failed to recognize firstly that the “permitted approximation” of the neutron quality factor was a “default value” to be used when little or no information about neutron energy was available and secondly that the dependence of individual values of $Q(L)$ upon neutron energy is complicated. Finally, there was and still is some reason to be sceptical of the extrapolation of neutron RBE data obtained by the irradiation of mice in air to humans.

The LET distribution of the radiation field in the tissue of animals exposed to neutrons is greatly influenced by the amount of neutron moderator (largely water) and thus by the size of the animal. RBEs measured in small biological systems irradiated in air by neutrons may not therefore be directly applicable to organs deep within a human body. For example, a considerable proportion of the absorbed dose deposited in a human body irradiated by intermediate-energy neutrons is deposited via photon interactions (electrons) while the corresponding proportion in smaller mammals, such as rats or mice, is much smaller (Fig. 11a, 11b). One might therefore expect that when extrapolating from mice to humans “RBEs for radiological protection” might decrease as the proportion of the dose contributed by photons increases or as animal size increases. This is not a matter of biology but physics—the radiation fields differ. Neither the Paris Statement nor Section B.4.5 of Publication 60 (ICRP 1991 in reference data base) makes it clear if such considerations were taken into account when the extrapolations were made. ICRP 92 (2003) has some discussion of this matter but still leaves the issue unresolved.

These increases in $\bar{Q}$ and conversion coefficients announced in the Paris statement, apparently based only on data for fission or degraded-fission neutrons, were to have profound changes in ICRP policy with respect to all neutrons and high-LET radiations.
Radiation Weighting Factors, \( w_R \), and Ambient Dose Equivalent, \( H^*(d) \). In its Publication 60 ICRP made fundamental changes to its view of radiation weighting. In Paragraph A8 it defined a new \( Q(L)-L \) relationship to “reflect the higher RBE\(_M\) values for intermediate-energy neutrons . . .” and to recognize “the reduced effectiveness of heavy ions with \( L \) greater than 100 keV \( \mu \text{m}^{-1} \).” Fig. 12 shows this revised recommendation compared with its forerunner. A caveat immediately follows the definition in Paragraph A8: “The Commission now believes that the detail inherent in using a formal \( Q-L \) relationship to modify absorbed dose to reflect the higher probability of detriment from exposure to radiation components with high LET is not justified because of the uncertainties in the biological information. In place of \( Q \), or more precisely \( \overline{Q} \), the Commission now selects radiation weighting factors, \( w_R \), based on a review of biological information, a variety of exposure circumstances, and inspection of the traditional calculations of the ambient dose equivalent.” These radiation weighting factors, \( w_R \), are \( \overline{Q} \)'s specific to neutrons and the ICRU sphere and they are related to the operational estimate of effective dose, or ambient dose equivalent, \( H^*(10) \). Values of the ambient dose equivalent calculated with the \( Q-L \) relationship recommended by ICRP in 1977 were given for the energy range from thermal to 20 MeV in ICRP Publication 51. Revised values using the ICRP 60 relationship and extending up to neutron energies of 200 MeV were given in ICRU Report 57/ICRP Publication 74. For the purpose of consistent calculation of \( w_R(E) \) at neutron energy \( E \), ICRP gives the equation

\[
w_R = 5 + 17 \exp\{-[\ln(2E)]^2/6\}
\]

(Paragraph A12, ICRP 60 [ICRP 1991 in reference data base]).

The logical process seems confused. The use of yet another name for an established concept is itself confusing and unnecessary. ICRP seems to disapprove of its own recommended \( Q(L)-L \) relationship (or an alternative) that cannot, however, be abandoned because it is necessary for the calculation of ambient dose, ambient dose equivalent, and subsequently values of \( w_R \). There seems also to be a suggestio falsi
that the application of the product of \( w_R \) and \( H^*(10) \) better reflects “the higher probability of detriment from exposure to radiation components with high LET.”

There are significant problems with the practical application of the ambient dose equivalent radiation weighting system to neutron dosimetry, particularly at high energies (Ferrari and Pelliccioni 1998, Ferrari et al. 2004, ICRP 1997, ICRU 1998, Pelliccioni 2004).

It is of interest to compare values of the mean quality factor named \( w_R \) with other mean quality factors. This has been done to a limited extent in ICRP 92 (2003). Fig. 12 shows the ICRP values of \( w_R \) for neutrons from thermal energy to 1000 MeV (solid curve). ICRP has never explicitly explained the derivation of these values but the similarity with the broken line designated \( q^* \) which gives values of \( H^*(10) \) strongly suggests that calculations of ambient dose equivalent are the origin of the values for \( w_R \) and this conclusion is also consistent with ICRP comments. A graph of \( Q \) for the quantity effective dose equivalent (designated \( q_E \) and shown as a dotted line in Fig. 12), derived from calculations in an anthropomorphic phantom irradiated isotropically, shows marked differences. Up to neutron energies above 10 MeV the curve of \( q_E \), calculated in an anthropoid phantom, lies significantly lower than the curves for \( w_R \) and \( q^* \) calculated in the ICRU sphere—reflecting the work of Dietze and Siebert (1994 in reference data base). Note that identical functions for \( Q(L) \)—as recommended in ICRP 60—were used in all three sets of calculations.

If the primary radiation weighting generator—the \( Q(L) - L \) relationship—were “correct” (in the sense that it represents the present best judgment of ICRP), then the laws of physics and mathematical logic will inevitably generate “correct” values of \( Q, H^*(10), q^* \), and \( q_E \) under the irradiation conditions specified. The calculated values of the organ-weighted effective quality factor, \( q_E \), at a neutron energy near 1 MeV are about 65% and 60% lower than values of \( q^* \) and \( w_R \), respectively (see Fig. 12).

A human being would be better matched by an anthropoid phantom (with internal organs) than by the ICRU sphere (without internal organs) and values of \( w_R \) should be selected from the former. If \( Q(L) \) is “correct” a value of about 13 for \( w_R \) or mean quality factor for 1 MeV neutrons would appear to be
correct. Conversely if there is compelling evidence that a value of $q_E = 20$ at 1 MeV is correct the currently recommended $Q(L)$-$L$ relationship should be modified. The degree to which the radiobiology permits this to be done is a matter for the judgment of the scientific community.

**The Anticipated Revised Recommendations of ICRP.** Some changes in the recommended values of $w_R$ may be on the near horizon. In 2001 ICRP began a review of its then-current recommendations published as ICRP 60. In the interim there has been extensive public comment on drafts of the new proposed recommendations. For some months it has been expected the ICRP would publish its revised recommendations. It is possible that the new recommendations will address some of the issues raised here. At the time of writing this paper (November 2007) the revised recommendations were not available. However there are indications of the extent of likely changes to values of $w_R$. ICRP has shown itself to be somewhat flexible in its response to public comment and Publication 92 had already seen suggested substantial reduction in $w_R$ at energies below 1 keV (see Fig. 13). It is also expected that at high energies values of $w_R$ will be reduced from 5 to lower values more compatible with those for high-energy protons. ICRP appears, however, to be determined to retain a value of 20 for $w_R$ at energies of ~1 MeV (ICRP 2003). To avoid ambiguity there cannot be two independent determiners of radiation weighting and if ICRP desires a value of $q_E = 20$ at 1 MeV it should be encouraged to modify its current $Q(L)$-$L$ relationship. It is possible that nonscientific matters are bearing here. The following argument is made against radical simplification of $w_R$ because it: “... seems impracticable for the reason that it would tend to force tightening of the dose limits in general. If the current value of 20 for fission neutrons were reduced to 10, this would decrease the numerical value of the effective dose from exposure to fission neutrons by a factor of 2. This would amount to a relaxation of limits for neutron exposure, which may meet strong objections and would almost certainly generate pressure to offset the change by a decrease of the effective dose limits, which would then apply to all radiations including photons” (Paragraph 259, ICRP 92 [ICRP 2003]). One wonders why a proposed reduction is acceptable for 20 keV neutrons but is so egregious for fission neutrons?
The interested reader is encouraged to read ICRP 92 with some attention. It is thoughtful and contains much of interest; in addition it gives insights into the thinking of ICRP.

Suggestions and Solutions

- Explore whether there is still a consensus (or not) among radiobiologists whether a $Q(L)$-$L$ relationship is a reasonable model. If it is, what should the relationship be? If not, what model should replace it?
- Establish a data base of RBEs that are of interest for neutron dosimetry to give guidance to radiation weighting. Possible sources include neutron radiotherapy data and proton RBEs.
- Establish an independent review of the extrapolation of RBE data from small animals to humans.
- Experimentally determine if there are observable differences between RBEs for mice irradiated by neutrons in air compared to those for mice surrounded by tissue-like material.
- Adopt a scheme of radiation protection for high-LET and high-energy radiations based on fluence to supplement ICRP’s preferred modified absorbed dose system.
- Explore the limitations of the ICRU sphere and associated concepts, such as $H^*(d)$ and $w_R$, for practical dosimetry at high energies.
- Define standard anthropoid phantoms and select standard transport for calculations required in radiological protection.
- Thoroughly examine and understand the impact of new recommendations before promulgation and implementation.
- Recruit young minds to think “out of the box.”

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lecture the author has drawn liberally from his ideas in previous papers, particularly the Morgan Lecture of 2003 and his lecture to the J. Newell Stannard Lecture Series of 2005. It is hoped that the reader will forgive this “plagiarism by repetition.”

**References**

Space limitations do not permit a comprehensive set of references here. In many cases the reader is referred to the reference data base, a compilation of references provided in the 2003 Morgan Lecture (Thomas 2003).

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Shakespeare W. The tempest. Act 2, scene 1, line 261; 1611.


Fig. 1. The Cockcroft-Walton Accelerator. John Cockcroft is in the cabin observing nuclear disintegrations. Photo credit: Ernest Orlando Lawrence Berkeley National Laboratory.
Fig. 2. The first cyclotron, about 10 cm (4 in.) in diameter and capable of accelerating ions to energies above 1 MeV. Photo credit: Ernest Orlando Lawrence Berkeley National Laboratory.
Fig. 3. Joseph Hamilton demonstrating the circulation of the blood by drinking radio-sodium. The lead shielding around Hamilton’s right wrist and the radiation detector are clearly visible (1936). Photo credit: Ernest Orlando Lawrence Berkeley National Laboratory.
Fig. 4. The installation of Moyer’s roof shielding above the Bevatron in progress at the Lawrence Radiation Laboratory. The interlocking roof-blocks are keyed together with one another and to the supporting cylindrical shield wall so as to ensure seismic stability. Bending magnets of the synchrotron are clearly visible (1963). Photo credit: Ernest Orlando Lawrence Berkeley National Laboratory.
Fig. 5. Schematic representation of the Moyer Model.
Fig. 6. Concrete assembly for a 6 GeV proton shielding experiment at the Lawrence Radiation Laboratory. Michael Pick is seen inserting radiation detectors into the experiment (1964). Photo credit: Ernest Orlando Lawrence Berkeley National Laboratory
Fig. 7. The variation of transmission of hadrons (mainly neutrons) through concrete along the axis of a proton beam of incident energy 2.2, 4.2, and 6.2 GeV. (The data were measured by the $^{27}$Al(n,α)$^{24}$Na reaction and are normalized at a depth of 2.44 meters (8 feet). (Smith et al. in reference database)
Fig. 8. The variation of transmission of hadrons (mainly neutrons) as a function of angle from the point of incidence of the proton beam, for angles between 0° and 60°. The incident proton energy was 6 GeV. The data were measured by the $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$ reaction and separated for ease of viewing. (Smith et al. in reference database)
Fig. 9. Experimental curves of RBE versus LET; mammalian cells are indicated by the symbols *, ⭐, and ⧫. (NCRP 1967)
Fig. 10. The two Q(L)-L relationships recommended by ICRP. Lower curve from ICRP 21 (1973 in reference data base); upper curve from ICRP 60 (1991 in reference data base).
**Fig. 11(a).** The ratio \((D_\gamma/D)\) of absorbed dose contributed by photons \(D_\gamma\) to the total, \(D\), versus neutron energy for neutrons incident on phantoms of different size.

**Figure 11(b).** \(\bar{Q}\) versus neutron energy for the conditions described for Fig. 11a.

Key: Mouse; O rat; \(\Delta H^*(10)\) (value at 10 mm in the ICRU sphere); \(\nabla\) weighted mean value in the ADAM phantom (Dietze and Siebert 1994 in reference data base).
Fig. 12. Radiation-weighting factor, $w_R$ (solid curve), and the ambient quality, $q^*$ (broken curve). The dotted curve gives the effective quality factor, $q_E$; i.e., the external weighting factor that would have made, for isotropic exposure, and with the current $w_T$ and $Q(L)$ values, the effective dose $E$ equal to the effective dose equivalent, $H_E$ (data for $q^*$ from Leuthold et al. [1992]; for $q_E$ from Mares et al. [1997] and for an anthropomorphic phantom for energies beyond 20 MeV interpolated to the values derived by Pelliccioni [1998]); from ICRP Publication 92 (ICRP 2003).
Fig. 13. The current radiation weighting factor for monoenergetic neutrons (upper broken curve) and the proposed modification (solid curve). The lower broken curve gives the effective quality factor (ICRP 2003).