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Environment, Health and Safety Division

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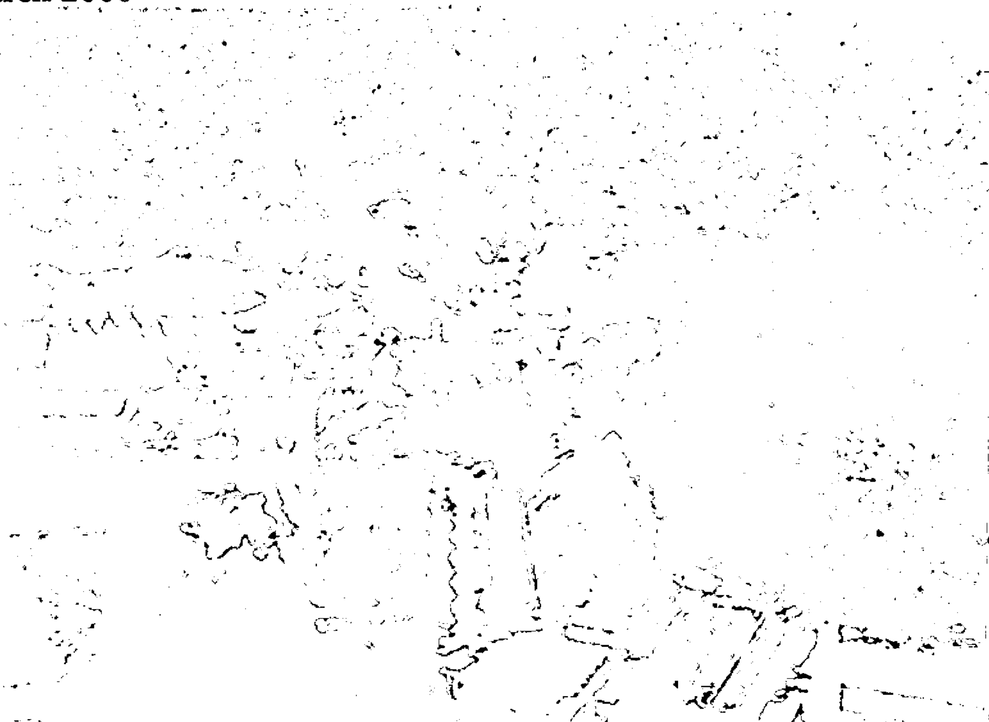

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A Reappraisal of the Reported Dose Equivalents at the Boundary of the University of California Radiation Laboratory during the Early Days of Bevatron Operation

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Abstract

Accelerator-produced radiation levels at the perimeter of the Ernest Orlando Lawrence Berkeley National Laboratory (the Berkeley Laboratory) reached a maximum in 1959. Neutrons produced by the Bevatron were the dominant component of the radiation field. Radiation levels were estimated from measurements of total neutron fluence and reported in units of dose equivalent. Accurate conversion from total fluence to dose equivalent demands knowledge of both the energy spectrum of accelerator-produced neutrons and the appropriate conversion coefficient functions for different irradiation geometries. At that time (circa 1960), such information was limited, and it was necessary to use judgment in the interpretation of measured data. The Health Physics Group of the Berkeley Laboratory used the best data then available and, as a matter of policy, reported the most conservative (largest) values of dose equivalent supported by their data.

Since the early sixties, significant improvements in the information required to compute dose equivalent, particularly in the case of conversion coefficients, have been reported in the scientific literature. This paper reinterprets the older neutron measurements using the best conversion coefficient data available today. It is concluded that the dose equivalents reported in the early sixties would be reduced by at least a factor of two using current methods of analysis.

The absence of romance in our history will, we fear, detract somewhat from its interest; but we shall be content if it is judged useful by those inquirers who desire an exact knowledge of the past.

Thucydides

Introduction. The Bevatron was one of the first-generation weak-focusing proton synchrotrons to be planned and constructed during the first decade after the end of the Second World War. It was designed to accelerate protons to a kinetic energy of 6.2 GeV with an initial beam intensity of 10^9 protons per pulse, at a repetition rate of 11 pulses per minute. At this design intensity, no significant radiation problems were expected at large distances from the synchrotron. Shortly after its first operation in 1954 the intensity of 10^9 protons per pulse was achieved. Improvements in operating efficiency increased the beam intensity and, as Figure 1 shows, the number of protons accelerated per annum during the decade 1954–64 increased by roughly four orders of magnitude. Consequently, there was a potential for exposure to high-energy neutrons and photons similar in character to, but at greater intensities than, those resulting from the interaction of cosmic radiation with the Earth's atmosphere. Shielding was placed around the accelerator components as the radiation intensity increased. In 1962 an extensive modification to the Bevatron included both an increase in beam intensity and the addition of more effective shielding (Moyer 1961, 1962; Thomas 1970).

From the outset, measurements to characterize the radiation environment of the Bevatron were made both near the accelerator, throughout the laboratory and around the laboratory perimeter (Patterson 1955; Solon 1957). Figure 1 also compares the reported site boundary dose equivalent with the number of protons accelerated.

Accelerator Radiation Measurements. The philosophical basis of radiation monitoring at the Berkeley Laboratory was the systematic identification of the components and characteristics of the "high-energy" radiation fields. This required the measurement of integrated particle fluence and energy spectra. Such a procedure had (and has) the advantage that the physical data possess a permanence not typical of the ICRP[1] and ICRU[2] dose equivalent quantities. It is, in principle, a relatively simple matter to determine the values of dose equivalents required by regulatory agencies with the use of fluence-to-dose-equivalent conversion coefficients (now referred to in what follows as "conversion coefficients").

The measurement techniques used at the Berkeley Laboratory have been fully described in the scientific literature (see, for example, Moyer 1952, 1954; Hess *et al.* 1959; Patterson and Thomas 1973; and IAEA 1988). Systematic studies of high-energy accelerator radiation environments led to the conclusion that in the late 1950's and early 1960's neutrons with energies below 20 MeV contributed 80%–90% of the total dose equivalent. Neutrons with energies greater than 50 MeV and gamma rays each contributed a few percent of the total dose equivalent. Patterson *et al.* (1959) showed these results to be consistent with those obtained for the equilibrium neutron spectrum generated by the interaction of primary cosmic rays in the Earth's atmosphere (Hess *et al.* 1959; Patterson *et al.* 1959; Patterson 1962). Measurements of total neutron fluence rates were made in occupied areas within the laboratory and at various points around its perimeter. The neutron fluence at a distance of more than about 100 meters from the Bevatron was shown to obey the inverse square law (Patterson 1962). The identification of those locations at the site boundary where the radiation levels from the laboratory's accelerators were highest provided the foundation for a routine environmental radiation-monitoring program (see Thomas 1976).

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[1] International Commission on Radiological Protection

[2] International Commission on Radiation Units and Measurements

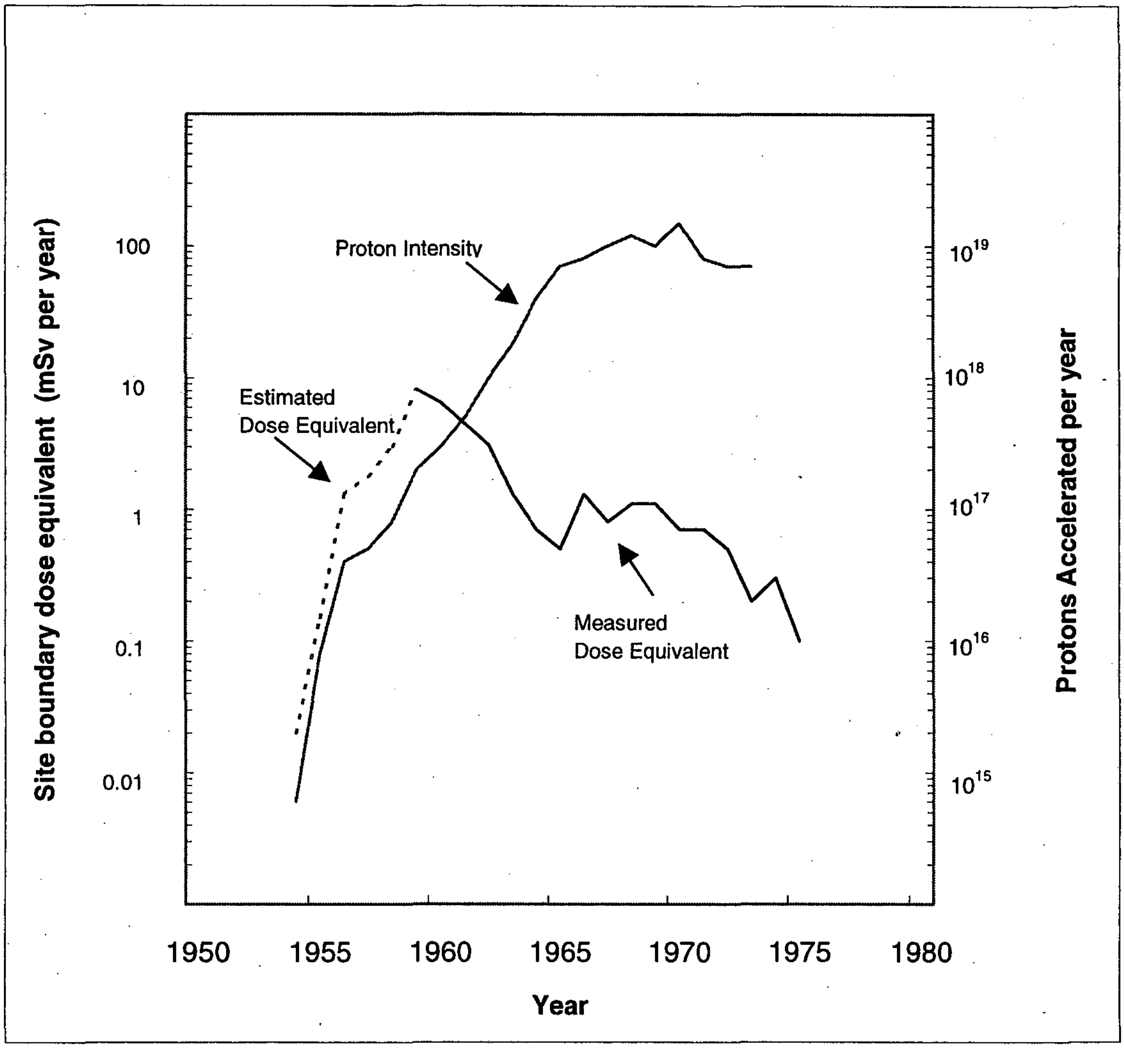

Figure 1. Reported site boundary dose equivalent, based on neutron fluence measured at the Olympus Gate Environmental Monitoring Station, compared with the number of protons accelerated by the Bevatron per year.

Conversion of Neutron Fluence to Dose Equivalent. By convention, radiological protection advisory organizations, such as the ICRP and NCRP[3], and the administrative and regulatory agencies of the United States express dose limits in dose equivalent quantities. Over the years, increasing sophistication in radiobiological modeling has improved the definition of dose equivalent quantities, and they have been given different names [*viz.* Effective Dose Equivalent (ICRP 1977, 1980) and Effective Dose (ICRP 1991)]. These quantities may be considered identical for the purposes of this paper, and the generic term "dose equivalent" is used throughout.

The dose equivalent *H*, corresponding to a monoenergetic neutron fluence, Φ(E), is obtained by the application of a conversion coefficient, *g(E)*, defined as the ratio of the dose equivalent to the fluence of neutrons at the specific energy E. A set of conversion coefficients over a range of neutron energies and for a specified irradiation geometry is defined to be a "conversion function". Values of conversion functions for neutrons of energy up to 200 MeV have been tabulated in ICRU Report 57 (ICRU 1998). Ferrari et al. (1997) and Yoshizawa et al. (1998) have published data for higher energies.

For neutrons with energies ranging over a broad spectrum, a spectrum-weighted fluence-to-dose-equivalent conversion coefficient <*g*> is determined by folding the appropriate conversion function with the neutron spectrum and integrating over the entire energy range of the spectrum. The values of both *H* and <*g*> depend upon the irradiation geometry *G*:

$$H_G = \langle g_G \rangle \Phi \qquad (1)$$

where $\langle g_G \rangle$ is defined as

$$\langle g_G \rangle = \frac{\int_{E_{min}}^{E_{max}} g_G(E)\left(\frac{d\phi}{dE}\right)dE}{\int_{E_{min}}^{E_{max}} \left(\frac{d\phi}{dE}\right)dE} \qquad (2)$$

and

E_{min} and E_{max} are the minimum and maximum energies of the spectrum
g(E) is the fluence-to-dose-equivalent conversion coefficient function for monoenergetic neutrons
$d\phi/dE$ is the neutron differential energy spectrum
G is the irradiation geometry (AP, PA, LAT, ROT, or ISO[4])

Only in a few (usually trivial) cases is it possible to solve equation (2) by analytical means, and it is necessary to resort to numerical integration techniques to calculate the values of the integrals of equation (1). By these means values of <*g*> may be determined, provided both the neutron spectrum and the conversion coefficients as a function of neutron energy and geometry (the conversion coefficient functions) are known. At the time of the original measurements (circa 1960), precise information on these necessary data was limited and had to be developed during the sixties.

Conversion Coefficient Functions and Spectrum-Weighted Conversion Coefficients. In the late fifties and early sixties, published neutron conversion coefficient functions were limited with respect to both energy and irradiation geometry. For example, the data of National Bureau of Standards (NBS) Handbook 63 extended only to 30 MeV and were calculated only in a front-to-back (AP) irradiation geometry (NCRP 1957).

[3] National Council on Radiation Protection and Measurements
[4] Geometries include radiation incident from the anterior direction (AP), from the posterior (PA), laterally from either side of the body (LAT), horizontally while the body is rotated about vertical axis (ROT), and isotopically (ISO). See ICRP Publication 74 or ICRU Report 57

Values of <*g*> were inferred both from inspection of the NBS data at the measured values of the average (effective) energy of the neutron spectra (Patterson 1962) and by comparison with the Hess cosmic-ray neutron spectrum (Hess *et al.* 1959; Patterson *et al.* 1959). By these means the Berkeley Laboratory derived conservative estimates for the Bevatron-spectrum-weighted conversion coefficient of 360 pSv cm^2 (Patterson 1960), 370 pSv cm^2 (Dakin and Patterson 1962), and 408 pSv cm^2 (LBL 1965). This last value was used in environmental radiation-monitoring reports published in the early and mid-sixties.[5]

It was the policy of the Laboratory that, if there were any uncertainties in the conversion of fluence to dose equivalent, the more conservative values (higher dose equivalents) should be reported. It was well understood that the use of conversion coefficient functions calculated for an AP geometry would overestimate dose equivalents resulting from exposure to accelerator radiation fields (see, for example, Shaw *et al.* 1969). This was particularly so in those cases where the major contribution to the dose equivalent arose from neutrons with relatively low energies that were isotropically-scattered by the atmosphere ("skyshine"). Nevertheless, as a matter of policy, the estimates of dose equivalent historically reported by the laboratory have been based on conversion coefficients for AP geometry.

As information on the detailed character of the neutron spectra around high-energy accelerators became available in the mid-sixties, the degree of conservatism of these early estimates of <*g*> could be explored. For example, Gilbert *et al.* (1968) reported a value of 317 pSv cm^2 for the spectrum around the shielded Bevatron (see discussion below).

The conversion coefficient function applied by Gilbert *et al.* (designated as RHT-1965) was based on the work of Thomas (1965) and is now more than thirty-five years old and in need of revision in the light of current data. The ICRP and ICRU have recently recommended neutron conversion coefficients up to energies of 200 MeV and for several irradiation geometries (ICRP 1997; ICRU 1998). Ferrari *et al.* (1997) and Yoshizawa *et al.* (1998) have published data at higher energies.

Even though the basic physics of the deposition of energy in tissue was well understood thirty-five years ago, there are several reasons why changes in the early conversion coefficients might be expected. These include great advances in computational and radiation transport techniques, the development of sophisticated anthropomorphic phantoms, changes in the definitions of the dose equivalent quantities and changes in the methods of the radiation-weighting of absorbed dose.

Analysis of the new ICRU/ICRP data for AP irradiation geometry shows that the values of the conversion coefficients have not greatly changed over time (McDonald *et al.* 1998). This suggests that the combined influence of all the individual changes mentioned in the previous paragraph is minimal.

However, the recent ICRP/ICRU data also show that, for neutron energies below 200 MeV, the values of conversion coefficients can differ significantly between various irradiation geometries. For example, the data of ICRU Report 57 clearly show that in the MeV energy region the conversion coefficients for AP geometry are about twice as large as those for ISO geometry. For neutron energies above 200 MeV, the newer data show that the conversion coefficients used by Gilbert *et al.* were too high, even though the influence of irradiation geometry differs from that at lower energies (see Thomas 2000).

A revised set of analytical expressions for conversion functions, designated RHT-2000, has been prepared. These new results are based on the ISO and ROT conversion coefficients of ICRU Report 57 for neutrons with energies up to 200 MeV, and on more recent data for higher energies. Details are given in Thomas (2000), and Figure 2 displays both sets of functions for neutron energies from 10^{-8} to 10^4 MeV. The availability of these new results based on ISO and ROT conversion functions now allows a more realistic evaluation of dose equivalents than was possible in the past for the highly scattered neutron fields produced by the Bevatron near the site boundary of the Berkeley Laboratory.

[5] For his estimates of shielding for the Bevatron Improvement Program, Moyer adopted an even greater degree of conservatism by using a value of 1000 pSv cm^2 for <*g*> (Moyer 1961, 1962; Thomas 1970).

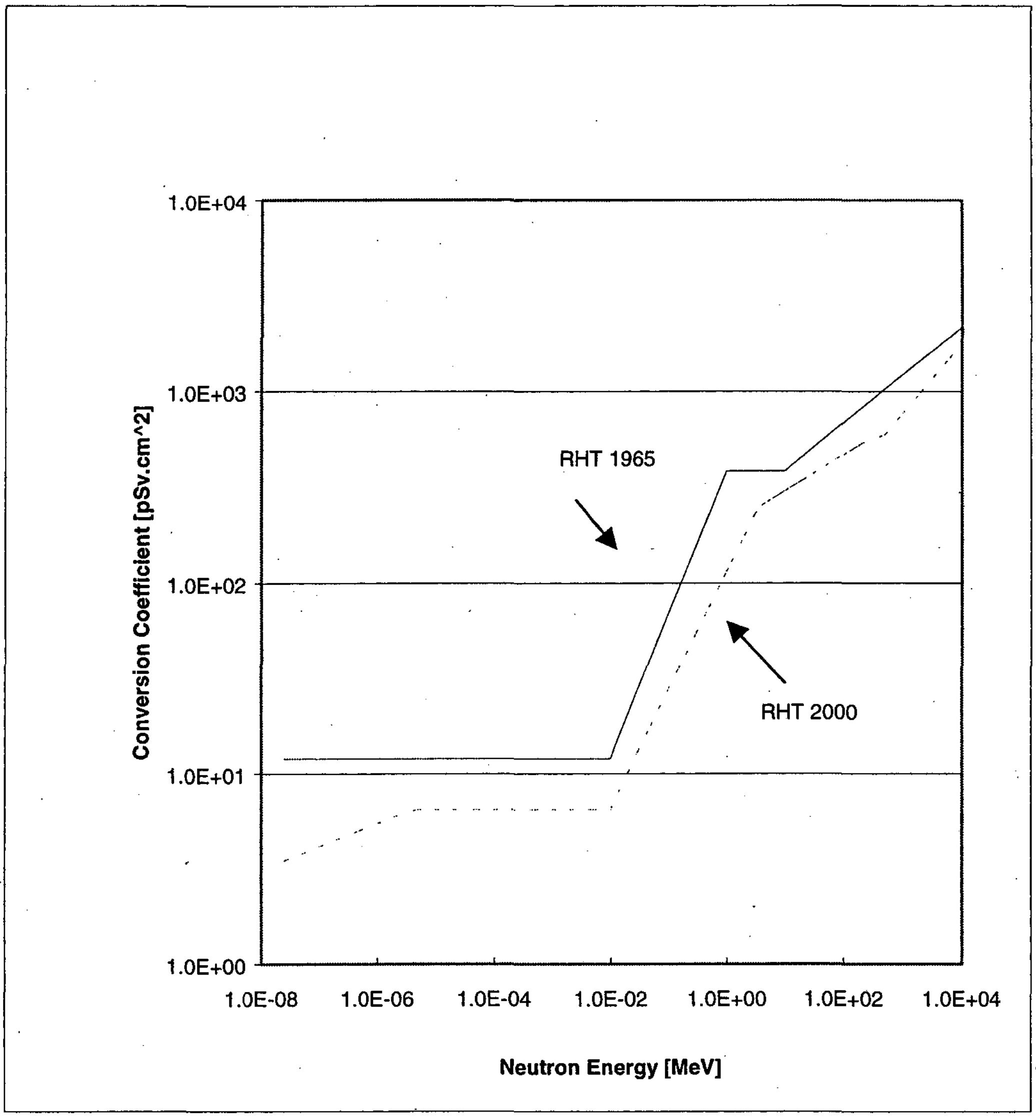

Figure 2. A comparison of the fluence-to-dose-equivalent conversion coefficients RHT-1965 and RHT-2000.

Calculation of Spectrum-Weighted Conversion Coefficients. Values of <*g*> depend upon the neutron differential energy spectrum, the conversion coefficient functions, and the limits of integration. Values have been calculated for three spectra cited by Gilbert *et al.* (1968), for two sets of conversion coefficients, and for various energy ranges. Numerical integration techniques were used, with checks being made by analytical methods in the case of "1/E" spectrum. A sample of the results is given in Table 1.

Table 1. Calculated spectrum-averaged conversion coefficients <*g*>, for three neutron spectra and for the conversion functions RHT-1965 and RHT-2000. For each spectrum, values are shown (i) as reported by Gilbert *et al.* (1968), (ii) as recalculated using the integration limits and conversion function used by Gilbert *et al.*, (iii) as recalculated using integration limits based on Bevatron energies, (iv) as calculated using RHT-2000, and (v) as calculated using the revised integration limits and RHT-2000.

Energy Range		***Conversion Function***	***Spectrum Averaged Conversion Coefficient <g> (pSv cm^2)***			***Author***
E_{min} (MeV)	**E_{max} (MeV)**		**"1/E"**	**"Shielded Bevatron"**	**"Hess Cosmic-Ray"**	
6.0E-05	3.4E+04	RHT-1965	585	317	230	Gilbert *et al.*
6.0E-05	3.4E+04	RHT-1965	581	329	238	This work
6.0E-05	3.4E+04	RHT-2000	420	200	124	This work
2.5E-08	6.2E+03	RHT-1965	294	288	193	This work
2.5E-08	6.2E+03	RHT-2000	184	176	100	This work

Analysis of Results. The results reported by Gilbert *et al.* for <*g*> have been replicated to better than 4% for three neutron spectra, using the integration limits 6×10^{-5} to 3.4×10^4 MeV. Values of <*g*> have also been calculated using the Bevatron energy range 2.5×10^{-8} to 6.2×10^3 MeV. Analysis of the results shows that, for the "Shielded Bevatron" and "Hess Cosmic-ray" neutron spectra, the values of <*g*> are relatively insensitive to the choice of integration limits.

Table 1 shows that values of <*g*> calculated using the conversion function RHT-2000 are in all cases lower than those based on RHT-1965. For the "Shielded Bevatron" spectrum, the revised values of <*g*> are reduced by a factor of approximately 1.6; for the "Hess Cosmic-ray" spectrum, the corresponding reduction is a factor of about 1.9.

In the early and mid-sixties, the value of the spectrum-averaged conversion coefficient used by Berkeley Laboratory was 408 pSv cm^2. Using the newer conversion function and integration limits corresponding to the Bevatron energy range, the computed values of <*g*> were 176 pSv cm^2 and 100 pSv cm^2 for the Bevatron and cosmic ray spectra, respectively, i.e. between two- and four-fold lower than that originally used. Figure 3 shows a comparison of the annual dose equivalent values for the Bevatron as originally reported (using 408 pSv cm^2) and as revised (using 176 pSv cm^2) based on the results of this study.

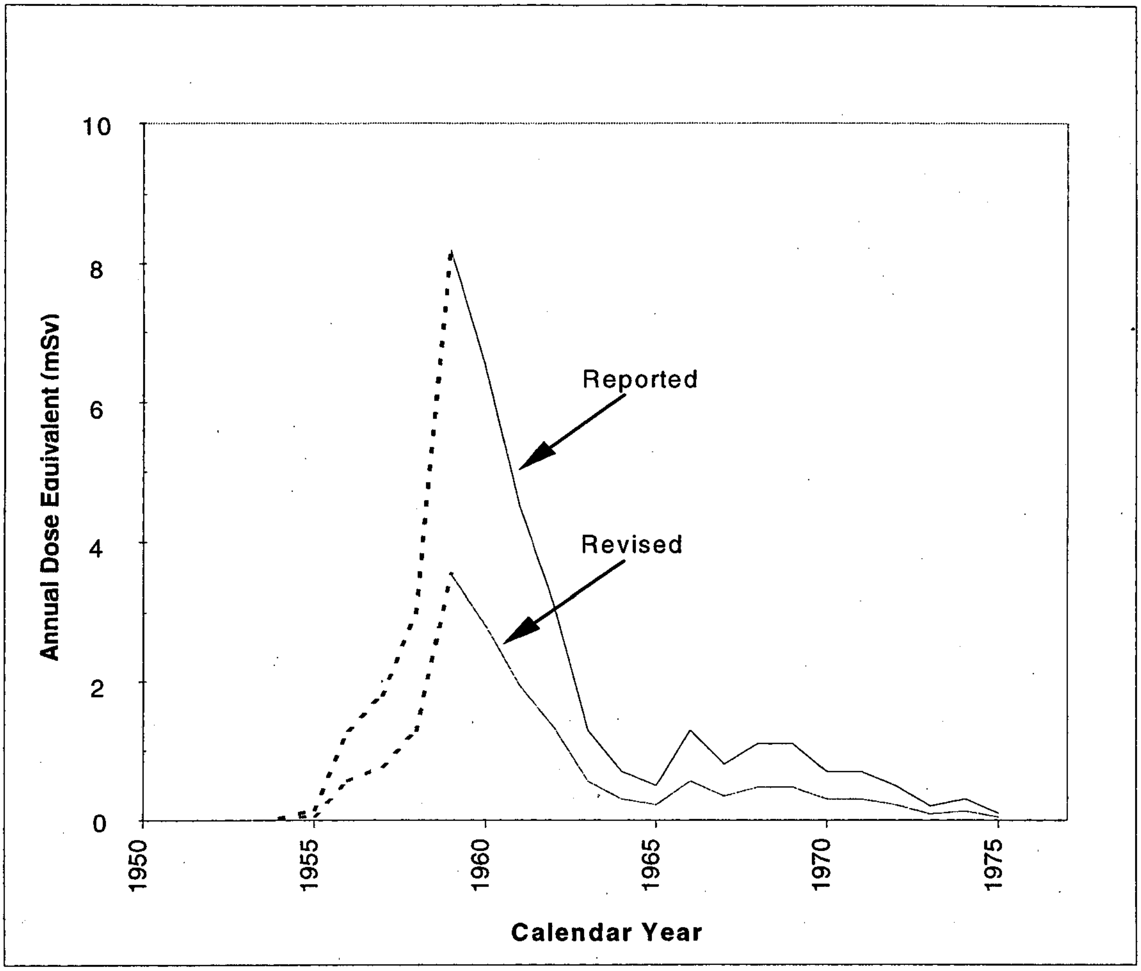

Figure 3. Comparison of reported dose equivalents for 1959–75, with revised dose equivalents. The dashed lines reflect estimates based on the number of protons accelerated per year at the Bevatron.

Summary and Conclusions. This paper has re-appraised the conversion to dose equivalent of neutron fluence measurements made at the site boundary of the Berkeley Laboratory in the decade following the Bevatron's commissioning in 1954.

The techniques used to measure neutron fluence at that time at Berkeley have subsequently been given international validation. Similarly, the early assessments of the character of the accelerator-produced neutron spectrum have been verified at many laboratories (IAEA 1988). During the forty years since these measurements were made, however, improved fluence-to-dose-equivalent conversion coefficients have become available. An analysis of recent conversion coefficient data has been expressed as a set of improved conversion coefficient functions entitled RHT-2000.

Analysis of the methods of converting measured neutron data to dose equivalent, based on neutron energy spectra and the most recently recommended conversion coefficients, suggests that the dose equivalents reported in the late fifties and early sixties were conservative by factors between two and four. In any current review of the historical data, therefore, it would be prudent to reduce the reported dose equivalents by at least a factor of two. It must be emphasized that this paper has addressed only the uncertainties in the conversion of integrated neutron fluence to dose equivalent. No attempt has been made here to appraise any intrinsic uncertainties in the measured neutron fluence itself. Of course, any conservatism in the reported neutron fluence will be correspondingly reflected in the estimate of dose equivalent.

The dose equivalent at the site boundary represents an upper bound on the potential exposure to members of the public. More precise evaluation of potential exposure to people living near the laboratory boundary at that time would involve determination of several factors, including times and duration of occupancy, influence of the inverse square law, the shadowing effects of hills, and the shielding provided by houses.

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