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Simulations of the Neutron Energy-spectra at the Olympus Gate Environmental Monitoring Station due to Historical Bevatron Operations

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Abstract

Offsite neutron fluences resulting from Bevatron operations reached a maximum in 1959, prior to the addition of a permanent concrete roof shield, which was constructed in 1962. From the first operation of the Bevatron measurements of neutron fluence were made at locations around the perimeter of the Lawrence Berkeley National Laboratory (LBNL) campus. Since the late 1950's measurements made at several locations, and particularly at the site of what is now called the Olympus Gate Environmental Monitoring Station[1], have been routinely reported and published. Early measurements were used to establish the shape of the neutron-energy spectrum from which an energy-averaged fluence-to-dose equivalent conversion coefficient could be derived. This conversion coefficient was then applied to a measured total neutron fluence to obtain the appropriate dose equivalent quantity required by regulation. Recent work by Thomas *et al*. (2000) have compared the early conversion coefficients used in the sixties with those accepted today and suggest suggested 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." However, that analysis was based on the "state of the art" neutron energy-spectra of the '60s.

This paper provides a detailed knowledge of the neutron energy spectrum at the site boundary paper thus removing any uncertainty in the analysis of Thomas *et al*., which might be caused by the use of the early neutron energy-spectra. Detailed Monte Carlo analyses of the interactions of 6.2 GeV protons in thick, medium-A targets are described. In the computer simulations, neutrons produced were allowed to scatter in the atmosphere. Detailed neutron energy spectra were calculated at a distance and elevation corresponding to the location of the Olympus Gate EMS. Both older and newer sets of conversion coefficients were applied to the calculated neutron energy spectra. It is concluded by this independent assessment that early dose equivalent estimates were conservative by at least a factor of 4. This reduction results from three factors:

(i) a better understanding of the neutron energy spectrum at the laboratory site boundary (factor of ~2)
(ii) revised conversion coefficients (factor of ~2)
(iii).the intrinsic conservatism of the reported dose equivalents (factor of ~2).

An investigation of the detector response to neutrons strongly suggests an additional systematic overestimation of the total neutron fluence by the routinely used environmental monitors. The influence of the ground on detector response has also been studied. Based on IAEA response functions, when calibrated with standard ^{239}PuBe neutron sources, 6" dia. spherical polyethylene moderators would have overestimated the dose equivalents in the accelerator spectra by a factor of about 1.3.

It was also possible to show that at locations near the Olympus Gate Environmental Monitoring Station radiation levels at places not in direct view of the Bevatron were further reduced by a factor of about 2 because skyshine contributed about half the total dose equivalent.

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[1] The name is taken from Olympus Avenue, Berkeley that lies to the NE of the laboratory perimeter. Access to the laboratory is possible here via gate through the perimeter fence (the Olympus Gate). One of the laboratory's several environmental monitoring stations is situated here and is colloquially known as the Olympus Gate Environmental Monitoring Station, abbreviated to Olympus Gate EMS (Thomas 1976).

1. Introduction

Interest has been revived in the dose equivalents reported due to Bevatron operation at the laboratory in the late fifties and early sixties (the historical doses equivalents). At that time the reported dose equivalents were close to, but did not exceed, the recommended dose equivalent limits (NCRP 1957, USAEC 1958, Thomas 1976). It was understood at that time that these reported dose equivalents were conservative estimates (overestimates) but the information needed to improve them was not then available. Forty years later the means of obtaining this information is available and can be applied to a better understanding of the environmental radiation at the laboratory boundary, including a more precise estimate of the historical dose equivalents

By convention, radiological protection advisory organizations, such as the ICRP[2] 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.* Dose Equivalent (ICRP 1964), Effective Dose Equivalent (ICRP 1977, 1980) and Effective Dose (ICRP 1991)]. Although there are subtle differences between these quantities they may be considered identical for the general purposes of this paper, and the generic term “dose equivalent” is used throughout [McDonald *et al*. (1998), Thomas and Zeman (2001)].

At LBNL dose equivalents due to neutrons are determined by measurements of total neutron fluence and the application of appropriate neutron fluence to dose equivalent conversion coefficients. A recent assessment based on two early 60's "state of the art" neutron energy-spectra concluded that the historical dose equivalents were conservative by factors between 2 to 4 (Thomas *et al.* 2000). This reduction was principally due to the application of present-day conversion coefficients for the correct irradiation geometry. [Typically the neutron fields at a large accelerator are produced by many diffuse sources. The preponderance of the dose is deposited by neutrons having energies much smaller than the primary proton beam and which are scattered by the air, and by surrounding structures. Furthermore, the nature of the random movement of people in these fields (walking, sitting, sleeping) leads to the conclusion that their exposure will be isotropic in character].

An independent assessment is possible using present-day radiation transport computer codes by simulating the characteristics of the neutron source produced by the Bevatron. Transport calculations can then determine the neutron energy spectrum at locations at the laboratory boundary. It is then possible to determine the response of the detectors routinely used in environmental monitoring and the influence of ground-scattering on the detector responses. It is also possible to compare the dose equivalents using old and new conversion functions for a more realistic neutron energy spectrum than those used in the previous work of Thomas *et al*.

In their assessment Thomas *et al*. defined neutron energy spectrum-averaged dose equivalent conversion coefficients (so-called $<g_G>$values) using the best information about accelerator neutron energy-spectra that were available in the '60s. The spectrum averaged conversion coefficient was obtained by folding the neutron fluence as a function of energy into the dose equivalent conversion coefficients as a function of energy and then dividing by the total fluence. Thus $<g_G>$ is defined by:

$$< g_G > = \frac{\int_{E_{min}}^{E_{max}} g_G(E)\left(\frac{d\phi}{dE}\right)dE}{\int_{E_{min}}^{E_{max}} \left(\frac{d\phi}{dE}\right)dE} \qquad (1)$$

where:

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 specifies the irradiation geometry

[2] International Commission on Radiological Protection.
[3] National Council on Radiation Protection and Measurements.

The advantage of this method is that, given a predetermined $\langle g_G \rangle$ value, one can measure total neutron fluence and then readily convert to the required dose equivalent quantity. A possible disadvantage is that the value of $\langle g_G \rangle$ may be sensitive to the lower limit of integration of the fluence integral, whereas the total dose equivalent produced is not so sensitive to the lower limit of integration. This will be discussed in more detail in section 4.

Thomas *et al.* utilized two sets of dose equivalent conversion coefficients in their analysis. The first set, referred to as RHT-1965 and developed in 1965, was a synthesis of then extant published data for anterior-to-posterior (AP or front-to-back) irradiation geometry (Thomas 1967). The second set, referred to as DSTZ-2000, based on isotropic irradiation geometry, is more appropriate to actual irradiation conditions beyond the laboratory perimeter which were both at large distances from the radiation source and protracted in time (Thomas and Zeman 2001). Both sets of conversion coefficients are listed in the Appendix.

2. Simulations

The MCNPX Monte Carlo Code (LANL 2000) was used for the simulation work described in this paper. This code is a newly released combination of the low energy MCNP code with the high energy LAHET code. The neutron energy spectrum from 6.2 GeV protons interacting in a thick, medium-A target was calculated. The resulting neutron energy-spectra, including components both directly from the source and scattered in the air, were then converted to dose equivalent using the two sets of dose equivalent conversion coefficients RHT-1965 and DSTZ-2000 to generate relative estimates of dose equivalent.

The calculations proceeded in three steps:

1. Determination of the initial source terms - the energy spectra of neutrons produced at the Bevatron for two cases - a copper target with and without overhead steel shielding.
2. The transport of the initial source neutrons through the atmosphere to the location of the Olympus Gate EMS.
3. Conversion of the fluence spectra thus calculated to dose equivalent using the two sets of conversion coefficients RHT-1965 and DSTZ-2000.

The two resultant values of relative dose equivalent estimates may be compared.

The calculated neutron energy spectra at the Olympus Gate EMS described in this paper are based on a detailed knowledge of Bevatron operations are detailed and facilitate a more exact analysis than was possible by Thomas *et al*. who used historical spectra from the late 50's and early 60's.

No attempt was made to estimate the absolute value of dose equivalent at the Olympus Gate. Such a calculation would have been impracticably complex because of the variability of operating conditions and source geometry. The Bevatron a was a large structure with a circumference of about 126 m. Beam target locations varied and proton losses could occur over large regions around the ring. Shielding above the straight sections and the self-shielding provided by iron and copper of the magnet structure would even further complicate the calculation. The approach taken here was to calculate the neutron energy spectrum at the Olympus Gate Environmental Monitoring Station (Olympus Gate EMS), convert to dose equivalent using the two sets of dose equivalent conversion coefficients (RHT-1965 and DSTZ-2000) and then compare the values of dose equivalent per unit fluence, ($\langle g \rangle$), thus obtained.

2.1 Bevatron Source Spectra

The primary neutron source was modeled by a 6.2 GeV beam of protons striking a 30-cm thick (approx. 2 nuclear interaction lengths) block of copper. Copper was selected for the calculation to be representative of materials of medium mass number for which the neutron energy spectrum is not strongly dependent on target material. This model was representative of the eventual loss of the accelerated protons to the wall of the vacuum chamber and subsequently in the iron yoke of the magnets. Neutrons are produced via spallation reactions with the target (iron/copper) nuclei and subsequent evaporation processes from the residual excited nuclei. The resulting neutron energy spectrum is strongly dependent on angle as measured with respect to the direction of the incident beam. In general, the higher the energy of the spallation neutrons the more forward they are directed. Evaporation neutrons are emitted isotropically. On average, in each 6.2 GeV interaction, only a few high-energy spallation neutrons may be produced but as many as 20-30 evaporation neutrons may be produced in high-energy spallation reactions.

Figure 1 shows two calculated source spectra, the first at 0° to the beam direction (indicated by squares) and the second at 90° to the beam direction (indicated by diamonds). It can be seen that the spectrum is much harder (energetic) at 0°, extending up to approximately the incident proton energy. The evaporation peak, which has a maximum at about 1 MeV and extends to about 15 MeV, is clearly evident. This peak dominates the total neutron yield.

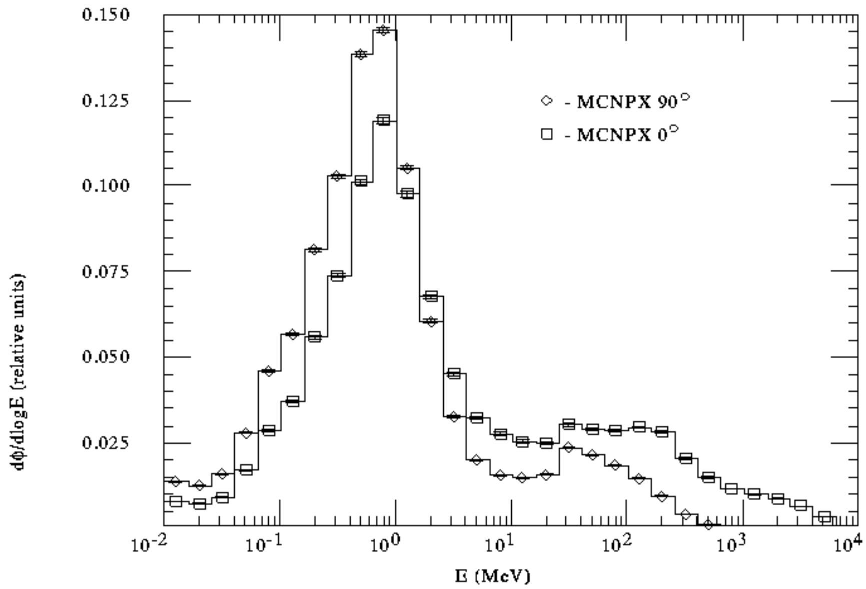

Figure 1
Neutron energy-spectra produced by 6.3 GeV protons incident on a 30 cm. thick Cu target. Two spectra were calculated: the first at 0° to the beam direction (squares) and the second at 90° to the beam direction (diamonds).[4]

From early after its first operation until 1962, when permanent roof shielding was added, the Bevatron, which was an almost circular accelerator, was contained within a cylindrical concrete shield-wall. The circulating proton beam was located about seven feet from the inner edge of the shield wall and about seven feet below its rim. The target interaction regions were shielded by the iron magnet yoke and additional iron shielding plates. The effect of this shielding on the spectra is discussed in the following section (2.2). Spallation neutrons produced in the forward direction would impinge on the approximately seven feet thick concrete walls at a large angle normal to the wall surface. The evaporation neutrons and lower energy spallation neutrons produced at larger angles to the beam direction would radiate to the sky through the thin roof of the Bevatron Building. For this reason in subsequent simulations, the calculated neutron energy spectrum at 90° was used as the source for both direct and air-scattered (skyshine) neutron fluence estimates at the Olympus Gate EMS (see Section 3).

2.2 Modification of the Bevatron Source Spectrum by the Steel Magnet.
In its early phase of operation the Bevatron targets were often placed in the vacuum chamber where some intrinsic overhead shielding was provided by the magnet yoke and pole tips. In the straight sections concrete blocks were placed over sources of radiation (Patterson 1965). In these early days of operation the magnet yoke largely determined the character of the neutron leakage spectra. It is of importance therefore to determine the influence of

[4] The quantity d(ϕ)/dlogE = E d(ϕ)/dE is called the lethargy spectrum by radiation physicists, but is widely used to describe such quantities as differential cross sections when a logarithmic scale on the horizontal axis is used. It has the advantage that if the vertical scale is linear, the area under the curve is the integral of d(ϕ)/dE.

this steel shielding on the Bevatron neutron leakage spectra, both close to the accelerator and at the laboratory perimeter

The thickness of the magnet iron yoke and magnet pole tips above the locations of proton beam loss has been estimated at between 42 and 66 inches (1.07 to 1.67 m) [Patterson (1965), Smith (2000)]. To determine the impact of this shielding on the neutron fluence energy spectrum an additional calculation of the source spectrum was performed. In the computer simulation a thickness of 1 m of iron was added above the copper target (section 2.1) and the neutron energy spectrum was tallied and compared with the previous case without iron shielding.

Figure 2 compares the two spectra. The iron-shielded spectrum is shown as the dotted histogram. It may be seen that the iron-shielded spectrum is generally softer (lower in energy) than the unshielded spectrum, and contains structure at some energies which is indicative of nearby resonances in the iron cross section. This result was not unexpected and is in agreement with the many observations reported in the literature of "soft" energy spectra leaking from iron shields (see for example Patterson [1965]).

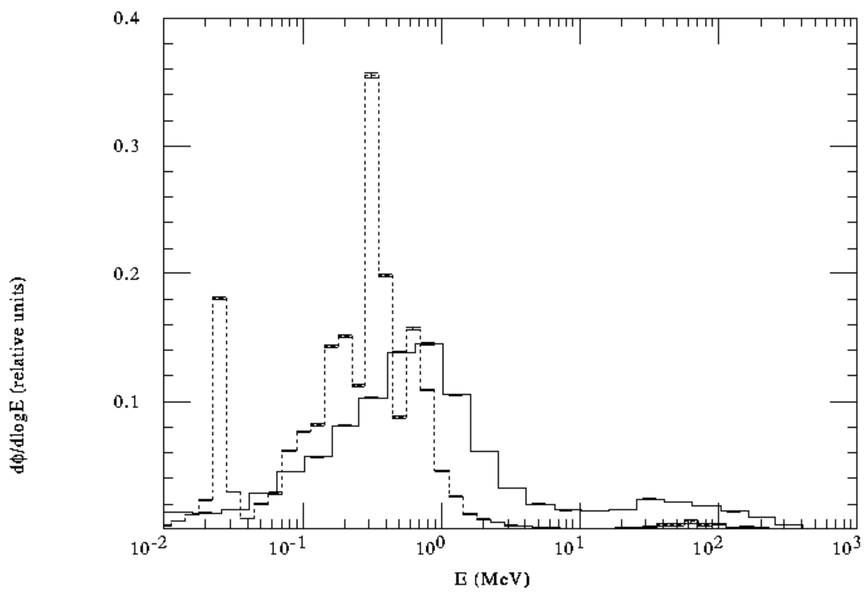

Figure 2

A comparison of two fluence energy spectra at 90° to an unshielded shielded thick Cu target bombarded by 6.3 GeV protons. The solid-line histogram shows the neutron spectrum above an unshielded target (also presented in figure 1). The dotted histogram shows the spectrum with a thickness of 100 cm. of iron above the target. Both neutron energy-spectra are presented as a lethargy plot and normalized to an area of 1.0.

3. Spectra and Dose Equivalent Estimates at the Olympus Gate EMS.

3.1 Neutron energy-spectra at Olympus Gate EMS.

Section 2 has described the determination of the spectrum of neutrons emerging into the air from the Bevatron beam target. This section describes the application of this primary source spectrum to determine the neutron energy spectrum observed at the Olympus Gate EMS.

A point isotropic neutron source, having the primary source spectrum, was placed at the center of a hemisphere of air. The neutron fluence was tallied at a location 427 meters (1400') laterally from and 122 meters (400') in elevation above the Bevatron, corresponding to a line of sight distance 444 meters (1457'), which approximates the location of the Olympus Gate EMS. Neutrons were transported from the source both directly (line-of-sight) as well as scattered in the atmosphere down to this location. Both the RHT-1965 and DSTZ-2000 conversion coefficient functions were folded into the calculated Olympus Gate EMS spectrum and integrated over all energies. The final dose equivalents were compared.

So that this comparison might be made it was first necessary to investigate any changes in calculated dose equivalent due to varying the size of the volume of the modeled atmosphere; by the influence of relative humidity and of the ground on the calculated neutron energy spectrum. The variation of neutron fluence with distance from the source was studied and the magnitude of the "skyshine" contribution estimated. Finally the two spectra at OGEMS resulting from the use of a bare copper target and a steel shielded copper target as the primary source spectra were calculated and compared. The softening of the overhead steel shielding reduced the dose equivalent per unit fluence by about 50% of the bare copper target value

3.2. Influence of the Atmosphere on Neutron Energy Spectra.

a. Dimensions of the Atmosphere. The effect of atmosphere size in the model is shown in Fig.3. The hemisphere radius was varied and the dose equivalents were tallied at the location of the Olympus Gate EMS. The results were normalized such that the value of the DSTZ-2000 dose equivalent was 1.0 at its asymptotic limit beyond a radius of about 1 km of air (approximately 120 $g.cm^{-2}$).

Two conclusions can be made from this graph. Firstly, the dose equivalent at the Olympus Gate EMS using the RHT-1965 dose equivalent conversion coefficients is consistently a factor of about two higher than the dose equivalent calculated using the DSTZ-2000 conversion coefficients. Secondly, the modeled atmosphere should have radius of at least 1 km to enable the skyshine component to reach its full value. Calculations reported here used a value of 3 km for the radius of the atmospheric hemisphere.

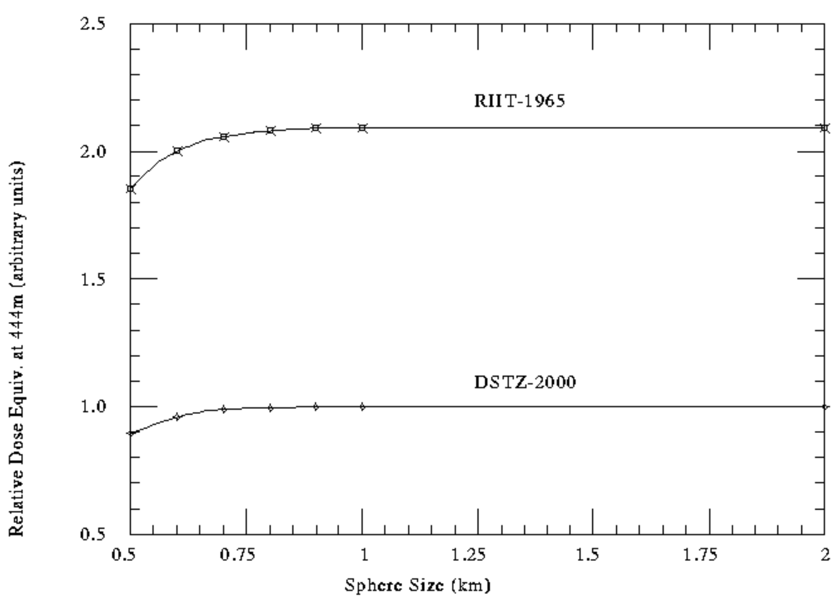

Figure 3

Neutron dose equivalents calculated at the Olympus Gate EMS as a function of the radius of the hemispheric model atmosphere. The two curves show the results obtained by folding the neutron spectrum at OGEMS with the two conversion functions RHT-1965 and DSTZ-2000.

b. Relative Humidity The effect of relative humidity on the dose equivalent at the Olympus Gate EMS was found to be insignificant.

The density of water in air, ρ_w, may be calculated from:

$$\rho_w = \frac{P_v}{P} . \rho_a . \frac{M_w}{M_a} \quad (2)$$

where:

P_v is the vapor pressure of water
P is the atmospheric pressure
ρ_a is the density of air
M_w is the molecular weight of water
M_a is the molecular weight of air

As an example: at a temperature of 22°C (72°F) and a relative humidity of 100% the vapor pressure of water is 19.8 mm Hg, Substituting this value, and with P= 760 mm Hg, ρ_a= 1.2.10^{-3} g.cm^{-3}, M_w = 18, M_a= 29, into eq. 2 yields:

$$\rho_w = 1.9\ 10^{-5}\ g\ H_2O/cm^3\ air \quad (3)$$

The hydrogen content of materials is important in determining their neutron shielding properties because of the large energy loss incurred in elastic scattering by neutrons on protons. This calculation shows that the moisture content in the air amounts to less than 0.2% hydrogen by weight. Several simulations were run varying the relative humidity of air. As expected, no statistical difference was evident between the resulting dose equivalents.

3.3. Influence of the Ground on Neutron energy spectra.

Scattering of neutrons by the ground ("ground scatter") may affect the shape of the fluence and dose equivalent energy spectra. Evidently the soil in the immediate vicinity of the tally point at the Olympus Gate EMS has a much greater effect on the results than ground/soil further away. It is the hydrogen content of the soil (mainly in the form of water) that has the greatest effect on the neutron fluence scattering in the soil. A simulation was performed by modeling the earth at the location of Olympus Gate EMS by a cylinder 20 meters in radius and 1 meter thick placed below the tally point. The cylinder consisted of soil with water content of 30% by weight (a conservative assumption). The resulting neutron energy-spectra at the Olympus Gate EMS, with and without the soil column, are shown in figure 4 and the corresponding values of <g> (equation 1) are summarized in Table 1.

The soil column (ground scatter) produced a statistically significant increase in the low energy fluence at energies below about 0.1 keV. In the case of the bare target source spectrum the absolute magnitude of the total dose equivalent is reduced by about 30% with either set of conversion functions. The corresponding reduction in the case of the steel shielded target was about 50%. In both case (shielded or unshielded target) the ratio of the two dose equivalents computed using either the RHT-1965 or the DSTZ-2000 sets of conversion coefficients was 2.2.

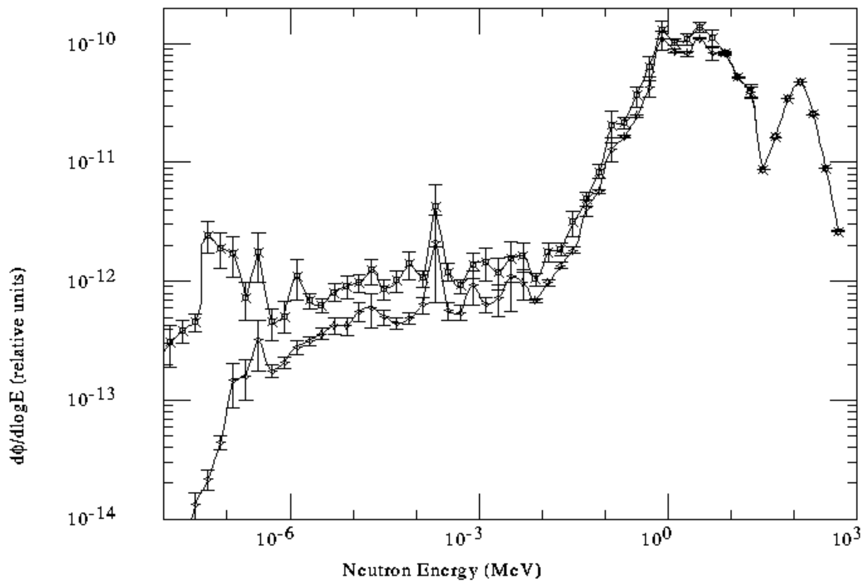

Figure 4

The influence of earth on the neutron energy-spectrum at the Olympus Gate EMS in the case of 6.2 GeV protons incident on an unshielded thick Cu target at the Bevatron. The upper curve shows the spectrum with the soil cylinder in place; the lower curve shows the spectrum without the soil cylinder (*i.e.* in air).

3.4 Modification by the Magnet Steel of the Neutron Energy Spectrum at the Olympus Gate.

Figure 2 shows that the intrinsic shielding of the steel magnet yoke had a significant influence on the Bevatron close-in neutron spectrum. Close to the accelerator the magnet yoke largely determined the character of the neutron leakage spectra [Patterson (1965)]. It was important to determine if this influence persisted as far as the Olympus Gate EMS.

Calculations were performed using 2 source spectra: (a) a bare thick copper target bombarded by 6.2 GeV protons and (b) a similar copper target but with 1 m of iron overhead shielding placed above it. The neutron fluence energy spectra were tallied and are shown in figure 5.

The iron-shielded copper target spectrum at OGEMS retains some of the characteristics seen in the shielded target spectrum of figure 2. The iron-shielded target spectrum is generally softer than the unshielded target spectrum, with a slightly lower dose equivalent per unit fluence. Air-scattering has reduced the significance of the neutrons in the 20 keV region of the spectrum. Applying the DSTZ-2000 conversion function the value of <g> for the iron shielded primary target, with ground at the Olympus Gate EMS is 43 pSv.cm^2 to be compared with the corresponding value of is 65 pSv.cm^2 for a bare target.

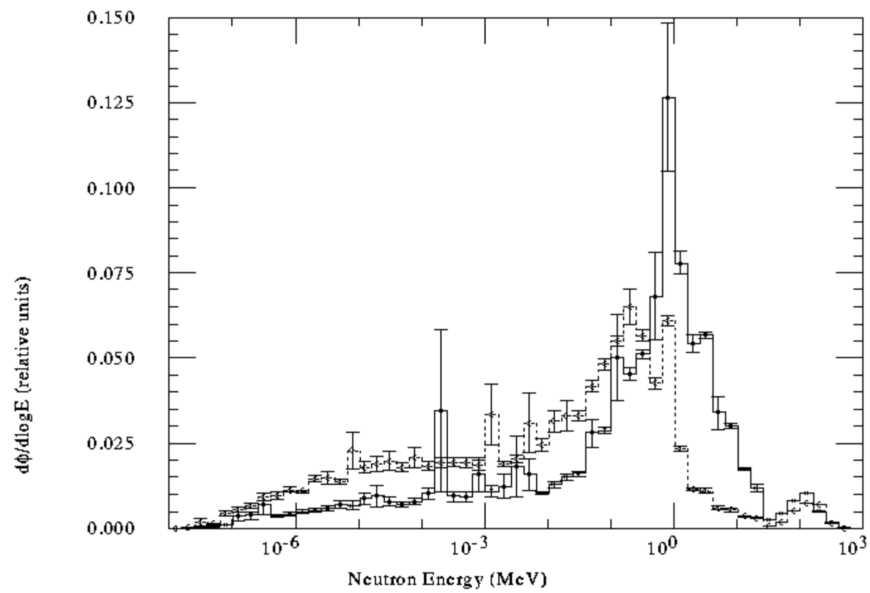

Figure 5

A comparison of the neutron energy -spectra at the Olympus Gate EMS resulting from a bare copper target bombarded by 6.2 GeV protons, located at the Bevatron, (a) with no overhead shielding and (b) with 1 meter steel overhead.

3.5 Summary of Values of Spectrum-Weighted Conversion coefficients for Simulated Spectra

Table1 summarizes the values of spectrum-weighted conversion coefficients, as defined by equation (1) for all the spectra determined at the Olympus gate EMS. Cases were calculated with two primary sources (bare thick Cu target; steel shielded Cu target); in air; with ground present and for both conversion coefficient functions RHT 1965 and DSTZ 2000.

The values of of spectrum-weighted conversion coefficients in Table 1 should be compared to with the early estimates made in the early sixties 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.

Table 1.
Summary of Values of Spectrum-weighted Conversion Coefficients for the Calculated spectra

Spectrum	Conversion Function	<g> ($pSv.cm^{2)}$	Energy Range (MeV)
OGEMS, bare target, in air	RHT-1965	199	2.5 10^{-8} - 6.2 10^3
OGEMS, bare target, in air	DSTZ-2000	94	2.5 10^{-8} - 6.2 10^3
OGEMS, bare target, with ground	RHT-1965	142	2.5 10^{-8} - 6.2 10^3
OGEMS, bare target, with ground	DSTZ-2000	65	2.5 10^{-8} - 6.2 10^3

OGEMS, Fe shielded target, in air	RHT-1965	94	2.5 10^{-8} - 6.2 10^{3}
OGEMS, Fe shielded target, in air	DSTZ-2000	43	2.5 10^{-8} - 6.2 10^{3}
OGEMS, Fe shielded target, with ground	RHT-1965	94	2.5 10^{-8} - 6.2 10^{3}
OGEMS, Fe shielded target, with ground	GSTZ-2000	43	2.5 10^{-8} - 6.2 10^{3}

In summary these calculations show that:

1. Application ISO conversion coefficients rather than AP conversion coefficients reduces the dose equivalent per unit fluence by a factor of slightly more than 2.
2. The influence of the magnet yoke is to reduce the dose equivalent per unit fluence for the spectrum in air by a factor of about 2.1.
3. The influence of the ground is to reduce the dose equivalent per unit fluence by a factor of about 2.1 when compared with the air spectrum.
4. The combined influence of the magnet yoke and the ground is to reduce the dose equivalent per unit fluence by a factor of about 2.2
5. For typical operating conditions the estimates of dose equivalent reported in the early 60s were high by a factor of 6-9.

4 The Variation of Dose Equivalent with Distance and Skyshine.

4.1 Variation of Dose Equivalent with Distance.

Collided and Uncollided Fluence. Figure 6 summarizes the variation of dose equivalent with distance from the Bevatron using the DSTZ-2000 dose equivalent conversion coefficients. The upper curve shows the total dose equivalent (due to both uncollided and collided radiation) while the lower curve shows the contribution from neutrons which are transported directly from the source to the detector location without interaction (direct or uncollided component). An inverse square line is also shown as a visual aid. It is evident that the dose equivalent rate decreases more rapidly than ($1/r^2$). There was evidence of this observation from historical measurements at the Bevatron. Previous work summarized by Dakin (1962) contains a number of plots showing measured neutron fluences at various distances and for various compass quadrants relative to the Bevatron. The text of his work states: "*-------most of the data from the present measurements appears to follow lines having a slightly steeper slope than would result from a purely inverse-square dependence*."

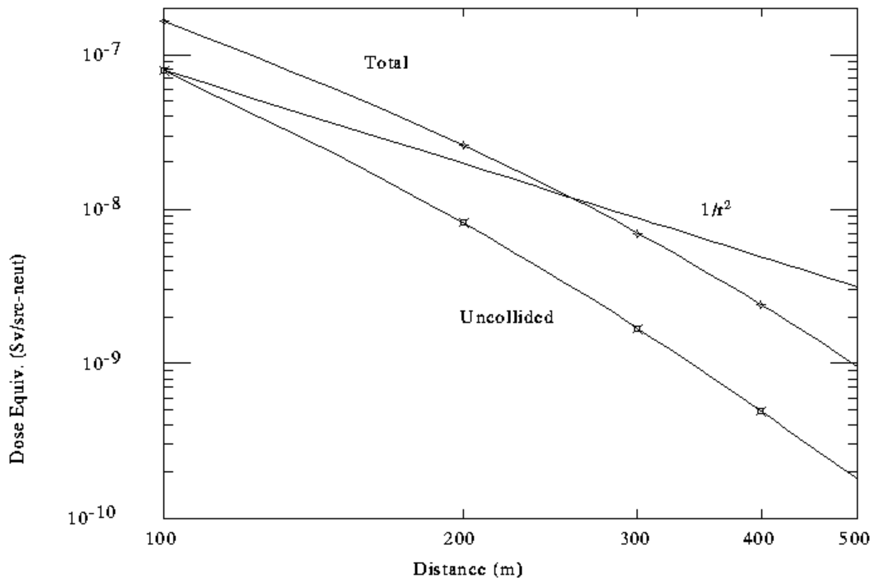

Figure 6

Dose Equivalent as a function of distance from the Bevatron. The upper curve shows the total (collided plus uncollided) fluence and the lower curve the uncollided neutron fluence. An inverse square ($1/r^2$) variation is shown as a visual aid.

At the location of the Olympus Gate EMS the collided fluence contribution is about 80% of the total dose equivalent. It is important to distinguish the collided component described here with what is usually referred to as "skyshine". In the definitions of the uncollided and collided components of the neutron field used for the calculations described here, a neutron elastically scattering at a very small angle but still reaching the tally/detector location is counted in the uncollided component. This definition is too restrictive for estimation of skyshine, which typically involves larger angle scattering [Rindi and Thomas (1975) and Stapleton *et al*. (1994)].

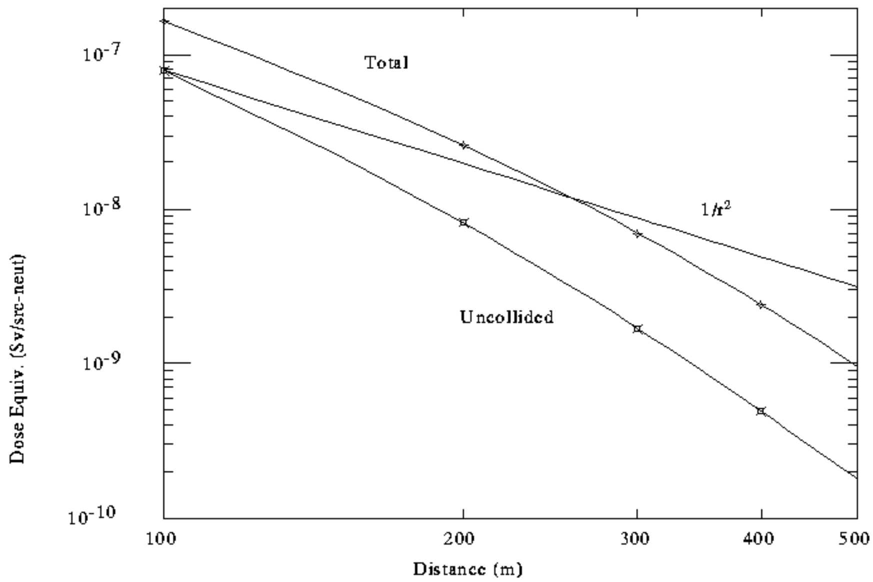

Figure 7

Dose Equivalent Spectra as a function of distance from the Bevatron. Three Curves are shown at 10m, 300m and 600m from the Bevatron. The error bars indicate the statistical uncertainty of the calculated values

Insight into the decrease in dose equivalent with distance was obtained by determining the neutron dose equivalent rate energy-spectrum at distances of 100, 300 and 600m from the Bevatron. The three spectra shown in figure 7, normalized in such a manner that the total area under each curve is 1.0.

It can be seen that the spectral shapes are not identical. If the decrease in dose equivalent rate with distance were due only to solid angle (inverse square law) the three spectra at different distances, when normalized, would have an nearly identical shapes. This is evidently not the case and fig. 7 that the energy spectrum becomes harder with increasing distance as the low energy evaporation neutrons emitted by the source are preferentially attenuated in air.

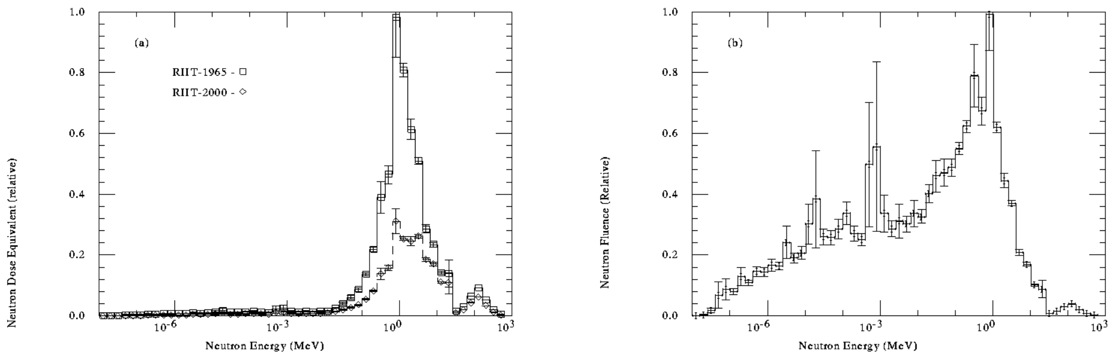

Figure 8

Fluence and Dose Equivalent Spectra at the Olympus Gate EMS.
Fig 8a shows the dose equivalent spectrum, Figure 8b the fluence spectrum

The dose equivalent and fluence spectra calculated at the Olympus Gate EMS are shown in figs 8a and 8b.

4.2 Skyshine

The Bevatron is partially surrounded by a steep hillside, with the boundary of the laboratory at the crest of the slope. Some houses are located at the crest and in direct line-of-sight of the Bevatron. Beyond the crest of the hill the Bevatron is no longer in direct line-of-sight. The Olympus Gate EMS is located near the crest of the hill, in sight of, and approximately 427 m horizontally and 122 meters vertically from the center of the Bevatron. The total neutron fluence at Olympus Gate EMS, and at those houses on the crest of the hill which were in direct line-of sight), was comprised of neutrons that had directly emerged from the roof of the Bevatron building and neutrons scattered by the atmosphere down to Earth. Beyond the crest of the hill the direct line-of-sight to the Bevatron vanishes and therefore any neutrons reaching those houses which are situated beyond the crest of the hill were the result of skyshine (large-angle scattering by the atmosphere). [For a review of neutron skyshine see Rindi and Thomas (1975) and Stapleton *et al*. (1994)].

Measurements by McCaslin (1976) suggested that, at the same distance from the Bevatron, neutron fluence rates were lower by a factor of about 1.8 when hills intervened. It is now possible to check this conclusion using computer simulations.

As previously discussed in section 4.1, the data shown in figure 6 do not correspond to "skyshine" which is due to relatively large-angle scattering. The uncollided (direct) contribution shown in fig. 6 was based on a very strict definition of "direct" - only neutrons which are transported directly from the source to the tally location and undergoing no interactions. Under these conditions the direct contribution was about 5 times smaller than the estimated total dose equivalent. This definition of uncollided radiation is too strict for the purposes of determining "skyshine" because a neutron may undergo a single small scatter and contribute to a tally at the site boundary hill. An additional set of calculations was therefore necessary.

In order to estimate the relative dose equivalent rate due to skyshine only (*e.g*. at houses beyond the hill-crest) a computer simulation was set up. A tally point was located at a distance of 444 meters from the Bevatron. A semi-infinite wall, 10 meters in height, was placed directly in front of the tally point. Any neutrons entering the wall were immediately terminated. Therefore, only neutrons scattered over the wall by the atmosphere were allowed to contribute to the neutron fluence at the tally point. The computed dose equivalent at the tally point with the wall in place was then compared with the dose equivalent with no wall in place.

The result of these calculations was that the dose equivalent due to skyshine was reduced by a factor of about 2.5 (statistical error ±4%) below the dose equivalent observed without the wall in place (*c.f.* McCaslin's estimate for the reduction in fluence of 1.8 with an estimated error of ±20%). One may conclude that the true skyshine contribution at Olympus Gate EMS is about half the total dose equivalent.

5. Detector Calibration and Responses to Fluence and Dose Equivalent

5.1. Fluence response versus Dose equivalent Response.

It is an axiom that if dose equivalent is to be determined by the procedure specified by equation (1) by using energy spectrum-averaged dose equivalent conversion coefficients (<g>values) that the total fluence Φ must be accurately determined. This is clear if equation (1) is written in the form:

$$H = \int_{E_{min}}^{E_{max}} g(E)\left(\frac{d\phi}{dE}\right)dE = <g> \int_{E_{min}}^{E_{max}} \left(\frac{d\phi}{dE}\right)dE = <g>\Phi \qquad (1a)$$

where, as before:

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.

dϕ/dE is the neutron differential energy spectrum.

and:

<g> is spectrum-averaged dose equivalent conversion coefficients.

Φ is the total fluence, given by $\Phi = \int_{E_{min}}^{E_{max}} \left(\frac{d\phi}{dE}\right)dE$.

Clearly if Φ□ is underestimated the use of equation (1) to determine dose equivalent might be misleading.

Many, if not most, of the routine neutron radiation surveys made around the Bevatron in the early 60's, including those at the site perimeter, were made using the detectors developed by Smith [Stephens and Smith (1958)]. Various thermal neutron activation foils were placed inside 6" diameter cylindrical polyethylene or paraffin moderators, encased in cadmium. This technique and much of the supporting dosimetry of that period has been described in Patterson and Thomas (1973).

No calculations of the energy response of the Smith cylindrical moderators have been published but the magnitude of this hypothetical uncertainty in the may be estimated from data for a spherical moderators given in IAEA Technical Report 318 Griffith et al. (1990).

Figure 9 shows the fluence response for a 6" (15.2 cm) diameter spherical polyethylene moderator as a function of energy. Assuming this response function the values of spectrum-averaged conversion coefficients, <g>, for the Olympus Gate EMS neutron energy spectrum, for different values of low energy cut-off and for the conversion functions RHT-1965 and DSTZ-2000, may be calculated. Table 2 summarizes the results for cut-offs at thermal energies and at 100 keV (A cut-off of 100 keV selected by inspection of figure 9 where it may be seen that the contribution to dose equivalent by neutrons less than 10^4 eV is very small).

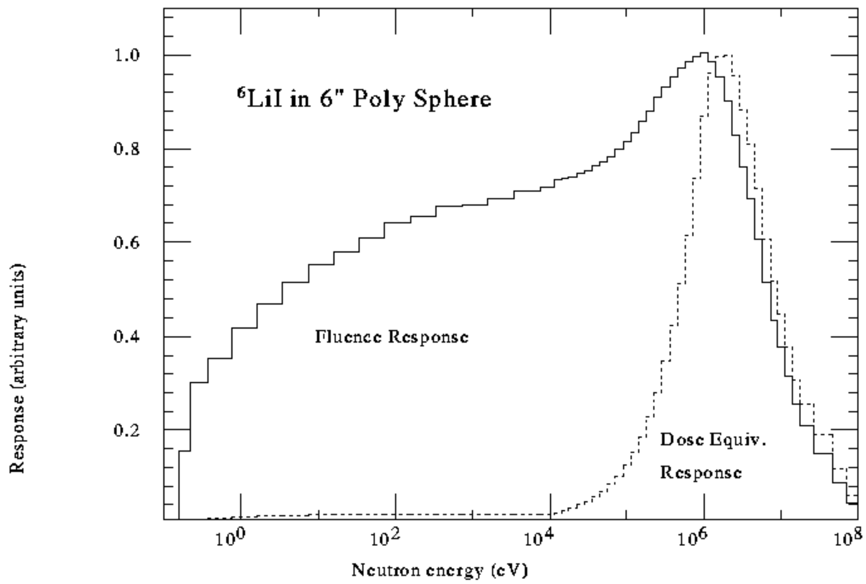

Figure 9

Differential dose equivalent and fluence response spectra of a 6" diameter polyethylene spherical moderator with a ^{6}LiF thermoluminescent dosimeter placed at its center to detect thermal neutrons. (Sphere response taken from IAEA Technical Report 318).

Table 2. Values of Spectrum Averaged Conversion Coefficients, <g>, calculated for the Olympus Gate EMS neutron energy spectrum, for different values of low-energy cut-off. The cut-offs used were thermal and 100keV.

Energy Range	Conversion Function	Spectrum Averaged Conversion Coefficient, <g> (pSv cm^2)
thermal to 6.2 GeV	RHT-1965	110
100 keV to 6.2 GeV	RHT-1965	277
thermal to 6.2 GeV	DSTZ-2000	48
100 keV to 6.2 GeV	DSTZ-2000	122

These results show that, under the assumptions of the calculation, that the values for <g> might vary by factors between 2 and 3 depending on the limits of integration of the fluence. This can be understood by examining figure 9. The differential dose equivalent response reveals that there is very little dose equivalent contributed by neutrons with energy below about 100 keV even though there is still a significant fluence. This, in turn, is because the dose equivalent conversion coefficients increase with energy by a factor of about 30 between thermal energies and 1 MeV (see Appendix).

It is therefore important to determine the accuracy with which the fluence was determined by the Smith detectors. This may be done by reviewing the experimental data and using the data of IAEA Technical Report 318.

5.2 Experimental Determinations Fluence Response

No calculations of the energy response of indium activation foils placed in cylindrical moderators have been published but some experimental determinations have been reported for a few neutron energies. Over the energy range from about 20 keV to 4.5 MeV calibrations were obtained using a variety of isotopic neutron sources. D-D and D-T neutrons provided points at 2 and 14 MeV. By removing the cadmium shield the moderator could be exposed to the thermal column of a nuclear rector and the thermal neutron response measured. The thermal neutron response is about the same as the 2 MeV response [Stephens and Smith (1958); Simpson (1964)]. *In toto* these measurements suggest that " the thermal-neutron flux detected ---(at the center of the moderator) ---by the (activation) detector is also nearly proportional to the incident fast neutron flux in the energy range from 0.02 keV to 20 MeV" (Patterson and Thomas 1973). Gilbert *et al*. (1968) and Shaw *et al*.(1969) have reported studies of the accuracy of dose equivalent determinations using only Smith-Stephens detectors in the broad energy spectra typical of high-energy accelerators. These studies suggest that, in unknown energy spectra, in extreme cases, the dose equivalent might be uncertain by as much as a factor if 3 or more. However, if the spectrum is known the dose equivalent may be determined with an uncertainty of about ±30% or better by the selection of an appropriate conversion coefficient.

5.3Calculated Dose equivalent Response and Calibration

No calculations of the energy response of the Smith-Stephens detectors (indium activation foils placed in cylindrical moderators) have been published but IAEA Technical Report 318 tabulates data for response functions for spherical moderators (Griffith *et al*. 1990). Figure 9 shows the response functions for fluence and dose equivalent of a 6" diameter polyethylene spherical moderator, with a ^{6}LiF thermoluminescent dosimeter placed at its center to detect thermal neutrons. [All of the thermal neutron reactions used inside these moderators have, above the cadmium resonance, the same dependence of activation cross with neutron velocity (*i.e*. dropping proportionally to 1/v). Therefore, the response function is essentially independent of the thermal neutron detector used (*e.g*. Au, In, BF_3, ^{6}LiF LTD *etc*.).]

Some caution should be used in applying these response functions to practical situations in the field. The most important reason for caution is that the response functions are calculated *in vacuo* and in the field ground-scattering can significantly enhance the neutron fluence below an energy of about 100 keV (see section 3.3). Other factors that may influence the conclusions, but to a lesser degree, are differences in geometry and conversion coefficients (IAEA Report 318 use conversion coefficients from ICRP Publication 21 [ICRP 1971]). Nevertheless it is instructive to determine the fluence and dose equivalent of this detector.

Section 3 has described the derivation of the neutron energy spectrum at the location of the Olympus Gate EMS. Figs. 8a and 8b show the dose equivalent and fluence spectra corresponding to this neutron energy spectrum. Assuming that the response for a ^{6}LiF thermoluminescent detector in a 6" polyethylene sphere is representative of the detectors used at the Bevatron, the detector response function from IAEA Report 318 was used to determine the efficiency of this detector in measuring the dose equivalent from the calculated neutron energy spectrum at the Olympus Gate EMS. The fluence-to-dose equivalent conversion coefficients given in IAEA Report 318 (ICRP Publication 21; ICRP 1973) were used to convert the fluence response spectrum into a dose equivalent response spectrum. Both are shown in Fig. 10 in which the results have been normalized such that the highest value for each response is 1.0 *i.e*. corresponding to a perfect response.

a. Calibration Procedure. The Smith-Stephens detectors were calibrated using ^{239}PuBe neutron sources having an average energy of about 4.2 MeV. Figure 10 shows the bare ^{239}PuBe fluence spectrum given in IAEA Report 318. This plot shows little or no fluence below about 0.5 MeV because no room return (low-energy neutron scattering back from floor and walls) is included. Also shown in this figure is the dose equivalent spectrum. Note that the dose equivalent and fluence spectra are almost identical because in the energy range 0.5-10 MeV the fluence-to-dose equivalent conversion coefficients do not greatly vary with energy.

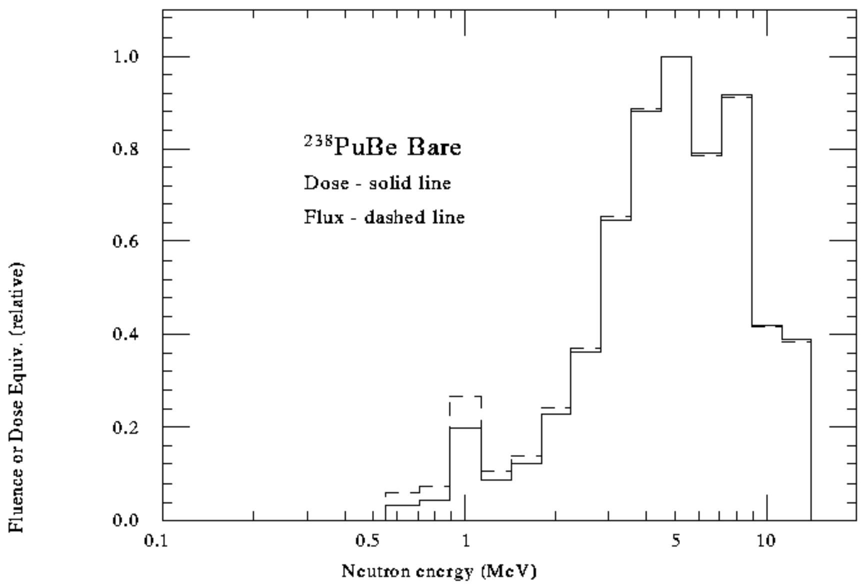

Figure 10

Dose equivalent and fluence spectra of a bare ^{239}PuBe(α,n)neutron source. (Fluence spectrum from IAEA Technical Report 318).

b. Figure of Merit for Dose Equivalent Determination. A characteristic of the calibration and measurement of the Smith detectors is that they measure neutron fluence. A dose equivalent is then inferred. A rather exact knowledge of the calibration geometry (scatter, room return) would be required to calculate the actual spectrum due to ^{239}PuBe neutron energy spectrum in which the detector is actually present when calibrated since the detector is sensitive to low energy neutrons. This may be seen from figure 9 where the relative response through three inches of moderator has dropped by only a factor of two at 10 eV compared with the peak response at 1 MeV. To circumvent this difficulty only dose equivalent response and dose equivalent spectra was used for comparison. A figure of merit, ε, which allows a quantitative measure of how well suited is the ^{239}PuBe neutron source and 6" diameter. moderator to the determination of dose equivalents in the actual neutron energy spectrum at the Olympus Gate EMS.
ε, is defined by:

$$\varepsilon = \frac{\int_{E_{min}}^{E_{max}} R_d(E) \cdot \frac{dH(E)}{dE} dE}{\int_{E_{min}}^{E_{max}} R_d(E) \cdot \frac{dH_c(E)}{dE} dE} * \frac{\int_{E_{min}}^{E_{max}} \frac{dH_c(E)}{dE} dE}{\int_{E_{min}}^{E_{max}} \frac{dH(E)}{dE} dE} * \qquad (4)$$

where:

$R_d(E)$ is dose equivalent response of the detector as a function of energy, E (a 6" diameter polyethylene moderator in this case see - fig. 9)

$\frac{dH(E)}{dE}$ is the differential neutron dose equivalent spectrum calculated at the Olympus Gate EMS (fig.8a)

$\frac{dH_c(E)}{dE}$ is the differential dose equivalent calibration spectrum (of the ^{239}PuBe neutron calibration source in this case - see fig. 10)

If the value of ε is <1, the dosimeter will underestimate the dose equivalent; if ε is >1the doe equivalent will be overestimated. Calculation yields a value of ε = 1.3 for the Olympus Gate Spectrum. Thus it may be concluded that, if the detector were calibrated to a known dose equivalent produced by the ^{239}PuBe source but irradiated in the neutron energy spectrum at the Olympus Gate EMS, the dose equivalent due to Bevatron operation would be overestimated by about 30%.

This work strongly suggests that there was no systematic underestimation of neutron dose equivalent at the Olympus Gate due to measurement errors caused by instrument response to different energy neutrons. Rather there was a modest but acceptable overestimation of dose equivalent. This overestimation is in addition to other factors previously discussed.

The instrumentation and the neutron calibration source are therefore appropriate for measuring Bevatron-produced neutron energy-spectra at the Olympus Gate.

5.Conclusions

Neutron energy spectra at the location of the Olympus Gate Environmental Monitoring Station of the Lawrence Berkeley National Laboratory have been calculated by state of the art Monte Carlo simulation and radiation transport methods. Several spectra were simulated to represent operating conditions of the Bevatron in the late 50s and early 60s. For typical conditions the values of spectrum weighted conversion coefficients <g> varied from 43 pSv cm^2 to 142 pSv cm^2 to be compared with a value of 408 pSv cm^2 in routine us in the mid 60s. Thus the estimates of dose equivalent reported in the early 60s were high by a factor of at least 4.

This reduction results from three factors:

(i) A more detailed understanding of the neutron energy spectrum at the laboratory site boundary (factor of ~2)

(ii) The application of conversion coefficients for isotropic irradiation geometry rather than for AP irradiation geometry (factor of ~2)

(iii).the intrinsic conservatism of the reported dose equivalents (factor of ~2).

The work reported here extends another recent assessment but based on "state of the art" neutron energy-spectra of the early sixties [(Hess et al. 1959); Patterson *et al*. (1959); Gilbert et al. (1967)] in which Thomas et. al. (2000) concluded "...that the dose equivalents reported in the late fifties and early sixties were conservative by factors between two and four".

Figure 11 compares the two "historical" spectra with the simulated spectrum at the Olympus Gate Environmental Monitoring Station. The values of <g> for the Hess Cosmic Ray Spectrum, the Shielded Bevatron Spectrum and the OGEMS spectrum (in air) were 107, 191 and 94 pSv cm^2 respectively. The value for the OGEMS spectrum taking into account the moderating effect of the ground is 65 pSv cm^2. In any current review of the historical data it would be reasonable to reduce the reported dose equivalents by a factor of four.

An investigation of the detector response to neutrons strongly suggests an additional systematic overestimation of the total neutron fluence by the routinely used environmental monitors.. Based on IAEA response functions, when calibrated with standard ^{239}PuBe neutron sources, 6" dia. spherical polyethylene moderators would have overestimated the dose equivalents in the accelerator spectra by a factor of about 1.3.

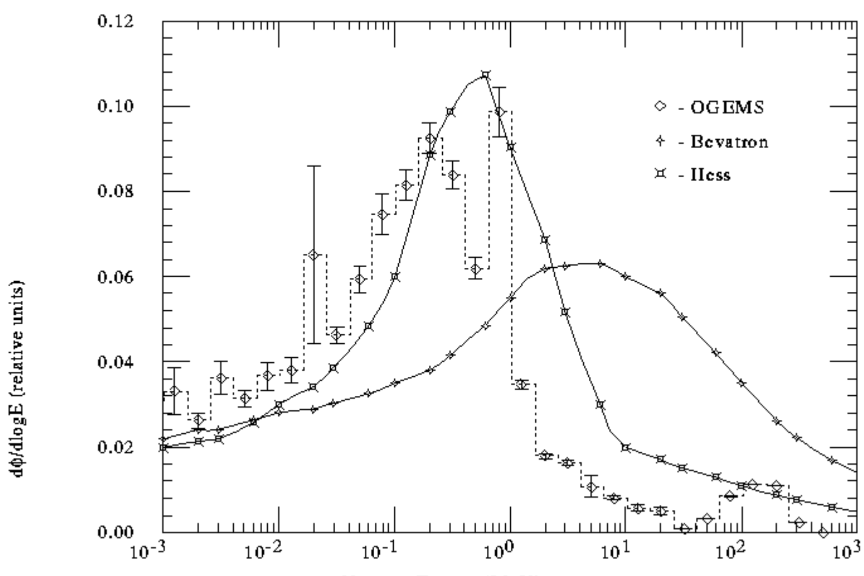

Figure 11

A comparison between the Hess Cosmic-ray Neutron Spectrum (1959); the Shielded Bevatron Spectrum (circa 1965) and the simulated spectrum at the Olympus Gate Environmental Monitoring Station

In addition to the reductions in dose equivalents of at least 4 it was also possible to show that radiation levels at places not in direct view of the Bevatron were further reduced by a factor of 2 because skyshine contributes about half the total dose equivalent.

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Appendix

Tables of Neutron Fluence to Dose Equivalent Conversion Coefficients

Energy (MeV)	Conversion Coefficients		
	RHT-1965 AP Geometry (pSv.cm2)	DSTZ-2000 ISO/ROT Geometry (pSv.cm2)	Ratio (2000/1965)
2.50E-08	1.20E+01	3.49E+00	3.44
1.00E-07	1.20E+01	4.12E+00	2.91
2.00E-07	1.20E+01	4.49E+00	2.67
5.00E-07	1.20E+01	5.01E+00	2.39
1.00E-06	1.20E+01	5.45E+00	2.20
2.00E-06	1.20E+01	5.93E+00	2.02
5.00E-06	1.20E+01	6.44E+00	1.86
1.00E-05	1.20E+01	6.44E+00	1.86
2.00E-05	1.20E+01	6.44E+00	1.86
5.00E-05	1.20E+01	6.44E+00	1.86
1.00E-04	1.20E+01	6.44E+00	1.86
2.00E-04	1.20E+01	6.44E+00	1.86
5.00E-04	1.20E+01	6.44E+00	1.86
1.00E-03	1.20E+01	6.44E+00	1.86
2.00E-03	1.20E+01	6.44E+00	1.86
5.00E-03	1.20E+01	6.44E+00	1.86
1.00E-02	1.22E+01	6.58E+00	1.85
2.00E-02	2.05E+01	1.01E+01	2.02
3.00E-02	2.78E+01	1.31E+01	2.13
5.00E-02	4.08E+01	1.79E+01	2.27
7.00E-02	5.25E+01	2.21E+01	2.37
1.00E-01	6.86E+01	2.76E+01	2.48
1.50E-01	9.30E+01	3.56E+01	2.62
2.00E-01	1.15E+02	4.26E+01	2.71
3.00E-01	1.56E+02	5.48E+01	2.86
5.00E-01	2.30E+02	7.53E+01	3.05
7.00E-01	2.95E+02	9.29E+01	3.18
9.00E-01	3.57E+02	1.09E+02	3.28
1.00E+00	3.86E+02	1.16E+02	3.33
1.20E+00	3.86E+02	1.30E+02	2.97
2.00E+00	3.86E+02	1.79E+02	2.16
3.00E+00	3.86E+02	2.30E+02	1.68
4.00E+00	3.86E+02	2.54E+02	1.52
5.00E+00	3.86E+02	2.65E+02	1.46
6.00E+00	3.86E+02	2.74E+02	1.41
7.00E+00	3.86E+02	2.82E+02	1.37
8.00E+00	3.86E+02	2.89E+02	1.33
9.00E+00	3.86E+02	2.96E+02	1.31
1.00E+01	3.86E+02	3.01E+02	1.28
1.20E+01	4.04E+02	3.12E+02	1.29
1.40E+01	4.20E+02	3.21E+02	1.31
1.50E+01	4.27E+02	3.25E+02	1.31

1.60E+01	4.34E+02	3.29E+02	1.32
1.80E+01	4.47E+02	3.37E+02	1.33
2.00E+01	4.59E+02	3.43E+02	1.34
3.00E+01	5.08E+02	3.70E+02	1.37
5.00E+01	5.77E+02	4.07E+02	1.42
7.50E+01	6.39E+02	4.39E+02	1.45
1.00E+02	6.86E+02	4.64E+02	1.48
1.30E+02	7.33E+02	4.87E+02	1.50
1.50E+02	7.59E+02	5.00E+02	1.52
1.80E+02	7.95E+02	5.18E+02	1.54
2.00E+02	8.16E+02	5.27E+02	1.55
5.00E+02	1.03E+03	5.93E+02	1.73
1.00E+03	1.22E+03	7.66E+02	1.59
2.00E+03	1.45E+03	9.89E+02	1.47
5.00E+03	1.82E+03	1.39E+03	1.32
6.20E+03	1.93E+03	1.50E+03	1.28
1.00E+04	2.17E+03	1.79E+03	1.21