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Abstract

The thickness of shielding wall and roof needed at the Bevatron in order to assure safe radiation levels in the surroundings is calculated on the assumption of a beam of 10^{13} protons per pulse at 10 pulses per minute expected as a result of improvements.

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Statement of the Problem

In anticipation of a beam level of 10^{13} protons per pulse at a pulse rate of 10 per minute from the contemplated Bevatron improvement, we here calculate the thickness of vertical shielding wall that must surround the Bevatron, and also of the roof that must cover it, in order to provide satisfactorily low radiation levels in the immediate vicinity and at the site boundary.

The radiation level in the working area immediately around the Bevatron should be such that on a long-time average not more than 5 rem radiation dosage would be accumulated per year (however, it is permissible to receive a dosage of 3 rem in one-quarter year so long as the long-term accumulation is not exceeded). At the site boundary the radiation field must not deliver a potential dosage greater than 0.5 rem per year. This last figure for the site boundary is of course to be computed on a 24-hour-day basis, whereas the radiation accumulation in the working areas can be considered as occurring only during working hours.

In making these calculations we first find the best available data on total neutron production, angular distribution, and spectrum of the neutrons created by the Bevatron. Then we consider a target in different positions characteristic of Bevatron operation and evaluate the necessary shielding to accommodate the situation within the bounds of the radiation guide rules.

Neutron Production and Spectra

Since the proton beam is not stopped by any of the targets employed in the Bevatron, the beam is finally distributed in the iron of the Bevatron magnet system in some pattern which depends upon the target location, target scattering, and beam oscillation characteristics. We may regard the neutron production then as occurring partly in the primary target (if it is of substantial thickness) and partly in a distributed manner over much of the interior surface of the magnet structure. The most severe requirements on local shielding will occur when a target of considerable thickness effects a concentrated creation of neutrons and secondary particles in its immediate vicinity. We calculate the shielding in relation to a target of one mean-free-path length (in the beam direction), with the understanding that if the shield is sufficient to handle this for any target position it will be easily capable of accommodating the distributed production of neutrons and secondary particles from the machine in general. Thus we consider a copper target whose dimension along the beam direction is about 100 g/cm^2.

The yield of neutrons from the traversal of such a target by protons of 6.3 Bev is estimated to be 20 neutrons per proton. This includes only those neutrons coming from the target proper and not those created by the secondary particles, originating in the target, in their further interactions in surrounding materials. The spectrum of this neutron yield is given in Fig. 1. This spectrum information arises from a blending together of cosmic ray information, the results of certain neutron experiments at the Bevatron, and the inferences from Monte Carlo calculations made by Metropolis.

Because the attenuation cross sections for high-energy neutrons become essentially constant at their minimum values for neutron energies above 180 Mev, we are primarily concerned with the high-energy portion of the spectrum, and in fact consider only the target yield of neutrons above 150 Mev in energy. Although the production spectrum is much more intense at energies below this figure, this greater intensity is more than compensated for by the considerably larger attenuation cross sections appropriate to the lower energies.

We next must ascertain the angular distribution with which these penetrating neutrons are emitted from the copper target. Again from the Metropolis Monte Carlo calculations, we can infer that their angular distributions are about as shown in Fig. 2. The area of Fig. 2 is normalized to yield 8 neutrons per proton, which is the total number per proton above the 150-Mev lower limit. With this information on neutron production we may proceed to locate the target in various positions and calculate the required shielding that must be associated with each situation.

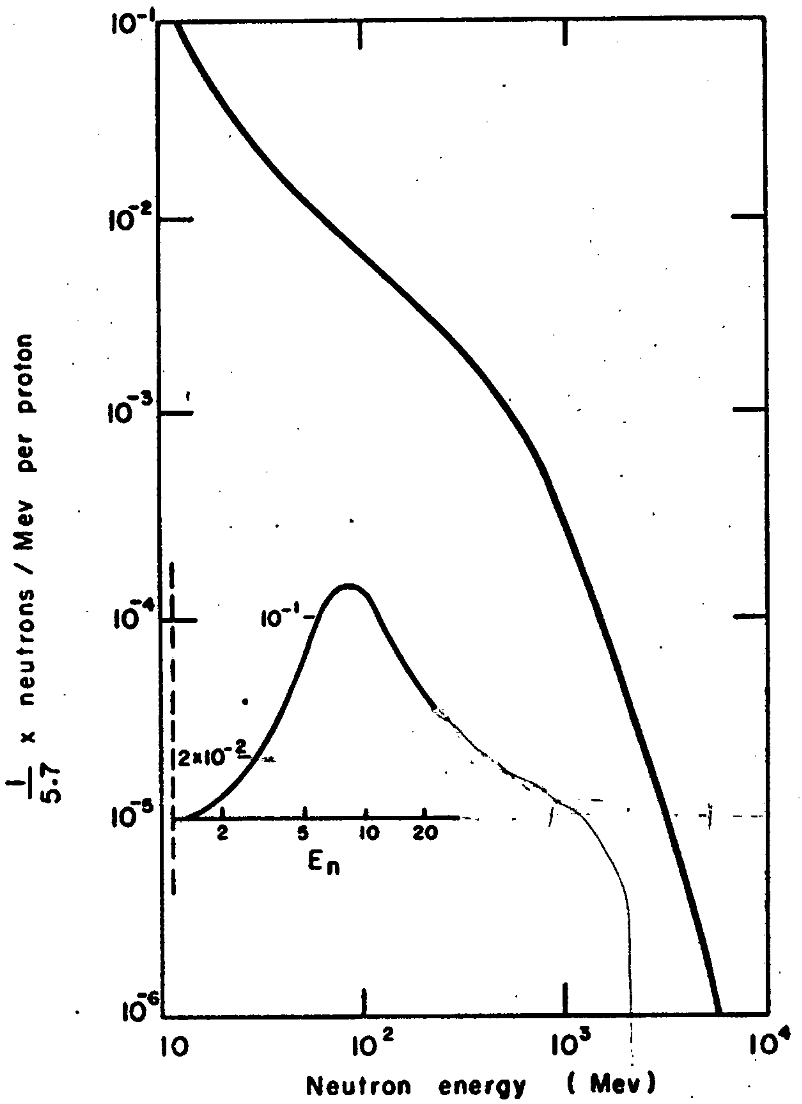

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Fig. 1. Neutron-emission spectrum from 1 nuclear mfp of Cu traversed by 6.3-Bev protons.
(To obtain neutrons/Mev per proton, multiply ordinate by 5.7.)

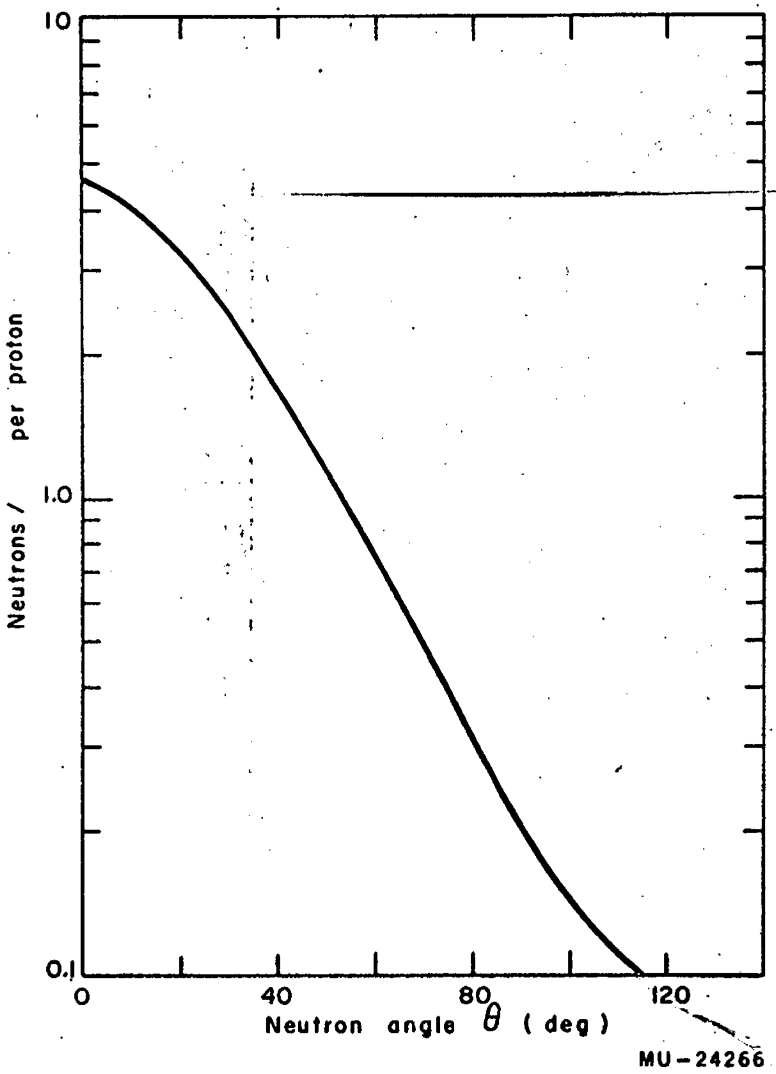

Fig. 2. Angular distribution of neutrons, over 150 Mev in energy, from 1 mfp of Cu traversed by 6.3-Bev protons.

(Integral=$2\pi \int_0^\pi f(\theta) \sin \theta d\theta$=8 neutrons/proton).

Basic Data

The following quantitative and qualitative assumptions are employed in drawing the subsequent conclusions: Except for the first, these assumptions derive from measurements and estimates made locally or from obvious calculation.

1. The high-energy neutron flux that delivers a biological dose of 1 rem is taken to be 10^7 per square centimeter. (This is conservative.)

2. The attenuation of the high-energy neutrons at minimum attenuation demonstrates a half-value of thickness of 18 in. in ordinary concrete (density 2.4 g/cm^3, or 150 lb/ft^3. For our variety of high-density concrete (3.5 g/cm^3, or 220 lb/ft^3) the half-value thickness is 12.4 in. For iron the half-value thickness is 5.5 in.

3. The build-up of neutrons of degraded energies emerging from the outer surface of the shield with the surviving high-energy neutrons amounts to a dosage increment not greater than that delivered by the surviving primary neutrons.

4. The biological dosage due to gamma radiation in the regions outside the Bevatron shield does not amount to more than 25% of that delivered by neutrons.

5. The radiation dosage due to μ mesons outside the shielding is negligible, because in material of the density of concrete (as distinguished from the atmosphere, in the case of cosmic rays) the π mesons predominantly interact before they decay.

Calculations of Shielding for Specific Target Situations

In the following examples we have attempted to select situations representative, for the most part, of familiar running conditions. In each case a beam intensity of 10^{13} protons/pulse, at 10 pulses/min, has been assumed, and a copper target 1 mfp thick has been considered.

Example No. 1

The target located in position 1 shown in Fig. 3 will deliver its forward-hemisphere neutrons through the magnet iron and the 10-ft concrete shield wall. It represents a target position for which the radiation escape is not dominated by a tangent tank area, and we inquire whether or not the concrete wall can be made solely of ordinary concrete (2.4 g/cm^3) in this case.

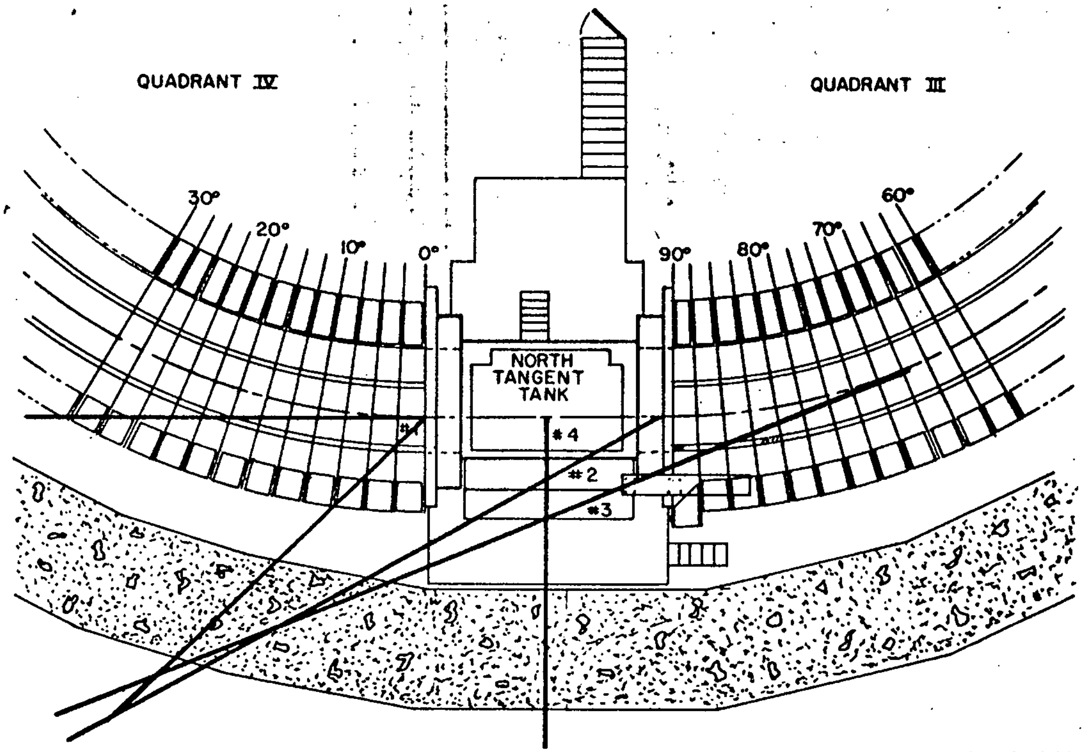

Fig. 3. Plan view of a tangent tank area, with a nominal 10-ft shield wall, showing target positions and beams here considered.

The answer is as follows: In the 0 deg direction from this target the obliquity and distance factors provide sufficient attenuation to allow ordinary concrete to be used. But for direction angles greater than 30 deg, the 10 ft of ordinary concrete is clearly insufficient; and beyond 45 deg the full 10 ft of the median course of blocks must be of heavy (3.5-g/cm^3) concrete. Even then, at 90 deg, the surviving primary flux density is calculated to be 15/cm^2 sec at the outer surface of the shield; and to this must be added an approximately equal additional exposure from the secondary neutrons and gamma rays emerging from the shielding. At 45 deg the corresponding flux density of surviving primary neutrons is 13/cm^2 sec.

Thus it is clear that the median course must be of heavy concrete in any quadrant where a target is to be placed if complete freedom of target location within the quadrant is desired.

Example No. 2

In this example we choose a situation very close to frequent practice. A target is located near the end of a quadrant, where its primary neutrons can escape through the tangent tank wall and strike the shield wall without any intervening magnet iron. The distance from the target to the point of concern is 45 ft. The oblique path length through the concrete is 15 ft. The surviving neutron flux density if the 10-ft wall is of heavy concrete is found to be 92/cm^2 sec. It is clear that we need a greater attenuation than the 10-ft wall will provide. Additional shield thickness of 27 in. of heavy concrete, or its equivalent, will be required in the region "illuminated" by the neutrons emerging through the tangent tank from this target.

Example No. 3

We place the target in a quadrant at such a point that the 0-deg neutron yield can escape through the aperture at the end of the quadrant iron and thus impinge upon the concrete shield as indicated on Beam 3 of Fig. 3. The distance from the target to the point just outside the shield is 68 ft, and the oblique path through the 10-ft concrete wall is 17.5 ft. The surviving flux density is 16/cm^2 sec for a 10-ft wall, indicating that a slightly greater thickness is required; but this need is more than fulfilled by the requirements of Example 2.

Example No. 4

In this rather unlikely case we place the copper target in the tangent tank and consider the result of the neutron flux at 90 deg directly striking the concrete wall. The distance from the target to the nearest point of exposure is 26 ft, if we consider a 10-ft wall. In this case the surviving primary flux density is $650/\text{cm}^2$ sec. The wall thickness in the 90-deg direction from this target would need to be 15 ft of heavy concrete to adequately attenuate the primary neutron flux. But since this is an unlikely target situation, and since the platforms of sufficient strength to support additional shadow shielding are provided, we consider that it is unnecessary to call for greater attenuation in the shield wall than would be provided by the 12.5 ft of heavy concrete already required by Examples 2 and 3.

Example No. 5

We consider the problem of the radiation level at a site boundary. We estimate that the worst situation will arise with a target situated at the entrance end of a tangent tank; and the neutrons that will penetrate most effectively will be those which emerge at from 45 to 90 deg from the beam direction and with an elevation angle which carries them through the minimum thickness of concrete roof near the junction between the roof and the top of the side wall. In this case there is no magnet iron providing attenuation, and only 7 ft of ordinary concrete as presently planned. We evaluate the surviving primary flux density at the project boundary at a distance of 1500 ft to be $6/\text{cm}^2$ sec.

The required limit on accumulation of not over 0.5 rem/year by a person who might live constantly at the project boundary (24 hr/day, 365 days/yr) would mean a time-average neutron flux density of $0.16/\text{cm}^2$ sec, at 10^7 neutrons/cm^2 per rem. The disparity between the calculated flux density and that nominally permitted can be reduced by the following considerations:

a. In the vicinity of the tangent tanks the roof blocks should be so designed at their outer ends as to provide 10 ft of concrete in neutron ray directions at 90 deg with respect to the beam for elevation angles up to 30 deg. This reduced the distant flux by a factor of about 4.

b. The fraction of time when Bevatron operation will involve this "worst" condition will quite certainly be less than one-third.

c. If distant measurements still indicate undesirable levels it is possible to install local shadow-shield blocks of iron at selected positions over the tangent tanks.

Consideration of Total Neutron Emission

From a distance large compared with Bevatron dimensions the accelerator appears approximately as a point source of neutrons, and the total neutron production is of concern rather than only that arising from a substantial target. Neutron-production data indicate that the average total yield of neutrons per proton of 6.3 Bev is 70. This includes all neutrons arising from both the primary collision and all secondary collisions associated with the average life history of a 6.3-Bev proton that is brought to rest in the Bevatron structure.

The spectrum of this total production will be more heavily weighted at low energies than is the distribution in Fig. 1, and some of these neutrons will be produced deep within iron or copper and will have small probability of emerging.

Nevertheless, to be conservative, we consider a production of 70 neutrons per proton with a spectrum as given by Fig. 1, and evaluate the number emerging from the top surface of the 7-ft thick roof shield. The 2 ft of iron of the top magnet yoke will also be present to attenuate the upward-moving flux.

By recourse to the angular distribution given in Fig. 2 normalized to this greater yield, and using the regular assumption of 10^{13} protons/pulse, we calculate that upward-moving high-energy neutrons emerge from the roof shield at the rate of 2×10^{9}/sec. If these were so scattered in emerging that they irradiated uniformly a hemisphere at 1500 ft, they would there produce a flux of 0.17/cm^2sec. This is felt to be a conservative estimate because of the spectrum assumption and because no advantage has been taken of oblique passage through the roof. It reveals, not surprisingly, that a thick target placed at a tangent tank can produce more severe distant fields (in a certain direction) than will arise from the total neutron ~~production~~ considered to be distributed uniformly within the orbit and under the magnet yoke. Consequently, if special target situations at tangent tanks are accommodated by specific local shielding, the 7-ft overhead roof of ordinary concrete is sufficient.

Conclusions

The foregoing results have been stated without tracing the calculational steps, in order to favor clarity of information.

The particular results to be noted are:

1. The median-plane course of blocks in the side-wall shield must be of dense concrete ($3.5\ g/cm^3$) through the full 10-ft thickness for any quadrant where a target may be located.
2. For certain target situations, where primary neutron flux escapes largely through the tangent tank walls, a supplement of 2.5 ft of heavy concrete may be required. This should be placed as close to the tangent tank as circumstances allow (usually on the platform).
3. If a thick target were operated actually in a tangent tank, further supplemental iron or concrete shielding would be required.
4. The roof blocks in the vicinity of the tankent tanks should be designed at their outer ends so as to provide a minimum of 10 ft of ordinary concrete for all ray directions in a vertical plane normal to the beam up to elevation angles of 30 deg subtended at the beam position. This is necessary to adequately shadow off-site hillside areas and certain Laboratory buildings that look down upon the Bevatron.

The foregoing estimates have involved a target thickness somewhat greater than usual. A thinner target, which would produce a more uniform distribution of neutron production throughout the accelerator, would cause the side-wall shielding to appear less marginal than it here seems to be.

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