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SHIELD DESIGN EXAMPLES - THE BEVATRON

Ralph H. Thomas

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SHIELD DESIGN EXAMPLES: PROTON SYNCHROTRONS - THE BEVATRON

1. Introduction

The earliest weak focussing proton synchrotrons were built in the anticipation of fairly moderate beam intensities, typically ~ 10^9 protons per pulse. Consequently no significant radiation hazards were anticipated, and no preliminary design considerations of shielding were undertaken. As a consequence of the early unduly pessimistic view of the probable beam intensity that could be attained with these machine, some difficulties have arisen in their use. Lofgren[1] has described graphically the consequences of leaving shielding as an afterthought.

In March, 1954, the Bevatron first achieved full energy at an intensity of 10^{10} protons per pulse and as experience developed the intensity has steadily increased. Shielding was added around the machine, but it was not possible to place shielding above the machine because of the high floor loading this would cause. Consequently it became clear that the upper operating intensity of the machine was limited to ~ 10^{11} protons per pulse simply by the radiation levels produced in the control room, experimental areas and even at the laboratory perimeter (where stricter regulations apply).

Concurrently with this intensity limitation, for reasons discussed by Wenzel[2], developed a demand for even higher beam current and the development of an external beam area. Such an improvement program necessitated drastic revision of the shielding around the Bevatron. Comprehensive surveys of the radiation field around the Bevatron[3] and measurements of the shielding properties of concrete by the LRL Health Physics Group[4] made it possible for Moyer[5] to estimate the shielding required for an improvement in beam intensity up to 10^{13} protons per pulse. A new shield which included roof shielding was designed upon the basis of these calculations.

In September, 1962, the Bevatron was taken out of operation for seven months to enable the necessary modification to be made, which included the installation of a 20 MeV linac and inflector system, provision of adequate foundations for the new shielding and installation of a beam extraction system.[6] Lofgren and Hartsough[7] have described in detail the improvements made to the Bevatron during this shut-down and Lambertson[8] has reported details of beam observations during the machine cycle. In February, 1963, the Bevatron operated at full energy with an intensity of 2 x 10^{10} protons per pulse, and this has been subsequently increased to 5 x 10^{12} protons per pulse (September, 1964.)

There has now been adequate time to assess the performance of the new shielding and make comparisons with Moyer's original estimates.

2. Brief Description of Shielding Around Improved Bevatron

Descriptions of the Bevatron have been published elsewhere,[9, 10] and the reader interested in details of construction is referred to these reports. Figures 1-4 inclusive show the shielding being installed and show in particular how the roof blocks are arranged. Figure 5 is a plan view of the shielding around the machine.

The existing shielding consists of a central wall, four feet thick, fabricated from poured concrete which lies within the Bevatron magnet. The thickness of this wall was determined by the loading of the roof blocks which are keyed into this inner wall to prevent their slipping loose during an earthquake. A concrete wall ten feet thick and sixteen feet high is stacked on the outer side of the magnet. This wall is made up from blocks four feet high, the two middle courses (centered roughly on the median plane of the machine) being fabricated from heavy concrete ($\rho = 3.5$ gm cm^{-3}) whilst the upper and lower courses are made from light concrete blocks ($\rho = 2.4$ gm cm^{-3}). Between the West and East tangent tanks, where the experimental area is situated, the median plane shielding is constructed from small blocks to enable beams to be set up. Figure 3 shows these blocks very clearly.

Long roof blocks span from the outer wall to a steel support rail, and shorter blocks cover the gap between the steel support and the "igloo" (Figs. 1, 2 and 4). The outer roof shielding, directly above the machine is in two staggered layers to prevent fast neutrons streaming along cracks in the shield wall and provides a total thickness of seven feet of light concrete directly above the magnet. The shape of the long roof blocks was determined by the necessity to ensure that neutrons emitted at elevations up to 30° had to traverse a minimum of ten feet of light concrete.

As a consequence of high neutron output at the injection area, particularly where beam strikes collimating slits, additional shielding is added in this region. A two feet thick concrete "blister" surrounds the beam chopper at the end of the linear accelerator. This shielding was based on estimates of the neutrons produced when the linac beam struck graphite beam cups,[11] from experimental data supplied by Patterson.

Access to the machine is obtained by four labyrinths shown in Fig. 5. The positions of these access points were chosen so as to as to avoid looking directly at targets or other sources of high level radiation, and they were designed to provide adequate attenuation of the neutron flux which streams down such tunnels.

3. Estimates of Shielding Required for the Improved Bevatron

Moyer[5] has outlined his calculations of shielding for the Bevatron assuming an intensity of 10^{13} protons per pulse^{-1} and these will be summarized in what follows.

There are two major sources of radiation from a weak focussing proton synchrotron:[12]

(a) Loss of high energy beam to the vacuum chamber walls after targetting or beam extraction. When internal targets are used to make scattered beams, almost all the circulating beam is lost to the walls. At present the extraction system efficiency is ~ 50% so that here the situation is slightly better. The detailed distribution of beam loss around the target depends upon many variables including target material, target position, beam dynamics, etc., and no attempt was made to study this problem in detail. (See below).

(b) When the extracted beam is used there can be a significant contribution to the radiation field from the backstop necessary to absorb the beam.

The most severe radiation hazards occur when a thick target is placed slightly upstream of one of the machine's straight sections. In this position there is no self-shielding from the magnet yoke itself. Moyer made calculations for a copper target ~ 100 gm cm^{-2} thick in four different positions. By providing shielding to handle these situations, one can be sure that less severe operating conditions will be adequately handled.

Moyer estimates that primary proton interactions in a thick copper target produce about 20 neutrons per proton and Fig. 6 shows their energy spectrum. This energy spectrum is derived by Moyer from cosmic ray information, experiments at the Bevatron and Monte Carlo calculations by Metropolis et al.[13]

Measurements of neutron attenuation at Berkeley and elsewhere have been summarized by Knowles[14] and show that the attenuation cross-sections become essentially constant at their minimum value above 180 MeV. As a consequence, the shielding thickness is determined by the neutrons above about 150 MeV, the much higher yield of lower energy neutrons being more than compensated by the shorter attenuation lengths appropriate to these energies. Figure 6 indicates that 8 neutrons ($E > 150$ MeV) are produced by 6.3 GeV neutrons incident upon a thick copper target. From the Metropolis calculations Moyer infers the angular distribution of neutrons of energy greater than 150 MeV, and this is shown in Fig. 7.

Basic Assumptions Used in the Calculations

(a) Beam intensity of 10^{13} protons per pulse; machine repetition rate of 11 pulses per min.

(b) Attenuation length of high energy neutrons was taken as 160 gm cm^{-2}, which corresponds to the following half value thicknesses:

Ordinary concrete	(ρ = 2.4 gm cm^{-3})	18 in
Heavy conctete	(ρ = 3.5 gm cm^{-3})	12.4 in.
Steel	(ρ = 7.8 gm cm^{-3})	5.5 in.

(c) Outside the shielding the biological dose due to low energy neutrons is not greater than that due to the surviving "primary" neutrons. (See below).

(d) The biological dose due to γ-rays is not greater than 25% of the dose from neutrons.

(e) The biological dose from μ-mesons may be neglected.

(f) 10^{7} high energy neutrons cm^{-2} are taken to be equivalent to 1 Rem. (This is conservative, but see below.)

A brief comment on these assumptions is in order in the light of more recent data. Moyer assumed that "the buildup 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."--Assumption (4). Detailed measurements of the neutron spectrum outside a thick concrete shield around high energy proton accelerators have not been made. However, it is plausible to assume a cosmic ray like spectrum on the basis of nucleon cascade calculations by Aismiller, et al.[15] Such an assumption is supported by determinations of the biologically effective mean energy as

about 1 MeV.[16] Hess, et al[17] have made measurements of the cosmic ray spectrum at various altitudes and Patterson, et al[18] have computed the dose deposited as a function of neutron energy from these results. This was done by folding the measured neutron spectrum with the curve of the flux of the neutrons which deposits 100 millirem/40 hour with energy.

Since concrete and air have similar nuclear properties, the contribution to neutron dose as a function of energy outside a thick concrete shield should be very similar to that for a cosmic ray spectrum. About 50% of the total neutron dose is deposited by neutrons below 2 MeV, about 80% by neutrons below 20 MeV and 90% by neutrons below 150 MeV.

Handbook 63 of the National Bureau of Standards[19] summarizes the maximum permissible flux that will deliver 0.1 rem in 40 hours. No official recommendation for maximum levels exists above 30 MeV, but Neary and Mulvey[20] have made estimates of the dose deposited in tissue by neutrons of energy between 40 MeV and 1 GeV. At 10 MeV and 30 MeV the N. B. S. data give 2.4×10^7 n cm^{-2} and 1.4×10^7 n cm^{-2} as equivalent to 1 Rem. At 110 MeV Neary and Mulvey estimate 0.9×10^7 n cm^2 ≡ 1 Rem.

Implications of Assumptions

If the total dose is written as the sum of the three components of the radiation field considered, we have:

$$D = D_f + D_s + D_\gamma \qquad (1)$$

D_f = dose due to fast neutrons (fast defined as $E > 150$ MeV in this case)
D_s = dose due to slow neutrons (defined as $E < 150$ MeV)
D_γ = dose due to γ rays.

Assumption (d) requires $0.75\ D = D_f + D_s$. Since $D_s = 9\ D_f$ (see footnotes to basic assumptions), Eq. (1) becomes:

$$D_f = 7.5 \times 10^{-2}\ D \qquad (2)$$

Since we take 10^7 n cm^2 ≡ 1 Rem and the maximum permissible dose in a 40 hour week is 0.1 Rem, the maximum permissible fast ($E > 150$ MeV) neutron flux is then:

$$\Phi_f = \frac{10^6 \times 7.5 \times 10^{-2}}{40 \times 3600}$$

$$= \underline{\underline{0.52 \text{ n cm}^2 \text{ sec}^{-1}}} \qquad (3)$$

Method of Calculation

Assume a beam intensity of i protons per pulse, with a machine repetition rate of f cycles sec^{-1} strickes the target T. Let $g(\theta)$ be the differential cross-section for production of neutrons with energy greater than 150 MeV. Then the number of neutrons, dI, scattered into solid angle $d\Omega$ at an angle θ to the initial beam direction is:

$$dI = f.i\ g(\theta)\ d\Omega \qquad (4)$$

and the neutron flux at p distance r from the target with no shield is:

$$\Phi = \frac{dI}{dA} = \frac{f\ i\ g(\theta)\ 2\pi \sin\theta\ d\theta}{2\pi r^2 \sin\theta\ d\theta}$$

$$= \frac{f\ i \cdot g(\theta)}{r^2} \qquad (5)$$

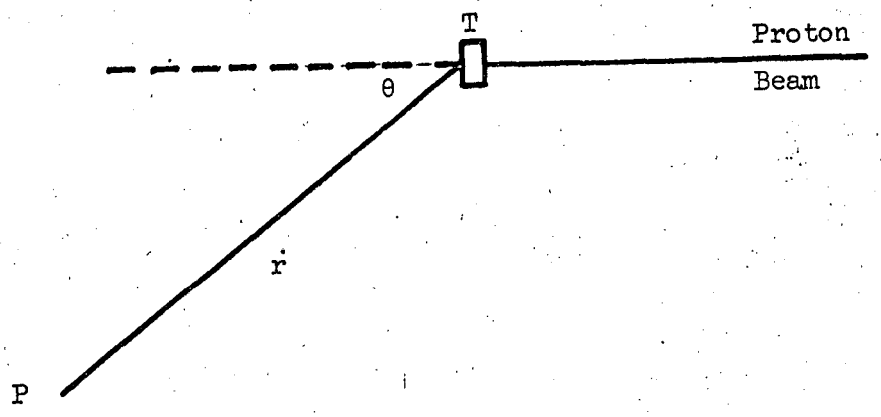

Figure 8.

The flux at P with a shield thickness t is then:

$$\Phi = \frac{g(\theta)\ f\ 1}{r^2} \cdot e^{-\frac{t \sec \theta}{\lambda}}$$

where λ is the attenuation length of neutrons with $E > 150$ MeV. Moyer made estimates of the shielding required in four different target situations, and these examples are quoted directly from UCRL-9769.

"Example No. 1

The target located in position 1 shown in Fig. 9 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/cm3) in this case.

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 of 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. 11. 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 $650/cm^2$ 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."

Finally Moyer made estimates of the neutron fluxes that would be observed at the boundaries of the laboratory, approximately 1500 ft from the Bevatron. With a target situated at the entrance end of the tangent tank, neutrons emitted between 45° and 90° to the beam direction could penetrate the minimum thickness of shielding near the junction of the roof blocks and the side wall. With only 7 feet of overhead shielding Moyer estimated the surviving primary flux at the project boundary is $6\ n\ cm^{-2}\ sec^{-1}$, a factor ~ 36 too high if the Bevatron were to operate entirely at 10^{13} proton per pulse. As a consequence, Moyer recommended that roof shielding at tangent tanks should be increased so as to provide at least ten feet of concrete in neutron ray directions at 90° with respect to the beam for elevation angles up to 30°. Measurements

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* N. B. At the time of these calculations were made this was in fact an unlikely situation. The two plunging magnets of the beam extraction system described by Wenzel[6] intercept the circulating beam and effectively act as thick targets. Measurements of the radiation levels above the s and w tangent tanks indicated the need for additional shielding as predicted by Moyer. It is intended to install this.

of the neutron flux observed at the laboratory boundary would indicate whether further shielding should be installed above tangent tanks.

A calculation of the neutron flux observed 1500' away from the Bevatron due to uniform beam loss indicated levels ~ 0.2 n cm^2 sec^{-1}, showing that thick targets placed in the tangent tank are the major source of large radiation fields at large distances.

Performance of the Bevatron Shielding

Since February, 1963, extensive data has been compiled on the radiation field around the Bevatron. Both the Health Physics and Bevatron operations groups cooperate in radiation surveys, much of their data being summarized in the Bevatron Operation and Development Reports issued quarterly.[21, 22, 23]

Many of the experimental techniques used to study the radiation fields have been described elsewhere.[3, 24, 25] Thermal neutron fluxes are measured by indium and gold foil activation and bare BF_3 counters. "Fast" ($E < 20$ MeV) neutron fluxes are determined by activation of threshold detectors,[26] paraffin-wax moderated BF_3 counters and indium foils[27, 28] and moderated silver-lined geiger counters. γ-ray levels are measured by conventional ionization chambers. These techniques used are extremely effective in measuring the γ-ray levels and the dose levels from neutrons below 20 MeV. Convenient and reliable techniques for measuring the dose from neutrons greater than about 20 MeV have not yet been developed. However, since the measurements of dose from γ-rays and neutrons below 20 MeV account for about 90% of the total dose, no large innaccuracies of dose estimates result from poor knowledge of the high energy flux ($E > 20$ MeV). Very similar conclusions have been reached at CERN[29] around the PS and at Brookhaven around the AGS[30]. Occasional checks on the high energy particle flux may be made using a bismuth fission counter[31] of by exposing nuclear emulsions but this technique is rather tedious. Such measurements have always confirmed the conclusions already reached.

It is clear that any comparison of experimental data with calculations is somewhat difficult. Calculations are made for idealized conditions which are not even approximated in practice. It is extremely hard to evaluate the effects of neutron streaming along entrance tunnels, back scattering from the experimental area and machine building and leakage

from cracks or holes in the shielding. Another difficulty is that the sensitivity of the wax moderated indium foil detectors falls off at energies greater than about 15 MeV. Consequently exact comparison of calculations and measurements is not possible. However, the results of surveys taken to date are encouraging in tending to confirm the calculations of Moyer.

Figure 12 shows a plan view of the Bevatron building and the experimetnal layout during the period July through September, 1963. The circled numbers indicate positions where the radiation field was monitored. Figure 13 summarized the measurements of neutron flux and γ-ray dose rates measured at these positions. Curve 1 shows neutron fluxes measured with a circulating beam of 5×10^{11} protons per pulse at an energy of 4 GeV. Approximately 90% of the beam was taken by the Moyer group target when these measurements were made. Curve 2 shows measurements when a circulating beam was $\sim 5 \times 10^{10}$ protons per pulse and $\sim 5 \times 10^{7}$ protons per pulse were extracted and dumped in the Chamberlain group backstop.

The lowest neutron levels observed are about 0.35 n cm^{2} sec^{-1} (neutrons of energy $\leq \sim 15$ MeV) with a circulating intensity of 5×10^{11} protons $pulse^{-1}$. If we assume a 1/E spectrum, this would imply a flux of ~ 0.15 n cm^{2} sec^{-1} for neutrons $E > 150$ MeV, which is in good agreement with Moyer's estimate of 0.14 n cm^{2} sec^{-1}. In fact, such good agreement is probably fortuitous but does indicate that the calculations agree with the measurements within a factor of say 2-3. Estimates of the mean neutron energy indicate it to be about 1 MeV.[16]

Neutron levels are higher in the experimental area ranging between 1-10 n cm^{2} sec^{-1}, but these fluxes almost certainly arise from the experiments themselves.

The neutron fluxes at the entrance to the machine labyrinths are also, not surprisingly, higher than adjacent areas.

Curve 3 (Fig. 13) shows the γ-ray intensities which are always less than 1 mr hr^{-1} with the exception of the region close to the injector. Here the X-ray level can be as high as 60 mr hr^{-1} at the surface of the injector tank. γ-ray levels between 0.1 and 1 mr hr^{-1} observed in the experimental area are due to (n, γ) capture processes in the shielding and floor. Assumption (d) (Paragraph 3) is validated by these measurements.

Pick, Everette, et al[32] have made an interesting comparison with measured fluxes and those calculated using Moyer's method above a copper target. Four feet of heavy concrete and 20 inches of steel were placed above the target. They concluded that in regions free of back scattering from a nearby back-stop that the measured fluxes agreed within a factor of three of those calculated.

No detailed measurements have yet been made of the neutron flux at large distances from the Bevatron, but neutron counters used to integrate dose levels at the laboratory perimeter have indicated values well below maximum permissible levels for members of the general public.

An extensive series of measurements was started early in 1964 to determine the performance of back-stop shielding. A large concrete back-stop 28 feet long and 21 feet wide was constructed and measurements of the neutron flux made at varying depths in the concrete.[33] At beam intensities of 8×10^{10} protons per pulse the neutron fluxes measured at the edge of the back-stop indicated the back-stop to be just a little "thin" at the sides and that increasing the dimension to 28' long by 24' wide would give levels below m.p.l. all around the back-stop.

Acknowledgements

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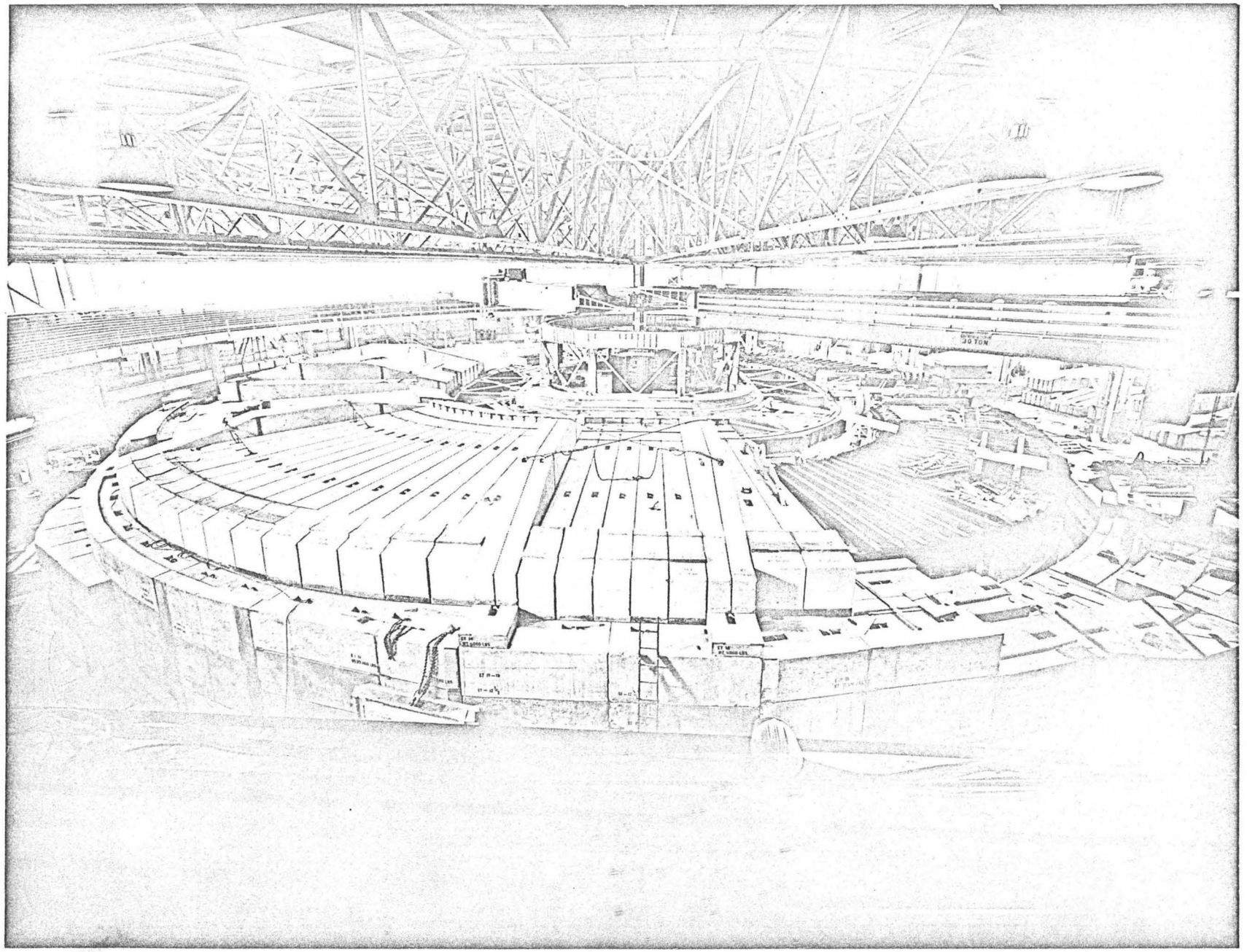

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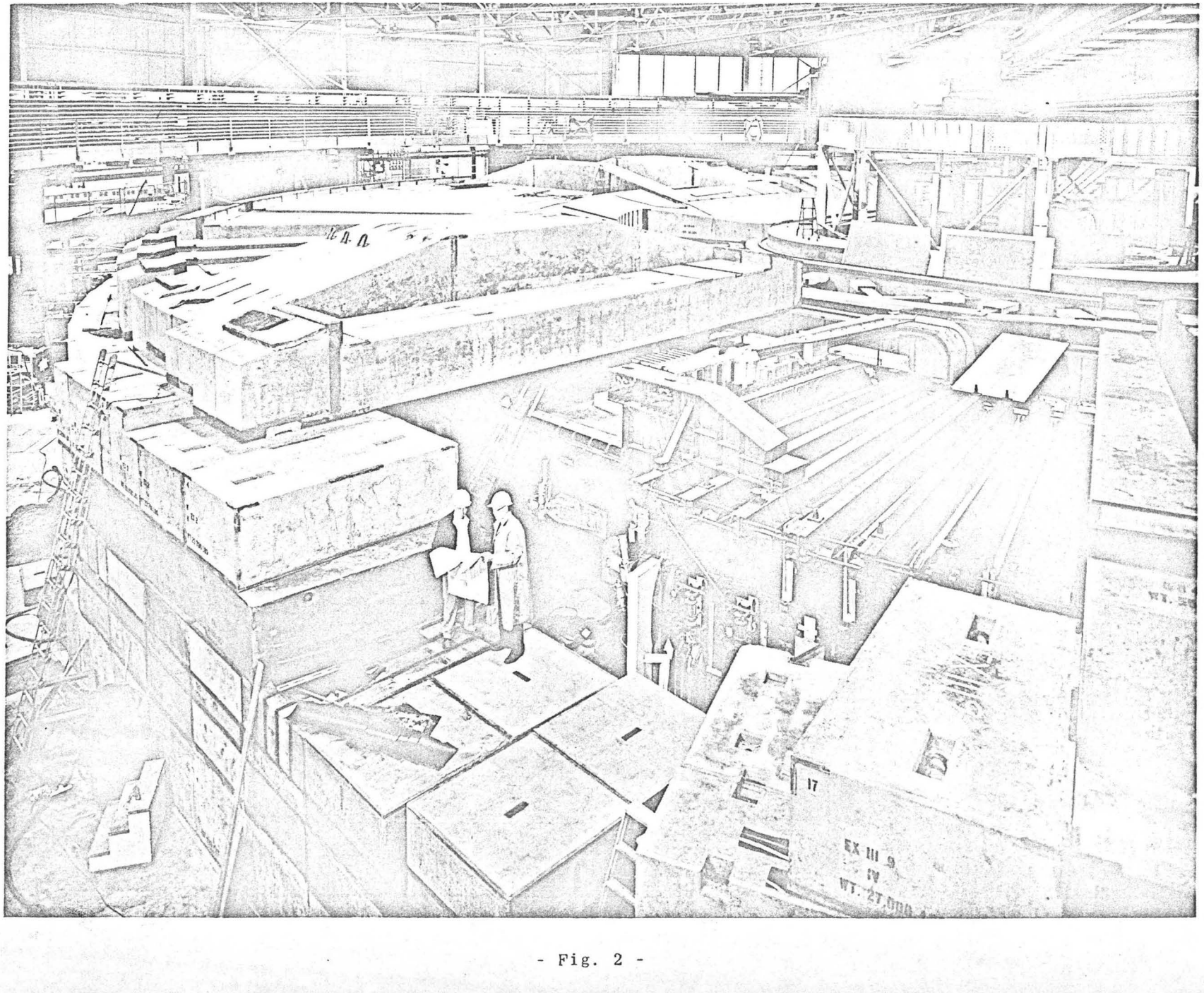

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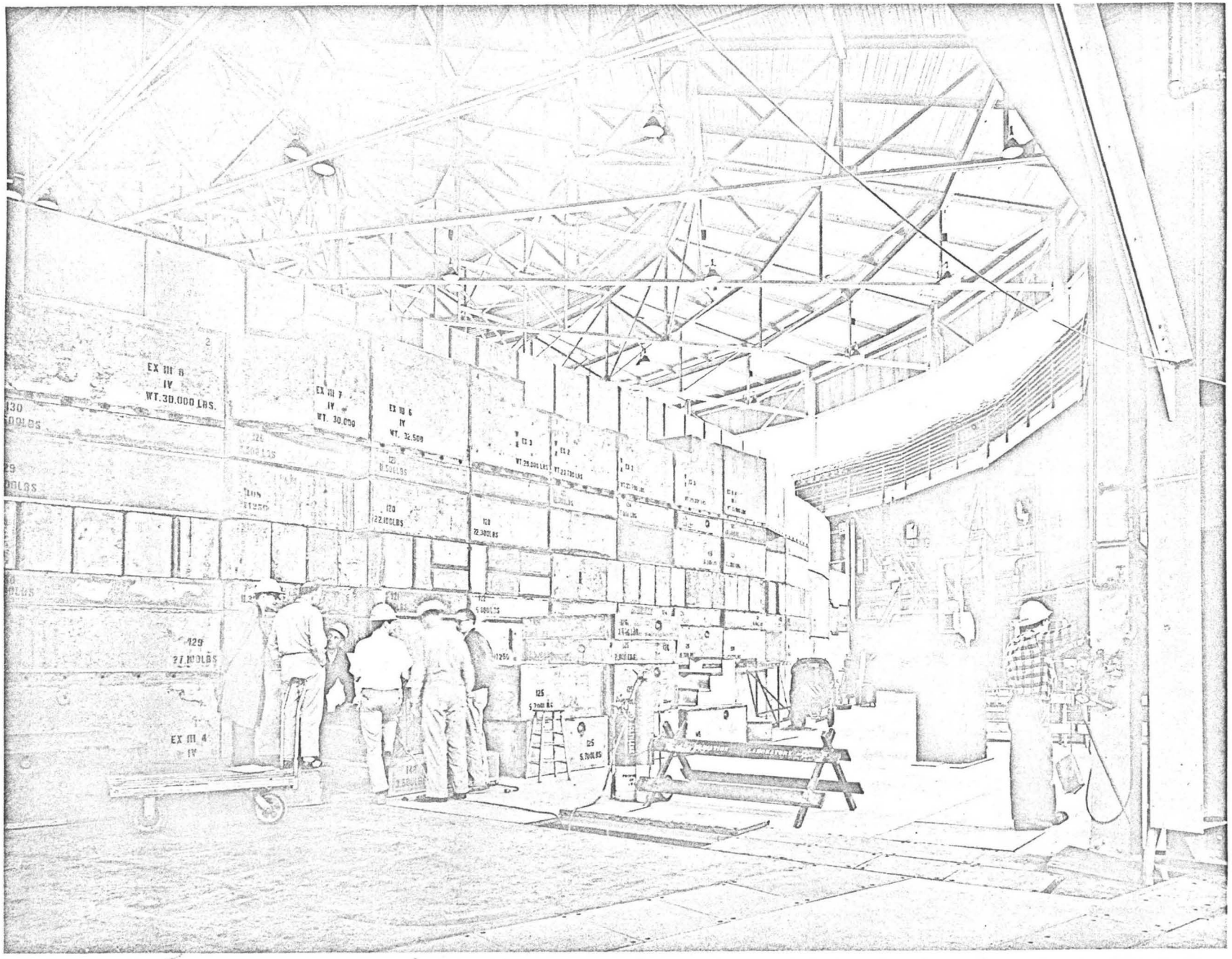
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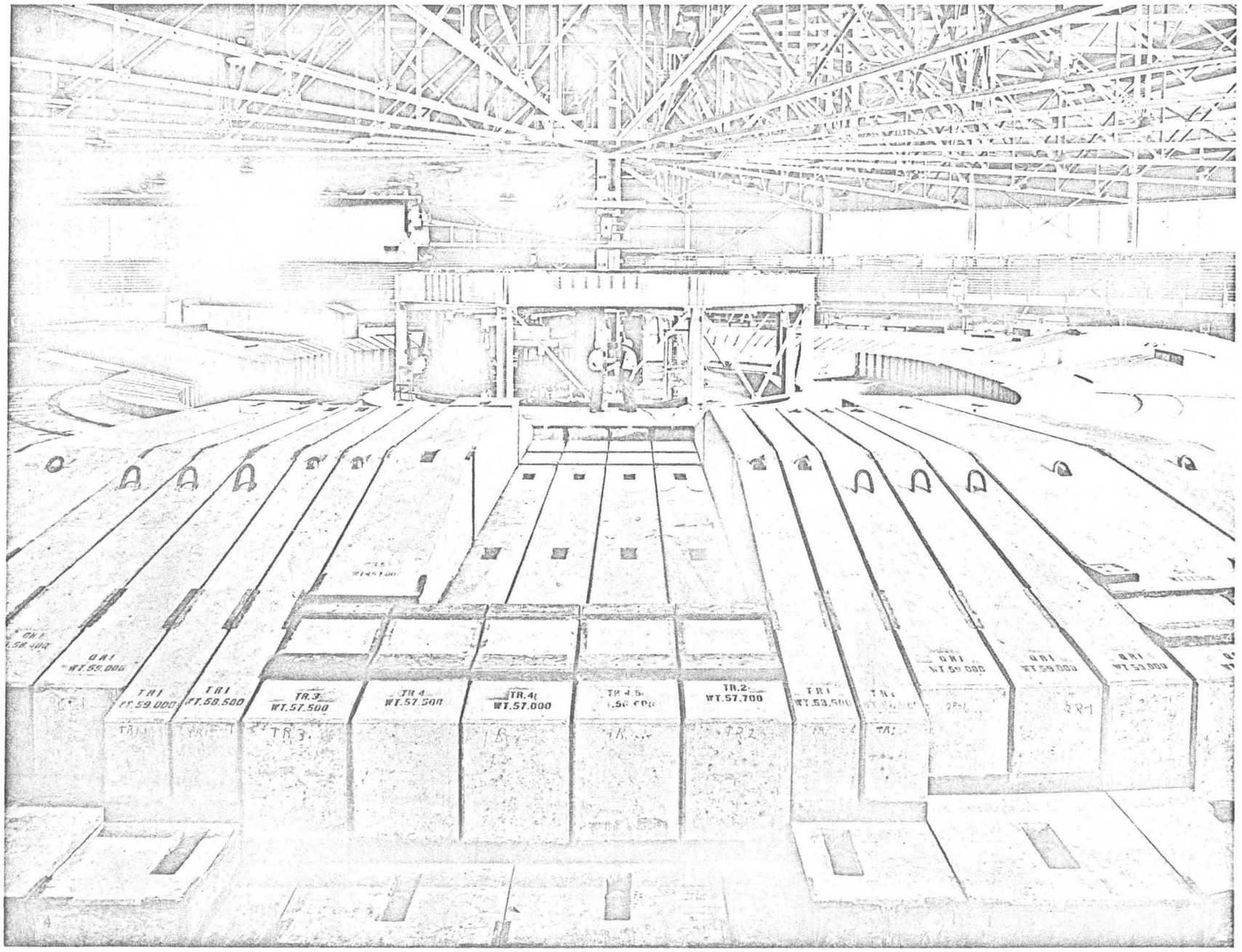
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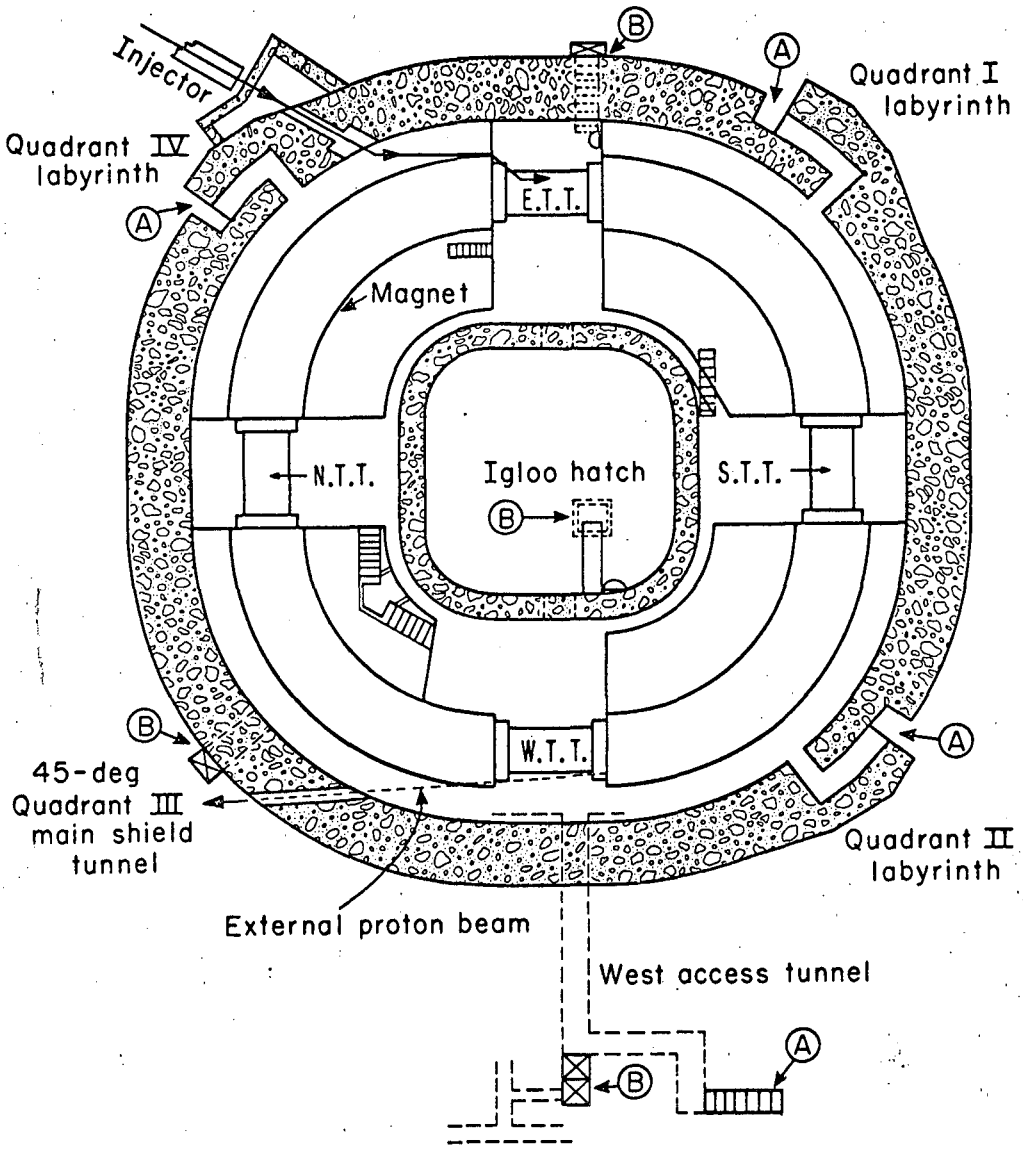
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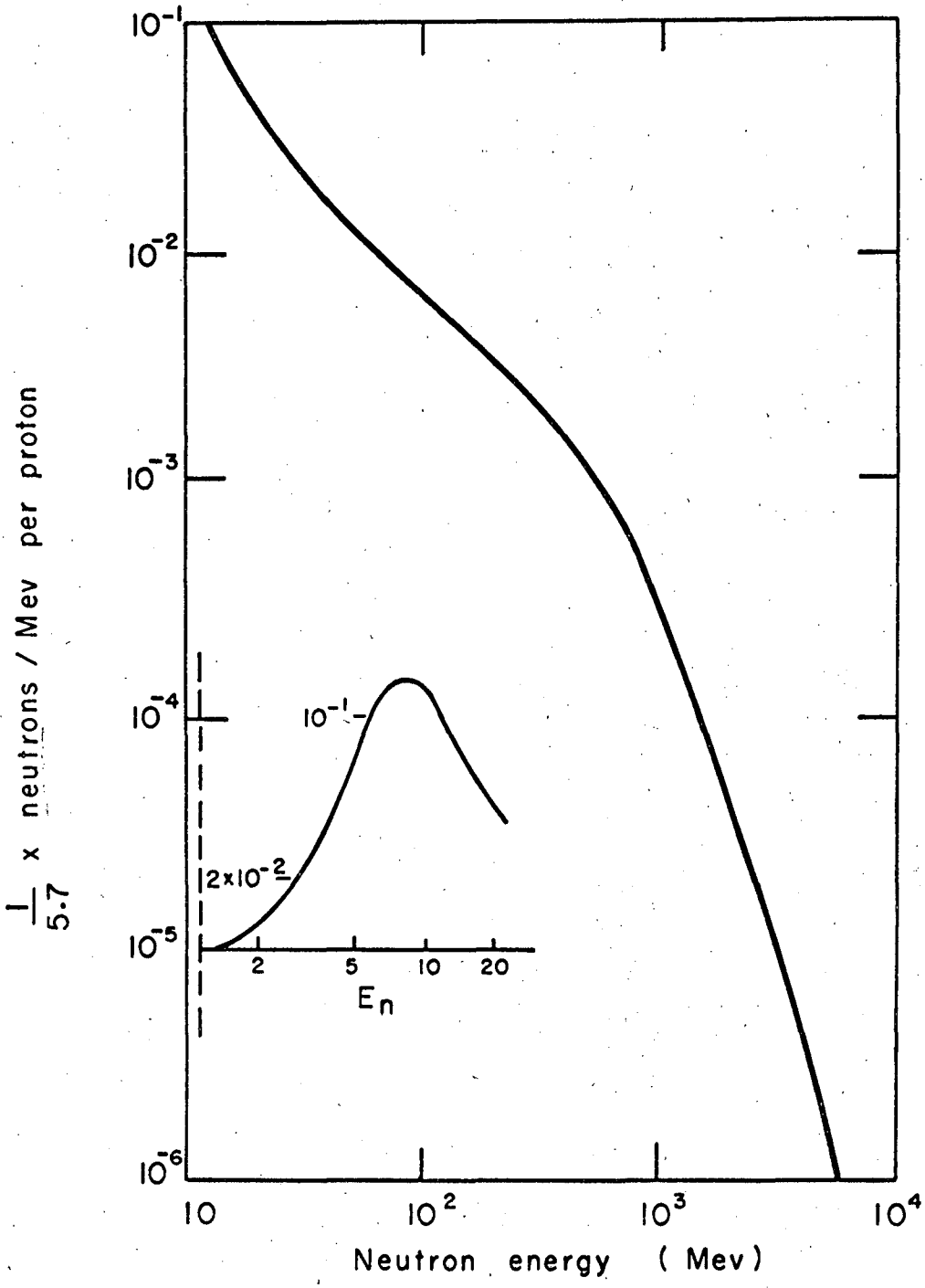
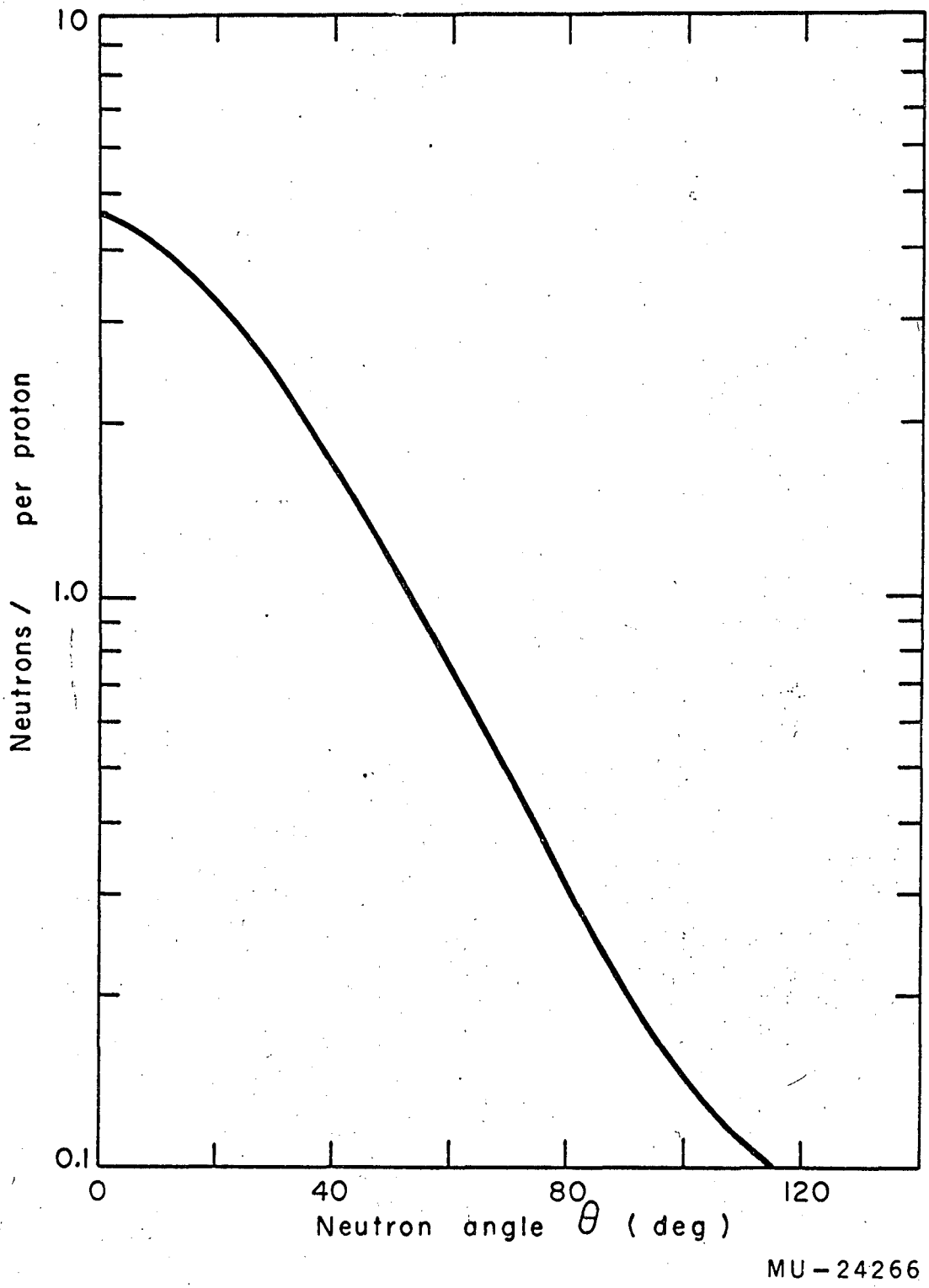
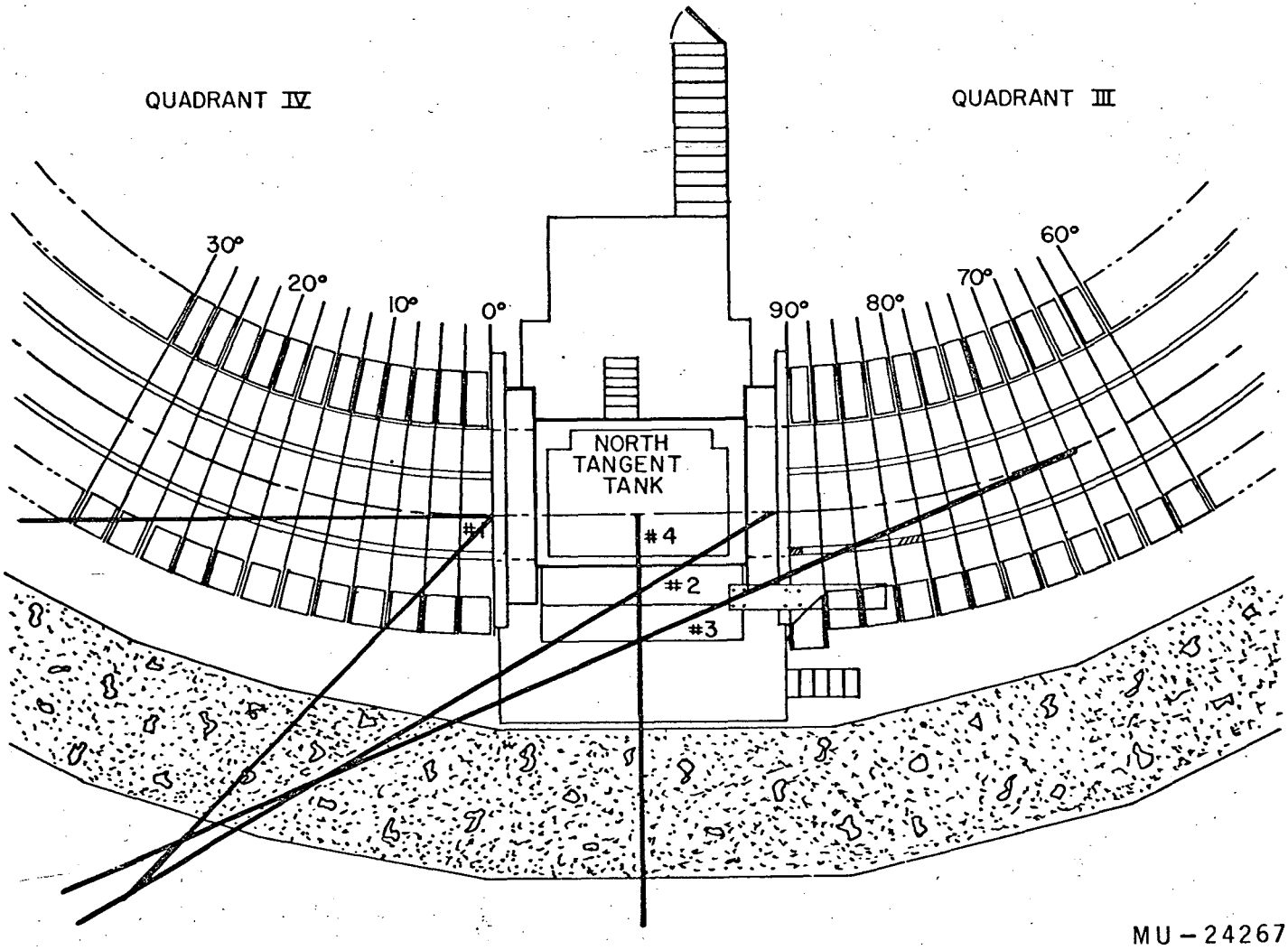


Neutron-emission spectrum from 1 nuclear mfp of Cu traversed by 6.3-Bev protons.
(To obtain neutrons/Mev per proton, multiply ordinate by 5.7.

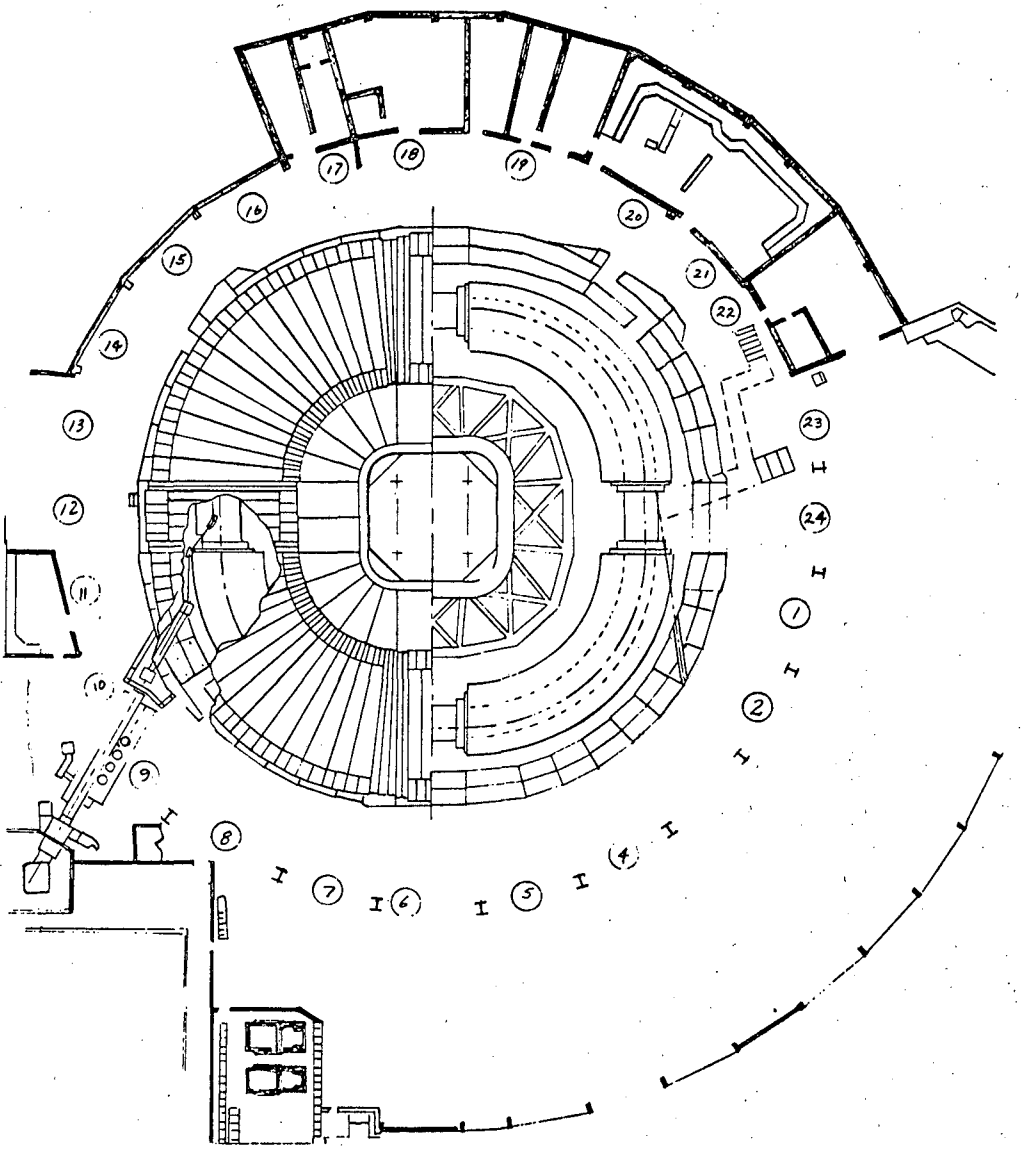
MU-24265


10
1.0
0.1
Neutrons / per proton
0
40
80
120
Neutron angle θ (deg)
MU-24266

- Fig. 7 -

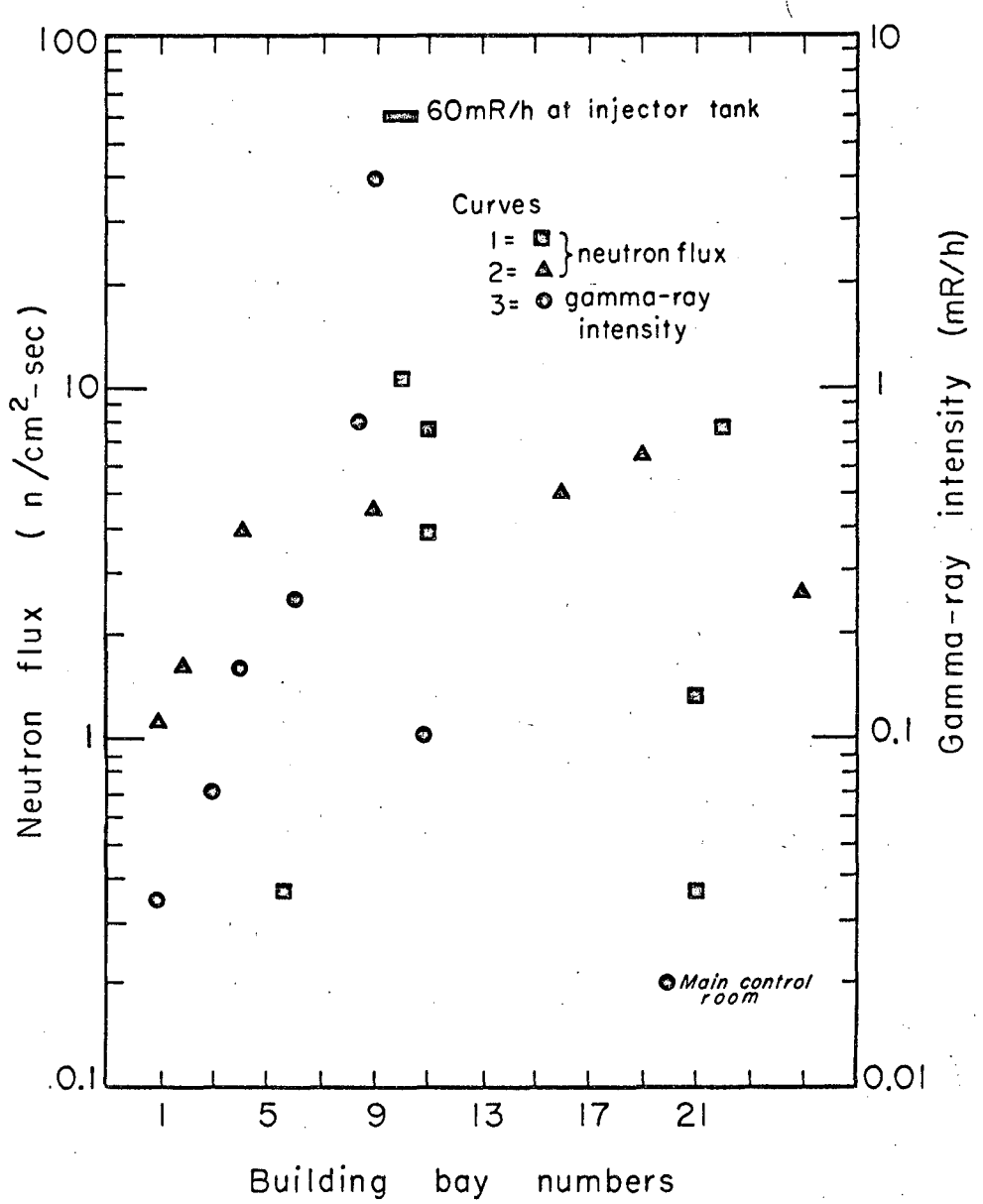


Plan view of a tangent tank area, with a nominal 10-ft shield wall, showing target positions and beams here considered.



MUB-2827

- Fig. 10 -



MUB-2863

- Fig. 11 -