SHIELDING AND EXPERIMENTAL LAYOUT

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The beam current from the high intensity, 500 Mev to 1 Bev, linear accelerator, indicated in the preceding reports, will be a factor of 1000 times greater than that of any previous accelerator. This introduces special shielding problems and, therefore, this has been considered as part of the Yale Design Study of Linear Accelerators. In one respect, the problem is simplified because such necessary measurements as neutron production in targets and attenuation in shielding have already been made for beam energies below 1 Bev. The shielding is, in principle, calculable.

The tolerance for on-project workers was set in 1957 at, in effect, 100 mrem per 40-hour week. The permissible fluxes of neutrons, gamma rays, and four kinds of mesons (π^+, μ^+, π^- and μ^-) which will give this permissible dose rate are shown in Fig. 1. The permissible neutron flux for neutron energies up to 10 Mev or so had been calculated by a variety of workers, and it was assumed that higher energy neutrons would have the same permissible flux, roughly 15 neutrons/cm^2-sec, as did 10 Mev neutrons (indicated by the dotted line). However, recent work by Neary, Gibson, and others takes into account the so-called intranuclear cascade effects of the higher energy neutrons. That is, the spallation process, in which a high energy neutron strikes a nucleus in the body and liberates a number of lower energy nucleons and pions, perhaps four or five fast particles in all. It was concluded that the permissible fluxes must be reduced in such a way that at a neutron energy of 1 Bev it will take a flux of only about 1 neutron/cm^2 to produce

100 mrem/40 hours. The cascade process is of the utmost importance in shielding work; it is the process by which the high energy neutrons are produced in the target and also the process by which they are attenuated in the shielding walls.

The gamma-ray curve is taken from the Los Alamos Handbook of Radiation Monitoring; gamma-ray dose rates are about the best understood of any of those.

With regard to the (approximate) curves for the meson fluxes, acknowledgment is made of the assistance of Dr. F. Hutchinson of the Yale Biophysics Department and of the work that was done on this by P. Kitching, B. Murphy and E. Yarosh. The curves are for generalized tissue, not the eyes, for example. This is also the case for the neutrons. All permissible meson fluxes increase sharply at 100 Mev. This is the energy of a meson which does not stop in the thickness of the human body, taken to be 30 cm on the average. The low energy μ^+, π^+ and μ^- mesons represent a gradual increase in rate of damage, while the π^- mesons of energies below 100 Mev are the most dangerous of all. This is because stopping mesons cause reactions of the following kind in the body tissues:

$$\pi^- + C^{12} \longrightarrow 2\alpha + 3n + p$$

$$\pi^- + O^{16} \longrightarrow 3\alpha + 3n + p$$

$$\longrightarrow C^{12} + 3n + p$$

and create a high ionization level near the point of stopping because of the low energy α particles and heavy fragments.

It is difficult to relate these to permissible body burdens of α emitters, because most of the latter are "bone seekers" and do the damage inside the skeletal structure. It is thought that π^- mesons stopping in bone give reactions of the following kind:

$$\pi^- + Ca \longrightarrow Ca^* + \quad (3 \text{ to } 4 \text{ neutrons}) .$$

This is based on the meager data available from π^- stars in emulsions, in which, other than those with the light nuclei (C,N,O), there are only π^- reactions with silver and bromine available for examination. These emit neutrons upon π^- absorption and it is assumed here that the intermediate nuclei such as calcium do the same. Apart from the health physics application, π^- induced nuclear reactions are an interesting class of experiments which have not been done very extensively up till now. High energy $\pi^\pm$ mesons may in fact have a slightly lower permissible flux than high energy $\mu^\pm$ mesons because of their inelastic reactions, which will tend to reduce their permissible fluxes in the same way that neutron fluxes were reduced.

The present interest here in meson damage is because some high meson fluxes will intentionally be directed through the shielding walls and, further, they come out of the shielding as a result of the intranuclear cascade process (except for the μ^-). The meson fluxes may also prove useful in biophysical and therapeutic applications and are, in addition, of some interest in space medicine.

To estimate the shielding needed, it is necessary to determine how many neutrons are produced. The total number produced from a hypothetical "Cu^{64}" beam stopper per incident proton stopped is shown in Fig. 2. This includes primary and secondary reactions (the inelastic mean free path is between one-half and one-fourth the range of a high energy proton, so more than one reaction is possible per proton). The neutrons are divided into "cascade", that is, directly ejected, and "evaporation", that is, delayed neutrons. The latter have energies of less than 30 Mev or so because it will turn out that a few of the highest energy neutrons control the shielding thickness. The cascade neutron yields were calculated from the theoretical work of Metropolis and collaborators and the evaporation neutron yields from the work of Dostrowsky and coworkers. The neutron yield curves can be used as a range-energy curve. If a certain amount of energy is lost in a copper target an equivalent number of neutrons will be produced per proton penetrating the target, and these curves, so applied, agree (within the experimental error) with some total neutron yield data taken at 340 Mev by Crandall, Millburn and others for copper targets which are less than one proton range. This improves confidence in the neutron yield calculations. No nucleus other than copper has been thoroughly treated theoretically for both cascade and evaporation, but it is taken as reasonably representative of the class of medium weight nuclei, and not too different from light nuclei for cascade yields.

In order to form a rough estimate of the number of high energy neutrons produced by a beam of certain current and energy, it should be noted first that the spectrum of the cascade neutrons is approximately an exponential if the angular distribution is neglected. Actually, the high energy neutrons are projected strongly forward and a correction must be included later for that effect. The attenuation of neutrons of energies between 1 and 10,000 Mev (in half-intensity thicknesses) in ordinary concrete (2.3 gm/cm^3) is given in Fig. 3. The half value thickness flattens off above 300 to 400 Mev at about 18 inches. One experimental point obtained at CERN for 20 Bev is shown which is a little lower, i.e. 16.4 inches, but it is heavily outweighed by the other data and calculations. The value of 18 inches corresponds rather closely to a one-tenth intensity thickness of 5 feet; it is clear that it is the higher energy neutrons that determine the amount of shielding needed. A one milliampere, 800 Mev proton beam will produce on stopping,

$$(6 \times 10^{15} \text{ protons/sec}) \times (\sim 2 \text{ cascade neutrons/proton})$$

$$\cong 1.2 \times 10^{16} \text{ neutrons/sec}$$

Of these perhaps 10% will be above 300 to 400 Mev. If isotropy is assumed, as a first approximation, this means a high energy neutron source intensity, arising from completely stopping the beam, of

$$\frac{1.2 \times 10^{16} \times 0.10}{4\pi} \cong 10^{14} \text{ high energy neutrons/sec-steradian.}$$

Someone standing 10 meters from this source will receive a high energy neutron flux of the order of

$$\frac{10^{14}}{(10^3)^2} \; \frac{\text{neutrons/sec}}{\text{cm}^2} \cong 10^8 \text{ neutrons/sec-cm}^2$$

A person should not be receiving more than about 10. Because an attenuation factor of 10^7 is needed, it is necessary to provide for shielding corresponding to 35 feet of concrete. This estimate is exactly that given by R. Wallace for a typical meson factory isochronous cyclotron, which is in fact a more truly isotropic source, because of the diffuse way the unextracted proton beam would be lost.

The estimate by R. Wallace was really done for a 100 microampere cyclotron, so one would expect a thickness of 30 feet. The <u>five</u> additional feet of concrete represents just about that additional factor of ten recommended by S.J. Lindenbaum over and above the amount needed to reduce the high energy neutron flux to its permissible level, in order to remove the protons, low energy neutrons and mesons produced by the high energy neutrons as they are attenuated by cascade processes in the last few feet of shielding. A recent calculation by Alsmiller et al. at ORNL confirms the persistence of these equilibrium particles in thick shields. So perhaps one should think in terms of 40 feet of concrete, or its equivalent.

The low energy neutrons do not get out of the shielding. Instead, they create another problem by activating almost any type of construction material put inside the area in which the beam is stopped: concrete, iron, aluminum or copper. Copper is in a way particularly bad; it undergoes two reactions, Cu^{65} (n, 2n) Cu^{64} and slow neutron capture by Cu^{63} leading to Cu^{64}. This,

Cu^{64}, has a half life of something like 6 hours. It should be emphasized that activation is a problem which becomes really serious when beam currents are increased to the order of magnitude indicated in the foregoing, although it has always existed in accelerators in this energy range.

The gamma levels, in milliroentgens per hour, arising inside a concrete room of dimensions 10 x 10 x 10 meters^3, in the middle of which the full 1 ma, 800 Mev beam has been stopped for 5 hours, are shown in Fig. 4. Some of the activities, notably those from silicon and oxygen, decay rapidly. However, the 4% of aluminum and the 1% or so of iron in the concrete* give some very nasty long-lived activities; the aluminum, in particular, has undergone the reaction Al^{27} (n, α) Na^{24}, with Na^{24} having a 15 hour half-life. The dose rate is pretty close to 1000 mr/hour inside the room from the Na^{24} alone. It should be stated that this may not be all of the activation. No data on the neutron activation cross section of calcium were available, for instance, and there is quite a lot of calcium in concrete. So the gamma ray background may be even higher than indicated.

For this reason alone, it seems better to produce the secondary beams in one area, using a thin target, and stop the beam in another enclosure, well isolated from the first, with limited access. This is advantageous because high energy π mesons have absorption mean free paths of the order of 100 g/cm^2 and targets of the order of 10-20 gm/cm^2 (as indicated by W.A. Blanpied in the preceding report) will give yields almost as high as thicker targets because of absorption. Further, at the same time the neutron production in the target area will be reduced, to the order of a few percent of the total, consequently the walls can be made thinner, thereby improving the efficiency of extraction of pions slightly and improving the ratio of

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*The composition was taken from the table of gamma ray attenuation coefficients by Gladys White and Goldstein.

meson to neutron flux by a large factor. Of course, for the same reason, the activation is reduced to a few percent of that shown in Fig. 4 and the room can be entered right after the beam is turned off.

These considerations are all involved in designing an experimental area. A second approximation to a useful experimental area is shown in Fig. 5. An earlier design is indicated in the previous report by W.A. Blanpied. In addition to the "target room" and the "beam stopping room" a new feature has been included, the so-called "meson gallery". This is oriented at 90° to the axis of the beam, and the mesons are directed into it achromatically by bending through two 45° wedges, separated by a distance of two times the mean bending radius. Such a system can be made to focus on the target both vertically and horizontally and to put out a parallel achromatic beam which will have an energy spread of perhaps 20% full width with reasonable apertures. This is a value approximately twice as large as that used by W.A. Blanpeid in the preceding report. To obtain an efficient μ beam, resulting from the π decay, it is desirable to have a large energy spread in the π mesons. The energy spread of the μ mesons from decay in flight is broad by itself and one would like to collect as many μ mesons as possible and then analyze for a specific energy later. The μ pipe is shown as a quadrupole-focused pipe, although it is not certain that quadrupoles would be used, because these have a poor angular acceptance, it goes to zero periodically. Therefore, doing so, there will be a low energy μ meson beam and a high energy μ beam transmitted, losing primarily those of large angle and intermediate energy. A long quadrupole system acts, in effect, as a "high momentum pass filter" so that the low energy μ mesons which are acceptable in angle will not be stable in such a system and will be lost. For lower energy π and μ beams consideration has been given to solenoidal focusing, which is achromatic and has a better angular acceptance, although it becomes very expensive in terms of power.

It is indicated that the μ pipe can be "tapped" at various positions for extracting mesons. Neutrino experiments would be done at the end of the long μ pipe, if proven feasible. A "neutron room" is shown in Fig. 5; it is believed that an excellent neutron beam can be obtained from the accelerator under consideration. Perhaps time-of-flight analysis could be done, because a relatively high frequency will probably be used in the last sections of the accelerator. For example, a maximum time uncertainty of the order of 10^{-10} seconds would exist for 1200 Mc/s.

The iron in the shielding walls may be used to replace quite a lot of concrete, because it is about 3 times as dense as concrete. However, the external part of this wall must still be about a one-tenth-intensity thickness (5 feet or so) of concrete or other low Z material, preferably hydrogenous, in order to stop the low energy secondary neutron flux generated in the iron by the cascade process. Iron, by itself, will not do the job; below a certain energy, the neutrons are transmitted by elastic scattering and lose very little energy per collision. The side wall of the target room, as shown in Fig. 5, which is normally 30 feet of concrete (reduced from the 35 feet needed on the side of the beam stopping room because of the lower neutron production), is replaced by about 8 feet of iron and 5 feet of concrete, with an additional foot of interior concrete facing to reduce activation. The wall thickness has been reduced by a factor of only two through the use of iron.

On the other side of the experimental area other features might be installed as needed, another meson gallery, possibly a medical cave. Further, in order to deal with the proton beam itself, a parallel achromatic translation system might be included and also a room for polarized proton experiments when the polarized source is installed.

It is apparent that the shielding must be largely installed before the accelerator can be run at full beam. Therefore, careful consideration of this problem at an early stage of the design study is important.

Discussion

R.B. Neal (Stanford): Did you take the neutron production anisotropy into account?

H.B. Knowles (Yale): Yes, although only very crudely. I assumed, as the next approximation, that half of all the high energy neutrons went forward at 60° and half come off at angles greater than 60°. Then we get a little variation in the thickness, 45 feet forward and perhaps 35 feet to the side. The difference is not going to be dramatic in any case, because the shielding thickness goes as the logarithm of the intensity. We could draw a sort of egg-shaped curve around the neutron source, representing the idealized thickness in any direction (the first approximation was a circle). I doubt if it would vary more than 25 feet from front to rear. The second approximation gives adequate information for designing the experimental area.

J.P. Blewett (BNL): The permissible dose rate is now 3 rems per 13 weeks.

H.B. Knowles (Yale): I took 100 mrem/week as a practical dose rate, and did not consider skyshine at all. Shielding on the top will be of the order of 25 feet, depending on control of personnel.

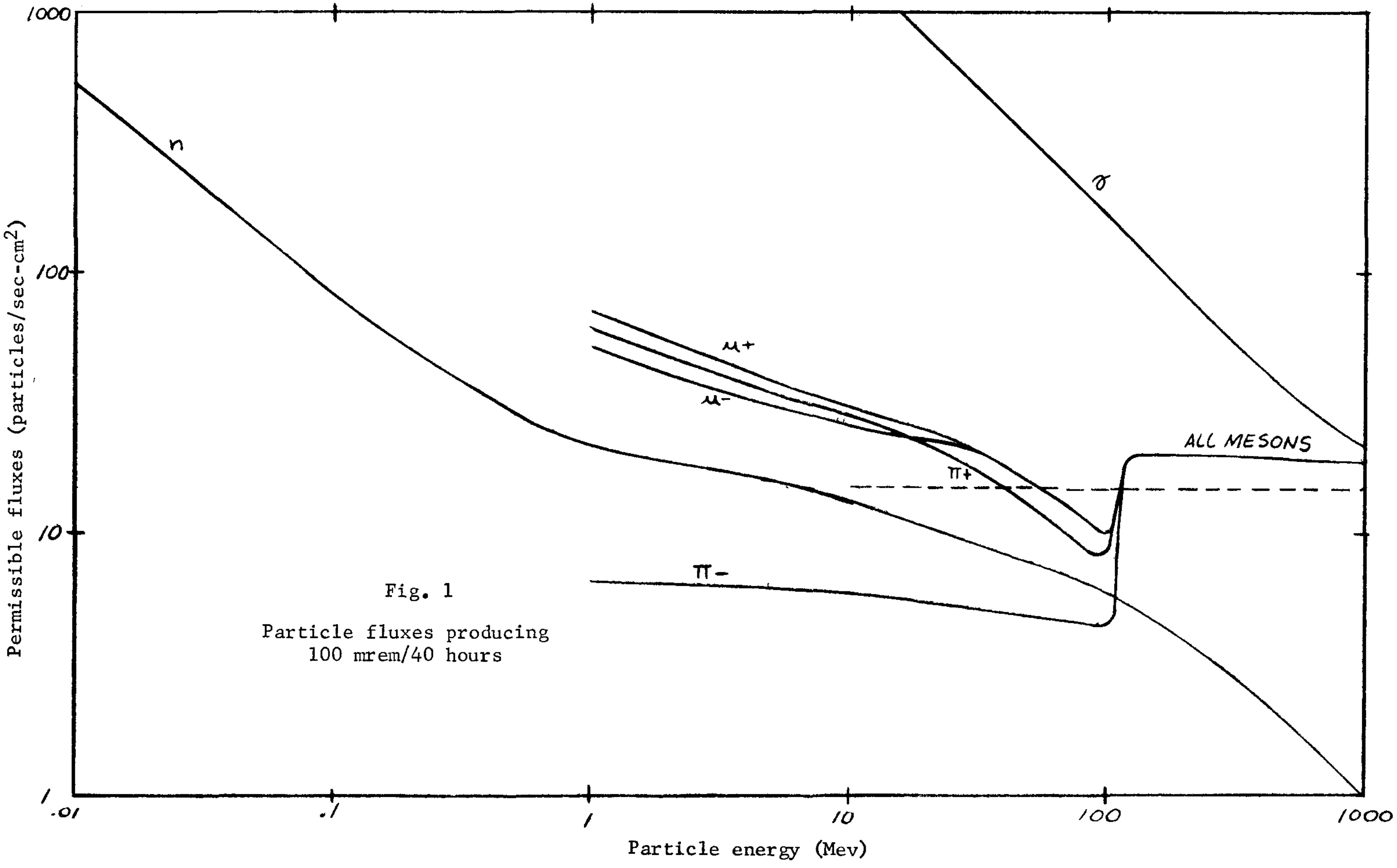

Fig. 1

Particle fluxes producing
100 mrem/40 hours

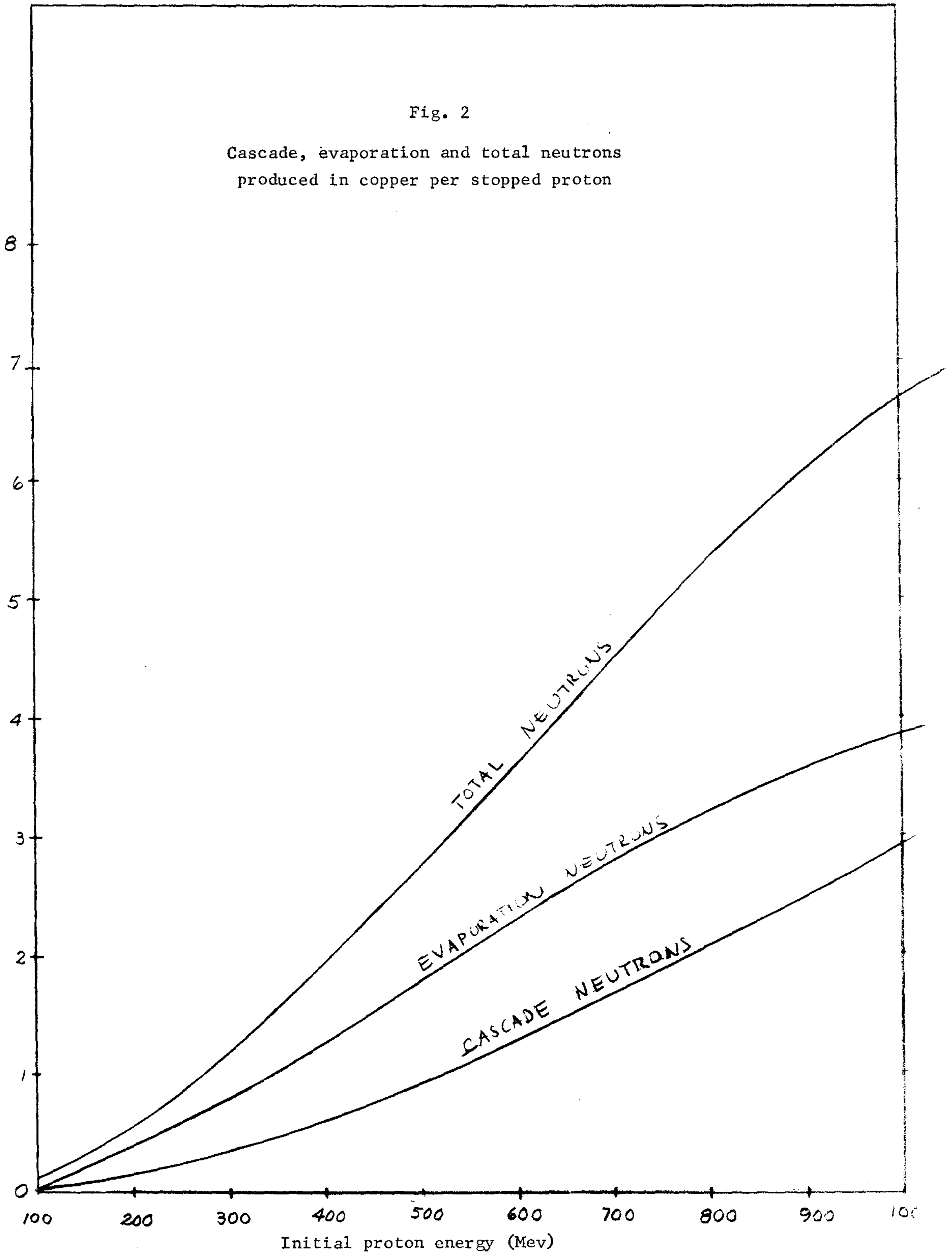

Fig. 2

Cascade, evaporation and total neutrons produced in copper per stopped proton

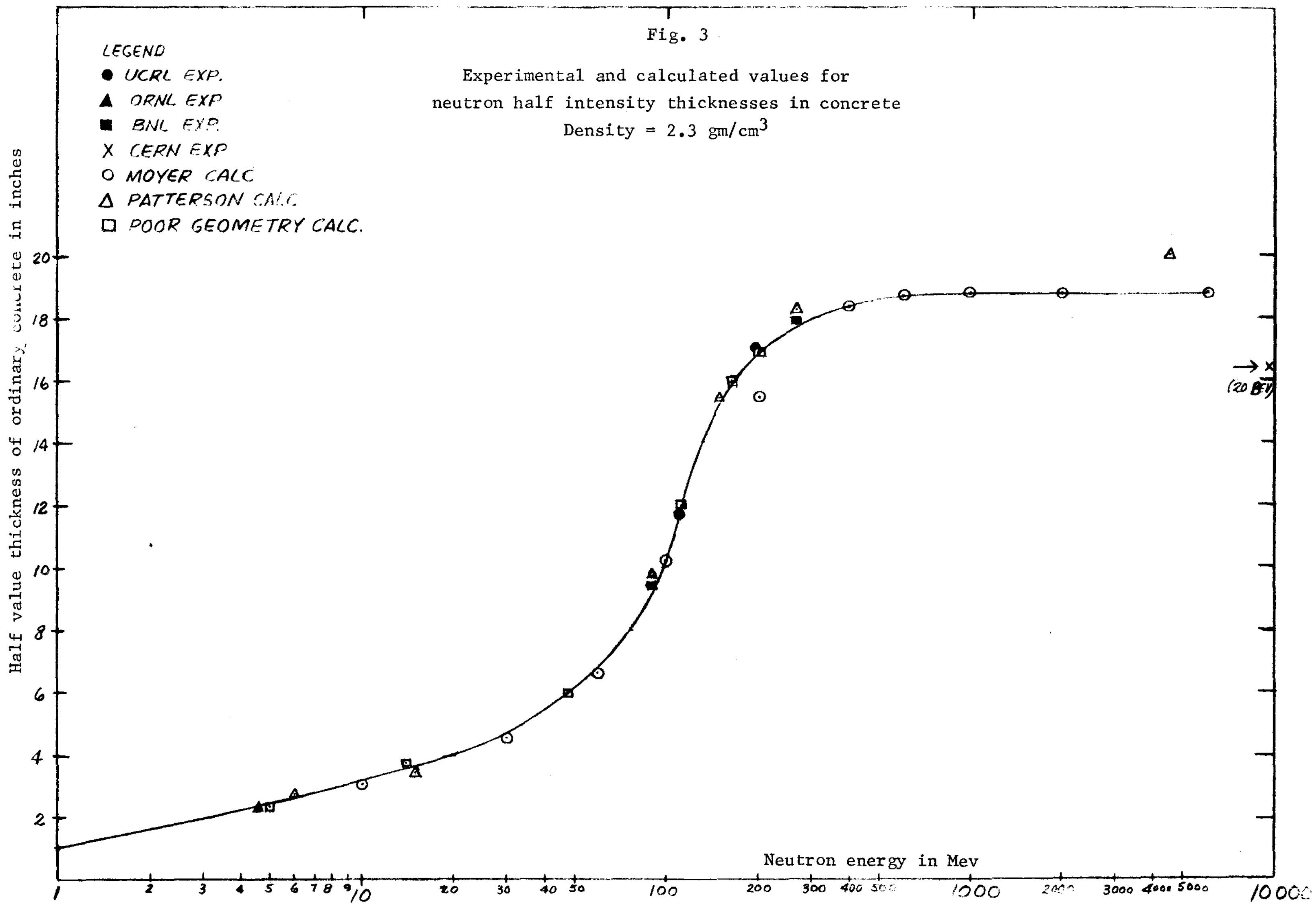

Fig. 3

Experimental and calculated values for
neutron half intensity thicknesses in concrete
Density = 2.3 gm/cm^3

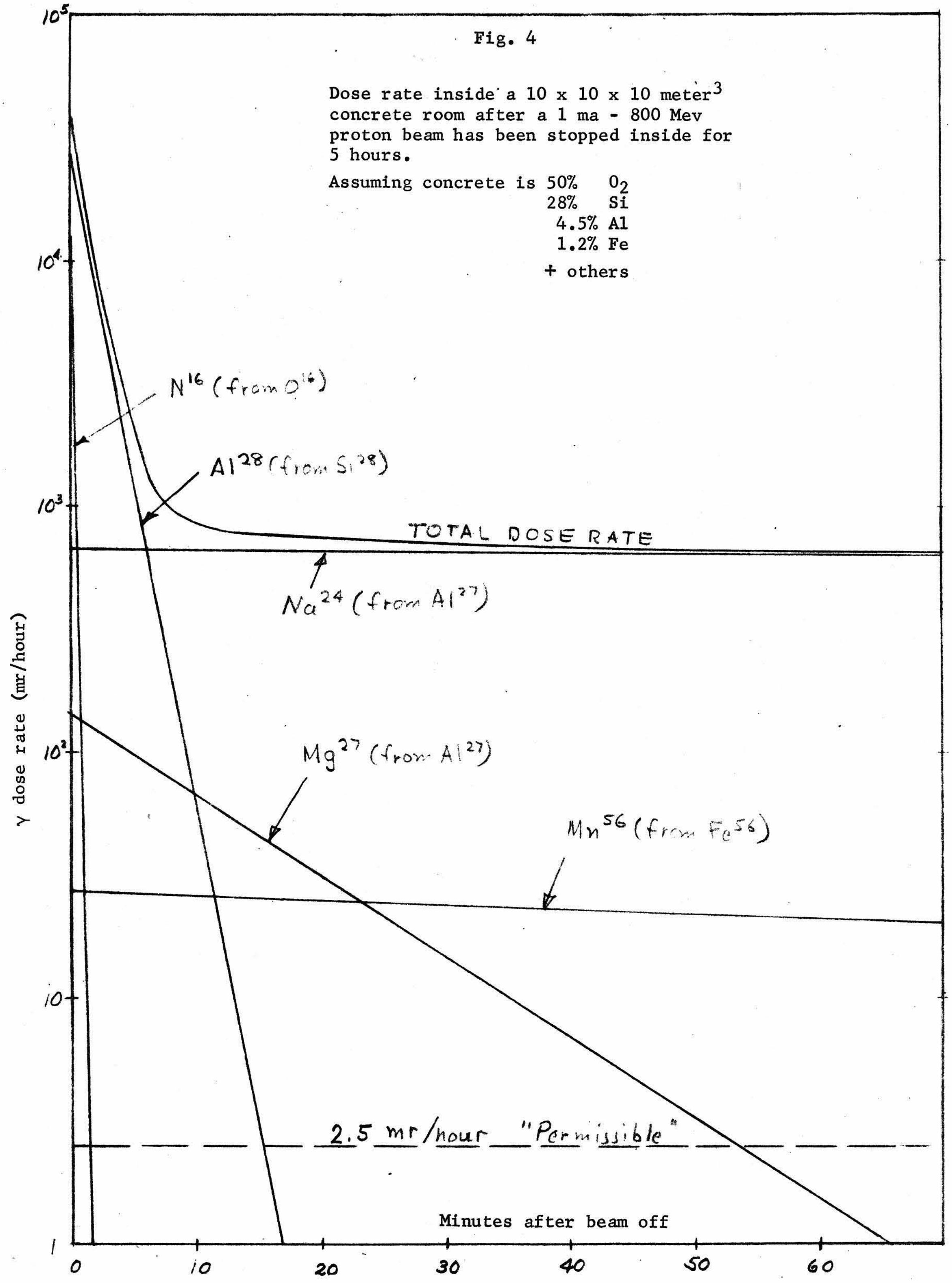

Fig. 4

Dose rate inside a 10 x 10 x 10 meter^3 concrete room after a 1 ma - 800 Mev proton beam has been stopped inside for 5 hours.

Assuming concrete is 50% O_2
28% Si
4.5% Al
1.2% Fe
+ others

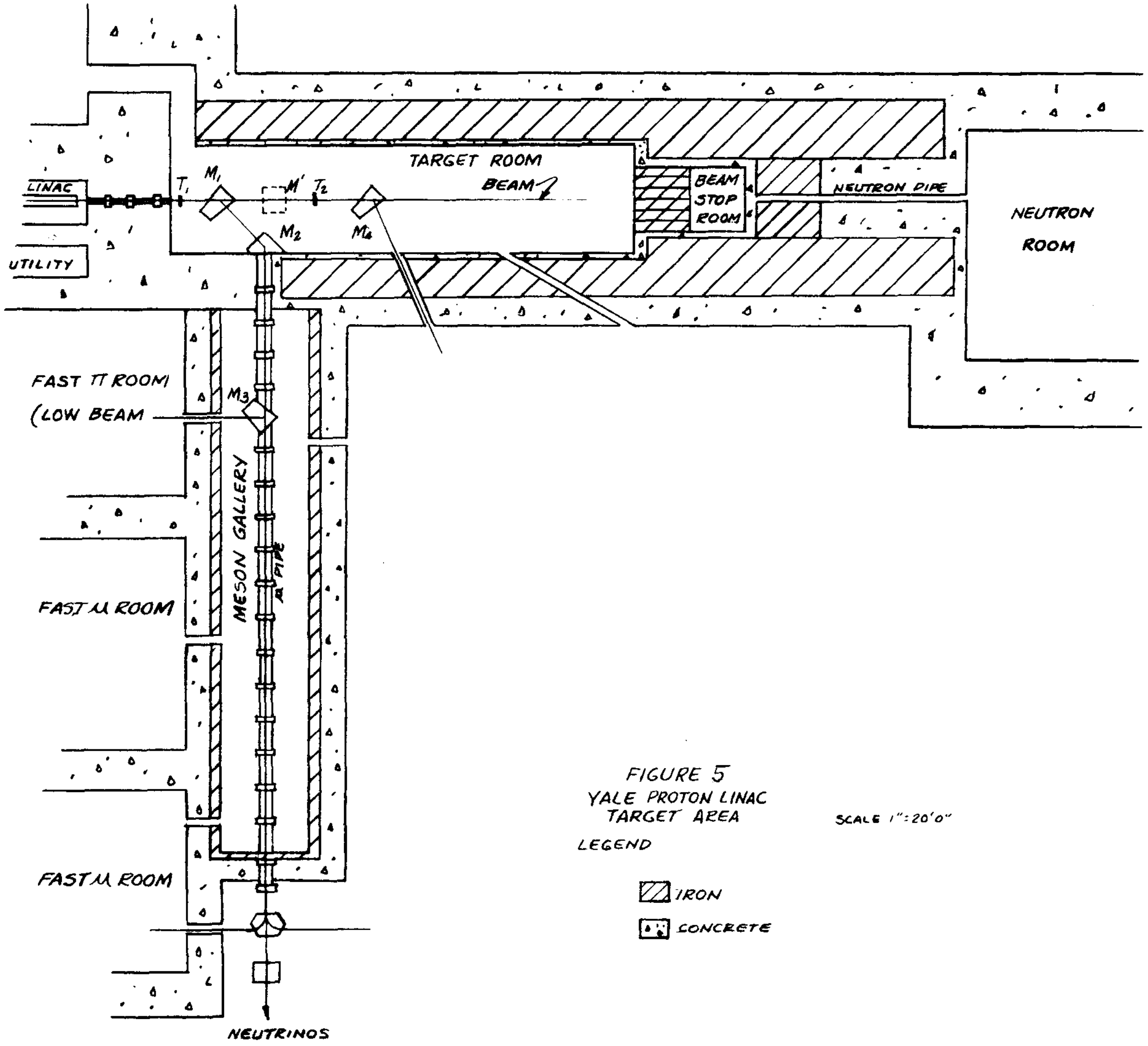

FIGURE 5
YALE PROTON LINAC
TARGET AREA