SHIELDING AND ACTIVATION OF HIGH-INTENSITY CYCLOTRONS

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(Presented by J.P. Blaser)

Accelerators now proposed for the production of high intensity proton beams in the range of 0.5 - 1 GeV are mainly of two types : sector-focused cyclotrons and linear accelerators. Though beam currents of several hundred μA or even one mA seem relatively easy to attain by the accelerator, it is generally accepted that the maximum current is more likely to be limited in practice by the formidable problems of shielding and servicing the highly radioactive parts of the accelerator and beam handling equipment. Both the problems of shielding and activation are determined on the one hand by the underlying physical processes, which in principle are known, but also very strongly by geometrical and technical conditions.

A detailed review of the basic physical processes involved and of the existing calculations and measurements on shielding and activation has been given at the 1962 International Conference on Sector-Focused Cyclotrons by Wallace[1], whose article contains also a complete list of references. In the present paper we wish mainly to report on further work undertaken at the CERN synchro-cyclotron in order to clarify some still open points and raise the problems determined by the general layout and operating procedures of an accelerator installation.

Shielding

Shielding is required for three purposes :

Biological protection : The required tolerances have to be satisfied in locations permanently occupied. Experiments themselves require shielding.

Background has to be kept low around experiments. The general background, more or less isotropic, and the contamination of the beam itself or a halo around the beam have to be taken into account.

Local shielding to reduce the beam hitting vital parts which should not be activated too much.

The sources of radiation, in the case of a cyclotron, are the following :

a) Beam loss in the accelerator.

b) Targets for production of secondary beams.

c) Experimental equipment using high intensity beams; parts of beam transport system.

As the ratio of intensities of the sources a) and b) may only be known after the accelerator is operating, a flexible shielding is necessary.

Generally, the shielding requirements for a high intensity machine can be extrapolated from existing synchro-cyclotrons. Indeed, even a factor 10^2 - 10^3

results with only a moderate increase of thickness, since absorption is exponential. On the other hand, beams have to traverse the shielding through channels. The leakage through such channels is determined mainly by geometrical conditions and decreases only very little with increasing wall thickness. The intensity level, at which this leakage becomes important compared with the neutrons traversing the wall and produces a halo of background radiation around the beam, is difficult to estimate. At present no theoretical estimates or measurements on the leakage of medium and high energy particles through holes exist. An investigation of this problem is planned at CERN, because it is believed to be one of the difficult points for high intensity machines.

As discussed by Wallace[1)], the design of a suitable shielding requires the exact knowledge of the energy spectra and angular distribution of the particles throughout the shielding. The nature, intensity and geometrical structure of the flux of primary particles depend on proton energy, target material and accelerator structure. According to the calculation and experiments undertaken in Berkeley and Oak Ridge, cascade nucleons are emitted at high energy (peaked at 3/4 of the initial energy) and essentially in the forward direction, when the protons interact with nuclei in the target (or in machine parts). The excited nuclei themselves emit isotropically evaporation nucleons at energies below some 20 MeV. Of these nucleons only the high energy neutrons are important as far as shielding is concerned, whereas the evaporation nucleons contribute to activation. The total number of cascade neutrons per incident proton (thick target yield) varies with energy, for Al from 1.5 to 4 between 450 MeV and 850 MeV. Between different target elements the total neutron numbers vary by as much as a factor of 10[1)].

Attenuation of fast neutrons in shield wall. The penetrating fast neutron component interacts with the shielding material and is degraded practically by inelastic collisions only. An equilibrium spectrum of the secondaries is formed after a few interaction lengths, so that the radiation leaving the shielding on the outside is composed of the remainder of the high energy neutrons and this equilibrium spectrum of secondaries. The biological dose is approximately doubled by the latter. All nucleons initially below approximately 150 MeV have a much shorter half-value reduction thickness and cannot penetrate the whole shielding. The value of the half-value reduction thickness for the high energy neutrons therefore determines the amount of shielding necessary. Its value has been calculated by Lindenbaum[2)] and Zerby[3)] and has been measured at the 184" cyclotron in Berkeley[4)]. It is around 45 cm in ordinary concrete at 400 MeV.

Measurements have also been undertaken at CERN using two methods :

a) Activation of a scintillator by the $C^{12}(n,2n)C^{11}$ reaction having a threshold at approximately 20 MeV;

b) Counting of stars in photographic emulsions. Threshold 50 MeV. The detectors were imbedded in the steel shielding inside a plugged-up meson channel.

Whereas the first method is in good agreement with the work previously mentioned (half-value thickness in steel of 18 cm), the second gave a considerably higher value of 27 cm (Fig. 1). The reason for the difference is not known. It could be due to the different spectral sensitivities of the methods or to a bias in star counts. There may also be errors due to inhomogenities in the shield-wall structure.

Another set of measurements has therefore been initiated with good geometry, i.e. external proton beam (600 MeV) impinging on different materials : iron, lead, ordinary concrete and carbon. Both high energy neutrons and protons are measured. This kind of measurement should allow one to study the build-up of secondaries and the subsequent degrading. This information is considered useful not only for the shield wall, but especially for estimating the radiation and activation produced by lost beam, e.g. impinging tangentially on the pole pieces.

Fig. 2 and 3 show some preliminary results for iron and lead. In iron, after some increase due to build-up, a rapid fall-off is observed towards the range of the protons, followed by a tail due to the high energy neutrons. In lead, the fraction of neutrons produced is much higher, resulting in a slow decrease from the start.

Local shielding against activation. The first results on carbon confirm that this material seems best suited as local shielding to prevent activation of accelerator parts, as it produces a minimum of neutrons per proton and has very low proper activity. However, due to the low density, much space is required. For higher energy cyclotrons this space may not be available inside the accelerator.

Shielding of experiments, beam dumps. For these problems a first measurement of the reflexion of 350 MeV neutrons has been made, using emulsions. Fig. 4 shows that there is a strong tendency for scattering in the backward direction.

The energy of the reflected neutrons goes up to 90 MeV and the albedo (backward, into cone of 50° around direction of incidence) is 0.5%. This low intensity and the general background did not allow a sufficiently precise measurement yet.

Further points in course of investigation :

a) Flux of thermal neutrons in the SC vault at CERN.

b) Leakage of radiation through channels. Reduction by broken channels with deflection magnets inside the shield-wall.

c) Energy spectra and angular distribution of neutrons emitted by thin meson production targets, using time of flight spectrometer.

d) Layout of external meson production targets allowing short beams and high reduction of background and beams contamination.

General layout. The arrangement of the shielding depends on the general layout chosen for the accelerator and the experimental areas. A design suitable for extreme intensities and high energies is proposed for the Mc^2 project of ORNL[5]. It uses the

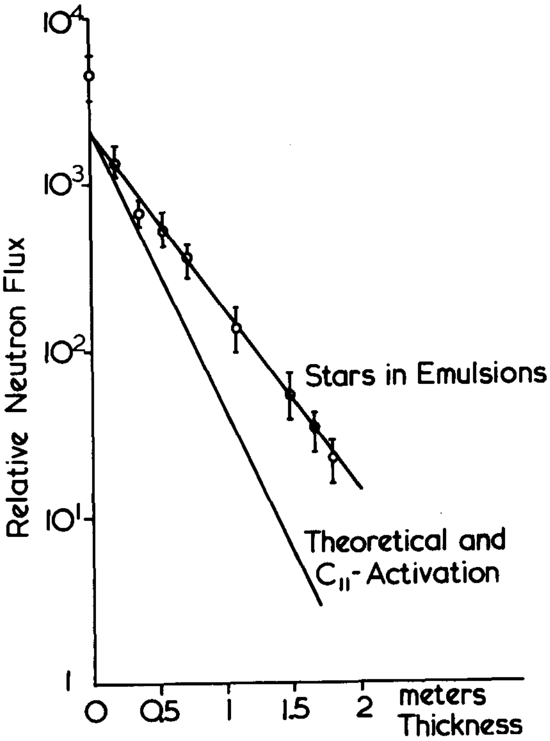

Fig. 1 Attenuation of 350 MeV neutrons in iron.

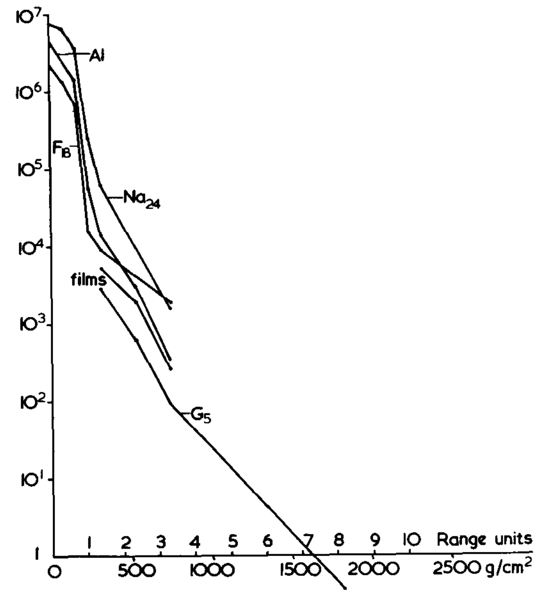

Fig. 2 Absorption of 600 MeV protons in iron by various methods :
Al = total Al activation
Na_{24} = $Al_{27} \rightarrow Na_{24}$ activation
F_{18} = Fluor activation
G_5 = Track density in G5/200μ - emulsions.

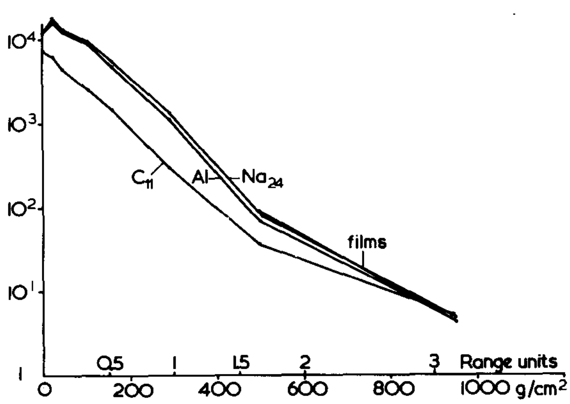

Fig. 3 Absorption of 600 MeV protons in lead by various methods :
C_{11} = $C_{12} \rightarrow C_{11}$ activation.

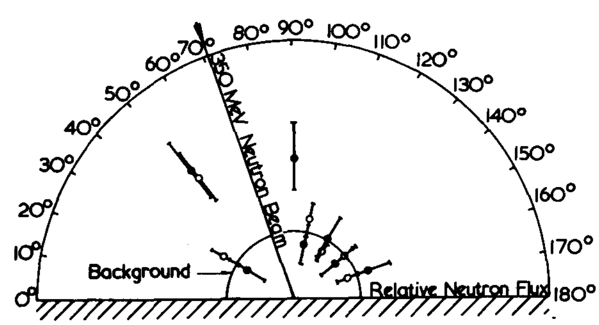

Fig. 4 Backscattering of 350 MeV neutrons on iron. Neutron flux measured by density of proton recoil tracks in emulsions.

external beam only, and separate underground halls are provided for secondary beam production, and proton, pion and muon experimentation. A more conventional layout is envisaged for the ETH Cyclotron (Fig. 5). Only analysed secondary beams are allowed into two open experimental areas where blockhouses can be built around high intensity experiments. A high intensity area is provided inside a part of the main shielding. A double wall with bending magnets in the gap is foreseen. For certain cases internal meson production targets can be used in the field-free valley of the cyclotron.

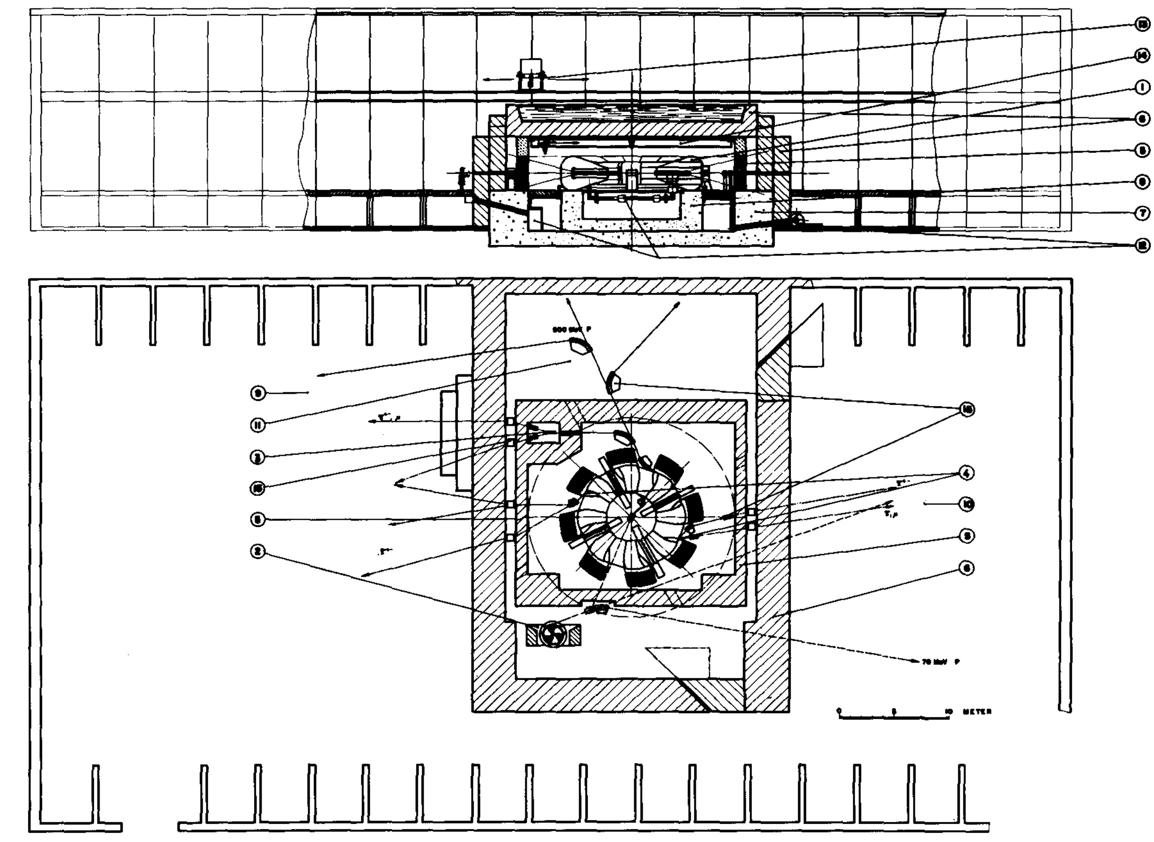

Fig. 5 Shielding project for the ETH Cyclotron.

Activation

A lot of attention has been paid recently to the activation of accelerators. It is recognized that it is the activation level of the machine that will set the practical limit to the beam intensities. With this in view, investigations have been made last year in several laboratories.

At the Bevatron in Berkeley, R.A. Krakowski and F.M. Miller[6)] have studied the long lived radiation in the magnet gap, and its radial and azimuthal distribution across the vacuum chamber. They find that all regions of activity can be explained by losses of the direct beam. Furthermore, the intensity of the gamma radiation at any particular position is function only of the intensity of impingement and not of other factors, such as excess of neutrons near the target, or energy of the incident particles. Presented spectra of metallic bodies show main lines in the 0.5 and 0.8 MeV regions.

Boom, Toth and Zucker[7)] of ORNL have made a radiation survey at the LRL 184" Cyclotron. They report radiation levels at various positions in the cyclotron vault that decrease by factors of 10 to 100 after 48 h cooling time. This has not been quite confirmed by corresponding measurements at the CERN SC, on which we will report later.

Apart from this gamma ray spectra were taken by looking into the cyclotron gap. These show similarity with those of Krakowski and Miller. Also the gamma ray spectra of long-exposure activities induced in metal foils were analyzed, and the relative abundance of the various lines were found to be in some agreement with the ratios of the known cross-sections for production of various elements by high energy particles.

The activation problem of accelerators is also examined at the Stanford Linear Accelerator SLAC, mainly for the arrangement of the target region, but we lack information on the work performed there as yet.

We will now report on measurements made at the CERN Synchro-Cyclotron. First the decay of the activity, as measured with a plastic scintillator counter 7.5 m from the machine centre, is shown in Fig. 6. The measurement started two minutes after shut down. The activity decreased by a factor of 2 in the first two hours, by another factor of two in the following 11 hours and by a third factor of two in the following 100 hours. It has been found that activity decay curves taken at a large number of various places in the hall show exactly the same decay.

Activity spectra at several places in the machine were also taken with a lead protected and collimated NaI spectrograph. Fig. 7 shows the locations where the spectra were taken and Fig. 8 gives the relative spectra taken at various positions and for

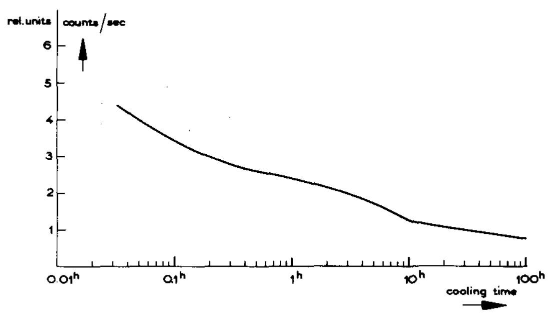

Fig. 6 SC activity decay. Pos. 7, March 27, 1963.

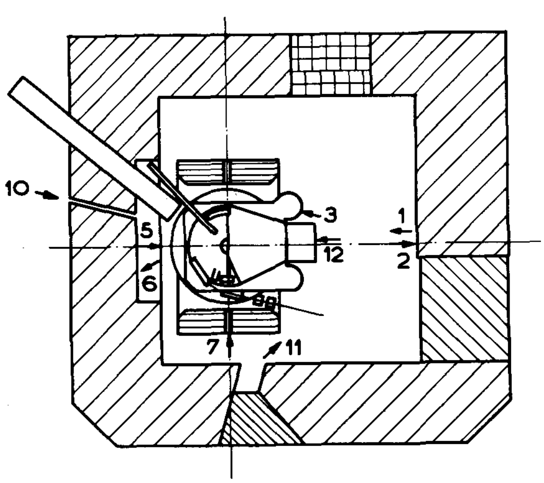

Fig. 7 CERN Synchro-Cyclotron.

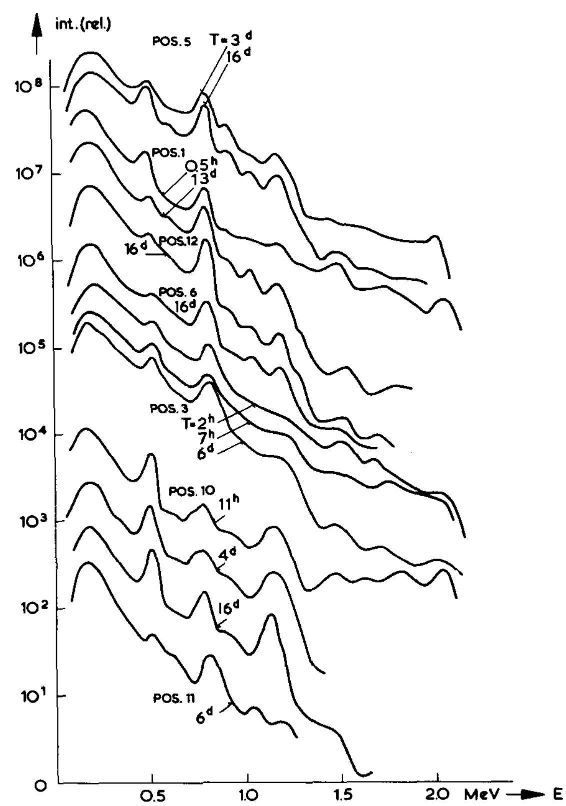

Fig. 8 Activity spectra in SC hall.

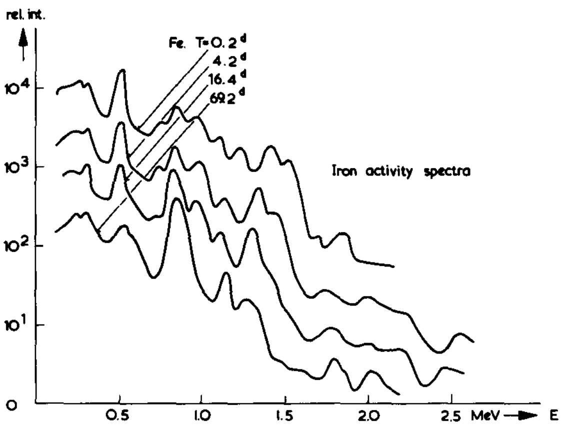

Fig. 9 Iron activity spectra.

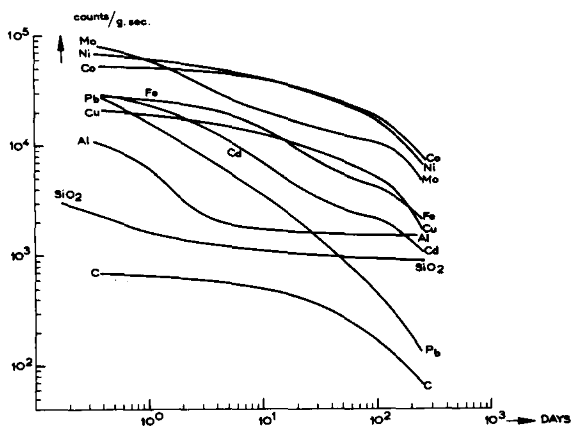

Fig. 10 Activity decay. Proton exposure 3 months.

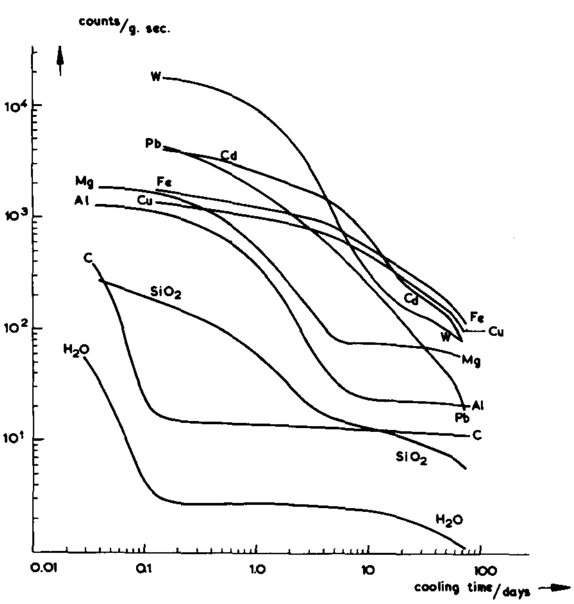

Fig. 11 Activity decay. Neutron exposure 6 weeks.

various cooling times. All the spectra have about the same character. Contrary to the spectra taken with small samples, we notice here the accumulation of gamma radiation at small energies, due to Compton scattering in the mass of the thick active bodies. Peaks are consistently apparent in the 0.5 and 0.8 MeV region. For comparison Fig. 9 shows spectra of a small sample of iron takent at different times. It can be seen that there is a great similarity between both. This, together with the fact that all decay curves taken around the room are the same, leads us to think that the main part of the activity hazard comes from the iron poles, where the beam loss occurs. Fig. 10 and 11 show decay curves of various materials exposed respectively to pure protons (inside the tank, away from the target, during 3 months) and pure neutrons (outside the tank in forward direction, for 6 weeks). The similarity of the activity levels and decay curves for the various elements is obvious. A survey of the activity in the symmetry plane between the pole pieces inside the tank was made using a spherical scintillator with an air guide to the multiplier and is shown in Fig. 12. The highest activities are found along the periphery and at the dee.

Last we show in Fig. 13 the decrease of the activity with the depth in the iron of the pole, as measured along a screw which was removed for this purpose. The steep decrease of the activity with depth is explained by the grazing incidence of the impinging protons.

It is apparent that the main source of

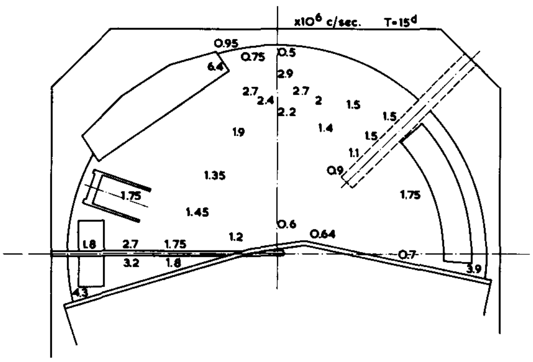

Fig. 12 Map of activity in SC tank.

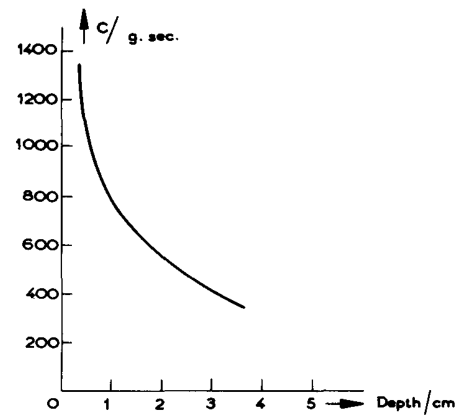

Fig. 13 Activity of screw as a function of depth in pole piece.

activation are protons. Because of self-shielding the dose produced depends very strongly on thickness and gamma absorbtion of the object hit by the protons. This is also the reason why neutron activation is less important in spite of the greater flux of neutrons. Thermal neutrons do not seem to contribute much to the activation.

Conclusions

Good agreement exists between theoretical estimates and measurements as far as shielding is concerned. However, the inevitable uncertainty on the extraction ratios expected and the difficulty in predicting the behaviour of an external production target assembly call for a sufficient flexibility of the shielding arrangement. Overshielding should be avoided not only for economical reasons, but also to keep the beams short in order to avoid meson losses through decay and imperfections in the beam optics.

As far as activation is concerned, a serious discrepancy on the measured decrease of general radioactivity level after shut down exists, and the reasons are not yet understood. The main sources of activity are materials which unfortunately are unavoidable, like iron, copper, aluminium. Every effort must be made to stop lost beams in carbon. As true remote servicing and repairing of a cyclotron is hardly conceivable, accessibility and small interdependency of parts is essential. Sufficient space allowing to install gamma ray shields around hot spots during work may be very helpful. Some parts, like deflectors, must be designed as disposable plug-in units.

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