SESSION VI: EXTERNAL FOCUSING SYSTEMS, INSTRUMENTATION, OPERATIONAL EXPERIENCE, AND SUMMARY OF OUTSTANDING PROBLEMS

W. W. Havens, Chairman

Some Observations On Cyclotron Shielding

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For many of the machines which have been discussed at this meeting the shielding can be almost an after-thought which can be placed into position, some way or other, around the machine to satisfactorily limit radiation levels in the regions where people must live and work. But for some of the machines, particularly those which are to deliver high current and those which are to operate at high energies where the secondary particle production is high, the shielding cannot be an afterthought. Its design and its location must be in view from the very beginning in architectural and engineering planning.

At the Shielding Symposium which was held two years ago in New York City, and which concerned itself primarily with high energy machines of the Cosmotron and Bevatron variety, the viewpoint emerged that research people are not at odds with the medical men in regard to the desirability of low radiation levels, because it is the experience of all of us that a low background is conducive to good experiments. The concerns of both groups are quite consistent quantitatively in the degree of radiation suppression to be sought.

We are currently involved at Berkeley with the development of an 88-inch, 60-Mev, deuteron machine which is to be capable of delivering high current in the neighborhood of a few milliamperes. The expected neutron production is really quite stupendous. It is outstandingly clear that the shielding with which we are concerned for this machine has to be considered from the very beginning, for it has a strong bearing on the preparations of foundations and floor plan.

The radiological problems with this machine fall into at least three categories which I should like to mention in the present discussion. First is the problem of the escape of radiation and its suppression to levels which are consistent with the occupation of the working regions nearby, and with the backgrounds required for radioactivity counting at a somewhat greater distance. Second, we are concerned with the activation of the parts of the cyclotron, because it is frequently necessary to work on the machine and the activation of the copper and other metal parts is of great importance at these times. Third, we must give attention to the exposure which may be received by a person upon entering the shielding enclosure just after the shut down of operation. This question strongly affects the problem of the rate of air interchange within the shielding enclosure because of the radioactivity induced in the air, and will also be a basis for the formulation of shutdown procedures which will control the time of entry in relation to the strength of the preceding operation. I shall discuss this last point first of all.

Our 60-in. cyclotron has been operating for many years in Berkeley at a typical deuteron target current of 50 microamperes. Of course the circulating beam in toward the center is somewhat larger than this. After several hours of operation the activity inside the shielding enclosure will deliver at shut-down, for a typical position where a worker might be located in doing some operation, about 6 roentgens per hour, initially. This decays rather rapidly, the first half-value disappearing in 5 to 10 minutes, and the second half-value after a further 15 to 20 minutes; there is then a longer period of the order of two or three hours for the next half-value reduction, and following that the decay goes into the 12.2-hr copper activity which is of course for the most part due to the dee's. The short-lived activities are mostly due to the nitrogen and oxygen activated by the neutrons; the intermediate life time is largely due to the argon activity induced in the air by slow-neutron capture. There is of course a short-lived copper activity also which appears early in the decay.

In the 88-in. machine which we are now planning we are aiming at a current of 5 ma as 60-Mev deuteron energy. The beam order-of-magnitude is up by a factor of about 100 which would in itself bring us to 600 roentgens per hour immediately upon shut down, but besides this the neutron production per deuteron is up by a factor of about 8 so that the possible exposure upon entering the enclusure immediately after shut down is really a serious matter. Of course this is not whole body irradiation, since the beta particles will not penetrate deeply, and also it is rapidly decaying, so that the exposure obtained is not expected to be lethal. Nevertheless, one can see that if he enters three or four times during one day, through failure to observe rules or failure to understand this situation, he could approach a very serious radiation exposure. Such considerations are basic in estimating the rate at which the air must be exchanged within the shielding enclosure. We have decided that this rate should be at least 1/10 the enclosed volume per minute.

The problem of the suppression of escaping radiation by shielding is dominated by the fast neutron production. That is to say, any shielding which adequately provides containment of the fast neutrons will be more than adequate to care for the suppression of the gamma radiation coming from the parts of the cyclotron during its operation. In estimating the order of magnitude of the shielding one finds it convenient to break the problem into two categories with regard to neutrons. First, the primary neutrons which are emitted by the target, and second, the neutron atmosphere which is created within the shielding enclosure by scattering from the walls of the primary neutrons emitted from the target.

It is the first category of neutrons which dominates the shielding problem. But the second category is primarily responsible for the activation of air and the inducing of radioactivity in the parts of the machine not irradiated by the accelerated beam. It is necessary to know both of these components of the neutron field.

In beginning the analysis we first estimate the total neutron production at the target, assuming a target and beam situation which is about the worst to be encountered in the expected operation of the machine. In our case we took a thick target of beryllium and considered a beam of 5 ma of 60-Mev deuterons incident upon it. It is true that a greater total neutron yield might be obtained, from a uranium garget for example, but from the standpoint of shielding, the beryllium target with its considerable yield of high-energy neutrons in the forward direction is probably as severe a condition as can be encountered. We estimate from data which we have collected that the neutron yield on a thick beryllium target for a 60-Mev deuteron is 0.2 neutrons. This means that for a 5-ma beam we have a few times 10^{16} neutrons per second emitted by the target.

We next need to know how this total yield of neutrons is distributed with respect to energy spectrum and angular distribution. We expect from energetic deuterons that one of the components of neutron yield will be due to the stripping reaction which will throw a strong forward beam of neutrons. Then there will be those produced by the direct interaction of either of the nucleons of the deuteron with the target nuclei. And finally, there will be neutrons from nuclear evaporation by the excited nuclei of the target.

The cross-section for deuteron stripping as a function of the atomic number of the target nucleus and of the energy of the deuteron is fairly well known. The original Serber theory requires modification to account for nuclear transparency effects, but we may look to the experimental data of Crandall, Schecter, and others to estimate the actual stripping yield. The spectra of the neutrons from stripping and their angular distribution are quite confidently known from the simplicity of the process and the theory which describes it, supported by empirical data.

For the rather indefinite processes which we term direct interaction we have much less certain knowledge of the angular distribution and spectra of the neutrons emitted. We have recently completed a study at Berkeley of such phenomena from the bombardment of nuclei by 32-Mev protons. (This was the last experiment performed on our linear accelerator before it was removed to the University of Southern California.) From it we have some information on the kinds of neutron spectra and angular distributions obtained when 32-Mev nucleons strike targets.

From the theory of the evaporation of nucleons from excited nuclei and from the many experiments which support this theory, one knows fairly well, if he can estimate the temperatures of the excited nuclei produced, the spectrum and angular distribution to be expected from the process of nuclear evaporation.

Thus by consideration of data on these three processes, stripping, direct interaction, and evaporation, we have prepared spectrum curves for six different angles of emission from the target, 0, 30°, 60°, 90°, 120°, 150° and 180°. The yields of these processes were adjusted relative to one another according to our best estimates and then normalized so as to deliver a total yield of 0.2 neutron per deuteron. In actual fact, because of the degradation in the energy of the deuteron as it passes through a thick target, these operations were required for various layers of the target. We subdivided the target into layers of equal deuteron energy loss of 5 Mev each, and these calculations of angular distribution and yield were done for the contributions of each of the layers with their respective deuteron entrance energies. So that while this process is simple in principle it was actually a considerable chore to complete it.

To obtain the spectrum and intensity of the neutron atmosphere developed within the shielding enclosure by this primary spectrum one would presumably perform a Monte Carlo calculation, or its equivalent, and follow the history of a representative number of neutrons as they scatter around inside the shielding and are finally absorbed or penetrate through it. But the accuracy required for the shielding problem probably does not warrant such an extensive calculational program as this, and the approach we have used is the following.

The spectrum of the total neutron emission, obtained by integration over the various angles of emission, looks approximately like that displayed in Figure 249. We then divide this neutron yield into eight different energy groups and consider the

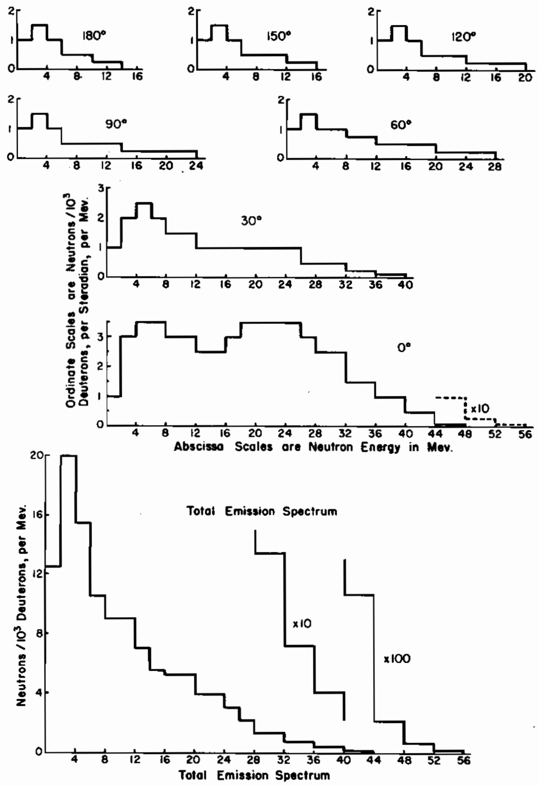

Fig. 249. Neutron spectra in various directions from a thick beryllium target. Also total emission spectrum obtained by compounding the former multiplied by appropriate solid angle factors. Deuteron energy 60 Mev.

problem of injecting into the shielding enclosure neutrons possessing the mean energies of these different groups with the respective intensities indicated by the total emission spectrum. We now consider that the neutron atmosphere produced by any one of these groups, let us say the i^{th} group, will be of the form $1/E - 1/E_i$ after the equilibrium condition due to scattering within the enclosure has developed. We must decide, however, upon the value of the multiplying constant which appears in front of this expression for the spectrum generated from the i^{th} group. The value of this constant we have determined by reference to a particularly simple relationship between the number of neutrons injected into an enclosure to the thermal neutron flux produced therein. This relationship is

$$\phi_{thermal} = 1.25\ Q/S,$$

where Q is the rate of injection of the original neutrons and S is the area of the internal surface of the shielding enclosure. This expression is obviously dimensionally correct, and from considerations of albedo and scattering it may be easily estimated that the constant multiplying Q/S must be near unity. The value 1.25 comes from a number of tests on shielding enclosures of various sizes extending from one cubic foot up to rather large rooms with thick concrete walls. We have found the number to be surprisingly independent of the volume and not very sensitive to the energies of the neutrons which are injected. The normalization of the 1/E spectra from the various groups into which we have divided the total emission spectrum is then accomplished by requiring that each of the equilibrium spectra arising from the various groups shall approach the value $1.25 \times (Q_i/S)$ for the region of "thermal" energies (arbitrarily defined as below 0.5 ev). By superimposing the 1/E spectra from the various groups, normalized as indicated, we obtain the neutron atmosphere existing within the shielding enclosure.

With the knowledge of the spectrum and intensity of the neutrons incident upon the inner wall of the enclosure in any direction we are prepared to calculate the thickness of the concrete required to provide the necessary attenuation. The effective attenuation coefficient for ordinary structural concrete as a function of neutron energy, assuming a broad slab type geometry, is sufficiently well known for the purpose and is presented, for example, in Figure 250. The attenuation calculation is performed with a trial thickness of shielding, and the spectral intensity of the emergent neutrons is found by applying the attenuation factors for the various energies to the neutron spectrum incident at the internal face of the shield. The emergent

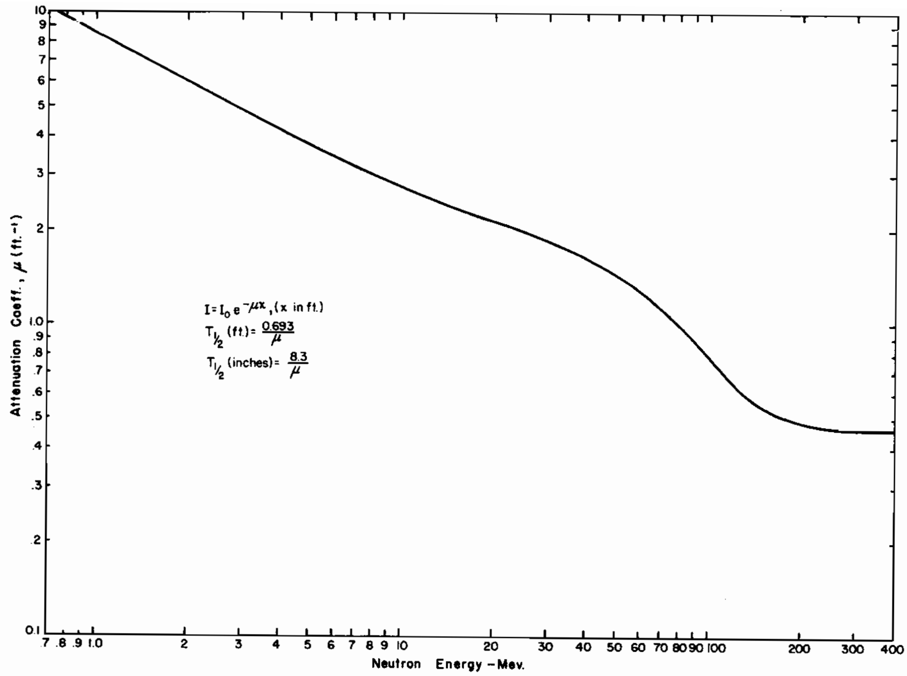

Fig. 250. Attenuation coefficient versus neutron energy for thick shields of ordinary structural concrete (2.4 g/cm2).

spectrum will typically be of a higher average energy than the incident spectrum because of the large attenuation coefficients for the lower energies of neutrons. By integrating under the spectrum for the emergent neutrons, the total number is evaluated and compared with the number to be allowed for purposes of radiological safety. Various trial thicknesses of concrete are employed until the neutron intensity, in relation to the emergent spectrum, is sufficiently low to meet the safety criteria. We have not mentioned in this discussion the build-up of secondary radiation which should in principle accompany the surviving primary radiation as it emerges from the external face of the shield. For neutrons of the energy range with which we are here concerned the build up factor is small, of order of magnitude unity and it is not a considerable problem. At higher energies this is not necessarily true.

In our particular case to achieve the low backgrounds for counting of interest to the chemists, as well as to achieve the margin of safety desirable for radiological protection, we have aimed at the escape of about 1 neutron per cm^2/sec. This has led us to the conclusion that in the forward direction from the target we require 11 to 12 ft thickness of equivalent concrete, assuming in this case ordinary structural concrete of density 2.5 grams per cubic centimeter. At 90° with respect to the beam at the target we require 9 to 10 ft equivalent of such concrete. In the backward direction possibly a little less could be predicted but we shall very likely use the 90° requirement even at 180°. The concrete thicknesses indicated are somewhat modified when one accounts for the shielding effect of the magnet iron. So for example, the roof, because of the influence of the magnet steel over the target, will not necessarily need to be the full 9 to 10 ft of concrete. Also in certain other directions, particularly the forward direction, a considerable amount of iron is to be used which will decrease the total thickness of the combined shielding.

It is immediately apparent upon performing these calculations that the shielding thickness is almost completely determined by the primary neutron emission from the target. The activation of the air however is determined by the neutron atmosphere, and the activation of the parts of the cyclotron, while due mostly to the direct bombardment of the neutron beam, is also in some measure due to the neutron atmosphere, particularly the activation of the magnet coils.

YAVIN: I would like to get copies of your curves, if possible, and any references of good work done elsewhere.

MOYER: I will be glad to send you such curves as we have. The reason nobody publishes anything about shielding is easily understood. What you do is always something just adequate for the circumstances, and not a treatment sufficiently general or complete to incline one to publish it.

LIND: I might call your attention to the Proceedings of the Shielding Symposium at New York. I made some very crude measurements one night at Los Alamos, wandering around in the brush with a counter, which seem to fit fairly well the calculations that are given, I believe by Lindenbaum in a Proceedings article. At least they agree within a factor of 2; so that is something to do on. The measurements I made were concerned primarily with attenuation in free space; that is, they were not shielding attenuation but air scattering, scattering behind shields, etc., out in a rather large dimensional geometry.

MOYER: I may say that there is really a gread deal of information developed at Oak Ridge on the shielding of reactors. There is no scarcity of information on attenuation of reactor neutrons, and we have quite a lot of data at the higher energies, up to 300 Mev. But you don't easily find these things published except in some ORNL or UCRL reports, or places like that.

SCHMIDT: What do you do about cooling the machine. You must have some air ducts, and you probably also have a lot of radioactivity. Do you need a gigantic stack?

MOYER: We are presently contemplating replacing about 1/10 of the volume inside the shielding with fresh air every minute. The worst air activity is argon-41, of course, which has a 1.82-hr. lifetime. Besides this there are the N^{13}, O^{15}, and N^{16} activities of much shorter lifetimes. The argon and nitrogen together will be built up to a serious degree in our machine. The active air will probably be discharged in a fenced-off area.