SHIELDING OF HIGH-ENERGY ACCELERATORS

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I. INTRODUCTION

The construction of high-energy accelerators with large intensity has created an increase in interest in shielding problems. Without adequate shielding, high-energy accelerators cannot be operated at full capacity. However, in attempting to provide an adequate shield for a high-energy installation, one finds that the size and cost of the shield is a large fraction of the size and cost of the machine itself. Therefore, it is important not to overshield by too large a factor.

This same problem has been a part of reactor technology from the beginning. For high-energy accelerators the problem is more difficult to solve because the secondary radiation is more complex and many of the decay and production processes are not known. The building of an accelerator, having an energy larger than any existing machine, precedes the measurements needed to make precise shielding estimates. One can only extrapolate from lower energies.

However, as pointed out by Panofsky,[1] accelerators are basically research, and not production, tools. The design of shields at a minimum cost has not, and probably will not, be emphasized. Still, it is important that the machine be adequately shielded and, in the competition for available funds, one cannot afford to overshield by too much.

II. SHIELDING DESIGN AND COSMIC-RAY INFORMATION

Fortunately, we are not completely in the dark in estimating the high-energy-particle shielding requirements. The earth is surrounded by an atmosphere that provides an adequate shield for extremely high-energy cosmic-ray primaries. The nucleon and photon-electron cascade processes that occur within the atmosphere due to the incidence of a high energy primary, are similar to those that occur within the shield. The information is difficult to extract because the energy of the primary cannot be accurately determined. Moreover, there are basic differences due to the large difference in density of the two media.

High-energy charged particles lose their energy mainly by nuclear interactions. The collision mean-free-path for air is of the order of 100 to 110 gm/cm^2, somewhat larger than the geometrical value.[2] (In different kinds of shielding material, the geometrical mean-free-path varies as $A^{1/3}$, where A is the atomic number of the shield material.) At each nuclear collision a number of high-energy particles are created. These secondary particles can be nucleons, mesons, and, if enough energy is available, hyperons. The high-energy secondaries can, in turn, undergo nuclear interactions and produce more secondaries. In this way, a buildup of very high-energy particles is obtained. As the available energy is shared among more and more secondaries, each particle becomes less likely to produce secondaries and more likely to lose energy by ionization or elastic and inelastic collisions. Eventually, the particles do not have enough energy to contribute to the cascade process and the absorption is expected to be exponential.

Experience shows that the high-energy component of the cosmic-ray cascade is very directional. Therefore, a one-dimensional diffusion equation can be written. If the energies are high enough, so that ionization losses and $\pi - \mu$ decays can be neglected, these equations can be written in the form

$$\frac{\partial n_i(E, x)}{\partial x} + \frac{1}{\lambda_i} n_i(E, x) = \sum_j \int K_{ij}(E, E')\, n_j(E', x) dE' \qquad (1)$$

where n_i (E, x) is the average number of particles of the ith kind having E at the depth x; λ_i is the mean free path of the ith kind of particle for nuclear collisions; and K_{ij} (E, E') is the average number of particles of the ith kind having energy E, produced by a particle of the jth kind having energy E'. Index 1 can refer to nucleons and Index 2 to charged mesons.

The physics of the problem is contained in the production kernel K_{ij} (E, E'). These equations were solved by Messel,[3] in 1954, using an assumption that the production kernel can be expressed as a homogeneous function of the primary and secondary energies only. More recently, the equations were solved by Olbert and Stora,[4] under very general conditions which included the statistical model of Fermi and the hydrodynamical model of Landau and Belenkii. The solutions show the expected rise to a maximum and subsequent exponential decay. Both the height of the maximum, and the distance within the shield before exponential decay takes place, increase with the energy of the incident particle.

Unfortunately, the solutions are good only for energies greater than 200 Gev which represents the lower energy limit for the application of the models. The existence of "jets," in some very high-energy stars, has led recently to a new "fireball" model for the production process.

If one cannot solve the problem, because of the unknowns that enter into the equations, perhaps measurements of the cosmic radiation, with respect to depth of the atmosphere, can provide enough information for shielding estimates. This method was used by Citron and Gentner[5] to determine the shielding requirements for the 30-Gev CERN proton synchrotron. The neutrons are the most penetrating component. Below 30 Mev, they lose energy only by elastic and inelastic collisions. They finally reach thermal energies and are captured. Since the diffusion length of the thermal neutrons is comparable to the slowing-down length of the fast neutrons, the flux of fast neutrons leaving the shield should be of the same order as that of the thermal neutrons. The tolerance flux is much higher for the thermal neutrons and, therefore, one needs to consider only the fast neutrons.

In the atmosphere, the number of fast neutrons builds to a maximum at a distance of about two interaction mean-free-paths and then appears to decay exponentially. Citron and Gentner proposed to estimate, from known cosmic-ray-star data, the number of neutrons produced by each primary after two generations of star production within a transition layer taken to be about two mean free paths. This number of neutrons, about 15, was assumed to decay exponentially with the known attenuation length of the cosmic-ray neutrons, suitably corrected for differences of direction and energy of the primary particles and the assumed absence of the $\pi-\mu$ decay in the shield. The attenuation length published by Citron and Gentner is 220 gm/cm^2, which has been considered too large in view of later shielding experiments at lower energies. (I have recently heard, from Dr. Citron,[6] that the published value was in error and that the absorption length actually used for shielding estimates was 180 gm/cm^2.) The spread of the beam was estimated by assuming that half of the secondaries are emitted in the forward 30-degree cone and half are emitted isotropically.

Recently, A. Citron and L. Hoffmann of CERN and C. Passow of DESY have performed shielding experiments using the CERN Proton Synchrotron.[6] I am deeply indebted to Drs. Citron and Passow for providing me with the details of these experiments prior to publication in "Nuclear Instruments and Methods." A 24-Gev proton beam was allowed to penetrate a large concrete and earth shield. The density of stars, produced in nuclear emulsions distributed throughout the shield, was measured. In one experiment using the full width of the synchrotron beam (± 12 cm horizontal, ± 4 cm vertical), the measured star density was found to rise to a maximum, at 180 gm/cm^2, of 3 times the initial value. It dropped down again to the initial value at 550 gm/cm^2. From there on, the absorption was roughly exponential with an attenuation length of 145 ± 10 gm/cm^2.

A second experiment, using a collimated beam, showed a smaller initial rise and a stronger subsequent attenuation. The authors point out that the faster attenuation, associated with the collimated-beam experiment, is caused by the geometrical scattering of the beam. This scattering is also present in the full-beam experiment but to a smaller extent. In this sense the attenuation length of 145 gm/cm^2, for the wide-beam experiment, represents a lower limit for the true attenuation length.

III. THE 1957 NEW YORK SHIELDING CONFERENCE

In 1957, a shielding conference for high-energy accelerators, sponsored by the U. S. Atomic Energy Commission, was held in New York. At this conference, the shielding facilities of 21 existing and planned high-energy accelerators were presented and discussed. Theoretical papers were presented by O'Neill, Williams, Moyer, Lindenbaum, Blizard, Livingston and Panofsky. The published report of this conference[1] contains most of the known concepts needed for shielding calculations.

If one is going to rely on the idea of a buildup and subsequent decay of the penetrating radiation, one must estimate the amount of the buildup. The work of Citron and Gentner, mentioned above, presents one method. At the conference, Moyer[7] presented a method for estimating the total amount of radiation of various kinds that should accompany each surviving primary particle throughout the shield.

The number of primary interactions, that occur within the last thickness x of the shield, is given by the formula:

$$n\ (x) = \phi_1\ (e^{x/\lambda} - 1) \qquad (2)$$

where ϕ_1 is the number of particles that survive passage through the shield, and λ is the mean-free-path for nuclear interactions. If one knows the number and energy distribution of the particles produced in a nuclear interaction, one can select the effective depth x from which it is possible for these secondaries to emerge. Thus, one determines the number of first-collision particles accompanying each surviving primary. In order to estimate the total number of particles of all kinds that accompany each surviving primary, Moyer made estimates based on the known relative intensities of the different components outside a well-shielded synchrocyclotron.

Moyer arrives at a total of 77 fast neutrons for each surviving primary throughout the shield for 6-Gev incident protons. The value used by Citron and Gentner for each 30-Gev incident proton, at two mean-free-paths within the shield, was 15 neutrons. In comparing the two results, it should be noted that e^2 primary protons would be required to produce one surviving proton at a distance of two mean paths, so that the Moyer figure represents 10 neutrons at the end of the two mean-free-path transition region per incident proton.

If the estimated buildup factor is wrong by a factor of two or three, the estimated shielding requirements will be in error by about one attenuation length, i.e., of the order of 0.4 meters of heavy concrete. However, the determination of the attenuation length is more critical since, normally, a total attenuation of the order of 10^{10} is required. At the Shielding Conference, Lindenbaum presented data on the attenuation of the high-energy penetrating charged particles through a heavy concrete shield with 3-Gev incident protons.[8] The attenuation length, for the region of the shield in which the incident beam had an energy of 1 to 2 Gev, was measured to be between 130 and 150 gm/cm^2. There was some indication that the attenuation length was somewhat larger in the higher-energy portion of the shield.

O'Neill presented the results of a Monte-Carlo calculation for 3-Gev protons incident on iron.[9] Only single interactions within the nucleus were considered and assumptions had to be made about the amount of energy remaining in the nucleus and the relative direction of the two emerging nuclei. An attenuation length of about 160 gm/cm^2 was obtained using 150 cascade histories. If one considers the $A^{1/3}$ factor for the expected difference in mean-free-paths, it is perhaps understandable that the attenuation length for iron is somewhat larger than the value for heavy concrete.

A solution of the "skyshine" problem was presented by Lindenbaum.[10] The main feature of the calculation is that any radiation directed upward from a target source will, because of air scattering, be attenuated radially as $1/r$. The direct radiation through the shield is attenuated as $1/r^2$. Hence, the amount of radiation at large distances is controlled mainly by the radiation escaping over the top of the shield. Therefore, it may be necessary to provide a roof shield over strong sources of radiation.

The shielding of high-energy electron machines was discussed by Panofsky, Livingston, and Williams.[11] The shielding problem is essentially the same as that for proton machines because of the photo-production of high-energy neutrons. The high-energy neutrons prove to be the most penetrating component of the radiation.

In all shield calculations, some concern has been created by the possibility of a high intensity of fast μ-mesons. These particles are extremely penetrating since they are absorbed only by ionization loss at the rate of 2 Mev/cm/cm^2. The mean free path for the $\pi-\mu$ decay is given by the relation

$$\lambda_{\pi-\mu} = 2.5 + 10^{-8}\ \gamma\beta c\ \text{cm}, \qquad (3)$$

where γ is the ratio of the energy of the π-meson to its rest energy, and βc is the velocity of the meson. Within a shield material, the π-μ decay has not been considered important because the mean-free-path for the decay of the more energetic π-mesons is much larger than that for nuclear interaction. The very low-energy π-mesons produce such low energy μ-mesons that they are stopped within the shield. There may still be a problem for the mesons created near the ends of long shields. Certainly any air path between a thick target and the shield can be a source of high-energy μ-mesons. Most estimates have indicated that the shield required for the μ-mesons produced in a few feet of air may be of the same order of magnitude as the shield required for the neutron absorption.

IV. RECENT CALCULATIONS

One result of the discussions at the New York Shielding Conference was the decision to sponsor a calculation program for shielding purposes. This program is now being carried out in various stages at the Oak Ridge National Laboratory. I have recently received a communication from Clayton Zerby giving an outline of the program.[12] Most of the calculations are in the development stage, and only short progress reports on a few of them have appeared in the annual reports of the Neutron Physics Division at Oak Ridge. The names listed below are the people most directly involved with the calculations at the present time.

A program for calculating the "Transport of High-Energy Particles Through Shields" is being developed by C. Zerby, R. R. Coveyou, and W. E. Kinney. This will be a basic shielding calculation of the penetration and reflection of high-energy radiation from shields with slab geometry. It is planned that the calculation will include consideration of all the important secondary radiation, with all types of source particles having energies up to 50 Gev. It is a Monte-Carlo calculation that will require a considerable amount of basic information on the interaction cross sections.

The interaction cross sections will eventually be given by a nuclear-cascade calculation being performed by H. W. Bertini and C. Zerby. This is also a Monte-Carlo calculation which includes a very elaborate model for the nucleon-nucleon and π-nucleon interactions. The isobar model, of Lindenbaum and Sternheimer,[13] for pion production is used. At the highest energy range, they plan to include a statistical production model such as that proposed by Hagedorn.[14] The variation of the nucleon density inside the nucleus is taken into consideration. Different well depths, corresponding to the differences in density, are used for protons and neutrons. Some preliminary results on the total inelastic cross sections, and their comparison with experiment, have already been published.[15] The calculation eventually will provide the angular distribution and energy spectrum for the emitted particles.

Detailed information on the nuclear evaporation, after a nuclear cascade has occurred, will be calculated by L. Dresner in another program. Monte-Carlo methods will be used in this program also.

Another program, being developed by W. S. Snyder and J. Neufeld, will determine the spatial distribution of the biological dose in tissue, resulting from the penetration of high-energy particles. The dose will be given in REM units. The principal purpose of this calculation is to help determine safe dose tolerances for high-energy radiation.

R. G. Alsmiller and F. S. Alsmiller plan to solve, numerically, an approximation to the Boltzmann transport equation. Cosmic-ray data will be used in this method for solving the penetration of high-energy particles through shields.

Finally, a calculation of the electron-photon cascade, at various depths within a shield, will be performed by C. Zerby and H. S. Moran. The source radiation will be either photons, electrons, or positrons at any energy up to 50 Gev.

When these calculations are concluded, one will indeed have much information for use in estimating shielding requirements. However, the calculations are only as good as existing information concerning the nucleon-nucleon and π-nucleon interaction cross sections. At the highest energies planned for the calculations, experiments will have to be performed to check the models. Thus, again, the information one needs in order to calculate the shielding may not be available until after the machine is built. The advantage does exist that the measurement of the basic cross sections is physically more rewarding than the humdrum shielding experiments which few people ever get around to doing. Also, there is the advantage that the results of the calculations, based on good nuclear models, will provide more detailed information on the penetrating radiation than one is usually able to determine by shielding experiments.

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DISCUSSION

R. F. MOZLEY: I think it might be worth pointing out that an experiment has been done recently at CERN, by Ballam and Lock, in which nuclear emulsions were exposed, behind baryte shielding, to the external, scattered proton beam. These were developed to see minimum ionizing particles and are being scanned by, I believe, several groups but certainly by a group at Livermore under Gilber and Oliver. The difference between this experiment and the others, the one of Citron, is that minimum ionizing particles are visible; also they are trying to get to attenuation factors of over 10^5 as compared with what I believe was a 10^3 attenuation factor in the earlier measurements. The data probably will not be available on the scanning, at least from the Livermore group, until late this fall.

G. K. O'NEILL: I would like to verify that shielding calculations should be taken seriously, by mentioning some early history on this subject. The hand calculation, which was just described by Dr. Crosbie (flat-slab geometry) and which was carried out in 1955, was done by one student in about two weeks, and even that was accurate to about 10 percent. The calculation which was carried out at Princeton by Dr. Tsao, using the earliest available form of the Fortran code on a 704 computer, was done in 1957. It was able to take into account a quite complicated shield design in which the actual iron of the magnet, the shape of the tunnel, the dirt, the concrete and all the rest of the geometrical complexity was actually put into the program. Even in that rather "stone-age" version of computing technology, he was able to do a calculation which we now know, from these recent measurements by Citron, must have been fairly accurate. The buildup factor, the point at which the actual radiation intensity in the shield drops to its value at the entrance to the shield, and also the over-all exponential absorption length, seems to agree quite well. There seems to be good agreement between the recent measurements at CERN and the calculation which Dr. Tsao did. The virtue of the computer calculations is just that they can take account of complex shield geometries, involving many thousands of tons of earth and concrete, whereas the verifying experiments are usually quite restricted in the geometries they can test directly.