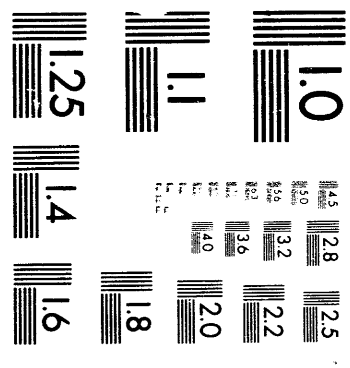
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Practical Aspects of Shielding High-Energy Particle Accelerators

Ralph H. Thomas
Lawrence Livermore National Laboratory
Livermore, California

and

University of California
School of Public Health
Berkeley, California

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Practical Aspects of Shielding High-Energy Particle Accelerators

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LAWRENCE LIVERMORE NATIONAL LABORATORY
University of California • Livermore, California • 94551

Abstract

The experimental basis of shielding design for high-energy accelerators that has been established over the past thirty years is described. Particular emphasis is given to the design of large accelerators constructed underground. The first data obtained from cosmic-ray physics were supplemented by basic nuclear physics. When these data proved insufficient, experiments were carried out and interpreted by several empirical formulae—the most successful of which has been the Moyer Model. This empirical model has been used successfully to design the shields of most synchrotrons currently in operation, and is still being used in preliminary design and to check the results of neutron transport calculations. Accurate shield designs are needed to reduce external radiation levels during accelerator operations and to minimize environmental impacts such as "skyshine" and the production of radioactivity in groundwater. Examples of the cost of minimizing such environmental impacts are given.

Beginnings

The first idea of accelerating protons to very high energy using the synchrotron was developed by Australian born Mark Oliphant during the Manhattan Project.[1] Almost immediately after World War II, proposals were made for the construction of proton synchrotrons at the University of Birmingham, England; at Brookhaven National Laboratory, New York; and shortly thereafter, at the University of California, Berkeley. These early proton synchrotrons were designed with little or no thought for radiation shielding. Beam intensities were higher than expected, and radiation problems were apparent almost from the beginning when the Cosmotron and Bevatron began operation. Hindsight is always perfect, and this now obvious lacuna may be forgiven when it is remembered that the beam intensities anticipated in the initial design of these accelerators were quite low. Accelerator designers were, in this regard, too successful because beam intensities were soon much higher than the design goals.

Today, one would not design an accelerator radiation shield without using one of the many computer programs that can estimate the production, development, and transport of electromagnetic and hadronic cascades initiated by the interaction of high-energy particles in matter. These computer programs have only been available for a relatively short time, with the first primitive codes becoming available in the late 1960s. In a recent paper, Stevenson et. al[2] pointed out that "most proton synchrotrons were built before any cascade simulation codes became available."

Designers were presented with the task of calculating the shield thicknesses of earlier accelerators without knowledge of radiation production and transport or what type of information to expect after these accelerators were designed. This calculation was made using information from cosmic-ray physics and nuclear physics. When the data from these sources proved insufficient, further calculations were made using empirical information from shielding experiments.

The purpose of this paper is to trace the developments of radiation shielding from the late 1950s to the early 1970s—the time during which the data obtained permitted an understanding of the basic phenomena of radiation production and transport. In addition, these developments provided data with which the calculations of the cascade simulation codes might be compared.

The Cosmic-Ray Paradigm

Because of excessive radiation levels around the early proton synchrotrons, radiation shield design became an important component of accelerator design. In the 1950s, basic nuclear physics data (e.g., inelastic cross sections) guided shield design. Extrapolation of these data to higher energies was made possible by studies of the interaction of galactic cosmic radiation with the Earth's atmosphere.

In many ways, the Earth's atmosphere is like an accelerator shield. It is about 1000 g/cm^2 thick—comparable with the thickness of the shield around high-energy accelerators. The atomic composition of concrete and air are not dissimilar. Given these similarities, the production and transport of radiation in the Earth's atmosphere should be very much like the production and transport of radiation in an accelerator shield.

The one practical and significant way in which air differs from concrete is that it is three orders of magnitude less dense. This difference influences the relative development of both the hadronic and electromagnetic cascades, which is fortunate because it makes possible the study of both. The electromagnetic cascade is important for electron accelerators (the development of the electromagnetic cascade in solid materials is relatively unimportant for proton accelerators) and the hadronic cascade is important for proton accelerators.

Thus, it was the studies of the interaction of cosmic radiation with the atmosphere that provided valuable insights into radiation shielding, including data on the radiation attenuation length and neutron spectrum (for a detailed summary on these studies, see Patterson and Thomas[3] and Thomas and Stevenson[4]).

Experimental Shielding Studies

During the 1960s and 1970s, it was necessary to improve our understanding of shield design by empirical means. The accelerators being constructed at that time were used as research instruments. Budgets were limited. The expense of shielding has a significant impact on the facility in which the accelerator may be placed for its primary tasks, and shielding often makes access to the accelerator difficult. Agencies that fund research give lip-service to safety considerations but are usually hard-headed when budgets are scrutinized. Thus, overshielding was to be avoided for economic, political, and practical reasons.

Basic nuclear physics suggested that high-energy particles would be removed by inelastic interactions. Thus, an approximate value for the attenuation length (λ) in matter of density ρ g/cm^3 for these particles would be obtained from the equation[3]:

$$\rho\lambda = 38\ A^{1/3}\ g/cm^2 \qquad (1)$$

The attenuation length obtained from Equation 1 was confirmed by data obtained from measuring the attenuation of the cosmic radiation in the atmosphere. Although of qualitative value, these data were insufficient to predict shielding needs with adequate precision. Thus, empirical data were needed for shield design in the absence of an adequate theoretical basis.

Experimenters drawn from national laboratories around the world collaborated on several studies of the transmission of radiation through shielding materials. The results of these studies have been summarized by Patterson and Thomas[5], Patterson and Thomas[3], and Stevenson and Thomas.[4] The initial focus of these studies was on cascade development in the longitudinal direction (i.e., along the incident particle-beam direction) because of the need to determine the length of "beams stops" in experimental areas. The data obtained showed the longitudinal variation of particle fluence, including the lateral broadening of the radiation profiles. These experiments eventually became so sophisticated that they were able to produce detailed isopleths of particle fluence within the beam stop.[6]

In the mid-to-late 1950s, the first two strong-focussing accelerators were constructed at Brookhaven National Laboratory in New York and at the Centre des Etudes Recherche Nucléaire (CERN) in Geneva. To economize on the costs of the construction and to provide adequate shielding, these accelerators was placed underground. Consequently, shield designers focussed attention on radiation transport in a direction orthogonal to the beam in order to determine the proper depth at which to construct these accelerators.

The design of two large proton synchrotrons at CERN and at FemiLab in Batavia, Illinois, in the mid-1960s provided a stimulus for the most comprehensive accelerator-shielding studies ever made.[7] The data obtained from these experiments, which were carried out at CERN, were so extensive that they are used even today.

Empirical Models

In the absence of an adequate theoretical basis to interpret the extensive data obtained from studies conducted by Patterson and Thomas[3], Stevenson and Thomas[4], and Patterson and Thomas[5], empirical models were developed to permit interpolation and, to some degree, extrapolation of the data. The most widely known and successful of these is the Moyer model[2], which is expressed simply by the equation:

$$H = H_0 \left(\frac{E_p}{E_0}\right)^{\alpha} \frac{1}{R^2} \exp\left(-d/\lambda\right), \quad (2)$$

where H = the maximum dose equivalent rate at a given radial distance (R) from a dump configuration; d = the shield thickness; E_p = the proton energy; E_0 = 1 GeV; and where H_0 and α are constant and have the values, $H_0 = 2.6 \times 10^{-14}$ m^{2}Sv (Ref. 4) and α is about 0.8 (Ref. 9). An extensive review of this model, summaries of the best values for its parameters, and variations of these parameters with energy are given by Stevenson et. al.[8] and Thomas and Thomas.[9]

Considerations for the Radiation Environment

It is important to accurately estimate the radiation intensities outside the shielding to be able to predict the radiological impact that accelerators have on the environment. In general, there are four pathways whereby the general public may be exposed to the ionizing radiation produced as a result of particle accelerator operations[10]:

1. External exposure to "prompt radiation" during accelerator operation.
2. External and internal exposure to radionuclides produced in the air, including dust transported from the accelerator vault.
3. Internal exposure to radionuclides produced in the Earth and in groundwater that migrates to drinking-water supplies.

4. external and internal exposure to radionuclides released into the environment during dismantling or recycling operations.

Only the first and third of these potential sources of impact will be discussed in this paper because they have been well studied. Data on the exposure to radioactive gases and dust are quite reliable.[4] Few studies have been conducted on the radiological impact of recycling accelerator materials; however, that impact is believed to be extremely small.

Skyshine

Observations of radiation scattered by air back to Earth was first reported using early accelerators that were designed with inadequate roof shielding. Neutrons generally dominate this radiation environment. Early observations of the neutron fluence rate, as a function of distance from the Bevatron, showed that the dominating influence was the inverse-square law. Later measurements permitted the development of empirical formulae that predicted neutron dose-equivalent rates at large distances from accelerators.

In general, systematic experimental measurements were not made to study skyshine phenomena. Rather, interpretations were made from a variety of radiation survey data obtained in an ad hoc manner. New data are not forthcoming because radiation control at particle accelerators no longer permits measurable radiation intensities at large distances from accelerators. Thus, the bulk of data available is now very old. Rindi and Thomas[11] have summarized most of the older data available and the qualitative and quantitative interpretations of these data.

Progress in our understanding of skyshine has been aided by the use of neutron and photon transport calculations. Alsmiller et al.[12] tabulated "importance functions" for distances out to 1000 m from the sources of monoenergetic photons and neutrons. The calculations extend up to energies of 400 MeV for neutron and up to 14 MeV for photons. Because the importance functions have only been calculated for limited distances from the source, several authors have developed empirical formulae that are suitable for estimating neutron dose rates for a typical accelerator neutron spectrum.[4,11,13,14] The most recent formula is that of Stapleton et al[14] :

$$H(r) = \frac{a \exp\left[\dfrac{-r}{\lambda(E_c)}\right]}{(b + r)^2}, \tag{3}$$

where $H(r)$ = the dose equivalent rate at distance r from the neutron source. The authors suggest that the values of $a = 2 \times 10^{-15}$ m^{2}Sv, $b = 40$ m, and they give values for λ as a function of neutron energy cutoff.

Recently, Stapleton[15] has focussed on photon skyshine and has shown that simple prescriptions in NCRP Report 51, when corrected for photon buildup and attenuation, give results in fair agreement with those of Alsmiller et al.[12]

In the United States accelerator designers must take account of the requirements to limit annual dose rates to 10 mrem per annum at the boundary of accelerator facilities. Stapleton[16] has estimated that the added cost of doing this for a 4-GeV, 1-MW electron accelerator at the Continuous Electron Beam Accelerator Facility (CEBAF) in Virginia was about U. S. $ 0.7 M.

Radioactivity in the Ground Water

Because accelerators constructed underground may produce radioactivity in the ground and in groundwater, it is important to be able to predict the quantity of radioactivity produced outside any shielding and reduce its production to comply with regulatory limits.

Stapleton[16] has discussed the design of beam dumps at CEBAF and suggested that induced activity may be reduced by the use of underground shielding. To ensure that concentrations of radioactivity are below Virginia's regulatory limit (4 mrem per annum), he estimates that the added cost of concrete shielding amounts to U. S. $ 2.3 M. Clearly, there is a great incentive to ensure that the shielded designs are accurate.

Summary

Experiment Versus Theory

To repeat what has already been said, no one today would design an accelerator shield without using the sophisticated computer codes that are available. These codes have high utility and are capable of calculating complex geometries. They do, however, have an Achilles' heel. Initially, the codes depend on their input data (in the words of a computer specialist, "garbage in, garbage out!") Therefore, one should never allow oneself to depend totally upon theoretical extrapolations. Always check the data obtained by cascade simulation codes against the measurement.

In a recent paper, Stevenson et al.[2] expressed this view in an emphatic way:

> It is useful to recall several Golden-Rules when making detailed simulations of radiation transport for design purposes at an accelerator. One should *never trust a simulation* without a simple cross-check against *e.g.* Moyer model, energy conservation, universal curves, experimental data.......
>
> It is easy to have:
>
> - mis-typed the input
> - made an error in your User-Code
> - used the wrong units
> - be suffering from poor statistics (not evident in weighted Monte-Carlo)
> - used unfair biasing (energy/space cuts without protection)
> - an artifact of the code (energy deposited in the middle of a step, accumulated events on boundary crossings *etc.*)
> - have mis-interpreted approximations used in the code(*e.g.* fixed-angle bremsstrahlung, P3 Legendre expansion for single-scattering)

In all cases it should be remembered that simulations are only as good as the available experimental data.

However the simulation is probably the most accurate step in the assessment process. The beam-loss estimation is often less precise than the simulation. Thus in many cases a quick and purposely simplified simulation which is made in time may be more valuable than a detailed and accurate simulation which may be costly and take years to complete. In all cases the real cost of a detailed Monte-Carlo simulation must be balanced against the extra cost which might be engendered if conservative, empirical methods are used. However, it can in some cases be self-defeating even to offer such detailed simulations when other parameters in the problem are known with much less precision.

Increasingly, the shield designer's task is being made easier by the addition of computer codes. Stevenson et al.[2] have observed that the shielding of most proton synchrotrons in operation today was designed before the development of sophisticated computer programs. In general, the shields of early accelerators have functioned well permitting reliable and essentially trouble-free operations. Thus, these empirical techniques have served shield design well, and even if they are now being supplanted by the computer codes that calculate both radiation production and transport, there will be a continuing need for empirical data and methods for some time to come. Empirical means will be needed both to provide checks of calculated data and to make possible rapid assessments of shielding.

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