IEEE Transactions on Nuclear Science, Vol.NS-23, No.4, August 1976

THE HISTORY OF HIGH-ENERGY RADIATION PROTECTION

Mario Ladu*

The practical application of Roentgen's fortuitous discovery of x rays in 1895 was taken up with amazing rapidity. For example, within three months, x rays were being used to assist surgery in hospitals. Neither did it take long to discover the deleterious biological effects of these rays; the need for protection from their effects became obvious all too soon.

The users of x-ray facilities first and of radioactive sources later, were the first to suffer from the radiation dangers. Physicists and radiologists, in fact, often found burns on their hands which appeared after the exposure to radiation without any premonitory sign. Sometimes these burns appeared serious because of high doses locally absorbed. Immediate precautions were taken to prevent such problems, the consequences of which had not been foreseen because there was no experience on the matter. Therefore, maximum absorbed doses were established for the people exposed to radiation. Initially, these maximum doses were very high; subsequently they were gradually reduced as the knowledge of the somatic and genetic effects of radiation increased.

The maximum permissible doses recommended by the I.C.R.P. find their justification in the past history of radioprotection, the advance of which, at first uncertain and limited in its importance, has subsequently developed and extended itself, thanks to the more and more widespread use of radiation sources in the medical, industrial and scientific research fields. I am not going to speak here about radioprotection in a wide sense, but I think it proper to point out at once that the necessity of specialization on this subject was rather late to assert itself. The first steps to prevent the dangerous effects of radiation were, in fact, empirical, even though the importance of some basic factors in radioprotection, such as the duration of the exposure, the distance from the source and its shielding was already known. Practically, radioprotection began leaving empiricism only in 1942, when the term "Health Physicist" was first introduced implying precise tasks, such as the resolution of specific problems, at the base of which there were particular competences not yet defined or organized as they are today.

The term "Health Physics" was coined in the Metallurgic Laboratory of the Chicago University in 1942, to indicate, substantially, a new science, between Physics and Radiology, devoted to the study of problems and to the development of every means to reduce to a minimum the absorbed dose and the exposure dose rate.

*University of Cagliari
Cagliari, Italy

It was in the summer of 1942 when E. Fermi began assembling the first uranium pile; it went into operation on December 2 of the same year, with a power of 200 W, each watt being equivalent to 3.1×10^{10} fission/sec, each fission producing about 200 MeV of energy. On the basis of what was known about the biological danger of radiation and taking into account the pile power and the consequent levels of radiation, it was decided to organize a group of health physicists and this was the first one. Immediately this group had to face new problems, such as testing of radiation protection devices, developing new survey and monitoring instruments, determining the exposure at the surface of a large sheet of uranium, testing shields, calculating radiation absorption and scattering in materials, setting tolerance levels for various kinds of radiation exposure to man, and checking and assisting in the design of new piles and radioisotope separation plants to be constructed.

At that time no serious protection problem around the accelerators was yet felt, although the first cyclotron had already been constructed by Lawrence in 1931 and the Cockcroft-Walton and Van de Graaff accelerators had been in operation since 1932. However, these machines did not yet present any serious radioprotection problems largely because of their low intensity and energy. With some care and empiric interventions, it was possible to work with these machines with acceptable margins of safety. But the increasing progress of nuclear physics and the necessity of disposing of higher and higher energy and intensity in order to have a better exploration of atomic nuclei, impelled the physicists to study and develop more and more powerful accelerators.

There was, in effect, a transition period during which the physicists, studying high-energy reactions, made use of cosmic rays; this was a golden period for high-energy physics: study of showers, important results on the mesons, strange particles, tracks of heavy nuclei -- in short, much information was amassed. However, it did not allow the physicist to gain rich statistics from which to draw reliable conclusions and confirmations of the developing theories. At this point physicists thought again of accelerators and studied all the problems that might allow them to increase the efficiency of the machines. So in a relatively short period of time, accelerator study gained momentum again with remarkable results. It became the period of great machines, with more powerful cyclotrons, betatrons, proton and electron synchrotrons, and linear accelerators, followed by the present-day machines, such as tandem accelerators, bevatrons, storage rings, etc. which are now reaching a very high degree of perfection.

No silence should be maintained on one very important fact. Studies on the various problems connected with radioprotection around accelerators did not proceed at the same pace as the technical development of the great machines themselves. I mean that radioprotection in its various aspects was taken into consideration only after the machine construction. In particular, the shieldings were put in place in a very empirical way, often with excessive costs which might have been avoided if shielding calculations had been previously made. Accelerators were often placed in underground tunnels and only subsequently was the shielding efficiency checked; it would be re-checked when there were radiation leaks. Sometimes the accelerator was ready to work, but it was kept off for a while because the shielding had not been planned in time.

With the second generation accelerators, those between 1950 and 1960, the situation changed completely and the health physicists became important, starting with the planning phase of the great machines. In those years, the knowledge about radiation dangers was limited. One of the most evident dangers -- the cataracts which were to be ascribed to neutrons which struck some researchers -- was the result of inadequate shielding and a lack of minimum precautions and care. Nowadays, the health physicist participates directly in the planning of construction and shielding of accelerators and, as a result, such errors and dangers are greatly minimized.

It might seem, from this part of my talk, that the duty of health physicists may be completed with the shielding; but it is not so. Their tasks, in fact, are manifold and different problems are posed by the various types of accelerators, according to their intensity and energy. These specific problems have been discussed more than once, in meetings and congresses, to which various specialists have brought remarkable contributions of experience and ideas. I will list the problems which seem to me the most important or even fundamental. They are the following: 1) shielding; 2) skyshine; 3) induced activity; 4) production of toxic and radioactive gases.

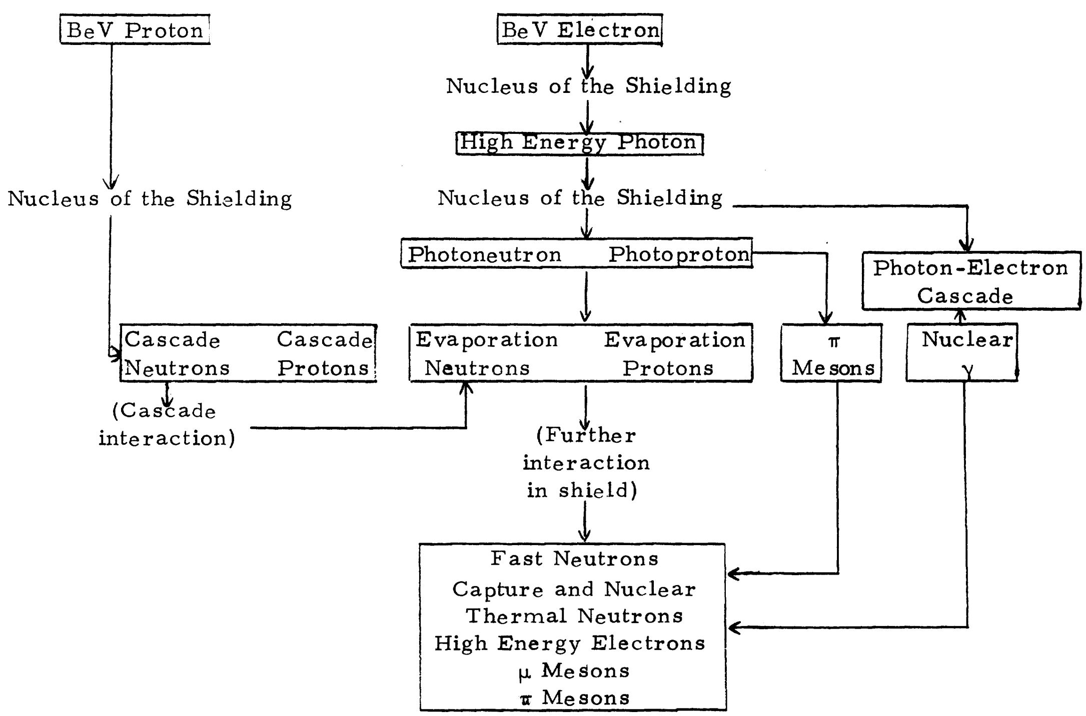
To these we have to add the various problems posed by detection and measurement in mixed fields of radiation, by pulsed fluxes, by RF, and, particularly, by the detection of neutrons in a wide range of energy, which contributes in a remarkable measure to the radiation level around the accelerators.

In examining these problems, I will not go into detail; they will be treated in subsequent lectures, and they will certainly be treated with greater competence than mine.

I must also remark that what I will be saying refers, in a particular way, to the problems of protection around the accelerators of the last generation, since the earlier ones imposed certainly minor problems because of their low intensity and energy.

Why give so much importance to the problem of shielding? Because, obviously, a full exploitation of the accelerators requires a first-rate protection against diffused radiation. The fundamental basis for effective radioprotection is the shielding, which must be specifically designed to ensure that the radiation levels never exceed the maximum permissible values in areas where people are working.

A suggested scheme, although incomplete, of the interactions caused by high-energy primary protons and electrons and by the secondary radiation around accelerators is the following:



An accurate computation of the shielding for high-energy accelerators is rather difficult, owing to the complexity of the physical phenomena which must be taken into account. In any case the main shielding problem is posed by high energy neutrons, and when these particles are well attenuated, any other component of the diffused radiation field will practically disappear. The only exception could be represented by μ mesons, which lose their energy only by ionization and can pass through shielding slabs which would normally stop all the other particles.

In order to attenuate the fast neutrons, it is not necessary to make complicated and detailed calculations. Many results can be derived in fast, simple ways.

For instance, to calculate the attenuation in concrete, Patterson used the equation

$$I_t = I_o \exp(-N \sigma_a t) \qquad (1)$$

where N is the number of atoms/cm^3 which depend on the particular type of concrete and σ_a is the attenuation cross-section in removing a neutron during its passage through a slab of thickness t.

The points calculated by Patterson for concrete, solving equation (1) for the value of t required to give a 50% reduction are shown in Fig. 1.

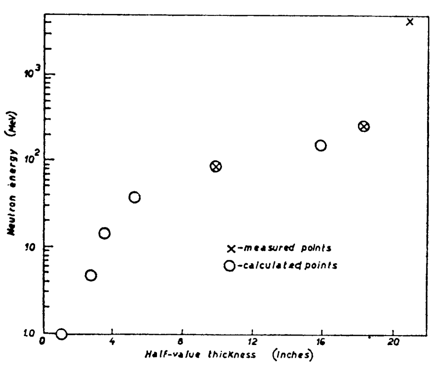


Fig. 1.

Some phenomenological and theoretical methods of shielding calculations have been described by Lindenbaum in 1961 and 1962. For the attenuation of a monochromatic parallel neutron beam incident on an infinite plane slab, he obtained the following expression

$$\Phi(X) = \Phi_o \exp(-X/\lambda_p) \qquad (2)$$

where λ_p is the mean free path for effective removal of the primary component.

If n is the number of interactions required to remove a primary particle, he gives for the flux after n interactions, the relation

$$\Phi_n(X) = \Phi_o \beta_n (X/\lambda_p) \exp(-X/\lambda_p) \qquad (3)$$

where β_n is the particle buildup factor which can be obtained from nuclear star data.

Another simple method for shielding calculations is that proposed by Moyer for a beam of 10^{13} protons per pulse at 6.2 GeV of energy. He considers a production of 20 neutrons per incident proton in 100 g/cm^2 copper target. Then, in order to calculate the attenuation thickness, he takes into account only the angular distribution of those neutrons whose energy is higher than 150 MeV. Neutron attenuation by concrete is shown in Fig. 2

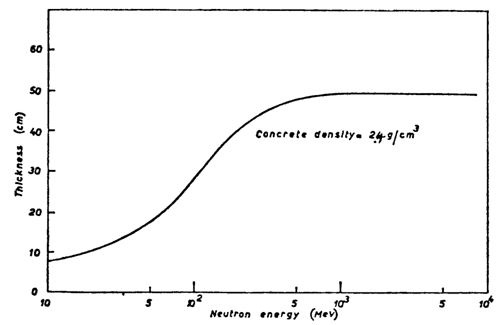


Fig. 2.

The attenuation thickness for high-energy neutrons (E_n > 300 MeV) is almost constant, while it is a rapidly increasing function of E_n between 100 and 300 MeV.

The half-value thickness for material commonly used in shields are given in the following table:

Materials:	Earth	Concrete	Iron	Lead
Half-values at 100 MeV (in.)	15	10 (measured)	4.5	4.5
Half-values at 300 MeV (in.)	25	18 (measured)	8	8

An attenuation curve for the total number of neutrons per incident electron as a function of shield thickness in ordinary concrete is given in Fig. 3.

This curve was calculated by Panofsky for the attenuation of the neutron component of the 45 GeV electron accelerator with 2.10^{13} electrons per second.

I cannot dwell longer upon this subject, I just wanted to touch in the spirit of the content of my lecture. Dr. Thomas, on the other hand, will speak about the same subject with greater competence than mine and with more particulars.

I must, however, touch other problems connected with shielding, but I will be very short.

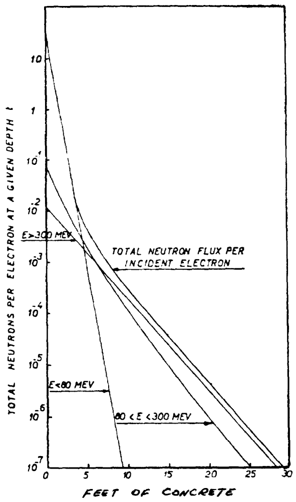


Fig. 3

The problem of π mesons is the same as that for the neutrons. The μ mesons, however, having a negligible small cross section for nuclear interactions, can lose their energy only by ionization. The rate of energy loss for these particles at relativistic velocities is very small, while the penetration depth is directly proportional to the energy.

Hence, for multi-BeV accelerators the shielding required to reduce the diffused radiation to permissible levels is not sufficient to absorb completely the energy of μ mesons. On the other hand, as they are mainly caused by the decay of π mesons, it is possible to remove their background by placing a shielding made up of high density material near the target where the π are produced. This shield must be sufficiently long to attenuate the forward collimated beam through nucleonic interactions.

Connected to the shielding problem is that of skyshine effect and that of the beam catcher. The first one, very important for the neutrons, has been studied phenomenologically by Lindenbaum. He concludes that at a distance r from the source, there are two components of the flux: one (direct) which decreases as $1/r^2$ and another (scattered) which decreases and $1/r$. From many experimental surveys, it was concluded that all the accelerators producing a neutron source larger than 10^9 n/sec require upper shielding.

As far as the beam catcher is concerned, the problem is serious for high-power beams. In this case the beam catcher can be made up of a stainless steel tank filled with rapidly circulating water, so as to avoid local heating. The beam penetrates into the water which attenuates its various components and especially the neutrons.

Another serious problem, when the energy and the intensity of the beam is sufficiently high, is that of induced radioactivity. At the energy of the order of a few hundred MeV we have a wide variety of possible interactions. The cross section of the nuclear reactions occurring at these energies can be assumed to be proportional to the geometrical dimensions of the hit nucleus. The highest degree of activation is obviously in the targets, collimators, deflectors and their surroundings. However, it should be borne in mind that any part of the accelerator and of the auxiliary plants can be activated, owing to the presence and the scattering of high and mean energy neutrons and to the direct interactions of the particles lost during the acceleration. It is reasonable to assume that the higher the current of accelerated particles, the more intense will be the induced activity.

Residual radioactivity constitutes a serious protection problem whenever the machine must undergo maintenance and repair work. In this case remote-handling systems are required for target changing and for all other special and routine operations.

The number of activated nuclei relative to 1 g of exposed material as a function of the incident flux is given by the equation

$$N_i(t) = \Phi \sigma_i \frac{N}{A} \int_0^t \exp(-\frac{t-\tau}{T_i})\, d\tau$$

The number is referred to a certain isotope i at time t. Φ is the flux of incident particles, t is the time during which the sample has been exposed, σ_i is the cross section in cm^2 relative to the production of the element i, N/A is the number of atoms per gram of the substance exposed, and T_i is the time-constant to decay to 1/e of the activity formed; The activation has been evaluated numerically for different elements: O, C, Al, Fe, Cu, Co, Zn.

Induced activity measurements have been made around many accelerators, and, from the experimental as well as theoretical results, we can conclude that it is possible to minimize the intensity of the induced activity by a careful choice of the materials subjected to the beam bombardment. Of course, the radioprotection problems posed by the presence of induced activity become gradually more serious as the energy and the intensity of the beam increase. This involves both a careful choice of the material to be employed around the accelerators and the development of control systems and devices, which make possible safe conditions for work from the radioprotection viewpoint.

As far as the production of radioactive and toxic gases is concerned, the problem is important for the high-power electron accelerators. The production of radioactive gas, especially O^{15} and N^{13}, is common for all electron accelerators which produce bremsstrahlung radiation intensity with energy higher than 20 MeV. The production of toxic gas, especially O_3 and NO_2, is important both around high intensity electron accelerators and near high activity gamma sources.

For the production of radioactive gas, it is reasonable to take into account only that coming from isotopes which are more abundant in the air, like N^{14}, O^{16} and A^{40}. The data relative to these isotopes and their activation are the following:

Initial nucleus	% in air	Re-actions	Final nu-cleus	$T_{1/2}$ (min)	Decay pro-ducts	Cross-sections (mbarn)
N^{14}	78.1	(γ, n)	N^{13}			
		$(n, 2n)$	N^{13}	10.1	β^+	2.5
		$(\gamma, 2np)$	C^{11}	20.4	β^+	0.05
O^{16}	21.2	(γ, n)	O^{15}	2.1	β^+	16
A^{40}	0.46	(γ, np)	Cl^{38}	37	β^-, γ	20

The maximum admissible concentration for these radioactive isotopes in the air is 0.5 pCi/cm^3.

The disposal of radioactive and toxic gases in the atmosphere by means of proper ventilation of the rooms is another important problem. In fact, in the rooms where the radiation level is so high as to create strong concentrations, it is not possible to enter immediately after the machine has been stopped; it is necessary to wait until concentrations are lower than the maximum permissible values.

The calculations carried out prove that the disposal of O_3 alone and its reduction to admissible concentration values creates the necessary conditions regarding the concentration of other toxic and radioactive gases. This is easily understandable if we think of the low value of the maximum admissible concentration of O_3. The following formula gives the time t in hours required to reduce O_3 concentration up to a value C after the machine has stopped:

$$t = \frac{2.3}{n} \ln C_1/C$$

where n is the number of air changes per hour and C_1 is the O_3 concetration in ppm at the momentum when irradiation stops. Typical results are given in the following table.

Ventilation for Electron Accelerator Delivering 0.1 kW of Radiation Power to the Air in a Room 10^4 ft^3 in Volume

Air changes per hour	O_3 level during irradiation (ppm)	Minutes after irradiation for O_3 level to reach 0.1 ppm
180	0.1	0
100	0.18	0.2
50	0.36	1.5
25	0.71	4.7
10	1.8	17
5	3.6	43

Since the smell of O_3 can be detected at 0.1 ppm or even less, an accelerator room can be entered immediately after the smell has disppeared.

The safety and radiation protection problems posed by high-energy accelerators and in general by high-energy radiation have not been exhaustively dealt with in this lecture. There are other important problems which I want to touch. They will be more fully discussed in subsequent lectures.

Allow me to list them briefly. They are specific problems that are imposed on physicists, who are obliged to use accelerators having higher energies and intensities. On of the problems is the disposal of radioactive gas and water. This requires consideration of the safety of the population living in the neighborhoods of the accelerators.

As far as the air and any radioactive dust are concerned, the problem can be generally solved by using adequate filters. As regards the water employed for cooling or other technical requirements, its maintenance in closed loops is normally thought of as a good solution.

Another very important problem is the instrumentation necessary for the measurement of radiation levels, taking into account their components and energies, the pulsed fluxes and any other factor that, however, contributes to create the particular mixed fields around the accelerators.

Finally, it is not possible to neglect the radiobiological problems raised by the great machines, especially as regards the correct evaluation of the dose equivalent, which sometimes requires flux density and spectra measurements; there is no instrument with direct reading of the dose equivalent in any field of radiation.

I would like to add that, as regards the biological effects of high-energy radiations, there is still much information to be learned in addition to that already available.

Still on the subject of high energy radiation, a separate mention must be made of the radiation fields in spacecraft and the relative doses to personnel on space missions, a subject treated in some recent international congresses and to which in this school, specific lectures are devoted.

Before closing I would like to say that I have not treated the proposed theme exhaustively, not even having touched on the history of high-energy radiation protection.

On the other hand, the subject is, by itself, impossible to treat in a single lecture. However, I think I have included, in a wide view without details, many of the problems connected with radioprotection around accelerators.

It is very difficult to say what the future holds for health physicists regarding protection against high-energy radiations. It is not impossible that a new generation of accelerators will be created having energies and intensities higher than those reached so far. It is not impossible that new and more difficult problems will be imposed on health physicists by space research.

Anyway it is to be wished, above all, that the relations between the accelerator and space researchers and the experts responsible for radioprotection will be always based on a spirit of close and friendly cooperation, with the common aim of attaining the best possible results, in the interest of scientific research.