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PROBLEMS OF SAFETY AND RADIATION PROTECTION AROUND HIGH-ENERGY ACCELERATORS

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INTRODUCTION

Over the past years remarkable progress has been achieved in the field of high-energy physics, thanks to the ever-increasing use of large particle accelerators. These machines, whose technology is steadily improving, supply the physicists with particle beams of growing intensity and energy. The actual cost of these powerful means of investigation is very high; it is therefore natural that they ought to be exploited in the most suitable way—in other words, be operated for periods of time as long as possible and under conditions of maximum efficiency.

Obviously, a full exploitation of these accelerators requires a first-rate protection against diffused radiation and any other sources of damage they give rise to. The fundamental basis for an effective radioprotection are the shieldings, which must be specifically designed to ensure that the radiation levels never exceed the maximum permissible values in areas where people are working.

As is well known, such values were established by the I.C.R.P.(48) and represent a safety limit for the radiation dose which a person may absorb without suffering any appreciable injury. The maximum value of permissible dose is 5 rem per year. Thus, the mean dose per week would amount to 100 mrem, which corresponds to a mean dose of 2·5 mrem/hr, on the assumption that a week has 40 working hours. Anyway, it is admissible that a total amount of 3 rem be absorbed by a person in 13 weeks, always provided the limit is 5 rem per year. If a dose of 3 rem is absorbed during a single exposure, the said amount represents also the maximum permissible dose in one year. The shielding cost for a large accelerator normally represents a considerable portion of the machine's total cost. This fundamental problem should therefore receive due consideration and be most accurately evaluated at the initial designing stage. At the same time, all the other safety problems must be seriously studied, so as to achieve a thorough and full-time exploitation of the accelerators.

In recent years the problem of radioprotection around high-energy accelerators has assumed a growing importance, owing to the increase both in energy and intensity of the particle beams involved. This fact is, of course, especially related to the biological effects of high-energy radiations, a topic on which we no doubt require far more information in addition to that already available.(1–2, 8–10)

Other important problems connected with radioprotection are the induced activity as well as the production and disposal in the atmosphere of the toxic and radioactive gases. The first one is a problem common for all types of accelerators, while the second concerns mostly electron accelerators. Another essential point is the construction of the beam catcher, especially in the case of high-power beams, like the ones which are now obtainable with linear accelerators.

Some recent congresses(11, 28) were devoted to the various aspects of protection around accelerators.† They helped clarify many important questions, in particular those whose solution will lead to the best use of these machines. At this point we should like to stress that, apart from the specialists' justified interest, this field ought to draw greater attention from the high-energy physicists, since it concerns the safety conditions of their own research work.

DIFFUSED RADIATION AROUND THE ACCELERATORS

The radiation field around high-energy accelerators is generally rather complex. It does not depend solely on the type of accelerated particles and on their energy, but also on the nature and thickness of the targets and of any other material which interacts with the primary beam.

From the protection point of view, however, the principal field components still remain the electromagnetic radiation and the neutrons.

The bremsstrahlung radiation constituted the main contribution to the electromagnetic field. High- and low-energy γ yielded in cascade processes or in excitations of nuclear levels, even though always present, give a contribution of minor importance. Also the capture γ-rays,(5) produced by (n, γ) reactions owing to the absorption of slowed neutrons inside the shielding, have a secondary importance.

The neutron component, in the case of the electron accelerators, is caused by a photoproduction process and the produced neutrons are usually subdivided into a low-energy group ($E < 80$ MeV) and high-energy group ($E > 80$ MeV).‡

The most important in the first group are the giant resonance neutrons produced by a (γ, n) reaction. Their mean energy is about 5 MeV and their distribution is practically isotropic. The production cross-section has a very pronounced maximum for incident photons whose energy lies between 15 and 20 MeV.(42)

The production of these neutrons for a primary electron of energy E_0 in an absorbing material of atomic weight A can be obtained from the relation:(49)

$$Y(n)_r = \frac{NX_0}{A} 10^{-24} \int \sigma(k)\, g(E_0, k)\, \mathrm{d}k \ (n/\text{electron}), \tag{1}$$

where $Y(n)_r$ is the number of neutrons per electron, N is the Avogadro's number, X_0 is the radiation length in g/cm^2 relative to the material, $\sigma(k)\mathrm{d}k$ is the cross-section for the production of neutrons by incident photons whose energy lies between k and $k + \mathrm{d}k$ and $g(E_0, k)$ is the track length.

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† Another congress, sponsored by the U.S.A.E.C., was held at Brookhaven National Laboratories from 3rd to 5th November 1965. The main papers contributed were dealing with the various aspects of safety conditions around accelerators.

‡ The above subdivision is somewhat arbitrary and it is based on the fact that for the first neutron group the attenuation in absorbing materials is nearly the same as for fission neutrons while for the second group the attenuation in the same materials is much lower.

The $Y(n)_r$ value relative to the giant resonance can be easily deduced from equation (1) by substituting the appropriate value of the energy for E_0.

The high-energy neutrons, on the other hand, are produced by direct interaction of the photons with the nucleons. Such a process can be explained by means of the "effective deuteron" model developed by Levinger.(31) The number of neutrons per primary electron, $Y(n)_p$, can be obtained by suitably using equation (1). It is necessary in fact to introduce in equation (1) the track length and the cross-section for high-energy neutron production in the material. This cross-section is obtained as the product of the actual number of deuterons in the absorbing material and of the photodisintegration cross-section of deuterium $\sigma_p(D)$. $\sigma_p(D)$ is almost constant and equal to 7×10^{-5} barn between 80 and 300 MeV, while for energy values between 300 and 900 MeV(55) it depends on the energy given by the relation $\sigma_p(D) = 6/k^2$ (barn).

Thus, by integration we obtain:

$$\int \sigma_p(D)\mathrm{d}k = \int_{80}^{300} 7 \times 10^{-5}\,\mathrm{d}k + 6\int_{300}^{E_0} \frac{\mathrm{d}k}{k^2} \text{ (MeV barn).} \tag{2}$$

As an example we have reported in Table 1 the values of $Y(n)_r$ and of $Y(n)_p$ for 1 BeV primary electrons relative to three different materials.

TABLE 1.

Photoneutron Yields from 1 BeV Electrons(36)

Neutron/electron	Concrete	Iron	Lead
$Y(n)_r$	0·18	0·27	0·23
$Y(n)_p$	0·58	0·30	0·09

In the case of the proton accelerators the low- and high-energy neutrons are mainly produced by nuclear disintegrations caused by a high-energy primary, with the consequent production of a large number of charged and neutral particles. This number depends on the energy of the primary and on the hit nucleus mass. The interaction occurs with the production of a nucleon cascade and the almost instantaneous expulsion of those nucleons whose energy exceeds 30 MeV.(56) This phenomenon is followed by the well-known evaporation process(29) with emission of charged and neutral particles whose energy is less than 30 MeV. Such an interaction can give rise also to the simultaneous emission of mesons and heavy fragments and is generally accompanied by a γ-ray production.

The nuclear emulsion technique enables us to determine and classify the charged particles according to their energy. On the other hand, statistical considerations makes it possible to evaluate the number and energy of the neutral particles which do not leave any visible track on the nuclear emulsions. Their number is almost equal to that of the charged particles.

Table 2 reports the average composition of a star produced by a 6 BeV proton in concrete and shows how the energy of the incident particle is subdivided among the various interaction products. These calculations were performed by Moyer(38) on the assumption that the 6 BeV proton mean free path in concrete is equal to 130 g/cm², i.e. almost the same as for primary cosmic rays in the air.

TABLE 2.

Distribution of Particles and Energies of a 6 BeV Proton Star in Concrete

Particles	Energy (BeV)	
Evaporation 4 protons 5 neutrons	Total kinetic energy	0·2
Cascade or recoil 3 protons 2 neutrons	Total kinetic energy	3·0
2 charged 1 neutral	Total energy	2·6
	Binding energy of 14 nucleons	0·2

Another of Moyer's calculations gives the various components accompanying each surviving 6 BeV proton reported after having passed through an ordinary concrete thickness. The results are reported in Table 3.

TABLE 3.

Estimated Radiation Accompanying each Surviving 6 BeV Nucleon

Protons from cascade and evaporation	4
Charged π	3
Muons	0·3
Neutrons from cascade and evaporation	7
Slow neutrons	70
Electrons	10(?)
γ	3×10^{-4} mr

The thermal and skyshine neutrons are also part of the neutron field; but it may be said that they do not constitute a serious protection problem, unless they are added to a background radiation not far from the maximum permissible values. The thermal neutrons are mainly generated inside the shieldings and their maximum permissible flux is rather high.(48)

The skyshine neutrons whose phenomenology has been studied by Lindenbaum(32) are those which, initially emitted upwards, undergo collisions with the air nuclei and are scattered towards the ground. They may be found also at large distances from the accelerators, but in this case their flux is rather low.

Together with the γ-rays and the neutrons, depending on the energy, there is always a production of charged and neutral pions, caused by photoproduction or by nucleon interaction.

In the case of the photoproduction they can be subdivided, as were photoneutrons, into a resonance group and a direct production group.

The resonance peak occurs at about 300 MeV with a cross-section of approximately 2×10^{-4} barn.(18, 19, 37)

At energies higher than 500 MeV the photoproduction cross-section is constant and equal to 6×10^{-5} barn.(7)

We may calculate the quantities $Y(\pi)_r$ and $Y(\pi)_p$ referred to a 1 BeV primary electron, by introducing the suitable values in equation (1). In Table 4 we report some values of $Y(\pi)_r$ and of $Y(\pi)_p$ for various materials.

TABLE 4.

Photopion Yields from 1 BeV Electrons(36)

Photopion/electron	Concrete	Iron	Lead
$Y(\pi)_r$	1×10^{-3}	2×10^{-3}	4×10^{-3}
$Y(\pi)_p$	1×10^{-3}	5×10^{-4}	2×10^{-4}

When the pions are generated in nucleon interaction, their production starts being appreciable for energies higher than 300 MeV; as for primary energies above 1 BeV, their production can become multiple, as occurs in those processes which lead to the disintegration stars.(56)

Diffused radiation can comprise also μ-mesons originated by photoproduction processes or by π-mesons decay and other particles, but up to now they do not represent a serious problem from the protection point of view although it is not to be excluded that they may do so in the near future.

A suggestive scheme, although incomplete, of the interactions caused by high energy electrons and protons and of the diffused radiation around accelerators is shown in Fig. 1.(50)

SHIELDINGS

An accurate computation of the shieldings of high-energy accelerators is rather difficult, owing to the complexity of the physical phenomena which must be taken into account. We are thus compelled to use simpler descriptions of the phenomena and some reasonable approximations which are many cases due to the insufficient knowledge we have about interaction cross-sections at high energies. In any case by avoiding an excessively thick or insufficient shielding it is possible to obtain fairly reliable results. Of course, excessive shieldings are too expensive, while insufficient shieldings lead to a waste of time. In the latter case it usually becomes necessary to further improve protections around the machine.

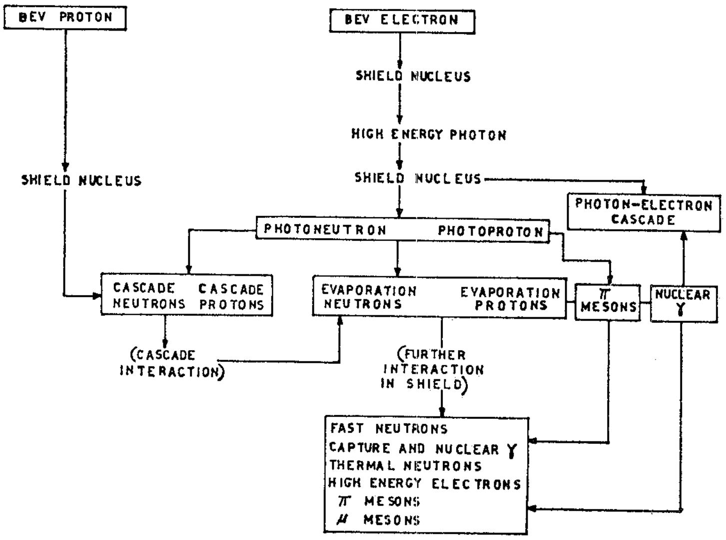

FIG. 1. Stray radiation production from high-energy particle accelerators.

We would also like to point out that in such areas as are reserved to experiments, the shielding must minimize the background radiation up to limits consistent with the experiments being conducted. This would require mobile shieldings, readily adaptable to any experiment requirement.

As regards radioprotection, the thickness of the shieldings ought to be designed in such a manner as to ensure the maximum permissible radiation levels—lower than the current ones, since we cannot exclude that the present maximum values will be further reduced, in case our knowledge about the biological effects of radiation improves in the meantime.

No general method exists as yet for calculating the shieldings of high-energy accelerators. There are, on the other hand, a few phenomenological considerations which make it possible to develop the problem in relatively simple terms.

In any case, the primary radiation incident on the shieldings gives rise to an electromagnetic or to a nucleon cascade, with the consequent production of secondary radiation.

The attenuation of the various cascade components and of any other radiation they produce depends on their nature and energy. The attenuation thicknesses are, of course, related to these two factors and to the characteristics of the shielding material. We do not propose to give here a detailed description of the suggested methods for shielding calculations since this is beyond the scope of our present article. We will therefore confine ourselves to mentioning only briefly here what has been done by some of the most experienced researchers in this field. For more details on the many aspects of the problem, the reader is referred to the bibliography.(11, 28, 33, 51).

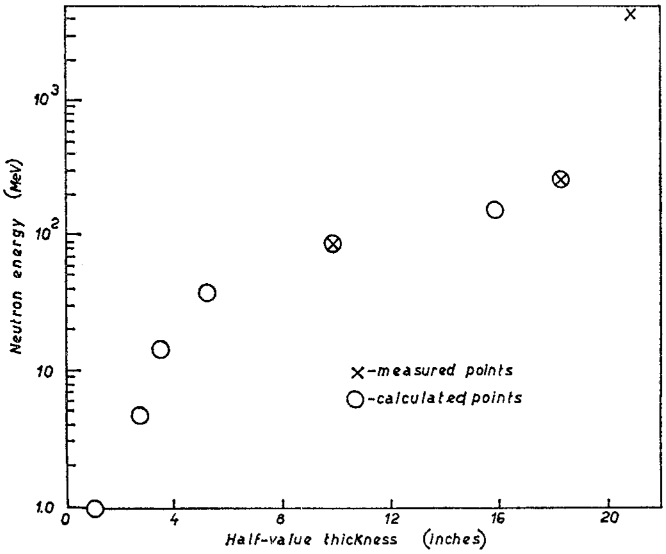

FIG. 2. Neutron attenuation half-value thickness in ordinary concrete vs. neutron energy.

It is now necessary to stress that, in more rigorous terms, the problem is different for the various types of accelerators (linear or circular) as well as for electron or proton accelerators.

In any case, however, the main problem is posed by the high-energy neutrons; so that when these particles are satisfactorily attenuated, any other component will practically disappear. The only exception, in some particular cases, could be represented by the 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 obtain the attenuation of fast neutrons, it is not necessary, as

Patterson observed,(46) to make complicated and detailed calculations. Many results can be derived in simpler and faster ways.

For instance, to calculate the attenuation in concrete we can use the equation:

$$I_t = I_0 \exp(-N\sigma_a t), \tag{3}$$

where N is the number of atoms/cm^3, which depends on the particular type of concrete, and σ_a is the attenuation cross-section or the fraction of the total cross-section which is effective in removing a neutron during its passage through a thick slab.

The points shown in Fig. 2 were calculated by Patterson by summing $N\sigma_a$ for all the elements in concrete and solving equation (3) for the value of t required to give a 50% reduction.

Some phenomenological and theoretical methods of shielding calculations concerning high energy accelerators have been described by Lindenbaum.(33, 34)

In the unidimensional case, he obtained for the attenuation of a monochromatic parallel neutron beam incident on an indefinite plane slab the following expression:

$$\Phi(x) = \Phi_o \exp(-x/\lambda_p), \tag{4}$$

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 then gives for the flux after n interactions the relation:

$$\Phi_n(x) = \Phi_0 \beta_n \left(\frac{x}{\lambda_p}\right) \exp\left(-\frac{x}{\lambda_p}\right), \tag{5}$$

where β_n is the particle build-up factor which can be obtained from nuclear star data.(38)

The method can be employed by using the half-value thicknesses and the removal mean free paths given in Table 5(45) for neutrons having an energy of

TABLE 5.

Bismuth Fission-chamber Measurements at Berkeley

Material	Average neutron energy 90 MeV		Average neutron energy 270 MeV	
	Half value thickness (in.)	Calculated removal m.f.p. (in.)	Half value thickness (in.)	Calculated removal m.f.p. (in.)
Pb	4·7	6·8	5·8	8·4
Cu	4·2	6·1	5·7	8·3
Al	10·7	15·7	18·0	26·0
C	15·1	22·0	—	—
Ordinary concrete	9·5	13·8	18·0	26·0

90 MeV and 270 MeV and for various materials. This simple method will not prove very useful if the neutron mean free paths are rapidly varying functions of the energy.

Another simple method for the shielding calculation is that proposed by Moyer(39) for a beam of 10^{13} protons per pulse at 6·2 GeV of kinetic energy. He considers the actual neutron production in a 100 g/cm^2 copper target, which results equal to 20 neutrons per incident proton. Then, in order to calculate the attentuation thickness he takes into account only the angular distribution of those neutrons whose energy is higher than 150 MeV.

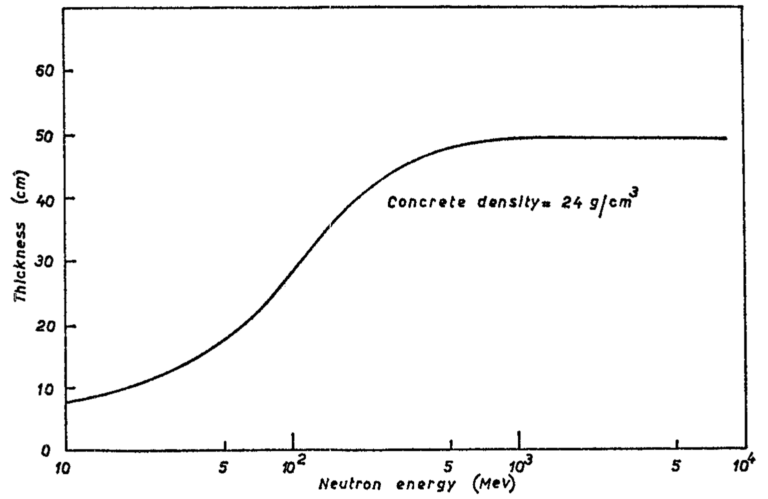

FIG. 3. Half-value reduction thickness for high-energy neutrons in ordinary concrete.

Neutron attenuation by concrete is shown in function of the neutron energy in Fig. 3; essentially this function is equivalent to that given in Fig. 2. From this it results that the attenuation thickness for high-energy neutrons ($E_n > 300$ MeV) is almost constant, while it is a rapidly increasing function for E_n between 100 and 300 MeV.

In this energy range the most important interaction is the nucleon–nucleon scattering. The cross-section varies with the energy, but depends only to a small extent on the atomic number of the absorber. As a first approximation, the half-value thicknesses are inversely proportional to the density of the materials. These half-value thicknesses for materials commonly used in shields are given in Table 6.(55)

An attenuation curve in ordinary concrete for the total number of neutrons per incident electron as a function of shield thickness is given in Fig. 4.

TABLE 6.

Half-value Thickness for High-energy Neutrons

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

This curve was calculated by Panofsky⁽⁴³⁾ for the attenuation of the neutron component of the 45 GeV electron accelerator (2 × 10^{13} electrons/sec).

After having calculated the low- and high-energy neutron production, and the angular distribution of the latter in the nucleon cascade, the author shows how the shielding thickness required in the forward direction of the beam is considerably greater than the transverse one.

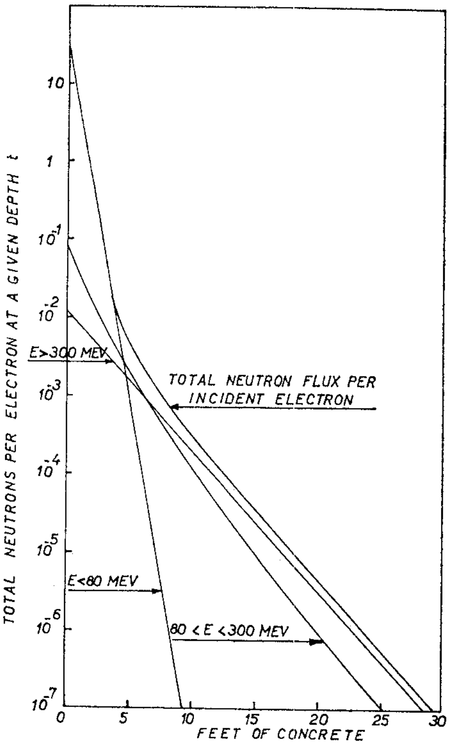

FIG. 4. Neutrons per incident electron surviving at a depth *t* in ordinary concrete.

The calculated values are reported in Table 7.

TABLE 7.

Shielding Thickness Requirement in the Forward and Transverse Direction of the Beam (1 × 10^{13} electrons/sec; $E_0 = 45$ GeV)

Materials	Forward direction thickness (ft)	Transverse direction thickness (ft)
Ordinary concrete	35·0	22·0
Earth	45·0	29·0
Ferrite concrete	24·9	15·0
Iron loaded concrete	19·2	12·0
Iron	12·3	8·0
Lead	12·7	8·8

For the same 45 GeV accelerator a complete and accurate study of the transverse shieldings has been worked out by De Staebler.(15)

He first calculated the average beam loss and the flux of particles incident inside the shield. After having studied the effects of the angular spread on the nuclear cascade through the shield and the radiation levels on the outer surface of the shield and far from the machine, he gives a useful comparison with previous calculation methods.

Other methods and valuable considerations in connection with the shielding calculations can be found in the references at the end of this article.(11, 28, 33, 51, 55)

Taking now into consideration the attenuation of the mesons, we must distinguish between π- and μ-mesons.

The first ones are particles which generate nucleon cascades, like protons, or the neutrons with the same energy, so that the problem is the same as for the above particles. In other words, in the case of the π-mesons, the most significant of the interaction products are the high-energy neutrons.

The μ-mesons, instead, having a negligibly 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 (7·0 ft/BeV in concrete; 2·5 ft/BeV in iron; 2·1 ft/BeV in lead).

Hence, for multi-BeV accelerators the shielding required to reduce the radiation to permissible levels is not sufficient to absorb completely the energy of the μ-mesons. On the other hand, as they are mainly caused by the decay of the π-meson, it is possible to remove their background by placing near the target where the π are produced a shield made up of high-density material. This shield must be sufficiently long to attenuate the forward collimated beam through nucleonic interactions.(44)

As for the skyshine neutrons, whose phenomenology has been largely developed by Lindenbaum,(33, 34) it may be said that the general solution of the scattering equation consists of two terms.

More precisely, at a distance r from the source, there are two components of the flux: one which decreases as r^2 (direct) and another which decreases as r (scattered).

This latter component can be neglected for small values of r, but it becomes larger than the first one if r is sufficiently increased.

Many experimental surveys have been carried out around several accelerators,(27, 46, 52) but the importance of the shieldings in attenuating the skyshine neutrons results quite evident from some practical examples given by Livingston.(36) He concludes that all accelerators producing a neutron source larger than 10^9 n/sec require upper shieldings.

Before closing this chapter we deem it worth while to add that the choice of the shielding material depends on many factors.

Davis(12) has dealt quite thoroughly with this topic, concentrating above all on the properties of various materials (their practical duration, possible useful concretes) and also on the costs involved which must, of course, be taken into due consideration. On the whole, the commonly employed shielding materials are the ordinary concrete, the iron-loaded concrete and other heavy materials like earth, iron and lead. Their well-known properties are exhaustively illustrated in numerous publications.(11, 21)

INDUCED ACTIVITY

When an accelerator is operating, the primary and secondary particles interact with the material making up the machine and also with the surrounding materials, thus causing induced activity.

At energies 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 is assumed to be, with a good approximation, proportional to the geometrical dimensions of the hit nucleus. The highest degree of activation is obviously in the targets, collimators, deflectors and in their surroundings. However, it should be borne in mind that any part of the machine 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.

In general it may be reasonably assumed that the higher the current of accelerated particles, the more intense will be the residual activity.

Residual radioactivity constitutes a serious protection problem whenever the machine (once it has stopped operating) must undergo maintenance and repair work.

In fact the β- and γ-rays from the radioisotopes produced are highly dangerous for anyone who happens to be in the immediate neighbourhood of the more intense radioactivity sources. This imposes, of course, restrictions to the direct handling of some apparatus or machine parts.

In these cases remote-handling systems are required for target changing and for all other special and/or routine operations.

It is possible to calculate the radiation field due to the induced activity in a material sample exposed to the action of a given flux of high-energy particles.

More precisely, we can obtain the number of activated nuclei relative to 1 g of exposed material as a function of the incident flux. This number(4) referred to a certain isotope i is given, at time t, by the equation:

$$N_i(t) = \Phi \sigma_i \frac{N}{A} \int_0^T \exp\left(-\frac{t-\tau}{T_i}\right) \mathrm{d}\tau, \tag{6}$$

where Φ is the constant flux of the 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 of decay to $1/e$ of the activity formed.

The factor $\Phi\sigma_i(N/A)$ represents the number of activated nuclei per time unit. This number decreases exponentially with T_i, from the formation time τ up to t.

By deriving equation (6) with respect to time we obtain the number of nuclei which decay in a second. The result, for all the formed nuclei, is as follows:

$$n = -\frac{\mathrm{d}}{\mathrm{d}t} \Sigma_i \mathrm{N}_i = \Phi \frac{N}{A} \Sigma_i \sigma_i \exp\left(-\frac{t-T}{T_i}\right)\left[1 - \exp\left(-\frac{T}{T_i}\right)\right], \tag{7}$$

where $t - T$ is the time which elapsed since the end of the exposure.

The above relation has been evaluated numerically for the following elements: O, C, Al, Fe, Cu, Co, Zn.(4)

In the case of the activity being induced by photons we can perform a similar calculation(14, 16) and deduce, for a given element, the number of nuclei which decay in a second as well as the value of the saturation activity.

However, owing to a particular geometry, this calculation is closely related to the knowledge of both the development of the electromagnetic cascade in the material and of activation cross-section for photons and neutrons present together in the cascade.

It depends also on the self-shielding effects of the activated material and on the distribution in space and time of the electron beam power loss. Since these important factors are not sufficiently well known, at the present time it is quite difficult to find a general solution to the problem. Nevertheless, by simplifying the terms of the phenomenon, it is possible to obtain some results which constitute a reasonable upper limit for the radiation levels.

To obtain such an upper limit, De Staebler(16) assumed that 1 % of the incident energy is absorbed by the nuclear reactions and that every reaction requires a mean energy of 50 MeV.

On this assumption it results that a 1 MW/cm^3 of absorbed power corresponds to a saturation radiation level of about 10^7 mrem/h at a distance of 5 ft from the irradiated material.

De Staebler, moreover, supposed that each interaction gives a radioactive nucleus which releases 1 MeV of γ energy when it decays and that the γ-flux is converted into rem by using the conversion factor:(41)

$$F = 4 \cdot 6 \times 10^{-10} \text{ rem/MeV-cm}^{-2} \tag{8}$$

or its equivalent:

$$F' = 1 \cdot 7 \times 10^{-3} \text{ mrem hr}^{-1}\text{/MeV-cm}^{-2}\text{-sec}^{-1}. \tag{9}$$

More detailed calculations by the same author prove, on the other hand, that the value of 10^7 mrem/hr is a reasonable upper limit to the saturation radiation level of the induced activity.

Thus at a distance r from a point source whose saturation activity is R, the dose intensity D in mrem/hr is approximately given by:

$$D = \frac{R}{4\pi r^2} F'.E\gamma, \tag{10}$$

where F' is the conversion factor given by relation (9) and $E\gamma$ is the energy released per disintegration.

We deem the attenuation of the γ-decay in the same activated material to be important, since it may reduce by a factor 10 the level of the produced radiation.(16)

When the activated material is shielded by a slab of thickness t, the transmission of dose T relative to the photons of different energy is important. T can be written as follows:

$$T = B \exp(-\mu t), \tag{11}$$

where μ is the total photon cross-section for a good geometry and B the dose build-up factor for a point isotropic source. B values for water, iron and lead (point isotropic geometry and plane monodirectional geometry) and for photon energies up to 10 MeV are given by H. Goldstein and J. E. Wilkins.(22) The T value as a function of t for γ of different energies, is shown in Figs. 5 and 6 in respect of iron and lead.

A large part of the residual activity in the materials subjected to a high-energy electron beam is a photon-induced activity, but in addition there is also a residual activity, which is produced close to the stopped electron beam, by the nuclear particles accompanying the soft shower.

An evaluation of this activation can be made by calculating the energy fraction of the soft shower going into high-energy nuclear particles, which is given by:

$$f = 0 \cdot 57\, N X_0\, \sigma \ln E_0/K_0, \tag{12}$$

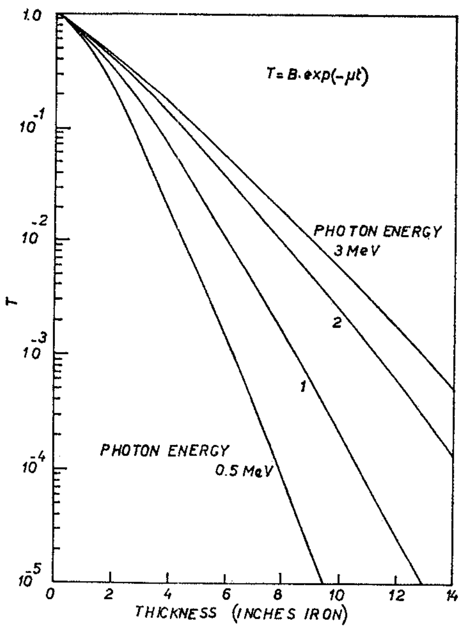

FIG. 5. Photon dose transmission in iron.

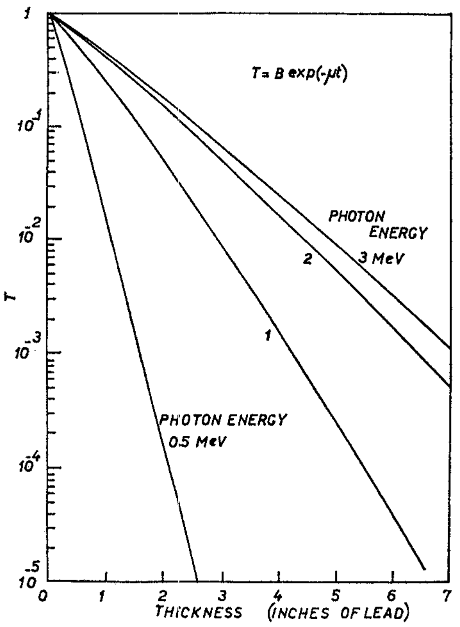

FIG. 6. Photon dose transmission in lead.

where X_0 is the radiation length in the material, N is Avogadro's number, σ is the interaction cross-section per nucleon, E_0 is the energy of the primary electrons and k_0 is the energy of the produced nucleons.

Since the protons lose a large part of their energy by ionization, we may assume this activation process is actually caused by the neutrons, so that the required energy is $f/2$.

Induced activity measurements have been made around many accelerators(3, 4, 6, 16, 20, 53, 54) 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 the accelerators.

The radioprotection problems posed by the presence of induced activity become gradually more serious as the energy and intensity of the beams increase.

This involves both a careful choice of the materials to be employed around the accelerators, and the development of control systems and devices, which make work possible in conditions of safety from the radioprotection view point.

PRODUCTION OF RADIOACTIVE AND TOXIC GASES

The production of radioactive and toxic gases concerns particularly the high-power electron accelerators.

The production of radioactive gases, especially O^{15} and N^{13}, is, to a larger or smaller extent, common for all electron accelerators which produce bremsstrahlung radiation intensity with an energy higher than 20 MeV(23) (the production cross-section has its peak value of $1{\cdot}6 \times 10^{-26}$ cm^2 at about 23 MeV).

The production of toxic gases, on the other hand, especially O_3 and NO_2, is important both around high intensity electron accelerators and near high activity γ sources (e.g. Co^{60}).

As far as the radioactive gases are concerned, it would be reasonable to take into consideration only those coming from isotopes that are more abundant in the air, like N^{14}, O^{16} and A^{40}, disregarding all the others.

The data relative to these isotopes and their activation are reported in Table 8.

TABLE 8.

Initial nucleus	% in air	Re-actions	Final nucleus	$T_{\frac{1}{2}}$ (min)	Decay products	Cross-sections (mbarn)
N^{14}	78·1	(γ, n)	N^{13}	10·1	β^+	2·5
		$(n, 2n)$	N^{13}			
		$(\gamma, 2np)$	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 concentrations of radioactive isotopes in the air, reported in Table 8, are $0{\cdot}5 \times 10^{-12}$ Ci/cm^3.(13)

The production rate of active nuclei depends on the number of photon and neutron interactions. This in turn depends on their mean free paths and on their angular distribution.

By using the same mean free paths L(cm) for photons and nuetrons, the production rate, R, of active nuclei in air per second is given by:

$$R = I \frac{N}{A} \rho L \epsilon \sigma, \tag{13}$$

where I is the total number of photons and neutrons passing through the air per second, N Avogadro's number, A the atomic weight of initial nucleus, ρ the density of the air in g/cm^3, ϵ the fractional abundance in the air of the initial nucleus and σ the cross-section per nucleus per incident particle in cm^2.

Taking into account the data reported in Table 8 for $L = 900$ cm and $I = 1{\cdot}2 \times 10^{15}$/sec^{-1},(13) we obtain for the nuclides C^{11}, N^{13}, O^{15} and Cl^{38} the values of R shown in Table 9, which reports also the values of the equilibrium concentrations.

TABLE 9.

Final nuclide	$R \times 10^{10}$ (nuclide/sec)	Equilibrium concentration S ($\mu\mu$Ci/cm^3)
C^{11}	0·24	3·1
N^{13} incident γ	12	
N^{13} incident n	3	
N^{13} total	15	190
O^{15}	17	220
Cl^{38}	0·42	5·5

If in volume V there is good mixing of the air, the equilibrium concentration S may be represented by:

$$S = \frac{R}{V} (\mu\mu\text{Ci/cm}^3). \tag{14}$$

Calculations similar to those of De Staebler were performed by other authors,(24, 26, 47) both in order to find the values of R and of the equilibrium concentrations as well as the doses that would be absorbed by the persons exposed in particular zones in the neighbourhood of the accelerators, in relation to the disposal conditions of the radioactive gases produced.

As far as the production of toxic gases is concerned, this is a problem which, as already said, deals mainly with high-intensity electron accelerators.

Many toxic gases are produced in their surroundings as in the case when the air is irradiated by intense γ sources. Among these, the most important are O_3 and NO_2.(30)

The maximum permissible concentrations in the air are, respectively, 0·1 and 5 ppm in weight.

These values give an accurate idea of the great danger represented by O_3, whose production in function of the Co^{60} γ-dose for various dose rates is shown in Fig. 7.

The production of toxic gases by an electron beam(24, 26) can be calculated simply by assuming that each electron produces in the air eighty pairs of ion per cm and that for each ion pair a molecule of toxic gas is formed.

The same production can be obtained from the bremsstrahlung radiation, by observing that the energy fraction lost at distance x in the air is given by $1 - e^{-\mu x}$ (μ is the mean absorption coefficient in the air $= 0{\cdot}02$ cm²/g) and by assuming that the energy needed to form a pair of ions is 33 eV and that we have a dangerous molecule for each pair of ions.

Thus assuming the same irradiation conditions in the air, nearly the same values for the production of toxic molecules were found.(24, 26, 47)

In addition to the production of O_3 and NO_2 in the electron or γ-irradiated air, there are also HNO_3 vapours which can easily corrode the metallic parts of the apparatus.

Since this seems to be of importance, for practical reasons we have reported in Fig. 8 the production of HNO_3 as a function of Co^{60} γ-dose.

Another problem closely connected with production of radioactive and toxic gases is their disposal in the atmosphere by means of a proper ventilation of the rooms. In fact, in the rooms where the radiation levels are so high as to create strong concentrations of toxic and radioactive gases, it is not possible to enter

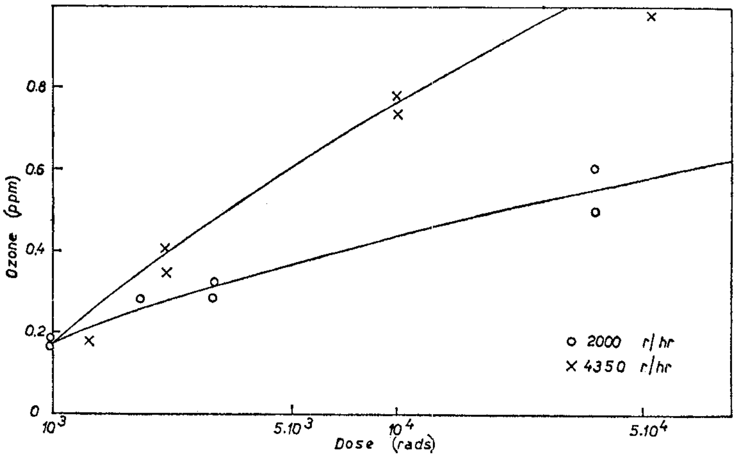

FIG. 7. O_3 production in air, as a function of Co^{60} γ-dose for various dose-rates.

immediately after the machine has been stopped; it is necessary to wait until the concentrations are lower than the maximum permissible values.

The calculations carried out[40] prove that the disposal of ozone alone and its reduction to admissible concentration values creates the necessary safety conditions also as regards the concentrations 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.

A simple formula[30] gives the time t in hours required to reduce the O_3 concentration up to a value C after the machine has been stopped:

$$t = \frac{2 \cdot 3}{n} \ln \frac{C_1}{C}, \tag{15}$$

where n is the number of air changes per hour and C_1 is the O_3 concentration in ppm at the moment when irradiation stops.

Typical results are given in Table 10.

TABLE 10.

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

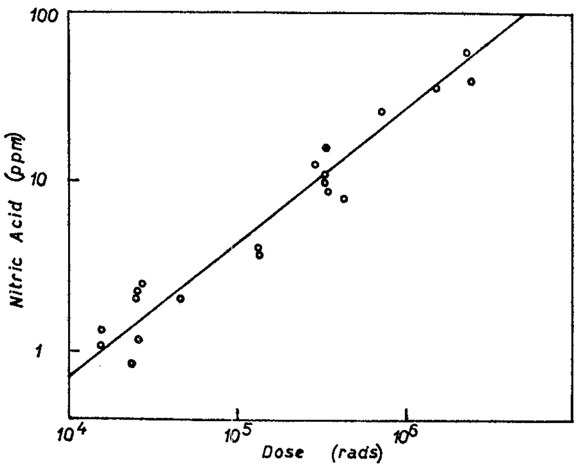

FIG. 8. HNO_3 production as a function of Co^{60} γ-dose.

Since the smell of O_3 can be detected at $0 \cdot 1$ ppm or even less, from a practical point of view an accelerator room could be entered immediately after the smell has disappeared.

OTHER PROBLEMS AND CONCLUSIONS

The safety and protection problems posed by high-energy accelerators have, for obvious reasons, not been exhaustively dealt with in the preceding chapters. There are, of course, other problems, such as the disposal of radioactive dust and water, which require solutions taking into account above all the safety of the population living in the neighbourhoods of the accelerator. As far as the air and any radioactive dust are concerned, the problem can generally be 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. However, when for some reason it becomes necessary to discharge it into public water supplies or into the ground, its degree of radioactivity must be well below the danger level. It is therefore essential to control continually its radioactivity and make sure it is diluted before disposal.

Another particular important problem regarding all accelerators is that of the beam catcher. In the case of low-power beams(25, 35) the problem is easy to cope with, but when it comes to high-power beams it is extremely serious. In this latter 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 is incident on the front of the tank and then penetrates into the water, which attenuates its various components and especially the neutrons. In addition, the water is demineralized, so as to reduce its activation to a minimum; this does not prevent, however, the formation of tritium(17) and of radicals with the consequent generation of oxygen, which must somehow be disposed of.

Since the tank and its auxiliary equipment will, after some time, become highly activated, it is indispensable to adopt remote handling control systems.

Finally, we should like to mention briefly a few general safety rules that should be observed in connection with radioprotection:

the access to zones under irradiation should be prevented by means of adequate safety systems;
the presence of dangerous radiation levels should always be clearly indicated;
the accelerator's entry into operation should at all times be preceded by acoustic and bright warning signals;
the radiation level in the vicinity of the accelerator must be under careful and continuous control.

It goes without saying that the above-mentioned measures would be quite superfluous without a strict and scrupulous observance on the part of the persons concerned of all the safety norms regulating work with and near the accelerator.

A last aspect of the problem we should like to emphasize before closing is that of the relations between researchers operating the accelerator and the experts responsible for radio-protection. We sincerely hope that such relations will always be based on a spirit of close and friendly co-operation, with the common aim of attaining the best possible results, in the interest of scientific research.

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