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AN EFFECTIVE RADIOLOGICAL SAFETY PROGRAM FOR ELECTRON LINEAR ACCELERATORS*

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Summary

An outline is presented of some of the main elements of an electron accelerator radiological safety program. The discussion includes types of accelerator facilities, types of radiations to be anticipated, activity induced in components, air and water, and production of toxic gases. Concepts of radiation shielding design are briefly discussed and organizational aspects are considered as an integral part of the overall safety program.

Types of Accelerator Installations

The great majority of electron linear accelerator installations fall conveniently into four categories:

(1)	Medical	4 - 40 MeV
(2)	Industrial radiography	2 - 40 MeV
(3)	Other industrial uses	2 - 40 MeV
(4)	Nuclear and particle research	20 - 28000 MeV.

Categories (1) and (2) are mature, in that the equipment specifications have stabilized enough so that one model is easily comparable with another. As a consequence their installations tend to be quite similar and safety practices are quite standardized. On the other hand, categories (3) and (4) tend more to be customized and safety needs must be re-thought from the ground up for each new facility. This paper will try to say something applicable to all of these categories, except that those who work at one of the special categories (3) or (4) may find it the most useful.

A good way to conceptualize an accelerator's ability to generate radiological problems is to look at two parameters, the maximum electron energy E_0 (MeV) and the maximum beam power P (kW). I choose P rather than current, because, above a certain energy some kinds of radiation tend to become independent of energy for the same beam power delivered to the target. Unless the machine is very unusual, it will lie, to within a small factor, near the straight line on Fig. 1. The points represent category (4). Categories (1) and (2) fall in the lower left corner and the other industrial uses tend to be grouped between 10-50 MeV, with perhaps 20 MeV the median. Once E_0 and P are specified, one can almost visualize the dimensions of the installation, remembering that the overall length depends on the accelerating gradient and factors of two in power correspond to only inches of concrete.

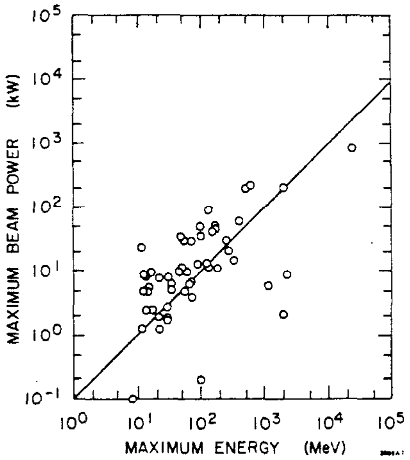

Fig. 1. Beam power (kW) of representative electron linacs plotted against beam energy (MeV). The line represents a typical average current of 100 μA.

Figure 2 shows qualitatively that the isotropic kinds of radiation, such as neutron production, bremsstrahlung (apart from the forward peak), and induced activity, are close to being constants with beam power, soon after their energy thresholds are exceeded. On the other hand, the forward-peaked radiations tend to rise as the second or third power of beam energy, for constant beam power (for example, the forward bremsstrahlung peak and muon production). This is basically because their angular distributions contain the electron energy squared in the denominator, resulting in tight bundling in the forward direction. Few industrial accelerators will be bothered by muon production, but research facilities operating above about 500 MeV may be. The behavior of bremsstrahlung and neutron production is better shown in Figs. 3 and 4.

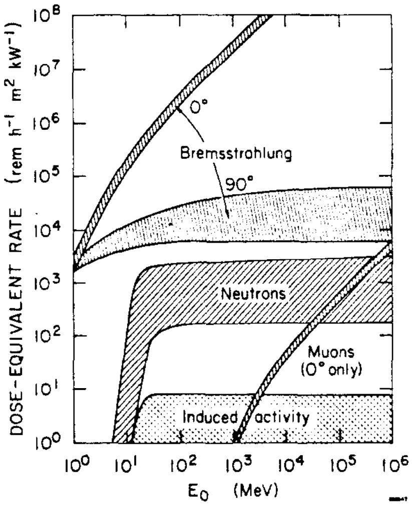

Fig. 2. Dose-equivalent rates per unit primary beam power of types of radiation produced at an electron accelerator facilty, as a function of electron beam energy (illustrative).

Planning of New Facilities

In planning a new installation, it is convenient to consider the kinds of radiation in this order -- one sees that bremsstrahlung production is important at all kinds of facilities, because that is what electrons do best. Neutron production will be important at those that operate above about 15 MeV. These two radiations basically determine the shielding needs. Induced activity is a concomitant of neutron production and depends greatly on the material placed in the direct beam. Beginning with the accelerator specifications, the dimensions of the facility take shape. At the early planning stage, it is essential that a person experienced with accelerator radiation protection be consulted to

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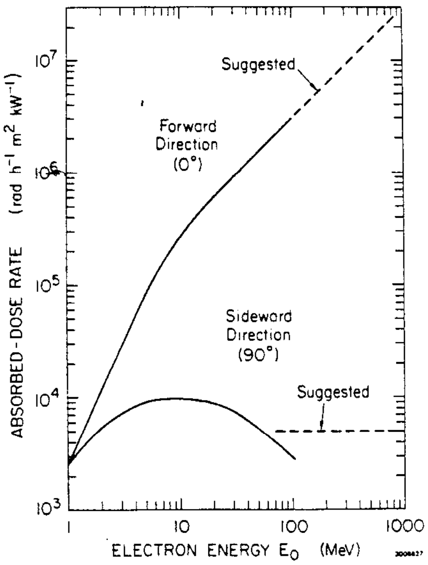

Fig. 3. Thick-target bremsstrahlung from a high-Z target. Absorbed dose rate at 1 meter per incident electron beam power. Dashed lines are extrapolations.

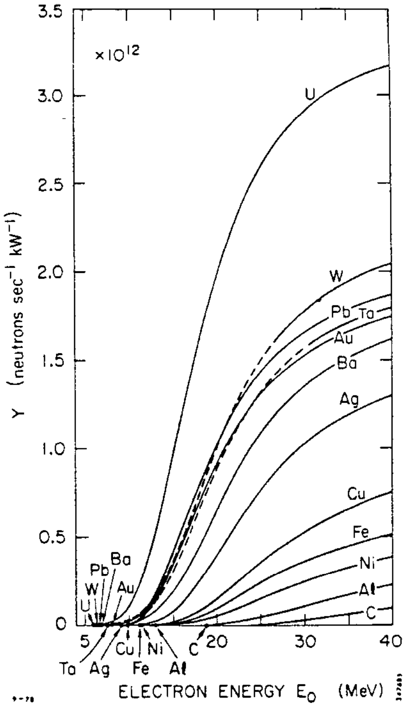

Fig. 4. Neutron production per unit electron beam power incident on various materials. Thresholds are indicated in the lower left corner.

assist in the development of architectural plans. Things to be considered at this stage are:
(1) Dimensions and materials of shielding
(2) Proper baffling of all penetrations
(3) Removal of toxic and radioactive gases
(4) Handling of radioactive water
(5) Provision for safety devices
  (a) door interlocks
  (b) emergency shutoff switches
  (c) warning lights
  (d) aural warning
  (e) run/safe switches
  (f) permanent radiation monitors
(6) Location and interlocking of klystrons.

All of these provisions are best incorporated into the initial plans so that elegant solutions are found rather than having improvisations forced upon you later. Technical details can be found in references below.$^{1-9}$ The most important points to be made are: (1) the early plans should have safety cast into them, along with the concrete; and (2) a relationship be developed between the facility management and the radiation-safety personnel, which will be carried over to the period of operation.

The NCRP has recommended the use of Occupancy and Use Factors in conjunction with a Workload for shielding of medical accelerators. This practice has proved quite satisfactory over a period of many years and I believe it can well be adapted for industrial applications. An estimate of the on-time per 40-hour week should be made. For radiographic installations, 10 h per 40 h week is suggested, which is an attempt to take into account the setup times. For radiation processing or research, 40 hours per 40-hour work week would probably be more appropriate. Shielding needs can then be estimated from a plan of the facility and a knowledge of the radiations produced. The shielding of the primary bremsstrahlung is quite straightforward (Fig. 5), but scattered and leakage radiation are also significant and must be considered (see Fig. 6).

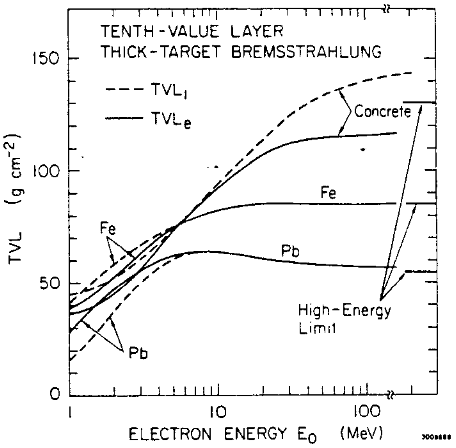

Fig. 5. Values of TVL in ordinary concrete, iron and lead for thick-target bremsstrahlung under broad-beam conditions at 0°, as a function of electron energy. Solid curves show the equilibrium TVL and dashed curves the first. TVL's are shown in units of areal density (g cm^{-2}) to facilitate comparison between materials.

There has been recent concern about neutrons from medical accelerators and neutrons should certainly be carefully evaluated for operations above about 15 MeV. Figure 4 gives quite reliable upper limits for neutron production if one assumes the electron beam strikes W or Pb. If the material struck by the beam is low-Z, the neutron production will be less. Concrete shielding which is designed to properly shield the bremsstrahlung will also attenuate the neutrons to an acceptable level (assuming $Q = 10$). The problem is, however, that neutrons stream through penetrations far more easily than photons and great attention should be given to the labyrinth design and to the geometry and location of other penetrations. The same generality that holds for concrete (and other hydrogenous materials) does not hold for non-hydrogenous materials. For example, if Fe or Pb

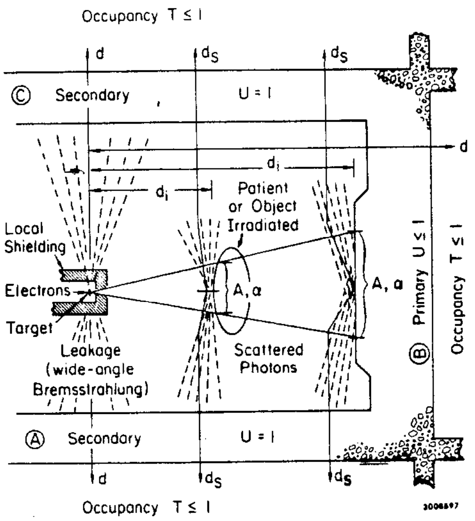

Fig. 6. Conceptual plan of a radiation room, illustrating the primary and secondary barriers, and sources of radiation to be considered. Occupancy Factors for adjacent areas and Use Factors for the barriers are also illustrated.

are relied on for part of the photon shield, the problem of neutrons should be carefully assessed, because these materials provide very little attenuation for photoneutrons. Photoneutrons require one further qualification; those having kinetic energy above about 100 MeV penetrate shielding much more easily than the more copious giant-resonance neutrons. Therefore if the accelerator operates above about 150 MeV, special care must be taken to shield against these high-energy neutrons.

In the design of large facilities, much reliance is sometimes put on large computer programs -- Monte Carlo or discrete ordinates calculations. These are of course very highly developed programs and should be used. However, much valuable insight can be obtained by applying rules of thumb to the back of an envelope. Certainly for conceptual designs, which give approximate dimensions, the back of the envelope is a very powerful tool and has the advantage that the user understands every step.

Activity induced in components will be a consideration at energies above about 10 MeV. One should look for it with a Geiger counter, in addition to the ionization-chamber survey meter. Look first at objects that are struck by the primary beam. The following materials are relatively insusceptible to activation by electron beams and should be used in or near the beam if otherwise suitable: ordinary concrete, lead (antimony-free), aluminum, wood, plastics and other organics. Iron and copper are usually essential at radiation facilities and are more susceptible to activation but their activity is relatively predictable. Stainless steel is definitely worse than ordinary steel and materials of high atomic number are bad as a rule. Use of materials whose (γ,n) reaction leads directly to a radionuclide having a half-life between a few minutes and a few years should be minimized.

The threshold for water activation is 15.67 MeV. If the average beam power is less than about 10 kW, once-through cooling and release of the cooling water to the sanitary sewer is generally acceptable. For higher beam powers a closed-loop system is needed. If possible, locate the heat-exchanger in the radiation enclosure so that all of the piping of radioactive water is out of the way of people. Generally only ^{15}O, ^{11}C and ^{7}Be need be considered as present in irradiated water ($T_{1/2}$ = 123 s, 20.34 m, and 53.6 d, respectively).

The threshold for air activation is 10.55 MeV. Even where present, air activation is not normally a limiting factor; normal air circulation is generally sufficient to reduce exposures from activated air well below those from activated components. The dominant radionuclides are ^{13}N and ^{15}O ($T_{1/2}$ = 9.96 m and 123 s, respectively). Air is activated by photonuclear reactions induced by bremsstrahlung, not by the primary electrons. Reduction of the amount of air that is irradiated will reduce the activity. Local lead shielding is quite effective in reducing the amount of stray radiation and consequently will reduce the amount of air activation, toxic gas formation and radiation damage.

Toxic gas production (ozone and oxides of nitrogen) will occur in considerable amounts where the primary electron beam is brought into the air. Of the gases produced, ozone will almost always be the limiting factor, owing to its much lower Threshold Limit Value (TLV: 0.1 ppm), high radiolytic yield and chemical reactivity. The amount produced is roughly proportional to the integral dose given to the air and this is largest if the electron beam is extracted, regardless of its energy. On the other hand, at medical and radiographic facilities, where the electrons are completely stopped within the accelerator system, toxic gases are rarely of any significance. The human nose can detect levels in the range 0.02 - 0.05 ppm. This is below the Threshold Limit Value, so if ozone is only rarely detected, the facility may be assumed to be safe with regard to radiogenic toxic gases. If the odor is strong or frequently detected, an assessment should be made with monitoring equipment and measures, such as improved ventilation or limiting personnel access, should be implemented.

To conclude this catalog of radiation hazards, it should be noted that RF equipment also emits X-rays. Klystrons are the most prominent example because they invariably serve as the RF power source for facilities operating above 10-15 MeV. They resemble an ordinary X-ray tube in the manner in which they produce radiation. The location, shielding and interlocking of klystrons should be planned at the same time as the rest of the radiation facility. Vacuum RF cavities are also strong X-ray sources, and these should be carefully assessed. These radiations are erratic and almost impossible to predict because they depend on changing microscopic surface conditions. Their X-ray output is also a strong function of the RF power applied to them (a dose rate dependence on the 5th power of the applied RF power has been observed at SLAC).

Safety Organization

The matters discussed thus far are mostly physical safety provisions. These of course are essential. But an effective safety program depends just as much on the personnel, their attitudes and habits.

As far as formal organization is concerned, there is no single organization chart that is necessarily best, even for a specific situation. Generally it is an extension of the organizational philosophy that has developed in the parent organization, except in the unusual case where a brand new independent facility is established.

The safety organization may include a Radiation Safety Committee and Radiation Safety Officer (RSO), assigned on a continuing basis to specialize in and oversee matters of radiation safety. A typical composition of the Radiation Safety Committee might include the head of the department which operates the accelerator, the RSO, a fire-protection officer and a senior member of the accelerator operating staff.

During times the accelerator is operating, the operator in charge of each shift should be specifically and directly responsible for its safe operation and be authorized to shut the accelerator off if he feels it is necessary. All employees have the responsibility of complying with safety practices, responding to emergency situations and reporting unsafe conditions.

Although I hesitate to prescribe a specific form of organization, there are at least two guiding principles that I feel are quite important:

(1) The ultimate responsibility for all kinds of safety, including radiation safety, must lie with the management of the facility.
(2) At the same time it is good idea to have separation between the people who assess the radiation safety and those who derive direct benefit from the radiation produced.

I believe that the first point needs no explanation, except that it points up the need for clean lines of communication between the accelerator management and the radiation-safety officer.

The second point means that the person(s) given the responsibility for determining matters of radiation safety should not be one of those individuals whose career or livelihood depends overwhelmingly on keeping the beam running. A clear example of this is the occasional experimenter who would feel it more important to override an interlock than to shut down a experiment that is producing important results. It should be someone detached enough that he can point out to management conditions that need to be remedied with a minimum of personal conflict. The formal point of contact should be between the RSO and immediate facility manager, but there should also be easy informal contact at all levels. If lack of cooperation is encountered at any level, the RSO should have access to higher authority.

It has been pointed out that one ingradient of accidents is almost always a personnel failure. A theme often repeated in the SLAC operating safety committee is that the margin of safety can usually be most effectively increased by instillation of good attitudes and habits, rather than by multiplying the number of safety devices. This instillation can be achieved by example, informal admonition and formal training. The best approach undoubtedly requires all of these in such amounts as to that ensure that each radiation worker is clearly aware of:

(1) The nature of the radiation fields, both within and without the radiation enclosure.
(2) The importance of the safety devices listed above.
(3) Some awareness of the radiation accidents that are conceivably possible and their likely consequences.
(4) Awareness of appropriate emergency procedures.
(5) Familiarity with the specific radiation-safety rules of the facility.

Many jurisdictions require lectures on radiation safety and the list of topics to be included is quite specific.

Each facility should have a written radiation safety procedure. In many cases a few pages will suffice. At SLAC, we have a 190-page Radiation Rule Book and a Radiation-Procedures document (about 12 pages long) for each of 6 major experimental areas. The Rule-Book is revised about once a year, but the procedures (in-house they are called Beam Authorization Sheets) are rewritten at the startup of each running cycle and are frequently modified in mid-cycle. These BAS's must be approved by radiation safety personnel and operations personnel before they are implemented. Thus the philosophy of dual-responsibility, or checks and balances, is automatically implemented on this level. Because of the constant change at a large experimental facility such as SLAC all of these documents are maintained in a computer system and, no matter how involved, a new copy can be generated on very short notice. Even where the needs are quite modest, use of a word processor to edit and print the radiation safety manual may be quite helpful.

Whether or not the radiation-safety personnel are formally integrated together with the other forms of occupational safety is probably best determined by each organization and may depend on the personalities involved as much as anything. Regardless of this it is salutary to attempt some kind of balance. so that undue emphasis is not given to radiation safety at the expense of other kinds. Bear in mind that serious radiation accidents have occurred less frequently than other types of occupational accidents around radiation facilities. At many, electrocution, poisoning or mechanical injury may be potentially greater hazards. Where the organizational safety is integrated, such imbalances are less likely to occur. Where radiation safety is maintained as a separate department, it is up to management to see that the right amount of attention is given to each aspect of safety.

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