TECHNICAL REPORTS SERIES No.188

RADIOLOGICAL SAFETY ASPECTS OF THE OPERATION OF ELECTRON LINEAR ACCELERATORS

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A manual written by
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*Work supported in part by the
United States Department of Energy*

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1979

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INTRODUCTION

More than a decade of experience has been gained since the publication of a manual devoted exclusively to radiological protection at high-energy electron accelerators. Because of the rapidly increasing use of electron linear accelerators, it was felt that it would be useful to prepare such a handbook that would encompass the large body of methods and data which have since been developed. Since the publication of NBS Handbook No.97, significant developments related to radiation protection at electron linear accelerators have occurred along the following lines:

(a) Electron linear accelerators for medical and radiographic purposes operating in the range 4 – 40 MeV are now widely accepted. The growing number of such machines operating above 10 MeV poses additional problems of undesirable neutron radiations and concomitant component activation.

(b) There has been a trend toward standardization of radiation-protection practices, and development of national and international radiation-protection guidelines for medical accelerators.

(c) The introduction of high-energy, high-power electron machines has brought new types of problems and magnified old ones. The higher energy has necessitated provisions for high-energy neutron dosimetry and shielding, muon dosimetry and shielding, and treatment of the neutron skyshine problem. The higher power has aggravated such problems as radioactive air and water and the possibility of burn-through of shielding by raw electron beams.

(d) Operating flexibility such as multibeam capability has placed new demands on personnel protection systems.

(e) Refinement of measurements of photonuclear reactions has made more reliable predictions of neutron production and component activation possible. These developments include improved consistency among cross-section measurements with monochromatic photons in the giant-resonance region, as well as new data on less frequent types of reactions at all energies.

(f) The development of Monte-Carlo techniques to a high degree has made it possible to undertake otherwise practically intractable calculational problems. Very useful calculations are now available on electromagnetic cascade development, on neutron production and transport, and on muon production and transport.

(g) The development of radiation protection practices at other types of accelerators has also provided a source of information useful at electron accelerators. Conferences on accelerator dosimetry and experience held in 1965, 1969 and 1971 presented occasions at which world-wide operating experience at accelerators of all kinds was shared.

(h) The growing sensitivity on the part of the general public to environmental concerns has required a greater degree of attention to radioactive releases.

While these have never been a serious problem at electron accelerators, it still is desirable to be able to make positive statements about the amounts produced and about their disposal.

Since much of this great body of information is scattered widely throughout the literature, it is the goal of this manual to gather it together in an organized usable form.

It is significant that no fatalities to personnel have ever resulted from acute radiation injury at an electron linear accelerator. The few serious accidents at research installations that have occurred were by electrocution and ordinary mechanical injury. A manual devoted to radiological safety is nevertheless useful, because radiation is a 'special' safety hazard connected with these accelerators and its management requires more specialized knowledge and instrumentation than do the programmes of conventional safety.

PURPOSE AND SCOPE OF THE MANUAL

This manual is intended as a guide for the planning and implementation of radiation protection programmes for all types of electron linear accelerators. It is hoped that it will prove useful to accelerator manufacturers, accelerator users, management of institutional and industrial installations, and especially to radiation safety officers and other persons responsible for radiation safety. Material is provided for guidance in the planning and installation stages, as well as for the implementation of radiation protection for continuing operations.

Because of their rapidly growing importance, the problems of installation and radiation safety of standard medical and industrial accelerators are discussed in separate sections. For higher-energy research installations, the basic radiation protection objectives are the same, but more types of potentially harmful radiation must be considered and shielded against. For such facilities, each major type of problem is briefly summarized and references are given to direct the user to more complete information in the literature.

Special discussions are devoted to the radiation protection problems unique to electron accelerators: thick-target bremsstrahlung, the electromagnetic cascade, the estimation of secondary-radiation yields from thick targets, and that annoying operational problem, instrumental corrections for accelerator duty factor. In addition, an extensive review of neutron production is given which includes new calculations of neutron production in various materials. A recalculation of activation in a variety of materials has been done for this manual, and specific gamma-ray constants have been recalculated for a number of nuclides to take into account the contribution of K X-rays. The subjects of air and water activation, as well as toxic gas production in air have been specially reviewed. In the section on radiation shielding, published data on bremsstrahlung attenuation have been reviewed to estimate a consistent set of attenuation parameters over a broad range of primary energies. Furthermore, the treatment of monochromatic photon reflection of Chilton and Huddleston has been adapted for use with bremsstrahlung spectra. The discussion of neutron shielding utilizes neutron transport calculations from Oak Ridge which properly account for the contribution of neutron-capture gamma rays to the dose equivalent. These data are presented in a form believed most convenient for direct use by the radiation protection specialist.

The present manual does not strive to provide results of great accuracy; this is very difficult unless all aspects of a given situation are taken into account. The intention is rather to present a balanced treatment of the major kinds of radiation and provide means to estimate them with simple algebraic manipulations based on physically well-grounded interpolations. For the sake of completeness and to provide additional perspective for the user, order-of-magnitude estimates are given for some radiations of lesser importance.

Betatrons and electron microtrons operating at the same energy produce essentially the same kind of secondary radiation as electron linacs and the material given in this manual is directly applicable to them. Accelerators which deliver primary beams of other types of particles, particularly protons, deuterons or heavier ions, give rise to secondary radiation of a somewhat different nature, owing to the mass and hadronic interactions of the primary particles; the amount of bremsstrahlung is negligible compared with the intense neutron fluences released by these particles. These accelerators are not discussed in this manual.

During the preparation of this manual, an ongoing dialogue was conducted with accelerator manufacturers and radiation protection specialists at several laboratories (see Acknowledgements). A number of visits were made to clinics and research installations to gather first-hand impressions of safety practices that are actually in use.

The material presented here is of course based on earlier work by many persons and organizations. A reasonable attempt is made to acknowledge, by citation, the work of individuals where appropriate, but as the field of radiation protection extends over many decades, completeness in this regard is impossible. Radiation protection manuals which are heavily drawn upon are listed in the General Bibliography (Section 7). It is recommended that persons responsible for radiation protection have a selection of these references available, for additional perspective on the problems and their solutions.

Recommendations for clinical calibrations of beams used in therapy are not given in this manual, but the reader is referred to reports of international organizations such as the IAEA and ICRU and other authoritative bodies which deal with this important subject (see Section 7).

It should be borne in mind that there may be additional regional and local requirements for radiation protection that must be met. Governmental authorities and qualified experts are best consulted to ensure that each installation is operated in compliance with all legal requirements.

TABLE I. FREQUENTLY USED SYMBOLS AND UNITS

Name	Symbol	Units		
		SI[a]	Special	Conversion factors
Absorbed dose	D	gray (Gy)	rad (rad)	1 rad = 10 mGy = 10 mJ · kg^{-1}
Absorbed dose rate	$\dot{D}$	Gy · s^{-1}	rad · s^{-1}	1 rad · s^{-1} = 10 mGy · s^{-1}
Exposure	X	coulomb per kilogram (C · kg^{-1})	röntgen (R)	1 R = 258 μC · kg^{-1}
Exposure rate	$\dot{X}$	C · kg^{-1} · s^{-1}	R · s^{-1}	1 R · s^{-1} = 258 μC · kg^{-1} · s^{-1}
Dose equivalent	H	(dimensions of J · kg^{-1})	rem	1 rem = 10^{-2} Sv
Dose equivalent rate	$\dot{H}$	-	rem · s^{-1}	
Activity	A	becquerel (Bq)	curie (Ci)	1 Ci = 37 GBq = 3.7 × 10^{10} s^{-1}
Quality factor	Q	-	-	
Electron kinetic energy	E	MeV	-	1 MeV = 1.602 × 10^{-13} J
Incident or initial kinetic energy	E_0	MeV		
Photon energy	k	MeV		

Useful conversions

1 Bq = 1 radioactive disintegration per second = 1 s^{-1} = 27.027 pCi
1 Gy = 1 J · kg^{-1} = 100 rad
1 eV = 1.602 × 10^{-19} J, approx.
1 MeV ≅ 1.602 × 10^{-13} J = 1.602 × 10^{-13} kg · Gy = 1.602 × 10^{-8} g · rad = 1.602 × 10^{-6} erg
1 W = 1 J · s^{-1} = 1 V · A
Absorbed dose corresponding to an exposure X of 1 C · kg^{-1}: to air: D = 33.7 Gy
to tissue: D = 36.4 Gy (Co–60)

TERMINOLOGY AND UNITS

Where possible, the terminology and units correspond to those defined in ICRU Report 19 (see Bibliography, Section 7). Table I gives frequently used symbols and units. (See Appendix A for additional useful physical and numerical constants.)

Note

The question of an SI-coherent unit with a special name for dose equivalent H is undergoing review. The sievert (Sv), which is the absorbed dose D (in Gy) multiplied by dimensionless modifying factors (in particular the quality factor Q) has been proposed to the Conférence Générale des Poids et Mesures (CGPM) by the International Commission on Radiation Units and Measurements (ICRU) and the International Commission on Radiological Protection (ICRP). The sievert would stand in the same relationship to the gray as the rem does to the rad. Since a final resolution of this matter has not been made at the time of publication, values of dose equivalent H are given in rem in this manual. In all other instances radiation quantities are given in *both* the SI-coherent units and the existing special units. Also note that no special SI-coherent unit has been proposed to the CGPM for exposure X; the SI-derived unit $C \cdot kg^{-1}$ is used for exposure.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the kind hospitality and support of the International Atomic Energy Agency and the Stanford Linear Accelerator Center in the preparation of this manuscript, and particularly thanks F.N. Flakus and R.C. McCall for their personal help and encouragement.

The author is deeply indebted to F.H. Attix, G.R. Higson, M. Ladu, T.G. Martin III R.C. McCall, T. Nakamura, C.S. Nunan, J. Rassow and K. Tesch for valuable comments on a preliminary draft, and to my colleagues D.D. Busick, T.M. Jenkins, K.R. Kase, W.R. Nelson and G.J. Warren of the Stanford Linear Accelerator Center, and R.H. Thomas of the Lawrence Berkeley Laboratory, for generously sharing their knowledge and experience.

Many other individuals, representing a large number of organizations, were extremely cooperative and helpful in supplying useful information. These include: R. Alvarez, L. Armstrong, A. Asami, M.L. Berger, B. Berman, J. Bly, J. Broberg, A. Burrill, R. Byers, A.B. Chilton, T.R. Chippendale, J.B. Czirr, J. Fenger, H. Fujita, E.G. Fuller, G. Gilbert, T.F. Godlove, T.W. Grunewalt, D. Hankins, P. Hardaker, T.G. Hobbs, J. Jasberg, R. Jean, R. Johnson, J. Kaehler, M.J. Karaffa, C.J. Karzmark, N.N. Kaushal, N.L. Kay, J.G. Kelliher, E.A. Knapp, J.D. Koenig, S. Kurihara, M. Lara, J. Lebacqz, J.E. Leiss, G. Loew, P. Maschka, T.P. McReynolds, B. Mecklenburg, B. Meyer, V. Moré, R.B. Neal, P. Ogren, S. Penner, F. Peregoy, E. Petersilka, V. Price, D. Reid, J.C. Ritter, R. Rorden, R. Ryan, A. Smith, W. Smith, V. Stieber, I.A. Taub, G. Tochilin, G. Trimble, W. Turchinetz, Yu.P. Vakhrushin, R. Van de Vyver, N. Van Hooydonk, D. Walz, K. Whitham, D. Willis, U. Yelin, and many others who provided information about specific accelerator installations or discussed certain portions of the material.

The author acknowledges with deep appreciation the considerable help in the preparation of this manuscript by V. Smoyers and personnel of the SLAC Drafting Department under the leadership of T. Hunter. D. Dupen, W. Field and A. Schwartz provided very helpful advice at critical moments.

1. USES AND CHARACTERISTICS OF ELECTRON LINEAR ACCELERATORS

1.1. Fields of application

Several decades of technological development have culminated in the modern microwave electron linear accelerator, or electron linac, an instrument useful in medicine, industry and science [1, 2, 3]. The technologies combined in this simple and powerful tool are high-power pulsed microwave generation, high-vacuum technology, electronics, and metal forming and assembly. Originally developed as a research instrument to study the basic structure of matter, it has become useful in several other important ways.

(a) Medical applications

In radiation therapy, second- and third-generation electron linacs are widely employed in the treatment of cancer. They offer the advantages of simplicity and reliability, higher output, larger treatment fields, and the choice of both electron and photon irradiations. The higher energies are useful because of the greater penetration of the radiation to treat deep-lying tumours and afford a greater degree of protection to the skin. A small focal spot allows precise beam definition. Space requirements for the accelerators are modest and they are readily adaptable to rotational therapy. Both because of its societal importance and in terms of numbers of accelerators in operation (over 800), cancer therapy is the leading application of the electron linear accelerator [4, 5, 6].

(b) Industrial applications

High-intensity radiography is now an accepted, standard application of the electron linac, such as in the X-ray inspection of large welds, castings, complex assemblies and solid propellants [7]. Radiation processing applications [8] include curing of paint and adhesives, polymerization of plastics, food preservation [9] and sterilization of heat-sensitive medical products [10].

(c) Research applications

A third major category of uses is in scientific research. Research in nuclear physics employs linacs operating in the range 25–500 MeV, generally using the copiously produced photons to study nuclear structures. Facilities for studies using neutron time-of-flight and monoenergetic photons have permitted much greater detail in the experimental results than previously possible [11, 12].

Laboratories doing research in elementary particle physics use linacs producing electron beams with energies as high as 22 GeV and positron beams up to 15 GeV [3] (1 GeV = 1000 MeV). The extremely short wavelength corresponding to the electron or positron momentum (10^{-15} cm at 20 GeV) permits the substructure of the much larger proton and neutron (radius $\approx 1.2 \times 10^{-13}$ cm) to be explored.

Linacs are used as injectors for electron synchrotrons and electron/positron storage rings for elementary particle research. The discovery in 1974–75 of massive (compared with the nucleon) elementary particles at the $e^+ - e^-$ storage rings is considered one of the most important scientific results of recent times because it reveals the existence of a previously unknown property of matter, with implications concerning nuclear substructure [13].

Pulse radiolysis is a field of chemistry which uses to advantage the short radiation pulses available from electron linacs to study the dynamics of chemical reactions, particularly of free radicals.

A list of experimental uses under study might include such diverse subjects as: the use of intense beams of negative pi mesons (π^-) for cancer therapy, production of short-lived isotopes for prompt use in nuclear medicine, earth tunnelling and free-electron lasing.

1.2. Types of electron linear accelerator installations

The electron linear accelerator itself is fundamentally a conducting tube, usually of copper, accurately shaped to contain an electromagnetic wave of the proper characteristics – a kind of waveguide [14, 15, 16]. The beam energy is proportional to the length and to the electric field strength within the cavity or, equivalently, to the square root of the microwave power inserted. Typical gradients achieved lie in the range 2–4 MeV/ft. Because the electrons achieve relativistic velocities quickly, the spacing of cavities within the tube is uniform almost throughout its length. A high-energy accelerator differs from a low-energy machine mainly in its total length.

Two different configurations are in modern use. In the *travelling wave accelerator* (Figs 1, 2), microwave power is supplied to the input of the accelerator section and travels to the other end, remaining at all times in phase with the moving electron bunches. The accelerator interior is partitioned into accelerating cavities dimensioned in such a way that the phase velocity of the microwave field equals the electron velocity.

Another configuration is the *standing-wave accelerator* [17, 18] in which additional side cavities provide a 180° phase shift between accelerating cavities (Fig.3). This type has the advantage of being less sensitive to temperature or dimensional variations and achieves the same beam energy in a shorter length.

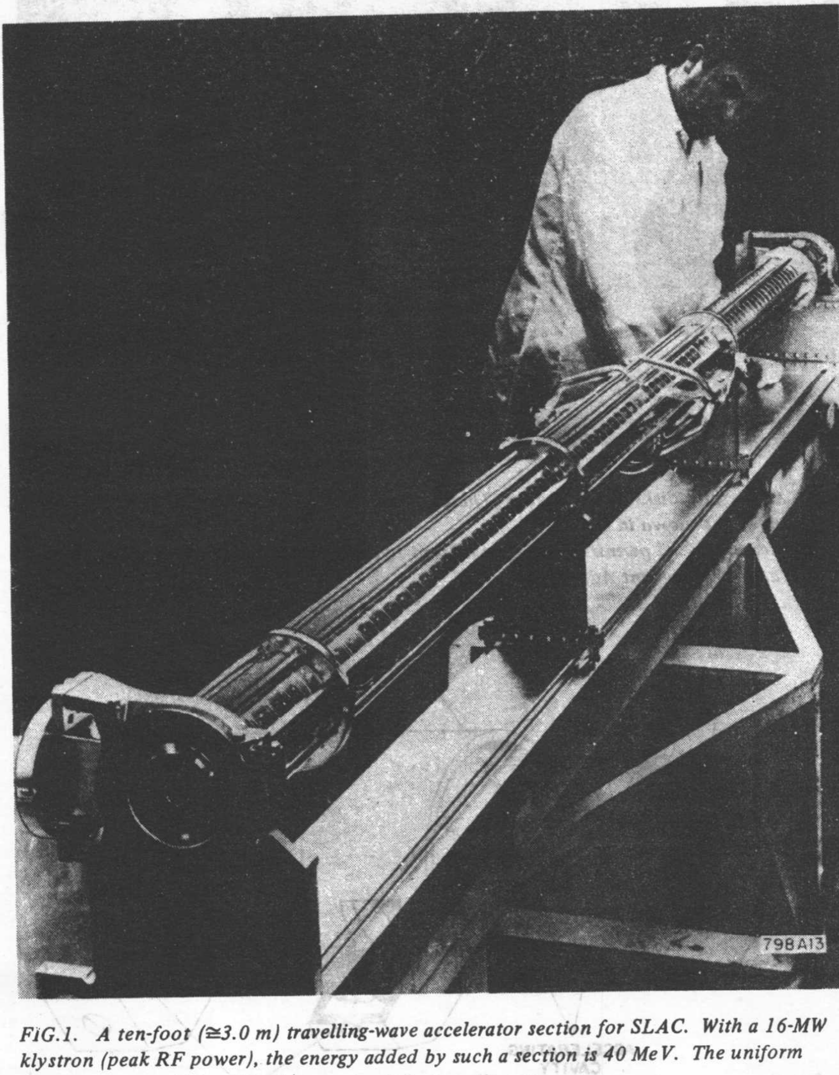

FIG.1. A ten-foot (≅3.0 m) travelling-wave accelerator section for SLAC. With a 16-MW klystron (peak RF power), the energy added by such a section is 40 MeV. The uniform partitioning into RF cavities by annular disks is easily seen.
(Reproduced with kind permission of the Stanford Linear Accelerator Center and the Energy Research and Development Administration.)

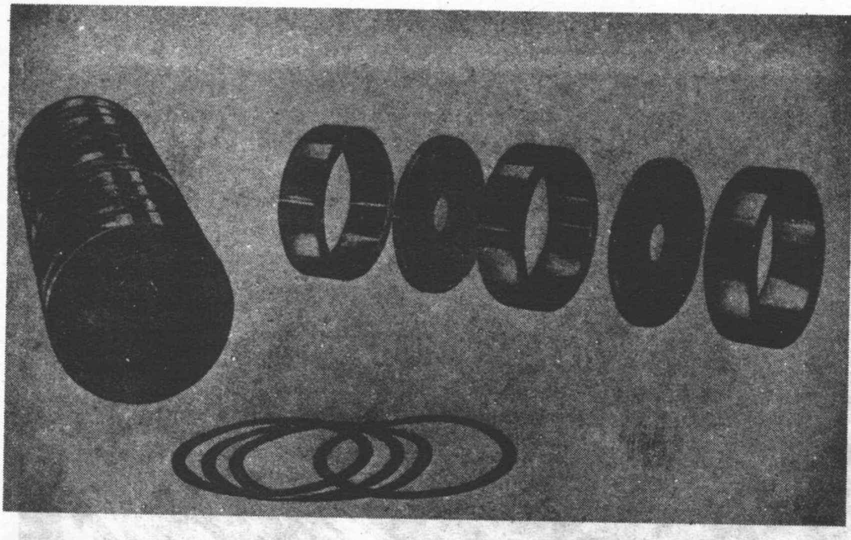

FIG.2. Accelerator disks and cylinders. These components are assembled to form the 10-ft (≅3.0 m) sections shown in Fig.1.
(Reproduced with kind permission of the Stanford Linear Accelerator Center and the Energy Research and Development Administration.)

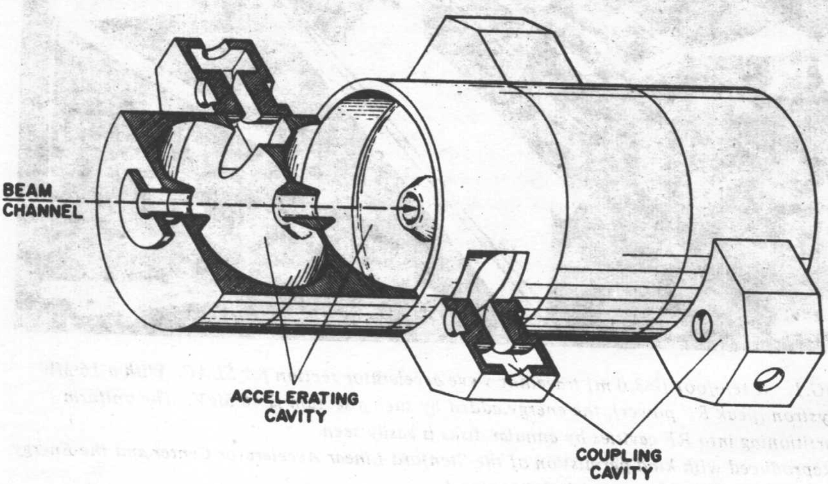

FIG.3. Structure of a standing-wave accelerator. The coupling cavities provide a phase change such that the accelerating cavities maintain a 180° phase shift with respect to each other.
(Reproduced with kind permission of E.A. Knapp, the Los Alamos Scientific Laboratory and Review of Scientific Instruments.)

Microwave power for low energies is generally developed by magnetrons, but all higher-energy accelerators use klystrons. The nominal frequency of 3000 Hz (wavelength 10 cm in free space at 2998 MHz) is usually used. Peak RF powers generated per unit are 2–5 MW (magnetrons) and 20–40 MW (klystrons).

The following components are common to all types of installations:

(a) The injector, containing the gun or electron 'source';
(b) The accelerator itself, composed of one or more sections, fed by separate microwave generators;
(c) The microwave generators: one or more magnetrons or klystrons, driven in phase;
(d) A modulator to energize each microwave generator;
(e) A target and/or beam dump to provide useful secondary radiations and stop the electrons.

In addition, most installations have at least one beam-transport magnet. Most medical accelerators operating above 6 MeV are equipped with a magnet which is an integral part of the apparatus which deflects the beam by 90° or 270°. Research installations may also have secondary beam lines, transporting a variety of particle types — photons, electrons, positrons and mesons.

Three categories of installations with similar radiation protection problems are easily identifiable: (a) medical, (b) industrial, and (c) research. These categories may differ somewhat in the types of radiations to be protected against, but more so in the physical layout and movements of personnel and members of the general public around them. Special needs of these types of installations are discussed where appropriate, and descriptions of typical installations are given. It is hoped that useful information for meeting the requirements of novel or unique installations will be found in this manual, although every case cannot be foreseen.

1.3. Parameters of electron linear accelerators

A list of physical parameters of the two-mile Stanford Linear Accelerator (Fig.4) is given in Table II. Although the example chosen is at present the highest-energy linac, most of its parameters are quite representative of many other travelling-wave accelerators if the differences related to its great length (multiplicity of sections and therefore of beam energy and power) are taken into account. The particularly unique features of the SLAC facility are the interlaced-multiple-beam capability, the ability to accelerate also positrons and polarized electrons to high energies, and a special facility for extremely short (10 ps) beam pulses.

Tables III, IV and V provide an overview of three classes of linear accelerator installations. It is seen that the development in medical accelerators within the past decade (Table III) has been toward a capability for isocentric therapy using

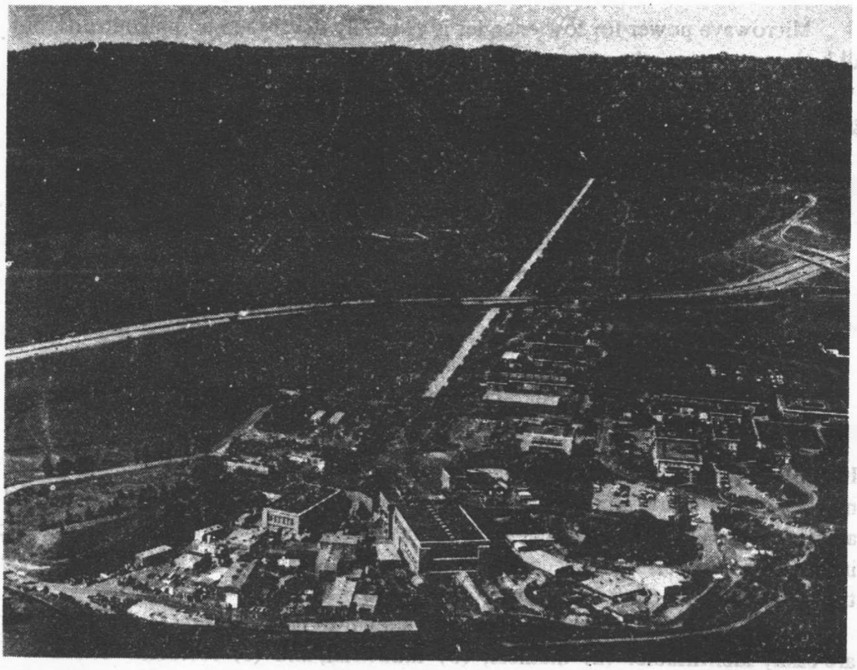

FIG.4. Aerial view of the Stanford Two-Mile Accelerator (SLAC), a modern high-energy facility for elementary-particle research. The Research Area with multiple-beam capability is in the foreground. The electron-positron storage ring SPEAR is to the lower right. The 360 beam pulses accelerated per second are shared by as many as six different beam paths, each with separately adjustable energy, current and pulse length.
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both electrons and photons [4]. The maximum useful energy appears to be approximately 40 MeV. The radiation characteristics at each energy are surprisingly similar among these modern facilities, reflecting a general consensus among manufacturers and users.

Accelerators for industrial radiography are surveyed in Table IV. The very high outputs of these machines may pose a great potential hazard to operating personnel in industrial settings.

Table V contains an abbreviated list of physical parameters of representative operating research and special-purpose installations. There is great variety in the capabilities of these installations, reflecting the purposes to which they are applied. Figure 5 illustrates the general rise in beam power with accelerator energy.

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