Proceedings of the 1984 Linear Accelerator Conference, Seeheim, Germany

APPLICATIONS OF LINEAR ACCELERATORS IN INDUSTRY

Marshall R. Cleland*

6 Jordan Road
Lynnfield, MA 01940 USA

Summary

Linear accelerators are now being widely used for applications in industry and medicine. The largest market for electron linacs is cancer therapy while industrial radiography is in second place. The use of linear accelerators for radiation processing has been severely limited by other technologies, but the prospects in this area are now improving due to increasing demand for penetrating radiation sources. This perception is stimulating the development of several new types of industrial accelerators. Various research accelerator systems, which have been developed for national programs, may also have industrial potential in the future.

Introduction

Radiation Therapy

Although cancer therapy may not be considered an industrial application, the increasing acceptance of linacs in the medical field is strong evidence of the viability of this technology outside of the research environment. There are now about 1000 therapeutic linacs in the USA. Worldwide, the total may exceed 2000 installations. Sales of new equipment are running about 150 to 200 annually[1-3].

Medical linacs are now made by ten organizations in seven countries. A variety of models are offered for either electron or x-ray treatments. Photon energies range from 4 to 25 MeV and electrons up to 32 MeV. Radiation intensities range from 100 to 1000 rad/min at 1 meter distance with 200 to 500 rad/min being typical. Beam power levels are modest, from a few hundred watts to a few kilowatts[4-6].

Industrial Radiography

Non-destructive testing is the largest industrial application for linear accelerators. Radiographic linacs are now offered by six organizations in six countries. The total number in service is estimated to be about 200 units and 15 to 20 new machines are sold annually[7].

The attractive features of linacs for high-energy radiography are the same as those for radiotherapy, i.e., high energy, high intensity, large field size, compactness and mobility. Standard equipment specifications cover a wide range of maximum energies from 1 to 15 MeV. X-ray intensities vary from 20 to 15,000 rad/min at 1 meter distance. Steel objects with thicknesses up to 50 cm can be inspected with the largest machines.

The short, high-intensity bursts of radiation from pulsed linacs can be useful in some radiographic applications. One example is the synchronization of the pulse repetition rate with the rotational speed of an aircraft jet engine to obtain stroboscopic pictures under load conditions[8]. Another is the imaging of exploding shells with an intense flash of x-rays. A peak pulse current of 1000 A for 150 nsec at an energy of 50 MeV is feasible by utilizing the stored energy in an intense rf field[9].

Radiation Processing

This application involves the stimulation of chemical reactions in various materials with ionizing radiations in the form of energetic electrons or photons. It includes the modification of polymeric materials, the sterilization of medical devices, the preservation of foods and the treatment of wastes[10].

Electron energy requirements for processing linacs range from 5 to 15 MeV. Beam power requirements are much higher than for therapy or radiography and may extend from 5 to 50 kW. Only a few industrial linacs are now being used for radiation processing. Their energies range from 6 to 12 MeV with beam powers from 5 to 10 kW[11,12].

The sale of linacs in this marketplace has been stifled by competition from lower-energy dc accelerators and large gamma-ray sources. The present situation and the prospects for improvement will be examined in the next section of this paper.

Prospects for Radiation Processing

Polymer Modification

A major sector of the radiation processing field is the modification of polymers, including coating systems and various plastic and rubber products. Most of these items are thin and can be penetrated by electrons with energies under 3 MeV. Production rates and radiation doses are high enough to require electron beam power ratings in the range of 10 to 100 kW[13].

These requirements can now be met with dc accelerators made by several equipment manufacturers. In addition to being more suitable for high beam current, dc accelerators are also less expensive and more efficient than linacs with high power outputs. So, this part of the processing market is not fertile ground for microwave equipment.

Sterilization

Another important application for ionizing radiation is the sterilization of medical devices. This sector of the market is now dominated by large gamma-ray facilities. A penetrating form of radiation is required to treat products in large shipping cartons to compete with the conventional sterilization method of fumigation with ethylene oxide gas.

---

*Formerly with High Voltage Engineering Corp. and Radiation Dynamics, Inc.

There are over 110 gamma-ray sterilization facilities in the world containing about 70 million curies of Co-60 in all. Recently, the growth rate of this industry has exceeded 5 new gamma facilities and 10 MCi of Co-60 per year[14].

Due to increasing demand, large gamma-ray sources are now in short supply. Deliveries of new orders are being extended and prices are rising. This situation may soon be alleviated by an increase in the production of radioactive cobalt, but meanwhile, it is causing some concern among the users of this technology. These recent changes in the availability of gamma sources have created a more favorable outlook for the use of electron linacs for sterilization.

Only a few linacs are now being used for this purpose with electron energies in the 6 to 12 MeV range and beam power levels from 5 to 10kW. Beam penetration at these energies is adequate because of the low average densities of the cartons (typically 0.2 g/cm^3) but thruput rates at these power levels are marginal.

To be competitive, linear accelerators must be able to provide equivalent amounts of ionizing radiation at about the same price as large gamma sources. Commercial sterilization plants now contain anywhere from 1 to 4 MCi of Co-60 with gamma power outputs of from 15 to 60 kW. Since directed electron beams can be utilized somewhat more efficiently than isotropic gamma radiation, the equivalent linac power outputs may be from 10 to 40 kW.

At the present price of about $1/Ci of Co-60, the sources listed above would cost from $1 to $4 million, respectively. Processing linacs should be priced commensurately, i.e., a machine providing only 10 kW of beam power should not cost more than $1 million. This criterion may be achievable with a reasonable volume of sales, but at higher power levels of 20 kW or more, linacs will be less expensive than Co-60 sources of equivalent productivity.

Food Preservation

After 40 years of research, the idea of preserving food with ionizing radiations is finally gaining acceptance internationally. Following a strong endorsement by the Joint Expert Committee of the UN agencies, FAO, IAEA and WHO, the US FDA has recently issued a Proposed Rule to regulate the commercial uses of this process[15,16].

Although the market for irradiated foods is small today, the level of interest is rising all over the world and it is timely to consider the types and quantities of radiation sources that may be required by these new industrial processes. In some cases, existing accelerators and gamma-ray facilities may be adequate, but for others, more powerful equipment will have to be developed.

For granular substances like bulk grain and ground poultry feed that can be transported through an electron beam in a thin layer, medium-energy (1 to 3 MeV) dc accelerators will be suitable and probably the least expensive type of radiation source. Thicker products requiring electron energies greater than 4 to 5 MeV will be candidates for microwave accelerators. The maximum electron energy will be limited to 10 MeV to avoid the induction of radioactive isotopes, but this will provide enough penetration for many food processes.

Food items too thick for treatment with 10 MeV electrons will require the use of photon radiation, i.e., gamma-rays or bremsstrahlung (x-rays). The generation of high-intensity bremsstrahlung may be a viable industrial application for high-power cw linacs.

The output of a 5 MeV bremsstrahlung generator for photon processing has been evaluated by the Monte Carlo method. The results indicate that the radiation from a 200 kW electron beam on a tungsten target would be equivalent in productivity to 1.6 MCi of Co-60[17]. At this level, a cw linac would probably be more expensive than a gamma-ray source, but for larger facilities and higher power ratings, the linac would be less expensive[18].

Waste Treatment

High-power electron accelerators can also be applied in the environmental field. The disinfection of sewage sludge to reduce the risk of land application, the disinfection of municipal waste water without using chlorine, the destruction of toxic substances in drinking water supplies and the extraction of sulfur and nitrogen oxides from combustion gases are intriguing possibilities[19].

The technique of irradiating liquid sludge at high thruput rates with low-energy dc accelerators has been developed in Boston and will soon be demonstrated in Miami. The beam power for a city of 1 million people may lie between 100 and 250 kW, depending on the volume of material and the dose requirement.

Presently available dc accelerators, which can provide up to 150 kW of beam power per unit, will be satisfactory for most sludge treatment plants. High-power linacs could also be used but may not be competitive in price with dc equipment at this power level. On the other hand, the use of more energetic beams with greater penetration would simplify the sludge irradiation technique.

The treatment of municipal wastewater is a very different case. The beam power requirements for this application will be much higher than for sludge disinfection because of the much greater flow rates, even though the dose level will be substantially reduced. Using the same example as above, the beam power requirement for a city of 1 million people would be about 4 megawatts. This very high power level is clearly beyond the capability of any existing dc machine and may be another opportunity for cw linac technology.

The power requirements for treating drinking water will be about the same as for wastewater disinfection, since the flow rates and dose requirements are similar. The same kind of equipment can be applied to either process. Irradiation not only disinfects but improves the taste of raw water supplies by decomposing trace organic contaminants that are dissolved in the water[20].

The scrubbing of combustion gases with energetic electrons can alleviate the problem of acid rain. The effectiveness of this process was evaluated in Japan and will soon be demonstrated in the USA[21]. The power requirements are quite high, about 10 to 15 MW for a 500 MW coal-fired power plant. Relatively low-energy accelerators can be used because of the long range of energetic electrons in gases at atmospheric pressure.

This application will need powerful accelerators with outputs up to at least 1 MW. Scaled-up versions of conventional dc equipment will probably be the most economical and efficient type of energy source, although higher-energy rf or pulsed accelerator systems may also be considered [22].

Processing Linac Developments

There are several new developments in linac design that will be able to provide more than 10 kW of average electron beam power for radiation processing. Some of these are described briefly in this section.

Novosibirsk ILU-6

The ILU-6 consists of a large resonant cavity driven by a triode tube at a frequency of 110 MHz. The tube and the cavity work together as a self-excited oscillator. The electron gun is mounted on one of the reentrant stubs inside the cavity and the beam is extracted by the rf accelerating field. The output end of the cavity is insulated from the grounded enclosure and supplied with a negative dc bias of a few kilovolts to suppress multipactoring and to protect the cathode surface from energetic ions[23].

This low-energy accelerator system can be operated in cw mode up to an excitation level of 350 keV and in pulsed mode up to 2 MeV. Average beam power can be 20 kW over the energy range from 0.7 to 2 MeV. Maximum pulse length is 700 usec and maximum repetition rate is 300 Hz. Typical running conditions are 15 kW beam power at 1.5 MeV with less than 2 MW peak rf power and a duty factor of 2%.

Several of these devices have been installed in factories in the Soviet Union to irradiate insulated wire and plastic tubing. A manufacturing license has been granted to the firm, Polymer Physik in Tubingen, FRG, which also makes low voltage dc electron accelerators for curing polymeric coatings.

CGR MeV Cassitron

The Cassitron accelerator is a three-cavity system driven by a single triode tube in a self-excited configuration. The resonant frequency is somewhat higher than the ILU-6 at 166 MHz. The electron beam is focused by three magnetic lenses located near the entrance to each cavity. The modulator uses low-voltage solid-state components followed by an 80/1 step-up transformer[24].

The performance objectives are an average beam power of 20 kW at an energy of 8 to 10 MeV with the possibility of operating at lower energies down to 4 MeV. Pulse length will be 300 usec at a repetition rate of 50 Hz. The shunt impedance is about 50 megohms. Peak and average rf power levels may be about 4 MW and 60 kW, respectively.

The prototype of this system is now under development in Buc, France. The first commercial unit will be used for food irradiation and the second for sterilization of medical devices.

Harwell Linac

This large L-band machine, made by Radiation Dynamics, Ltd. in Swindon, UK, consists of eight 2-meter travelling-wave guides powered by four Thompson TV2022 klystrons. The unloaded beam energy is 136 MeV, and the maximum beam power at 80 MeV is 90 kW with 160 kW input rf power[25]. A single section of this machine, powered by an improved version of the Thompson tube, would be capable of generating 40 kW of beam power at an energy of 10 MeV[26].

Los Alamos Concepts

Several "zero order" estimates of accelerator performance for high-power linac designs have been calculated at LANL using the parameters of the Hoyt standing-wave guide with side-coupled cavities. The results indicate that up to 70 kW of beam power might be obtainable with either the Varian VA-938D S-band or the Litton L-5081 L-band klystron. The lower peak power of the S-band tube was compensated by a higher duty factor to obtain the same average power as the L-band system[27].

Chalk River ETA

The Electron Test Accelerator at Chalk River Laboratories has been built to study the behavior of standing wave linac structures under heavy beam loading[28]. It consists of three interchangeable electron guns, a beam buncher, a graded capture section and two relativistic accelerator sections driven at a frequency of 805 MHz.

In cw mode it has reached a beam current of 22 mA at 4 MeV (88 kW of beam power) with a single fundamental buncher. Design improvements in the gun and buncher section are expected to increase the beam transmission up to 100 mA average current. If these improvements are successful, this cw technology would be able to produce very high-power beams of 500 kW at 5 MeV and even 1 MW at 10 MeV[29].

Future Linac Applications

A large number of special-purpose linacs have been developed at major universities and national laboratories to support programs in basic research, radiation applications, energy production and national defense. The knowledge and experience gained in designing, building and operating these systmes provide a technology base from which future industrial applications may evolve[30].

The versatility of particle accelerators is indicated by the variety of programs listed below. Applications for linear induction accelerators, drift-tube linacs and radiofrequency quadrupoles are included along with those for microwave and rf accelerators.

Electron Accelerators

- Synchrotron Radiation
  - Optics
  - Chemical Physics
  - Molecular Biology
  - Solid State Physics
  - X-Ray Lithography

Electron Accelerators (Continued)

- Free-Electron Laser
  - Microwave Generation
  - Far Infrared Spectroscopy
  - Isotope Separation
  - Pellet Fusion
  - Submarine Communication
  - Infrared Countermeasures
  - Directed Energy Weapons
- Explosive Radiography
- Material Degradation
- Nuclear Effects Simulation
- Nuclear Waste Transmutation

Light-Ion Accelerators

- Cancer Therapy
  - Protons
  - Mesons
- Intense Neutron Sources
  - Neutron Activation
  - Neutron Radiography
  - Fusion Materials Testing
  - Fissile Fuel Breeding
- Radioisotope Production
- Plasma Fuel Injection
- Pellet Fusion
- Nuclear Weapons Simulation
- Directed Energy Weapons

Heavy-Ion Accelerators

- Ion Implantation
  - Semiconductors
  - Metallurgy
- Cancer Therapy
- Plasma Heating
- Pellet Fusion

Many industrial firms have participated in the construction of these accelerator facilities as contractors or equipment suppliers. Some laboratories, like the National Synchrotron Light Source at Brookhaven, N.Y., are available for use by industrial participants. The national laboratories in the USA are now able to assist industrial firms to evaluate concepts and develop commercial products. Practical applications of these diverse accelerator technologies are hard to assess but many valuable spin-offs will surely occur.

References

1. Kramer, S., Hanks, G.E., Herring, D.F. and Davis, L.W., Summary Results from the Facilities Master List Surveys Conducted by the Patterns of Care Study, Int. J. Rad. Onc. Biol. Phys., 8, 883 - 88 (1982).

2. Directory of High-Energy Radiotherapy Centers, 1968 and 1976 Editions, International Atomic Energy Agency, Vienna, Austria.

3. Hanson, W. F., The Changing Role of Accelerators in Radiation Therapy, IEEE Transactions on Nuclear Science, NS-30, No. 2, 1781 - 83 (1983).

4. Loew, G.A., Electron Linacs, SLAC-PUB-830 (1976) Stanford Linear Accelerator Center, Palo Alto, CA

5. Fraser, J.S. and Schriber, S.O. Compendium of Linear Accelerators, Report No. AECL-5615, (1976) Atomic Energy of Canada, Ltd., Chalk River, Ontario, CA.

6. Swanson, W.P., Radiation Parameters of Electron Linear Accelerators, SLAC-PUB-2092 (1978) Stanford Linear Accelerator Center, Palo Alto, CA.

7. Nunan, C., Private Communication (1984) Varian Associates, Inc., Palo Alto, CA.

8. Materials Evaluation, XXXI, No. 3, 45A, (1973), Rolls Royce/Radiation Dynamics.

9. Starke, T.P., Phermex Standing-Wave Linear Electron Accelerator, IEEE Transactions on Nuclear Science, NS - 30, No. 2, 1402 - 04 (1983).

10. Transactions of the 1st thru 4th International Meetings on Radiation Processing, Rad. Phys. & Chem. 9, Nos. 1 - 3, 4 - 6 (1977), 14, Nos. 1 - 2, 3 - 6 (1979), 18, Nos. 1-2, 3-4, 5-6 (1981), 22. Nos. 1-2 and 3-5 (1983), Pergamon Press, Elmsford, N.Y. 10523.

11. Leboutet, H., Low Energy, High Intensity Electron Accelerators, Chapter 3.3, 471 - 493, Linear Accelerators, Ed. Lapostolle and Septier, North-Holland Publishing Co., Amsterdam, (1970).

12. Haimson, J., Advances in Electron Beam Linear Accelerator Technology, Proc. Int. Conf. on Sterilization by Ionizing Radiation, 71 - 106 (1974) Multiscience Publ. Ltd., Montreal, CA.

13. Becker, R.C., Bly, J.H., Cleland, M.R., Farrell, J.P., Accelerator Requirements for Electron Beam Processing, Rad. Phys. Chem., 14 Nos. 3-6, 353-375 (1979).

14. Cuda, J., Industrial Gamma Processing Overview, Tech. Paper GPS 311, (1983), Third Gamma Processing Seminar, Atomic Energy of Canada, Ltd., Ottowa, CA.

15. Wholesomeness of Irradiated Foods, Report of a Joint FAO/IAEA/WHO Expert Committee, WHO Technical Report Series 659 (1981), Geneva, Switzerland.

16. USFDA, Irradiation in the Production, Processing and Handling of Food, 21 CFR Part 179, Federal Register, 49, No. 31, (Feb. 14, 1984).

17. Farrell, J.P., Seltzer, S.M., Silverman J., Bremsstrahlung Generators for Radiation Processing, Rad. Phys. Chem., 22, Nos. 3-5. 469-478 (1983).

18. McKeown, J., Electron Accelerators -- A New Approach, Rad. Phys., Chem., 22, Nos. 3-5, 419-430 (1983).

19. Machi, S., Radiation Processing for Environmental Conservation, Special Issue, Rad. Phys. Chem. 24, No. 1, (1984).

20. Levaillant, C., Gallien, C.L., Sanitation Methods using High Energy Electron Beams, Rad. Phys. Chem., 14, Nos. 3-6, 309-316 (1979).

21. Trexler, E. C., DOE's Electron Beam Irradiation Developmental Program, Proceeding: Symposium on Flue Gas Desulfurization, Vol. 1., 359-374, (1983), Electric Power Research Institute, Palo Alto, CA.

22. McKeown, J., CW Linac for Processing, Symposium on Accelerators for Processing, Fuji, Japan (1983) Chalk River Nuclear Laboratories, Chalk River, Ontario, CA.

23. Auslender, V.L., et. al., Radio-Frequency Electron Accelerator, U.S. Patent No. 4,140,942, Feb. 20, 1979.

24. Leboutet, H., Aucouturier, J., An Electron Accelerator for Irradiation: "Cassitron," Rad. Phys. Chem. 22, Nos. 3-5, 403-408 (1983).

25. Cracknell, P.J., The Harwell 136 MeV Electron Linear Accelerator, IEEE Transactions on Nuclear Science, NS-28, No. 3, 3470-3472 (1981).

26. Cracknell, P.J. Electron Radiation Processing - Accelerators, Proc. Int'l. Conf. Radiation Processing for Plastics and Rubber, 11.1 - 11.10 (1981), The Plastics and Rubber Institute, London, U.K.

27. Stovall, J.E., Boyd, T.J., Private Communication (1983), Accelerator Technology Division, Los Alamos National Laboratory, Los Alamos, N.M.

28. Labrie, J.P., Chan, K.C.D., McKeown, J., The Chalk River Electron Test Accelerator: A Prototype for Industrial Irradiator Designs, IEEE Transactions on Nuclear Science, NS-30, No. 2, 1634 - 1637 (1983).

29. McKeown, J., New Accelerator for Radiation Processing: CW - Type Linac, Proc. 16th Japan Conf. on Radiation and Radioisotopes (1983). Chalk River Nuclear Laboratories, Chalk River, Ontario, CA.

30. Assessment of the Adequacy of U.S. Accelerator Technology for Dept. of Energy Missions, WJSA-83-228 (1983), W.J. Schafer Associates, Inc., Wakefield, MA 01880.

Appendix

Energy Requirement

The useful penetration of high-energy electrons in organic materials is about 3 to 4 mm/MeV in the range between 1 and 10 MeV. For equal entrance and exit doses, the energy requirement, E MeV, can be estimated by the following formula, where t is the product thickness in cm and p is its density in g/cm^3:

$$E = 2.6\ t\ p + 0.3$$

This indicates that 1 cm of water would require an electron energy of 2.9 MeV. If the product is irradiated from opposite sides, the thickness can be increased by a factor of 2.4. The 20% gain is due to the overlapping of the "tails" of the depth-dose distributions.

Power Requirement

The common unit for specifying absorbed dose in radiation processing is the megarad (Mrad) which is equivalent to 10 watt-sec/gm or 1/360 kW-hr/kg. The electron beam power requirement, P (kW), can be estimated by the following formula, where D (Mrad) is the absorbed dose, M/T (kg/hr) is the production rate and f is the beam utilization efficiency:

$$P = (D/f)(M/T)/360$$

When treating flat sheets of material or streams of water, a reasonable value for f is about 0.50. This allows for a 20% loss of beam current due to overscanning the product conveyor plus a 30% loss of electron energy due to penetration of the product and excessive dose in the middle of the product.

Sterilization

The energy efficiency of a gamma-ray sterilization plant can be estimated from the fact that 1 MCi of Co-60 can treat 1 million cubic feet per year of packaged medical products at a dose of 2.5 Mrad. With a typical package density of 0.2 g/cm^3 and an 8000 hr. year, the thruput would be 710 kg/hr. The absorbed power would then be:

$$P = 2.5x710/360 = 4.9\ kW$$

The emitted gamma power of encapsulated Co-60 sources is about 14 kW/MCi. So, the utilization efficiency is then:

$$f = 4.9/14 = 0.35$$

If the efficiency of an electron beam facility is 0.50, then the electron beam power can be reduced by a factor of 0.35/0.50 = 0.70 compared to the gamma power requirement.

Waste Treatment

In the USA, the flow rate of wastewater is about 100 gallons per day per person. So, one million people produce 16 million kg/hr. For a dose of 50 krad and an efficiency of 0.5, the power requirement is:

$$P = (0.05/0.5)(16x10^6/360) = 4,400\ kW$$

The yield of liquid sludge is much less than wastewater, only 0.3 gallons per person per day or 47 thousand kg/hr. The minimum dose requirement is higher, 400 krad, but the beam power is much lower:

$$P = (0.4/0.5)(47x10^3/360) = 105\ kW$$

The yield of combustion gases from a 500 MW coal-fired power plant is about 1.3x10^6 SCFM or 3.7x10^4 cubic meters/min. At normal air density of 1.2 kg/m^3 this is 2.7x10^6 kg/hr. For a dose of 1.5 Mrad, and a beam efficiency of 0.75, the beam power is:

$$P = (1.5/0.75)(2.7x10^6/360) = 1.5x10^4\ kW$$

The higher efficiency is justified in this case because the gas stream is irradiated from opposite sides and the maximum range of the electrons can be utilized. Dose uniformity is obtained by mixing the gas with impellers.