# Present and Future Applications of Industrial Accelerators

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Technology transfer - from national laboratories to industry and vice versa - implies that concepts, designs, and equipment get transferred. There is also another mode of transfer which historically has been important - the transfer of experienced people. One of the major things that accelerator physics research laboratories have done is to train physicists and engineers in advanced technology. If these people then transfer to industry they can carry with them a level of know-how and creative talent that can be very effective in the on-going application of accelerator-based technology to societal needs. A prime example is Ed Ginzton. Ginzton was a professor of physics at Stanford University and cofounder of SLAC, the Stanford Linear Accelerator Center. He was one of the founders of Varian Associates. People from other accelerator laboratories joined Varian over the years. They came from many U.S. and foreign laboratories. Some of the people subsequently left Varian to found other accelerator companies.

A recent example is Bob Hamm, a physicist who trained at Los Alamos National Laboratory, spent two years at Varian, founded AccSys Technology Corporation, was joined by other people from Los Alamos, and among other things, built the proton linac injector for the proton therapy synchrotron designed and built by Fermilab for Loma Linda University Medical Center. There are other examples of this form of genesis of accelerators in industry. In summary we should recognize the teaching aspects of the major laboratories and we should emphasize ''people-transfer'' in the future.

What is the economic value to society of accelerators produced by industry? It is interesting to make economic comparisons of the cost of building super-high-energy physics research accelerators to the total value of various kinds of accelerators manufactured by industry. Taking the largest example, the budget for the 40 million-MeV Superconducting Super Collider (SSC) (Fig. 1) is about $5000 million dollars.[1] This is comparable to the total value of all the accelerators manufactured by U.S. industry in the past 20 years. This includes about 2000 linacs for cancer therapy; 800 for irradiation, primarily of plastic products; 250 for industrial radiography; 3000 for ion implantation of semiconductors; plus a number of other types of accelerators for other applications. But the impact of these machines on society is far greater than their capital costs. The value to society of the items irradiated by these machines over their useful lifetime is of order 100 to 1000 times the price of the machines themselves. Three examples illustrate this point.

The U.S. output of products suitable for surface curing with electron beams of energy less than 0.3 MeV is about $15 billion per year. The useful penetration of a 0.3-MeV electron beam is about 1/2 mm of plastic or paper. These products (Fig. 2) comprise primarily containers, paper sacks, laminated and coated films, and labels and tapes. The typical price of such a sheet electron beam machine is about $0.4 million and it irradiates about $100 million worth of product over its 20-year useful life, a value ratio of 250.

As another example of cost/benefit ratio, the typical 4- to 25-MeV medical electron accelerator (Fig. 3) treats about 300 new patients per year. About half of these are treated for cure, with about 50 percent success rate, defined as no evidence of the cancer five years after treatment. The value of human life in the United States is somewhere between the average contract price for a hit-man to kill someone and the average award by the courts for a death due to malpractice. This ranges between about 10 percent and 100 percent of the price of one of these medical accelerators. Each machine over its average service life cures about 1000 people, thus providing a value ratio between 100 and 1000.

As a third example, electron accelerators in the 5- to 10-MeV range are used for irradiation sterilization of medical disposables (Fig. 4), such as syringes and surgical kits, which are used once and then discarded. A volume of something like 100 million cubic feet of such products per year is now sterilized by irradiation, primarily by Cobalt-60 but also with accelerators. A $2 million electron accelerator can sterilize about $2 billion worth of medical disposables over its useful machine life, a value ratio of 1000.

**igure 1**: Aerial view of site for uperconducting Super Collider (SSC)

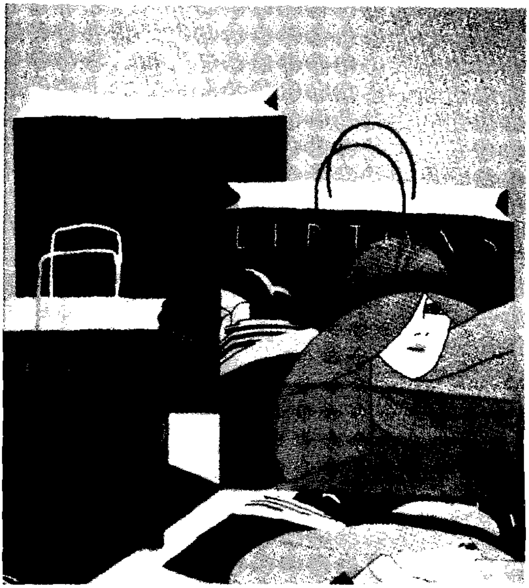


**Figure 2**: Products surface cured by sheet Electron beam. (Courtesy of ESI)

**Figure 3**: Radiotherapy linac with patient. (Varian Associates)

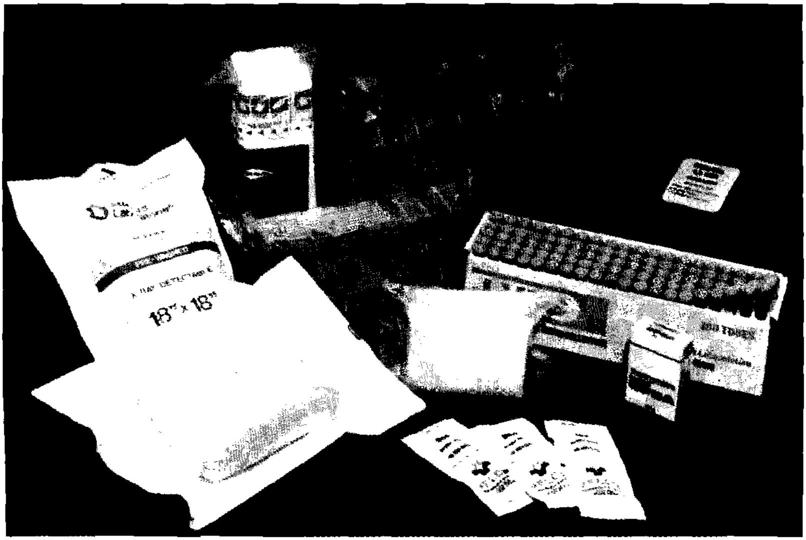


**Figure 4**: Medical disposables irradiated by electron beams.
(Courtesy of RDI)

Of course, there are many other capital and operating costs associated with the use of these various types of industrial and medical accelerators. But the point is that the economic value to society of the items irradiated by an installed base of all the accelerators produced by industry is 100 to 1000 times larger than the cost to build the biggest super-high-energy physics research machine conceived to date, a machine 20 times the energy of the Fermilab Tevatron. One can ask whether the accelerator industry would have built its small accelerators if there had never been any accelerator-physics research laboratories to invent the technology. Similarly, one could ask if industry would be building anything different in future decades if the present push by physics research laboratories toward better accelerator technology were stopped. The answer to the first question implies the answer to the second.

When we refer to industrial applications later we mean uses of accelerators other than for the medical treatment of patients. By accelerator we mean a system which delivers an external beam of electrons or ions, or of intense penetrating x-rays.

An important industrial application is the use of sheet-beam electron accelerators for surface curing. Typically these have an energy of 0.3 MeV or less. Figure 5 shows the radiation head of a sheet-beam accelerator. A high-voltage conventional power supply at up to 300 kV and 300 kW is mounted in a pressure chamber to provide insulation. The high voltage is fed by cable to a long cathode inside an evacuated metal cylinder which has a long metal foil window in its wall. The electrons emitted from the cathode are accelerated in a sheet beam through the window and into the web-like product which is moving by the window at rates up to 12 miles per hour in web widths up to 6 feet. The product enters and exits through a radiation shield. This self-shielding permits the radiation head to be located in the factory production line.

Typical industrial applications of sheet-beam irradiators in commercial use today are listed in Table I. Some major uses are curing of binder resin in magnetic floppy disks and tapes, cross-linking of plastic packaging films, curing of decorative overprint coatings for shopping bags, and high-strength laminates, which frequently incorporate a metallizing layer. There are about 150 of these machines being used for routine production and another 200 for research and development.[2]

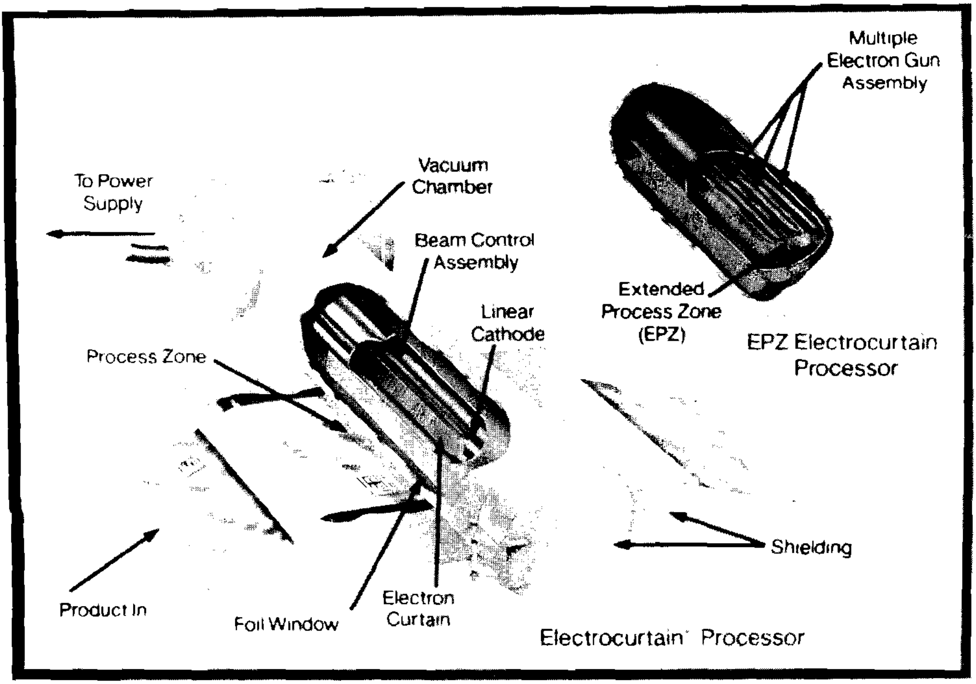
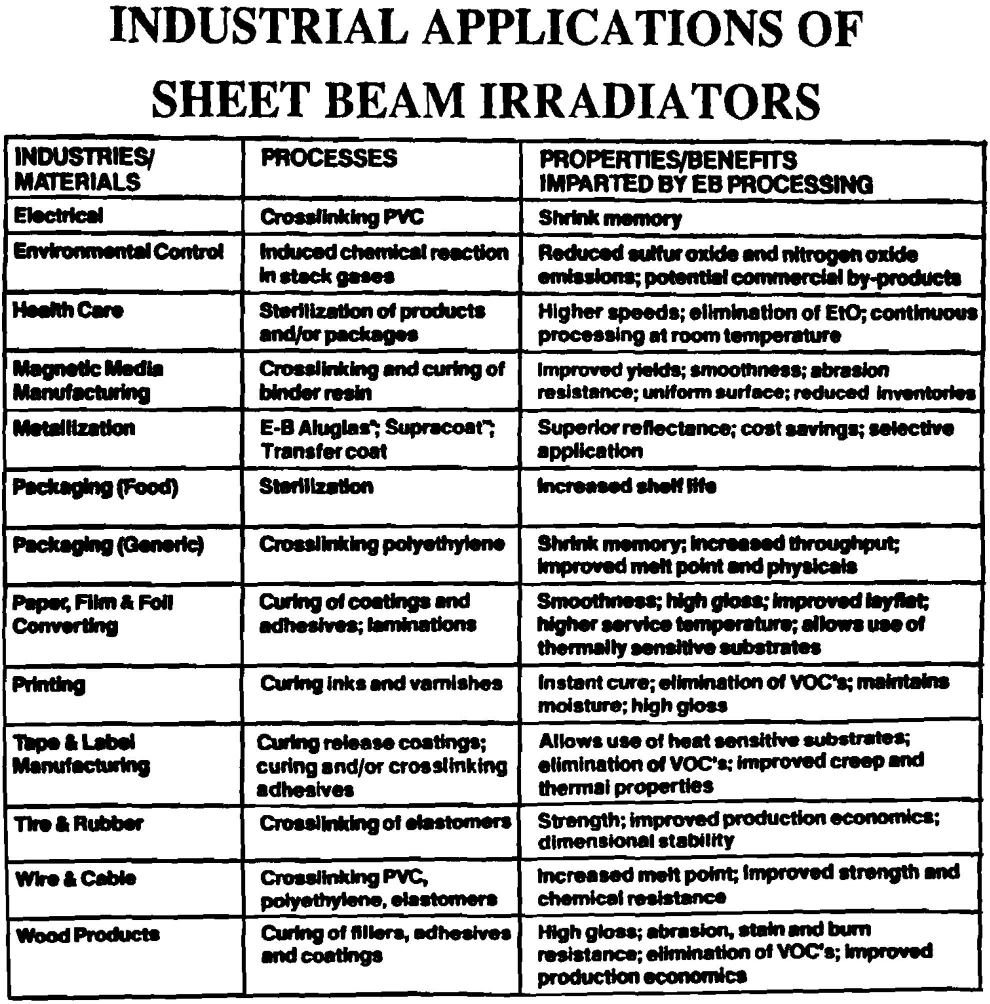


Figure 5: Vacuum chamber of sheet electron beam system with radiation shielding for web handling application. (Courtesy of ESI)



# INDUSTRIAL APPLICATIONS OF SHEET BEAM IRRADIATORS

| INDUSTRIES/ MATERIALS | PROCESSES | PROPERTIES/BENEFITS IMPARTED BY EB PROCESSING |
|---|---|---|
| Electrical | Crosslinking PVC | Shrink memory |
| Environmental Control | Induced chemical reaction in stack gases | Reduced sulfur oxide and nitrogen oxide emissions; potential commercial by-products |
| Health Care | Sterilization of products and/or packages | Higher speeds; elimination of EtO; continuous processing at room temperature |
| Magnetic Media Manufacturing | Crosslinking and curing of binder resin | Improved yields; smoothness; abrasion resistance; uniform surface; reduced inventories |
| Metallization | E-B Aluglas®; Supracoat®; Transfer coat | Superior reflectance; cost savings; selective application |
| Packaging (Food) | Sterilization | Increased shelf life |
| Packaging (Generic) | Crosslinking polyethylene | Shrink memory; increased throughput; improved melt point and physicals |
| Paper, Film & Foil Converting | Curing of coatings and adhesives; laminations | Smoothness; high gloss; improved layflat; higher service temperature; allows use of thermally sensitive substrates |
| Printing | Curing inks and varnishes | Instant cure; elimination of VOC's; maintains moisture; high gloss |
| Tape & Label Manufacturing | Curing release coatings; curing and/or crosslinking adhesives | Allows use of heat sensitive substrates; elimination of VOC's; improved creep and thermal properties |
| Tire & Rubber | Crosslinking of elastomers | Strength; improved production economics; dimensional stability |
| Wire & Cable | Crosslinking PVC, polyethylene, elastomers | Increased melt point; improved strength and chemical resistance |
| Wood Products | Curing of fillers, adhesives and coatings | High gloss; abrasion, stain and burn resistance; elimination of VOC's; improved production economics |

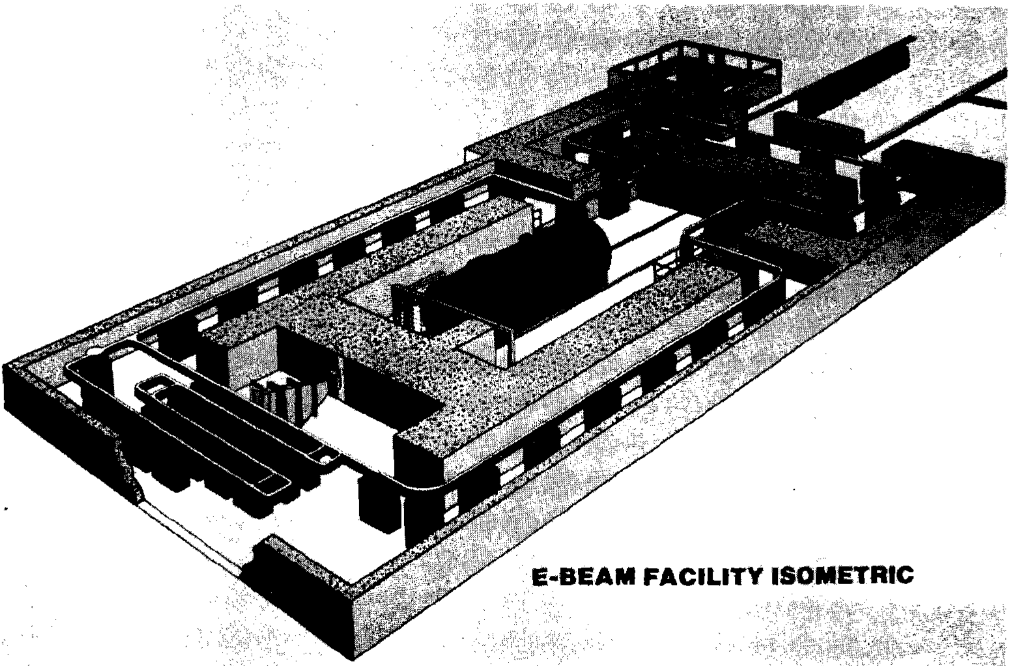
ble I: Typical Electrocurtain applications (Courtesy of ESI)

A second industrial application is irradiation with direct electron accelerators, usually in the 0.4- to 5-MeV range. Figure 6 shows a type of irradiation accelerator in wide use. It is called a Dynamitron. It was invented by Marshall Clelland when he was a graduate student at Washington University. An rf oscillator at about 0.5 MHz applies an oscillating electric field between two long electrodes inside a large tank which is pressurized for insulation. In a parallel-to-series charging arrangement, the oscillating electric field causes electrons to flow up through stacks of rectifiers to charge a high-voltage dome. Electrons emitted from a cathode in this dome are accelerated down an evacuated electrode column and pass through a scanner window into the product. Beam power is typically in the range of 50 to 100 kW, at energies from 0.5 to 2.5 MeV. About 400 such machines are used in routine production.[2] About half are used for thermal enhancement of wire and cable insulation and for heat-shrink tubing. One quarter are used for heat-shrink packaging film such as around your Thanksgiving turkey. The remainder are used for partial curing of tire components, for foam manufacture, and for other applications.

Higher energy Dynamitrons, in the 3- to 5-MeV range, have also been developed. To provide insulation at these energies, the high-voltage tank can get quite large. The tank for the 5-MeV, 200-kW machine is 25 feet long, 9 feet in diameter, plus 6 feet for a side pod for the rf transformer. These machines are used in the manufacture of heat shrinkable plastic products for wire and cable (Fig. 7), for cross-linking molded plastic products, and to sterilize medical disposables such as syringes.

Microwave electron accelerators in the 1- to 15-MeV range are also used for irradiation. A few microwave electron linear accelerators (called linacs) are in use, for irradiation of medical disposables, thick-walled plastic components and tubing, food, and color enhancement of gems. Figure 8 shows an artist's sketch of a 10-MeV 50-kW electron linac being developed for irradiation.

About 250 linacs in the 1- to 15-MeV range are currently in use for nondestructive x-ray inspection. About half are used for detection of flaws which could cause a malfunction in solid-propellant rocket motors, such as bond separations between the propellant and casing liner. Solid-propellant rocket motors are made in diameters up to 10 feet or more, so megavoltage x-rays are required for adequate penetration. The x-ray attenuation through the rocket may be of



**'igure 6:** 5 MeV Dynamitron in facility for electron irradiation of medical disposables. (Courtesy of RDI)

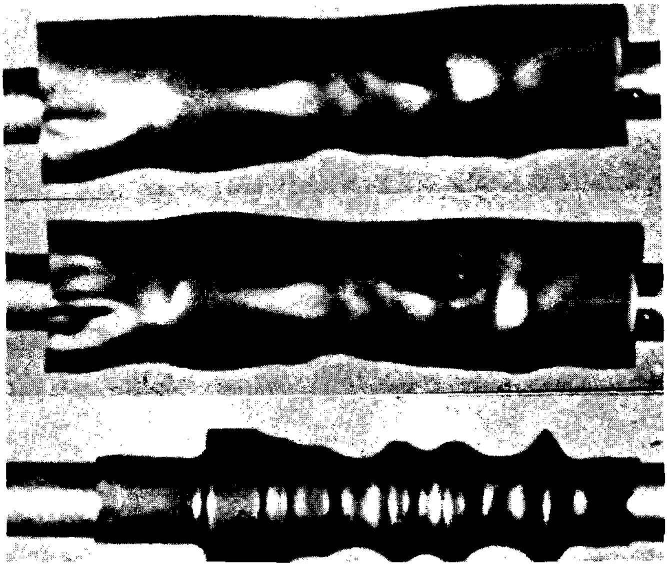


**Figure 7:** Product cross-linked by electron irradiation. (Courtesy of RDI)

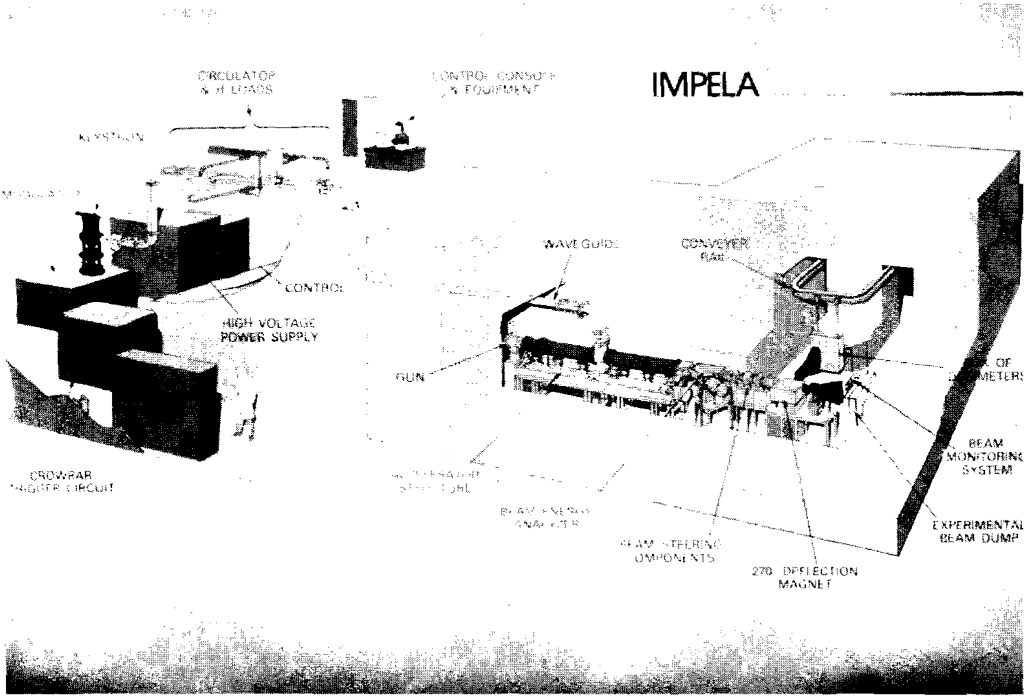


**Figure 8:** 10 MeV 50 kW linac irradiation facility. (Courtesy AECL)

order 10,000 to 1, so a high x-ray dose rate is required for practical exposure times. For mobility to move around and along the motor, the x-ray head must be of moderate size, as shown in Figs. 9a and 9b. Images of flaws are taken with film, but to save time in searching for regions that are suspect, electronic imaging is used. For more precise delineation of locations of flaws, CT (computerized tomography) images are taken by translating and rotating the rocket motor through a fan x-ray beam from the linac, detecting the transmitted x-ray flux profiles with a linear array of thick scintillator crystals attached to photodetectors, and reconstructing the slice image from these profiles in a computer. The technique is similar to that of medical CT scanners, but with 100 times the x-ray energy.

Linacs are used in foundries to detect flaws in large steel castings, some of which can be repaired before expensive machining operations are started. By using radiography the foundryman can also maintain quality control over his casting techniques.

Linacs are also used for inspection of welded joints in heavy cast, rolled, or forged parts, which are made of steel or other alloys (Fig. 10). For example, cracks in the first weld pass must be found or they will extend through all subsequent weld passes and will result in a massive defect. It is essential to detect even small cracks. This requires mobility of the x-ray source so that it can be aligned with the crack. This requires a small-size x-ray focal source.

Compact portable linacs have been developed for field inspection of structures such as oil platforms, bridges, and nuclear reactors (Fig. 11). Radiographing for deterioration of welds in the very constricted space of nuclear reactor piping presents a challenge, which has been met by designing especially small, compact, portable linacs at shorter than conventional wavelengths. The accelerator radiation head is very small and is fed through 20 feet of X-band flexible waveguide from the microwave transmitter.

Ion accelerators also have a number of industrial applications. Ion implantation of semiconductors using heavy-ion beams generated by direct accelerators at acceleration potentials of order from 10 keV to 1 MeV are routinely used for production. Integrated circuits go through at least one step of ion implantation during their manufacture. Some go through many steps. Figure 12 shows an ion implantation system. These machines might not normally be thought of as

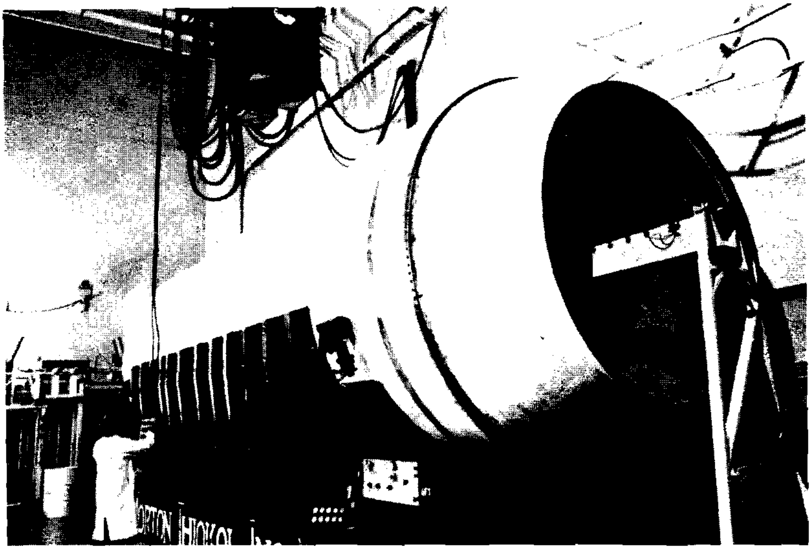
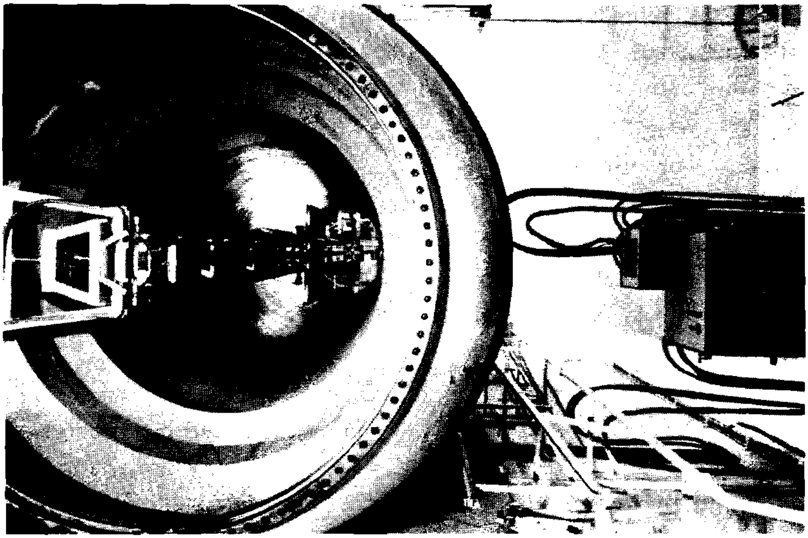
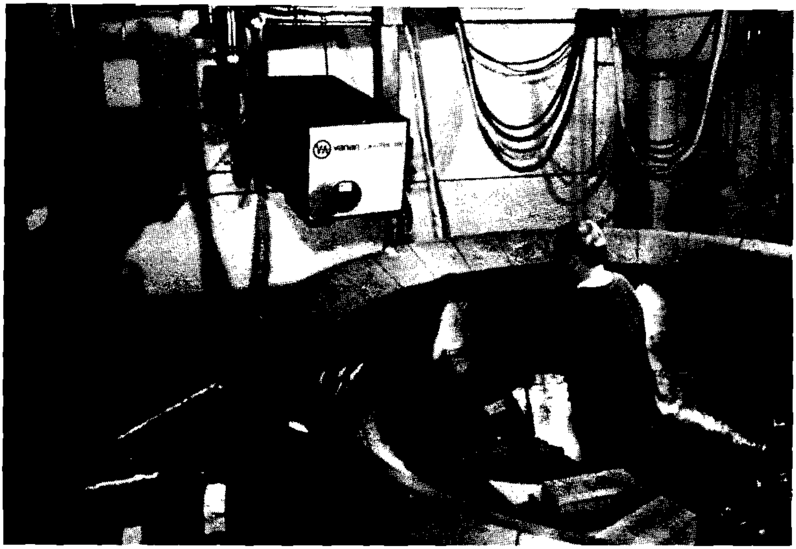


**Figure 9**: Radiographic linac with rocket motor stage of Challenger.
(Varian Associates)
a) Tangential inspection.



b) Radial inspection with film carriage in bore.



**igure 10:** Radiographic linac and weld in pressure vessel.
(Varian Associates)

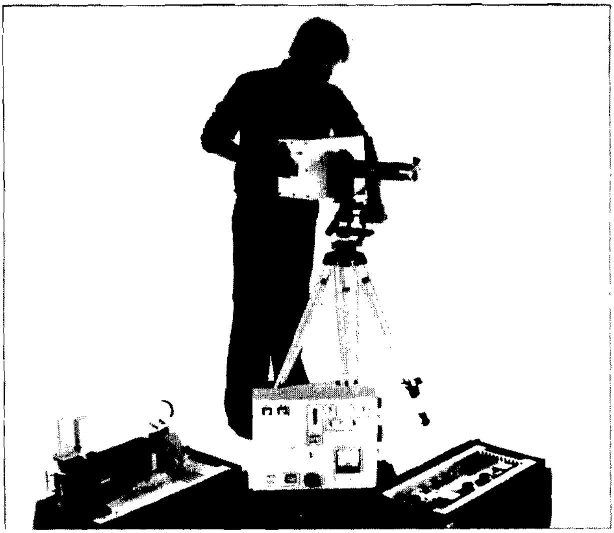


**Figure 11:** Minaturized portable radiographic linac.
(Courtesy Schonberg Radiation Corporation)

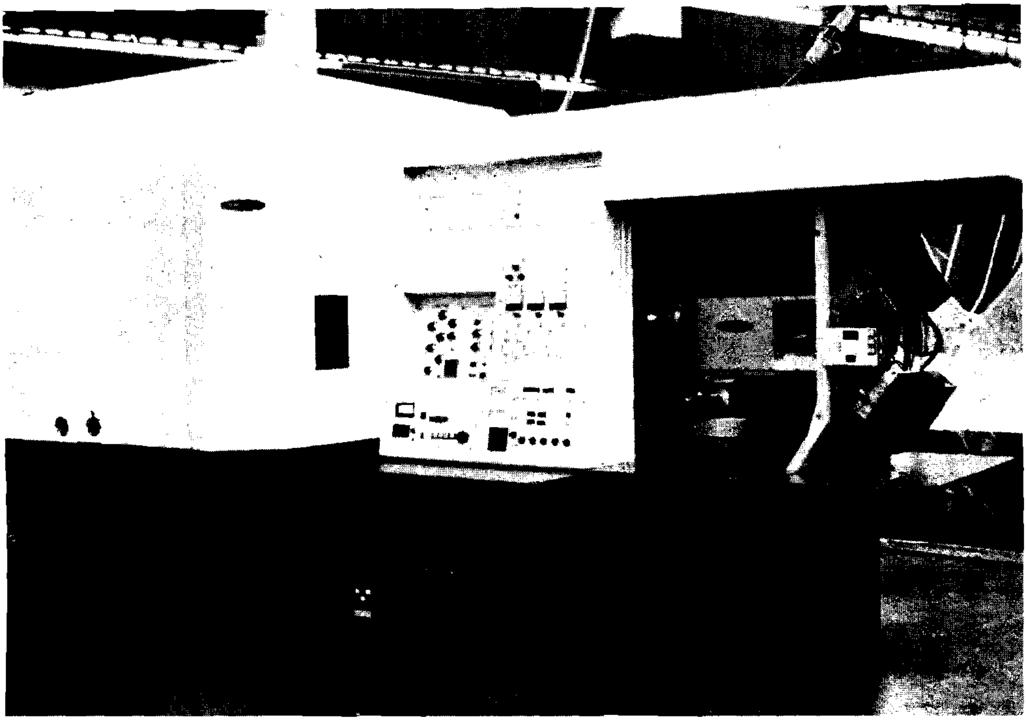


**Figure 12:** Ion implanter for semiconductors. (Varian Associates)

particle accelerators by a high-energy physicist. Nevertheless, they represent direct application of many of the techniques developed by these accelerator physicists. They include an ion source, an analyzing magnet, an accelerator section, a beam-focusing system, a beam scanning system, a vacuum system, and a target chamber to position the semiconductor wafers. About 3000 of these machines are now in use.

Figure 13 shows a very high beam-current ion implanter for pre-deposition of silicon wafers. Note how much this machine looks like the typical particle beam experimental equipment in an accelerator physics laboratory.

The techniques of ion implantation may be extended to other industries. We now import more than 90 percent of certain metals used in high technology, and the world supply of these metals is dwindling. Instead of producing expensive bulk alloys, substitution of other metals and limiting their use to the surface of the base metal is being tried using ion implantation.[3] Reductions in wear of 100 percent have been achieved. Surprisingly, the wear resistance extends to depths as much as 100 to 1000 times the ion implant range. Much higher ion doses are required than for implanting semiconductor wafers. The shapes of metal components to be implanted can vary greatly, so a whole new configuration of ion implantation machines may need to be developed.

Ion implantation in the energy range above 1 MeV is also being used for semiconductors and other applications. Most of these machines use direct acceleration technique. However, radio-frequency quadrupole (RFQ) acceleration is also being tried (Fig. 14). The RFQ technique was invented in the U.S.S.R., improved upon at Los Alamos National Laboratory, and is now being developed by industry.

What are the potential future industrial applications of accelerators? There are a number of possible future markets for linacs where it is still too early to tell how important and large they may become. Some of these applications will require development of linacs with characteristics far superior to those conventionally available. They may employ technology now in an early stage in accelerator-physics research laboratories.

One example of a new technique is the compact free-electron laser or FEL. A free-electron laser works by using a distributed magnetic field to wiggle an

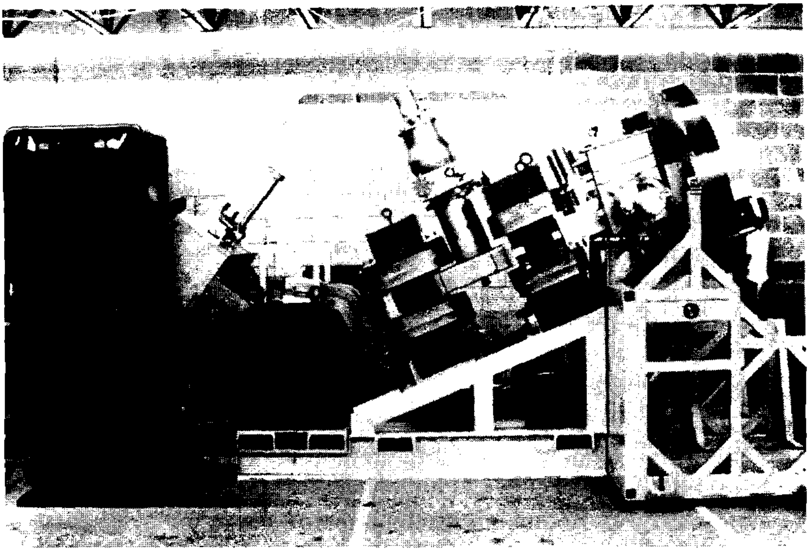


**Figure 13**: High current ion implanter for pre-implantation of semiconductor wafers. (Varian Associates)

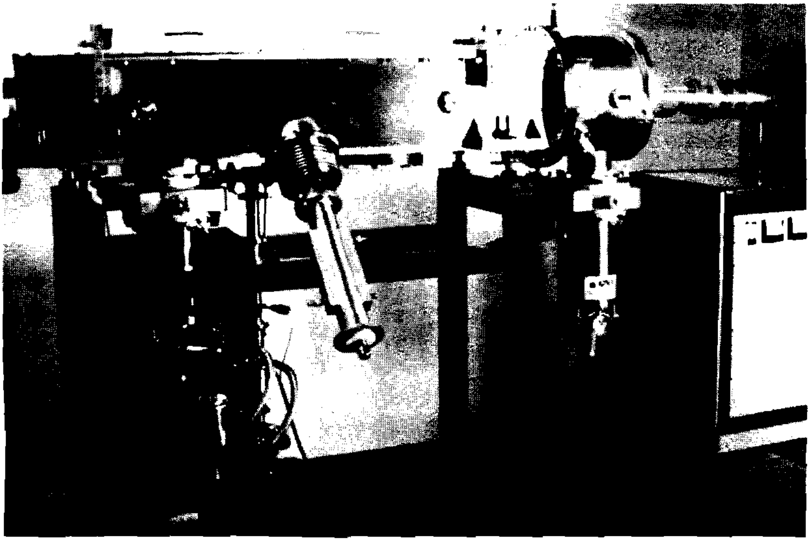


**Figure 14**: RFQ type ion linac. (Courtesy AccSys Technology Corporation)

electron beam transversely as shown in Fig. 15. This transverse acceleration causes the electrons to radiate light in the forward direction. The electrons travel at a little less than the velocity of light and they slip by one wavelength of light each wiggle period.[4] This maintains coherence of phase of the emitted light from each wiggle of the series, thereby giving rise to laser light. The laser wavelength can be varied over a wide range by varying the energy of the linac electron beam. The electron is in vacuum instead of in an atom of gas or solid. This is where the word ''free'' comes from in the term free-electron laser. There are major programs in accelerator laboratories aimed at producing very powerful FEL's for military and space applications. However, there is a need for a modest-power compact FEL that could be installed in a moderate-size room in an industrial or university laboratory. Such a compact FEL requires a very special linac at about 20 MeV. Its beam must have narrow energy spread with low emittance at high-micropulse beam current. A very short period, small-gap undulator is required.

Compact-FEL research applications in physics and chemistry include solid state excitations for study of picosecond dynamics of amorphous semiconductors, dynamics of polymer films, and study of semiconductors. Potential industrial applications include laser-induced chemical chain reactions, large-area deposition of dielectric and metallic films, gas-phased powder syntheses, and microfabrication by laser-controlled chemistry. Biomedical applications include angioplasty (the spallation of placque in arteries), surgery, ophthalmology, microsurgery, molecular and cellular biology, neurology, physiology, photodynamic cancer therapy, diagnostics, and biostimulation. The tunability of the FEL is important in optimizing each application.

Another accelerator application discussed for the future is sub-micron x-ray lithography. Synchrotron radiation at about 2 nanometers is desired for x-ray lithography of sub-micron features in integrated circuits. Intense radiation at this wave length can be achieved with a compact 600-MeV superconducting storage ring. Figure 16 shows a model of such a ring being developed for industrial use. A superconducting magnet permits a small orbit radius, hence reduced beam energy for a given critical wavelength of emission. A low-emittance, narrow energy spread electron injector is required to fill the ring. An injection energy of at least a few tens of MeV is desired to avoid a variety of instability ef-

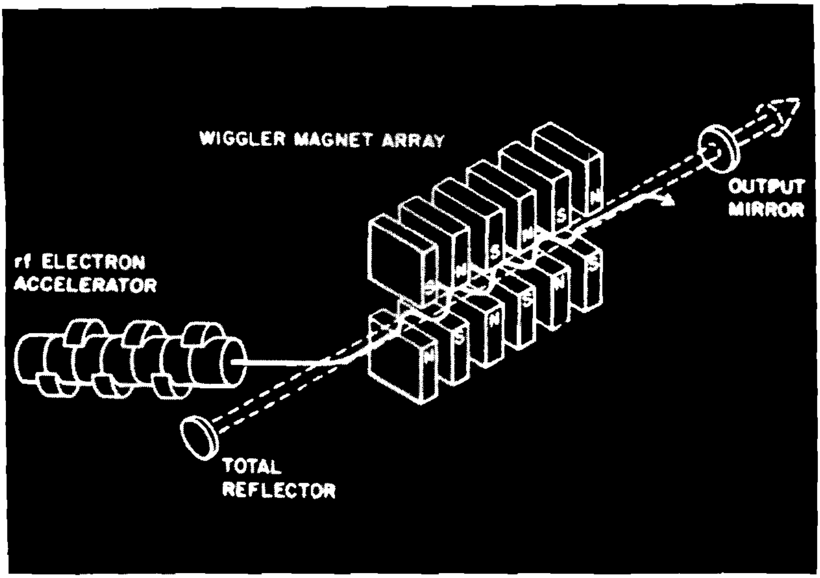
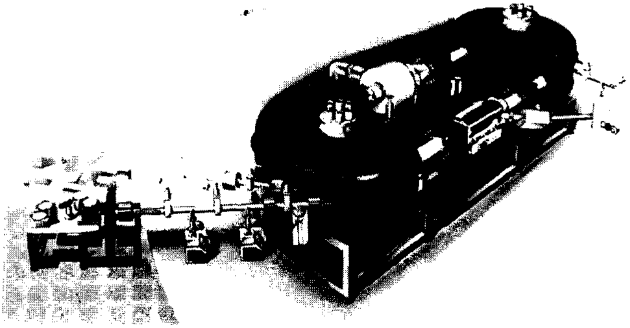


Figure 15: Schematic of linac beam in wiggler of free electron laser.



Model of the 600 MeV compact storage ring COSY at BESSY/FhG in Berlin with two superconducting magnets of 180° and up to eight beam lines. The ring is complete with injection, correction, and rf accelerator components.

Figure 16: Model of compact storage ring for x-ray lithography.

fects. Since the ring is filled with electrons only infrequently, the requirements for beam current are modest. A 150-MeV linac has been built as a storage ring injector for this application. There is an estimated need for more than 100 of such compact storage rings by the semiconductor industry. Compact synchrotron-light sources are also of interest to universities and industry for a wide array of research opportunities using synchrotron radiation.

Accelerators could also be used to replace radioactive sources in oil well logging. Figure 17 shows an oil well rig in Siberia. Wells are being drilled as deep as 40,000 feet. The drilling mud pressure at great depths is of the order of 25,000 psi, so interrogation devices are contained in a steel cylinder called a sonde. The temperatures at these depths can be 200°C. In the search for oil-bearing strata, the sonde is pulled up the well on a cable to produce a log of various data about the region surrounding the well. About 30 different methods are used to characterize deep formations in the search for oil. Of particular interest are layers of limestone laid down in ancient sea-beds, particularly porous layers, since the pores may contain oil. Such porous layers have reduced density, hence increased x-ray transmission.

In present gamma-gamma logging, a radioactive cesium source emits radiation from one point in the sonde. The radiation penetrates the formation surrounding the well and scatters back to detectors in another part of the sonde. The degree of transmission indicates the porosity of the rock. High-resolution refrigerated crystal detectors have been developed to work in this hostile environment. For the safety of the logging crew, the intensity of the radioactive source is limited to about 1 curie, which limits the precision and speed of the density measurement.

The radiation intensity can be increased at least two orders of magnitude by using an electron accelerator instead of the cesium source. The entire accelerator system, including its modulator, other electronics, and cooling system, must be confined to a diameter of about 4 inches and a length of 20 feet and be operated remotely through perhaps 10 km of cable. Figure 18 shows a concept sketch of a 15-MeV linac intended for x-ray transmission logging of wells. Successful experiments have been conducted ''down-hole'' with a linac of about 4-MeV energy. If the price of oil rises to the point in the future where it is eco-

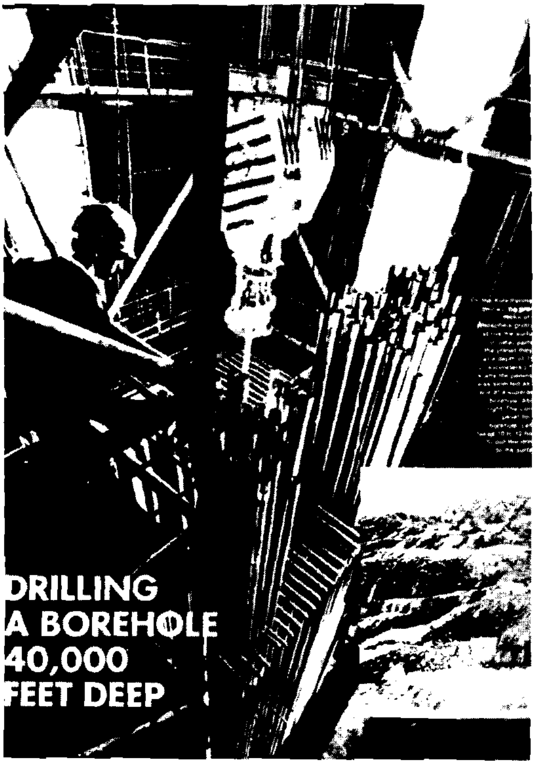


**Figure 17:** Oil rig in Siberia, drilling 40,000 feet deep.

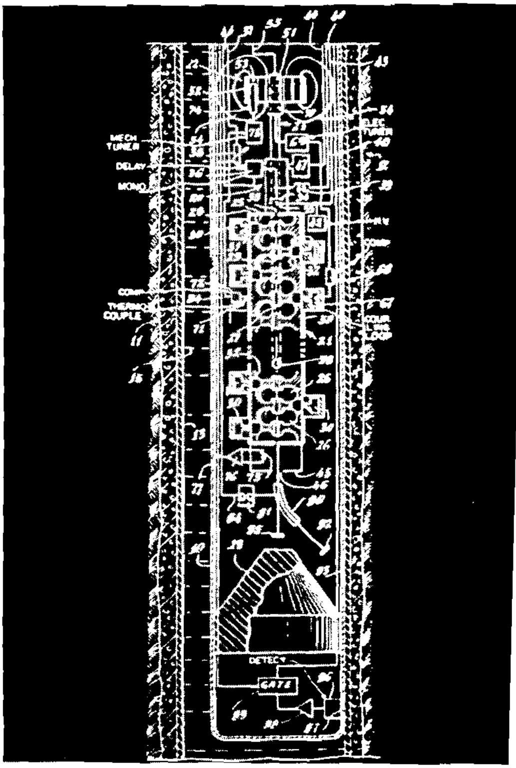


**Figure 18:** Schematic of linac in sonde for oil well logging.

nomical to resurvey abandoned wells, there could be an eventual need for about 1000 sonde-type linacs.

Accelerators can also be employed to screen for explosives and other contraband. The number of international terrorist incidents is increasing year by year.[5] There were about 750 such incidents in 1985 and 856 incidents in 1988. About 65 percent involve bombs. Approximately 30 percent are against business and 30 percent of these are directed against the U.S. in Latin America. Arms smuggling, infiltration of sensitive areas, and illegal drug trafficking are related and widespread problems. Air terrorism is making headlines and experts predict that it will come to the United States. Systems employing radiation-generating machines and detectors are being developed to detect such contraband in checked baggage and air-cargo containers at airports and in vehicles and cargo containers at border crossings and seaports. Explosives can be identified with accelerators by neutron activation or by high-energy gamma activation. An ion linac can be used to produce the neutrons; an electron linac to produce the gammas. Similar techniques can also be used by the military to detect land mines, which may be made of plastic and be buried as much as 15 inches below the surface of the ground.

For inspection of vehicles and cargo containers, especially for drugs and weapons, a megavoltage x-ray imaging system has been developed as shown in Fig. 19a. The vehicle or cargo container is moved through the fan x-ray from a linac and the transmitted flux is detected by a collimated linear array of scintillation detectors. A transmission image is built up in real time. Image enhancement and pattern recognition techniques facilitate the search for items of interest. Figures 19b through 19f show detection of an artillery shell hidden in a truck carrying sacks of concrete; contraband in an air-cargo container; cocaine inside a tire; hand grenades inside a car door. A system like this is being installed in the U.S.S.R. to verify that their missiles comply with the INF treaty.

The use of a fan x-ray beam instead of a full-cone x-ray beam provides several advantages. For one thing, the x-rays that are scattered out of the fan by the cargo miss the detector so they don't fog the image. In the second place, the radiation dose to the cargo is very low, so that a stowaway would receive a whole-body dose less than his annual exposure to natural background radiation such as cosmic rays. Further, the leakage radiation outside the linac and cargo

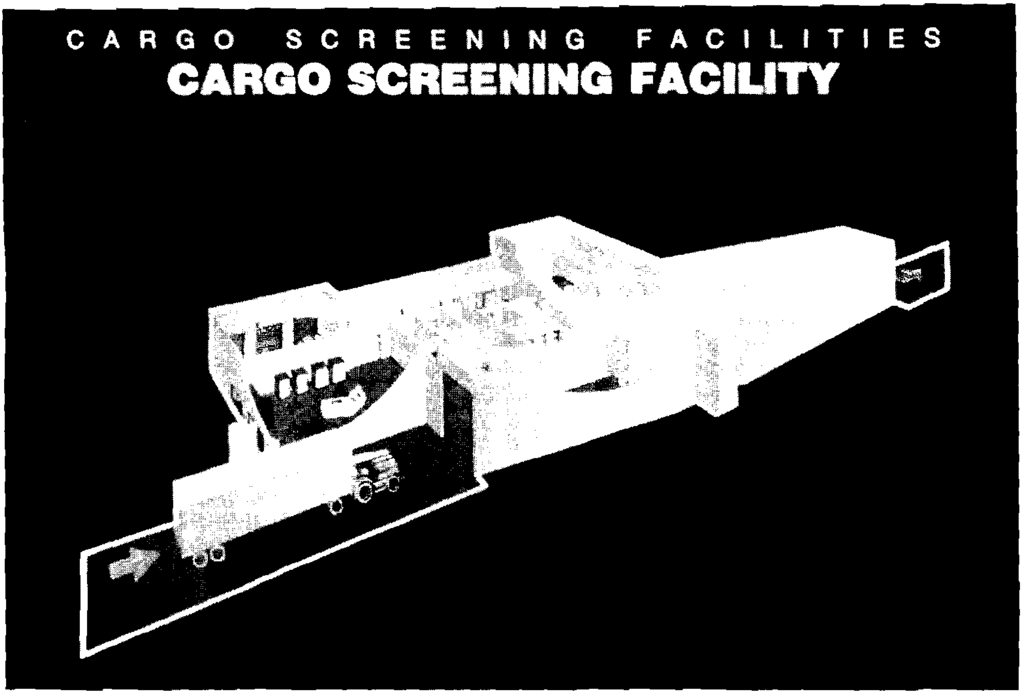
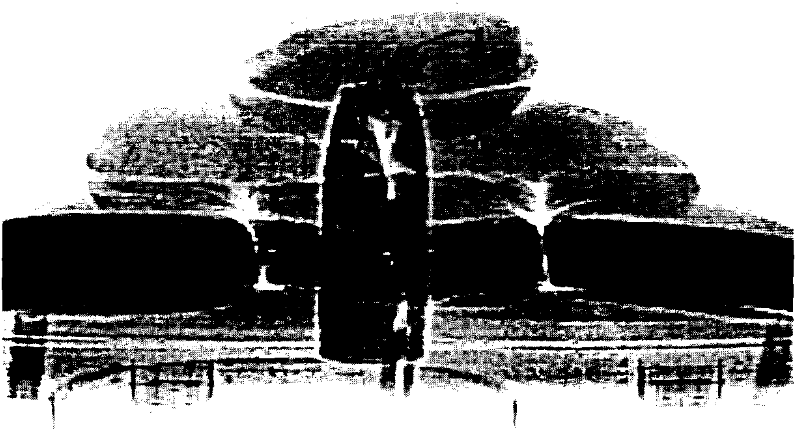
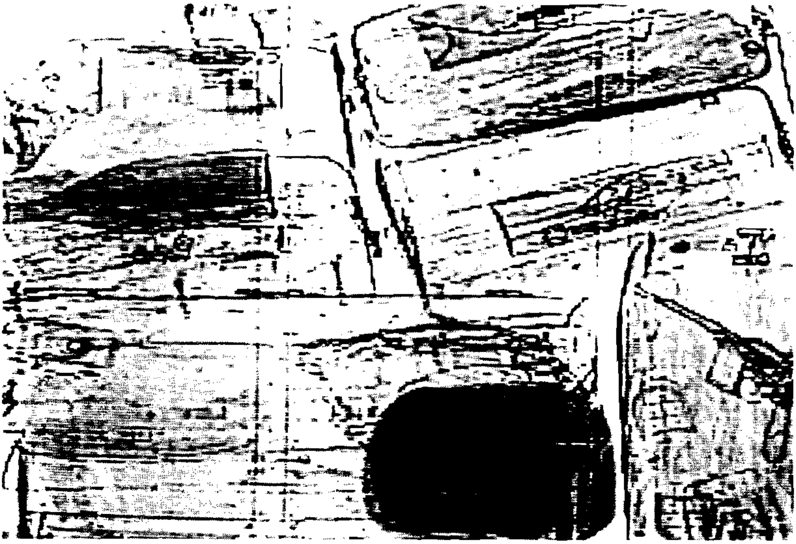


**Figure 19a:** Radiographic linac facility for cargo screening.
(Courtesy of Bechtel)

**Figure 19b:** Images of cargo



**gure 19c:** Images of cargo



**ure 19d:** Images of cargo

**Figure 19e**: Images of cargo

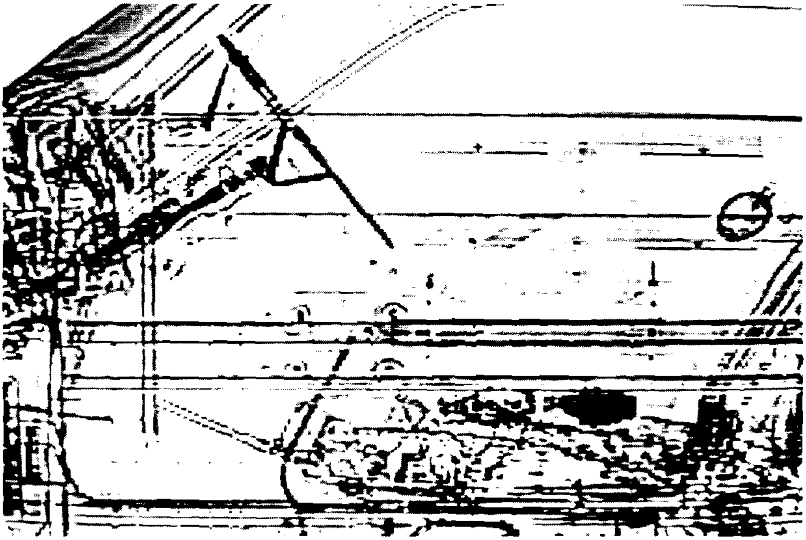


**Figure 19f**: Images of cargo

tunnels can be far less than the recommended annual limits for the general public.

Accelerators even have potential for producing a cleaner environment. International pressures are mounting to reduce the devastating effect of acid rain and to improve air quality, with consequent benefits to health. West Germany has taken the lead in enforcing stringent regulations, with much of Europe close behind. American industry is pouring 2.7 billion pounds of toxic chemicals per year into the air, as illustrated by Fig. 20a.

Experiments are being conducted on the use of electron beams of order 1 MeV and 200 kW in the presence of ammonia. Figure 20b shows a concept sketch of such a system. Harmful gases such as nitrogen oxides and sulfur dioxide in industrial- and power-plant smoke stacks are converted into useful products such as agricultural fertilizer and soil conditioner. The process has been proven to be economically viable and highly competitive with conventional chemical processes.[6,7] The critical factors are the cost of ammonia and the market value of the by-products.

Electron beams have also been used to disinfect sewage and sludge,[8,9] permitting their use to enrich agricultural land.

Food irradiation using accelerators has been discussed for many years. Figure 21 shows a linac that is being used to irradiate frozen slabs of deboned and ground chicken meat, which is used for making chicken sausage in delicatessens in France. It has been proposed that packaged chicken parts be irradiated. Electrons of less than 10 MeV would be used to avoid induced radioactivity. The shelf life of fresh poultry in the consumer's refrigerator is only about four days. Irradiation at 3.7 kGy (3.7 watt seconds per gram) dose to destroy spoilage bacteria has been found to extend the shelf life of chicken legs to eight days and chicken breast meat to 21 days. It has been estimated[10] that there are 2 million illnesses per year in the United States from Salmonella poisoning, primarily from chicken and egg products. Salmonella is controlled at this dose. The irradiation cost is of order one cent per pound. If the major chicken-packing plants in the United States were to process chicken by irradiation, there would be a need for about 100 linacs.[11]

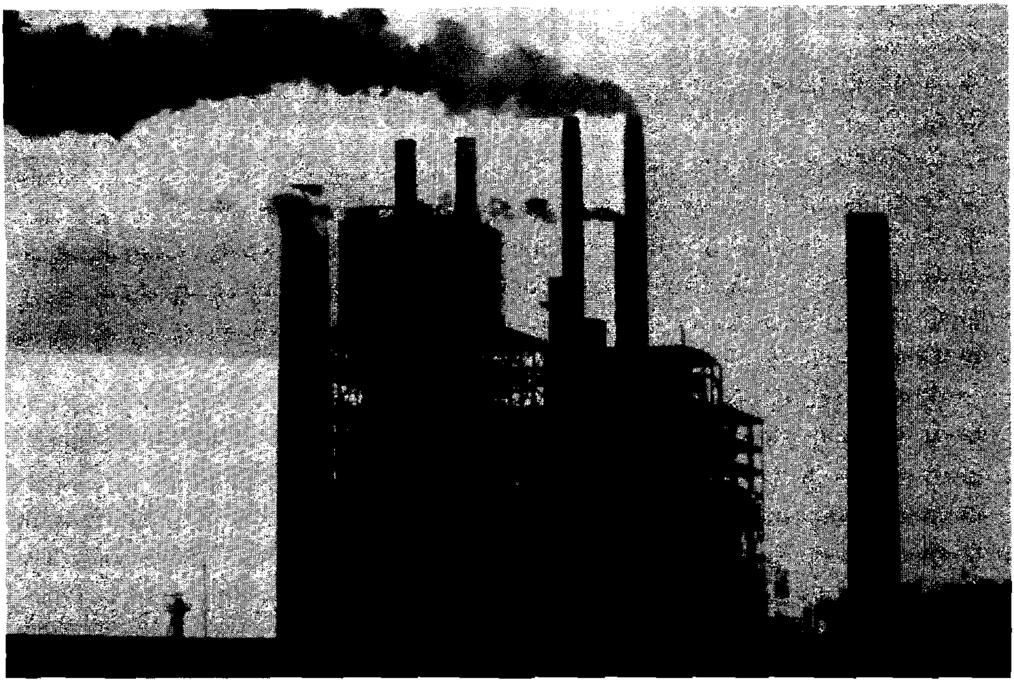
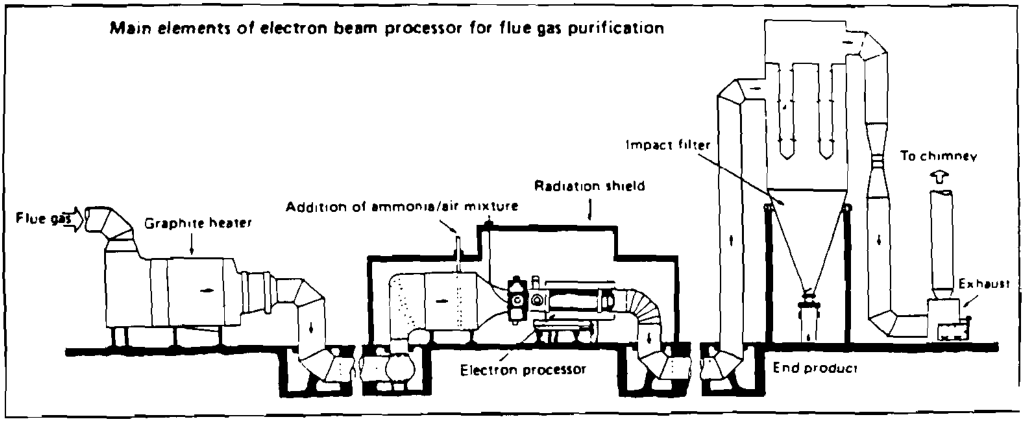
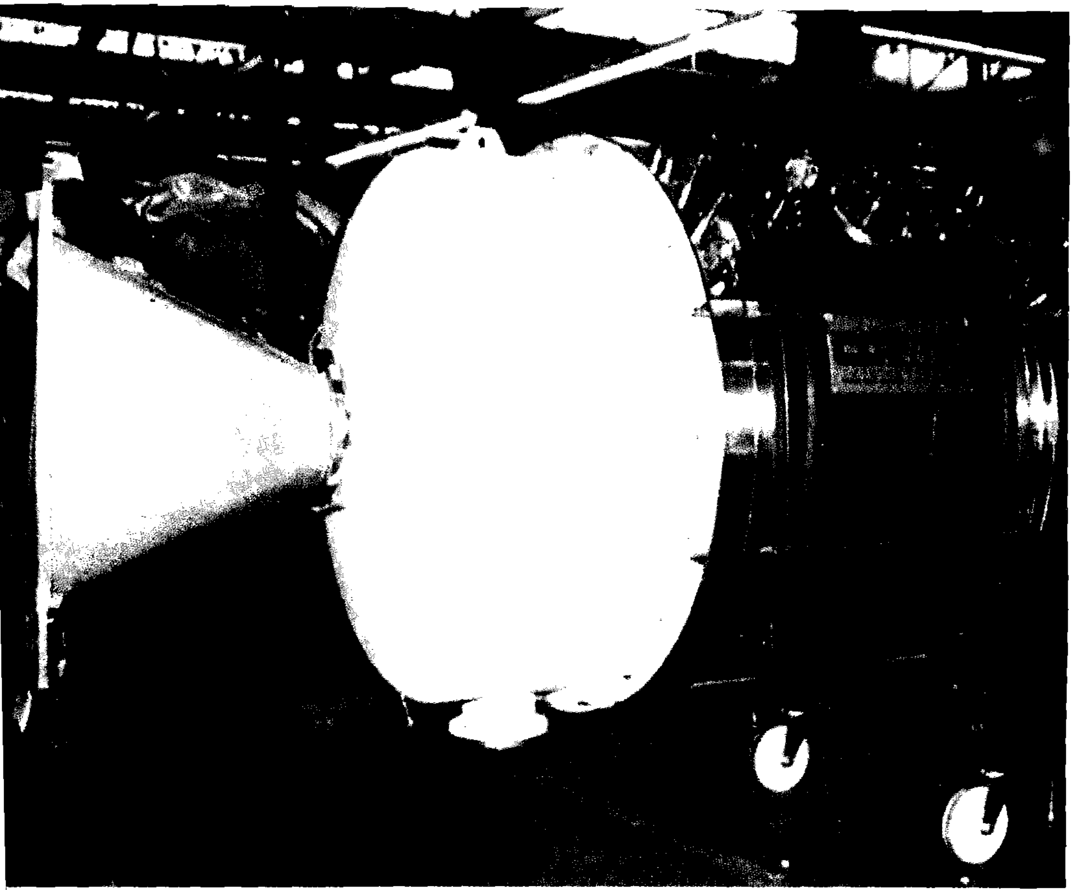


**Figure 20**: Smoke stack irradiation.
a) Noxious gas (Courtesy RDI)



b) Schematic of product flow (Courtesy IAEA)



**igure 21:** Electron linac used for irradiation of deboned chicken.
(Courtesy of CGR-MeV)

Linacs with 10-MeV, 20-kW electron-beam rating are being installed in locations in the United States to carry out pilot production irradiation studies on a number of foods in order to provide a solid basis for possible future implementation of irradiation by the food industry. Figure 22 shows some of the foods on which irradiation research is being conducted.[12] There are many cases where food irradiation can be justified on the basis of economics, convenience, and the health of the public. However, public fear of the unknown will delay its broad acceptance.

In summary, over the past 25 years, various kinds of accelerators in the 0.1- to 150-MeV range have been developed by industry for a wide range of industrial as well as medical applications as listed in Table II. In many cases the technology used in these industrial accelerators is based on similar technology which was developed in major accelerator-physics research laboratories. People learned the technology while working in these laboratories, then left to start accelerator-manufacturing operations. In turn they trained other people who then left to start more accelerator manufacturing operations. The economic value to society of the application of these industrial accelerators outweighs by several orders of magnitude the cost of building the original physics research accelerators.

And this is only the end of the beginning. There are many potential future applications of small accelerators to be developed by industry, such as those listed in Table III. Some of these accelerators will present difficult design challenges which will require continued cooperation between industry and the national accelerator laboratories.

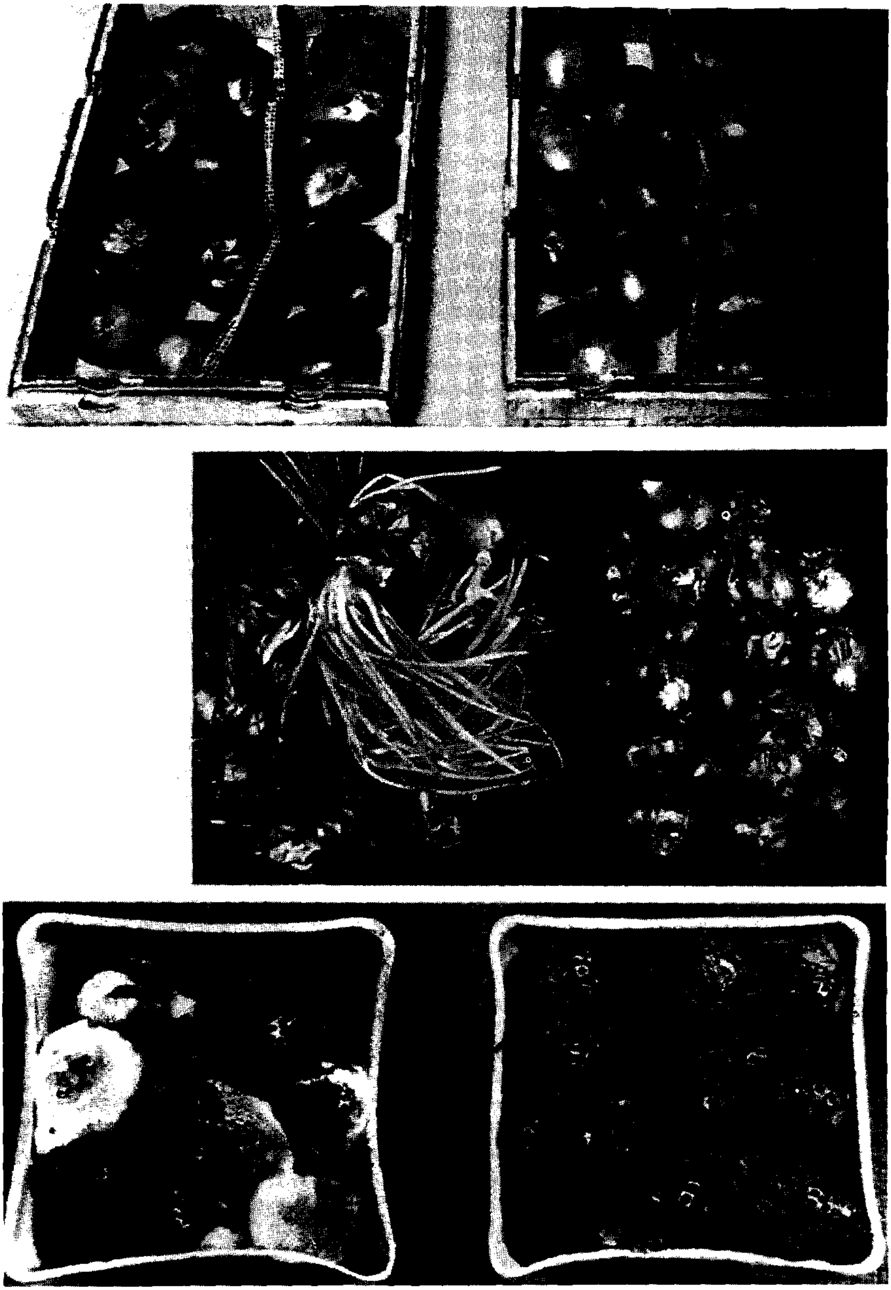


Figure 22: Irradiated foods.

# SUMMARY OF ACCELERATOR TYPES AND PRESENT MAJOR APPLICATIONS

| BEAM TYPE | MEV | POWER | MAJOR APPLICATIONS | IN USE |
|---|---|---|---|---|
| Sheet electrons | 0.1-0.3 | High | Surface curing | 350 |
| Scanned electrons | 0.5-5 | High | Plastics cross linking | 400 |
| X-rays/electrons | 4-25 | Low | Cancer therapy | 2500 |
| Scanned electrons | 1-12 | Medium | Medical disposables, food | 15 |
| X-rays | 1-15 | Low | Radiography of rocket motors, steel castings, weldments | 250 |
| Ions | 0.1-2 | High | Implantation of semiconductors | 3000 |

**Table II:** Summary of accelerator types and present major applications.

# SUMMARY OF ACCELERATOR TYPES AND POSSIBLE FUTURE APPLICATIONS

| BEAM TYPE | MEV | POWER | MAJOR APPLICATION |
|---|---|---|---|
| Electron | 20 | Low | Compact FEL |
| Electron | 50-150 | Low | Compact storage ring injection |
| X-rays | 1-4 | Low | Oil well logging |
| Ions (neutrons) | 2 | Low | Explosives detection |
| Ions | 1 | High | Implantation of metal |
| X-rays (fan) | 6-15 | Low | Cargo inspection |
| Electrons | 1 | High | Stack gas |
| Electrons | 3 | High | Sewage, sludge |
| Electrons | 5-10 | Medium | Food |
| X-rays | 5 | High | Food |
| Ions | 10 | High | Radioisotope production |

**Table III:** Summary of accelerator types and possible future applications.

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