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Environmental and Industrial Applications of Pulsed Power Systems

E. L. Neau
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185

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This work performed at Sandia National Laboratories is supported by the U.S. Department of Energy under contract DE-AC04-76DP00789.

Abstract

The technology base formed by the development of high peak power simulators, laser drivers, free electron lasers (FEL's), and Inertial Confinement Fusion (ICF) drivers from the early 60's through the late 80's is being extended to high average power short-pulse machines with the capabilities of performing new roles in environmental cleanup applications and in supporting new types of industrial manufacturing processes. Some of these processes will require very high average beam power levels of hundreds of kilowatts to perhaps megawatts. In this paper we briefly discuss new technology capabilities and then concentrate on specific application areas that may benefit from the high specific energies and high average powers attainable with short-pulse machines.

Introduction to Technology Developments

Many applications of electron beam, ion beam, or X-ray processing have been described in the literature^(1,2,3,4). Low power beam applications, such as crosslinking of polymers in tubular form or on packaging surfaces and sterilization of foods or medical devices, are applications that have been in development for 10 to 20 years using existing accelerator capabilities. These low power accelerators, with over one thousand units installed worldwide, use transformers or capacitively coupled rectifier decks to generate beam potentials of 100 keV to 5 MeV with average beam powers of up to approximately 200 kW⁽⁵⁾. RF linear induction accelerators are available for commercial applications and operate at beam energies of up to 10 MeV and average power levels of 50 kW with possible extension to 250 kW⁽⁶⁾. This paper will give a brief overview of a new class of high average power accelerators and then focus on possible near term applications that are not in the commercial stage. These applications require, and benefit from, short (~50 ns to 500 ns) electron, ion, or gamma ray pulses with energies between 500 keV and 10 MeV at average beam power levels greater than 200 kW.

The electron and ion beams from large, single-shot, pulsed power machines developed over the last 30 years for the Inertial Confinement Fusion program, for flash X-ray sources for radiation effects studies, or for directed energy weapons

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programs offer unusual combinations of energy density, temperature, and pressure not attainable in more conventional thermal processes. Unlike thermal processes that heat a total volume, high power beams offer the possibility of efficiently depositing energy in a specific work volume or in a well defined surface layer. Accelerator developments, such as the use of large-scale saturable magnetic switches^(7,8,9), high peak power linear induction voltage adders (LIVA's)^(10,11), and large-area electron and ion beam diodes^(12,13,14), with the addition of thermal heat management techniques and an understanding of reliability issues, make this type of accelerator a good candidate for use in high average power industrial processing applications. The machines being developed in the Repetitive High Energy Pulsed Power (RHEPP) project typifies this new generation of high average power accelerator⁽¹⁵⁾.

Selection of energy efficient accelerator technologies, with potential for long life reliable operation, however, requires extended prototype demonstrations before they can be expected to achieve acceptance in the commercial marketplace where slim profit margins dictate the amount of risk that can be taken on a new process technology.

Recent High Average Power Accelerator Developments

The pulsed power technology base developed for defense applications of beams has evolved to a common format of the pulse compression and voltage addition stages for the short-pulse high average power accelerators now in development as shown in Figure 1. The short pulse technology allows the use of LIVA cavities, with METGLAS[®] magnetic isolation cores, to achieve output voltages from 1 MeV to as much as 20 MeV at high average currents. The adder cavities may be used to accelerate a central electron beam supplied by an injector, as in the ETA accelerator⁽⁹⁾, or they may have a vacuum or magnetically insulated metal stalk on axis, first demonstrated in the HELIA⁽¹⁰⁾ accelerator, with a single stage electron or ion beam diode on the output of the adder⁽¹¹⁾.

Figure 1

Short-pulse accelerators at Physics International, Science Research Laboratories and Sandia National Laboratories, are now beginning to deliver beams with average powers of from 10 kW to 120 kW with 350 kW continuous expected within the next year. The Physics International Compact Linear Induction Accelerator (CLIA), shown in Figure 2 uses thyratrons in the primary pulse compression stage and has ten stages of linear induction voltage addition on a magnetically insulated stalk to achieve a 50 ns output pulse with a beam accelerating potential of 750 kV at average power levels of 120 kW for periods of five seconds⁽¹⁶⁾. The Science Research Laboratories SNOMAD IV accelerator, shown in Figure 3, uses semiconductor switches in the primary pulse compression module which can be configured as a beam injector, with dispenser

cathode, or as a series of LIA beam acceleration stages with a 1 mm to 6 mm diameter, 500 A, electron beam⁽¹⁷⁾. The semiconductor switches offer the possibility of multi-kilohertz operation with high average beam power. This device, with a 50 ns FWHM output pulse, is presently delivering a 1.5 MeV electron beam at an average beam power of 38 kW. The Sandia RHEPP accelerator uses an all magnetically switched approach to generate a 1 MeV beam from an oil insulated LIVA, shown in Figure 4, and has been tested at 7-kW⁽¹⁵⁾. This accelerator is being upgraded for continuous 120 kW operation at 120 Hz using a Westinghouse alternator as the prime power source. A second accelerator is being assembled for operation in early 1994 which will provide a 2.3 MeV beam, from a vacuum insulated LIVA, with 350 kW of beam power. A future development will include the substitution of high average power SCR semiconductor switches for the first stages of magnetic pulse compression. The 1 MeV and 2.3 MeV accelerators are designed to provide large area electron beams at current densities of about 25 A/cm² over an area of approximately 1000 cm² from cold, field emission type cathodes. The 1 MeV RHEPP accelerator is also being used to deliver ion beams for exploration of new, large area, surface modification applications. This new family of short-pulse accelerators minimize power consumption by operating at efficiencies, from wall plug to electron beam, of at least 50%. These high average power accelerators will be important for future industrial applications because they offer the possibility of supplying very high average power beams which are beyond the capabilities of present commercial accelerators.

Figure 2, Figure 3, and Figure 4

Applications for the new high average power accelerators must be identified which cannot be adequately addressed by less efficient, pure thermal, techniques for putting energy into the desired product volume, because of the relatively high capital costs and need for radiation shielding. Also, changing regulatory requirements may eliminate some traditional chemical treatments, such as the use of ethylene oxide or methyl bromide, which may, in turn, make accelerator treatment methods more appealing. To gain acceptance, the technology must be shown to offer a robust and cost effective solution to a specific need.

Introduction to Environmental Applications

In reviewing possible uses of short-pulse high average power accelerators, one has to be impressed by the fact that many of our current environmental problems have been identified since the early 70's or even earlier. Many experiments have been conducted using irradiation sources to destroy the toxic compounds now being identified as hazardous by-products of our industrial society. Many experiments have been conducted identifying the capabilities of radiation sources in killing bacteria that are harmful to society, such as e-coli and salmonella.

What appears to be needed is the establishment of an infrastructure to provide the ready availability of cost effective, long-life, high average power machines for incorporation into industrial plants, for materials fabrication, chemical production, food pasteurization, medical product sterilization, or as a treatment method for waste effluents that pollute air or ground waters.

An Organic Waste Destruction Application

Electron beams have been shown to be very effective, >99%, in destroying a number of organic compounds such as trichloroethylene, propanes, benzenes, phenols, and halogenated hydrocarbons in contaminated water by Cooper and Nickelsen at Florida International University with Waite and Kurucz at the University of Miami⁽¹⁸⁾, and Matthews at the Lawrence Livermore National Laboratory⁽¹⁹⁾. Others have shown effective destruction of pesticides and solvents such as Malathion, Lindane, carbon disulfide and carbon tetrachloride by electron beam irradiation⁽²⁰⁾. The irradiation of aqueous solutions creates the free radicals, e^-_{aq} , H^* , and OH^* as the injected electrons lose energy in the process creating a shower of ever lower energy electrons⁽²¹⁾. These free radicals react with organic molecules producing salts, CO_2 , and water in a process called mineralization. Hydrogen peroxide is the stable oxidant formed during irradiation and it can also impact the conversion process. Electron beam irradiation has also been shown to be capable of destroying ferrocyanides in solution⁽²²⁾.

A possible new application of high average power electron beams arose out of an attempt to identify an organic waste destruction problem which appeared to be expensive and potentially dangerous when using traditional thermal incineration or other processes. The Hanford nuclear reservation, in southwestern Washington State, has approximately 60 million gallons of waste that is a mixture of organic compounds and low-level and high-level radioactive wastes stored in 177 single and double-walled underground tanks⁽²³⁾. Because the waste consists of mixtures of caustic salts, organic compounds, and radioactive materials, the waste cannot be separated into high level and low-level waste streams without extensive chemical treatment. In addition to the organic compounds, such as ethylene diaminetetraacetic acid (EDTA) used in the PUREX process to recover uranium and plutonium, some of the tanks contain ferrocyanide salts in a sodium nitrate/sodium nitrite matrix. Twenty three of the tanks periodically release quantities of flammable gases such as hydrogen and nitrous oxide in explosive concentrations. The stored waste has been altered from its original composition by continual radiolysis due to the decay processes of the radioactive components, chemical reactions between the various constituents, and thermal effects. It is estimated that perhaps as much as 100 Mrads have been accumulated since the storage of materials began in 1943. High average power accelerators have the capability of delivering doses much higher than 100 Mrads in a relatively short time to speed up the mineralization process.

Competing processes such as supercritical water oxidation, wet air oxidation, steam reforming, or treatment with hydrogen peroxide, ozone, or ultraviolet light are also being evaluated. These concepts have the potential drawbacks that they involve either liquid dissolution, which increases the volume by factors of 3 to 5, or the process operates at very high temperatures, which may affect subsequent separation of high and low level radioactive waste components.

A series of electron beam organic destruction experiments, by Patterson et al.⁽²⁴⁾, were conducted on a tank 10¹-SY simulant prepared using a formula provided by Herting of the Westinghouse Hanford Company⁽²⁵⁾ in the geometry shown in Figure 5. Two 1 MeV accelerators provided total doses to simulant samples of up to 1600 Mrad with dose rates of 2.5×10^8 rad/s from the KITE accelerator and 2.7×10^{14} rad/s from a PI-112 accelerator. As shown in Figure 6, the higher dose rate accelerator, with a pulse width of 30 ns, proved to be more than three times as effective in organic destruction capability. Approximately 1500 Mrad will be required for 95% organic destruction, from a short-pulse accelerator, based on these experimental results.

Figure 6

The data obtained in this experiment, being somewhat limited in scope, will require more accurate assessment before proposing the use of the electron beam organic destruction technique at the Hanford site. Based on these preliminary experiments, the technique has been proposed as a method of mitigating the Hanford wastes. The temperature rise of the waste material, in the proposed process, would be limited to keep the maximum temperature below the boiling point of the material, in turn limiting the irradiation to about 19 Mrad per pass. The limited temperature rise would therefore require waste material cooling and multiple passes through the irradiator. Preliminary costs for treating the Hanford waste with a high average power electron beam accelerator, using RHEPP technology, have been roughly estimated to be approximately \$11/gallon including capital, operating, and maintenance costs for an electron beam plant with a treatment rate of 20 gallons per minute. Material handling costs are not included in this estimate.

Proposed Approaches to Flue Gas Cleanup Applications

Fossil fuels are used in many power plants worldwide producing sulfur dioxide (SO₂) and nitrogen oxides (NO_x) as gaseous emissions in the fuel burning process. These emissions are known to be active in producing acidic rainfall that damages trees, lakes, and buildings. Utilities which rely on high sulfur coal, in the U.S., will be most affected by new regulations, such as the New Clean Air Act, that will require significant NO_x emissions reduction after 1995. Non-thermal plasma techniques offer an energy efficient approach to the

simultaneous destruction of both types of gaseous oxides. Non-thermal plasma processes can be induced by electron beam irradiation or by treatment in a high electric field geometry which accelerates the electrons present in the gas stream. Both methods increase the electron temperature while leaving the bulk of the gas at near ambient temperature. The dissociation and ionization of the gas stream produces free radicals which subsequently cause decomposition of the pollutants.

Electron beam treatment of flue gases has been the subject of research in Japan, the USA, Germany, and Russia since 1970^(26,27,28,29). Electron beam irradiation of flue gases has shown simultaneous removal of more than 94% of SO₂ and 80% of the NO_x in tests in Japan⁽³⁰⁾. This multi-step process is outlined in Figure 7.

Figure 7

The byproducts of this process are ammonium sulfate and nitrate that can be used as fertilizer. A pilot plant, also using this approach, has been constructed at the Electropower Station Kaweczyn, in Poland, that has a gas flow capacity of 20000 Nm³/h as a by-pass loop on a main flue gas stream of 250,000 Nm³/h⁽³¹⁾. The flue gas contains 0.9 - 1.2 g of SO₂/Nm³ and 0.2 - 0.55 g of NO_x/Nm³. Two ELW-3 accelerators, from the Institute of Nuclear Physics in Novosibirsk, Russia, each supply 50 kW at 700 keV to provide the required electron beam power. Additional pilot plants are in operation in Japan at the Ebara facility in Fujisawa⁽³²⁾ and at the Chubu Electric Plant in Nagoya⁽³³⁾. The beam power required, for typical flue gas irradiation of about 1 Mrad, is estimated to be about 1.5% to 3% of the total plant generating capacity⁽³⁴⁾. It is this requirement that is driving the development of very high average power accelerators to satisfy cost and sizing considerations. The electron beam treatment process is also being investigated to treat the exhaust emissions from the metropolitan vehicle tunnel under the Tokyo Bay⁽³⁵⁾.

Another approach to reducing SO₂ and NO_x emissions in flue gases, which bypasses the concerns of shielding of high voltage electron beam sources, consists of using pulsed corona discharges in the flowing gas stream to create free radicals similar to those produced by the electron beam approach. The pulsed corona can be produced by applying an AC voltage to electrodes, separated by a dielectric barrier, as a silent discharge process in the gas or by applying a short high-voltage pulse to the electrodes in a high field configuration as shown in Figures 8a and 8 b. The silent discharge was first used by Siemens in the 1850's for the production of ozone and is still in use today in water purification plants. The Italian National Electricity board (ENEL) has supported pulsed corona experiments at a power plant near Venice in cooperation with the University of Padua^(36,37). Work on pulsed corona destruction of SO₂ and NO_x has also been performed at the Florida State University⁽³⁸⁾.

Figures 8a and 8b

Both pulsed corona reactor (PCR) methods produce free radicals at the tip of prebreakdown streamers in the gas. The discharge is arrested in the silent discharge, or dielectric barrier, configuration by the reduction in applied field as charge builds up on the dielectric medium and in the coaxial high field geometry by tailoring the applied pulse length to terminate before the formation of an arc discharge. Efficient destruction of the SO_2 and NO_x or other organic contaminants, such as volatile organic contaminants (VOC's), in the flowing gas stream rely on short pulse operation to avoid transferring energy to the gas ions that would raise the bulk temperature of the gas^(39,40). Pulse parameters, such as rate of voltage rise and pulse length, determine the energy and charge deposited in the flue gas volume in the form of streamers⁽⁴¹⁾. Pulse amplitudes depend on reactor dimensions but range from 50 kv to 200 kV and pulse lengths range from 50 ns to a few hundred nanoseconds. A fraction of the field required to sustain the streamer may be supplied by a DC bias circuit to improve the efficiency of the pulsed source in coupling to the streamer formation. The pulsed corona method is less efficient than the electron beam process, requiring about 50 eV per NO_x molecule removed (compared to 14 eV per NO_x molecule removed using an e-beam), and the amount of pulsed corona power which must be properly conditioned is on the order of 5 percent of the power plant output⁽⁴²⁾. The power conditioning required for the pulsed corona method does not involve as many stages of pulse compression nor does it require a high average power electron beam diode and beam window which must be kept free of fly ash and corrosion. The elimination of these components should greatly reduce the power conditioning system capital costs to perhaps as little as \$2/w to \$3/w⁽⁴³⁾.

Introduction to Industrial Applications:

Material surface treatments like galvanizing, sputtering, electroplating, and plasma spraying have made new products possible and opened new markets. Multi-use technology based on pulsed UV sources or short-pulse high average power electron and ion beam processors is beginning to open the development of next-generation cost-effective, environmentally conscious materials surface treatment. These new techniques will require the availability, for the first time, of low-cost reliable sources of pulsed energy for high volume industrial applications.

Paint Stripping Using Pulsed UV Radiation:

The Environmental Protection Agency, under the Toxic Substance Control Act (TSCA) is reducing the permissible exposure levels (PEL's) for many types of

solvents. The PEL for methylene chloride, used in paint stripping operations, is scheduled to be reduced from 500 ppm to 25 ppm by the mid-1990's. The emerging technology of composite airframe components is also driving the search for a non-damaging method of paint removal in the aircraft maintenance industry. Improvements in productivity and elimination of a hazardous work environment can all be obtained in the FlashBlast process by using an intense 3 ms burst of UV light coupled with a blast of CO₂ pellets ⁽⁴⁴⁾. Experiments have demonstrated complete removal of polyurethane types of paint commonly used on airframes at a cost of a few dollars per square foot.

Ceramics Processing:

Electron beams with a few megavolts of energy can penetrate several millimeters into ceramics and carbon or boron composites. Input beam energy is converted to heat with nearly 100% efficiency within the target material. Pulsed accelerators, using short-pulse high average power technology, can easily heat materials in less than one microsecond. These beams can be propagated in a one atmosphere environment eliminating the need for vacuum chamber processing. The beam energy-time profile can be tailored to obtain desired heating rates and treatment volumes. The emerging high average power accelerators also are demonstrating overall electrical efficiency of about 50% which has the promise of supporting low cost operations in high throughput applications.

Ceramic and Composite Joining

One possible application for high average power beams is in the joining of ceramic or carbon based materials or in the bonding of these materials to a substrate material⁽⁴⁵⁾. A joining or brazing material, with a melting temperature much higher than the materials to be joined can conceptually be used to form bonds with this technique. If the joining material has a higher atomic number (higher density) than the ceramic material, the electron beam deposition is greater in the joining material creating a higher temperature at the joint rather than in the bulk of the ceramic. The concept is shown in Figure 9a with a calculated temperature profile given in Figure 9b.

Figures 9(a) and 9(b)

Powder Synthesis

Pulsed electron beams may be used to vaporize materials in a reactive gaseous environment which favors the formation of useful nanophase powders such as silicon nitride. Applying approximately 14.5 kJ/g to silicon surface in a nitrogen environment could produce 300 g/h/w of high purity silicon nitride at a cost of approximately \$1/kg to \$10/kg using a RHEPP-like 350 kW high average

power accelerator. These estimates should be compared to a cost of about \$20/kg to \$200/kg, depending on grade, for powder production by conventional methods⁽⁴⁵⁾.

Introduction to Metal Processing Using Ion Beams

Researchers in the Russia have demonstrated the improvement in a number of material surface properties by bombardment with pulsed ion beams^(46,47). This new technology has the potential to improve hardness, corrosion resistance, and tribological properties of materials for use in hostile environments. Intense, pulsed, high energy Ion BEam Surface Treatment (IBEST) can produce surface conditions ranging from localized high temperature annealing to surface melting, both followed by rapid thermal quenching to ambient temperatures as shown in Figure 10⁽⁴⁸⁾. In metals this can produce complex surface alloys, by liquid phase mixing, and/or non-equilibrium microstructures including amorphous, disordered crystalline, and nanocrystalline phases. Other potential applications include etching of polymer films, surface glazing and sealing of ceramic surfaces, and cost-effective dry processes for surface deburring, polishing, and cleaning without the use of potentially harmful solvents. The unique energy deposition characteristics of high energy ion beams allows this technology to be developed for the bonding of thin films to substrates. Unlike the laser beams that deposit their energy near the surface (≈ 30 nm) or are reflected by the surface, ion beams deposit their energy throughout their multi- μ m range. Ion beams also have the unique capability to deposit energy preferentially near the end of their penetration depth, in the interior of the sample, due to the inverse dependence of ion stopping power with energy. Ion beams offer the possible advantage of treating large (200 - 1000 cm²) surface areas for reduction of edge effects and lower cost, high throughput, materials processing applications.

Figure 10, Ion beam energy deposition

Surface Smoothing and Modification

The rapid heating of the top 1 to 10 microns of a material surface provided by an ion beam, with a current density of a few A/cm² and an energy of approximately 1 MeV, can easily bring metals and ceramics to the melting temperature. Figures 11, 12, and 13 show a titanium machined surface, a Metglas® surface, and an alumina ceramic surface that have been smoothed by 1 MeV, 60 ns, 10 J/cm² mixed carbon and proton ion beam. The Metglas® magnetic properties have not been evaluated following the surface melt treatment. Very smooth surfaces may have application in medical prosthesis fabrication and possibly as reduced electron emission surfaces in high voltage applications.

Figures 11, 12, and 13

The results of treating a type O-1 tool steel surface, shown in Figure 14, with a 10 J/cm^2 , 1 MeV mixed proton and carbon beam illustrate some of the effects of the IBEST surface modification. The surface of the O-1 steel was converted from an equilibrium ferrite and carbide microstructure to a mixture of amorphous material and retained metastable austenite. The equilibrium carbides were absent in the beam-treated layer, indicating that they had been dissolved during melting and then frozen in solution by the rapid cooling.

Figure 14

Sub-surface Heating

When ions stop in materials they deposit energy preferentially near the end of their range because of an inverse dependence of stopping power with ion energy⁽⁴⁹⁾. This peak in energy deposition is called the Bragg peak. Different ion species and energies can be used to give a deposition profile tailored to deposit most of the beam energy at the maximum penetration depth. The peaked deposition profile shown in Figure 15, for 0.9 MeV protons in titanium, provides a unique IBEST capability to melt subsurface layers and interfaces without melting the material surface. This may provide a new method of bonding thin films to substrates, perhaps with greatly improved adhesion. Ion beam pulses with proton energies of over 500 keV, with pulse lengths of 100 ns or less, are required to produce significant (x2) peak in the deposition profile. The pulse length is limited by the requirement that the deposited heat energy not be significantly conducted away from the treated zone during the heating process. Availability of ion beams with spectral and specie purity are required and may be provided by the Magnetically-confined Anode Plasma ion beam system from Cornell University^(49, 50).

Figure 15, Bragg peak

Ion Diode Developments

Operation of the Magnetically-confined Anode Plasma (MAP) ion beam source was demonstrated with repetitive pulse rates of 100 Hz in 10 pulse burst mode operation at Cornell^(49, 50). An improved version of this system is now being fielded on the RHEPP facility⁽¹⁵⁾ for burst mode operation. The MAP source operates on the principle of drawing ions from an anode plasma rather than from a solid anode as used in a single pulse mode application. A fast gas valve on the axis of the anode assembly produces a puff that is delivered to the anode through a supersonic nozzle to produce a highly localized volume of gas directly in front of the surface of a fast driving coil. After preionization by a 1 microsecond induced

electric field, the fast coil is energized, inducing a loop voltage of up to 20 kV on the gas volume, driving a breakdown to full ionization and pushing the resulting plasma toward the flux-excluding anode field shaping electrodes in about 1.6 microseconds to form a thin, magnetically confined plasma layer. The RHEPP pulse then accelerates ions from this plasma layer to form the ion beam. The anode plasma can be formed using a variety of gases including hydrogen, nitrogen, and argon. The beam propagates ballistically to the target plane, also located in the vacuum chamber, as shown in Figure 16.

Figure 16, MAP Ion Beam Diode

The selection of ions with larger mass, such as nitrogen or argon, will allow energy deposition in surface layers of less than 1 micron. This process can deposit sufficient energy to vaporize the surface for cleaning, etching, or vapor deposition applications.

Materials Processing Using Electron Beams

Many of the materials treatment processes that can be done with ion beams may be performed with greater penetration depths by using suitable energy electron beams. In experiments at the Lawrence Livermore Laboratory, Elmer deposited energy from a 6 MeV, 60 ns, electron beam into O-1 tool steel and found an increase, by about a factor of 3, in the hardness of the material⁽⁵¹⁾. The hardness increased over a depth of about 2 mm while the range of the electrons in the material was 1 mm.

The short range of the megavolt ion beams require the deposition process be carried out in a vacuum. Electrons could be deposited in materials surrounded by atmospheric pressure gases when differentially pumped windows are developed.

Food Irradiation

Consideration of food irradiation is driven primarily by concerns for the safety of the food supply. As many as 10,000 deaths per year, in the US., are attributed to food poisoning, and wide-spread use of food irradiation could drastically reduce this rate⁽⁵²⁾. Reduction of food spoilage and extension of marketable shelf-life is a second reason for using food irradiation. As much as 40% of produce harvested in the fields is lost due to spoilage before it reaches the consumer. Up to 90% of the fresh fish harvest is lost due to spoilage. This loss amounts to several billion dollars annually and could be drastically reduced by the use of food irradiation. Third-world countries have a more severe food contamination and spoilage problem than does the United States, due to a less advanced transportation and

refrigeration system⁽⁵²⁾, so the use of food irradiation could help increase the available food supply.

Dose levels are generally divided into three ranges:

Disinfestation	≤ 100 Krad
Pasteurization	100 to 300 Krad
Sterilization	> 300 Krad to 3 Mrad

The scientific background for the effectiveness of removing bacteria and insect infestation is extensive. Food irradiation treatment data has been comprehensively reviewed⁽⁵³⁾. There is no doubt that the treatment is extremely effective in removing such contaminants as salmonella, listeria, and E. coli. Salmonella cell populations are reduced by at least 6 orders of magnitude with an exposure of 300 Krad (3 Kgrays). Annual health care costs in the U.S. due to salmonellosis alone are estimated at approximately \$2B⁽⁵⁴⁾. There is a large data base to show that no radiolytic byproducts are introduced into the food as a result of the treatment process at the FDA approved treatment levels^(52,55). Food irradiation can undoubtedly reduce the loss of life and costs of medical treatment that is now attributed to illness from food contamination, in the US. and world society.

Presently there are a limited number of choices for accelerators for food irradiation processing^(56,57). These accelerators are based on RF Linac technology or DC accelerator technology. Low power X-ray and electron beam generating machines are available from MeV Industrie, France, AECL Accelerators, Canada, and the Titan Corp. as well as from several Russian Institutes. These accelerators have limited capability for extension to the high average power levels required for high through-put applications. Typically these accelerators have output power levels of 100 kW or less. A large scale food operation is desirable to make food treatment profitable. In order to treat a large volume of foods, the X-ray mode will likely be used because of the greater depth of penetration compared to using electrons. The power requirement is estimated to be in the range of 500 kW to 1000 kW to make an accelerator facility cost effective. Customer education, additional regulatory actions, and development of long-life systems will be required to expand the use of short-pulse, high average power accelerators into the food irradiation market.

Conclusion

Over 20 years of scientific research have been conducted on beneficial applications of electron and ion beams. Most industrial applications used beam power levels of up to a few hundred kW with beam energies of less than 1 MeV. Defense applications have concentrated primarily on single pulse accelerator

operation with beam energies of up to a few 10's of MeV. Various university experiments have demonstrated the usefulness of beams in mitigating organics and other type of industrial pollution. Irradiation of foodstuffs with Cobalt-60 sources is now seeing some acceptance in the US. Scientists and engineers dedicated to fighting the cold war are now finding themselves in a position to convert defense oriented devices, such as short-pulse simulators, to economically sound approaches that deal with environmental and exciting new industrial applications. Availability of long-life, short-pulse, high average power accelerators, pulse compression components, and high power ion and electron beam diodes is occurring on a parallel path with the development of an increasing awareness of society's need for ways of dealing with problems such as waste pollution, bacteriological outbreaks, and an increasing desire for new and less polluting manufacturing methods. These problems can be, at least partially, attributed to increasing population densities and waste management policies of the past. The magnitude of some of the present pollution problems now being identified may seem to greatly overshadow society's ability to pay for the treatment needed to restore the environment. Creative and economical solutions from the scientific establishment, with the assistance of short-pulse, high average power beams, may present a way out of this dilemma. The applications presented in this review are not intended to be all inclusive, but rather to indicate just some of the possibilities for pulsed beams that are available now and waiting for sufficient economic and political emphasis to be commercialized.

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Figure 1 - Short-pulse high average power accelerators use a common approach to pulse compression and beam generation.

Figure 2 - The Physics International
750 kV, 10 kA, 120 kW CLIA accelerator
has 50 ns output pulses.

Figure 3 - The Science Research Laboratories
SNOMAD IV accelerator delivers 1.5 MeV,
500 A, beams with 38 kW average power.

Figure 4 - The RHEPP 1 MeV accelerator uses an oil filled LIVA to deliver 25 kA, 60 ns pulses with 7 kW of continuous beam power at 5 PPS. This system is being upgraded for 120 kW, 120 PPS operation.

Figure 5 - Hanford simulated waste irradiation cell geometry used to evaluate organic destruction efficiency

Figure 6 - Results of pulsed irradiation of simulated Hanford waste show complete destruction of organics will require about 1500 Mrad from a short pulse accelerator.

Figure 7 - Electron beams can be used to destroy SO₂ and NO_x in power plant flue gases and produce fertilizer as an output product.

Barrier configuration

* discharge arrested by charging of barrier

(a)

High-field, fast pulse configuration

* discharge arrested by removing drive field

(b)

Figures 8a and 8b - Dielectric barriers or shaped pulses can be used to create free radical at the tip of a streamer discharge in a flowing gas.

(a)

(b)

Figures 9a and 9b - Electron beams can deposit energy into a buried braze material which bonds ceramic materials.

Figure 10 - Ion beams can efficiently deposit energy into micron deep surface layers on a variety of materials

(a)

(b)

Figure 11 - Ion beam smoothing of titanium

Figure 12 - A pulsed ion beam can remove Metglas surface roughness. Debris, in lower photo, will be eliminated with the MAP diode.

Figure 13 - This sample of polished alumina was subjected to a 60 ns, 10 J/cm², 1 MeV beam of mixed protons and carbon. Controlled surface melting and resolidification was seen .

Figure 14 - Type O-1 tool steel shows absence of equilibrium carbide structure and a 3x increase in surface hardness after treatment with a 10 J/cm^2 ion beam.

Figure 15 - A 0.9 MeV H⁺ beam preferentially heats at a depth of 7 to 8.5 microns in titanium

Figure 16. This is a schematic of the Magnetically-confined Anode Plasma (MAP) ion beam source. The cathode assembly mounted to the (negative polarity) RHEPP output stalk is at the right. The ion beam propagates to the target plane at the right. The figure shows the MAP diode, on the cathode side (A) the cathode magnetic insulating field coils; on the anode side (B) the puff valve; (C) the fast driving coil; (D) the gas nozzle; (E) the field-shaping electrodes. The magnetic flux surfaces superimposed are as they are at the time of the RHEPP accelerating pulse which in the present negative polarity operation is applied to the cathode structure.

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