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THE USE OF ELECTRON BEAMS FOR PASTEURIZATION OF MEATS*

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ABSTRACT

Electron beam accelerators can be used for electronic pasteurization of meat products by: 1) using the electrons directly impacting the products, or 2) optimizing the conversion of electron energy to x-rays and treating the product with these x-rays. The choice of process depends on the configuration of the product when it is treated. For electron treatment, ten million electron volt (MeV) kinetic energy is the maximum allowed by international agreement. The depth of penetration of electrons with that energy into a product with density of meat is about five centimeters (cm). Two-sided treatment can be done on products up to 10 cm thick with a two-to-one ratio between minimum and maximum dose. Ground beef patties are about 1.25 cm (0.5 inch thick). Beams with 2.5 MeV electron energy could be used to treat these products. Our calculations show that maximum to minimum dose ratios less than 1.2 can be achieved with this energy if the transverse beam energy is small.

If the product thickness is greater than 10 cm, x-rays can provide the needed dose uniformity. Uniform doses can be supplied for pallets with dimensions greater than 1.2 m on each side using x-rays from a 5 MeV electron beam. The efficiency of converting the electron beam to x-rays and configurations to achieve dose uniformity are discussed.

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Brief descriptions of three types of accelerators that could be used for this treatment are given.

INTRODUCTION

A strong desire by the meat industry and United States Department of Agriculture (USDA) to continually improve the safety of our food supply, coupled with the increasing threat, and public awareness of illnesses from food borne pathogens has led to a resurgence of the interest in all methods to reduce the levels of microorganisms in meat products (Council of Agriculture Science and Technology, 1994, and National Live Stock and Meat Board, 1994). The American Meat Institute Foundation (AMIF) has a research program to better understand electronic pasteurization of ground beef and pork, a treatment more commonly called food irradiation. This research will provide a better understanding of the effectiveness of eliminating the bacterial threat versus the dose absorbed by the meat product and an understanding of changes, if any, in the sensory qualities of the product after treatment at the maximum dose allowed (American Meat Institute, 1993). Information from this study will support the petition that has been submitted to the Food and Drug Administration (FDA) for approval to irradiate beef at dose levels up to 4.5 kiloGray for fresh beef and 7 kiloGray for frozen beef. In this paper, we provide some background on the treatment of meats with electrons, x-rays and gamma rays that we feel could help industry representatives in their evaluation of this treatment method to prepare for an implementation decision when the FDA approves this petition. Some of the topics that should be of interest are: 1) the need for treatment, 2) the effectiveness of the treatment, 3) description of the accelerators that can supply electrons or x-rays for treatment, 4) information on radioisotopes that can supply gamma rays, 5) treatment uniformity with these sources, and 6) differences between these sources. In the remainder of this paper, we provide some information on each of these topics.

The increased public awareness of illness and deaths that have come from *Escherichia coli* O157:H57, *Listeria monocytogenes, Salmonella enteritidis*, and other food borne pathogens, is an important reason for the meat industry to stay abreast of new developments in treatment of foods to eliminate these microorganisms. Treatment of food products with electrons, x-rays and gamma rays have been studied for over forty years (American Meat Institute, 1993, Diehl, 1990, International Consultative Group on Food Irradiation, 1991, Josephson and Peterson, 1982, and Thayer, 1992). These studies have shown that treatment at moderate dose levels is a very effective means for reducing the level of microorganisms and bacteria in foods by several orders of magnitude (five or six log values). These results have led to international standards for treatment levels. In the United States, the treatment is considered a food additive by the FDA requiring approval for each class of product that is being considered for treatment. A broad selection of food products have been approved for treatment at moderate dose levels and the meat petition is expected to be approved in the near future.

ELECTRONIC PASTEURIZATION

Radiation dose is a measure of energy absorbed by the product that is exposed to the radiation. The dose is expressed in Gray or kiloGray (1000 Gray). One Gray is the absorption of 1 Joule of energy per kilogram of material. Effective levels for meat irradiation is 1.5 kiloGray to 7 kiloGray. In the scientific community, another unit is sometimes used. This unit is the rad which is 100 ergs of energy absorbed per gram of material. One Gray equals 100 rads. The amount of heat energy that is absorbed to raise the temperature of water one degree centigrade is 4180 J/kg or the equivalent of 4.18 kiloGray. Therefore, the energy that is supplied to the product for effective pasteurization using ionizing radiation is very small compared to that required to cook the product or clean it with hot water.

When electrons, x-rays or gamma rays interact with food products, hydroxyl and other short-lived radicals are formed. These radicals interact with the DNA in the cells of microorganisms that are present and cause damage to these cells, and death to a large fraction of the microorganisms. Since all of the forms of radiation that produce these radicals are effective in reducing microorganism contamination, the choice of which type to use for meat irradiation will be made on processing, cost, reliability and availability considerations. Diehl (Diehl, 1990) indicates in his 1990 publication that more than 520,000 tons of foods are irradiated each year. Electrons are used to treat the largest fraction of that material with 400,000 tons of grain in Russia and 7,000 tons of deboned chicken in France. Essentially, all of the rest is treated by gamma rays from radioactive isotopes. Since the meat production in the United States far exceeds the total tonnage stated above, advances in the infrastructure to supply these sources will be needed. AMI members can help shape this infrastructure so that it effectively satisfies their needs if they understand the advantages and limitations of each of these sources.

Food products can effectively be treated by electrons, or x-rays from accelerators, or by gamma rays from radioactive isotopes such as Cobalt-60 (^{60}Co) or Cesium-137 (^{137}Cs). The only radioactive isotope used in this country is ^{60}Co (Mylvaganum and Ronchka, 1990). Radioactive isotopes are unstable and continually decay in a process that is converting the isotope to non-radioactive elements. Gamma rays are emitted continuously in all directions during this decay process. Since the amount of radioactive material is decreasing continuously, the strength of the gamma ray source also decreases. The time it takes for half of the ^{60}Co to decay is 5.3 years. This time is referred to as the half-life of the material. This is a relatively long time, but if the gamma ray source needs to have the same strength at all times, a phased approach of replacing the radioactive isotope is necessary. Since the ^{60}Co continuously emits gamma rays, shielding and security must be provided at all times to ensure that workers do not get exposed to this ionizing radiation. Gamma rays and x-rays are short wave length electromagnetic waves that can penetrate deeply into matter. The gamma rays emitted from ^{60}Co have an energy of 1.3 MeV and can be used to effectively treat single packages or stacks of packages that are about 1.0 m (3.3 feet) maximum dimensions. Radioactive isotopes are formed in nuclear reactors. The only company in North America that is set-up to make ^{60}Co is Nordion, a Canadian firm that has a strong interest in supplying this product to the food industry. They presently furnish isotopes to firms conducting medical product sterilization and to the medical industry for therapeutic purposes. Nordion also supplies ^{60}Co to Vindicator for their food treatment facility in Florida that is used to pasteurize poultry, fruits and vegetables. Isomedix has medical products sterilization plants with ^{60}Co sources that will provide the basis for a plant to treat food products, and have submitted the petition to allow red meat irradiation to the FDA. If food treatment with gamma rays become broadly used, the demand for isotopes will exceed the ability of Nordion to supply them.

ELECTRONS AND X-RAYS FOR MEAT TREATMENT

Accelerators provide x-rays or electrons for treatment of food. As stated above, electron beams were used to treat about 80% of the food that was irradiated in 1990. International standards allow the use of electrons with kinetic energies up to 10 MeV for direct treatment of the food product, or the use of x-rays that are generated by electrons with 5 MeV kinetic energies (International Consultative Group on Food Irradiation, 1991). The function of an accelerator is to provide energy to electrons by providing an electric field (potential energy) to accelerate the electrons. If the electrons impact a metal plate after they have achieved their full kinetic energy, a small fraction of the kinetic energy will be converted to x-rays, and the remainder to heat. The fraction of energy converted to x-rays for a 1 MeV electron impacting a tungsten target is 0.076 and for a 5 MeV electron 0.21 (Berger and Seltzer, 1964). Some of this energy is absorbed by the target, or backscattered away from the product to be treated. Since about 79% of the electron energy produces heat in the x-ray generation process, and it is not possible to use all of the x-rays that are generated, x-ray treatment requires about ten times the accelerator power of direct electron treatment at the same amount of product per hour.

Electrons are atomic particles rather than electromagnetic waves, and their depth of penetration in the product is much smaller. Figure 1 is a representation of the difference of depth of penetration of x-rays and electrons. The x-rays produced from 5 MeV electrons are shown penetrating a 1.2 m (4 feet) thick crate. In contrast, 10 MeV electrons can be used to treat 9 cm (3.6 inch) thick products. This limits the direct use of electrons to meat packages less than four inches thick.

Figure 1. Package Thickness Requirements Determine
the Accelerator Mode of Operation

Figure 2. Relative Dose Versus Depth of Electron Deposition into Polystyrene for Electron Beam Energies of 1 MeV, 2 MeV, 4 MeV and 10 MeV (Josephson, Peterson and Martin, 1982). The profile will be very similar to this for meat products.

Figure 3. Two-Sided Treatment Provides Acceptable Dose Uniformity for Larger Thickness Products.

Figure 2 is the energy deposition profile in polystyrene for 1 MeV, 2 MeV, 4 MeV and 10 MeV electron energies (Berger and Seltzer, 1964). These profiles will be very similar for deposition in meat products. The FDA guidelines and international agreements specify the ratio of maximum to minimum dose. For poultry, this ratio is two-to-one. The petition for red meat requests a three-to-one ratio. A 0.8 cm thick product could be treated with a 2 MeV beam from one side and obtain better than the minimum to maximum dose ratio of three. If two-sided irradiation is used as shown in Figure 3, 1.6 cm thick products can be treated with a two-to-one maximum to minimum dose ratio. If more uniformity is desired, a 1 cm thick product can be treated with 2 MeV electrons with less than 1.2 maximum to minimum ratio as shown in Figure 4. These deposition profiles are calculated using the ITS codes (Halbleib, Kensek, Melhorn, Valdez, Berger and Seltzer, 1992) developed at Sandia National Laboratories and available for industrial use. Similarly, one can treat up to 10 cm thick products with 10 MeV electrons from two sides. The two-sided irradiation can be achieved either by using two sources as shown in Figure 3 and Figure 4, or by turning the product after applying the electron beam to one side and applying the beam to the opposite side.

Fig 4. Double-Sided Electron Illumination Can Yield
Excellent Dose Uniformity in Thin Products

Fig 5. Double sided Illumination with X-rays Provides 2.5:1 Ratio
of Maximum to Minimum Dose in a Large Crate.

X-rays are short wavelength electromagnetic waves that readily penetrate matter. Figure 5 shows a calculated dose profile for a 1.2 meter (4 feet) x 1.2 meter x 1.5 meter (5 feet) crate of produce with double-sided treatment. The plot indicates that the uniformity is about 2:1 at the center of the crate and at the bottom edge. The dose at the bottom edge is consistently 20% lower than the center. This data indicates a 2.5:1 ratio for minimum to maximum dose. The lower dose at the 60 cm point is due to the combination of decrease of dose with increasing distance from the x-ray source, and of absorption of the x-rays by the product. X-rays are produced from each point where electrons impact the converter and are forward directed in a cone with a half angle that depends on electron energy. The cone half angle is sixteen degrees for 5 MeV electrons. For a fixed exposure time, the dose is proportional to the x-ray energy per unit area. Therefore, the dose decreases as the square of the distance from a point source. If the x-ray source is comparable in size to the crate to be treated, the fall-off varies linearly with the distance from the source. As one moves the crate further away from the target, the distance dependence becomes less and the dose variation will become dominated by the x-ray absorption. This improved uniformity is at the expense of intercepting a smaller fraction of the total x-rays that are produced. Better uniformity can also be achieved by tailoring the shape and strength of the x-ray source. For example, in Figure 5 one could increase the source strength at the top and bottom of the crate. With pulsed electron beam accelerators, the beam can be configured to provide this tailoring. With small diameter sources such as radio frequency (RF) accelerators, the tailoring may be achieved by sweeping the beam over an x-ray target and controlling the dwell time on various parts of the target.

ACCELERATOR DESCRIPTIONS

There are three classes of accelerator that can be used to treat meat products. These are the continuous beam accelerator, the RF accelerator, and the pulsed accelerator.

Fig 6. Example of 5 MeV cw Accelerator.

An example of the continuous beam accelerator is shown in Figure 6 (Cleland and Pageau, 1987). This is a 5 MeV, 200 kilowatt (kW) accelerator that provides a millimeter diameter beam that is swept over the product using a deflecting magnet. The power is supplied from a 100 kilohertz (kHz) RF source and is rectified within the accelerator. The high voltage terminal is at the full 5 MeV and contains the electron source. The electrons are accelerated to ground potential at the bottom of the diagram.

Fig 7. Schematic Representation of RF Accelerator

The RF linear accelerator is powered by a microwave tube as shown schematically in Figure 7. It consists of a power conditioning subsystem that provides either continuous power or 10 millionths of a second (microsecond, μs) to 20 μs pulses to the microwave tube. Microwave energy from this tube is fed to several resonant cavities. The cavities provide an oscillating voltage across a gap that the beam traverses that accelerates the beam if it is properly phased. The beam is divided into beamlets that are about one billionth of a second long as shown schematically in Figure 7. The beam kinetic energy is increased in each cavity, and the number of cavities corresponds to the total beam kinetic energy required, divided by the energy gained per cavity. The accelerator that generates the beam that is used for pasteurizing chicken in France is a 10 MeV, 7.5 kW RF linear accelerator that runs in the pulsed mode (Sadat, 1991). Similar machines are in operation for food irradiation studies at Iowa State University and the University of Florida. These machines will operate at 10 MeV in the electron beam mode and provide about 15 kW of beam power. Thirteen microsecond pulses are generated at a rate of 450 pulses per second. These accelerators produce small diameter beams that are also magnetically swept across the product.

Pulsed accelerators produce beam pulses that are approximately fifty billionths of a second in duration (nanoseconds, ns), and these pulses are repeated many times per second. In the Sandia National Laboratories Repetitive High Energy Pulsed Power (RHEPP-II) accelerator, a 2.5 MeV, 25 kiloamp, 60 ns beam is generated 120 times per second to provide 350 kW of average beam power (Johnson, et al, 1993).

Pulsed power is used to generate high voltages over short time scales to avoid insulation breakdown. Extensive high voltage testing of insulation strength in the pulsed mode has shown that the breakdown field scales inversely with the pulse duration. Short pulses allow operation at electric fields above the normal dc breakdown limit, and fields of some 100 kV/cm for dielectric liquids, and some 200 kV/cm for pressurized SF_6 are commonly attained. The ability to operate at high breakdown limits results in a smaller, more compact machine.

Figure 8. Schematic of Voltage Adder and Electron Beam
Source for RHEPP Accelerator

Short pulses also allow voltage adding by using inductively isolated pulses stacked in series. This inductive isolation technique is illustrated in Figure 8. In this technique, voltage pulses can be added serially from multiple, parallel-charged acceleration stages. The individual stages are inductively isolated with ferromagnetic cores. This topology acts as a voltage step-up transformer with a gain of N, where N is the number of stages. With a stage voltage of V_0, synchronization of the stage pulses, and matched impedance of the adder, a peak voltage NV_0 is impressed at the output terminal. For the RHEPP design, the input voltage on each stage is 250 kV and pulse width is 60 ns. Four stages, with an output voltage of 1 MV, have been tested. The electron beam is generated by a cathode at the output terminal (labeled diode in Figure 8) and accelerated across the anode-cathode gap to form a beam with an energy of 1.0 MeV. Additional stages are now installed to extend the RHEPP output voltage to 2.5 MeV and evaluation of the accelerator at that level is underway.

The RHEPP power conditioning is based on the use of magnetic switching (saturable reactors). Magnetic switches are similar in construction to power transformers, and as such should have high reliability and long lifetime. Five compression stages are required with this type of switching to reduce the pulse width from an initial 8.4 ms input of 120 Hz delivered by an alternator to an output pulse width of one microsecond. A voltage step-up transformer is included between stages 2 and 3 to increase the working voltage from 15 kV to 270 kV. The pulse forming network (PFN) provides the final compression to 60 ns. The PFN is pulsed charged coaxial cylinders with water dielectric that provides a rectangular 250 kV pulse. High voltage cables deliver the output pulse from the PFN to a linear induction voltage adder, as shown in Figure 8.

Figure 9. Beam Pulse description and dose rate
for the three types of accelerators.

These three classes of accelerators produce radically different peak dose rates as shown in Figure 9. The 10-30 Grays per second dose rate for gamma ray sources is similar to that of a cw accelerator. The one million Gray/second shown for the RF accelerator is for a 13 microsecond pulse duration, the same pulse duration that is used in the RF accelerator that is in operation at

Iowa State University. The 60 billion Gray per second dose rate for pulsed accelerators is the calculated values for the planned electronic pasteurization experiments on RHEPP-II. The dose rate values cover eight orders of magnitude. The number of radicals produced at the same instant in time by the pulsed accelerator beam will be several orders of magnitude larger than those produced with the cw accelerator. This larger density results in more interactions within the group produced and less time for chemical reactions with other ions in the product. There has been some reports of dose rate improvements in pathogen reduction, but the bulk of the food treatment literature indicates that there is little or no difference due to dose rate effects for the moderate dose levels that food products are treated. Most of the dose rate effects data was taken in the 1960 time frame. Since the products are different and pulsed accelerator dose rates are higher than was previously tested, it is important to reevaluate both the quality and the pathogen reduction effectiveness. AMI Foundation plans to support studies to evaluate these differences.

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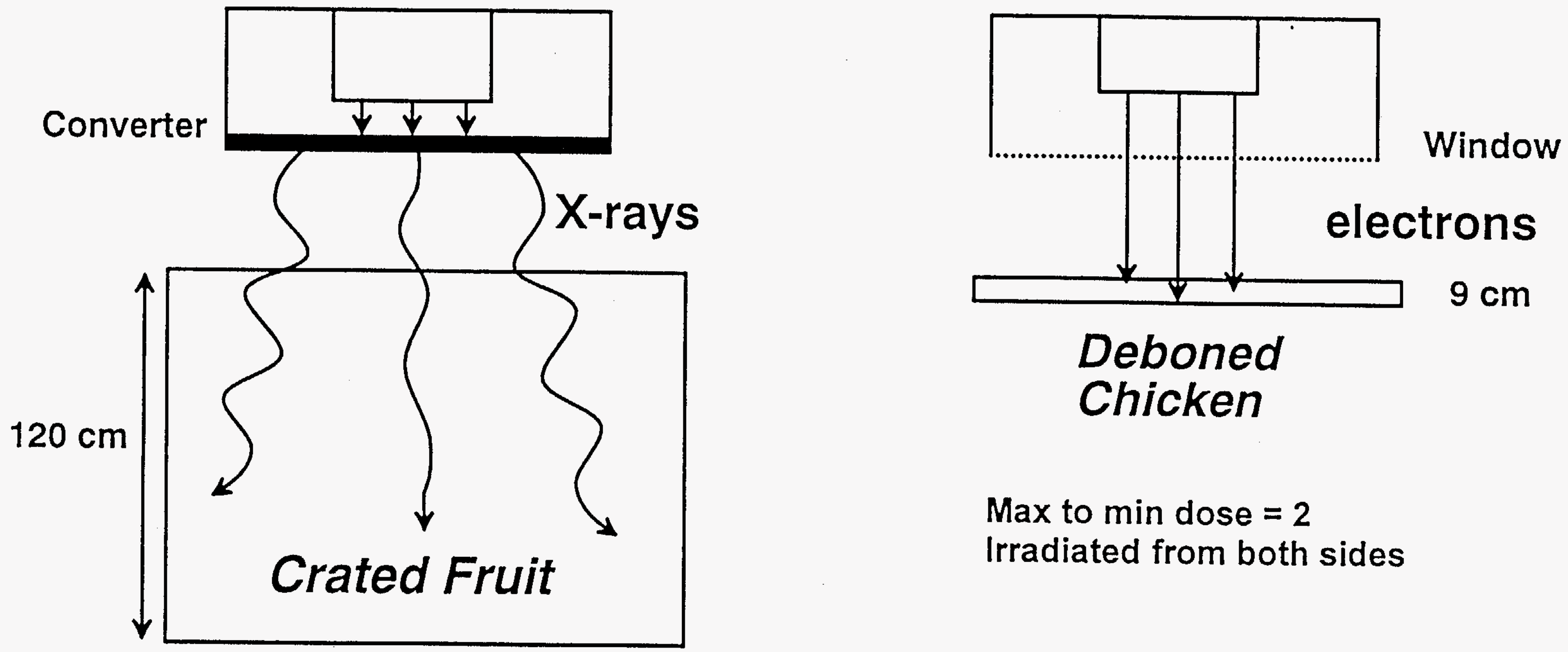
FIGURES

Figure 1



X-rays from 5 MeV Electrons

10 MeV Electrons

Max to min dose = 2
Irradiated from both sides

X-ray penetration is greater than electron beam penetration, but the conversion at 5 MeV is 10 times less efficient.

Figure 2

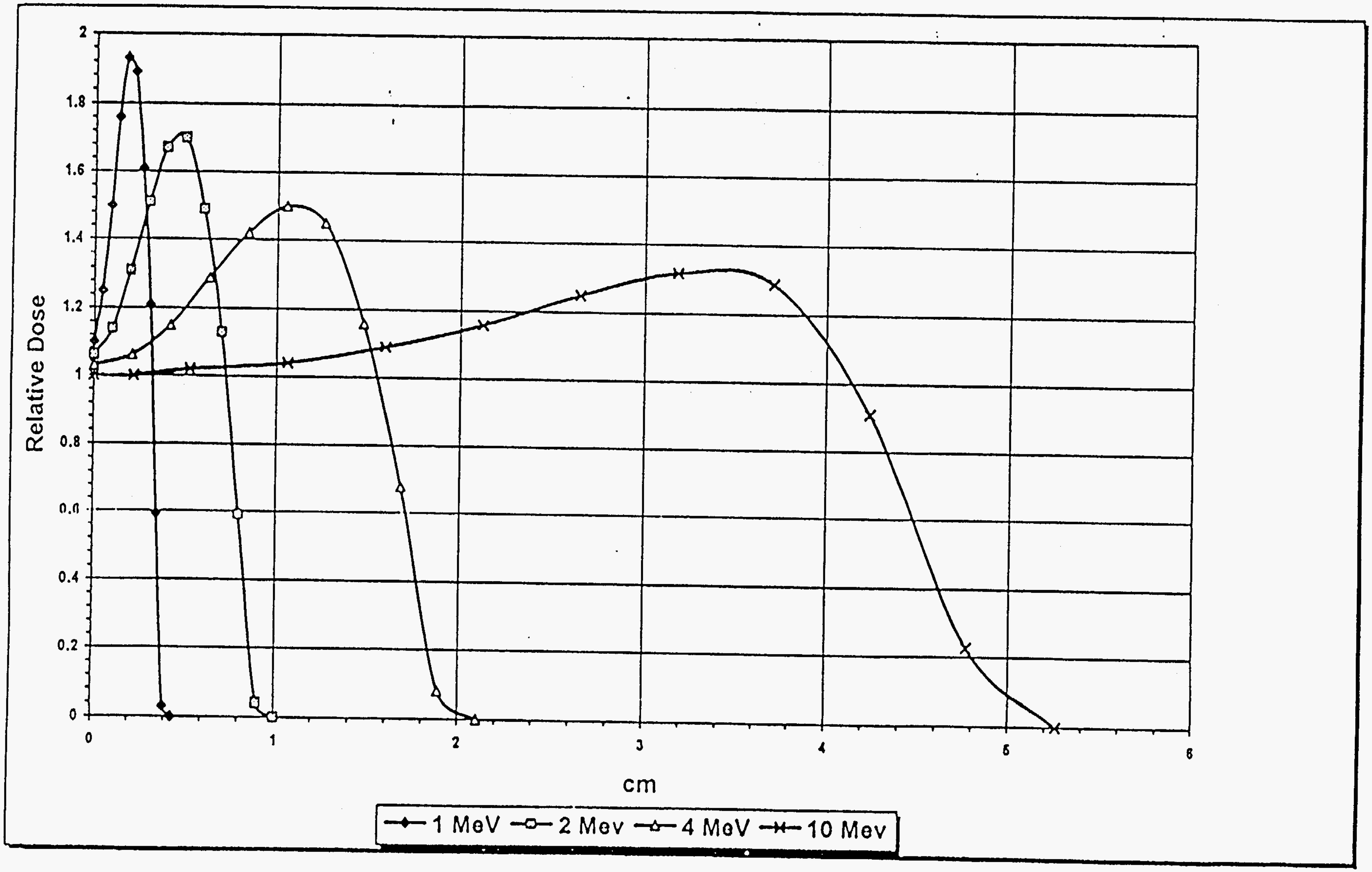
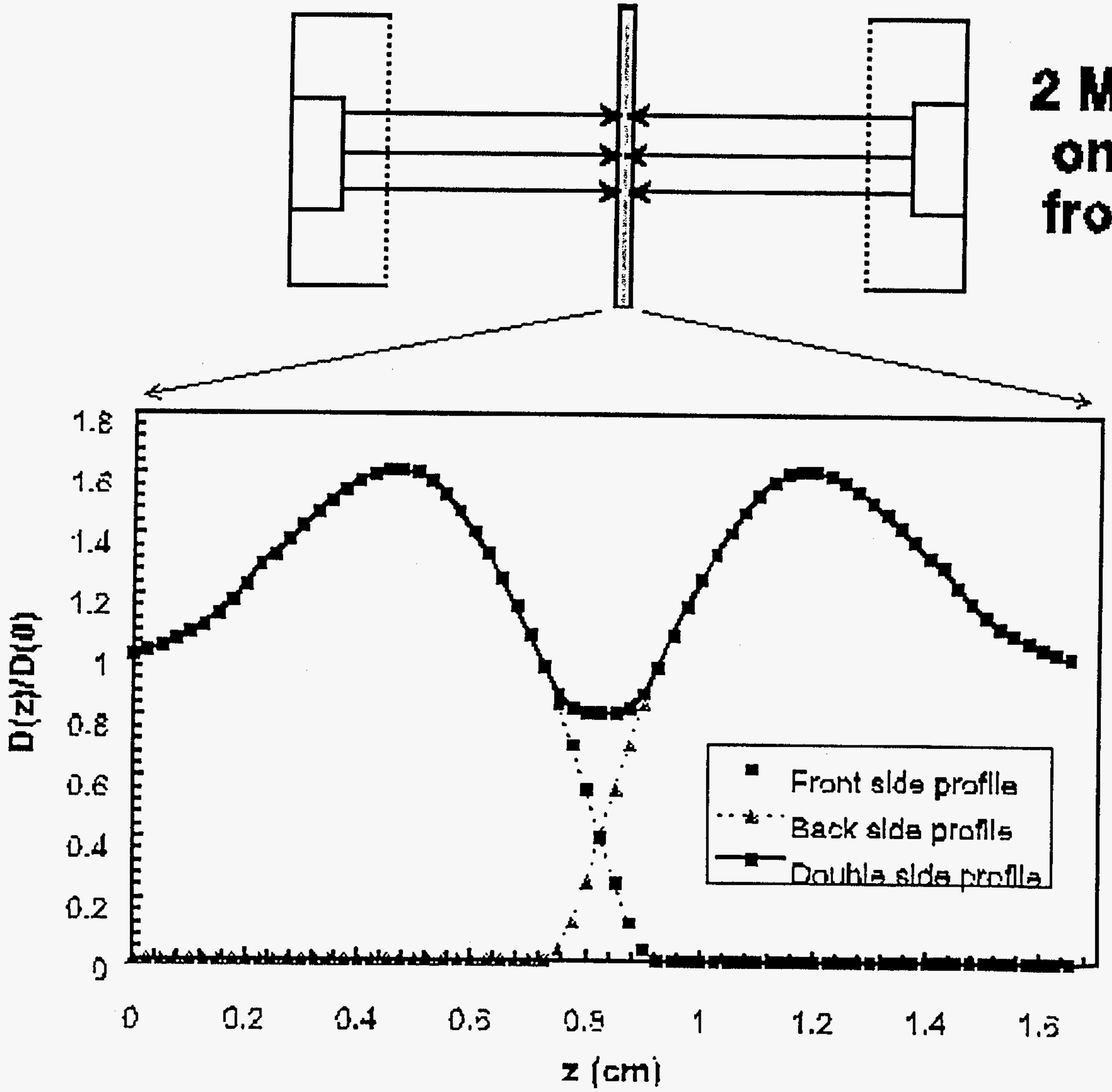
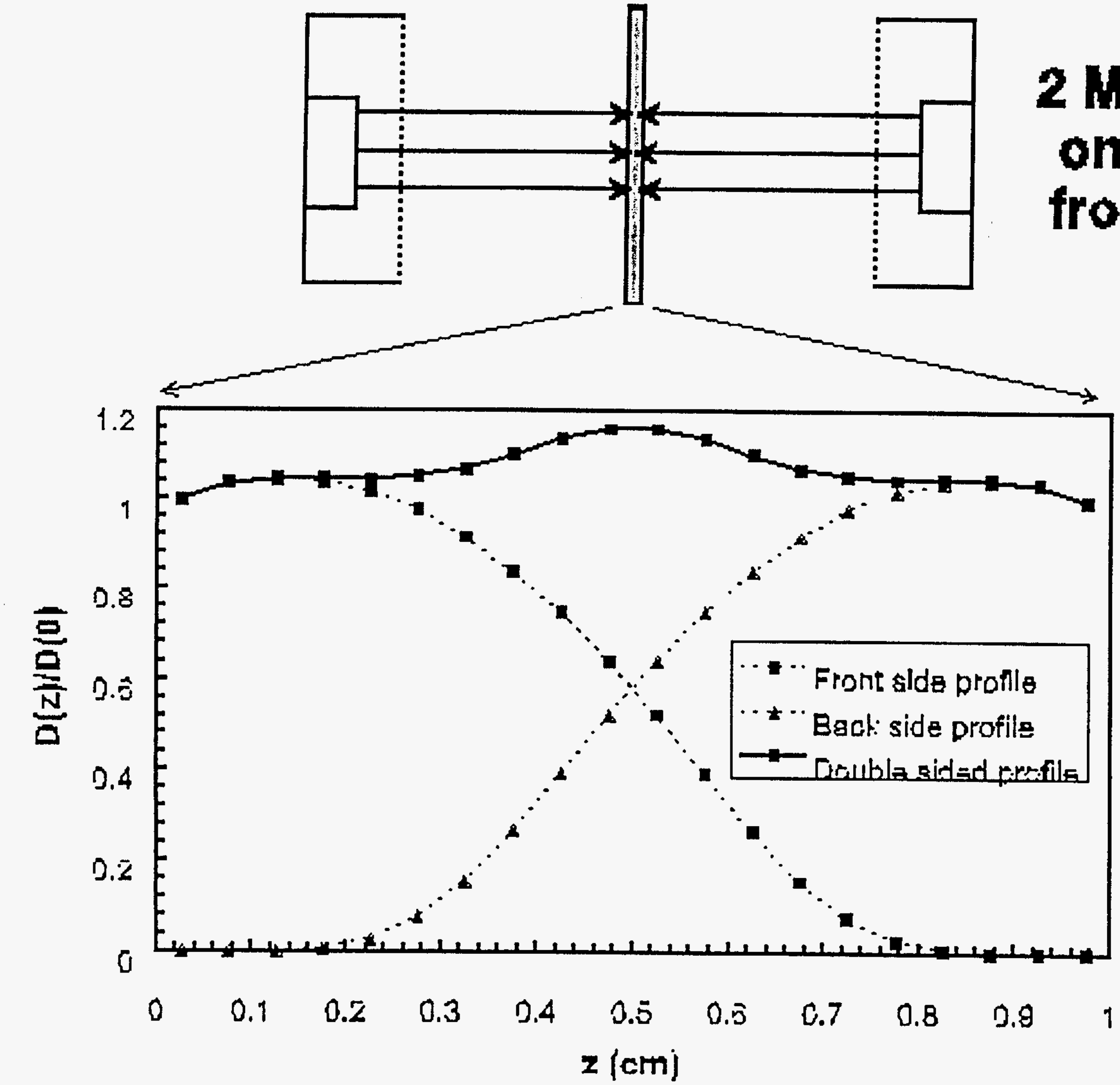

Relative Dose
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
cm
1 MeV
2 Mev
4 MeV
10 Mev

Figure 3



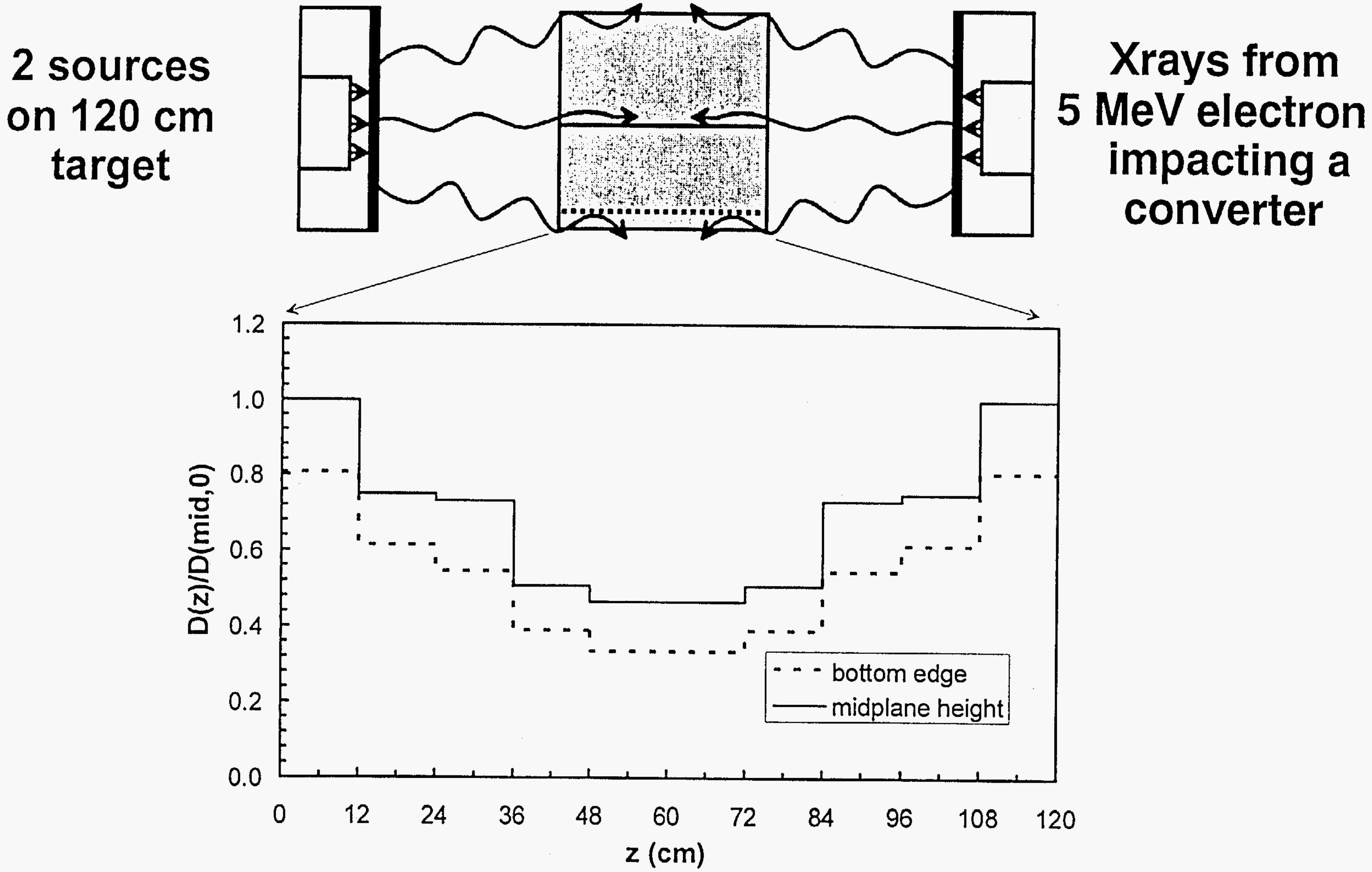
2 MeV electrons on 1 cm target from 2 sources

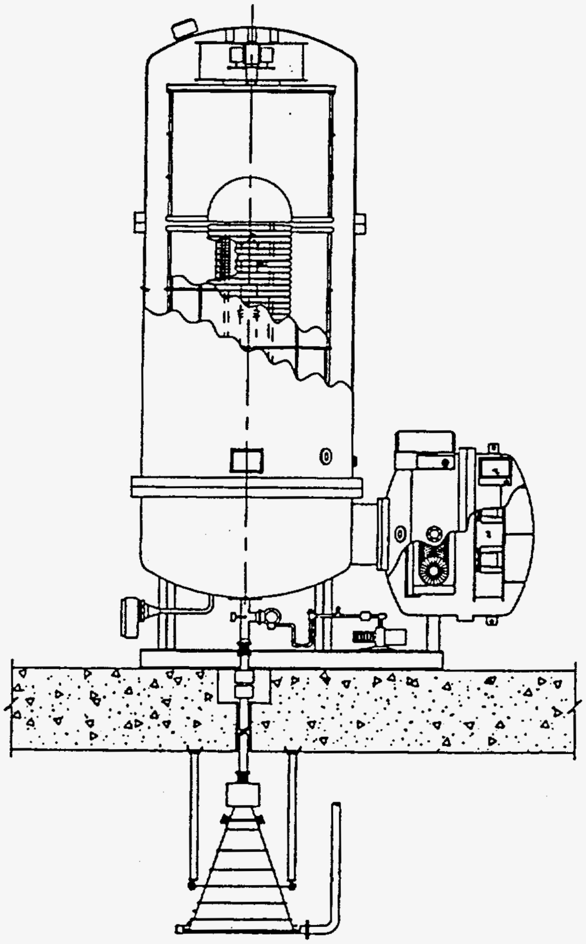
Figure 4



2 MeV electrons on 1 cm target from 2 sources

Figure 5


2 sources on 120 cm target
Xrays from 5 MeV electron impacting a converter
1.2
1.0
0.8
0.6
0.4
0.2
0.0
D(z)/D(mid,0)
0
12
24
36
48
60
72
84
96
108
120
z (cm)
bottom edge
midplane height



5.0 MeV/200kW DYNAMITRON® ELECTRON BEAM ACCELERATOR

Figure 6

Figure 7

RADIO FREQUENCY ACCELERATORS ARE BEING USED IN FRANCE FOR PASTEURIZATION OF DE-BONED CHICKEN

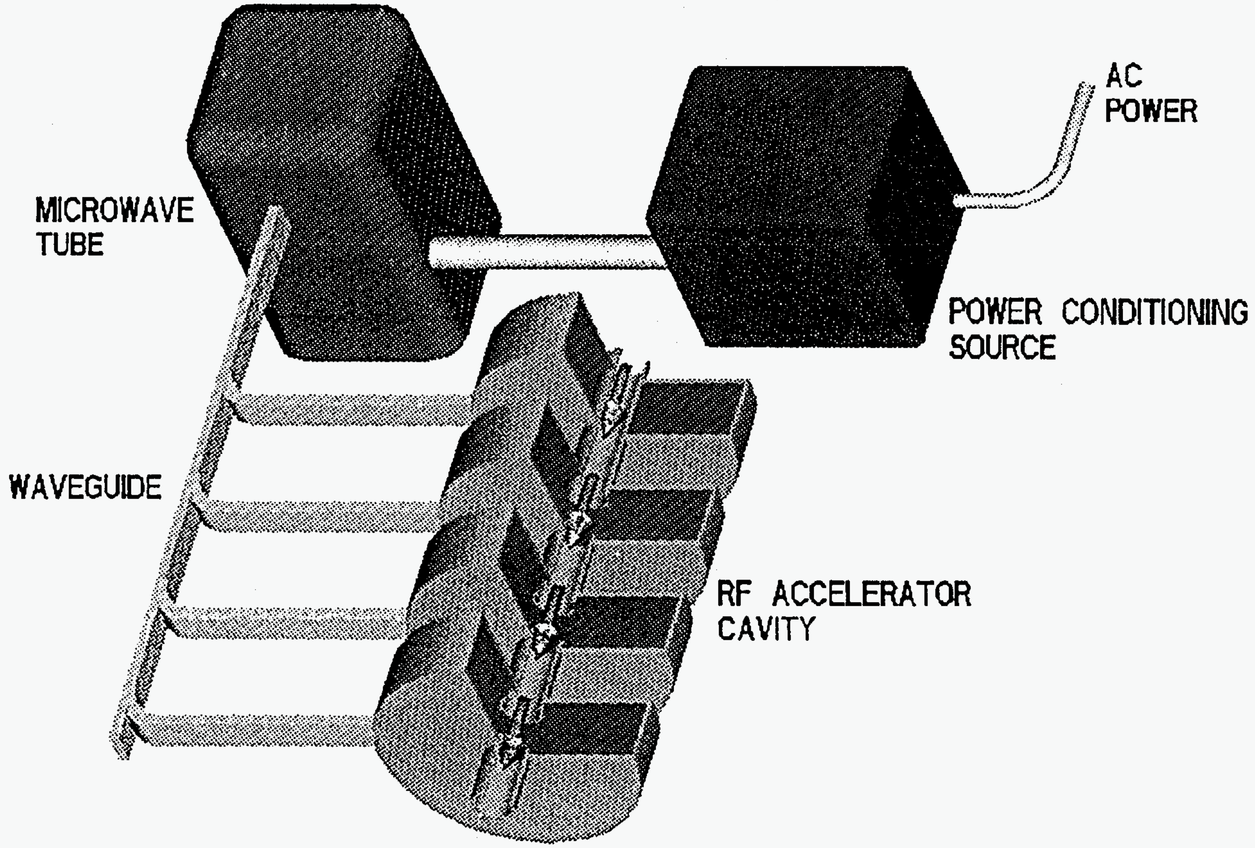
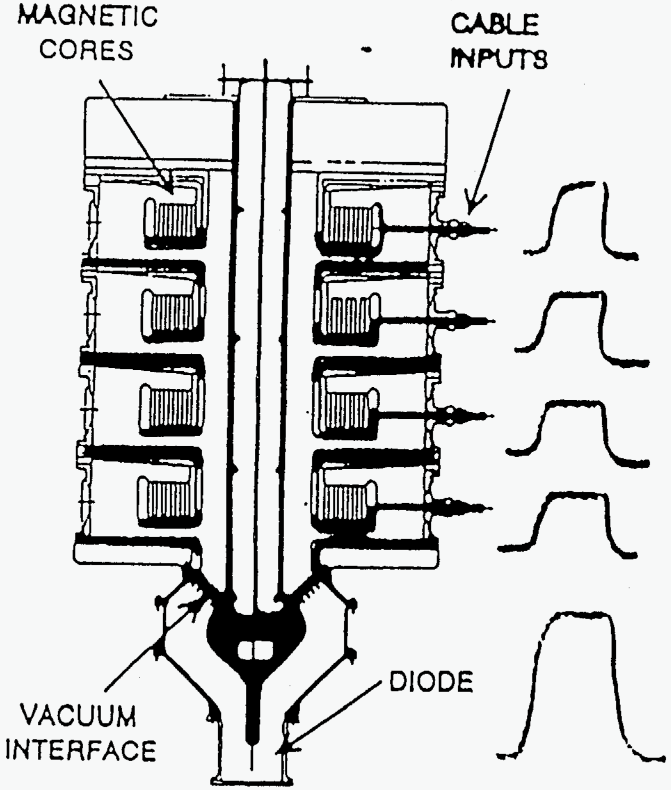
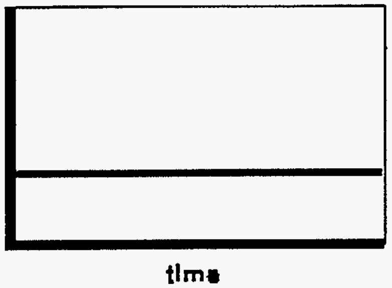


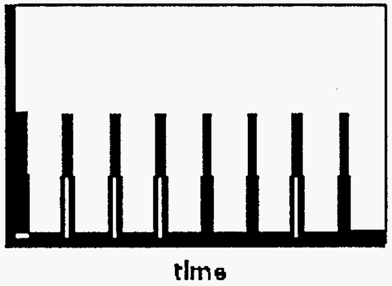
Figure 8

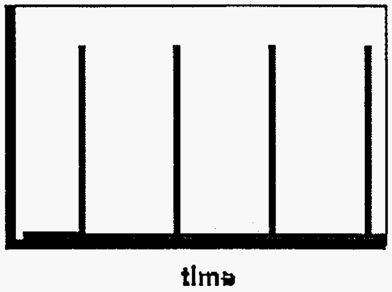


Voltage pulses added on a center conductor

Figure 9







	Cobalt-60	RF Linac	RHEPP
Mode:	continuous beam	13 μs pulses at 450 Hz	60 ns pulses at 120 Hz
Peak rate:	10 - 30 Gy/s	10^6 Gy/s	$6x10^{10}$ Gy/s
Avg rate:	10 - 30 Gy/s	5000 Gy/s	$4x10^5$ Gy/s
Power:	15 kW/MCI	10 kW	350 kW