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FOOD PROCESSING WITH ELECTRICALLY GENERATED PHOTON IRRADIATION

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ABSTRACT

Economic constraints require that a food irradiation processing facility have a throughput of approximately 1 MGy Ton/Day, requiring 3 MegaCuries of Cobalt 60 at each site. This requirement means that the total world amount of Cobalt 60 would have to be increased by about 60% just to handle the California almond and raisin crop during peak season. It is doubtful that public opinion would allow the increased distribution of radioactive isotopes, with the resultant burden upon the transportation networks, as a price to be paid to eat radiated food.

Electric sources have characteristics which allow the production of a more penetrating, uniform and efficient radiation than is available from nuclear isotopes. The heart of the electric radiation source is the electron accelerator. At present, there are no accelerators commercially available which can meet the requirements for food irradiation processing. However, the Department of Defense funded beam weapons programs have provided a very promising accelerator technology at the Lawrence Livermore National Laboratory. If this technology were to be commercialized, it appears that the required accelerators would be available for $1.5 million apiece, and quite possibly for less than this amount.

A conceptual design for a portable electric food irradiation processing machine is presented and analyzed for cost assuming the required accelerators are available for $1.5 million each. It is shown that food can be processed to 1 kGy for a price of $5.98/ton.

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FOOD PROCESSING WITH ELECTRICALLY GENERATED PHOTON RADIATION

Why Electric?

Food irradiation technology promises to have an impact upon the consumer as significant as the technologies of canning and refrigeration. For more than 20 years now, this technology has been almost upon us, yet it has never captured a meaningful portion of the food market. In order to do so, large numbers of economically viable food irradiation processing machines would have to be distributed almost everywhere. This can only be done with electric radiation sources.

Economic Viability.

In order to be profitable, the irradiation machine would have to process approximately 1 MGy Ton/Day and at least one such machine would be placed at each food packaging center. Each machine would process 1000 tons of food per day at the maximum dose of 1 kGy allowed by the FDA on most foods.

Cobalt 60

If these machines were powered with Co^{60}, then approximately 3 MCi of this isotope would be required at each site. Sixteen such machines would be required just to handle the California almond and raisin crop, which is 16,000 tons/day, during peak season around October 1.[1] The total amount of Co^{60} in use throughout the world today is approximately 75-80 MCi.[2]

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1 Almond Board of California.

2 Atomic Energy of Canada Radiochemical Company, Commercial Products Division.

Therefore, the world use of Co^{60} would have to be increased by about 60% just to handle the California almond and raisin crops.

The decay rate of Co^{60} is slightly greater than 12¼% per year. Therefore, each plant will take delivery of 367 kCi on an annual basis. The transportation networks would be burdened with large amounts of active isotope distributed throughout major rail and trucking routes. The potential for accidents or sabotage would be too great a price for the public to pay in order to eat radiated food. Economic viability demands that the public prefer to eat irradiation processed food instead of the food available today.

Construction of these processing sites would place an even more severe burden upon the transportation network.

<u>How Does an Electric Source Work</u>

An electrically powered radiation source produces radiation by aiming a beam of high energy electrons so they collide with a dense metal plate as shown in Figure 1. The electrons come from an electric source such as an electron accelerator. The processing radiation is produced within the plate when the electrons are stopped. This radiation is called x-ray or bremsstrahlung radiation, and it is the same type of electromagnetic radiation as the gamma rays which are emitted by Co^{60}.

There are differences between bremsstrahlung and gamma radiation which enable the electric source to be tailored specifically to the job at hand.

Energy Spectrum

The energy spectrum of a radiation source is important because it determines the penetrability of the radiation through the medium being radiated. Figure 2 shows the mean free path through water for electromagnetic radiation in the MeV energy part of the spectrum. The higher the energy, the greater is the radiation penetration through water. High energy radiation sources with their deeper penetration are needed to process thick samples of food with a reasonably uniform dose throughout the processed volume.

The energy of the radiation is not to be confused with its intensity. An intense, low energy radiation source would overprocess the surface of the food while underprocessing its interior.

A bremsstrahlung source produces a spectrum of electromagnetic radiation over a broad energy band with energies bounded between zero at the low end and the energy of the electron beam at the high end. A 5 MeV electron beam produces electromagnetic radiation in a broad spectrum out to a maximum energy of 5 MeV as is shown in Figure 3. This spectrum is entirely within the FDA guidelines of 1981. An isotope source, on the other hand, is monoenergetic and emits gamma radiation at an energy which is determined by the structure of the nucleus. Cobalt emits at 1.3 MeV, and cesium emits at 0.67 MeV.

It is possible to filter the bremsstrahlung radiation to preferentially remove the lower energy components of the spectrum. This makes the radiation more penetrating, but it lowers the intensity. This technique is called hardening the radiation. A bremsstrahlung spectrum which has been hardened with 1/4" lead is shown in Figure 3 and is compared with the unhardened spectrum. If the radiation is inexpensive to produce, then it would be beneficial to harden it to achieve a more even dose throughout the irradiated sample. Monoenergetic radiation produced by cobalt and cesium cannot be hardened.

Forward Scattering Direction

Nuclear radiation is emitted in all directions isotropically, unlike high energy bremsstrahlung radiation which is emitted preferentially in the direction of the electron beam which produces it. This forward scattering property of high energy bremsstrahlung results in most of the produced radiation being emitted out of the forward facing side of the bremsstrahlung plates and a corresponding lower reduction in intensity with distance from the plates. If the plates were made of Co^{60}, then equal amounts of radiation would be emitted from both sides of the plates resulting in a less efficient photon usage. Also, the intensity of the radiation field would be less uniform throughout the irradiation volume with the isotope source. The forward scattering property of the bremsstrahlung radiation, in addition to the more penetrating broad band spectrum, helps to achieve a more uniform dose through the bulk of the processed sample.

Design For Electric Processor

A conceptual design for an electric food irradiation processor is shown in Figure 4. The design consists of two square bremsstrahlung converter plates, each 4' on a side. The plates are placed parallel to each other and are separated by 2' making a radiation volume of dimensions up to 4'x4'x2'. A conveyor belt carries packages between the plates.

The electrons are supplied by two identical electron accelerators which have output energies of 5 MeV. Each of these accelerators would have to supply an electron beam power of approximately 140 kW in order to process 1 MGy Ton within a 24-hour working day.

Electromagnets are placed between the outputs of the accelerators and the rear of the bremsstrahlung plates. These devices control the electron beam sweep over the rear of the plates and are used to control the shape of the irradiation field between the plates. Various size boxes can be accommodated with no loss in photon efficiency. The radiation field is mainly confined to the volume between the plates, and the radiation intensity within this volume is more uniform than can be achieved with isotope sources due to the harder spectrum and to the forward scattering property of the bremsstrahlung.

Performance of the Conceptual Design

The performance of the bremsstrahlung food processor is considered with respect to 4'x4'x2' boxes filled with food of average density, 0.75. A box of this size will contain 3/4 ton of food, and a processing time of 65 seconds is required to deposit a dose of 1 kGy at the center of the box. This is equivalent to a throughput of greater than 1 MGy Ton/Day if the machine operates on a 24-hour basis.

Uniformity of Dose

A higher dose of radiation is deposited at the 1/2' depth than is deposited at the center of the box due to lack of perfect uniformity. The uniformity ratio of dose at the 1/2' depth to dose at the center of the box is 1.25 with the bremsstrahlung source. The radiation can be hardened with 1/4" thick lead filters to improve this ratio to 1.19, but this will lower the throughput from 1 MGy Ton/Day to 0.63 MGy Ton/Day. By comparison, the uniformity ratio achievable with plates made of Co^{60} is 1.93, due mainly to the lower energy, less penetrating radiation produced by this isotope. Cesium is even worse with a uniformity ratio of 2.4.

Portability

The electron accelerators used in the conceptual design each have a length of approximately 15' thereby allowing the food processor to fit within a standard 48'x102" trailer as illustrated in Figure 5. This type of design would allow a much more flexible use of the irradiation processor since the machine could be transported to simple underground, earth-shielded centers as shown in Figure 6. Portability of operation is not feasible unless the radiation is produced electrically because an isotope source must be heavily shielded at all times while an electric source can be turned off like a light bulb.

Operating Parameters

A portable food irradiation processing machine with a capacity of 1 MGy Ton/Day will require electric power to operate the electron accelerators, electromagnetic beam sweeps, assorted vacuum pumps and other related equipment. The total power consumption while operating at full load is approximately 750 kW.

This power can be supplied by an external 750 kW diesel generator which is mounted in a separate 48' trailer and consumes 55 gallons of fuel per hour while operating at full load. The entire generator unit is a standard item and is available for a purchase price of less than $140,000.[3]

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[3] Clemintina Equipment Rentals, San Leandro, California.

The metal bremsstrahlung plates will require water cooling during operation to remove the heat build-up caused by continuous electron bombardment from the rear. This can be accomplished by a water flow through channels within the plate and has the added advantage of providing process hot water as a bi-product of the operation. The heat removal rate at full capacity operation is 955,000 BTU/hr and is equivalent to 21 gallons of water per minute heated from 55 degrees F to 145 degrees F. If this water were heated in a gas fired hot water heater at 75% efficiency, the heater would consume almost 13 therms of gas per hour.

The general operating parameters for the described commercially viable food irradiation machine are summarized in Table I.

Food Irradiation Processing Costs

The heart of the electric radiation processing machine is the electron accelerator which must supply a reliable, continuous beam of electrons at reasonable cost with an annual up time of 80%. Unfortunately, there is no commercially available accelerator on the market today which can meet the requirements outlined in this report.

Accelerator technology at the University of California Lawrence Livermore National Laboratory has evolved to a maturity at which a commercial accelerator design, which meets these requirements, may well be possible. This possibility has developed as an outgrowth of Department of Defense funded beam weapons programs.

The initial costs for commercializing this technology are uncertain. The required first steps in this direction would be to design and build a test bed accelerator which is specifically engineered for mass production to process food. The construction of such a device would provide a much better understanding of eventual costs as well as providing a dedicated machine for efficacy studies with the 5 MeV bremsstrahlung radiation.

It is reasonable to assume that the purchase price for an operational accelerator will drop as more units are built, unlike the cost of Co^{60} which will increase with increased demand. It is not at all unreasonable to assume that the required accelerator would be available for $1.5 million once the technology is commercialized, and, quite possibly, the cost may be considerably less than this amount.

The capital expenditures and operating costs for the described irradiation processor are summarized in Table II.

The operating cost of $5.98 per ton processed to 1 kGy is similar to current fumigation operating costs. The 1 kGy dose is the maximum allowable exposure considered by the FDA for most foods and is generally greater than the fumigant replacement dose.

It is not clear how the commercial development of this technology will be financed. The taxpayer, who has paid the bill thus far, should be the primary beneficiary of its outgrowth. The University of California, with its ties to the major technological and agricultural centers of the free world is an excellent place in which this development can occur.

TABLE I

PEAK CAPACITIES FOR ELECTRIC IRRADIATION UNIT

Throughput	1 MGy Ton/Day 24 Hr. operation
Size of radiation field	Adjustable up to 4'x4'x2'
Uniformity of radiation field 1/2' to 1' depth dose ratios in density 0.75 medium	 1.25 normal operation 1.19 hardened with 1/4" lead at reduced throughput of 0.63 MGy Ton/Day
Accelerator (2 required)	Each, 140 kW, 5 MeV electron beam CW operation
Unit sized to fit standard 48' trailer	
Unit input power	750 kW
Coolant requirements to bremsstrahlung plates	21 gal/min water 55 degrees F input 145 degrees F output 955,000 BTU/hr
Input power may be provided by diesel generator in separate 48' trailer	
Generator fuel consumption	55 gal/hr

TABLE II

COST SUMMARY - BREMSSTRAHLUNG PROCESSOR

Initial Capital Expenditure	
Two accelerators @ $1.5 million	$3,000,000
Magnets, pumps and other related equipment	500,000
48' trailer and tractor	110,000
750 kW diesel generator with separate 48' trailer	140,000
Total Expenditure	$3,750,000
Annual Operating Expenses	
Fixed Expenses	
Capital expenditure payback at 15% 15-year financing	$ 630,000
Maintenance, insurance, overhead 15% of capital investment	563,000
Total Fixed Expense	$1,193,000
Variable Expenses (Assumed 80% Uptime)	
Diesel fuel @ $1.50/gal	$ 579,000
Water coolant @ $1.00/1000 gal	9,000
Heat recovery from 145 degree F water gas equivalent @ 40 cents/therm	(35,000)
Total Variable Expense	$ 553,000
Total Annual Expense	$1,746,000
Total Annual Throughput	292 MGy Tons
Total Unit Cost*	$5980 per MGy Ton

*Total Unit Cost is $5.98 Per 1 kGy Ton
1 kGy is Max FDA Dose Allowed on Most Foods.

FIGURE CAPTIONS

Figure 1

Principle of Operation for the Production of Radiation With Electric Power.

Figure 2

Penetrability of Radiation Through Water as a Function of the Radiation Energy.

Figure 3

Bremsstrahlung Spectrum of Energies Produced By 5 MeV Electron Beam; With and Without 1/4" Thick Lead Filter.

Figure 4

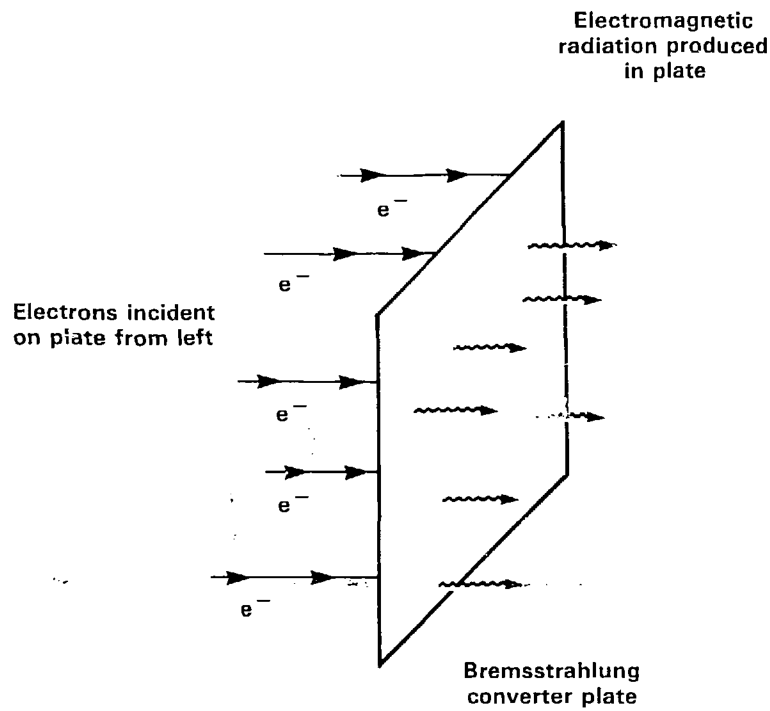
Conceptual Design For an Electric Food Irradiation Processor.

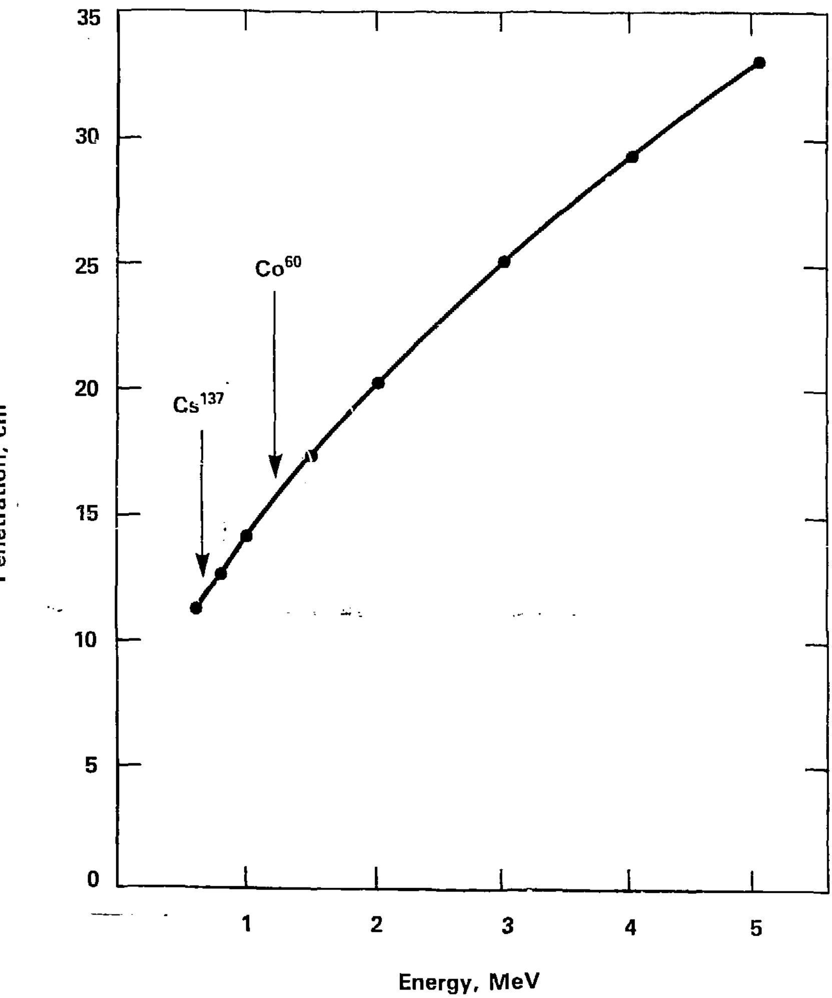
Figure 5

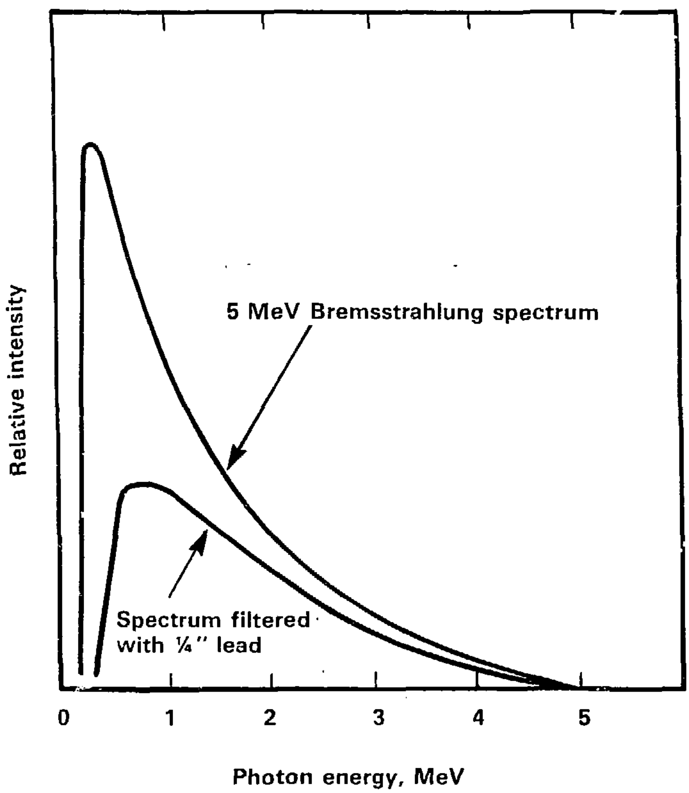
1 MGy Ton/Day Portable Electric Food Irradiation Processor.

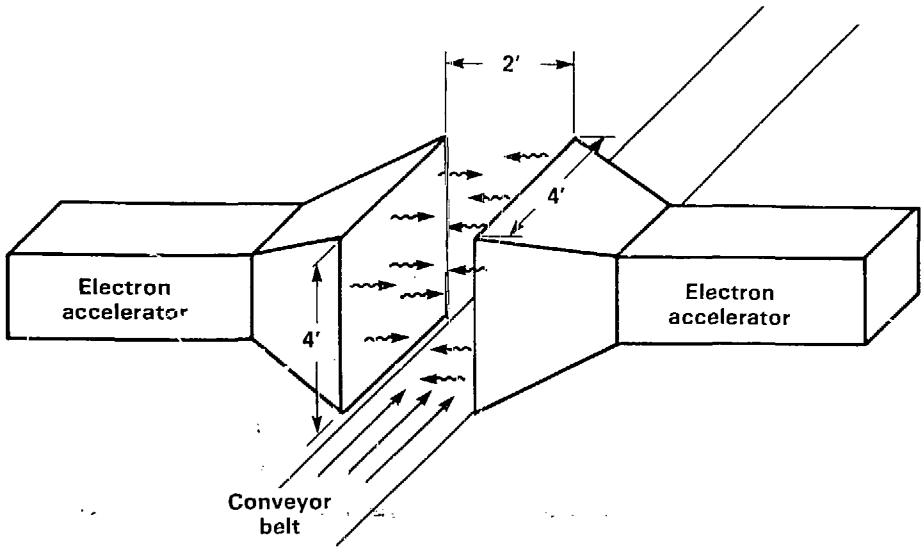
Figure 6

Portable Processor Within Underground Irradiation Site.


Electromagnetic radiation produced in plate
Electrons incident on plate from left
e⁻
e⁻
e⁻
e⁻
e⁻
Bremsstrahlung converter plate


Penetration, cm
35
30
25
20
15
10
5
0
Cs137
Co60
1
2
3
4
5
Energy, MeV


5 MeV Bremsstrahlung spectrum
Spectrum filtered with ¼" lead
Relative intensity
0
1
2
3
4
5
Photon energy, MeV


2′
4′
Electron
accelerator
4′
Electron
accelerator
Conveyor
belt