PHYSICAL ASPECTS OF X-RAY PROCESSING

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This paper reviews the physical aspects of processing products with high-energy X-rays (bremsstrahlung). This form of ionizing radiation is emitted when energetic electrons strike any material. The emission efficiency increases with the kinetic energy of the incident electrons and the atomic number of the target material. Tantalum, tungsten and gold are practical materials for high-efficiency, high-power X-ray targets. The broad photon energy spectrum extends up to the incident electron energy. With electron energies greater than 2 MeV, the maximum X-ray intensity is in the direction of the electron beam, and the angular dispersion decreases as the electron energy increases. In contrast to the isotropic emission of gamma rays from radioactive nuclides, the narrow beam of high-energy X-rays facilitates treating pallet loads of products. This reduces product handling and allows quick changes in product density or absorbed dose. With electron energies greater than 3 MeV, the X-ray penetration in low-density materials is greater than that from a large-area, uncollimated source of gamma rays from ^{60}Co. Photo-neutron emission from X-ray targets can be avoided by limiting the maximum electron energy to 6.2 MeV, 7.6 MeV and 8.1 MeV for tungsten, tantalum and gold, respectively.

1. INTRODUCTION

Radiation processing involves the treatment of materials and commercial products with ionizing radiation to modify their physical, chemical or biological properties. Such effects can increase their usefulness and value, or reduce their impact on the environment. Ongoing applications are the curing or polymerization of inks, coatings and adhesives on paper, plastic and metal products, the crosslinking or vulcanization of plastic and rubber products, such as insulated wire, heat-shrinkable packaging film, plastic tubing and pipe, automobile tire components and molded parts, and the sterilization of packaging materials and of single-use medical devices. Emerging applications are the curing of fiber-reinforced composite plastic materials, the preservation and pasteurization of foods and the treatment of toxic gaseous, liquid and solid waste materials.

Accelerated electrons, X-rays emitted by energetic electrons, and gamma rays emitted by radioactive nuclides are being used for these purposes. All of these energy sources can produce similar chemical reactions by ejecting atomic electrons within irradiated materials. The choice of radiation source for a particular application is determined by practical considerations, such as absorbed dose, dose uniformity, dose rate, material thickness, density and shape, processing rate, and economics.

High-energy, high-power electron beams can process thin materials at very high line speeds, but their depth of penetration is limited to a few centimeters. Larger objects, such as packages of medical devices and foods, are usually irradiated with gamma rays from encapsulated cobalt-60 sources, which can irradiate more than 30 cm (12 in) of unit-density materials. X-rays with maximum energies greater than 3 MeV are even more penetrating than gamma rays from Co-60, but previously their use has been inhibited by lower processing rates and higher costs. Recent increases in the price of Co-60 sources and increases in the beam power capabilities of industrial electron accelerators have improved the prospects for X-ray processing. The basic characteristics of this technology are described briefly in this paper.

2. X-RAY PROPERTIES

Broad-spectrum X-rays, also called bremsstrahlung or braking radiation, are produced when accelerated electrons are deflected by atomic nuclei. The photon energy spectrum extends up to the maximum energy of the incident electrons, but the average photon energy from a 5 MeV electron beam is about 0.75 MeV and the most probably energy is about 0.3 MeV. The X-ray intensity increases with the energy of the incident electrons and with the atomic number of the target material.

High-density metals, such as tantalum, tungsten and gold, are suitable target materials. However, tantalum is preferable for large targets. It is not as hard to work as tungsten and it is much less expensive than gold. The optimum target thickness for maximum X-ray yield is

about 40% of the maximum electron range in that material. Increasing the thickness reduces the yield by internal absorption. The efficiency for converting electron beam power to X-ray power emitted in the direction of the electron beam is about 8% at 5 MeV, 12% at 7.5 MeV and 16% at 10 MeV.

In contrast to the isotropic emission of gamma rays from radioactive sources, high-energy X-rays are concentrated in the direction of the incident electron beam, and the dispersion decreases as the maximum energy increases. At 7.5 MeV, the divergent angle for half intensity is only about 15 degrees. This characteristic increases the penetration and the power utilization efficiency of X-rays in comparison to ^{60}Co gamma rays. It also allows the treatment of single pallet loads, which reduces the transit time through the treatment facility, and facilitates changing operating conditions for products with different densities and absorbed dose requirements.

The X-ray attenuation curves are nearly exponential vs depth from the surface of the irradiated material. To obtain the maximum X-ray power utilization efficiency when materials with low atomic numbers are treated from opposite sides, the optimum thickness should be about 34 g/cm^2 (34 cm in unit density material) at 5 MeV, 38 g/cm^2 at 7.5 MeV and 43 g/cm^2 at 10 MeV. The practical value of X-ray power utilization efficiency is calculated by multiplying the minimum dose in the middle by the total mass and dividing by the emitted X-ray power. Thicknesses less than the optimum value reduce the power utilization efficiency because of increased X-ray transmission, while thicknesses greater than the optimum value reduce the minimum dose more than the mass increases, so the power utilization efficiency decreases[1-4].

The maximum X-ray energy should be limited to 7.5 MeV to avoid inducing radioactivity in a tantalulm target and in the treated materials. The United States Food and Drug Administration has recently increased the X-ray energy limit from 5.0 MeV to 7.5 MeV for food irradiation in response to a petition submitted by IBA[5-8].

3. HIGH-POWER ELECTRON ACCELERATORS

Dynamitron™ accelerators use a cascaded rectifier system to generate high-voltage dc power. All of the rectifiers are energized in parallel via the capacitive coupling between a pair of semi-cylindrical electrodes and an array of semi-circular corona rings, which are connected to the rectifiers. These electrodes are connected to an iron-free, high-Q inductor, which forms a resonant circuit with the electrode capacitance. This ac circuit is energized with a self-tuning triode oscillator at a frequency of about 100 kHz. High-voltage insulation is provided with sulfur hexafluoride gas at a pressure of about 6 to 7 atm. See Fig. 1. The high-voltage terminal is connected to an evacuated, multi-stage acceleration tube to produce a high-energy, high-power electron beam. The electrons are emitted by a directly-heated, thoriated tungsten filament. More than 200 Dynamitrons have been made with electron energies from 0.4 MeV to 5 MeV and with electron beam powers up to 300 kW[9-12].

Rhodotron™ accelerators use a single, large, coaxial resonant cavity to accelerate electrons without requiring a high-voltage power supply. The electrons gain 1 MeV of energy per pass through the cavity. Higher energies are obtained via multiple passes through the same cavity. The rf power is generated with a self-tuning tetrode amplifier at a frequency of 107.5 MHz. See Fig. 2. Continuous wave (cw) excitation produces an electron beam, which is bunched at the resonant frequency. The absence of macro-bunching reduces the peak beam current, in comparison to a microwave linear accelerator (linac). The very short time intervals (about 9 ns) between beam bunches allows the beam to be scanned rapidly without producing gaps on a moving product conveyor. More than 20 Rhodotrons have been made with electron energies from 5 MeV to 10 MeV and with electron beam powers up to 700 kW[13-16].

4. X-RAY PROCESSING FACILITIES

There are several industrial irradiation facilities that can provide both electron beam and X-ray processing. There are three such facilities in Japan, one in Germany, one in France and three in the USA. One of the Japanese installations has a 5 MeV, 150 kW Cockcroft Walton accelerator[17]. Another has a Dynamitron rated for 5 MeV, 200 kW[18-19] and the third has a Rhodotron with two beam lines rated for 135 kW at 5 MeV and for 200 kW at 10 MeV[20]. The German installation also has a similar Rhodotron[21-22]. The French facility is equipped with a pulsed S-band microwave linac rated for 20 kW of electron beam power at 10 MeV[23]. One of the USA facilities has an L-band microwave linac rated for 100 kW at 5 MeV[24]. Another has a Dynamitron rated for 90 kW at 3 MeV[25]. The third USA facility has a Rhodotron with three beam lines for 5 MeV, 7 MeV and 10 MeV electrons. The two lower-energy lines are equipped with X-ray targets[26].

The USA Rhodotron facility was originally built to irradiate plastic materials and products with 10 MeV electrons and packages of food with 5 MeV and 7 MeV X-rays. Following the anthrax attack in 2002, the U.S. Postal Service acquired exclusive use of this facility for sterilizing mail addressed to critical government offices in Washington, D.C. Flat mail is being irradiated with 10 MeV electrons and packages of mail are being irradiated with 5 MeV X-rays.

5. X-RAY IRRADIATION METHODS

Rotational Pallet System

A unique concept for irradiating large pallet loads of dense materials, such as fresh fruits and meats, is called the Palletron™. The pallet is placed on a turntable in front of an elongated X-ray target and rotated while being irradiated from the side. For all densities between 0.1 and 0.8 g/cm^3, the dose uniformity ratio (DUR) can be kept below 1.5. For densities above 0.40 g/cm^3, thick steel collimators are placed on each side of the X-ray beam. These collimators limit the divergence of the beam, thereby reducing the dose near the outside of the pallet, but they do not reduce the minimum dose in the middle of the pallet. The optimum collimator spacing depends on the density of the product load. Monte Carlo calculations and experimental measurements have confirmed the validity of this concept. Increasing the X-ray energy from 5 MeV to 7.5 MeV substantially reduces the treatment time and increases the throughput rate for the same electron beam power. See Fig. 3.

An extension of the rotational method involves placing 4 pallets on one turntable. See Fig. 4. This increases the X-ray power utilization efficiency for low-density products by reducing the transmission losses. Still further improvements in X-ray power utilization efficiency and dose uniformity can be obtained by placing 8 pallets on one turntable. With this method, 4 pallets are placed on the lower level and 4 more are placed on the upper level. Then these groups are exchanged and irradiated for a second time. This procedure compensates for the lower doses at the top and bottom of the stack when only one level is used. The DUR can be kept below 2.0 for densities below 0.3 g/cm^3 (Refs. 27-32).

Two-Sided Pallet System

For treatment from opposite sides with two continuous passes in front of the X-ray target, the thickness must be reduced as the density increases. In order to keep the dose uniformity ratio below 2.0, the thickness must not exceed 60, 80, 115 and 175 cm with densities of 0.8, 0.6, 0.4 and 0.2 g/cm^3, respectively. With product densities below 0.4 g/cm^3, full pallets can be used, and the throughput rate can be increased substantially with three rows of pallets passing in front of the X-ray target to reduce the transmission losses. X-ray power utilization efficiency reaches a maximum value of about 47% with a product density of 0.4 g/cm^3 and three rows of pallets[32].

6. X-RAY AND COBALT-60 COST COMPARISONS

Assuming that the capital costs for land, building, radiation shielding, product handling systems, etc., are similar for industrial X-ray and gamma-ray processing facilities, the main differences are the prices of X-ray generators and ^{60}Co sources with equivalent output power and throughput capacity. ^{60}Co emits two coincident gamma rays with energies of 1.17 and 1.33 MeV or a total of 2.50 MeV per disintegration. The emitted gamma-ray power from 1.0 megacurie of Co-60 is 14.8 kW, but the external emission from encapsulated sources is 13.5 kW, because of 9% internal absorption. The power utilization efficiency of a low-divergence 5 MeV X-ray beam is about 20% higher than that of the isotropic gamma rays from ^{60}Co sources, so the emitted X-ray power can be multiplied by 1.2 to obtain the equivalent gamma-ray power[3].

For example, the emission efficiency of 5 MeV X-rays is about 8.0%. So, a 5 MeV, 300 kW electron beam emits 24 kW of X-rays in the forward direction. Then the equivalent ^{60}Co source loading is 1.2 x 24 / 13.5 = 2.13 MCi. At the present price of about $2 USA per curie, this is worth $4.27 million USA. The budgetary price of a Dynamitron with this X-ray capability is about $3.5 million USA, which is 82% of the equivalent Co-60 price.

The Rhodotron TT000, which can provide 100 mA of electron beam current at 5 MeV, 6 MeV and 7 MeV, can generate 40.0 kW, 57.6 kW and 78.4 kW of X-rays with emission efficiencies of about 8.0%, 9.6% and 11.2% at these energies. The ^{60}Co equivalents are 3.56 MCi, 5.12 MCi and 6.97 MCi, respectively. At $2 USA per curie, these source loadings are worth $7.11, $10.24 and $13.94 million USA, respectively. The budgetary price of a Rhodotron with these X-ray capabilities is about $7.0 million USA, which is nearly the same as the equivalent ^{60}Co price at 5 MeV, but substantially less than the ^{60}Co prices at 6 MeV and 7 MeV. See Table 1.

Assuming that the management, labor and overhead costs are similar for industrial X-ray and gamma-ray processing facilities, the main differences in operating costs are the electricity for the X-ray generator and replenishing the radioactive decay of the equivalent ^{60}Co sources. If the input power is conservatively estimated to be twice the electron beam power, then the annual cost of electricity for a 5 MeV, 300 kW Dynamitron at $0.10 per kilowatt hour, assuming 8,000 hours per year, would be 2 x 300 x 8,000 x 0.10 = $480,000 USA. ^{60}Co has a half life of 5.27 years, so the decay rate is 12.34% per year. The annual replenishment for 2.13 MCi is 0.263 MCi, which is worth $526,000 USA at $2 USA per curie. Therefore, the Dynamitron's electricity cost is 91% of the ^{60}Co replenishment cost.

Similar estimations for the Rhodotron TT1000 give electrical costs of $800,000, $960,000 and $1,120,000 USA for 500 kW, 600 kW and 700 kW of electron beam power, respectively. The equivalent ^{60}Co replenishment costs are $879,000, $1,264,000 and $1,720,000, respectively. Therefore, the Rhodotron's electricity costs are 91%, 76% and 65% of the ^{60}Co replenishment costs, respectively. The more favorable comparisons at higher electron energies are the results of the increases in X-ray emission efficiency. See Table 2.

7. CONCLUSIONS

Various X-ray systems have been evaluated using Monte Carlo simulations. Pallet irradiation systems have been shown to be practical for high-density food products and low-density medical devices. The rotational Palletron is a low dose-uniformity-ratio (DUR) system for medium to high-density products. The rotational batch system is a simple and compact method designed for in-house irradiation. The multiple-row system is a high-throughput method that is advantageous for low to medium-density products.

The physical properties of high-energy X-rays (bremsstrahlung) are well known. The high power ratings of modern electron accelerators compensate for the low efficiency of X-ray generation. The practicability of radiation processing with high-energy X-rays has already been demonstrated in industrial facilities. Capital costs for high-power X-ray generators are lower than for ^{60}Co sources with source loadings greater than 2 MCi. The X-ray operating costs for electricity at 5 MeV are comparable to the replenishment costs for radioactive decay of ^{60}Co, but substantially lower at 6 MeV and 7 MeV.

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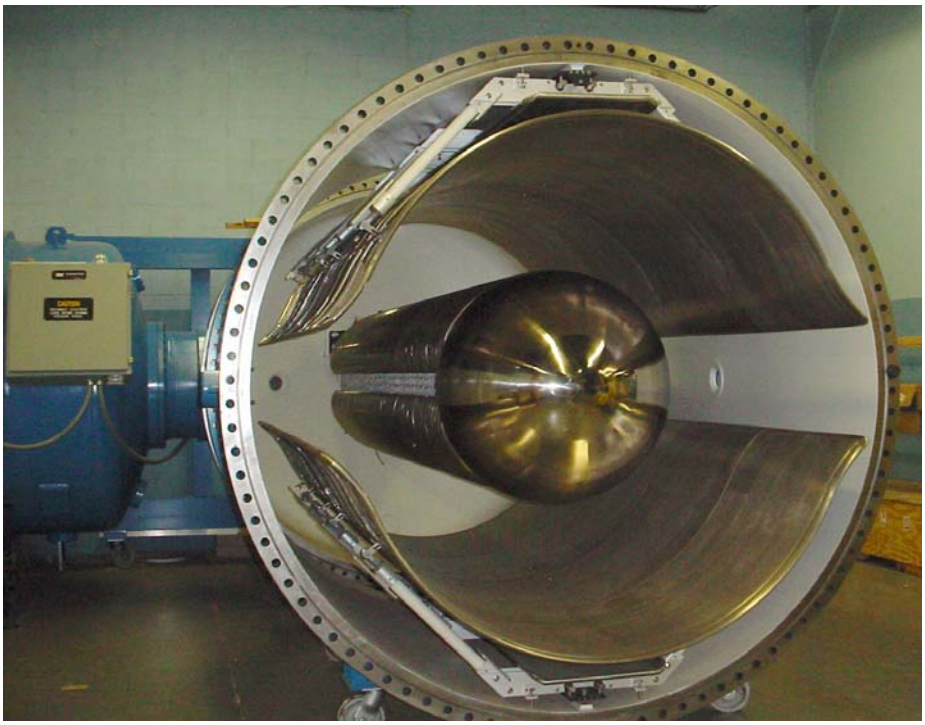

Fig. 1. 5 MeV, 300 kW RDI Dynamitron™ Electron Accelerator

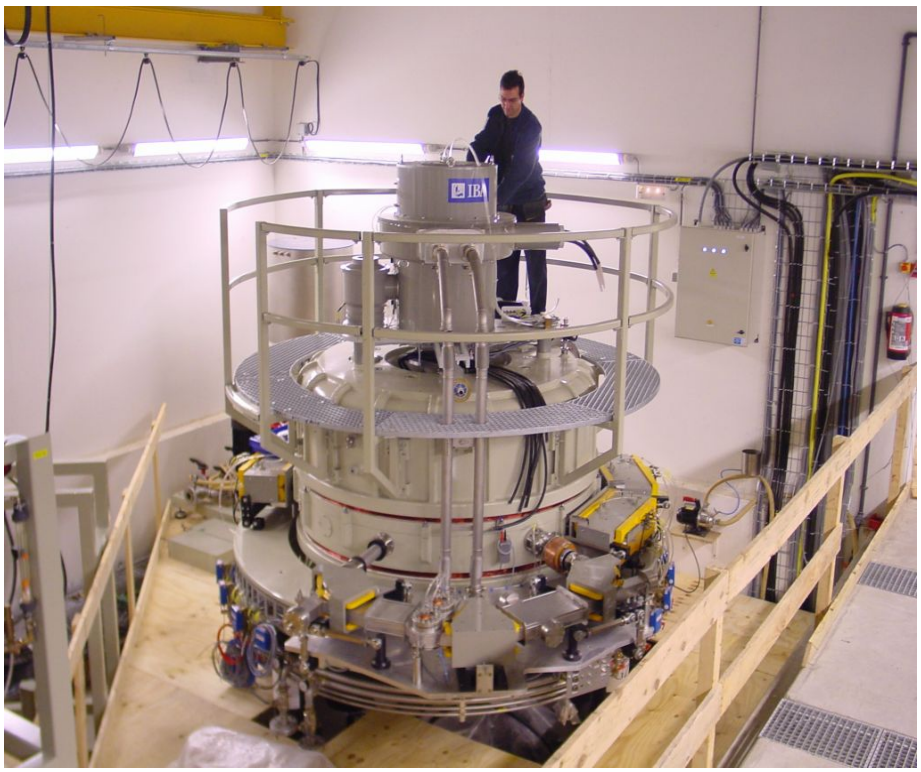

Fig. 2. 7 MeV, 700 kW IBA Rhodotron™ Electron Accelerator

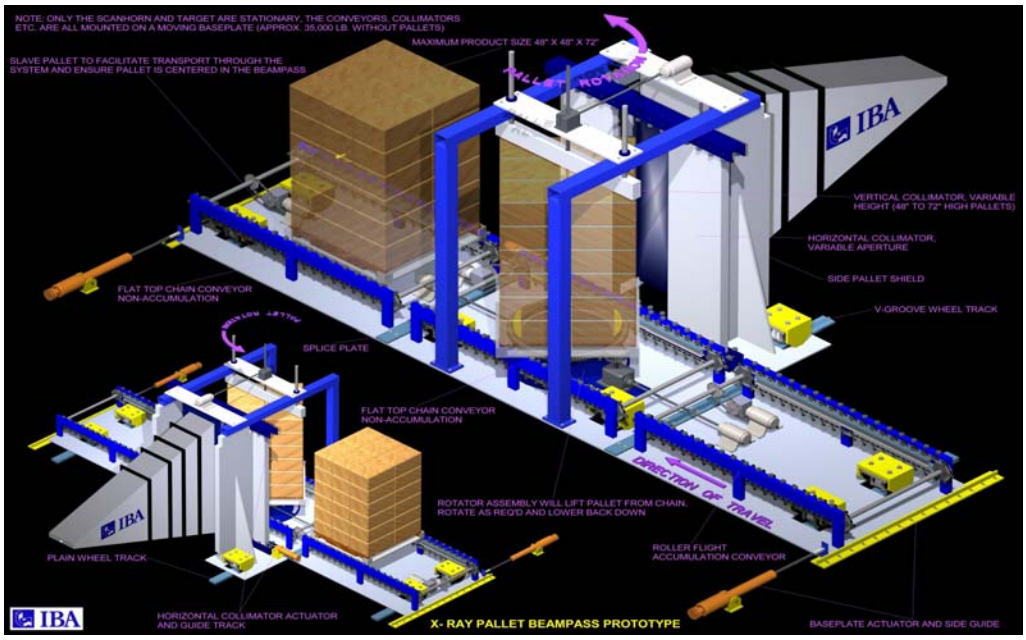

Fig. 3. Palletron™ Rotational X-Ray Processing System

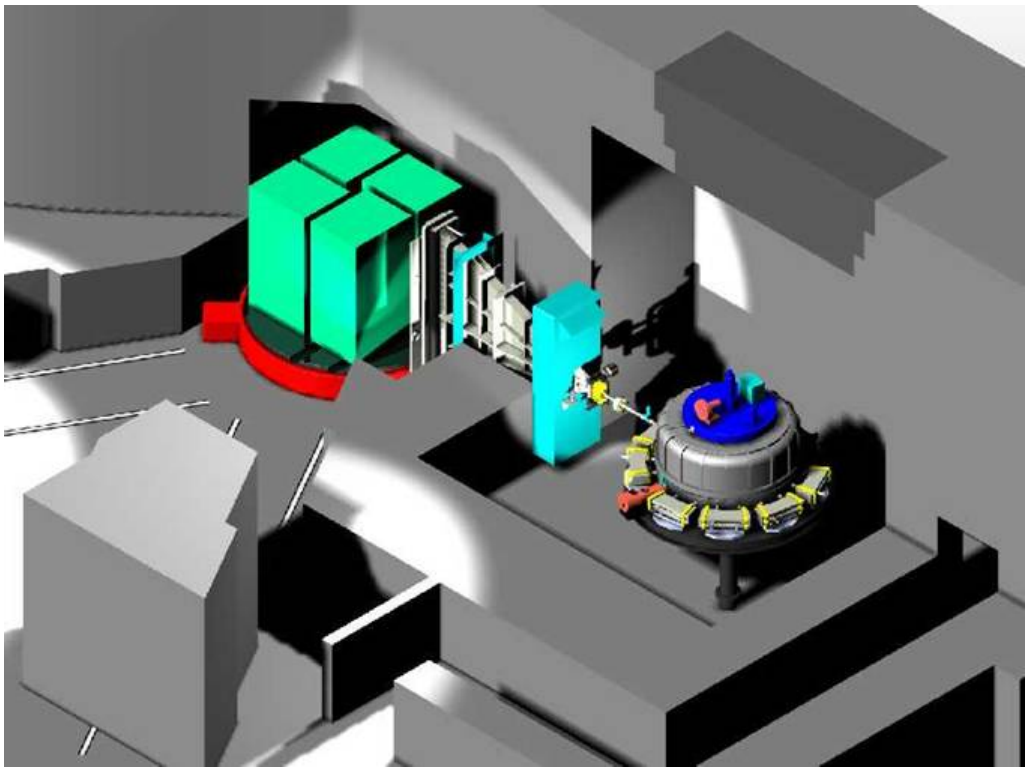

Fig. 4. Four-Pallet Rotational X-Ray Processing System

TABLE 1. Budgetary Price Comparisons of X-Rays and ^{60}Co Gamma Rays

BUDGETARY PRICE COMPARISONS OF X-RAYS AND CO-60 GAMMA RAYS

ELECTRON ENERGY (MeV)	E-BEAM POWER (kW)	X-RAY EMISSION (%)	X-RAY POWER (kW)	X-RAY PRICE (M $US)	CO-60 SOURCE *(MCi)	CO-60 PRICE *(M $US)
DYNAMITRON						
5.0	300	8.0	24.0	3.75	2.13	4.27
RHODOTRON						
5.0	500	8.0	40.0	7.57	3.56	7.11
6.0	600	9.6	57.6	7.57	5.12	10.24
7.0	700	11.2	78.4	7.57	6.97	13.94

*CO-60 SOURCE LOADING IS BASED ON AN EMITTED POWER OF 13.5 kW/MCi AND MULTIPLIED BY 1.2 TO ACCOUNT FOR LOWER POWER ABSORPTION VS X-RAYS.
*CO-60 COST IS BASED ON A PRICE OF 2 $US/Ci.

TABLE 2. Comparisons of Power Costs for X-Rays and ^{60}Co Gamma Rays

COMPARISONS OF POWER COSTS FOR X-RAYS AND CO-60 GAMMA RAYS

ELECTRON ENERGY (MeV)	E-BEAM POWER (kW)	INPUT POWER (kW)	ANNUAL TIME (h)	X-RAY COST *(M $US)	CO-60 DECAY *(MCi)	CO-60 COST *(M $US)
DYNAMITRON						
5.0	300	600	8000	0.480	0.263	0.526
RHODOTRON						
5.0	500	1000	8000	0.800	0.439	0.879
6.0	600	1200	8000	0.960	0.632	1.264
7.0	700	1400	8000	1.120	0.860	1.720

*X-RAY POWER COST IS BASED ON AN AVERAGE RATE OF 0.1 $US/kWh.
*CO-60 DECAY RATE IS 12.34%/YEAR DUE TO A HALF LIFE OF 5.27 YEARS.
*CO-60 REPLENISHMENT COST IS BASED ON A PRICE OF 2 $US/Ci.