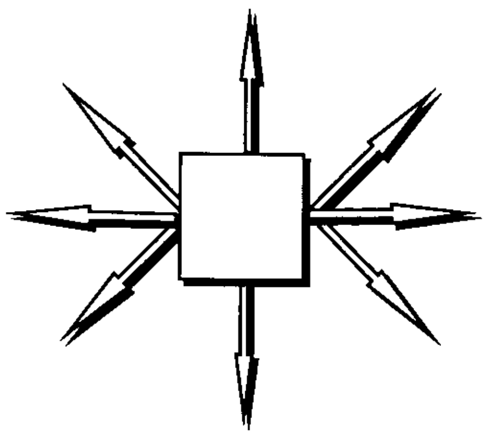
Industrial Irradiators for Radiation Processing

Radiation processing beacame a reality with the availability of particle accelerators and artificially produced radioactive sources (^{60}Co and ^{137}Cs)

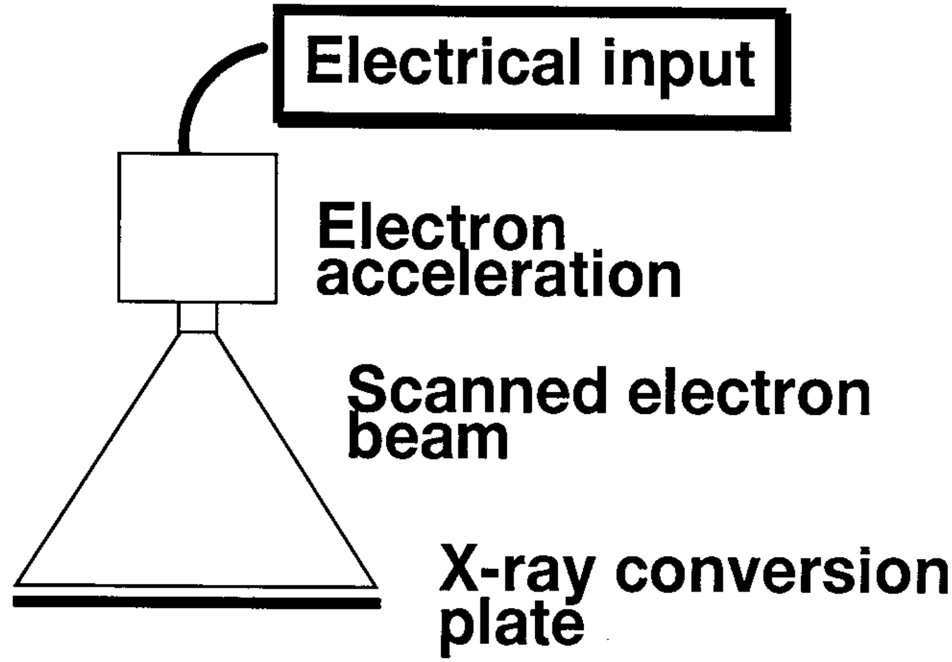
Industrial Irradiators

- Electron accelerators widely used, 0.1 to 10 MeV
- X-rays, mostly used in medical diagnostics and radiography; some used in radiation processing (3 to 10 MeV)
- Isotope sources; medical sterilization and food irradiation
- Heavy ion accelerators, mostly for ion implantation
- Synchrotrons, mostly for resist work
- Nuclear reactors, for producing radioisotopes

Radioisotope vs Electron Accelerator Source



^{60}Co or ^{137}Cs photon emission, continuous, in all directions



Electron or X-ray beam available when needed, in the desired direction

Components of an Irradiation Facility

1. Radiation Source
   - Electron accelerator of specified power and electron energy
   - ^{60}Co source of specified strength

2. Radiation Shielding
   - Concrete (≤ 3 m, for 10 MeV electrons) or lead shielding, or pool of water between the irradiator and workers

3. Target Room
   - The area where actual irradiations are done

Components of an Irradiation Facility (contd)

4. Product Conveyance
   - Conveyor system for the product through the shielding to the target room for irradiation
5. Control Room
   - Outside the shielded area; computer control of product conveyance and irradiation times
6. Human Safety
   - (i) Operation by trained operators only
   - (ii) Appropriate interlocks
   - (iii) Single key for irradiator room door and the control panel
   - (iv) Pre-irradiation inspection of target room
   - (v) TV camera/monitors
   - (vi) Emergency shut-off systems

Components of an Irradiation Facility (contd)

7. Shipping and Receiving Areas

   - They should be well separated from each other to prevent mixing of irradiated and unirradiated products

8. Safety Devices and Monitors

   - Radiation monitors, set to shut - off the system at predetermined dose
   - Air conditioning - temperature fluctuations detrimental to processing
   - Large air flow - to maintain ozone and NO_X levels low
   - Ozone monitors - to show when it is safe to enter the target room

^{60}Cobalt Irradiators

- ^{59}Co (pellet, slugs or disk) + n $\rightarrow$ ^{60}Co
- Enclosed in stainless steel casing
- Lead shielding for Laboratory sources (~25,000 Ci)
- Concrete shielding, and pool storage, for Industrial sources (~1 MCi)

^{60}Cobalt Industrial Irradiators

Total ~150 in 45 countries

- Service facilities ~60
- In-house facilities ~90
- Food irradiation ~20
- Medical sterilization and miscellaneous applications ~130

Characteristics and Cost of ^{60}Co and ^{137}Cs

Characteristics	^{60}Co	^{137}Cs
Half-life (years)	5.27	30.2
Gamma Energy (MeV)	1.25 (average)	0.66
Specific Activity (Ci/g)	up to 400	~25
Dose Rate (Relative/Ci @ 1 meter)	1	0.25
Chemical Form	metal	salt (CsCl)
Density (g/cm³)	8.0	3.9
Melting Point, °C	1493	545
Cost (in 1993)	~$1.45 (US)/Ci	unavailable

^{60}Cobalt Irradiators

Advantages

- Simple
- Reliable (availability > 95%)
- Good penetration
- Insensitive to cost of electricity

^{60}Cobalt Irradiators

Disadvantages

- Radiation not fully used (hours of operation, geometry of irradiation)
- Cost higher than electrons, for large volumes
- Low dose rate
- Disposal of low activity ^{60}Co required (20-50 years)
- Source needs to be periodically recharged

Electron Accelerators

Basic Features

- Electrons emitted by a cathode (tungsten, tantalum, lithium hexaboride)
- Accelerated under vacuum by electrostatic or electromagnetic field
- Beam exit from a thin metal window (tantalum, aluminum)
- Beam scanned by electric or magnetic field

Electron Accelerators

Advantages

- Various power and electron energy levels available
  - Very high dose rates
  - Generally, short processing times
- Cost increases only marginally with power
- Cost increases with electron energy
- Can be switched off when not required
- Can be used for electrons or X-rays
- Directional beam (horizontal or vertical)
  - Better utilization of beam energy >95% availability reported

Electron Accelerators

Disadvantages

- High-tech equipment, expert maintenance needed
- Relatively limited penetration of electrons
- Conversion efficiency to X-rays energy dependent (5 MeV, ~8%; 10 MeV, 20%)
- Sensitive to cost of electricity

Safety Considerations for Industrial Electron Accelerator Facility

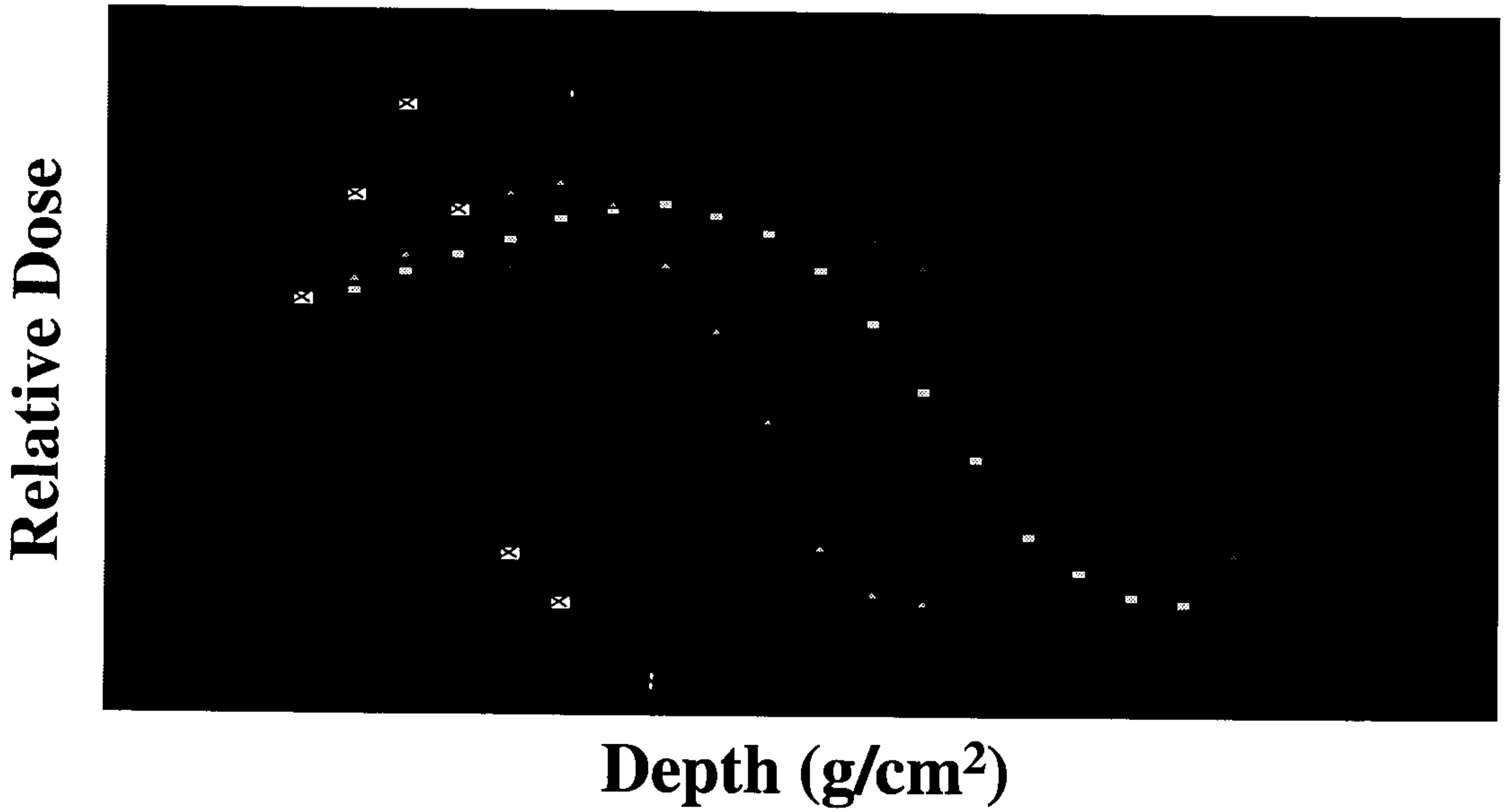
- Radiation Hazards
  - Bremmstrählung (X-ray)
  - Neutrons
  - Induced radioactivity
  - Radio-frequency radiation
- Direct and Scattered Radiation
  - Accelerator level
  - Upper and lower levels

Safety Considerations for Industrial Electron Accelerator Facility (contd)

- Conveyor System
  - Prevent recontamination of irradiated product by unirradiated product
  - Prevent material being caught in conveyor system
  - Accelerator shut down if conveyor under the scan horn stops
- Energy Control
  - Interlocks between various entrances and the control panel

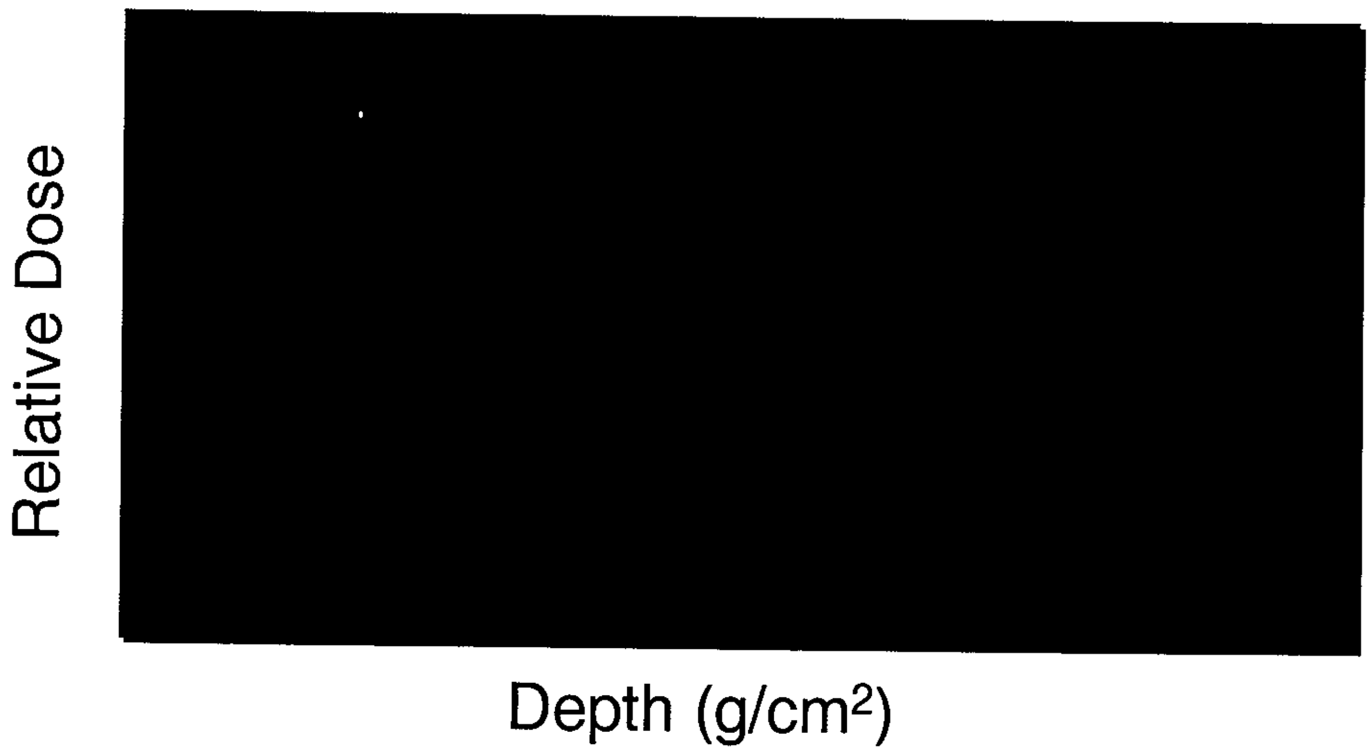
Barnard and Wilkin (1987)

- The penetration of electrons increases with increasing electron energy as shown by the depth/dose curves



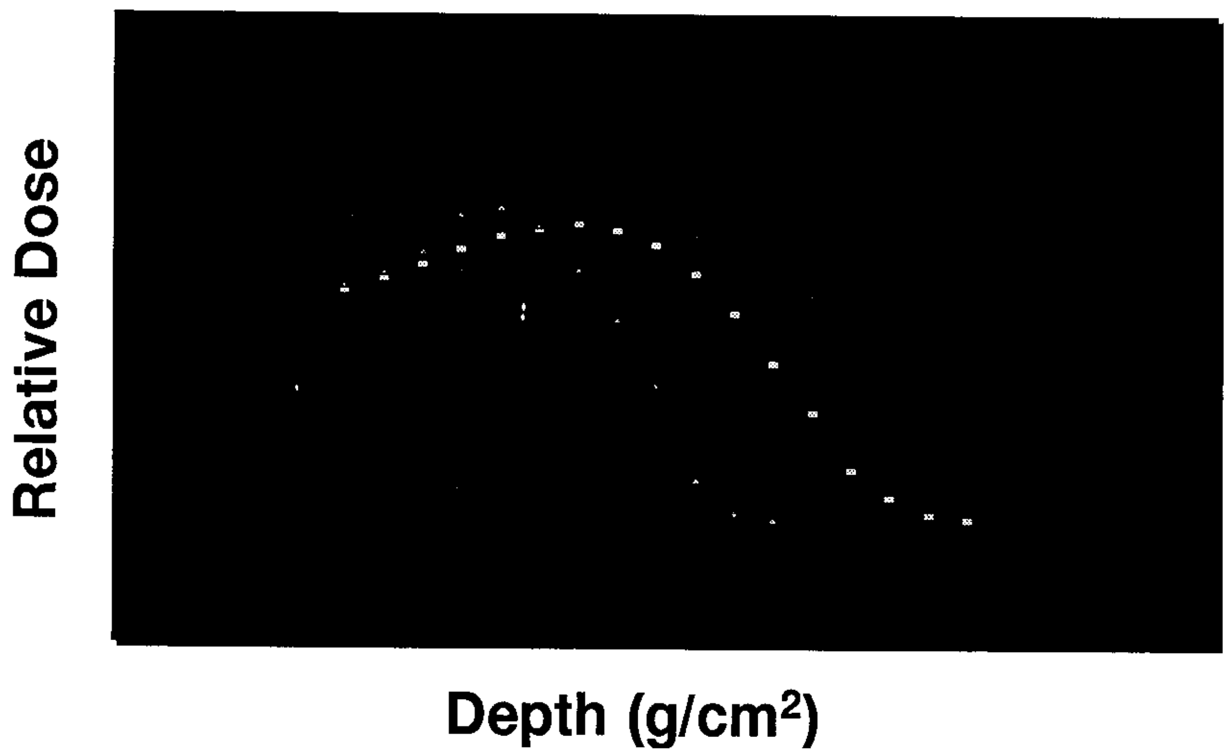
- The dose uniformity increases with increasing electron energy

- **The penetration of electrons increases with increasing electron energy as shown by the depth/dose curves**



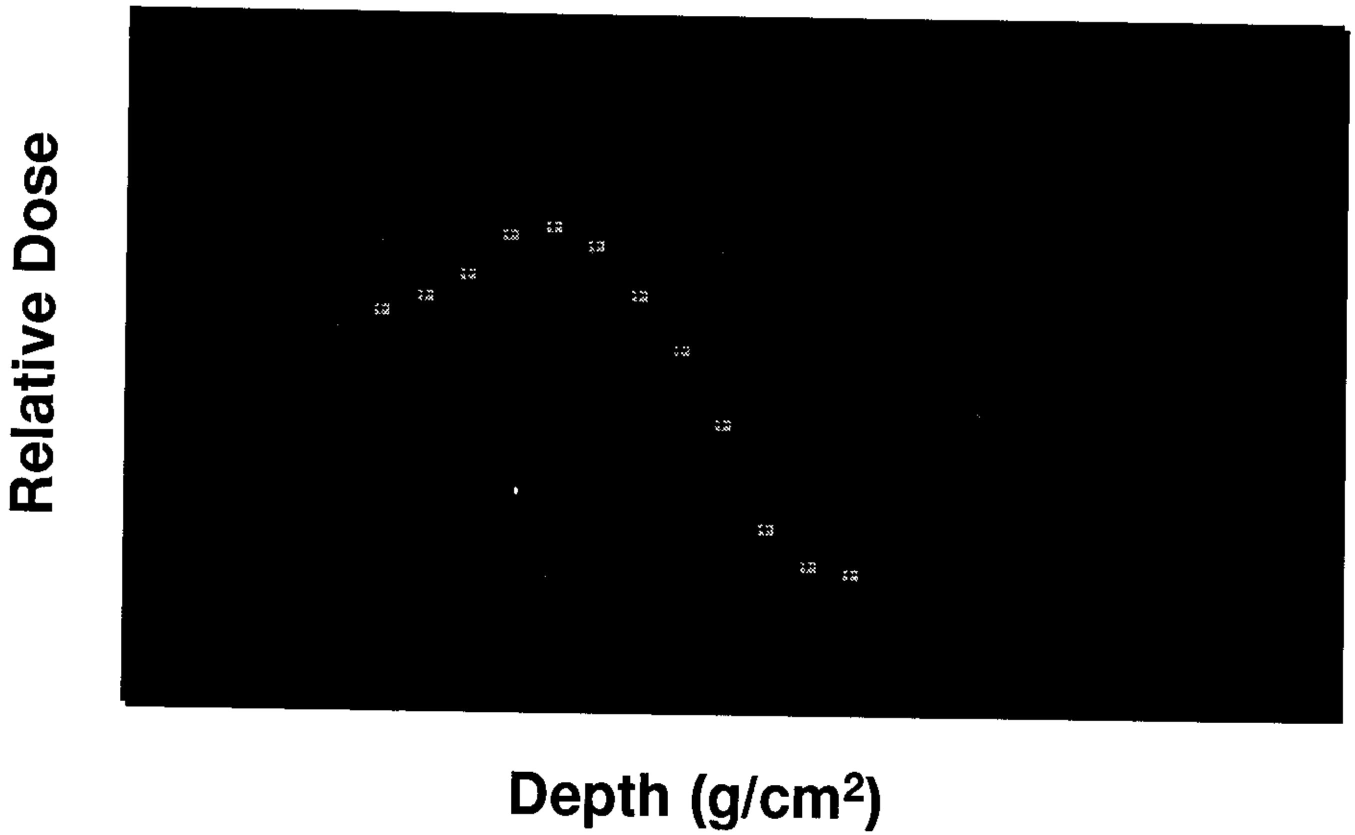
- **The dose uniformity increases with increasing electron energy**

- The penetration of electrons increases with increasing electron energy as shown by the depth/dose curves



- The dose uniformity increases with increasing electron energy

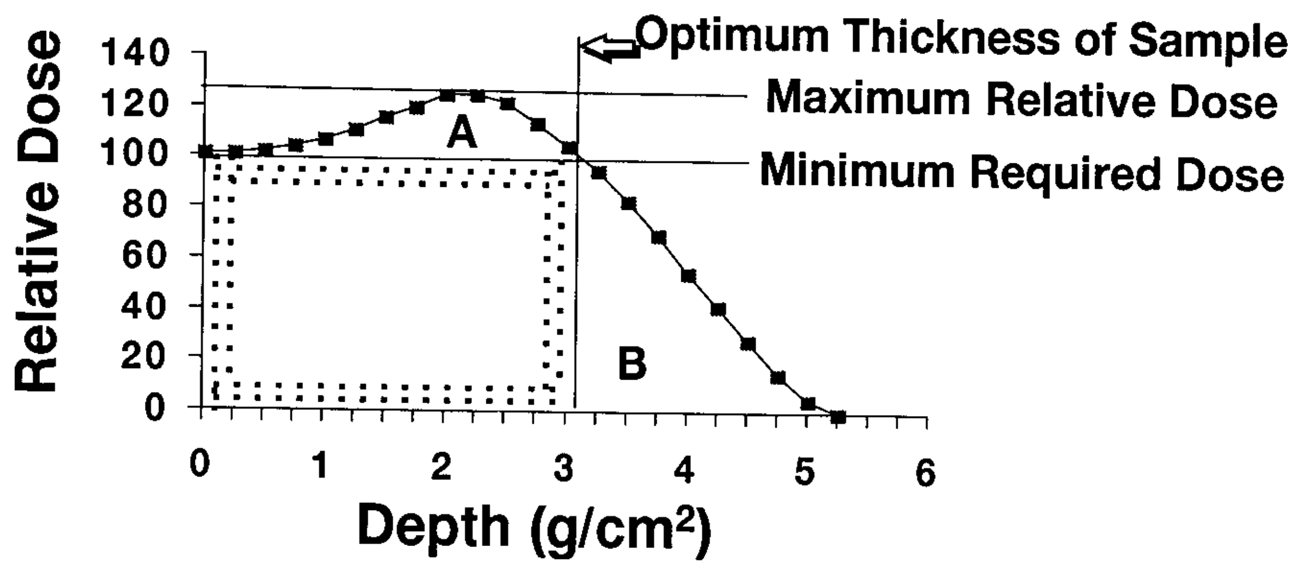
- The penetration of electrons increases with increasing electron energy as shown by the depth/dose curves



- The dose uniformity increases with increasing electron energy

Electron Beam Penetration

Typical Depth/Dose Curve for 10 MeV Electrons

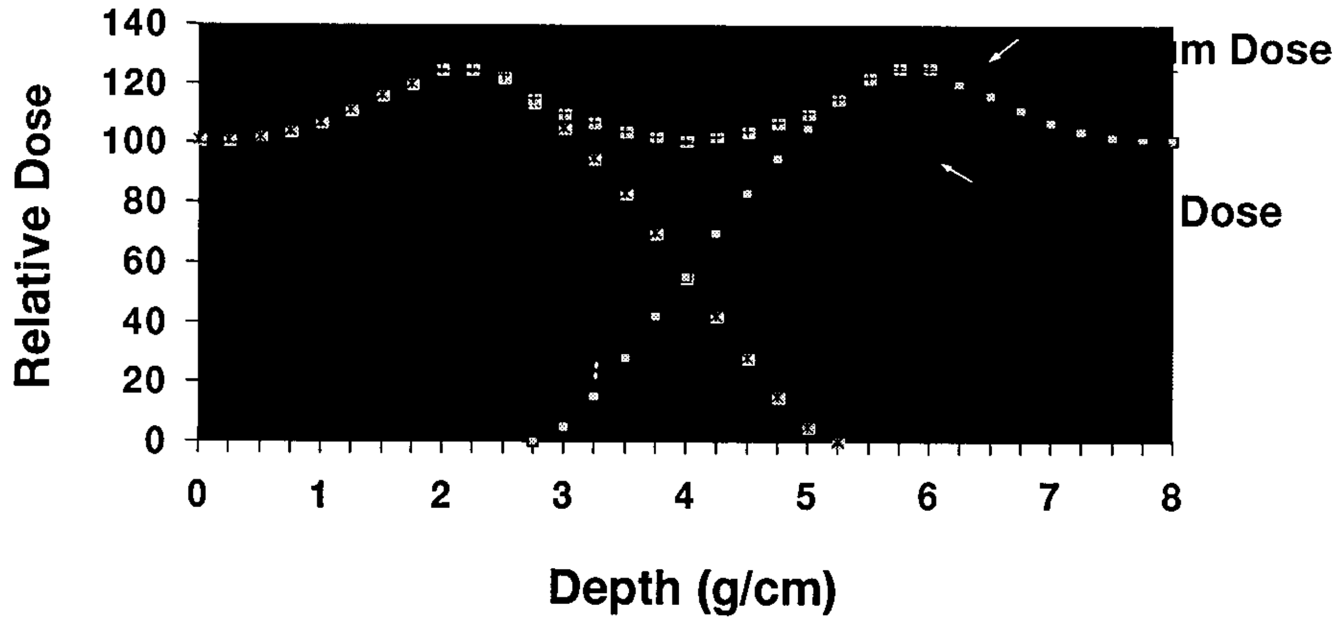


- Dose first increases with penetration and then decreases
- Penetration proportional to 1/density
- At optimum thickness, dose uniformity is ±12.5%

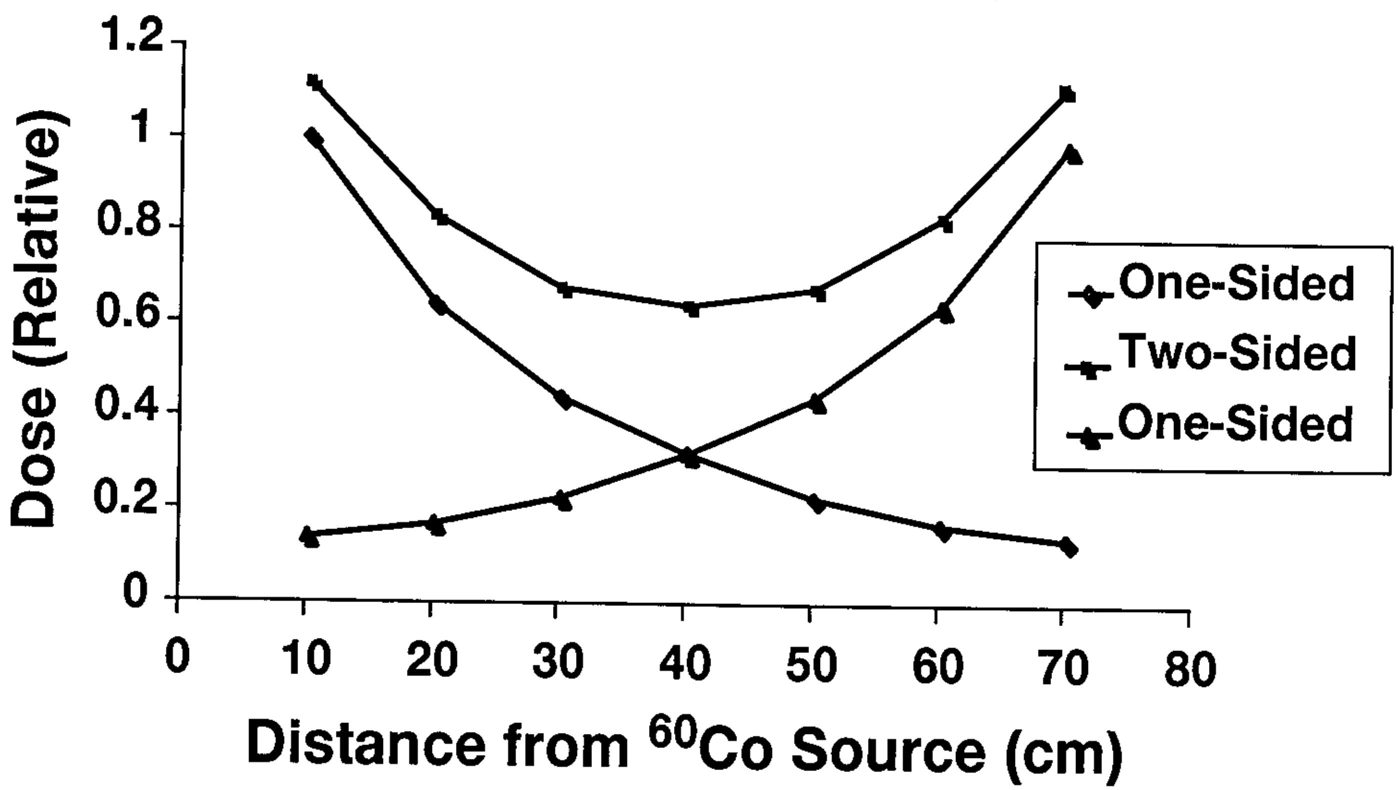
ELECTRON BEAM PENETRATION

One-Sided vs Two-Sided Irradiation for 10 MeV Electrons

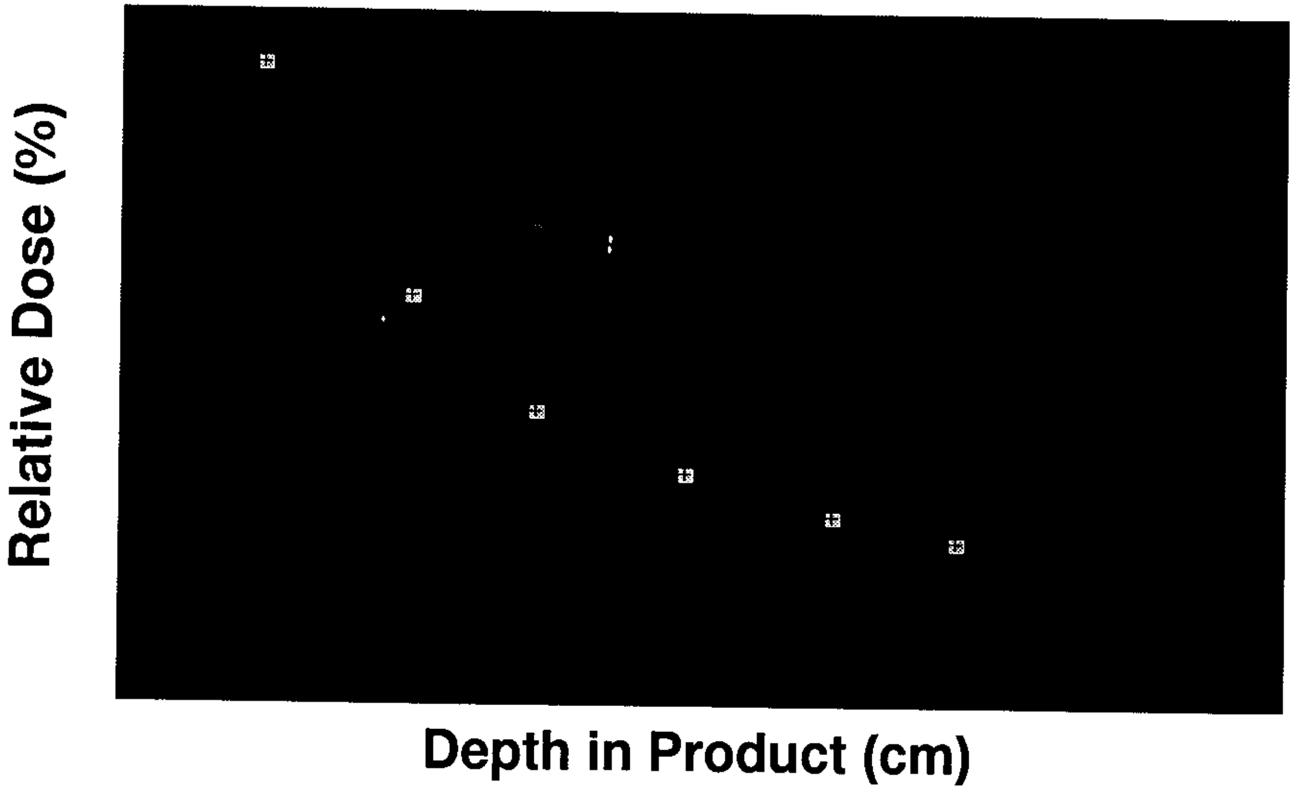
- By optimizing two-sided irradiation, the effective penetration of e^- beam can be increased by a factor of >2



Dose Distribution in Water as a Function of Depth
(Gamma Radiation from ^{60}Co; Saylor, 1997)

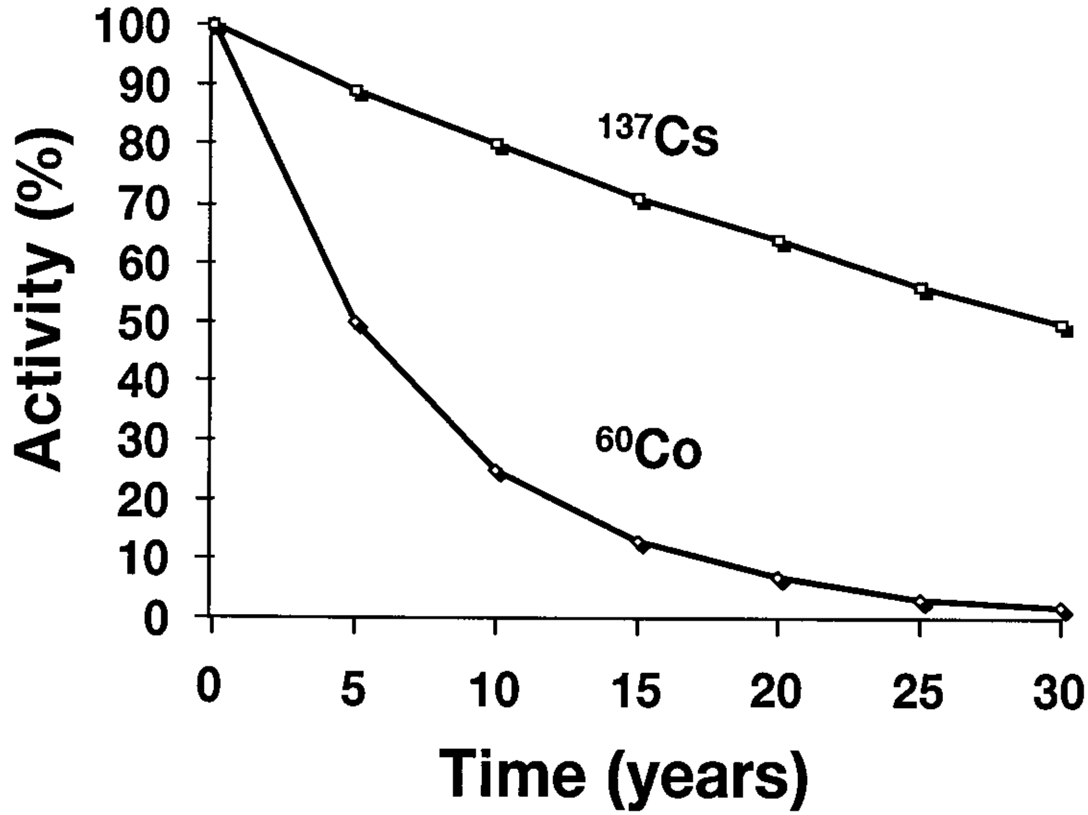


Comparison of Relative Dose vs Depth For ^{60}Co γ-Rays and 5 MeV X-Rays



- For sterilizations of typical packages of medical disposables

Radioactive Decay of ^{137}Cs and ^{60}Co



Cost of Electron Processing

(Cleland, 1992)

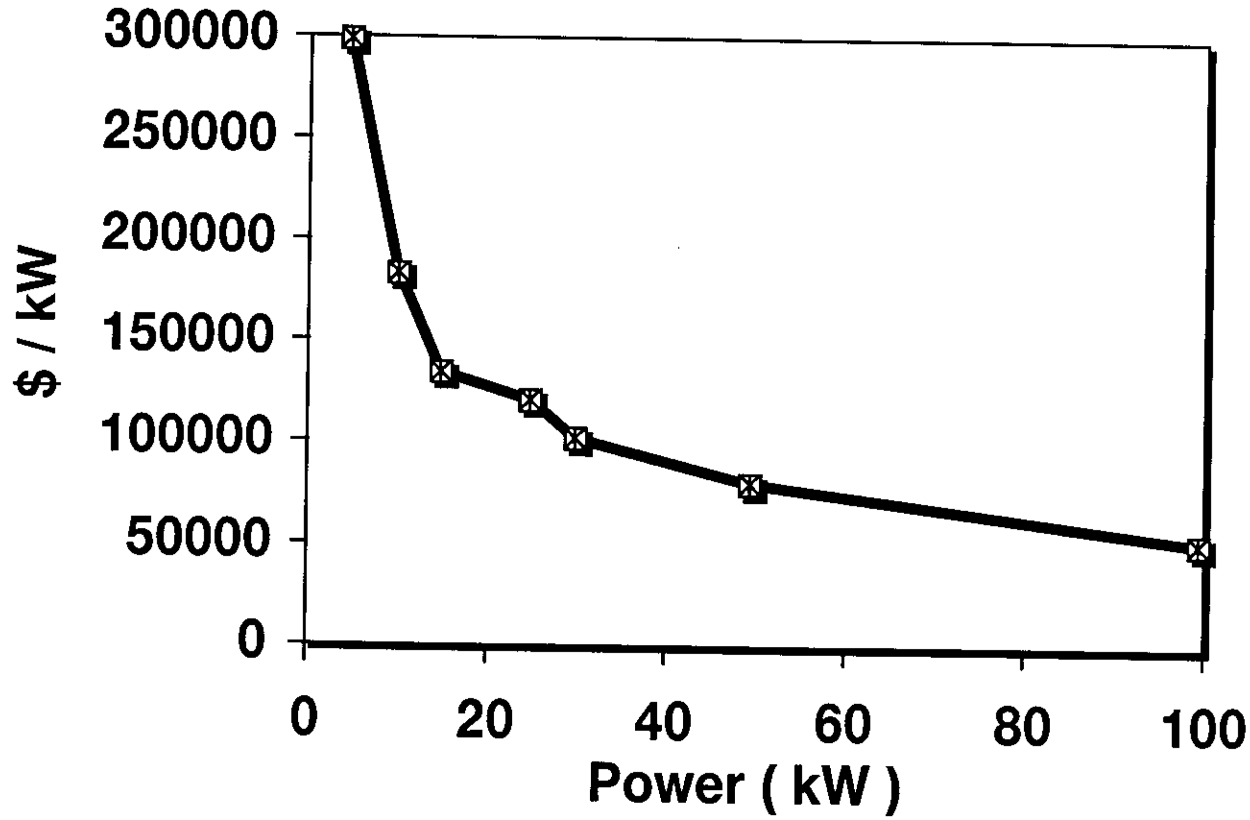
- Electron accelerator, 0.5-10 MeV, $0.5 to 3M
- Cost calculation

	Cost $
(1) Capital cost $3M; Annual cost $0.45M (6000h/a) cost per hour	75
(2) 100 kW power; line power 200 kW; electricity, $.10/kWh, cost per hour	20
(3) Labour, 2 persons, $10/h	20
(4) Facility and Equipment Maintenance, per hour	20
(5) Overheads, per hour	40
Total Cost	175/h

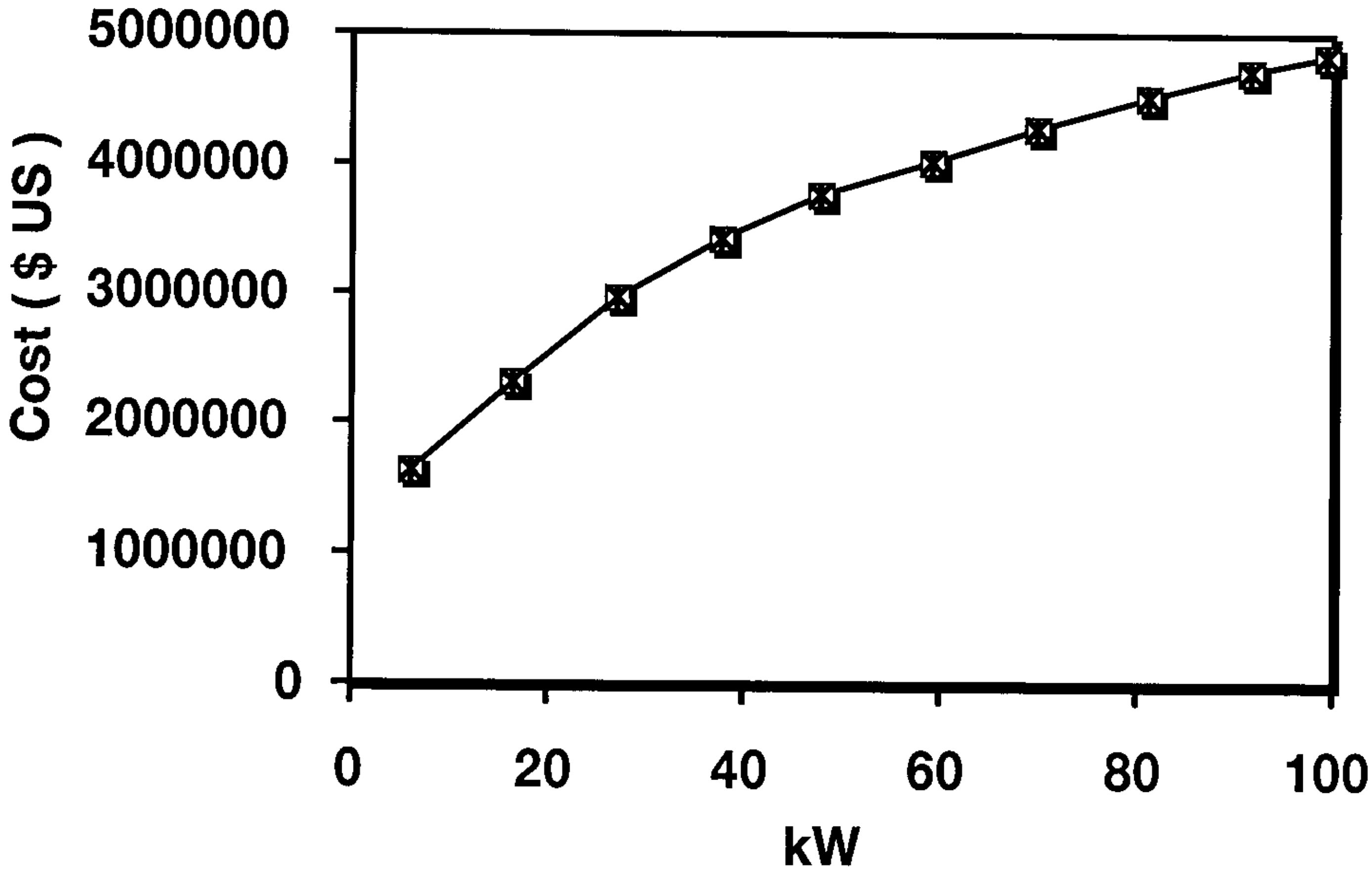
Cost of Electron Processing (contd)

- Material processed, 2500 kg/h
- According to Cleland (1992), the cost of irradiation would be \$0.07/kg for a dose of 100 kGy (10 Mrad)
- More recent estimates (Borsa, 1993) give the cost as \$0.2 to 0.4/kg for a dose of 100 kGy

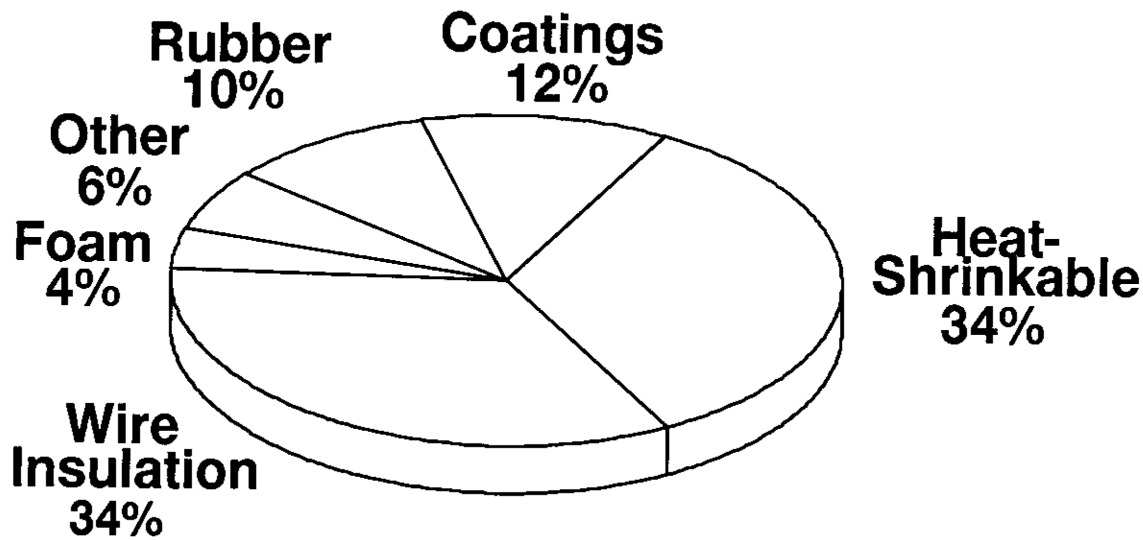
Capital Cost per kW of Electron Accelerator
(10 MeV)



Cost vs Power of 10 MeV Accelerators



Electron Processing



- ~500 Accelerators Worldwide (Saunders,1988; now ~1000)
- ~150 γ - Sources Woldwide for Medical Sterilization and Food Irradiation

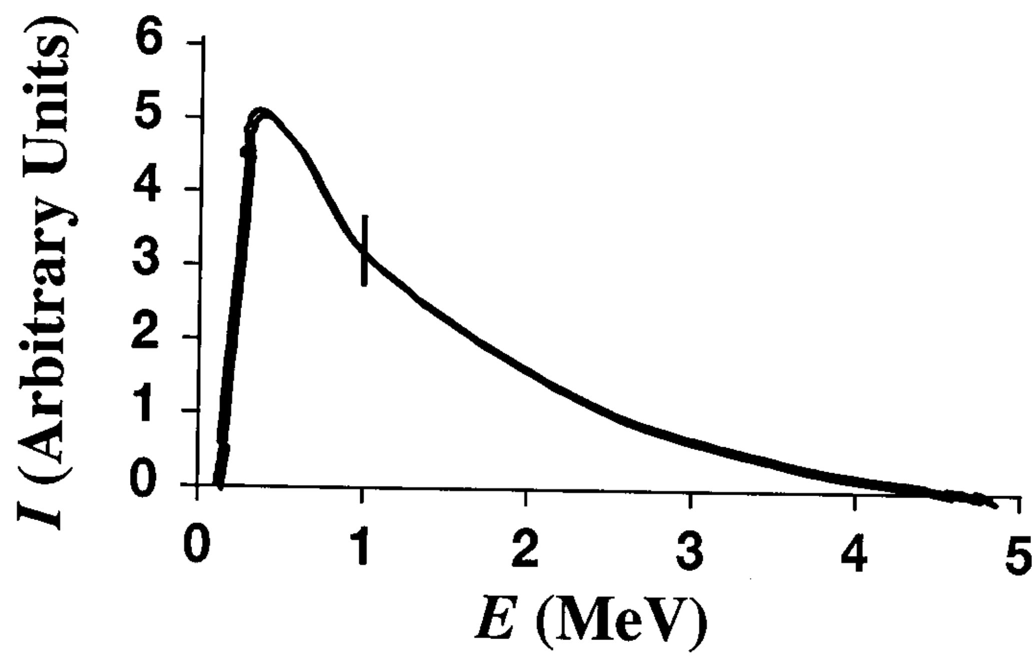
X-Rays

- Produced when accelerated electrons stopped by materials

- Intensity of X-rays function of
  - Increasing electron energy
  - Increasing atomic number of the target

- The conversion efficiencies for electron energy into X-rays are ~8% for 5 MeV and ~20% for 10 MeV electrons; the rest is converted into heat

Energy Spectrum of X-Rays from 5 MeV Electrons



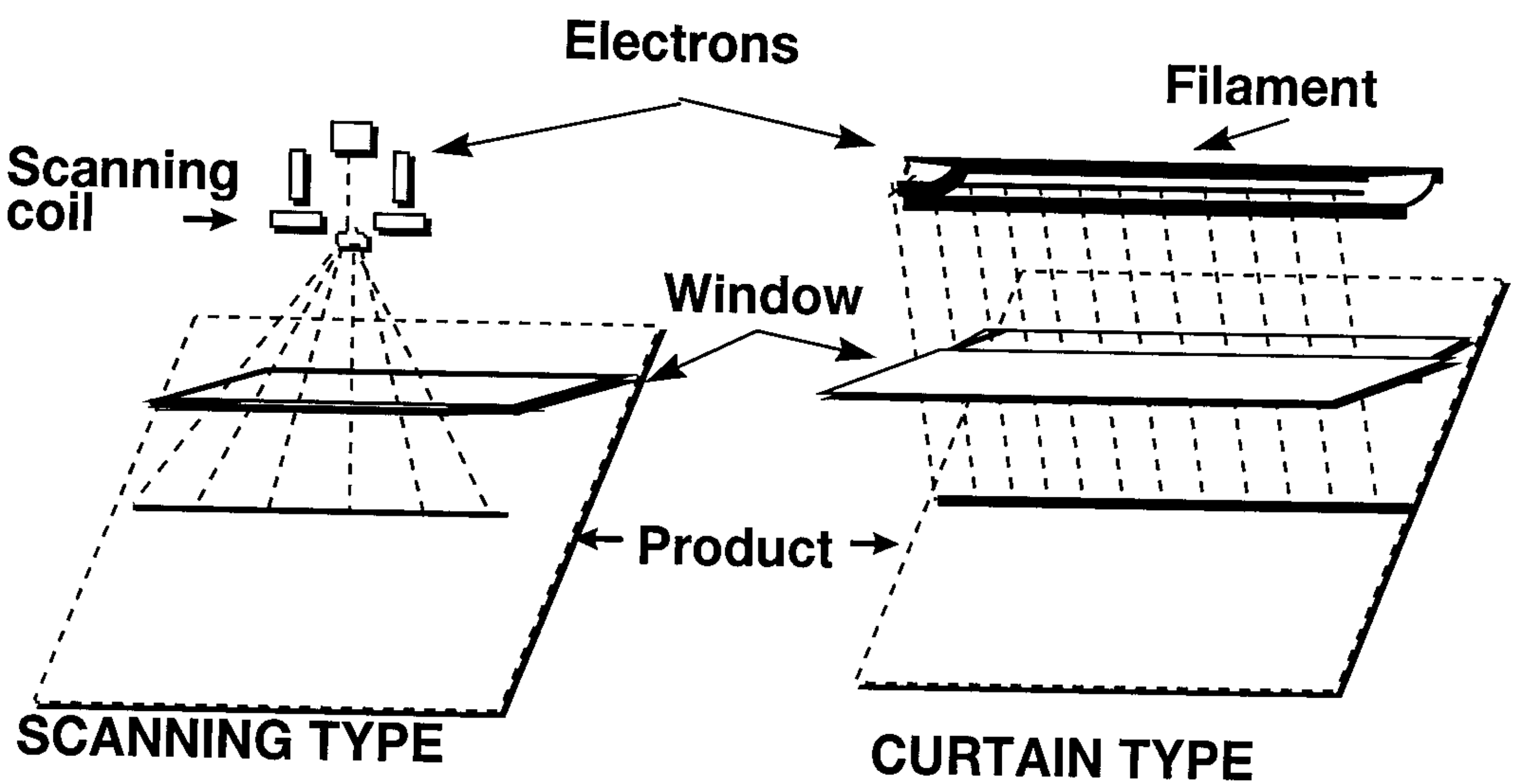
Woods and Pikaev, 1994

- The average energy of X-rays is 1.06 MeV

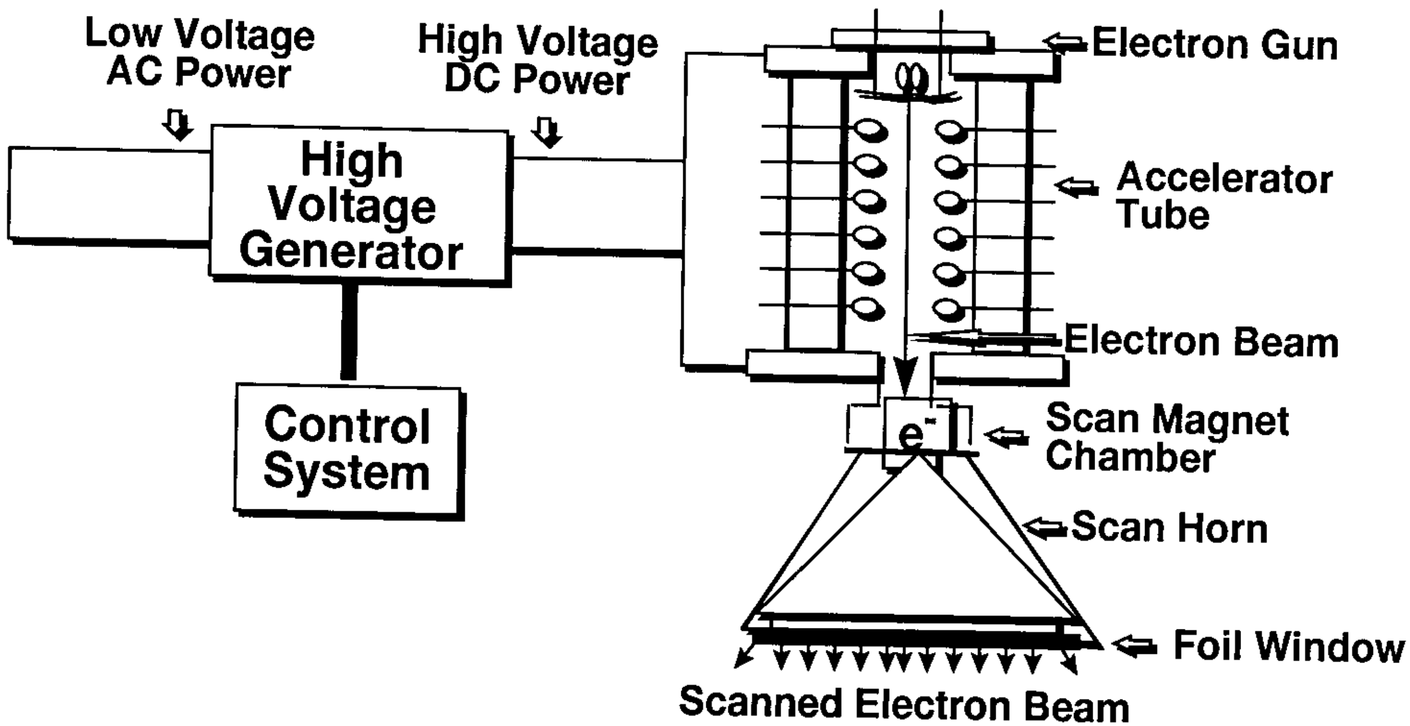
Nominal Equivalence of Electron Accelerators and ^{60}Co

- 50 kW of electron beam = 3.38 MCi ^{60}Co
- X-rays from 5 MeV, 200 kW electron accelerator
  = 16 kW ≈ 1.1 MCi ^{60}Co
- X-rays from 10 MeV, 50 kW electron accelerator
  = 10 kW ≈ 0.67 MCi of ^{60}Co

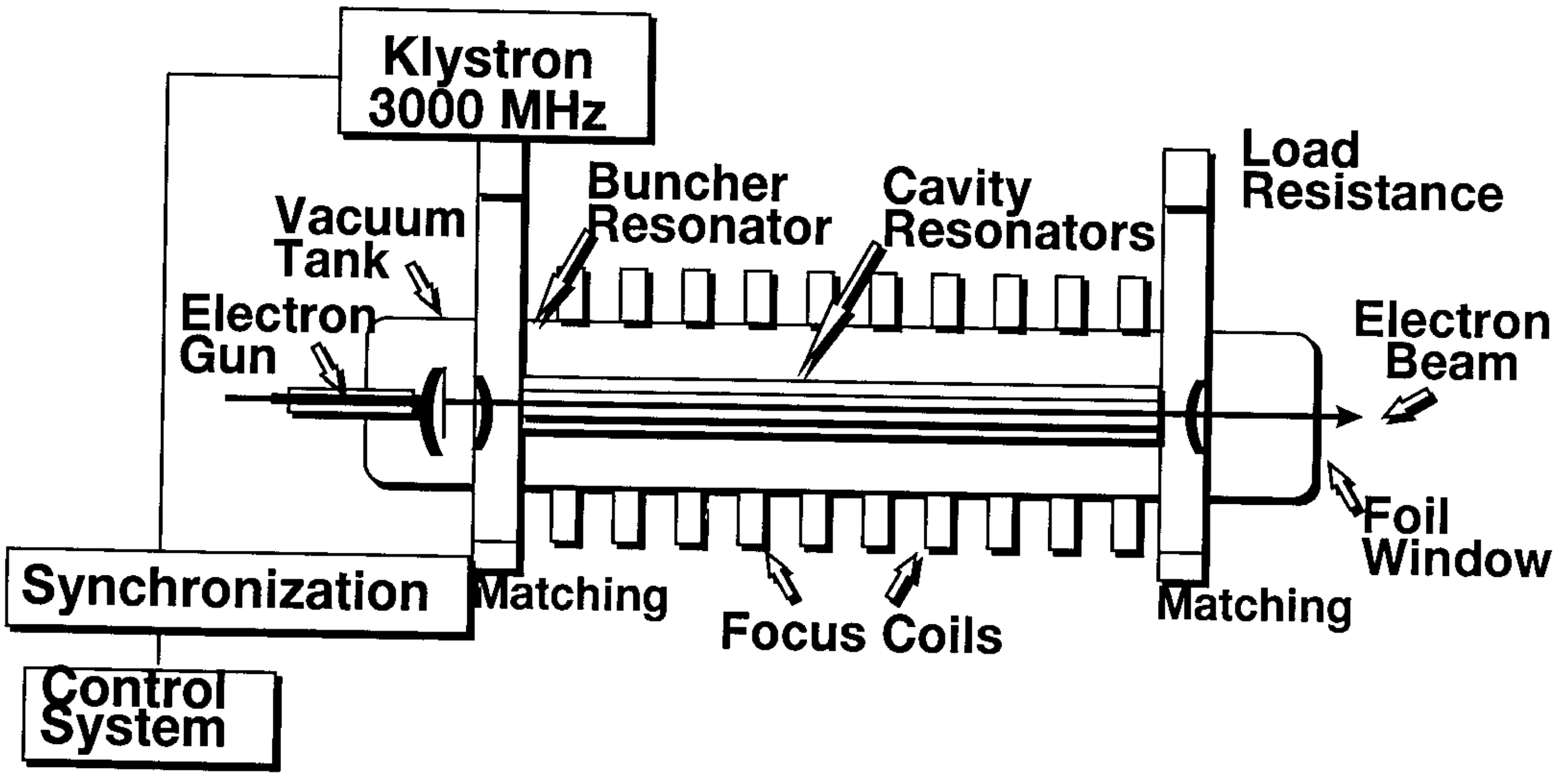
Types of Scanning in Low-Energy Electron Accelerators



Direct Electron Accelerator Principle Of Operation (Cleland,1992)



Traveling-Wave Linear Electron Accelerator



I-10/1 Electron Linear Accelerator

(I=Industrial; 10 = 10 MeV; 1 = 1 kW)

- Pulsed Beam, 19 to 300 Hz
- Pulse Width, 4 μs
- Vertical Beam Bent 270° from Horizontal
- Scanned Beam, 2-7 Hz, 60 cm wide
- Spot size at Conveyor Level, 10 cm
- Dose Rate at Conveyor,

  Pulsed: 5.7 Gy/pulse
  1.4 MGy/s
  Average: 1.7 kGy/s (unscanned)
  130 Gy/s (50 cm scan)

IMPELA 10/50 Electron Linear Accelerator

(IMPELA=Industrial Materials Electron Linear Accelerator
10=10 MeV; 50=50 kW)

- Pulsed Beam, 250 Hz at Full Power
- Pulse Width, 250 μs
- Vertical Structure, beam not bent
- Scanned Beam, 2-7 Hz, 100 cm wide
- Spot size at window, 10 cm
- Dose Rate at Beam Window

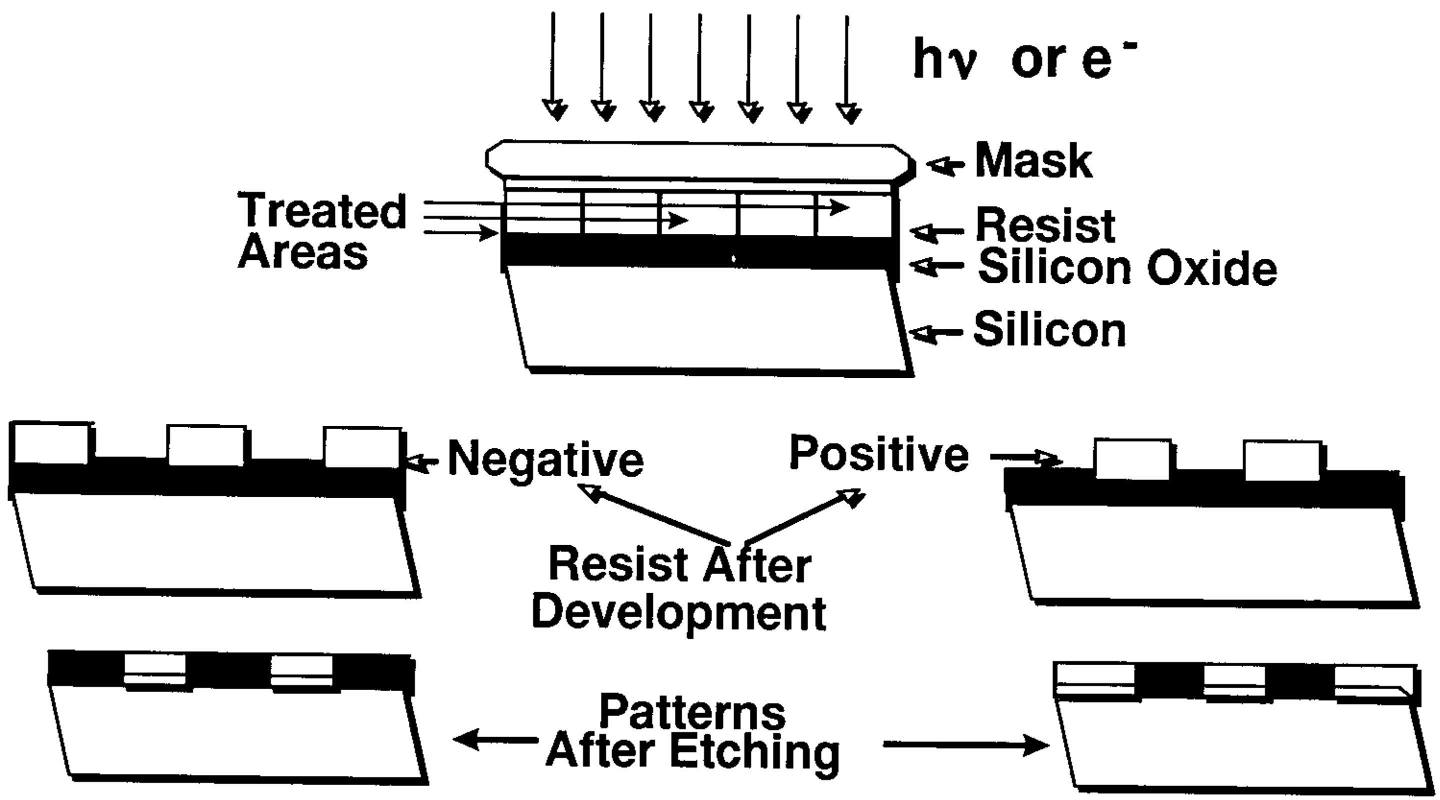
  Pulsed: 340 Gy/pulse
  1.9 MGy/s
  Average: 85 kGy/s (unscanned)
  6 kGy/s (50 scan)

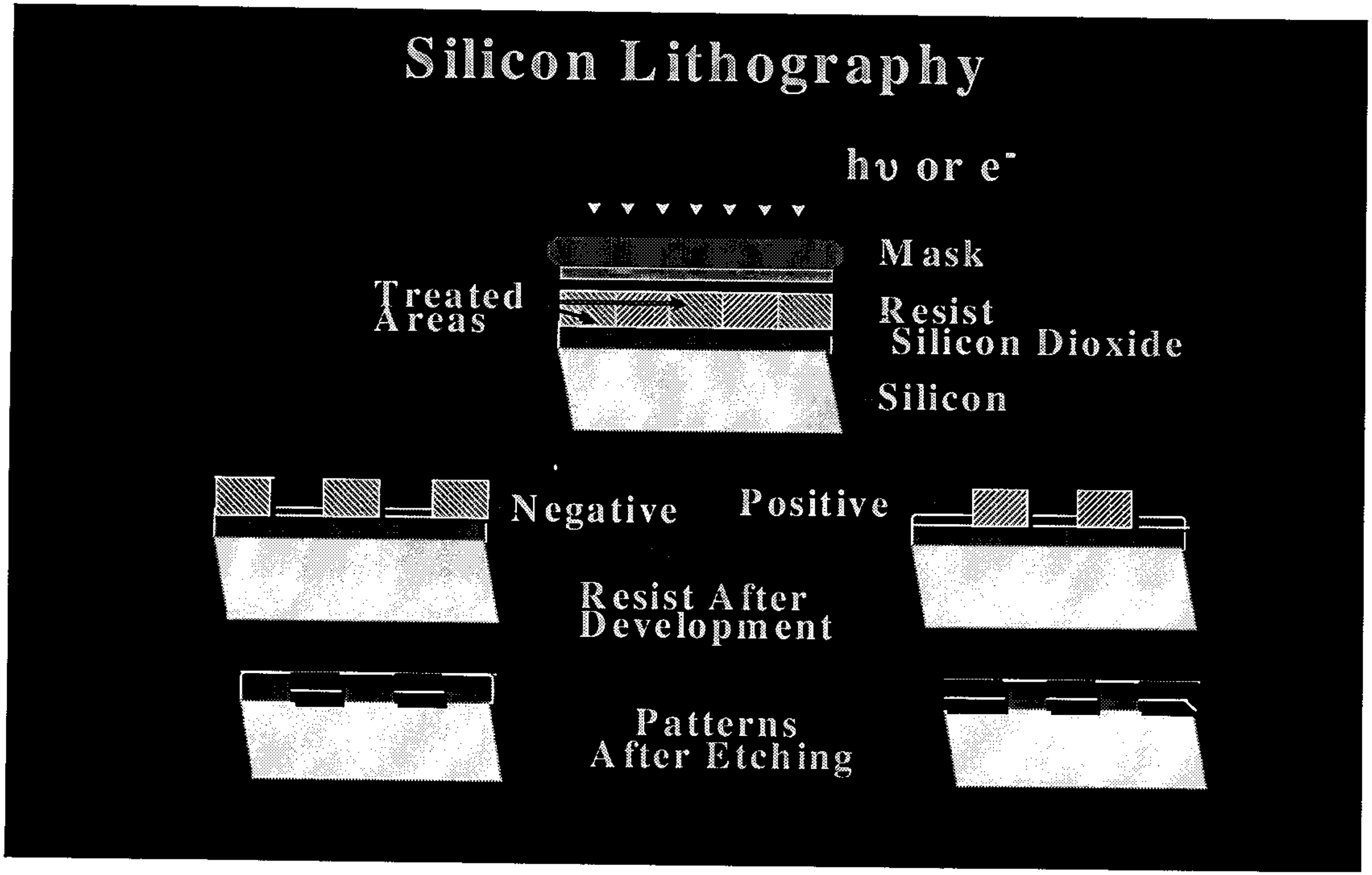
Rhodotron T T200

(IBA, Electron Accelerator, 10 MeV)

• Beam Power	1 to 80 kW
• Power Consumption (at 80 kW beam power)	260 kW
• Diameter	3 m
• Height	2.4 m

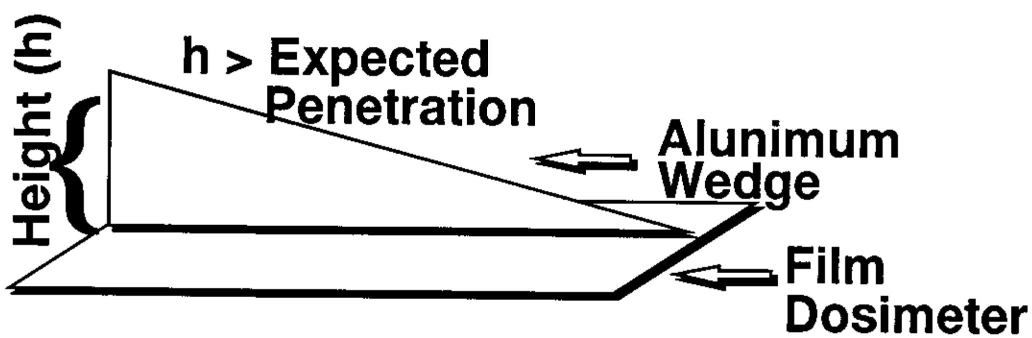
Silicon Lithography




Silicon Lithography
hυ or e⁻
Mask
Treated Areas
Resist
Silicon Dioxide
Silicon
Negative
Positive
Resist After Development
Patterns After Etching

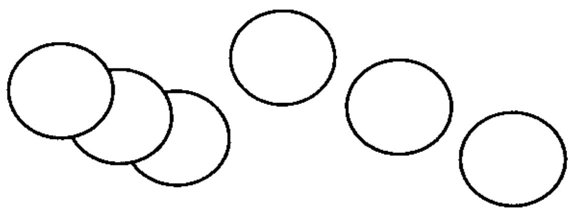
Characterization of the Irradiator

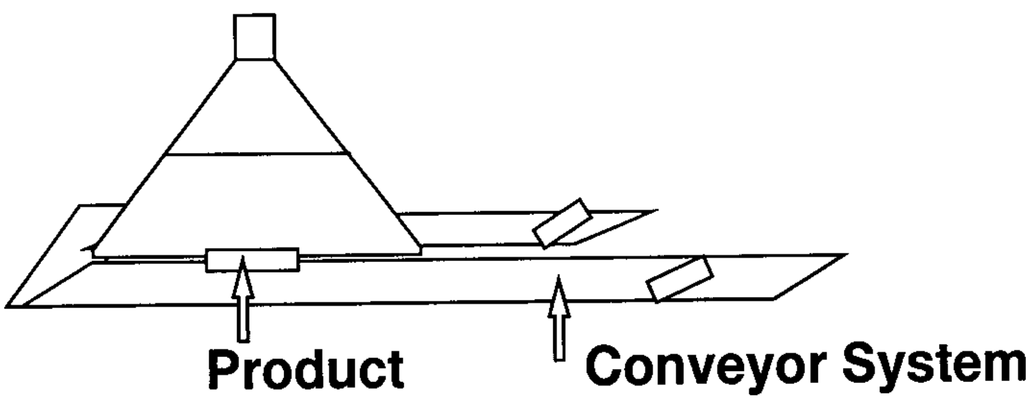
	Source:	
	e^-	γ
• Determine depth/dose curves wih a wedge	Yes	Yes
• Determine dose profile	Yes	Yes



Characterization of the Irradiator

	Source:	e^-	γ
• Determine Dose Profile	Scan	Yes	Yes
• Determine Nominal Dose Received by Product		Yes	Yes





Conclusions

- Gamma irradiation would continue to be an important component of industrial radiation processing
- Industrial electron irradiation would continue to grow for most of the current products
- Areas of major growth for electron accelerators are most likely to include environmental (water purification, sewage sludge irradiation, flue gas irradiation), viscose, and advanced composites
- The availability of a good variety of electron accelerators in a wide energy range (0.2 to 10 MeV) is conducive to growth of the radiation processing industry
- Continued effort to increase understanding and usefulness of the technology would also help the growth of this industry