Industrial Irradiators for Radiation Processing

Radiation processing became 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

Electrical input

Electron acceleration

Scanned electron beam

X-ray conversion plate

$^{60}\text{Co}$ or $^{137}\text{Cs}$ 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 ($\leq 3$ 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\textsubscript{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 ($\sim$25,000 Ci)
- Concrete shielding, and pool storage, for Industrial sources ($\sim$1 MCi)
$^{60}$Cobalt Industrial Irradiators

Total \( \sim 150 \) in 45 countries

- Service facilities \( \sim 60 \)
- In-house facilities \( \sim 90 \)
- Food irradiation \( \sim 20 \)
- Medical sterilization and miscellaneous applications \( \sim 130 \)
# Characteristics and Cost of $^{60}$Co and $^{137}$Cs

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>$^{60}$Co</th>
<th>$^{137}$Cs</th>
</tr>
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<tbody>
<tr>
<td>Half-life (years)</td>
<td>5.27</td>
<td>30.2</td>
</tr>
<tr>
<td>Gamma Energy (MeV)</td>
<td>1.25 (average)</td>
<td>0.66</td>
</tr>
<tr>
<td>Specific Activity (Ci/g)</td>
<td>up to 400</td>
<td>~25</td>
</tr>
<tr>
<td>Dose Rate (Relative/Ci @ 1 meter)</td>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>Chemical Form</td>
<td>metal</td>
<td>salt (CsCl)</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>8.0</td>
<td>3.9</td>
</tr>
<tr>
<td>Melting Point, °C</td>
<td>1493</td>
<td>545</td>
</tr>
<tr>
<td>Cost (in 1993)</td>
<td>~$1.45 (US)/Ci</td>
<td>unavailable</td>
</tr>
</tbody>
</table>
$^{60}$Cobalt Irradiators

Advantages

- Simple
- Reliable (availability > 95%)
- Good penetration
- Insensitive to cost of electricity
$^{60}\text{Cobalt Irradiators}$

**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 $^{60}\text{Co}$ 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
  - Bremmstrahlung (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.
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- 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 $\pm12.5\%$
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 $^{137}\text{Cs}$ and $^{60}\text{Co}$

![Graph showing the decay of $^{137}\text{Cs}$ and $^{60}\text{Co}$ over time. The x-axis represents time in years, ranging from 0 to 30, and the y-axis represents activity in percent. The graph shows exponential decay for both isotopes.](image-url)
Cost of Electron Processing
(Cleland, 1992)

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

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>Capital cost $3M; Annual cost $0.45M (6000h/a) cost per hour</td>
<td>75</td>
</tr>
<tr>
<td>(2)</td>
<td>100 kW power; line power 200 kW; electricity, $.10/kWh, cost per hour</td>
<td>20</td>
</tr>
<tr>
<td>(3)</td>
<td>Labour, 2 persons, $10/h</td>
<td>20</td>
</tr>
<tr>
<td>(4)</td>
<td>Facility and Equipment Maintenance, per hour</td>
<td>20</td>
</tr>
<tr>
<td>(5)</td>
<td>Overheads, per hour</td>
<td>40</td>
</tr>
</tbody>
</table>

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)

- 300,000
- 250,000
- 200,000
- 150,000
- 100,000
- 50,000
- 0

Power (kW)

$ / kW
Cost vs Power of 10 MeV Accelerators

![Graph showing cost vs power for 10 MeV accelerators]
Electron Processing

- ~500 Accelerators Worldwide (Saunders, 1988; now ~1000)
- ~150 $\gamma$ - Sources Worldwide 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
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 M Ci $^{60}$Co

- X-rays from 5 MeV, 200 kW electron accelerator
  = 16 kW ≈ 1.1 M Ci $^{60}$Co

- X-rays from 10 MeV, 50 kW electron accelerator
  = 10 kW ≈ 0.67 M Ci of $^{60}$Co
Types of Scanning in Low-Energy Electron Accelerators
Direct Electron Accelerator
Principle Of Operation (Cleland, 1992)
Traveling-Wave Linear Electron Accelerator

- Klystron 3000 MHz
- Vacuum Tank
- Electron Gun
- Buncher Resonator
- Cavity Resonators
- Load Resistance
- Electron Beam
- Foil Window
- Matching
- Focus Coils
- Control System
- Synchronization
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 260 kW
  (at 80 kW beam power)
- Diameter 3 m
- Height 2.4 m
Silicon Lithography

hv or e-

Mask
Resist
Silicon Oxide
Silicon

Treated Areas

Negative
Positive

Resist After Development

Patterns After Etching
Silicon Lithography

hv or e⁻

Treated Areas

Mask
Resist
Silicon Dioxide
Silicon

Negative  Positive
Resist After Development

Patterns After Etching
Characterization of the Irradiator

**Source:** $e^-$ \quad $\gamma$

- Determine depth/dose curves with a wedge  
  - Yes  
  - Yes

Diagram:
- Height ($h$)  
- $h >$ Expected Penetration  
- Aluminum Wedge  
- Film Dosimeter

- Determine dose profile  
  - Yes  
  - Yes

- Beam spot
Characterization of the Irradiator

Source: $e^- \quad \gamma$

- Determine Dose Profile
- Determine Nominal Dose Received by Product

Yes Yes

Product

Conveyor System
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