International Topical Meeting on Nuclear Research Applications and Utilization of Accelerators Vienna, Austria 4 - 8 May 2009.
Electron Beam for Environmental Conservation

- Flue gas/VOC Purification
- Wastewater treatment
- Sludge treatment
Technical Advantages of radiation process

*. Radiation Technology is Eco-friendly technology
  -. No secondary waste generation
  -. No catalysts, no heating and easy for automation.

*. Experienced in pilot plant and several industrial plants

*. Economical Advantages in capital cost and O & M cost

*. For flue gas treatment and sludge treatment, by-products are useful for fertilizer.
The total volume of water on Earth is about 1,400 million km$^3$ of which only 2.5 per cent, or about 35 million km$^3$, is freshwater.

The usable portion of these sources is only about 200 000 km$^3$ of water — less than 1 per cent of all freshwater and only 0.01 per cent of all water on Earth.
### Major Stocks of Water

<table>
<thead>
<tr>
<th>Stock</th>
<th>Volume (1,000 km³)</th>
<th>% of total water</th>
<th>% of total freshwater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oceans</td>
<td>1,338,000</td>
<td>96.54</td>
<td></td>
</tr>
<tr>
<td>Saline water/lakes</td>
<td>12,955</td>
<td>0.94</td>
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</tr>
<tr>
<td>Inland waters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glaciers, Snow covers</td>
<td>24,064</td>
<td>1.74</td>
<td>68.7</td>
</tr>
<tr>
<td>Fresh groundwater</td>
<td>10,530</td>
<td>0.76</td>
<td>30.1</td>
</tr>
<tr>
<td>Others</td>
<td>435</td>
<td>0.02</td>
<td>1.2</td>
</tr>
<tr>
<td>Total water</td>
<td>1,386,000</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Total freshwater</td>
<td>35,029</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>
If the World were a village of 100 peoples,

75 people have some supply of food and a place to shelter them from the wind and the rain, but 25 do not.

17 have no clean, safe water to drink.

Adopted from “If the World were a village of 100 peoples,” by Douglas Lummis
Severity of Water Stress (Data from UN report)
What is water/wastewater treatment?

Main purpose of wastewater treatment

- Removal of harmful impurities (COD, BOD, S/S etc.)
- Removal of color, odor etc.
- Removal of T-N, T-P

To discharge to river, or to re-use in industries or irrigation

- Disinfection of microorganisms
  (Coli-form & pathogenic organisms)
- Destruction of endocrine disrupter (natural and synthetic chemicals such as Nonyl phenols and its derivatives)
Why e-beam water/wastewater treatment?

1. Remove organic impurities with radiation chemical reaction
2. Remove colors by destruction of double bond
3. Remove odors by opening of rings in aromatic compound
4. Disinfection of microorganisms by destruction of DNA
5. Destruction of endocrine disrupter with radical reaction
6. Recycle for irrigation, impoundment and individual uses
Characteristics of e-beam wastewater treatment

Water/Wastewater treatment by Radiation-Chemical reactions

Radiation (electron-beam) treatment consists in the formation of very reactive radical particles upon the water radiolysis. They are:

- hydrated electron $e^{-}_{aq}$ (reducer);
- hydrogen atom ·H (reducer);
- hydroxyl radical ·OH (oxidizer).
Ionization, decay of excited states $\leq 10^{-12}$ s

\[
e^{-}_aq + H_2O^+ \rightarrow H + OH \rightarrow H + O + H_2O
\]

“Spur” reactions $\leq 10^{-8}$ s

\[
e^{-} \rightarrow e^{-}_\text{therm} \rightarrow e^{-}_aq
H_2O^+ + H_2O \rightarrow H_3O^+ + OH
e^{-}_aq + H_3O^+ \rightarrow H + H_2O
H + H \rightarrow H_2
OH + OH \rightarrow H_2O_2
e^{-}_aq + OH \rightarrow OH^-
\]
Principles of Wastewater treatment with e- beam

Water Molecule

Harmful Organic in Waste water

Active Radicals

- Complete Decomposition
- Partial Decomposition
- Suspended solid
- Monomer to Polymerization
- Removal of Toxic group
- Removal of Color, Odor

H$_2$O, CO$_2$

Coagulation

Bio-Treat
Application on water/wastewater treatment

**With high contamination**

- Textile dyeing wastewater
- Leachate from Landfill area
- from petrochemical plant
- from Paper-Mill
- from tanning industries
- from slaughterhouse & fisheries

  \[ \text{Removal of impurities (COD, BOD, S/S etc.)} \]
  \[ \text{Discharge} \]

**Low or less contamination**

- Underground water
- Water from lake or marshes
- Effluent of municipal plant

  \[ \text{Disinfection} \]
  \[ \text{Removal of Color, Odor, residuals} \]
  \[ \text{Re-use} \]
Application of e-beam on water/wastewater treatment

- Wastewater from Textile Dyeing Companies
- Wastewater from Papermill
- Leachate from Sanitary Landfill
- Wastewater containing Heavy metals (Cd, Hg, Pb, Cr\textsuperscript{6})
- Re-use of effluent from municipal wastewater plant
- Remediation of contaminated water (PCB, Explosives)
- Contaminated Underground water
- Drinking water
<table>
<thead>
<tr>
<th>Comparison of Flue Gas Purification, Wastewater &amp; Sludge Treatment</th>
</tr>
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<tbody>
<tr>
<td><strong>Contaminants to clear</strong></td>
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<tr>
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Why e-beam processes are not widely used?

Barriers for Industrial Application

- Public Acceptances
  Uneasy for the Radiation Safety
  New Species by Radiation
Why e-beam processes are not widely used?

Barriers for Industrial Application

- Public Acceptances
  - Uneasy for the Radiation Safety
  - New Species by Radiation

- Technical problems
  - Reliability for year-round operation
  - Analysis of by-product, Toxicity
Why e-beam processes are not widely used?

Barriers for Industrial Application

- Public Acceptances
  Uneasy for the Radiation Safety
  New Species by Radiation

- Technical problems
  Reliability for year-round operation
  Analysis of by-product, Toxicity

- Regulation from Authorities

- Competition with Other processes (Economics)
  Difficult to beat the conventional processes
  High investment cost and long returns
  No Alternatives or by-passes for shut-down
  Not universal for all environmental plant
  Difficult to find BP
Ionizing radiation is an expensive form of energy.

If the e-beam process is the only and unique solution

- no restrictions on cost

- sterilization of some medical items,
  removal of toxic compound etc.

If not, severe competition with other process

- in cost, performance, safety, etc.

- especially in emerging technology
  Wastewater, Flue gas treatment, Sludge Hygienization

- even in well-known technologies, such as cross-linking of wires, heat-shrinkable materials and sterilization etc.
Performance

Raw material + radiation → added value

(improvement in physical/chemical properties, etc.)

Cost assessment

radiation + logistics + management > Before or to other process

When Performance > Cost Acceptable in market

When Performance < Cost Kick-off from market
Radiation process (e-beam, γ-ray etc.) can survive only when it has Technical & Economical advantages over existing processes.
Radiation processing should be 
Better & Cheaper to other processes.
1. Find the proper radiation source for products - Gamma-ray, X-ray, or e-beam
Steps of decision

- Decide what you want to treat
  (Polymer, Food, Medical items, Water, Gas, Sludge)
- Decide what Kind of Radiation (e-beam, Gamma, X-ray)

- E-beam?
  + Limitation in penetration

- Gamma ray?
  + Low dose rate – slow productivity

- How about X-ray?
  + Less efficient for energy utilization
1. Find the proper radiation source for products
   - Gamma-ray, X-ray, or e-beam

2. Reduce doses
   - with combined methods (Bio-, Physical/chemical etc.)

3. Apply cost-effective accelerator (in case of e-beam)
ACCELERATORS FOR RADIATION PROCESSING  
(recent achievements)

<table>
<thead>
<tr>
<th>Accelerator type</th>
<th>Direct DC</th>
<th>UHF 100-200 MHz</th>
<th>Linear 1.3-5.8 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam current</td>
<td>&lt; 1.5 A</td>
<td>&lt; 100 mA</td>
<td>&lt; 100 mA</td>
</tr>
<tr>
<td>Energy range</td>
<td>0.1-5 MeV</td>
<td>0.3-10 MeV</td>
<td>2-10 MeV</td>
</tr>
<tr>
<td>Beam power</td>
<td>400 kW</td>
<td>700 kW</td>
<td>150 kW</td>
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<tr>
<td>Efficiency</td>
<td>80-90 %</td>
<td>25-50 %</td>
<td>10-20 %</td>
</tr>
</tbody>
</table>

Data from Dr. Z. Zimek of INCT, Poland
<table>
<thead>
<tr>
<th>Beam Power</th>
<th>20kW</th>
<th>40kW</th>
<th>100kW</th>
<th>200kW</th>
<th>400kW</th>
<th>1MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Cost (M$)</td>
<td>0.6</td>
<td>0.8</td>
<td>1.0</td>
<td>1.5</td>
<td>2</td>
<td>2.2*</td>
</tr>
<tr>
<td>Unit Cost ($/W)</td>
<td>30</td>
<td>20</td>
<td>10</td>
<td>7.5</td>
<td>5</td>
<td>2.2</td>
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</table>
1. Find the proper radiation source for products
   -. Gamma-ray, X-ray, or e-beam

2. Reduce doses
   -. with combined methods (Bio-, Physical/chemical etc.)

3. Apply cost-effective accelerator

4. Engineering Approaches
   -. Analysis of existing process → Calculate the present cost
   -. Economics of radiation → Max. allowable radiation doses
   -. Find useful additives or combination for lowering doses
   -. Laboratory test → Confirmation of process
   -. Pilot plant → Industrial scale design → Commercial plants
Scientists likes Numbers, Equations, Papers etc.

Engineer (not all of them, a few ...) cares Economics !!! - cost effective
What they do

-. Laboratory analysis  →  Find useful numbers
-. Analyze the meaning of those numbers  →  Some publications
-. Laboratory experiments  →  Basic design of plant
-. Estimation of plant  →  Calculation of necessary equipments
-. Comparison with existing process  →  ?

What we do

-. Analysis of existing process  →  Calculate the present cost
-. Economics of radiation  →  Max. allowable radiation doses
-. Find useful additives or combination for lowering doses
-. Laboratory test  →  Confirmation of process
-. Pilot plant  →  Industrial scale design  →  Commercial plants
Survival fraction of micro-organism

<table>
<thead>
<tr>
<th>Doses</th>
<th>Survival fraction of micro-organism</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
<tr>
<td>11</td>
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<td></td>
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<tr>
<td>11</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Area of engineering concern
Area of scientific concern

10kGy

Doses
Examples of Engineering Approaches

Example 1. Industrial e-beam Plant for Treating Textile Dyeing Wastewater.

Example 2. Disinfection of Effluent from the Municipal Wastewater Treatment Plant for Reclamation
Engineering Approaches

- Analysis of existing process
  → Calculate the present cost : 1.1~1.2 USD per m$^3$ of wastewater

- Economics of E-beam
  → Determine the target cost : below 1 USD including bio-treat
  → Cost for radiation processing : below 0.4 USD per m$^3$
  → Max. allowable radiation doses : less than 2 kGy

- Find useful additives or combination for lowering doses
  → Combined with bio-system (Activated sludge system)

- Laboratory test
  → Confirmation of process, engineering design (delivery etc.)

- Pilot plant → Industrial scale design → Commercial plants
Calculation of Required E-beam power

\[ P \ (\text{kW, kJ/s}) = D \ (\text{kGy, kJ/kg}) \times M \ (\text{kg/s}) / F \]

Where \( P \) = delivered power of e-beam (\( \text{kW} = \text{kJ/s} \))

- \( M \) = mass productivity (\( \text{kg/s} \))
- \( D \) = absorbed dose (\( \text{kGy} = \text{kJ/kg} \))
- \( F \) = efficiency of beam energy transfer (0.6~0.7)

Required E-beam for 1,000m\(^3\)/day

\[ P \ (\text{kW}) = \frac{1,000 \times 10^3 \text{kg}/ \ (24 \times 3600) \text{ sec} \times D \ (\text{kGy})}{0.6} \]

with
- 1kGy \( \rightarrow \) 20kW,
- 10kGy \( \rightarrow \) 200kW
- 100kGy \( \rightarrow \) 2000kW

for treating 1,000m\(^3\)/day, with 1~2kGy \( \rightarrow \) 40kW
Researches on Wastewater Treatment

- 1994~1995 : Lab. scale feasibility Test with e-beam and Gamma ray
- 95.12~99.5 : Researches on Dyeing Wastewater Treatment with e-beam
  (Dyeing Technology Center/EB-TECH Co.)
- 96.2 ~97.2 : Treatment of Dyes and Dyeing Wastewater
- 97.2~98.10 : Construction of e-beam Pilot Plant (1000m³/day)
- 98.10~ : Continuous operation of treatment facility
- 1998.9.16 : KT (Korea New Technology) Award
- 2000.7.19 : IR52 Industrial Research Award
- 2001~2006 : IAEA TC Project (Demo Plant Construction)
- 2001~2003 : Preparation for Plant Construction
- 2004 : Start up of Demo Plant Construction
- 2005.12 : Operation of Industrial scale plant (10,000m³/day)
Required E-beam for 10,000m³/day

\[ P \ (\text{kW}) = \frac{10,000 \times 10^3 \text{kg} / (24 \times 3600) \text{sec} \times D(\text{kGy})}{0.6} \]

with 1kGy → 200kW,
10kGy → 2,000kW
100kGy → 20,000kW

for treating 1,000m³/day, with 1~2kGy → 400kW

How to make 400kW machine?

- Energy and power
- How many irradiators?
- How to make uniform irradiation?
<table>
<thead>
<tr>
<th>Electron Energy (MeV)</th>
<th>Max. range in air (m) (20℃, 1atm)</th>
<th>Maximum range in water (mm)</th>
<th>Maximum range in Al (mm)</th>
<th>Maximum range in lead (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>109</td>
<td>132</td>
<td>53.8</td>
<td>10.2</td>
</tr>
<tr>
<td>10</td>
<td>43.1</td>
<td>49.8</td>
<td>21.7</td>
<td>5.42</td>
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<tr>
<td>1</td>
<td>4.08</td>
<td>4.37</td>
<td>2.05</td>
<td>0.69</td>
</tr>
<tr>
<td>0.1</td>
<td>0.13</td>
<td>0.14</td>
<td>0.069</td>
<td>0.027</td>
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<tr>
<td>0.01</td>
<td>0.0024</td>
<td>0.025</td>
<td>0.0013</td>
<td>0.00073</td>
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</tbody>
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Maximum range of accelerated electrons
## Service Conditions of Accelerator for Environmental Uses

<table>
<thead>
<tr>
<th>Flue gas/VOC Purification</th>
<th>Wastewater treatment</th>
<th>Sludge treatment</th>
</tr>
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<tbody>
<tr>
<td>Ti foil between accelerator and reactor</td>
<td>Window is open to wastewater</td>
<td>Sufficient gap to Sludge</td>
</tr>
</tbody>
</table>
### Cost for Unit Power ($/W)

![Graph showing the cost for unit power ($/W) against beam power (MW).](image)

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One-irradiator system

Multi-irradiator system
Experiences in Wastewater Treatment

• For treating 10,000m³/day of water with one –irradiator
  
  - The injection speed of water

\[
\frac{10,000 \text{ m}^3/\text{day}}{24 \times 3,600 \text{ sec/day}} = \frac{1}{0.004 \text{m} \times 2\text{m}} = 14.5\text{m/sec (52km/h)}
\]

• For treating 10,000m³/day of water with three –irradiators
  
  - The injection speed of water

\[
\frac{10,000 \text{ m}^3/\text{day}}{24 \times 3,600 \text{ sec/day}} = \frac{1}{0.004 \text{m} \times 1.5 \times 3} = 3.2\text{m/sec}
\]
H.V. Cable Connection ( <700kV)  

Solid Connection of H.V.
Double-window extraction device
- Power loss
  + Theoretical 15%, 75kW for 500kW
  + Too much power loss, requires huge cooling system

- Power loss
  + Less than 1%, 4~5kW for 400kW
  + Power loss concentrated on small area (jumping area)
High Power Accelerator (EB TECH & BINP)

ELV-12 Accelerator:
Energy: 0.6 - 1.0 MeV
Beam power: 400 kW
Beam current: 500 mA

Irradiators: 3 (0~200mA)
Window width: up to 2m
Double extraction window
Discharge protection
High frequency scanning
Configuration of e-beam Wastewater Treatment

Control System

Power Supply System

Gas System

Vacuum System

Cooling System

Water-Monitoring, Delivery System

COD, BOD, TOC, S/S

Reservoir
Master Schedule

- Project reporting (Dec. 2005)
- Long-term Operation (Nov. 2005)
- Operation of Plant (July 2005)
- Installation of Accelerator (May. 2005)
- Basic Design (Mar. 2004)
- Detail Design (May 2004)
- Purchase Orders (Jul. 2004)
- Shield Room Construction (Oct. 2004)
- Piping & Equipment (Nov. 2004)
- Operation of Plant (July 2005)

Copyright e6TECH 550 yongsan-dong Yuseong-gu, Daejeon 305-500, Korea 55/98
- Fixed cost: interest of 8% and depreciation in 20 years
- Variable cost (based on the year round operation: 8000hr/yr)
  + Electricity consumption (700kW):
    - accelerator 500kW (80% efficiency) other equipment 200kW
  + Labour cost (3-shift): 100,000$/yr

<table>
<thead>
<tr>
<th>Items</th>
<th>Cost Increase by Introducing E-beam</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>Operation Cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Invest (k$)</td>
<td>(3,000)</td>
<td></td>
</tr>
<tr>
<td>Interest</td>
<td>240</td>
<td>8% 20yrs</td>
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<tr>
<td>Depreciation</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>312</td>
<td>700kW 3 shift 2%</td>
</tr>
<tr>
<td>Labour</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Maintenance, etc.</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Total cost</td>
<td>882</td>
<td>E-beam only</td>
</tr>
</tbody>
</table>

- Operation cost for m³ of effluent
  + 882,000$ / 10,000 m³/day /300 \(\approx\) 0.3$ per m³ = 30 ¢ per m³
<table>
<thead>
<tr>
<th>Capital cost</th>
<th>Existing Facility</th>
<th>E-beam plant *</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Investment</td>
<td></td>
<td>(3,000)</td>
</tr>
<tr>
<td></td>
<td>Interest</td>
<td></td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>Depreciation</td>
<td></td>
<td>150</td>
</tr>
<tr>
<td>Operating cost</td>
<td>Chemicals</td>
<td>1,367</td>
<td>580</td>
</tr>
<tr>
<td></td>
<td>Sludge treatment</td>
<td>1,712</td>
<td>1,005</td>
</tr>
<tr>
<td></td>
<td>Electricity</td>
<td>497</td>
<td>809</td>
</tr>
<tr>
<td>Total</td>
<td>3,576</td>
<td>2,784</td>
<td>EB + bio</td>
</tr>
</tbody>
</table>

- Comparison with existing facility
  + Savings by reduction of Chemicals in pre-treatment
  + Savings of sludge treatment costs by reduction in chemicals and also the reduction in retention time in bio-treatment
  + Increase in electricity consumption
- Moreover, the quality of treated water has improved
Examples of Engineering Approaches

Example 1. Industrial e-beam Plant for Treating Textile Dyeing Wastewater.

Example 2. Disinfection of Effluent from the Municipal Wastewater Treatment Plant for Reclamation
What is water/wastewater treatment?

Main purpose of wastewater treatment

- Removal of harmful impurities (COD, BOD, S/S etc.)
- Removal of color, odor etc.
- Removal of T-N, T-P

To discharge to river, or to re-use in industries or irrigation

- Disinfection of microorganisms
  (Coli-form & pathogenic organisms)
- Destruction of endocrine disrupter (natural and synthetic chemicals such as Nonyl phenols and its derivatives)
E-Beam

\[ \text{H}_2\text{O} \rightarrow \text{•OH, } \text{H}^\bullet, \text{e}^-_{\text{aq}}, \text{H}_2, \text{H}_2\text{O}_2 \]

\text{•OH, H}^\bullet, \text{e}^-_{\text{aq}}, + \text{DNA (in microorganism)} \rightarrow \text{Damage to DNA, (Inactivation of bacteria)}

\text{Sterilization Mechanism}

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62/98
Variation of DNA at E. Coli before and after electron beam (Electrophoresis)
### Comparison in Disinfection Technology

<table>
<thead>
<tr>
<th>CHLORINATION</th>
<th>UV RADIATION</th>
<th>OZONE</th>
<th>ELECTRON BEAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Least expensive disinfection.</td>
<td>Not efficient in large scale</td>
<td>Biocidal activity is not influenced by pH.</td>
<td>Simple design and feasible to large scale.</td>
</tr>
<tr>
<td>Forms THMs.</td>
<td>Water with high calcium, turbidity &amp; phenols may not be applicable</td>
<td>Byproducts are formed (bromide, aldehydes, ketones).</td>
<td></td>
</tr>
<tr>
<td>Chlorine gas is a hazardous corrosive gas.</td>
<td>Maintenance cost of UV lamp is high.</td>
<td>Initial cost of ozonation equipment is high.</td>
<td>Needs Shielding (X-ray)</td>
</tr>
</tbody>
</table>
Municipal Wastewater Treatment Plant in Daejeon

Municipal wastewater treatment

**Influent**

1. Screening
2. Sedimentation
3. Aeration
4. Sedimentation

**Effluent**

Sludge treatment

1. Thickening
2. Digesting
3. Dewatering
4. Storage

- Sediment sludge
- Return sludge
- Excess sludge
- Land fill

**Capacity**: 900,000 m³/day

**Influent**: 664,000 m³/day
Existing System

- Discharge after Bio treatment
- Coli-forms etc.
- Residual odor, colors

Proposed System

- Radiation
- Disinfection, Removal of odor, colors

- Industries
- Irrigation
- Re-use
E-Coli

Dose (kGy)

E-Coli (CFU/mL)

STD

Guarantee
Effect of electron beam on the effluent from municipal wastewater plant:

a – radiation induced inactivation of some coliforms in the effluent;
b – variation of BOD, COD, TOC and Color with absorbed doses.
Design and Estimation of E-beam plant

- For Treating Effluent from Municipal Wastewater Plant or from the Contaminated Ground water

- To re-use in Irrigation or Industrial purposes

- Design Basis
  + Capacity: 100,000 m³/day
  + Dose: around 0.2 kGy
  + Expectation: Remove microorganisms over 99%
    Reduction in Color, Odor etc.
  + Operates year-round
### Investment

<table>
<thead>
<tr>
<th>Items</th>
<th>Investment</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accelerator</td>
<td>2,000k$</td>
<td>400kW</td>
</tr>
<tr>
<td>Facilities</td>
<td>1,000k$</td>
<td>Shield room</td>
</tr>
<tr>
<td>Others</td>
<td>1,000k$</td>
<td></td>
</tr>
<tr>
<td>Sub-total</td>
<td>4,000k$</td>
<td></td>
</tr>
<tr>
<td>Area</td>
<td>150m²</td>
<td></td>
</tr>
</tbody>
</table>

### Operation

<table>
<thead>
<tr>
<th>Items</th>
<th>Annual Cost</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Labor</td>
<td>100k$</td>
<td></td>
</tr>
<tr>
<td>2. Electricity</td>
<td>320k$ 800kW<em>0.05$/kWh</em>8000hr</td>
<td></td>
</tr>
<tr>
<td>3. Maintenance</td>
<td>80k$</td>
<td></td>
</tr>
<tr>
<td>4. Interest</td>
<td>(240k$) 6%</td>
<td></td>
</tr>
<tr>
<td>5. Depreciation</td>
<td>(200k$) 20yrs</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>500k$ (440k$)</td>
<td></td>
</tr>
</tbody>
</table>

**Operation cost** → 940k$/[(100,000ton/day)*330day] = 0.028$/ton
## Cost analysis of EB & other processes

<table>
<thead>
<tr>
<th>Technology</th>
<th>Ozone</th>
<th>Electron Beam (EB)</th>
<th>Ultraviolet (UV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>100,000 m³/day</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital Cost</td>
<td>7.4 M$</td>
<td>4.0 M$</td>
<td>2.4 M$</td>
</tr>
<tr>
<td>Annual O&amp;M Cost</td>
<td>1.2 M$</td>
<td>0.5 M$</td>
<td>1.0 M$</td>
</tr>
<tr>
<td>Etc.</td>
<td></td>
<td>Lamp life: 1 year</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lamp p/u: $550</td>
<td></td>
</tr>
</tbody>
</table>

2. Wastewater Technology Fact Sheet, Ultraviolet Disinfection [EPA 832-F-99-064] September 1999
4. EB-TECH Report[2001]
### Amount of wastewater ($m^3$/day)

<table>
<thead>
<tr>
<th></th>
<th>1,000 or less</th>
<th>1,000~10,000</th>
<th>over 10,000</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A/S Invest</strong></td>
<td>H</td>
<td>M</td>
<td>L</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td>M</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td><strong>Ozone Invest</strong></td>
<td>M</td>
<td>MH</td>
<td>H</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td>M</td>
<td>MH</td>
<td>H</td>
</tr>
<tr>
<td><strong>Membrane Invest</strong></td>
<td>M</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td>M</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td><strong>E-beam Invest</strong></td>
<td>H</td>
<td>M</td>
<td>L</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td>LM</td>
<td>L</td>
<td>L</td>
</tr>
</tbody>
</table>

**Relative cost for treating less-polluted industrial wastewater**
1. Find the proper radiation source for products
   - Gamma-ray, X-ray, or e-beam

2. Reduce doses
   - with combined methods (Bio-, Physical/chemical etc.)

3. Apply cost-effective accelerator

4. Engineering Approaches
   - Analysis of existing process → Calculate the present cost
   - Economics of radiation → Max. allowable radiation doses
   - Find useful additives or combination for lowering doses
   - Laboratory test → Confirmation of process
   - Pilot plant → Industrial scale design → Commercial plants

5. Show and Prove the feasibility by pilot operation
   - Laboratory experiments → Pilot scale test with Mobile machine
Lab. Scale Experiments (1~50m³/day)

Pilot scale Experiments (500~1,000m³/day)

- Cost
- Space
- O & M etc.

Lab. Scale Experiments (1~10,000Nm³/h)

Industrial scale Wastewater Plant (10,000m³/day)

Industrial scale EBFGT Plant (~600,000Nm³/h)
# Construction Cost for Pilot Plant

<table>
<thead>
<tr>
<th>Type</th>
<th>Capacity</th>
<th>Main facility</th>
<th>Others</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid</td>
<td>500<del>1,000m³/d with 1</del>5kGy</td>
<td>accelerator (50kW) 0.7M$ shieldroom and Civil 0.4M$ reactor/piping etc. 0.2M$</td>
<td>reservoir etc. 0.3M$ 0.1M$</td>
<td>1.7M$</td>
</tr>
<tr>
<td>Gas</td>
<td><del>20,000Nm³/h with 4</del>8kGy</td>
<td>accelerator (50kW) 0.7M$ shieldroom and Civil 0.4M$ reactor/piping etc. 0.2M$</td>
<td>cooler ESP etc. 0.2M$ 0.4M$ 0.1M$</td>
<td>2.0M$</td>
</tr>
<tr>
<td>Sludge</td>
<td>10~20m³/h with 10kGy</td>
<td>accelerator (50kW) 0.7M$ shieldroom and Civil 0.4M$</td>
<td>conveyor feeder piping etc. 0.1M$ 0.3M$ 0.2M$</td>
<td>1.7M$</td>
</tr>
</tbody>
</table>
Previous Mobile Accelerator (HVEA, U.S.A. 1990)

ICT accelerator
500 keV
0~40 mA
Max. 20kGy

for wastewater
Previous Mobile Accelerator (FZK, Germany 1984)

ESI Electrocurtain  200 keV, 0~150 mA
Flow rate : 1,000Nm³/h  for gas treatment

Previous Mobile Accelerator (BINP, Russia design)

Electron Accelerator

Experimental and analysis systems
Beam Energy : 0.4~0.7MeV,  Beam Power : 20kW
Self-sustaining system : Diesel electricity generator
Total weight : 40 tons
Treatment Capacity

Liquid waste : 500m³/day (at 2kGy)
Gaseous waste : 10,000Nm³/h (at 4kGy)
Sludge : 10m³/h (at 10kGy)
Window size: 640mm, Height from bottom to window: 560mm
Reactors for water, gas and sludge can be located upon the experiments
Application of mobile accelerator

- Reduction of SO\textsubscript{x} /NO\textsubscript{x}, Dioxin from power plant
- Removal of VOCs, stench stink etc.
- Treatment of contaminated underground water
- Treatment of Industrial wastewater
- Reclamationation of effluent from municipal plant
- Sludge hygienization
Current Application of e-beam wastewater

- Treatment of Textile Dyeing Wastewater (Korea, Sri Lanka, Brazil etc.)
- Removal of Toxic Chemicals from Pharmaceutical and Petrochemical Companies. (Pesticide, Explosives, Dyes etc.)
- Removal of PCBs from the Transformer Oils
Removal of PCBs in Transformer Oil

PCB (PolyChlorinated Biphenyl):
Current Application of e-beam wastewater

- Treatment of Textile Dyeing Wastewater
  (Korea, Sri Lanka, Brazil etc.)
- Removal of Toxic Chemicals from Pharmaceutical and Petrochemical Companies.
  (Pesticide, Explosives, Dyes etc.)
- Removal of PCBs from the Transformer Oils
- Reclamation of Municipal Wastewater
  (Disinfection, Removal of endocrine disruptors)
- Treatment of Contaminated Underground Water
  (MTBE, PCBs, Oils, etc.)
- Drinking Water (?)
Drawing by Villemard (1910) – Which will be possible in year 2000
(National Library of France)
Summary

1. Radiation processing has been one of the promising process for environmental treatment, such as Flue gas/VOC, Water/Wastewater, and Sludge from 1970s. However, implementation of large scale plant has still several barriers. (both in technical and economical)

2. Accelerators of several hundreds kilowatt power is already available in the market, and some of them have proved their reliability in long term operation in Flue gas treatment or Wastewater treatment.

3. In spite of tough competitions, radiation processes are promising as long as we keep in economic advantages. And in some cases, the radiation treatment is the only and unique solution for treatment (niche application).
Radiation process (e-beam, γ-ray etc.) can survive only when it has Technical & Economical advantages over existing processes.
Thank You for your attention

Electron Beam Technology

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