Electron beams for wastewater and sludge treatment

2013. 04. 11

BUMSOO HAN, EB TECH Co. Korea

Consultants’ Meeting on “Networking of Users of EB facilities and the Role of the IAEA Collaborating Centers” 8~12 April 2013 INCT, Warsaw, Poland
Major emerging issues identified in the survey (beginning of 2000)

- Climate change: 51%
- Freshwater scarcity: 29%
- Deforestation/desertification: 28%
- Freshwater pollution: 28%
- Poor governance: 27%
- Loss of biodiversity: 23%
- Population growth and movements: 22%
- Changing social values: 21%
- Waste disposal: 20%
- Air pollution: 20%
- Soil deterioration: 18%
- Ecosystem functioning: 17%
- Chemical pollution: 16%
- Urbanization: 16%
- Ozone depletion: 15%
Human Development and Pollution

Human Development

Impressive gains in human development, particularly in the developing world: incomes and income poverty have improved, people are living longer, are healthier, more literate and better educated than ever before.

Average annual incomes in developing countries have mostly risen during 1972-99 by 13 per cent in Africa, by 72 per cent in Asia and the Pacific and by 35 per cent in Latin America and the Caribbean.

World population increased from 3.85 billion people in 1972 to 6.1 billion in mid-2000, and is currently growing by 77 million people a year.

Most of the growth is concentrated in developing regions, with nearly two-thirds in Asia and the Pacific, Latin America and the Caribbean.
The Problems

By rapid economic growth, fast urbanization and enhanced industrial activities all of which add to the degradation of the environmental quality.

The environmental pollution caused by industrial discharges and urbanization, among others, has becoming an acute problem in developing cities in the world. In the current prospect, the problem is projected to be amplified in the future if suitable mitigation measures would not be taken.

The efficient treatment of pollutants discharged in various form and contents from the human activities could be an important contribution to the mitigation of the environmental quality management in the world.
The UN Millennium Development Goals

1. Eradicate extreme poverty and hunger
2. Achieve universal primary education
3. Promote gender equality and empower women
4. Reduce child mortality
5. Improve maternal health
6. Combat HIV/AIDS, malaria, and other diseases
7. Ensure environmental sustainability
8. Develop a global partnership for development
Radiation Technology for Pollution Control

- Flue gas Purification
- Wastewater Treatment
- Sludge Hygienization
Technical Advantages of Radiation process

*. Electron Beam 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 km³ of which only 2.5 per cent, or about 35 million km³, is freshwater.

The usable portion of these sources is only about 200,000 km³ of water — less than 1 per cent of all freshwater and only 0.01 per cent of all water on Earth.
<table>
<thead>
<tr>
<th></th>
<th>Volume (1,000 km³)</th>
<th>% of total water</th>
<th>% of total freshwater</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Salt water</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oceans</td>
<td>1,338,000</td>
<td><strong>96.54</strong></td>
<td></td>
</tr>
<tr>
<td>Saline water/lakes</td>
<td>12,955</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td><strong>Inland waters</strong></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><strong>0.76</strong></td>
<td>30.1</td>
</tr>
<tr>
<td>Others</td>
<td>435</td>
<td>0.02</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Total water</strong></td>
<td>1,386,000</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td><strong>Total freshwater</strong></td>
<td>35,029</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

**Major Stocks of Water**
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 with radiation chemical reaction
4. Disinfection of microorganisms by destruction of DNA
5. Destruction of endocrine disrupter with radical reaction
6. Recycle for irrigation, impoundment and individual uses
Radiation Chemistry of Water

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

Ionization, decay of excited states \( \leq 10^{-12} \text{ s} \)

\[ \text{e}^- \rightarrow \text{e}^-_{\text{therm}} \rightarrow \text{e}^-_{\text{aq}} \]
\[ \text{H}_2\text{O}^+ + \text{H}_2\text{O} \rightarrow \text{H}_3\text{O}^+ + \text{OH} \]
\[ \text{e}^-_{\text{aq}} + \text{H}_3\text{O}^+ \rightarrow \text{H} + \text{H}_2\text{O} \]
\[ \text{H} + \text{H} \rightarrow \text{H}_2 \]
\[ \text{OH} + \text{OH} \rightarrow \text{H}_2\text{O}_2 \]
\[ \text{e}^-_{\text{aq}} + \text{OH} \rightarrow \text{OH}^- \]

“Spur” reactions \( \leq 10^{-8} \text{ s} \)
Principles of Wastewater Treatment with E-Beam

Water Molecule

Active Radicals

Harmful Organic in Wastewater

Complete Decomposition
Partial Decomposition
Suspended Solid
Monomer to Polymerization
Removal of Toxic Group
Removal of Color, Odor

Coagulation

Bio-Treatment

H₂O, CO₂

H₂, OH*, H*
Radiation processing of water treatment plant

- Ontario, Canada (2003)
- Miami, USA (1985)
- Sao Paulo, Brazil (1995)
- Boston, USA (1980)
- Voronezh, Russia (1985)
- Minsk, Russia (1980)
- Moscow, Russia (1990)
- Novosibirsk, Russia (1993)
- Omsk, Russia (2000)
- St. Petersburg, Russia (2005)
- Takasaki, Japan (1991)
- Angarsk, Russia (1998)
- Daegu, Korea (2006)
- Daejeon, Korea (1993)
- Vosibirsksk, Russia (1993)
<table>
<thead>
<tr>
<th>Place</th>
<th>Boston, U.S.A.</th>
<th>Munic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goals</td>
<td>Drinking Water</td>
<td>Drinki</td>
</tr>
<tr>
<td>Capacity</td>
<td>700m³/day</td>
<td>Textile</td>
</tr>
<tr>
<td>Accelerator</td>
<td>ICT, 1.5 MeV, 75kW</td>
<td>Leach</td>
</tr>
</tbody>
</table>

1980 Boston, U.S.A.

Takasaki, Japan

Textile

Leach

East Germany

Gamma cells for Well conditioning

Voronezh, Russia

Contaminated Underground Water
Natural Reservoir
Biological Treatment
E-beam Treatment
Used for Industrial Water

Wastewater Treating Facility with e-beam in Boronezh

3-Beam Treatment

R = (CH3)3C-, (CH3)2CHCH2- or CH3CH2CH(CH3)‑

Nekal SO₃Na
(Isobutynaphthalene sulfonates)

Before after
BOD 500-1000 7-15
COD 1600-5000 60-100

550 yongsan-dong Yuseong-gu, Daejeon 305-500, Korea
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<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Water Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>Miami, U.S.A.</td>
<td>Leachate from Landfill Underground Water</td>
</tr>
<tr>
<td></td>
<td>HVEA, U.S.A.</td>
<td>Underground Water</td>
</tr>
<tr>
<td></td>
<td>Seibersdorf, Austria</td>
<td>Underground Water</td>
</tr>
<tr>
<td></td>
<td>Dubna, Russia</td>
<td>Mixed Wastewater</td>
</tr>
<tr>
<td></td>
<td>Angarsk, Russia</td>
<td>Mixed Petrochemical and Municipal wastewater</td>
</tr>
<tr>
<td></td>
<td>Taegu, Korea</td>
<td>Textile Dyeing Wastewater</td>
</tr>
<tr>
<td></td>
<td>SaoPaulo, Brazil</td>
<td>Dyes etc.</td>
</tr>
</tbody>
</table>

| Nation | USA |
| City   | Miami |
| Object | Wastewater treatment |
| Capacity | 650m³/day |
| Accelerator Model | ICT, 1.5MeV, 75KW |
Wastewater Treatment

What was done
- Textile Dyeing Wastewater (1993~2006)
### Why Textile Dyeing Wastewater?

<table>
<thead>
<tr>
<th>Industry</th>
<th>Number of Companies (%)</th>
<th>Amount of wastewater generated (%)</th>
<th>Amount of wastewater discharged (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Textile co.</td>
<td>1,423 (5.6)</td>
<td>473 (5.4)</td>
<td>457 (19.2)</td>
</tr>
<tr>
<td>Papermill</td>
<td>268 (1.1)</td>
<td>711 (8.1)</td>
<td>364 (15.3)</td>
</tr>
<tr>
<td>Light ind.</td>
<td>511 (2.0)</td>
<td>390 (4.5)</td>
<td>243 (10.2)</td>
</tr>
<tr>
<td>Processing ind.</td>
<td>3,376 (13.3)</td>
<td>439 (5.0)</td>
<td>200 (8.4)</td>
</tr>
<tr>
<td>Metal Fabrication</td>
<td>437 (1.7)</td>
<td>5,346 (61.1)</td>
<td>169 (7.1)</td>
</tr>
<tr>
<td>Others</td>
<td>19,284 (76.2)</td>
<td>1,382 (15.8)</td>
<td>942 (39.7)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>25,299 (100)</strong></td>
<td><strong>8,741 (100)</strong></td>
<td><strong>2,375 (100)</strong></td>
</tr>
</tbody>
</table>

The amount of wastewater generated and discharged in Korea, as of 1995

(1000m³/day)
Process Flow of Existing Wastewater Treatment Facility
Reactive Dyes (C.I. Reactive Black 4)
1,2-Benzenedicarboxylic acid

Formula: $C_8H_6O_4$

Other names: Phthalic acid;

Phthalic acid is one of three isomers with the composition benzenedicarboxylic acid, the others being isophthalic acid and terephthalic acid. Sometimes the term "phthalic acids" is used to refer to this family of isomers, but in the singular, "phthalic acid", refers exclusively to the ortho- isomer.

The toxicity of phthalic acid is low with LD50 (mouse) of 550 mg/kg. However, many phthalate esters have been implicated as endocrine sidrupters.
Further transformations of TPA radicals are realized (in reactions with other radicals donating H-atoms) in changing benzene ring into cyclodiene structure, formation of phenols and decyclization:
Average sludge activity (DHAe) at various HRT
Scientists likes Numbers, Equations, Papers etc.
Engineers – most all

$$\pi = 3.1415926535 8979323846 2643383279 5028841971 6939937510 5820974944$$

5923078164 0628620899 8628034825 3421170679 8214808651 3282306647
0938446095 5058223172 5359408128 4811174502 8410270193 8521105559
6446229489 5493038196 4428810975 6659334461 2847564823 3786783165
2712019091 4564856692 3460348610 4543266482 1339360726 0249141273
7245870066 0631558817 4881520920 9628292540 9171536436 7892590360
0113305305 4882046652 1384146951 9415116094 3305727036 5759591953
0921861173 8193261179 3105118548 0744623799 6274956735 1885752724
8912279381 8301194912 9833673362 4406566430 8602139494 6395224737
1907021798 6094370277 0539217176 2931767523 8467481846 9405132
0005681271 4526356082 7785771342 7577896091 7363717872 1468440901
2249534301 4654958537 1050792279 6892589235 4201995611 2129021960
8640344181 5981362977 4771309960 5187072113 4999999837 2978049951
0597317328 1609631859 5024459455 3469083026 4252230825 3344685035
2619311881 7101000313 7838752886 5875320283 8142061717 7669147303
5982534904 2875546873 1159562863 8823537875 9375195778 1857780532
1712268066 1300192787 6611195909 2164201989...........

some people – not all of them
Scientists likes Numbers, Equations, Papers etc.

Engineer (not all of them, a few …) cares Economics !!! - cost effective
Why Scientists are poor?

Basic Premise 1: scientia est potentia (Knowledge is power)  
(Sir Francis Bacon, 1561~1626)

Basic Premise 2: Time is money  
(Benjamin Franklin, 1706~1790)

Proof: In physics, power is the rate at which work is performed.  
\[ \text{Power} = \frac{\text{Work}}{\text{time}} = \frac{\Delta W}{\Delta t} \]

From premises 1 and 2,  
\[ \text{Power( Knowledge )} = \frac{\text{Work}}{\text{time (money)}} \]

Rewriting to  
\[ \text{Money} = \frac{\text{Work}}{\text{Knowledge}} \]

And  
\[ \lim (\text{Knowledge} \to \infty), \quad \text{Money} = \frac{\text{Work}}{\text{Knowledge}} = 0 \]

Less knowledge, more money?
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
Engineering Approaches

- Analysis of existing process
  → Calculate the present cost: 1.1~1.2 USD per m³ 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 m³
  → 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
Reseatches 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 (1000m$^3$/day)
Construction of Commercial Plant (2005)

Wastewater Treatment Facility in Daegu Dyeing Industrial Complex

Location of Pilot Plant

Commercial plant
<table>
<thead>
<tr>
<th>Electron Energy (MeV)</th>
<th>Max. range in air (m) (20³C,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>
</tr>
<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>
</tr>
<tr>
<td>0.01</td>
<td>0.0024</td>
<td>0.025</td>
<td>0.0013</td>
<td>0.00073</td>
</tr>
</tbody>
</table>

**Maximum range of accelerated electrons**
Nozzle-type Injectors used in Textile Dyeing Wastewater Treatment

Laboratory 50m³/day  Pilot Plant 1,000m³/day  Industrial Plant 10,000m³/day
Effect of electron-beam treatment on biological treatment of dyeing wastewater:

a - kinetics of biotreatment of irradiated (1) and unirradiated (2) wastewater;

b - absorbed dose effect on combined electron-beam/biological treatment.
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)
Cost for unit power ($/W)

<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>
</tr>
</tbody>
</table>
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
Double-window extraction device

1 ion pumps,
2 scanning system,
3 cylinder flange
4 protection cylinder,
5 foil blow cooling,
6 foil fixation frame,
7-extraction foils.
Double-window extraction device
Location of Pilot Plant and Commercial Plant

Wastewater Treatment Facility in Daegu Dyeing Industrial Complex
Technological Scheme of Commercial E-Beam Plant

Configuration of E-Beam Wastewater Treatment

Control System

Power Supply System

Gas System

Vacuum System

Cooling System

Water-Monitoring, Delivery System

Reservoir

COD
BOD
TOC
S/S
Construction of Commercial Plant
Construction of Commercial Plant
Construction of Commercial Plant
Construction of Commercial Plant
COD removal efficiency with 1kGy

Variation of DAHe at HRT 24hr (1Kgy)
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Exhibition at 50th General Meeting of IAEA, Vienna 2006
Wastewater Treatment

What was done
- Textile Dyeing Wastewater (1993~2006)
- Leachate from Land filling (1993~1997)
Process Flow of Papermill Wastewater Treatment

Papermill Wastewater

1st Chemical Treatment

BOD 800
COD 1100

Recirculation 50% or less

Effluent
BOD 5
COD 25

Carbon Filter

BOD 10
COD 35

Multiple Filtration

BOD 15
COD 45

2nd Chemical Treatment

BOD 20
COD 70

Filtration

Sedimentation

BOD 200
COD 350

Biological Treatment

BOD 200
COD 350

Wastewater Recirculation 50% or less
Nozzle Type Injector used in Bench-scale Experiments
Raw Wastewater

After biological Treatment
Effects of Irradiation and Coagulation (Color)
Effects of Irradiation and Coagulation (COD$_{Cr}$)
Effects of Irradiation and Coagulation (TOC)
E-Beam Treatment of Papermill Wastewater

1. Papermill Wastewater
   - BOD 800
   - COD 1100

2. 1st Chemical Treatment
   - BOD 200
   - COD 350

3. Biological Treatment
   - BOD 5
   - COD 20

4. Sedimentation
   - BOD 20
   - COD 70

5. Effluent 20~30%
6. 70~80% Recirculation

7. e-beam irradiation (coagulation)

8. DSF Filtration

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Wastewater Treatment

What was done
- Textile Dyeing Wastewater (1993~2006)
- Leachate from Land filling (1993~1997)
- Wastewater with Heavy Metal (1995~1997)
A Flow Chart for TNT Production

Toluene → Mixed Acid

Nitration

Crude TNT → Purification

Purified TNT Slurry

Spend Acid

Yellow Water

Finishing

Spend Acid Recovery

H₂SO₄ or Mg(NO₃)₂

99% HNO₃

60 - 65% HNO₃

Nitric Acid Concentration

Recycle

Steam - O₂ (NOₓ, SOₓ)

Byproduct

Red Water

To Disposal

Water Acid

Flake TNT

To Disposal

To Storage

Gaseous Emissions

* Neatly Amount

H₂SO₄ or Mg(NO₃)₂

* Toluene

* Trinitromethane

(NOₓ, SOₓ)
Variation of COD concentration during the experimental period
Variation of BOD concentration during the experimental period
Variation of TN during the experimental period
Influent Coagulation Irradiation Bio-system Effluent

Red Wastewater concentration

- COD
- T-N
- BOD
- Organic acid

reaction time

1.2 x 10^2 sec 2.0 x 10^1 sec 3.6 x 10^4 sec
Wastewater Treatment

What was done
- Textile Dyeing Wastewater (1993~2006)
- Leachate from Land filling (1993~1997)
- Wastewater with Heavy Metal (1995~1997)
- Wastewater from Power plant (1997~1998)
- Wastewater from explosives (2000~2004)
- Algal bloom control (2002~2006)
<table>
<thead>
<tr>
<th>MONTH</th>
<th>Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAR</td>
<td>Skeletonema costatum</td>
</tr>
<tr>
<td>APR</td>
<td>Heterocapsa triquetra</td>
</tr>
<tr>
<td>MAY</td>
<td>Eutreptiella gymnastica</td>
</tr>
<tr>
<td>JUN</td>
<td>Heterosigma akashiwo</td>
</tr>
<tr>
<td>JUL</td>
<td>Karenia mikimotoi</td>
</tr>
<tr>
<td>AGU</td>
<td>Prorocentrum triestinum</td>
</tr>
<tr>
<td>SEP</td>
<td>Prorocentrum dentatum</td>
</tr>
<tr>
<td>OCT</td>
<td>Prorocentrum micans</td>
</tr>
<tr>
<td>NOV</td>
<td>Prorocentrum minimum</td>
</tr>
<tr>
<td></td>
<td>Akashiwo sanguinea</td>
</tr>
<tr>
<td></td>
<td>Cochlodinium polykrikoides</td>
</tr>
</tbody>
</table>
Continuous flow under-beam water treatment facility
- **Reduction of Algae**

![Graph showing decrease in algae with e-beam irradiation dose]

**Decrease in Algae with e-beam**

- **Removal efficiency**

![Graph showing removal efficiency with irradiation dose]

- Depending on the Algae,
  - Removal of 50~60% at 1kGy, 60~70% at 2 kGy
● TEM observation \((C.\text{polykrikoides})\)
Wastewater Treatment

What was done
- Textile Dyeing Wastewater (1993~2006)
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- Wastewater with Heavy Metal (1995~1997)
- Wastewater from Power plant (1997~1998)
- Wastewater from explosives (2000~2004)
- Algal bloom control (2002~2006)
- Destruction of PCBs from Transformer Oil (2006~2008)
Removal of PCBs in Transformer Oil

PCB (PolyChlorinatedBiphenyl):

\[
\begin{align*}
3 & \quad 2 & \quad 2' & \quad 3' \\
\end{align*}
\]

5  6  6'  5'

Cl

Cl

4  4'

Removal of PCBs in Transformer Oil

PCB (PolyChlorinatedBiphenyl):
Wastewater Treatment

What was done
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- Wastewater with Heavy Metal (1995~1997)
- Wastewater from Power plant (1997~1998)
- Wastewater from explosives (2000~2004)
- Algal bloom control (2002~2006)
- Destruction of PCBs from Transformer Oil (2006~2008)

What is going on
- Effluent from Municipal plant for re-use (with Pele and HDR, 2008~)
Types of Water/Wastewater Treatment

High contamination
- Textile dyeing wastewater
- Leachate from landfill area
- from petrochemical plant
- from paper mills
- from mines (coal, metals)
- from chemical plants

Removal of impurities (COD, BOD, S/S etc.)
Discharge

Low or less contamination
- Underground water
- Water from lakes or marshes
- Effluent of municipal plants

Disinfection
- Removal of Color, Odor, Residuals
Re-use
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)
<table>
<thead>
<tr>
<th>Amount of wastewater (m³/day)</th>
<th>1,000 or less</th>
<th>1,000~10,000</th>
<th>over 10,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/S Invest</td>
<td>H</td>
<td>M</td>
<td>L</td>
</tr>
<tr>
<td>Operation</td>
<td>M</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>Ozone Invest</td>
<td>M</td>
<td>MH</td>
<td>H</td>
</tr>
<tr>
<td>Operation</td>
<td>M</td>
<td>MH</td>
<td>H</td>
</tr>
<tr>
<td>Membrane Invest</td>
<td>M</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Operation</td>
<td>M</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>E-beam Invest</td>
<td>H</td>
<td>M</td>
<td>L</td>
</tr>
<tr>
<td>Operation</td>
<td>LM</td>
<td>L</td>
<td>L</td>
</tr>
</tbody>
</table>

Relative cost for treating lowly-polluted industrial wastewater
## 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>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Existing System**

Discharge after Bio treatment

- Microorganisms, EDs etc.
- Residual odor, colors

**Proposed System**

Radiation

- Disinfection, Removal of odor, colors, EDs
- Irrigation
- Industries
- Re-use
(EB data is based on the experiments from EB TECH)
Wastewater Treatment

What was done
- Textile Dyeing Wastewater (1993~2006)
- Leachate from Land filling (1993~1997)
- Wastewater with Heavy Metal (1995~1997)
- Wastewater from Power plant (1997~1998)
- Wastewater from explosives (2000~2004)
- Algal bloom control (2002~2006)
- Destruction of PCBs from Transformer Oil (2006~2008)

What is going on
- Effluent from Municipal plant for re-use (with Pele and HDR, 2008~)
- Marine Ballast water (with U. Akron, 2010~)
Ten of the Most Unwanted

Marine plants, animals and microbes are being carried around the world attached to the hulls of ships and in ships’ ballast water. When discharged into new environments, they may become invaders and seriously disrupt the native ecology and economy. Introduced pathogens may cause diseases and death in humans.

North American Giant Jelly
Bougainvillea globosa
Native to: Eastern Pacific and North America
Introduced to: South America, Australia and New Zealand
Impact: High economic and legislative impact. The jellyfish can cause severe injury to humans and deplete some species.

Green Crab
Carcinus maenas
Native to: Europe and North America
Introduced to: Australia, New Zealand and South Africa
Impact: Economically important. It can outcompete native species, leading to a decline in biodiversity.

European Green Crab
Carcinus maenas
Native to: Europe and North America
Introduced to: South Africa and Australia
Impact: High economic and legislative impact. It can cause significant damage to shellfish and other marine life.

Asian Clam
Corbicula fluminea
Native to: Asia
Introduced to: Europe, North America and Australia
Impact: Economically important. It can cause significant damage to aquaculture and other marine life.

Zebra Mussel
Dreissena polymorpha
Native to: Europe
Introduced to: North America
Impact: Economically important. It can cause significant damage to aquaculture and other marine life.

Atlantic Cod
Gadus morhua
Native to: North Atlantic
Introduced to: North America and Europe
Impact: Economically important. It can outcompete native species, leading to a decline in biodiversity.

Mitten Crab
Charybdis dorab
Native to: North and South America
Introduced to: Europe and Australia
Impact: Economically important. It can cause significant damage to aquaculture and other marine life.

Tomato Azalea
(Red-Brown/Green Tides)
Native to: Various species with broad ranges
Introduced to: Various locations
Impact: High economic and legislative impact. It can cause significant damage to marine ecosystems.

Yellow-legged Mantis Shrimp
Hymenocera laevis
Native to: West Africa
Introduced to: Various locations
Impact: High economic and legislative impact. It can cause significant damage to marine ecosystems.

Further information:
- Global Ballast Water Management Programme
- International Maritime Organisation
- UN Convention on Biological Diversity
- FAO
Optical Microscope Observation of Irradiated Algal Cell

No irradiation

6kGy

a: Unirradiated *Chlorella* sp.

b: Irradiated *Chlorella* sp.

c: Disintegrated *Chlorella* sp.

---

a: Unirradiated *Chlorella* sp.

b: High molecular substance leaching out from the disintegrated *chlorella* sp.

c: Disintegrated *Chlorella* sp.
Wastewater Treatment

What was done
- Textile Dyeing Wastewater (1993~2006)
- Leachate from Land filling (1993~1997)
- Wastewater with Heavy Metal (1995~1997)
- Wastewater from Power plant (1997~1998)
- Wastewater from explosives (2000~2004)
- Algal bloom control (2002~2006)
- Destruction of PCBs from Transformer Oil (2006~2008)

What is going on
- Effluent from Municipal plant for re-use (with Pele and HDR, 2008~)
- Marine Ballast water (with U. Akron, 2010~)

What will be
- Disinfection of Frac water
Overview of Frac Water Treatment

1. Fracturing operations
   - Fresh water source
   - Frac water
   - Frac fluid to well
   - Disinfection
   - Production Well
   - Blending with fresh water source
   - Treated water storage
   - Near-site treatment & storage for re-use

2. Production operations
   - Separators
   - Oil stock tanks
   - Produced water tanks
   - Gas to sales
   - Oil to pipeline/trucked
   - Gas to flare

3. Frac flow-back operations
   - Sand trap
   - Flowback manifold
   - Separators
   - Oil recovery
   - Flowback water tanks
   - On-site treatment • Filtration
   - To storage/re-use

4. Near-site treatment
   - Filtration
   - Reclamation
   - Distillation

5. Off-site disposal/discharge
   - Offsite disposal
     - Injection well (Operator owned or Commercial)
     - Sub-surface disposal*
   - Off-site treatment
     - Filtration
     - Reclamation
     - Distillation
   - Surface discharge
Disinfection – Two new technologies: Chlorine Dioxide & Mixed Oxidants

**Adaptation of ClO₂ to frac operations**

- **Technology**
  - On-site, on-demand generation of Chlorine Dioxide from the blend of three precursor chemicals
  - Technology has been used to disinfect water for over 30 years. Effectiveness is not limited in treating produced water as is the current version of the MIOX technology
  - Based on well established ClO₂ generating technology from Dupont, being adapted to frac site environment (Dupont owns the IP on the blending generator)
  - Higher operating safety risk than MIOX due to handling of the precursors, but it can be mitigated

- **Status**
  - Pilot unit designed and currently being built
  - Pilot unit design is one that will be able to be made commercial pending adjustments determined during trials.

**Mixed oxidants through partnership with MIOX**

- **Technology**
  - On-site, on-demand generation of mixed oxidant by electrolysis of sodium chloride solution
  - Eliminates toxic biocides/ full disclosure
  - Does not interact with slickwater or X-linked frac fluids
  - Small footprint & low CAPEX
  - **Partnership**, New Mexico-based company developing novel water disinfectant solutions
    - Equity investment to develop mixed oxidant system for flow-back water and on-site Bromine or quat ammonia generator
    - Exclusive rights in all aspects of water treatment for fracturing/stimulation operations.

- **Status**
  - Full scale prototype completed with 2 field trials, one for SWN, one for CHK.
  - Currently working for CHK in the EagleFord.
E- Beam Sludge Treatment

+ Sludge Hygienization

\[ \text{H}_2\text{O} \xrightarrow{\text{Radiation}} \cdot\text{OH}, \text{H} \cdot, \text{e}_{\text{aq}}^-, \text{H}_2, \text{H}_2\text{O}_2 \]

\( \cdot\text{OH}, \text{H} \cdot, \text{e}_{\text{aq}}^- + \text{DNA of microorganism} \rightarrow \text{Damage in DNA} \) (no duplication)
Sludge Disinfection Plant in the World

- Takasaki, Japan (1991)
- Daejeon, Korea (2006)
- Tucuman, Argentina (1998)
- Baroda, India (1989)
- New Mexico, USA (1978)
- Edmonton, Canada (1993)
- Sao Paulo, Brazil (1993)
- Florida, USA (1984)
- Weldel, Germany (1980)
- Seibersdorf, Austria (1975)
- Warsaw, Poland (1994)
- Munich, Germany (1973)
- Florida, USA (1984)
- Sao Paulo, Brazil (1993)
<table>
<thead>
<tr>
<th>Facilities</th>
<th>Irradiation Source</th>
<th>Irradiated material</th>
<th>Operation condition</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geiselbullach, Germany (1973-1984)</td>
<td>Gamma-ray (Co-60, Cs-137) 0.57Mci</td>
<td>Liquid Sewage sludge, 145m3/day</td>
<td>2-3kGy</td>
<td>Commercial plant</td>
</tr>
</tbody>
</table>
IAEA: Consultants' Meeting 3 – 6 Nov. 2008

T. Lessel: 20 Years Experiences with a Practical Gamma Irradiation Plant...
<table>
<thead>
<tr>
<th>Facilities</th>
<th>Irradiation Source</th>
<th>Irradiated material</th>
<th>Operation condition</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baroda, India</td>
<td>Gamma-ray(60Co)</td>
<td>Liquid Sewage sludge, 110m³/day(4%SS)</td>
<td>3-5kGy</td>
<td>Commercial plant</td>
</tr>
<tr>
<td>(1989)</td>
<td>0.5Mci</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Facilities**

- **Irradiation Source**: Gamma-ray(60Co), 0.5Mci
- **Irradiated material**: Liquid Sewage sludge, 110m³/day(4%SS)
- **Operation condition**: 3-5kGy
- **Remarks**: Commercial plant

**Diagram**

- Radiation Process - Modified
- The source frame inside the irradiator
<table>
<thead>
<tr>
<th>Facilities</th>
<th>Irradiation Source</th>
<th>Irradiated material</th>
<th>Operation condition</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tucuman, Argentina</td>
<td>Gamma-ray (60Co)</td>
<td>Liquid Sewage sludge,</td>
<td>3kGy</td>
<td></td>
</tr>
<tr>
<td>(1998)</td>
<td>0.7 Mci</td>
<td>180 m³/day (8-10% SS)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Facilities | Irradiation Source | Irradiated material | Operation condition | Remarks
--- | --- | --- | --- | ---
Verginia Key Florida, USA(1984) | Electron beam (ICT type) (75kW/1.5MeV/50mA) | Liquid Sewage sludge, 645m³/hr, 4%ss | 4kGy 10mm-thick | Pilot plant
<table>
<thead>
<tr>
<th>Facilities</th>
<th>Irradiation Source</th>
<th>Irradiated material</th>
<th>Operation condition</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takasaki, Japan (1991)</td>
<td>Electron beam (Cockcroft-walton) (15kW/2MeV/15kW)</td>
<td>Sewage sludge cake</td>
<td>5kGy 1-10mm thick</td>
<td>Conveyor/Nozzle</td>
</tr>
</tbody>
</table>
Edmonton, Canada (1993)

<table>
<thead>
<tr>
<th>Facilities</th>
<th>Irradiation Source</th>
<th>Irradiated material</th>
<th>Operation condition</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edmonton, Canada (1993)</td>
<td>Electron beam (IMPELA) 50kW(10MeV, 5mA)</td>
<td>Dewatered Sludge, 63t/d</td>
<td>5-15kGy</td>
<td>Proposal</td>
</tr>
</tbody>
</table>
## Warsaw, Poland (1994)

<table>
<thead>
<tr>
<th>Facilities</th>
<th>Irradiation Source</th>
<th>Irradiated material</th>
<th>Operation condition</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warsaw, Poland (1994)</td>
<td>Electron beam (LAE13/9) (10MeV, 15kW)</td>
<td>Sewage sludge cake, 70t/day</td>
<td>5-7kGy 2-3cm thick</td>
<td></td>
</tr>
</tbody>
</table>
Sludge Treatment

What was done

- Improving dewatering efficiency of Sludge (1996~2000)
Dewatering of anaerobic digested sludge (EB Tech, 2000)

- Samples of Digested sludge
- Belt press
- Dewatering by Belt press
(a): Centrifuge
(b): Vacuum filtration
(c): Belt press

Effect of electron beam irradiation dose and dewatering methods on water content of dewatered sludge cake
Batch and CSTR with EB Pretreated Sludge

Gas collecting Bag → Wet Gas Meter → Gas Composition Analysis

Motor

Water Sealing

Substrate Feed

Effluent → Sample Analysis

Sampling Port

Gasket

Height = 42 cm

ID = 18 cm
Scanning electron microscopic (SEM) examination of unirradiated sewage sludge (left) and irradiated sludge at 6kGy (right)

Untreated T-S

EB 6kGy
Sludge Treatment

What was done

-. Improving dewatering efficiency of Sludge (1996~2000)
-. Disinfection Sludge Hygienation for re-use (2005~2009)
Sewage Sludge Treatment (ISRAEL)
Shafdan Wastewater Treatment Plant
Electron Beam Sludge System
Sludge Treatment

What was done

- Improving dewatering efficiency of Sludge (1996~2000)
- Disinfection Sludge Hygienation for re-use (2005~2009)

What is going on

- Removal of EDs for sanitary land-filling (2012 ~ )
Endocrine Desrupters (EDCs)

1. Normal
   - body's hormone receptor
   - Cell
   - reaction

2. Blocked
   - body's hormone
   - hormone blocker receptor
   - Cell

3. Insufficient
   - hormone mimic receptor
   - Cell
   - reaction

4. Excessive
   - hormone mimic receptor
   - Cell
   - reaction
Sludge Treatment

What was done

- Improving dewatering efficiency of Sludge (1996~2000)
- Disinfection Sludge Hygienation for re-use (2005~2009)

What is going on

- Removal of EDs for sanitary land-filling (2012 ~ )
- Commercial plant (with Israel 2008 ~ )

What will be

- Soil treatment (?)
Panax Ginseng pathology

- Fungal infection can readily destroy ginseng crops. One of the major diseases for *Panax ginseng* is the root rot caused by the fungus, *Cylindrocarpon destructans*, *Fusarium solani*, *Erwinia- Carotovora* and *Pseduomonas Fluorescens*.
- The exact causes of ginseng rusty root in which brown areas develop are unknown. It was reported that a rust spot formation could result from physiological stresses infection by fungal pathogens or enrichment of iron.

Rot Ginseng (Total Lost price : 0.6 billion $/year)
One month growth after electron beam sterilization

2007
Irradiated planted field for sterilization (1)
Irradiated replanted field for sterilization (2)
Non-irradiated replanted field (3)
Non-irradiated first planted field (4)

2008
Irradiated replanted field (1)
Non-irradiated replanted field (2)
<table>
<thead>
<tr>
<th>Years</th>
<th>Flue Gas</th>
<th>Wastewater</th>
<th>Sludge</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td></td>
<td></td>
<td>Munich, Germany (1973~1984)</td>
</tr>
<tr>
<td></td>
<td>Badenwerk, Germany (1985)</td>
<td>Ontario, Canada</td>
<td>Weldel, Germany (1980)</td>
</tr>
<tr>
<td></td>
<td>Beijing, China (2005)</td>
<td>Beijing, China (2010)</td>
<td>Tel Aviv, Israel (2007)</td>
</tr>
</tbody>
</table>

Red colored plants are with Gamma ray.
Capital Investment and O&M cost for Typical Wastewater and Sludge Treatment
## Treatment cost of typical wastewater and liquids

<table>
<thead>
<tr>
<th></th>
<th>Dose (kGy)</th>
<th>Amount (m³/day)</th>
<th>Required Beam (kW)</th>
<th>Capital cost (M$)</th>
<th>O&amp;M cost M$/y (with fixed cost)</th>
<th>O&amp;M cost $ per m³</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pilot plant of effluent from municipal plant</td>
<td>0.5</td>
<td>5,000</td>
<td>50</td>
<td>1.25</td>
<td>0.193* (0.318)**</td>
<td>0.12 (0.19)</td>
</tr>
<tr>
<td>2</td>
<td>Industrial Textile dyeing wastewater</td>
<td>2</td>
<td>10,000</td>
<td>400</td>
<td>3.0</td>
<td>0.81 (1.11)</td>
<td>0.24 (0.33)</td>
</tr>
<tr>
<td>3</td>
<td>Disinfection of effluent from municipal plant</td>
<td>0.4</td>
<td>100,000 (400X2)</td>
<td>800</td>
<td>5.7</td>
<td>1.62 (2.19)</td>
<td>0.049 (0.066)</td>
</tr>
<tr>
<td>4</td>
<td>Removal of PCBs from Transform. oils</td>
<td>50</td>
<td>100</td>
<td>100</td>
<td>1.5</td>
<td>0.26 (0.41)</td>
<td>7.9 (12.4)</td>
</tr>
<tr>
<td>5</td>
<td>Removal of PCBs from Transform. oils</td>
<td>50</td>
<td>20 (Mobile)</td>
<td>20</td>
<td>(1.3)</td>
<td>0.17 (0.30)</td>
<td>26 (45)</td>
</tr>
<tr>
<td>Any Liquid</td>
<td>1</td>
<td>5,000</td>
<td>100</td>
<td>1.5</td>
<td>0.26 (0.41)</td>
<td>0.16 (0.25)</td>
<td>Rule of thumb</td>
</tr>
</tbody>
</table>

* Variable cost only: labor, electricity, maintenance
** Both variable and fixed cost (Interests and depreciation)
Land Application of Sludge (ISRAEL)
## Treatment cost of typical sludge and solid wastes

<table>
<thead>
<tr>
<th></th>
<th>Dose (kGy)</th>
<th>Amount</th>
<th>Required Beam (kW)</th>
<th>Capital cost (M$)</th>
<th>O&amp;M cost M$/y (with fixed cost)</th>
<th>O&amp;M cost $ per m³</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Liquid sludge (0.5~3% solid)</td>
<td>5</td>
<td>1,000 (m³/day)</td>
<td>100</td>
<td>1.5</td>
<td>0.26* (0.41)**</td>
<td>0.79 (1.24)</td>
</tr>
<tr>
<td>2</td>
<td>Dewatered Sludge cake (18% solid)</td>
<td>10</td>
<td>7,000 (m³/mon)</td>
<td>100</td>
<td>2.0</td>
<td>0.17 (0.37)</td>
<td>2.0 (4.4)</td>
</tr>
<tr>
<td>3</td>
<td>Dewatered Sludge cake (18% solid)</td>
<td>10</td>
<td>7,000 (m³/mon)</td>
<td>50</td>
<td>1.75</td>
<td>0.19 (0.36)</td>
<td>2.2 (4.3)</td>
</tr>
<tr>
<td>4</td>
<td>Dewatered Sludge cake (18% solid)</td>
<td>10</td>
<td>15,000 (m³/mon)</td>
<td>100</td>
<td>2.0</td>
<td>0.26 (0.46)</td>
<td>1.5 (2.6)</td>
</tr>
<tr>
<td>5</td>
<td>Any Solids</td>
<td>10</td>
<td>15,000 (m³/mon)</td>
<td>100</td>
<td>2.0</td>
<td>0.26 (0.46)</td>
<td>1.5 (2.6)</td>
</tr>
</tbody>
</table>

* Variable cost only: labor, electricity, maintenance
** Both variable and fixed cost (Interests and depreciation)
Why e-beam processes are not widely used?

Theories are easy, but practical applications are not easy.
- Strong competition with conventional technology
- Hard to move from lab. to commercial scale.
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.
Lab. Scale Experiments (1~50m³/day)

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

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

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

Industrial scale EBFGT Plant (~600,000Nm³/h)

550 yongsan-dong Yuseong-gu, Daejeon 305-500, Korea
WWW.EB-TECH.COM
Mobile Plant is the Solution for Demonstration of e-beam

Pilot scale Experiments
(~500m$^3$/day of water)
(~2,000Nm$^3$/h of gas)
Beam Energy : 0.4~0.7MeV, Beam Power : 20kW
Self-sustaining system : Self-shielded accelerator
Built-in control and monitoring room
Diesel electricity generator (option)
Trailer and Shelter : Fit to U.S. and world standard
Total weight : 40 tons (trailer only 30ton)
Built-in Computerized Experimental & Monitoring System
Continuous Treatment of Wastewater/Flue gas on site
Treatment Capacity: Liquid waste: 500m$^3$/day (at max. 2kGy)
Gaseous waste: 2,000Nm$^3$/h (at max. 15kGy)
First Barrier
(Steel+Lead+Steel)

Second barrier
Polyethylene(PE)10mm-assume for MCNP
(real 50mm: EpoxyGlass+Urethane+EpoxyGlass)
Wastewater under Treatment with Mobile Accelerator
Mobile e-beam in Flue gas Purification from oil-refinery in Saudi Arabia

550 yongsan-dong Yuseong-gu, Daejeon 305-500, Korea

WWW.EB-TECH.COM
Future Plan

**Wastewater Treatment**
- Effluent from Municipal plant for re-use (with Pele and HDR, 2008~)
- Marine Ballast water (with U. Akron, 2010~)
- Disinfection of Frac water

**Gaseous Waste Treatment**
- Flue gas removal from heavy oil plant (with Saudi Aramco 2011~)
- VOCs removal from automobile industries (2012~)
- Demo plant in a larger scale (60,000 ~ 200,000Nm3/h)
- Combined treatment of wastewater and flue gas

**Sludge Treatment**
- Removal of EDs for sanitary land-filling (2012~)
- Commercial plant (with Israel 2008~)
- Mobile plant (?)
Ecological creditors and debtors
Environmental health risk transitions

Low income Populations in poverty

Middle income Populations in transition

High income Industrialized society

Basic risks: Lack of safe water, sanitization and hygiene, indoor air pollution, vector-borne diseases, hazards that cause accidents and injuries

Modern risks: unsafe use of chemicals, environmental degradation

Engineering risks: unsafe use of chemicals, environmental degradation