Application and Economies of Electron Beam Wastewater Treatment

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1. Why e-beam treatment ?
2. Characteristics of e-beam wastewater treatment
3. Review of previous works
4. Examples of e-beam water/wastewater treatment
6. Pros and Cons of e-beam wastewater treatment
7. Summaries

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. E-Beam treatment can not remove T-N, T-P and Salts

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** $\cdot H$ **(reducer);**
- **hydroxyl radical** $\cdot OH$ **(oxidizer).**

$$H_2O \rightarrow e^-_{aq} + H_2O^+ \qquad H_2O \rightarrow H + OH \qquad H_2O \rightarrow H_2 + O$$

Ionization, decay of excited states $\leq 10^{-12}$ s

$$e^- \longrightarrow e^-_{therm} \longrightarrow e^-_{aq}$$
$$H_2O^+ + H_2O \longrightarrow H_3O^+ + OH$$
$$e^-_{aq} + H_3O^+ \longrightarrow H + H_2O$$
$$H + H \longrightarrow H_2$$
$$OH + OH \longrightarrow H_2O_2$$
$$e^-_{aq} + OH \longrightarrow OH^-$$

"Spur" reactions $\leq 10^{-8}$ s

G-values of primary water radiolysis products at the end of "spur" processes (1/100 eV)

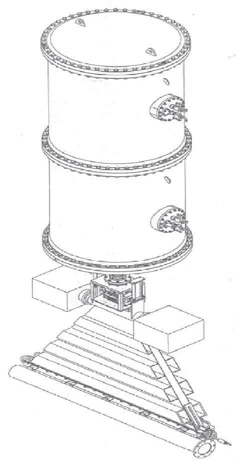
e^-_{aq}	H	OH	O	H_2	H_2O_2	H_3O^+	OH^-
2.8	0.6	2.8	0.007	0.45	0.7	3.3	0.5

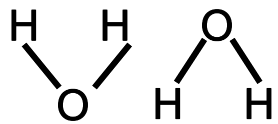
1 kGy = 1kJ/kg

1kJ ≈ 6.3 X 10^{21} eV → 1.8 X 10^{20} OH radicals

1kg of water ≈ 56 mole → 3.3 X 10^{25} H_2O molecules

radical concentration → 1/10^5





Water Molecule

e_{aq}

OH^*

H^*

H_2O_2

Active Radicals

Harmful Organic in Waste water

- Complete Decomposition → H_2O, CO_2
- Partial Decomposition
- Suspended solid
- Monomer to Polymerization

→ Coagu lation

- Removal of Toxic group → Bio-Treat
- Removal of Color, Odor

Principles of Wastewater treatment with electron beam

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^{+6})

-. Re-use of effluent from Municipal wastewater plant

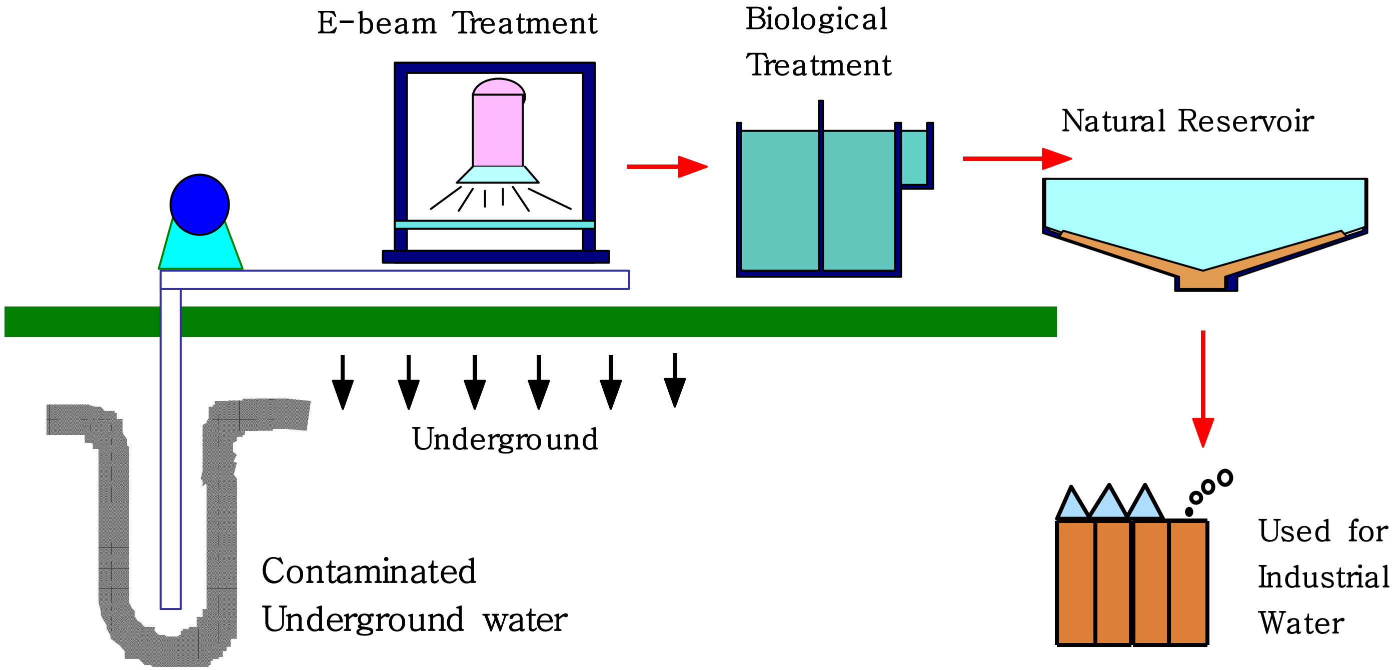
-. Remediation of contaminated water (PCB,Explosives)

-. Contaminated Underground water

-. Drinking water

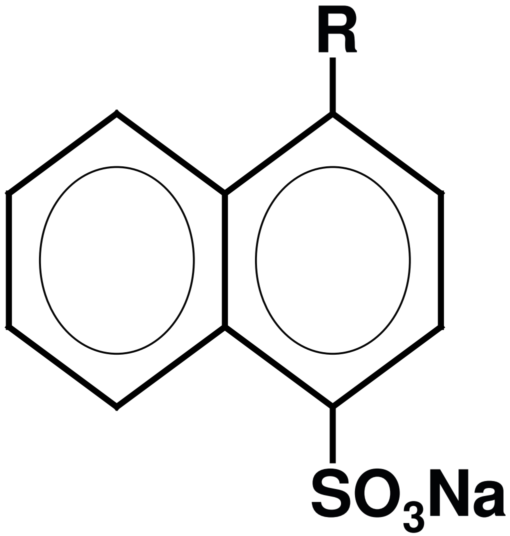
Review of previous works

1980	Boston, U.S.A.	Municipal Sewage
		Drinking Water
	Takasaki, Japan	Textile Wastewater
		Leachate from Landfill
	East Germany	Gamma cells for
		Well conditioning
	Voronezh, Russia	Contaminated underground water



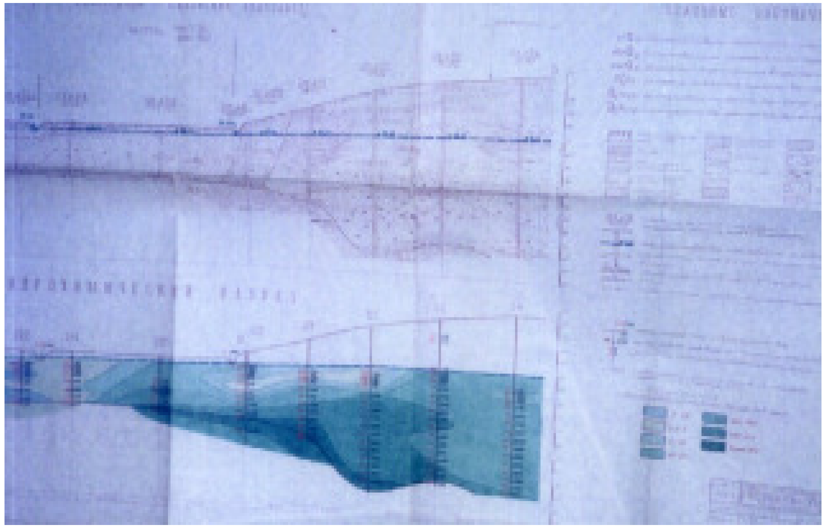
Wastewater Treating Facility with e-beam in Boronezh

Accelerators operated in Voronezh Wastewater Facility, Russia



Nekal
(Isobutylnaphthalene sulfonates)

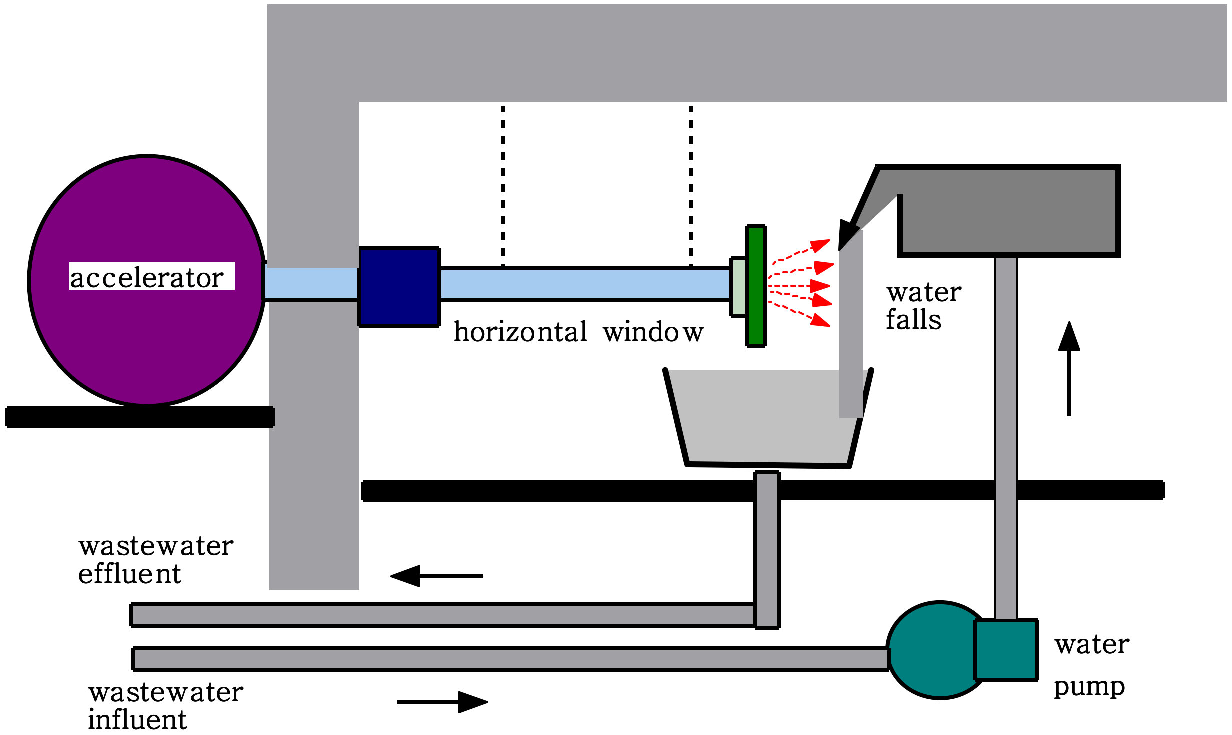
R = (CH3)3C-, (CH3)2CHCH2- or CH3CH2CH(CH3)-



Contamination Level in Underground Water of Voronezh City, Russia

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

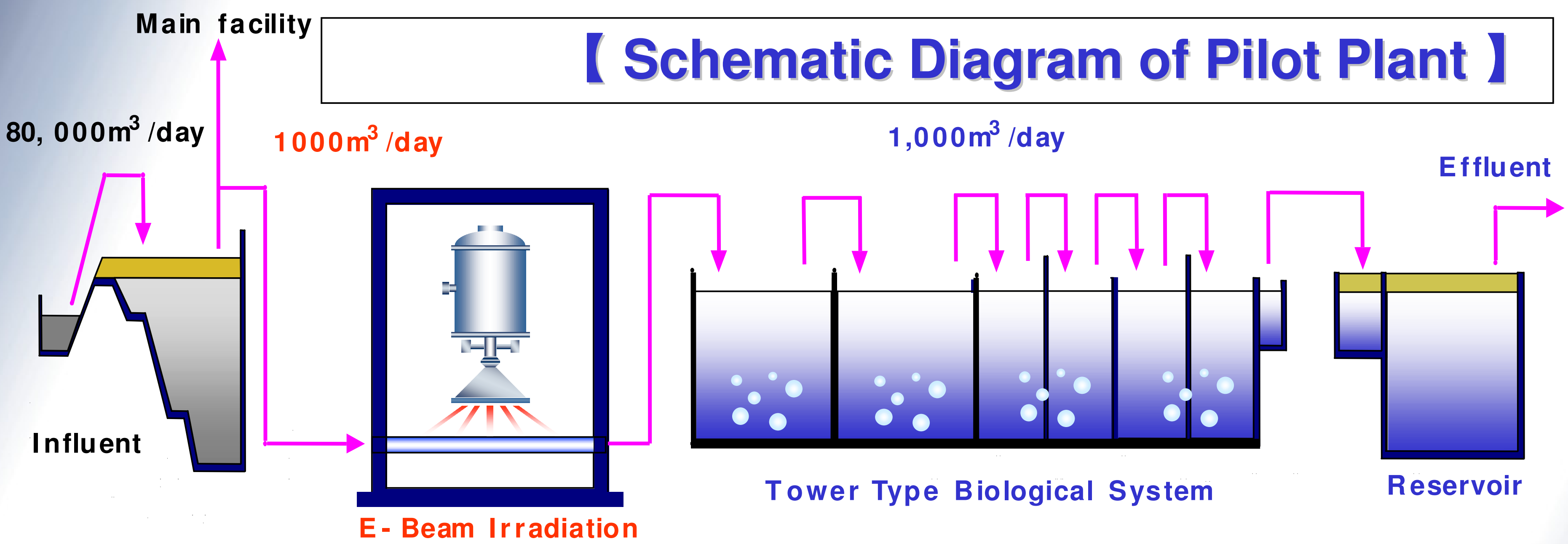
1990	Miami, U.S.A.	Leachate from Landfill
		Underground Water
	HVEA, U.S.A.	Underground Water
	Seibersdorf, Austria	Underground Water
	Angarsk,Russia	Mixed Petrochemical and
		Municipal wastewater
	Taegu, Korea	Textile Dyeing Wastewater
	SaoPaulo,Brazil	Dyes etc.

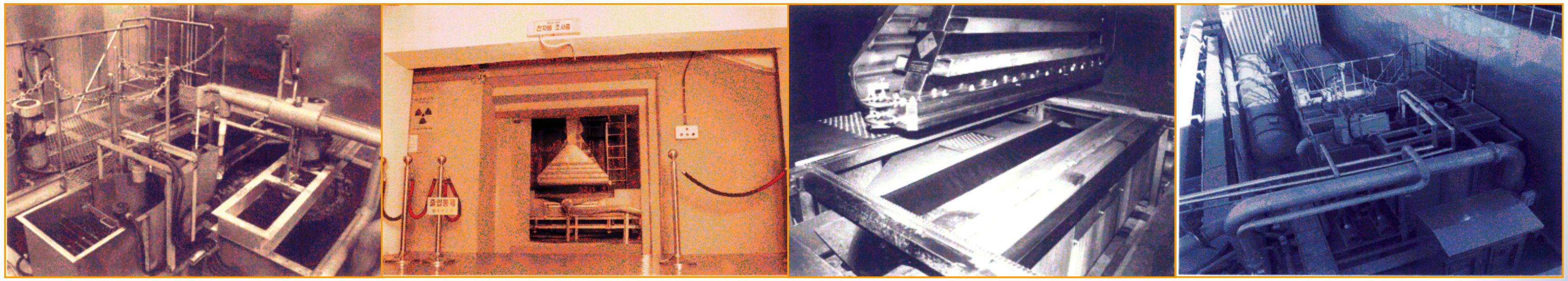


Wastewater Treating Facility with e-beam in Miami

2000	IPC, Russia	Wastewater from Distillery,
		Petrochemical co.
	UNCW, U.S.A.	Underground Water
	Seibersdorf, Austria	Underground Water
		Effluent from municipal plant
	EB-TECH, Korea	Textile Dyeing, Papermill,
		Re-use of effluent
	IPEN, Brazil	Dyes, Municipal waste
	Portugal, Hungary, Turkey, Poland, Jordan	

【 Schematic Diagram of Pilot Plant 】





Economies of e-beam water/wastewater treatment

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

- no restrictions on cost
- removal of toxic compound etc.

If not, severe competition with other process

- to make cost-effective, safe, reliable system
- Industrial wastewater, Re-use of effluent, Underground water, Drinking water etc.

Electron beam process can survive only when it has economical advantages over existing processes.

-. Accelerators for Environmental Application

-. Cost for e-beam process

-. How to improve economical efficiency

Electron Accelerators Required for Environmental Uses

In General

-. Firm and Stable for year-round operation (over 8,000hrs/yr)

-. High Efficiency - economical in power consumption

-. Easy and Safe operation

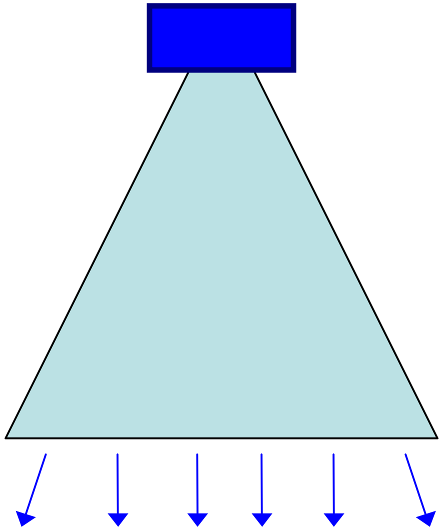
Technically

-. Uniform doses over effluent

-. Enough scanning speed compared to the speed of effluent

-. Stability of beam energy and power

Efficiency of E-beam Treatment



Beam Power (kW)

$$\text{Dose delivered} = \frac{\text{E-Beam Energy}}{\text{Amount of water}} \times \underbrace{f_1 \times f_2 \times f_3 \times f_i \ldots\ldots}_{(F)}$$

f_1 =	efficiency of E-beam Machine	0.2~0.9
f_2 =	efficiency of transmission thru air	0.2~0.8
f_3 =	efficiency of Water delivery system	0.3~0.9
f_i =	other factors affecting the efficiency	?

Normally in good machine, the efficiency F≈0.6~0.7

Calculation of required power

$$P\ (kW) = M\ (kg/s)\ D\ (kJ/kg)\ /\ F$$

Where P = required power of e-beam (kW = kJ/s)

M = mass productivity (kg/s = 86.4m^3/day for water)

D = dose delivered (kGy = kJ/kg)

F = efficiency of beam energy transfer (~0.6)

$$P\ (kW) = \frac{M(m3/d)\ D(kGy)}{50} \quad \text{or} \quad M(m3/d) = \frac{50\ P(kW)}{D(kGy)}$$

Required E-beam power for fixed amount of Wastewater

$$P(kW) = \frac{M(m3/d)\ D(kGy)}{50}$$

for 5,000m³/day, with 1kGy → 100kW

10kGy → 1000kW

100kGy → 10000kW

for treating 100,000m³/day, with 0.2kGy → 400kW

Amount of Wastewater treated with fixed E-beam power

$$M(m^3/d) = \frac{50\ P(kW)}{D(kGy)}$$

with 100kW accelerator, at 1kGy → 5,000m³/day

10kGy → 500m³/day

100kGy → 50m³/day

with your 400kW accelerator, at 1kGy → 20,000m3/day

with your 400kW accelerator, at 0.2kGy → 100,000m3/day

For the re-use of effluent 100,000m^3/day with 0.2kGy

Investment (I) - Accelerator, 400kW(A) = 2.0~2.5 M$

- BLDG & Tech. (B) = 1.0~1.5 M$
- Others (C) = 0.5 M$

I = A+B+C ≅ 4.0 (~4.5) M$

Excluding : Cost for Land

R & D Cost

Cost for approval from Authorities

Operation (O)

- Interest (In)	*6%*	= 240,000$	Fixed
- Depreciation (Dp)	*20yr*	= 200,000$	
- Electricity (E)		= 320,000$	Variable
+. Accelerator (500kW)			
+. Pumps etc. (300kW)			
where, r = cost of electricity (USD/hr)	*r = 0.05$*		
T = operation time (hr/yr)	*T = 8000hr*		
- Chemicals (Ch)			
- Labors (L)	*3 operator (1×10^5 $)*	= 100,000$	
- Maintenance (M)	*2%*	= 80,000$	

O = In + Dp + E + Ch + L + M = 940,000$

~ 1M$

For the operation of 400kW accelerator,

Investment 4.0M USD

Operation 0.5M USD/yr

(1.0M USD/yr with interest & depreciation)

It can treat up to 100,000m^3/day with 0.2kGy.

about 12Cents for Construction

and 1.5(3)Cents for operation for each m^3/day

Even in more conservative calculation,

Operation (O)

- Interest (In) *10%* = 400,000$
- Depreciation (Dp) *10yr* = 400,000$
- Electricity (E) = 400,000$
  - +. Accelerator (500kW)
  - +. Pumps etc. (300kW) + 200kW

  where, r = cost of electricity (USD/hr) *r = 0.05$*

  T = operation time (hr/yr) *T = 8000hr*
- Chemicals (Ch)
- Labors (L) *3 operator (1×10⁵ $)* = 200,000$
- Maintenance (M) *3%* = 120,000$

O = In + Dp + E + Ch + L ~ 1. 5M$

It cannot exceed 5Cents for operation for each m^3/day

Investment

items		Investment	Remark
Construction	Accelerator	2,000k$	400kW
	Facilities	1,000k$	Shield room
	Others	1,000k$	
Sub-total		4,000k$	
Area		150m^2	

Operation

Items	Annual Cost	Remark
1. Labor	100k$	
2. Electricity	320k$	800kW*0.05$/kWh*8000hr
3. Maintenance	80k$	
4. Interest	(240k$)	6%
5. Depreciation	(200k$)	20yrs
Total	500k$(440k$)	

Operation cost→ 500k$/[(100,000ton/day)*333day] = 0.015$/ton

Cost analysis of EB & other processes

Technology	Ozone	Electron Beam(EB)	Ultraviolet (UV)
Flow		100,000m^3/day	
Capital Cost	7.4M$	4.0M$	2.4M$
Annual O&M Cost	1.2M$	0.5M$	1.0M$
Etc.			Lamp life : 1year Lamp p/u : $550

1. *Combined Sewer Overflow Technology Fact Sheet, Alternative Disinfection Methods [EPA 832-F-99-033] September 1999*
2. *Wastewater Technology Fact Sheet, Ultraviolet Disinfection [EPA 832-F-99-064] September 1999*
3. *1999 Drinking Water Infrastructure Needs Survey, Modeling the Cost of Infrastructure [EPA 816-R-01-005] February 2001*
4. *EB-TECH Report[2001]*

How to Improve Economies and Survive ?

1. Reduce required doses
   - -. Find useful Additives (like Ozone etc.)
   - -. Combined with other methods

2. Improve efficiencies
   - -. Machine efficiency
   - -. Improve Wastewater delivery system

3. Reduce the cost of e-beam Facility
   - -.Use more Powerful Accelerator

Useful additives

To assist the radiation chemical reaction

- with radical enhancers, scavengers etc.
- with inexpensive, harmless additives (gluten etc.)
- with catalyst

Addition of Ozone

- To increase the number of OH radicals
- Additional effect of ozone

$$H_2O \xrightarrow{e^{\ominus}} \begin{cases} H_3O^{\oplus} ; OH^{\ominus} \\ \boxed{OH ; e^{\ominus}_{aqu} ; H} \\ H_2 ; O_2 ; H_2O_2 \end{cases}$$

$$O_3 + \begin{cases} e^{\ominus}_{aqu} \\ H \\ H_2O_2 \end{cases} \longrightarrow OH$$

Radiation is absorbed by the water not by solutes !

<u>Two</u> sources for OH (water radiolysis and O_3 decomposition)

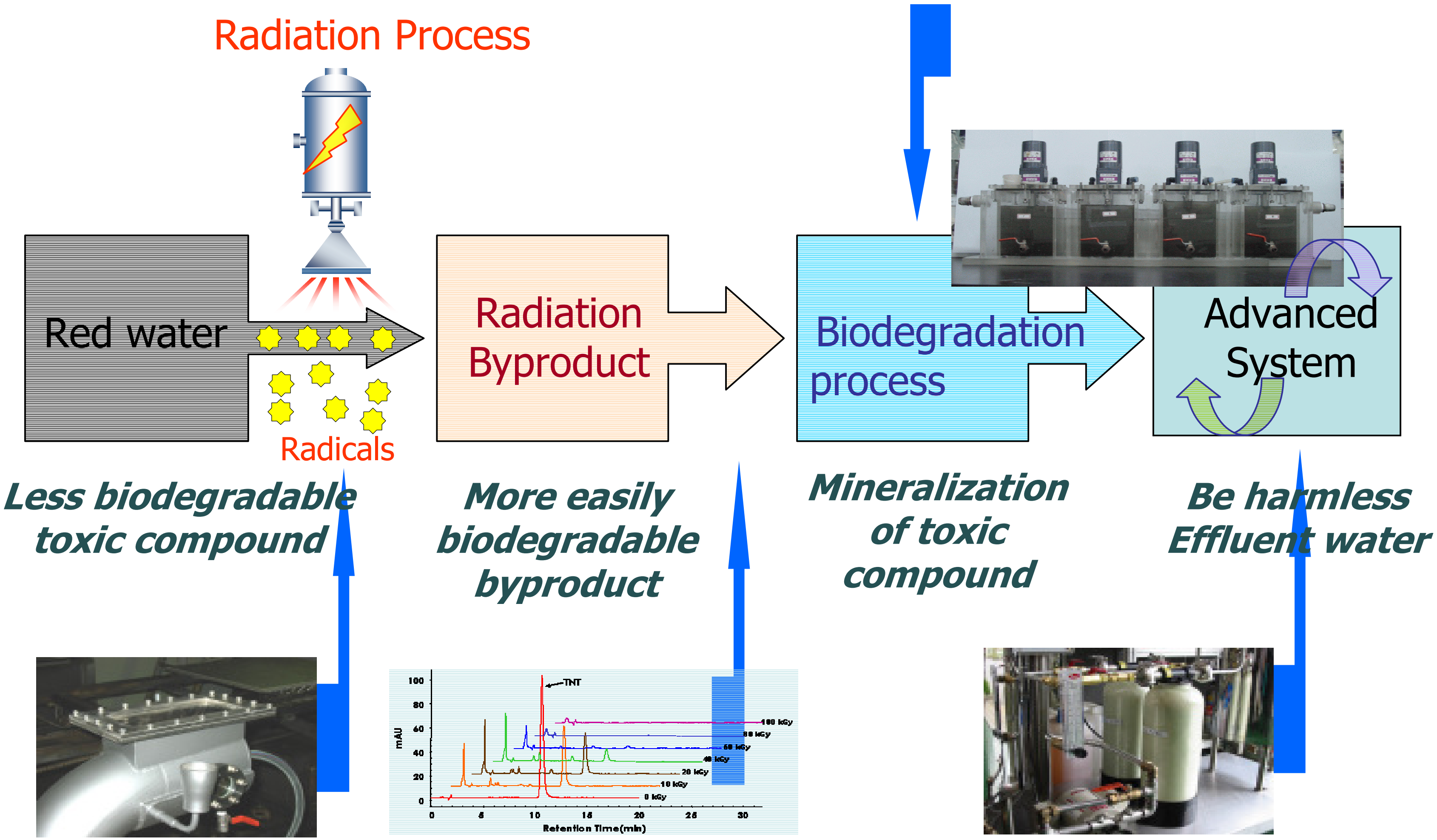
Combine with other systems

Biological system (activated sludge treatment etc.)

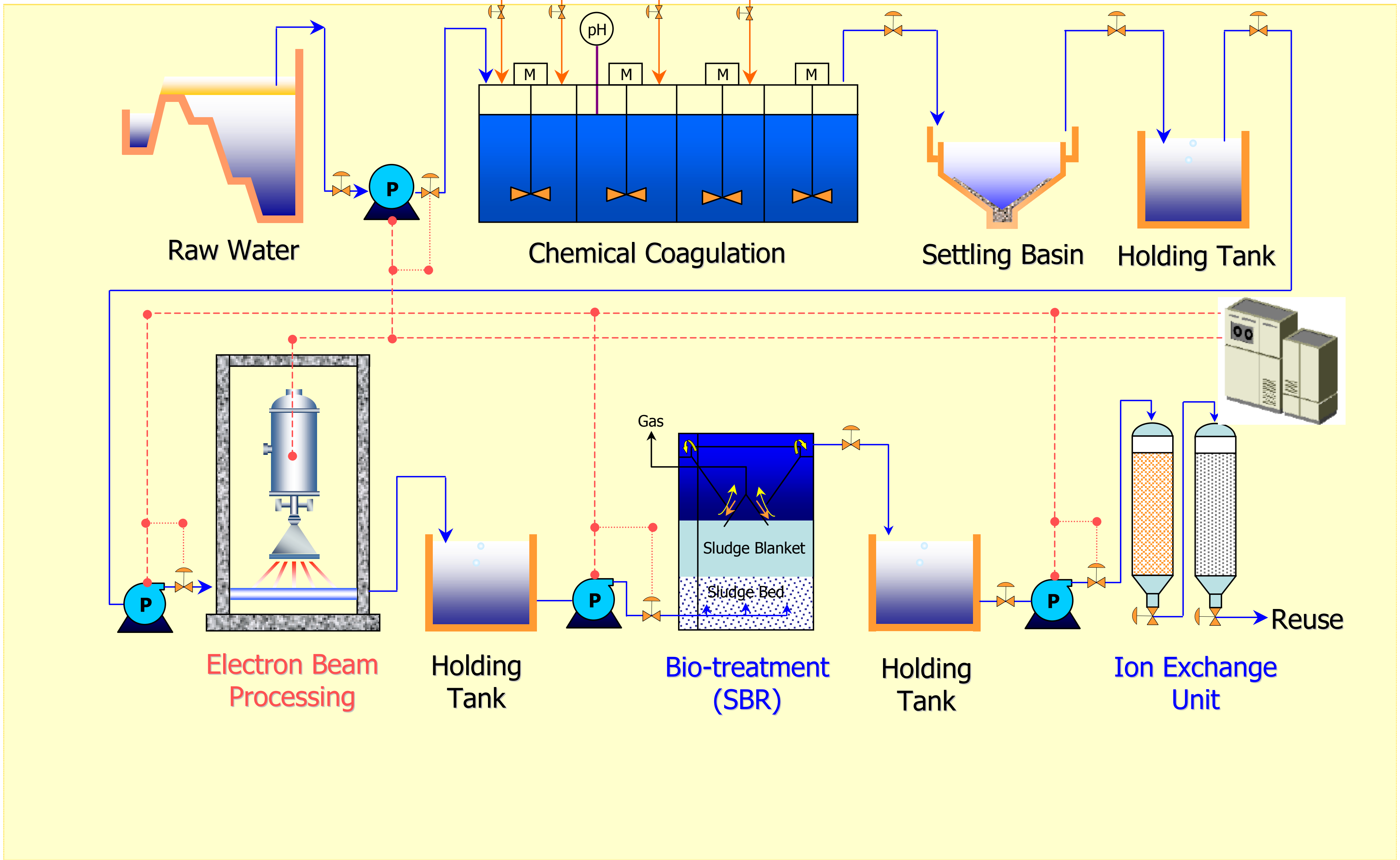
- Reduction in biodegradable organic impurities
- Removal of T-N, T-P
- Difficult to remove non-biodegradable substances
- Difficult to remove salts

Physico-chemical system (coagulation etc.)

- Reduction in organic/inorganic impurities
- Difficult to remove T-N, T-P

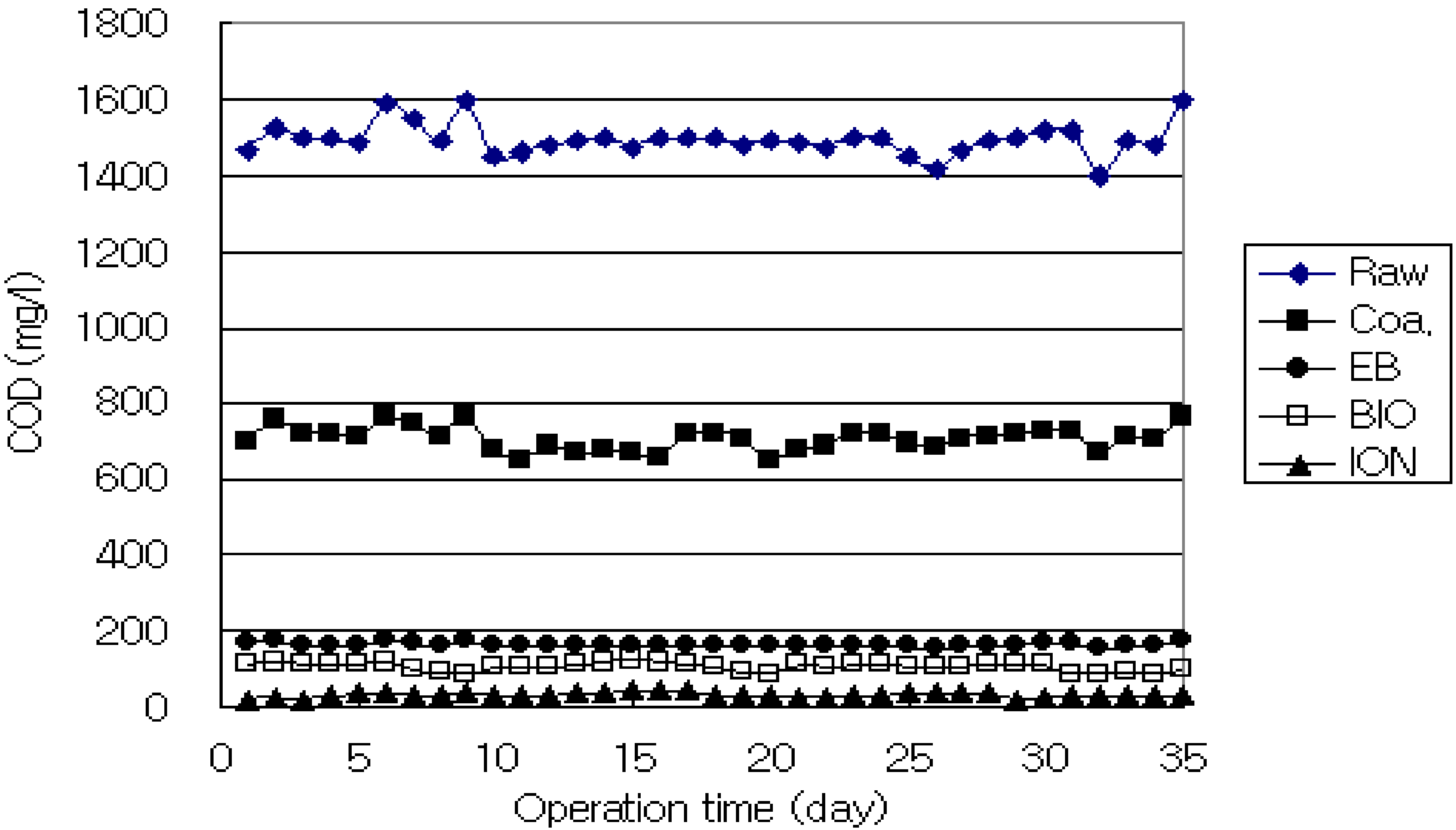


Radiation Process
Red water
Radicals
Radiation Byproduct
Biodegradation process
Advanced System
Less biodegradable toxic compound
More easily biodegradable byproduct
Mineralization of toxic compound
Be harmless Effluent water
TNT
mAU
Retention Time(min)

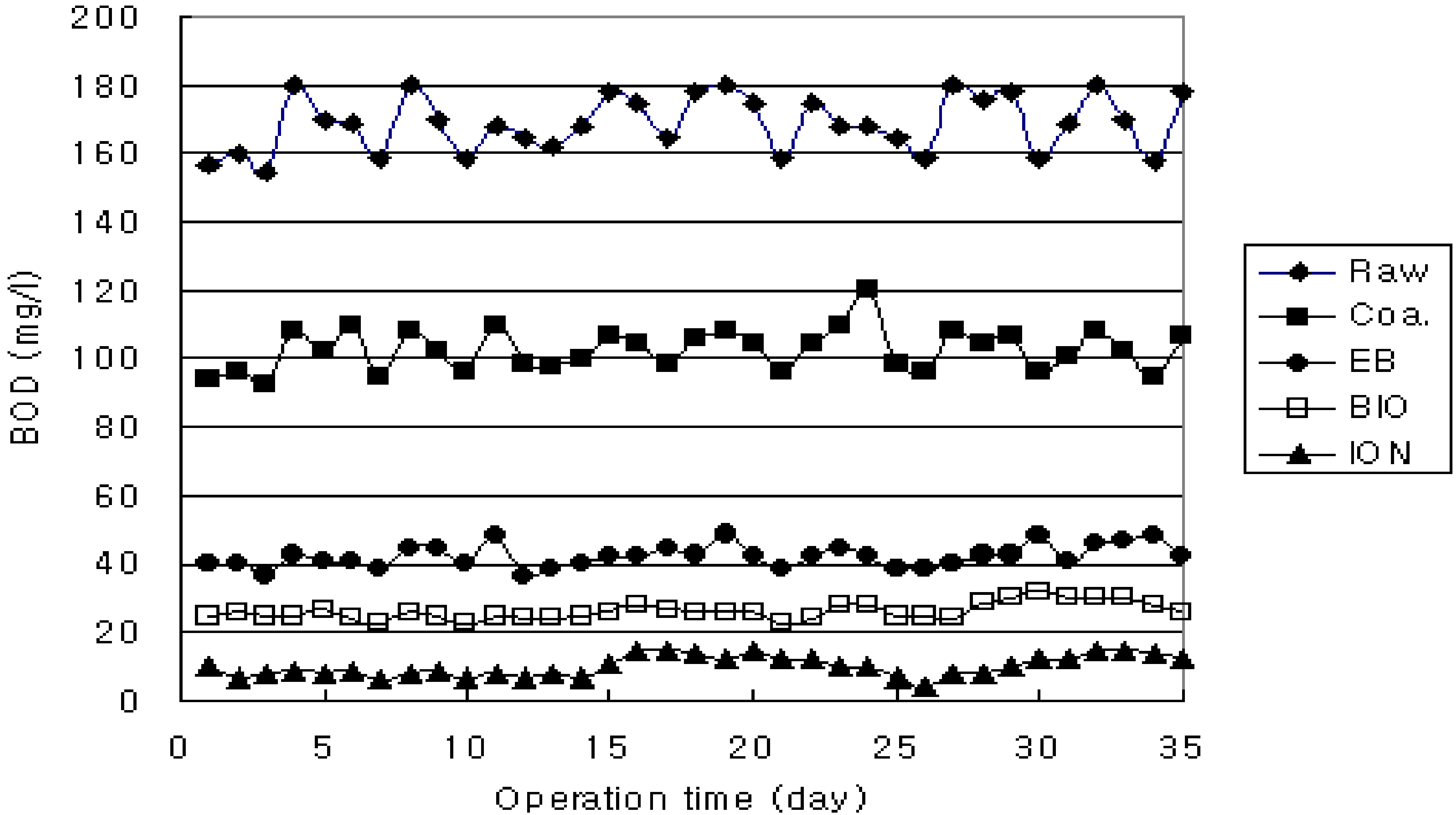


$Al_2(SO_4)_3$
NaOH
Polymer
pH
M
M
M
M
Raw Water
P
Chemical Coagulation
Settling Basin
Holding Tank
Gas
Sludge Blanket
Sludge Bed
P
P
P
Reuse
Electron Beam Processing
Holding Tank
Bio-treatment (SBR)
Holding Tank
Ion Exchange Unit

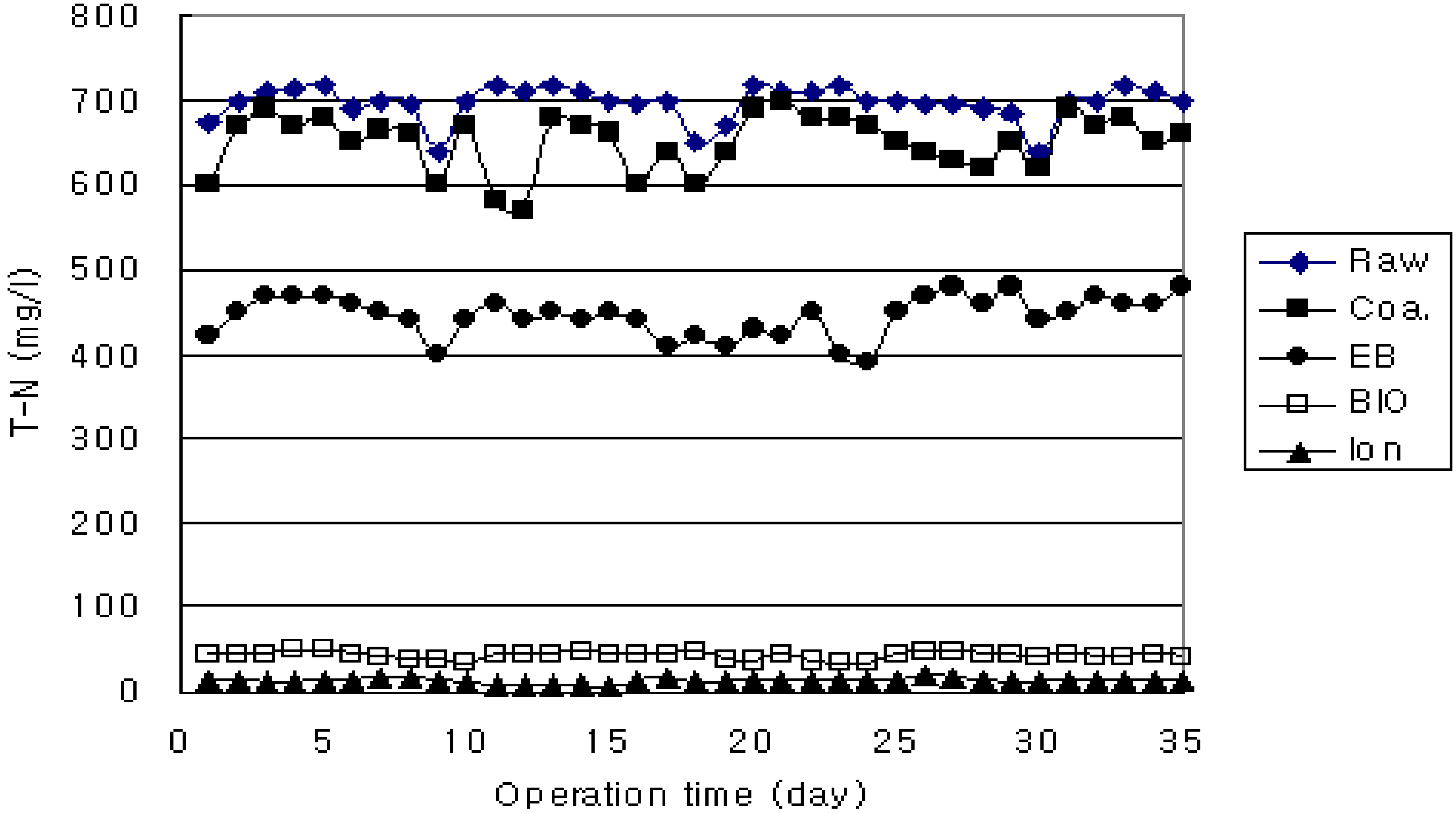
Variation of COD concentration during the experimental period

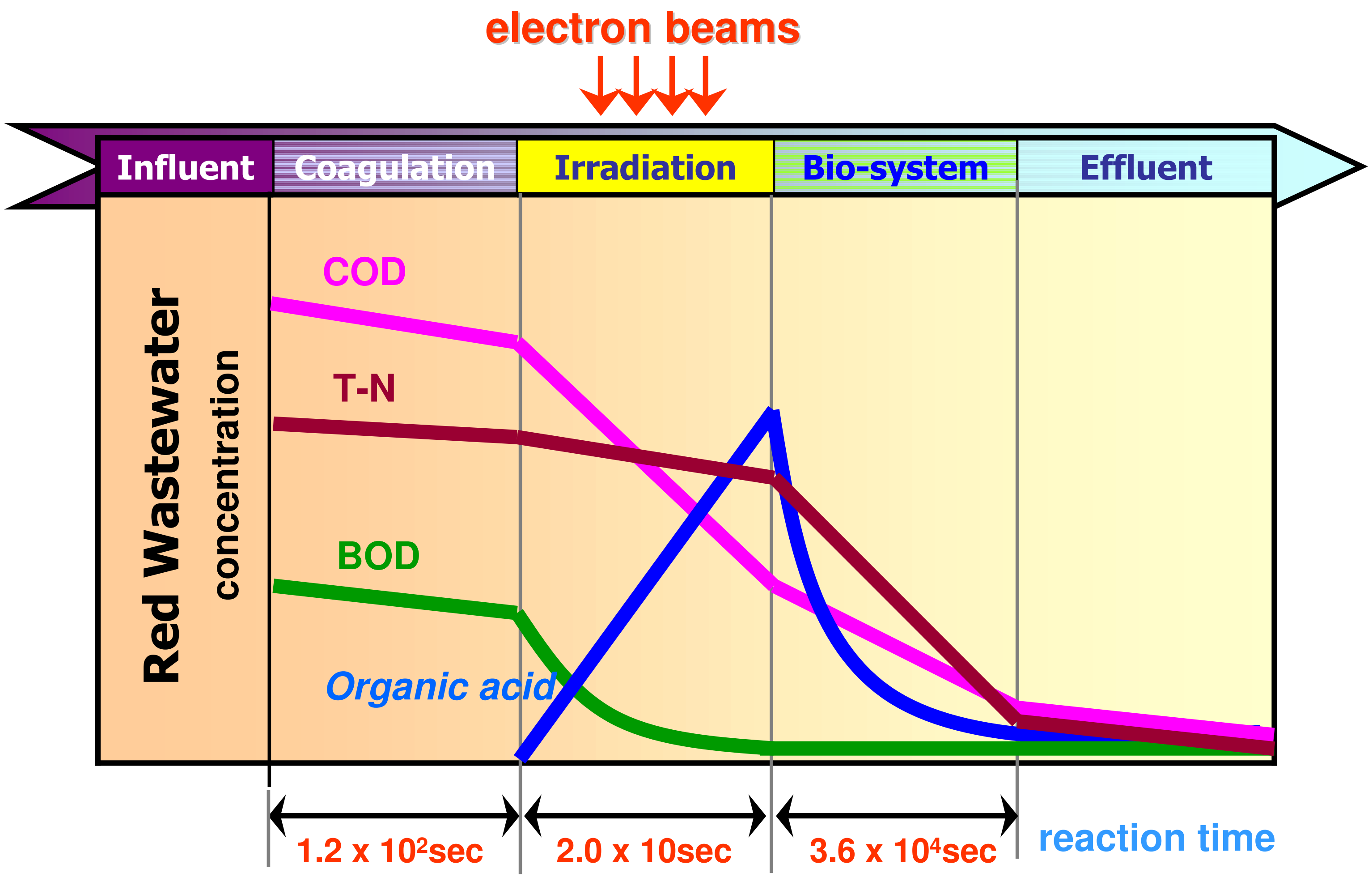


Variation of BOD concentration during the experimental period

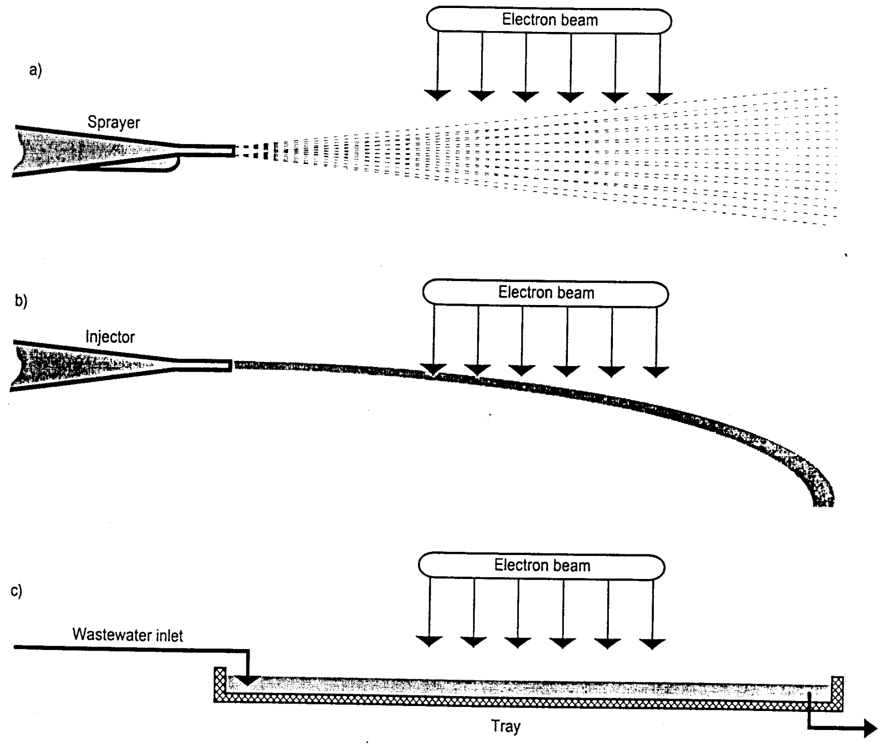


Variation of TN during the experimental period

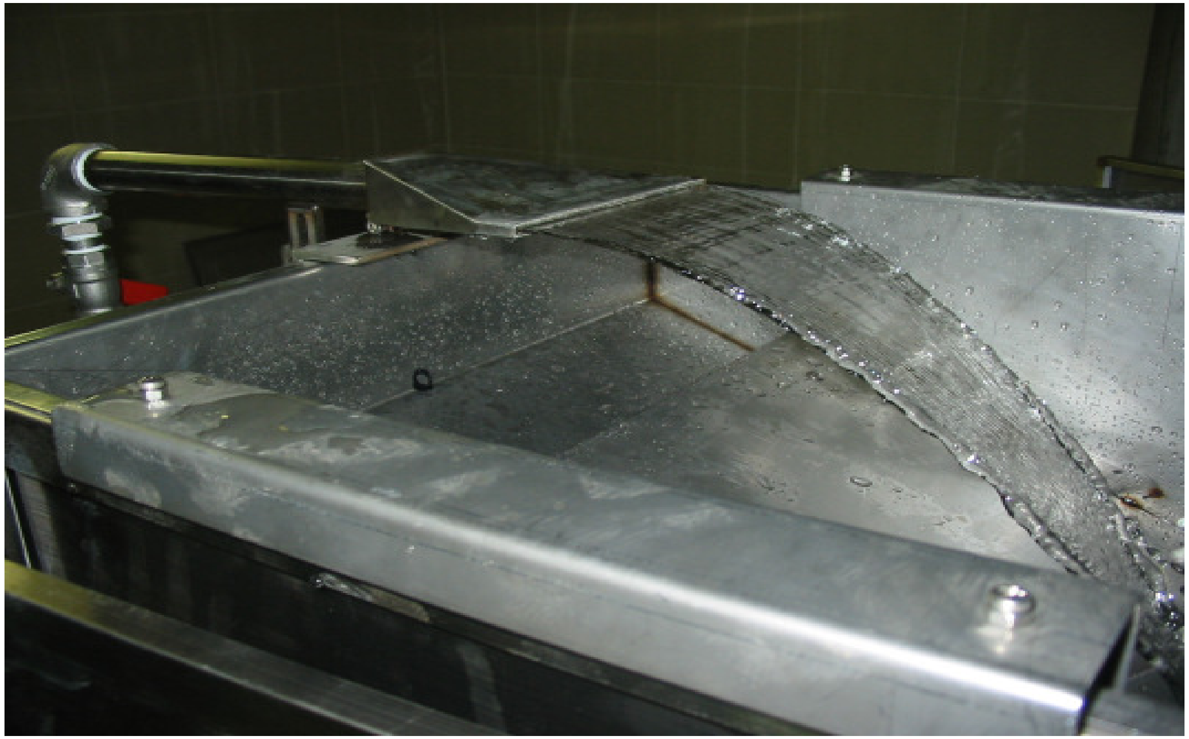



electron beams
Influent
Coagulation
Irradiation
Bio-system
Effluent
Red Wastewater
concentration
COD
T-N
BOD
Organic acid
1.2 x 10²sec
2.0 x 10sec
3.6 x 10⁴sec
reaction time

Improve Wastewater Delivery System



Different types of water reactor (Spray, Injection and Flow)

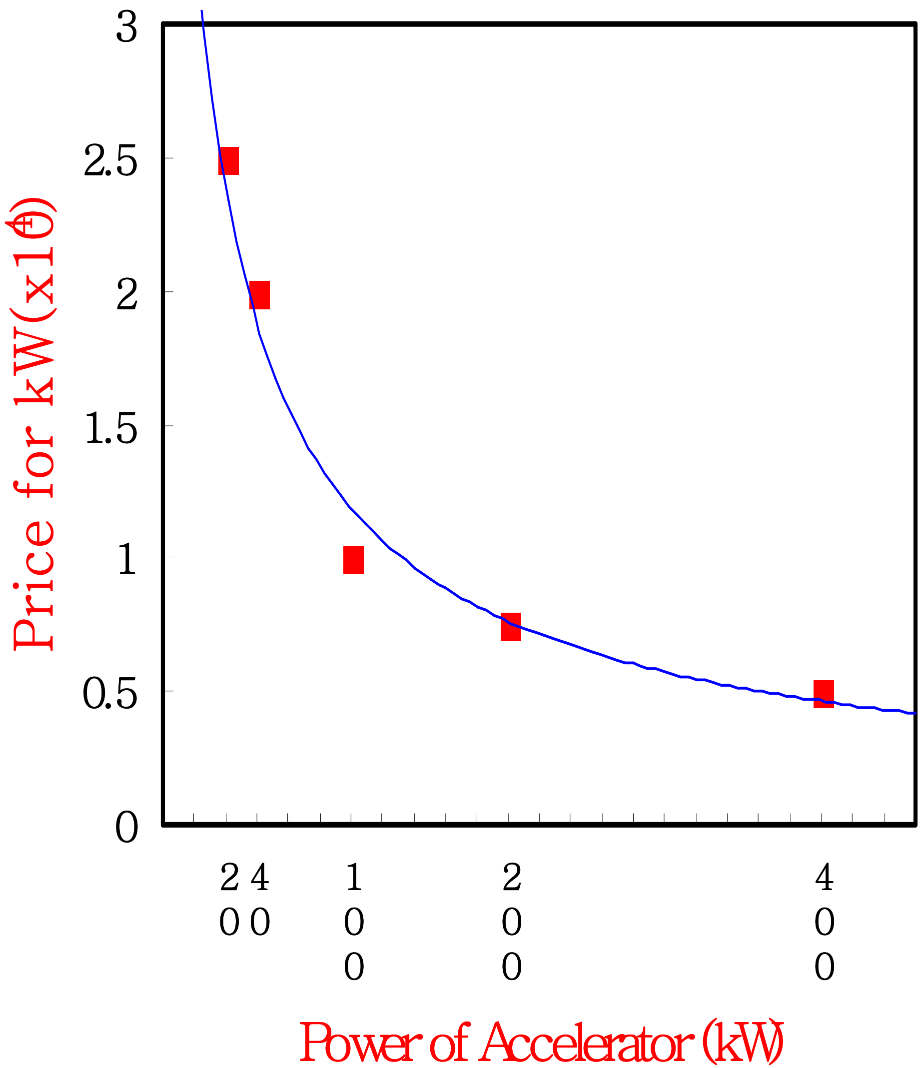


-. Uniform dose distribution

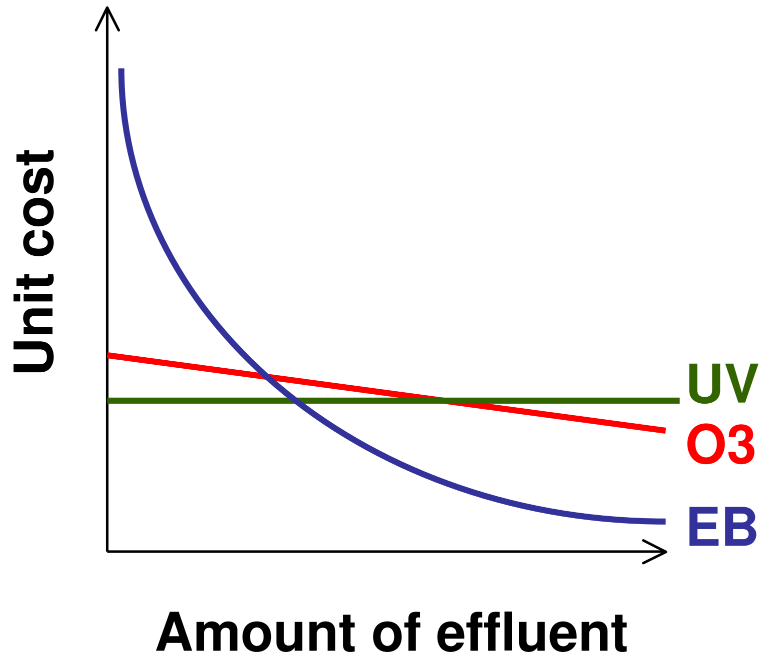
-. Less energy consumption on water delivery

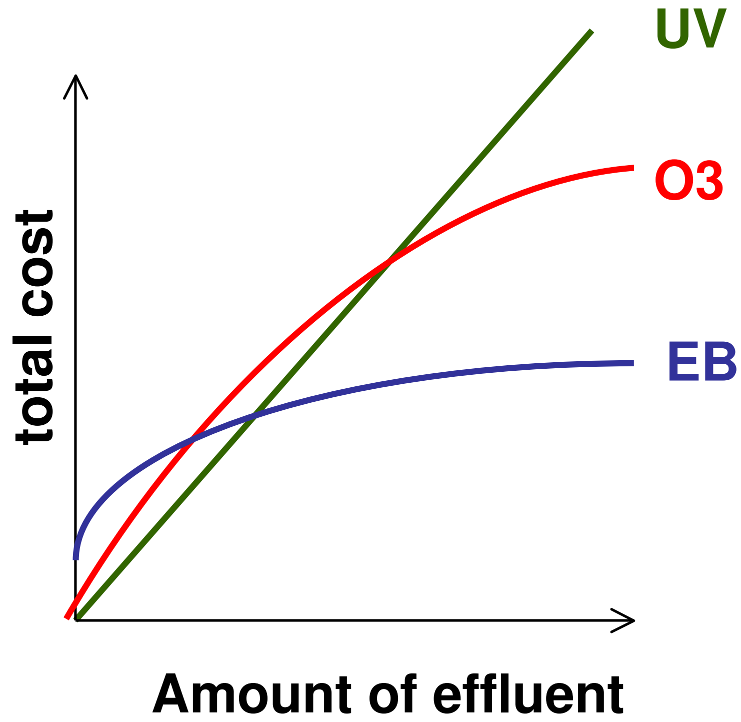
-. Mass productivity (up to 3,000m^3/d with one nozzle)

Nozzle-type Injector used in Textile Dyeing Wastewater Treatment



Power	Price (M$)	Price for 1kW ($10^4$$)
20kW	0.5	2.5
40kW	0.8	2.0
100kW	1.0	1.0
200kW	1.5	0.75
400kW	2.0	0.5





Cost variation with the amount of effluent

Electron Accelerators Required for Environmental Uses

- Energy range 1.0 - 2.0 MeV for wastewater
  0.6 – 1.0 MeV for gaseous waste
- Power of electron beam up to some MW
- It should consist of some hundred kW units
- Efficiency : 85 – 95%
- Continuously operation (over 8,000hrs/yr)
- Computer control system
- High reliability in operation (discharge protection etc.)

Electron Accelerators Required for Environmental Uses

In General

-. Firm and Stable for year-round operation (over 8,000hrs/yr)

-. High Efficiency - economical in power consumption

-. Easy and Safe operation

Technically

-. Uniform doses over effluent

-. Enough scanning speed compared to the speed of effluent

-. Stability of beam energy and power

Thank You for your attention

Electron Beam Technology

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Water/wastewater

With high contamination	Textile dyeing wastewater
	Leachate from Landfill area
	from petrochemical plant
	from Paper-Mill
	from tanning industries
	from slaughterhouse & fisheries
Low or less contamination	Underground water
	Water from lake or marshes
	Effluent of municipal plant

Goal of water/wastewater treatment

Industrial Wastewater	Removal of organic impurities
Municipal Wastewater	Disinfection of microorganisms
	Removal of Color, Odor
	Removal of residual organics
Underground Water	Disinfection of microorganisms
	Removal of harmful organics

Hydrated electron e^-_{aq}

(reduction reactions)

Inorganic 1. All the metal Cations
(exceptions :cations of alkaline and alkali-earth metals)
2. Majority of Oxygen containing and other complex anions, like NO_2^-, NO_3^-, CrO_4^{2-}, $Cr_2O_7^{2-}$, MnO_4^-. $Fe(CN)_6^{3-}$, etc.
(low reactivity to SO_4^{2-}, ClO_4^-, CO_3^{2-}, and some others)

Organics 1. Benzene ring and aromatic compounds
2. Hetero-atomic double or triple bonds (carbonyl, nitro, nitril)
3. Thiol, disulfide, halide, nitro functional groups in both saturated and unsaturated (including aromatic) hydrocarbons

Hydrogen atom H

(reduction reactions)

I. Reduction reactions (one electron transfer)

1. Majority of metal cations
   (low reactivity to Cd^{2+}, Zn^{2+}, some rare-earth metal cations, et al.).
2. Some strong oxidizing inorganic anions, like CrO_4^{2-}, $Cr_2O_7^{2-}$, MnO_4^{-}.
3. Disulfide, iodo, bromo, nitro functional groups and benzene ring in organic compounds.

II. Addition reactions to a double bond in unsaturated hydrocarbons, aromatic compounds.

III. Reaction of H-atom abstraction from saturated carbon in any organic compounds

Hydroxyl radical OH

(oxidation reactions)

I. Oxidation reactions (one electron transfer)
  1. Majority of inorganic cations and anions
  2. Benzene ring in aromatic compounds.

II. Addition reactions to a double bond in unsaturated hydrocarbons, aromatic compounds.

III. Reactions of H-atom abstraction from saturated carbon in any organic compounds.