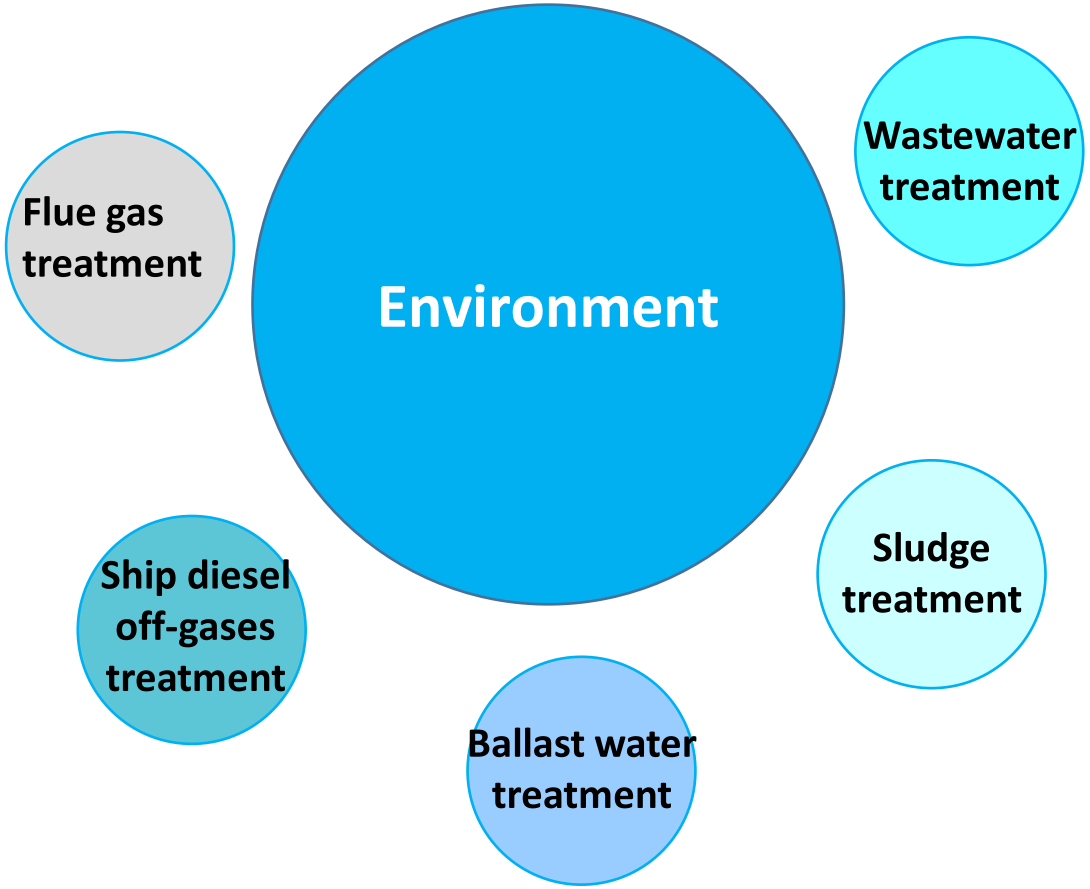
Environmental applications

Dagmara Chmielewska-Śmietanko



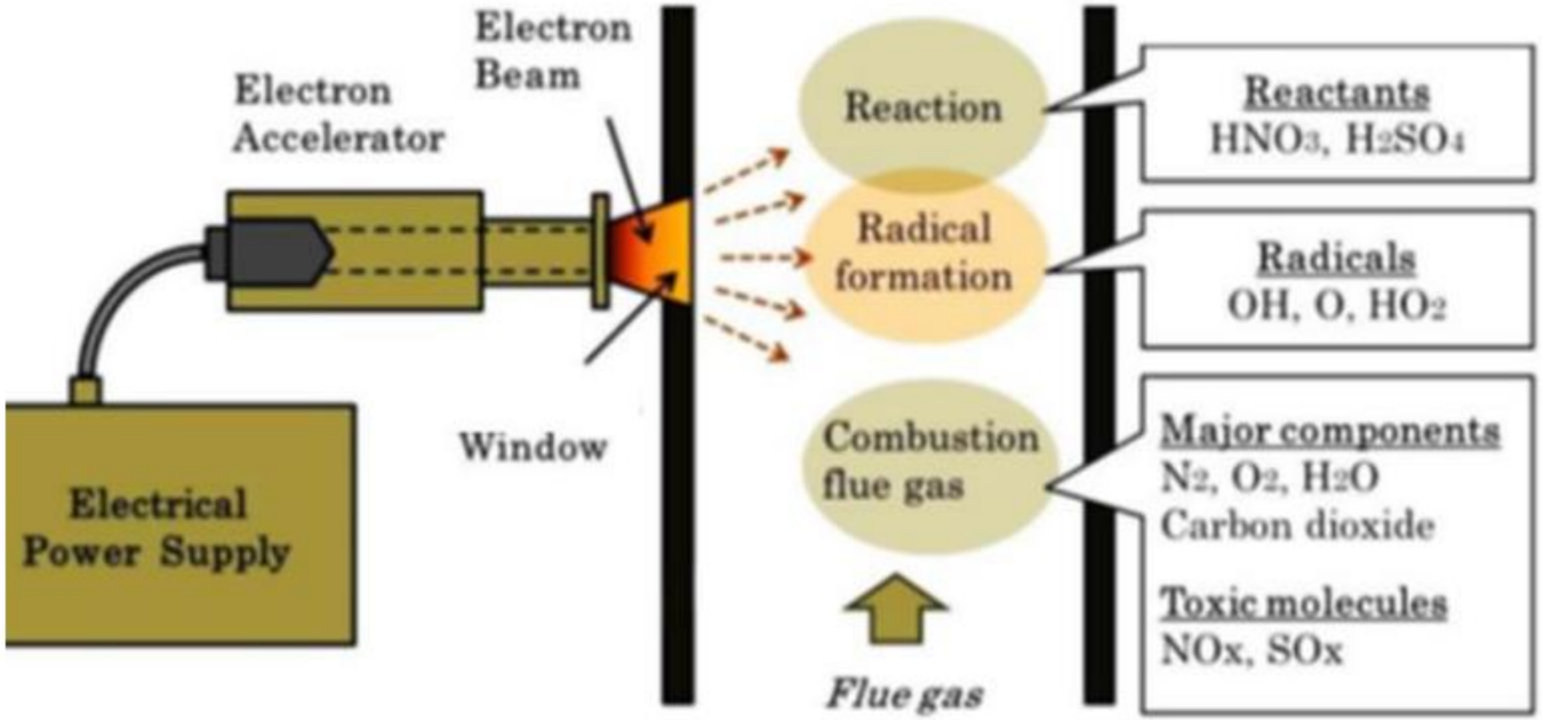
iiA's Leadership Program, Reims, 24-28 April 2023

Environment

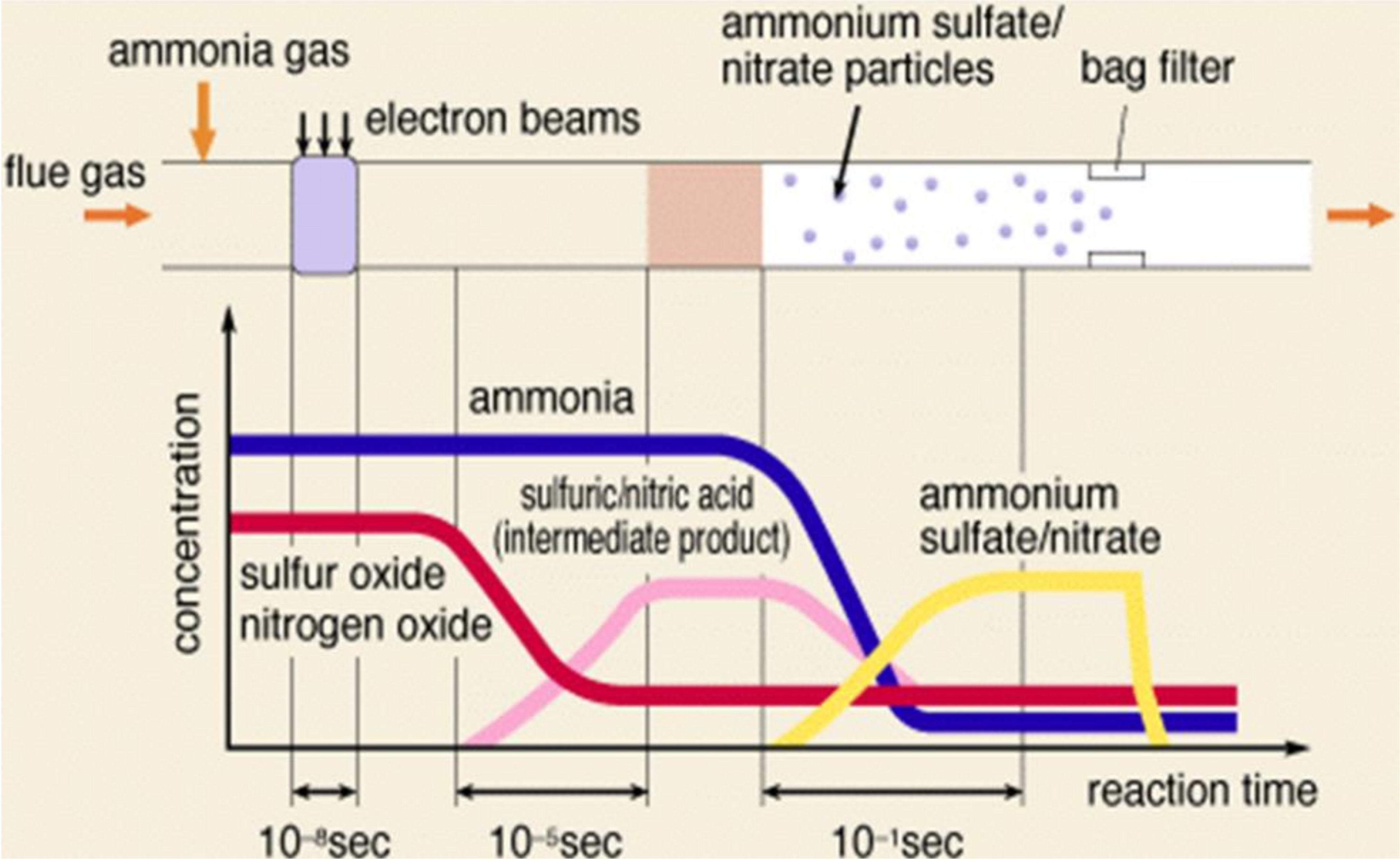
Radiation Processing as an Eco-friendly solution:

- No secondary waste generation;
- No catalysts, no heating and easy for automation;
- Experience in pilot plants and several industrial plants;
- Economical advantages in capital cost and O&M cost;
- The process by-product is used as agricultural fertilizer;
- Can be used as a retrofit or combined with the existing process

Flue gas treatment

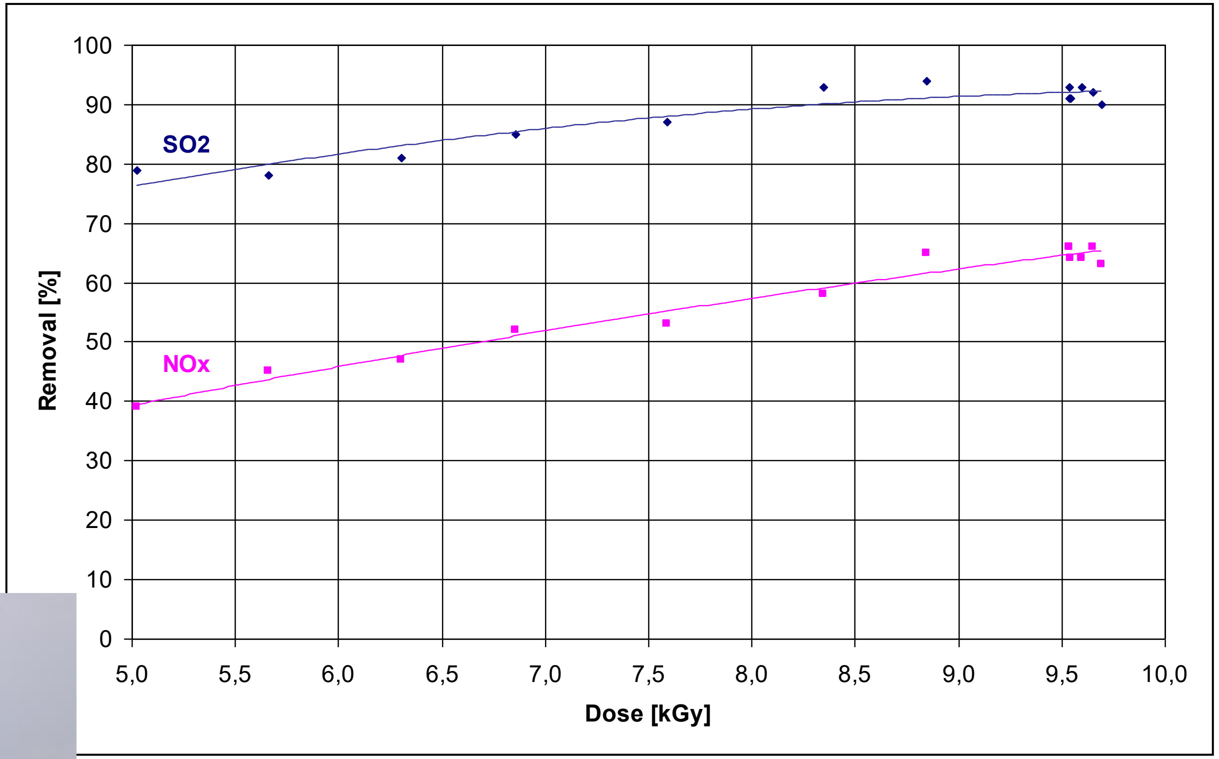


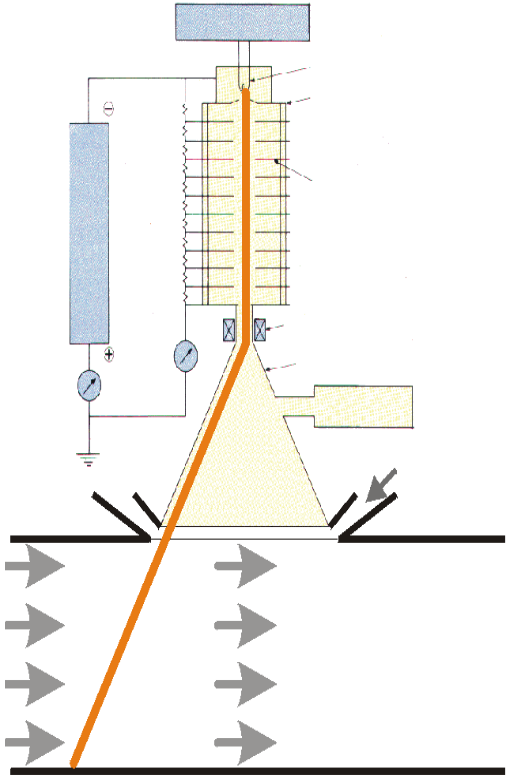
Flue gas treatment



Flue gas treatment

The dependence of SO_2 and NO_x removal efficiency on dose





Flue gas treatment

Flue gas treatment

Pilot and industrial facilities for flue gas treatment

Place	Flow rate [Nm^3/h]	Power [MW]	Accelerator	SO_2/NO_x [ppm]
Indianapolis, USA (1984)	24 000	-	2x800 keV; 160 kW	1000/400
Badenwerk, Germany (1985)	20 000	-	2x300 keV; 180 kW	500/500
Kawęczyn, Poland (1990)	20 000	-	2x700 keV; 100 kW	600/250
Nagoya, Japan (1992)	12 000	-	3x800 keV; 108 kW	1000/300
Chengdu, China (1997)	300 000	90	2x800 keV; 400 mA, 640 kW	1800/400
Pomorzany, Poland (2002)	270 000	112	4x800 keV; 375 mA 1 200 kW	385/340
Nisi-Nagoya, Japan (1998)	620 000	220	6x800 keV; 500 mA 2 400 kW	-
Hangzhou, China (2002)	305 400	-	2x800 keV; 400 mA 640 kW	1800/400
Beijing, China (2005)	640 000	150	2x1 000 keV; 500 mA 1x1 000 keV; 300 mA 1 300 kW	1900/400
Svishtov, Bulgaria (2008)	600 000	120	4x900 keV; 400 mA 1 400 kW	1680/780

Flue gas treatment

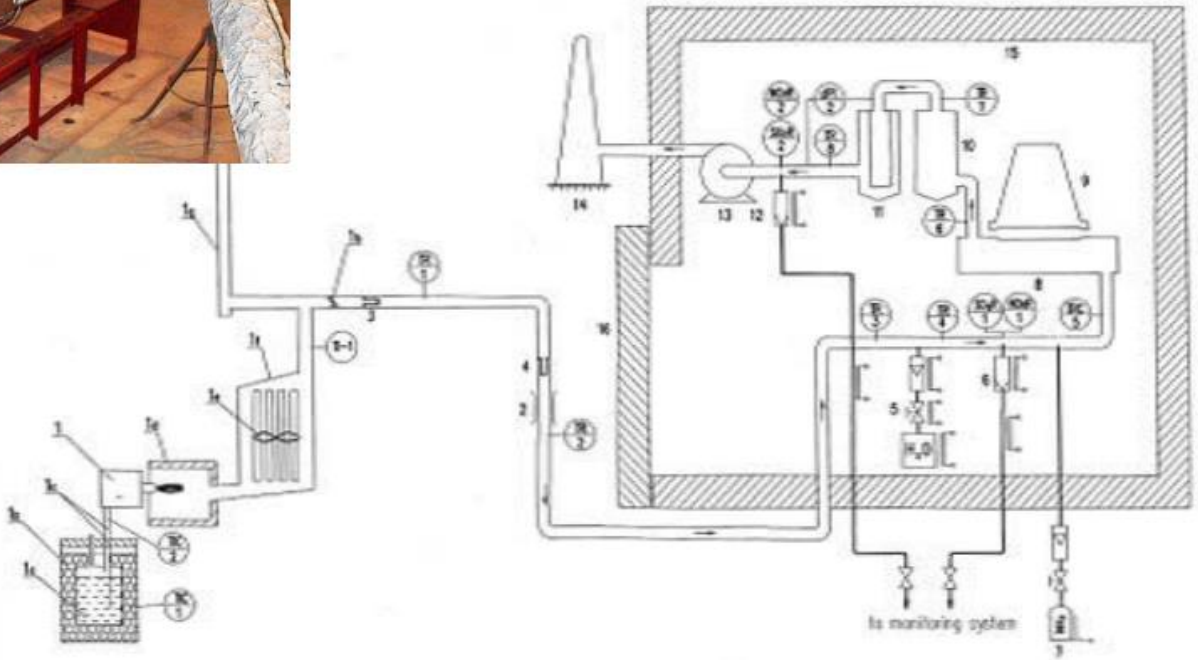
History of development

ILU 6 ACCELERATOR

Energy	0.5-2 MeV
Beam power	20 kW
Frequency	127 MHz

1987 – Laboratory unit: 400 Nm^3/h, accelerator: 20kW, 2 MeV

Oil burner



Schematic diagram of laboratory scale electron-beam flue gas treatment (EBFGT) installation

1–oil – fired burner	5–dosage of water vapour	9–electron beam accelerator	13–fan
2–orifice	6–gas sampling point	10–retention chamber	14–stack
3–preliminary soot filter	7–ammonia injection	11–bag filter	15–concrete wall
4–soot filter	8–process vessel	12–gas sampling point	16–concrete door

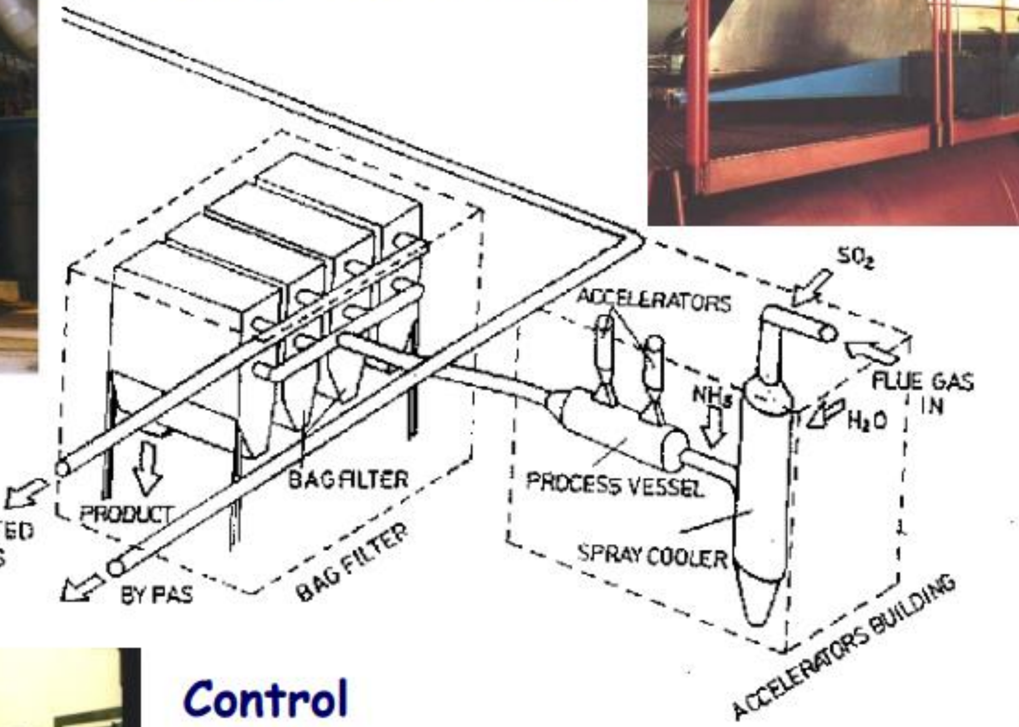
Flue gas treatment

History of development

Electrostatic precipitator

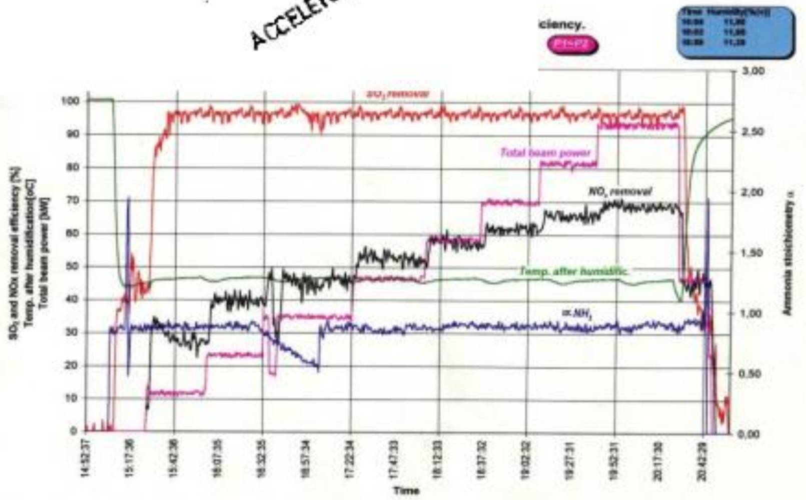
1990 – Pilot Plant PS Kawęczyn: 20 000 Nm³/h, accelerators: 2 x 50 kW, 700 keV

Two accelerators
Energy 0.7 MeV
Power 2 x 50 kW



Process vessel

Control room



Flue gas treatment

History of development

2002 – Industrial Plant PS Pomorzany;
270 000 Nm^3/h,
accelerators: 4 x 262.5 kW, 700 keV

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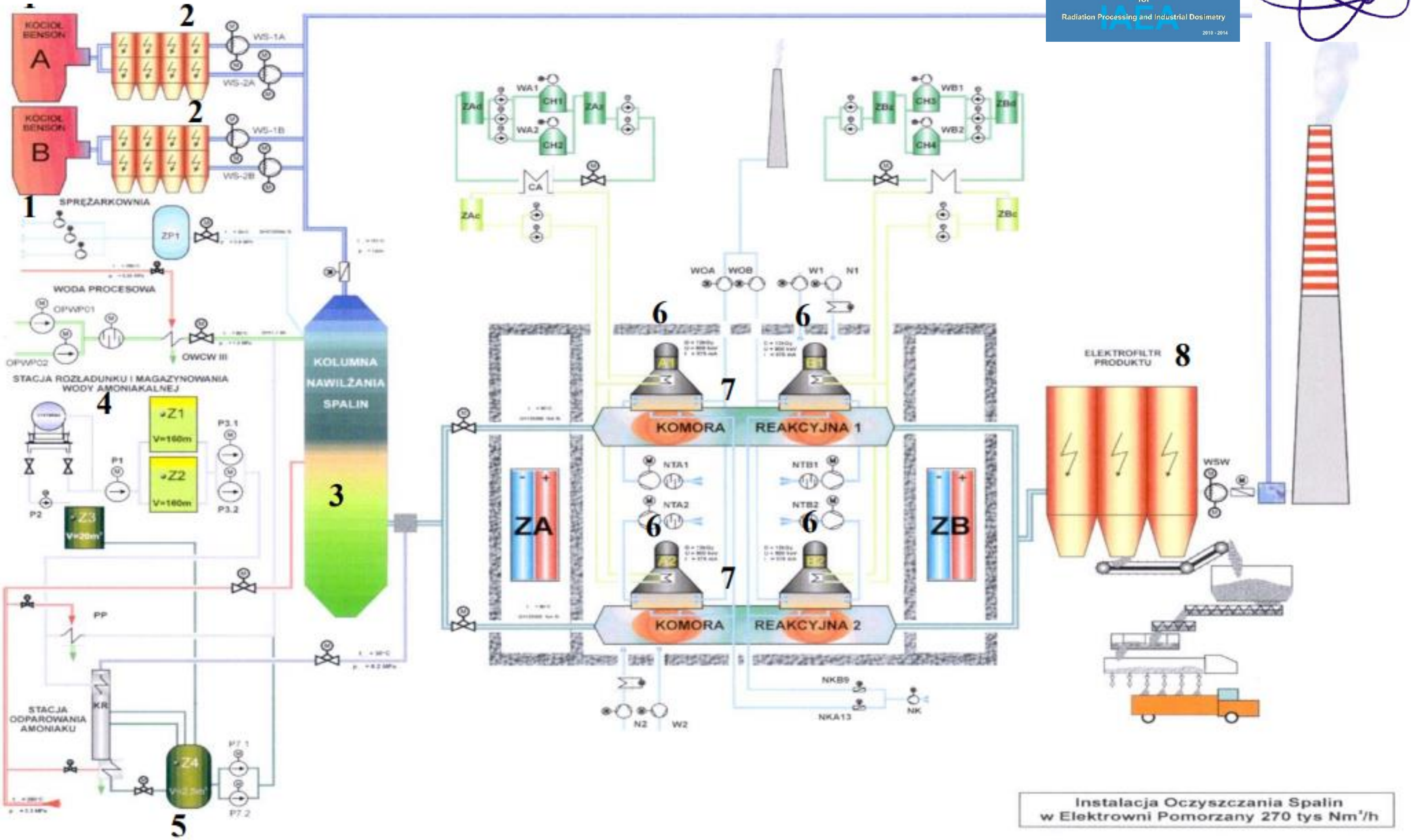


1. Boiler; 2. Electrostatic precipitator; 3. Spray cooler; 4. Ammonia water container; 5. Ammonia evaporator; 6. Accelerator; 7. Reaction vessel; 8. Electrostatic precipitator

Flue gas treatment

Flue gas treatment

Heavy metal content in by-product

By-product
Fertilizer
by-product yield: up to 700 kg/h

As	Cd	Cr	Co	Pb	Hg	Ni	Zn	Remarks
<0.02	<0.01	0.43	0.03	1.01	<0.03	63.5	18.3	averaged values for byproducts collected by cartridge bag filter
0.24	0.09	1.61	0.03	0.54	1.41	22.80	1476	byproducts collected by ESP
Limits for heavy metals content in NPK fertilizer								
41	39			300	17	420	2800	US EPA CFR40 Part. 503
75	20		150	500	5	180	1350	Canadian Fertilizer Act (1996)
50	50			140	2			Polish standard
	32.2	276.8	12.9	17.8		72.3		mean values of heavy metals concentrations in fertilizers marketed in the Kingdom of Saudi Arabia

Flue gas treatment

Laboratory tests for heavy oil

Flue gas treatment

EBFGT at ARAMCO, Jeddah

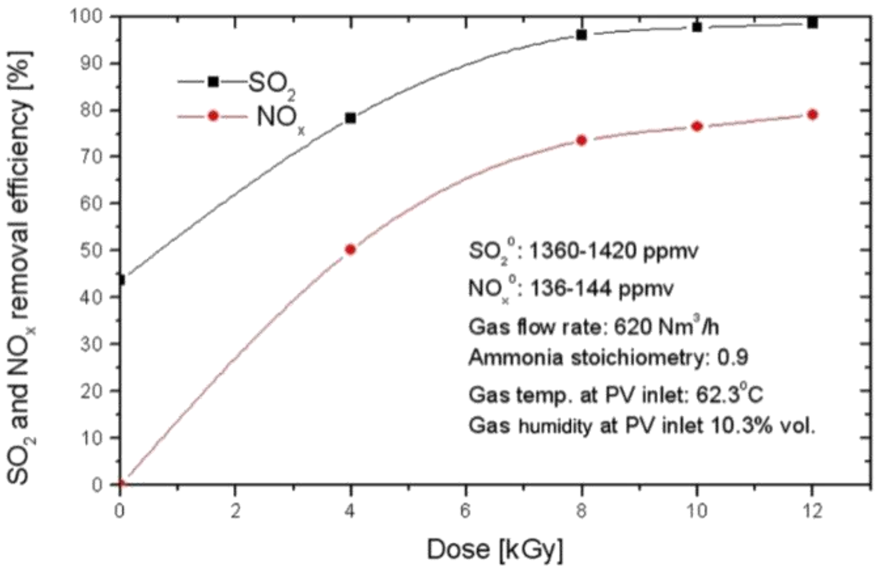
Institute of Nuclear Chemistry and Technology
IAEA Collaborating Centre for Radiation Processing and Industrial Dosimetry

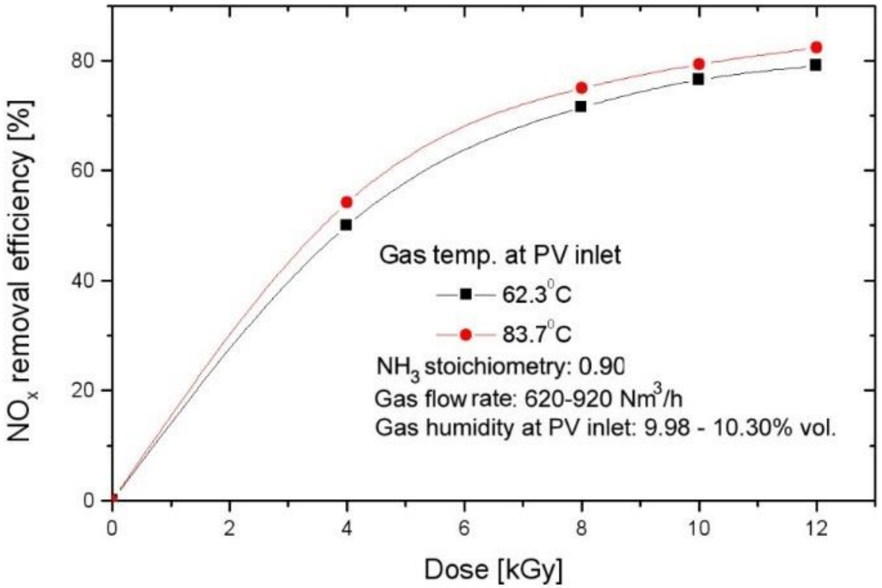
ارامكو السعودية
Saudi Aramco

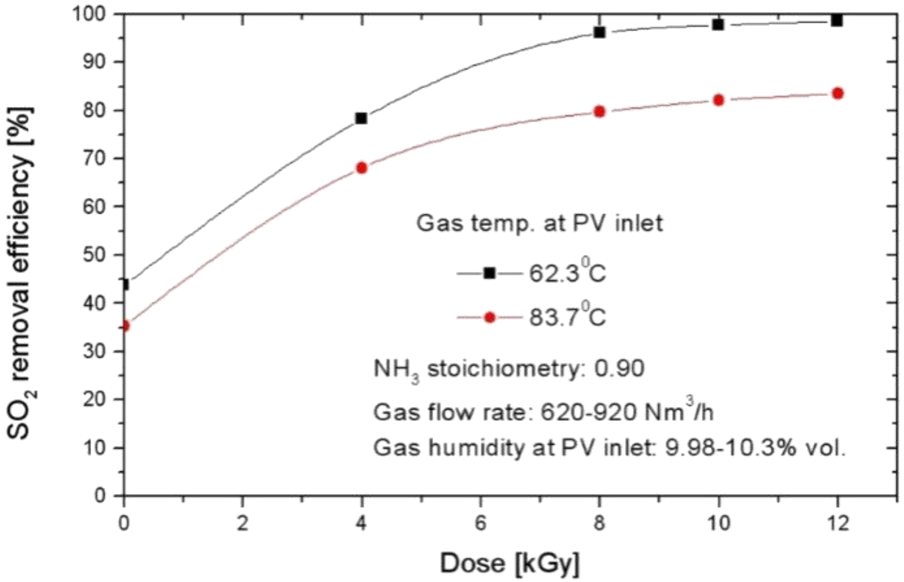
A.G.Chmielewski, J.Licki, A.Pawelec,S.Witman,
Bumsoo Han

Flue gas treatment

SO_2 and NO_x removal efficiency



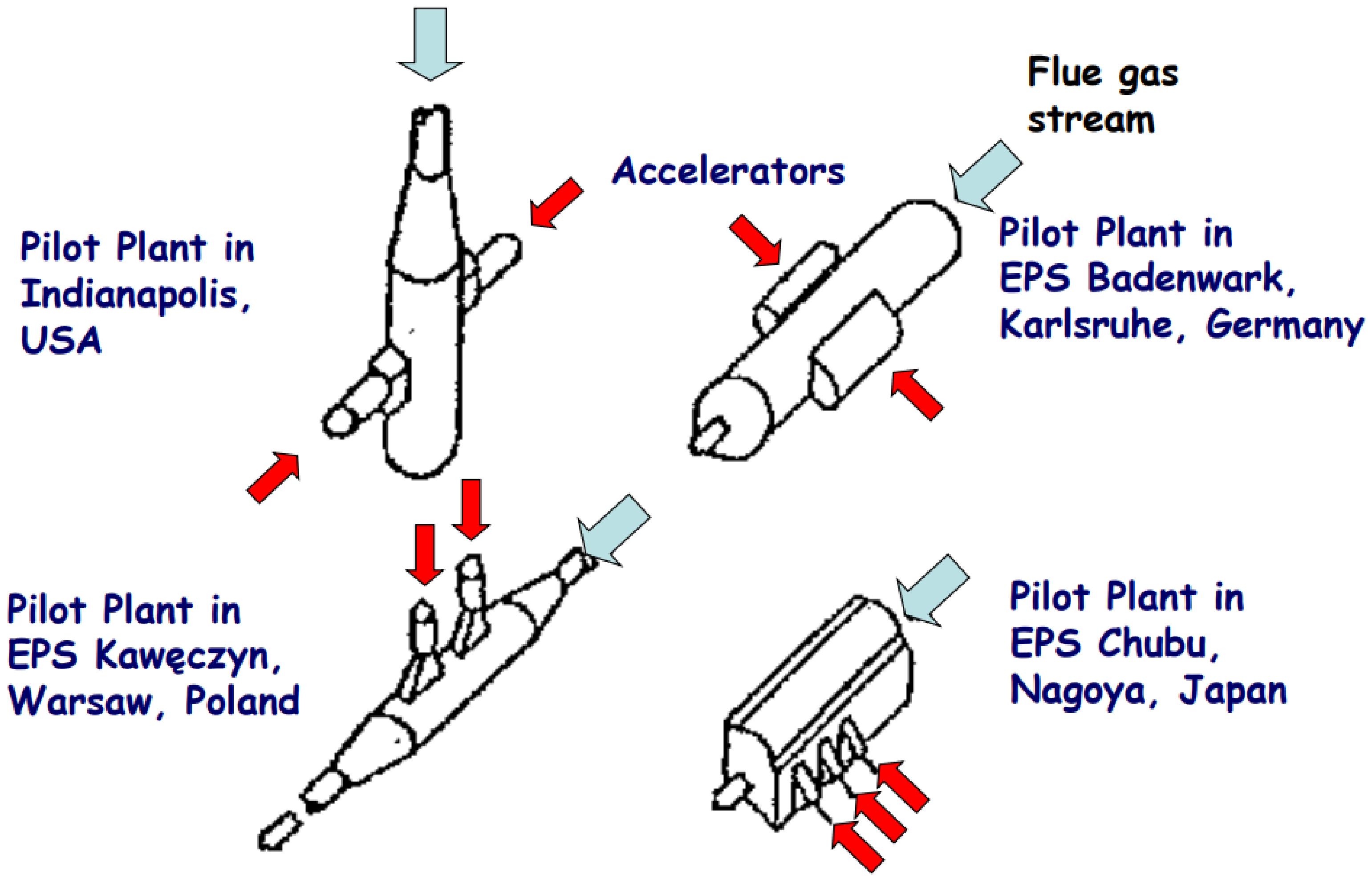




Flue gas treatment

Flue gas treatment

Radiation vessels construction for flue gas treatment



Flue gas treatment

Flue gas treatment

Investment and operational costs

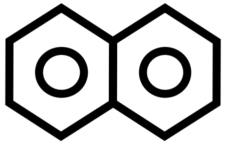
Table 2. Costs of various emission control methods for retrofit 120 MW(e) unit [14]

Emission control method	Investment cost USD/kW(e)	Annual operational cost USD/MW(e)
Wet flue gas desulphurization	120	3000
Selective catalytic reduction	110	4600
Wet FGD + SCR	230	7600
EB treatment EBFGT	160	7350

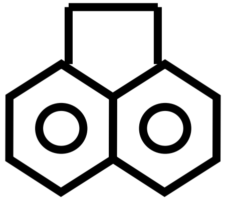
Source:A review on electron beam flue gas treatment (EBFGT) as a multicomponent air pollution control technology
A. Basfar, O. I. Fageeha, N. Kunnummal, A. Chmielewski, J. Licki, A. Pawelec, Z. Zimek, J. Warych
Nukleonika 2010, 55(3), 271-277

Flue gas treatment

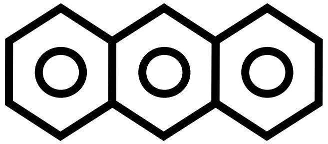
The structures of PAHs emitted from fossil fuels combustion



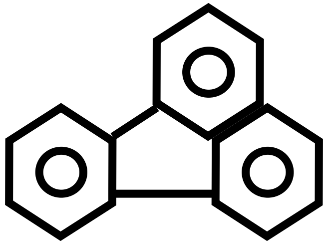
naphtalene



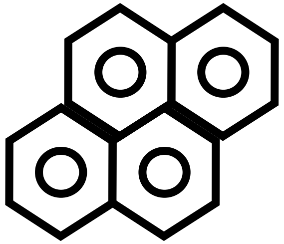
acenaphtene



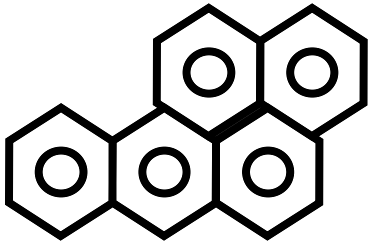
anthracene



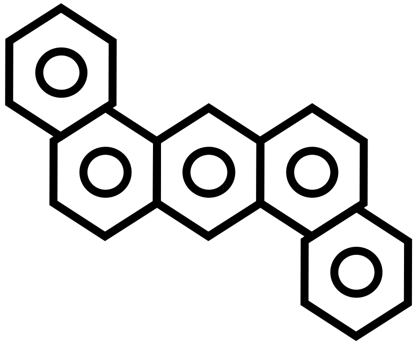
fluoranthene



pyrene



benzo(a)pyrene



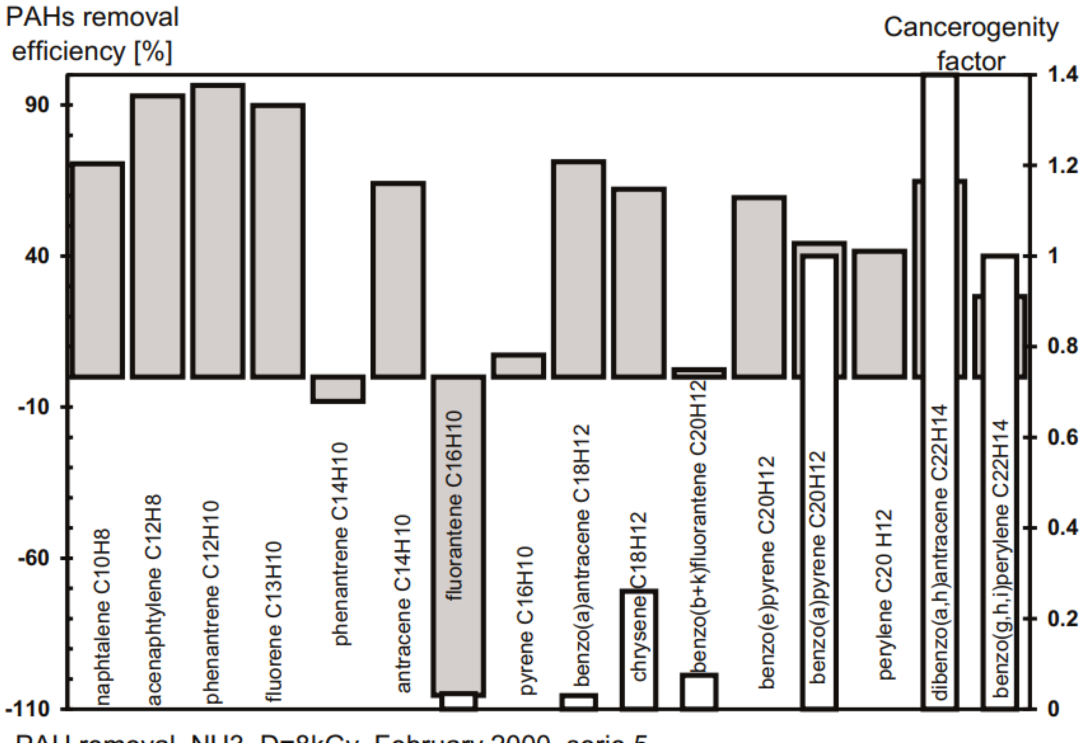
dibenzo(a,h) anthracene

Flue gas treatment

Flue gas treatment

Reduction of VOCs

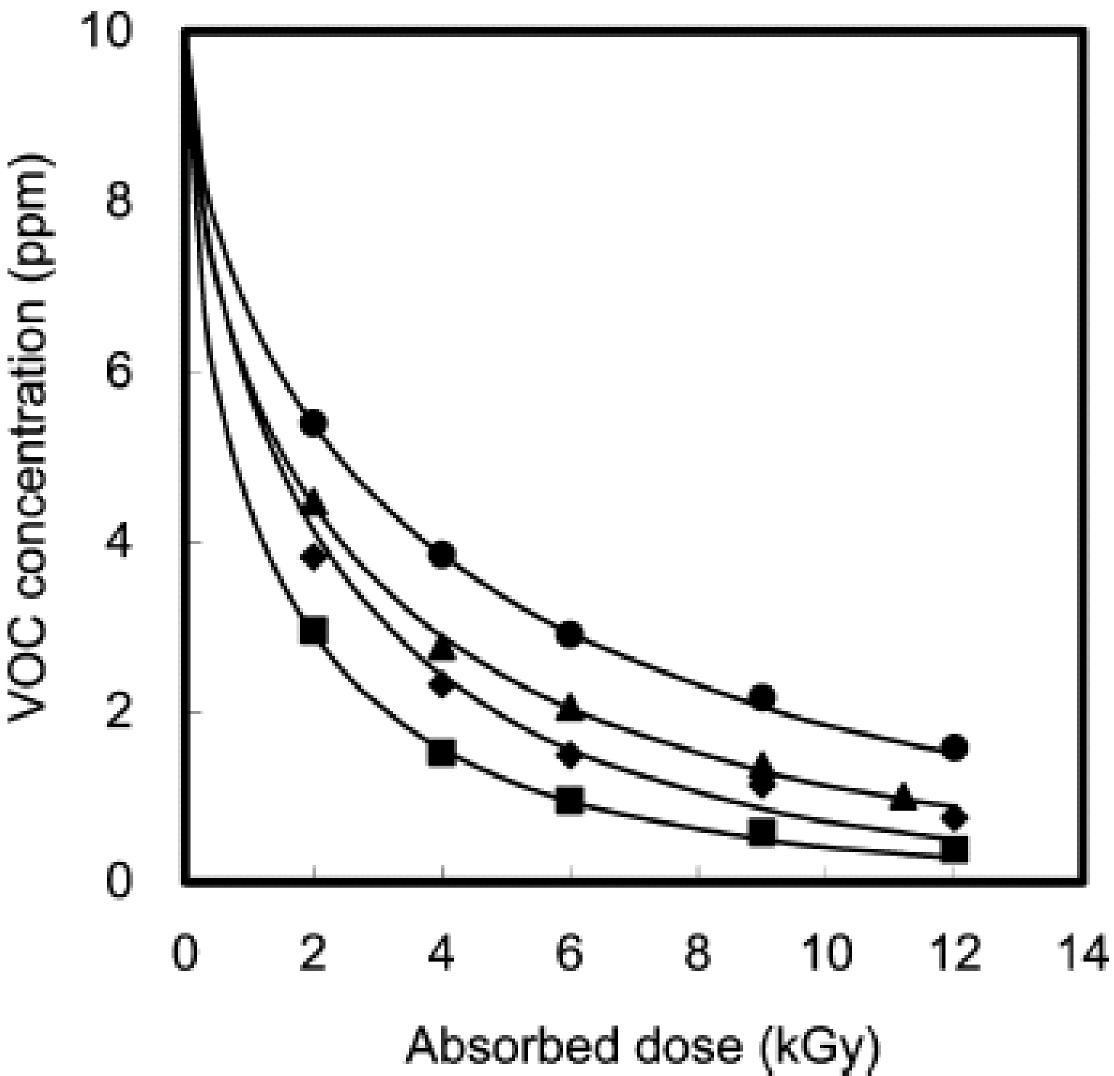
PAHs removal efficiency and their cancergenity factor



Source: A.G Chmielewski, A Ostapczuk, Z Zimek, J Licki, K Kubica,
Reduction of VOCs in flue gas from coal combustion by electron beam treatment,
Radiation Physics and Chemistry, Volume 63, Issues 3–6, 2002, 653-655

Flue gas treatment

Electron-beam treatment profiles of benzene(●) hexane (▲), methanol (♦), and cyclohexane (■).

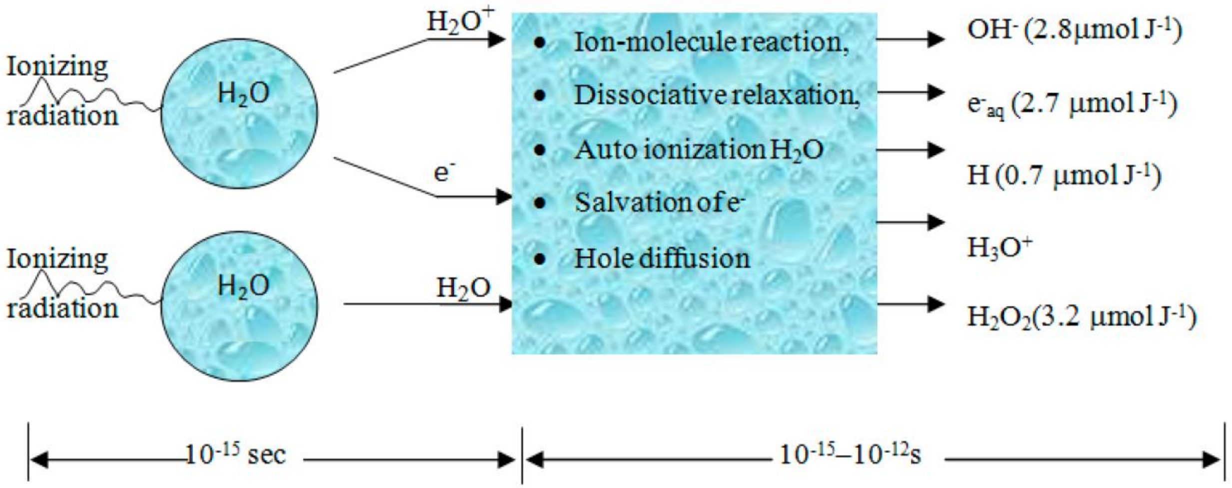


Wastewater treatment

Wastewater treatment

- chemical pesticides, herbicides, and fungicides (agricultural wastewater)
- organic dyes
- drugs, pharmaceutical compounds
- petrochemical wastewater
- microorganisms

Water radiolysis



Source: Abdel Rahman, R.O.; Hung, Y.-T. Application of Ionizing Radiation in Wastewater Treatment: An Overview. *Water* **2020**

Wastewater treatment

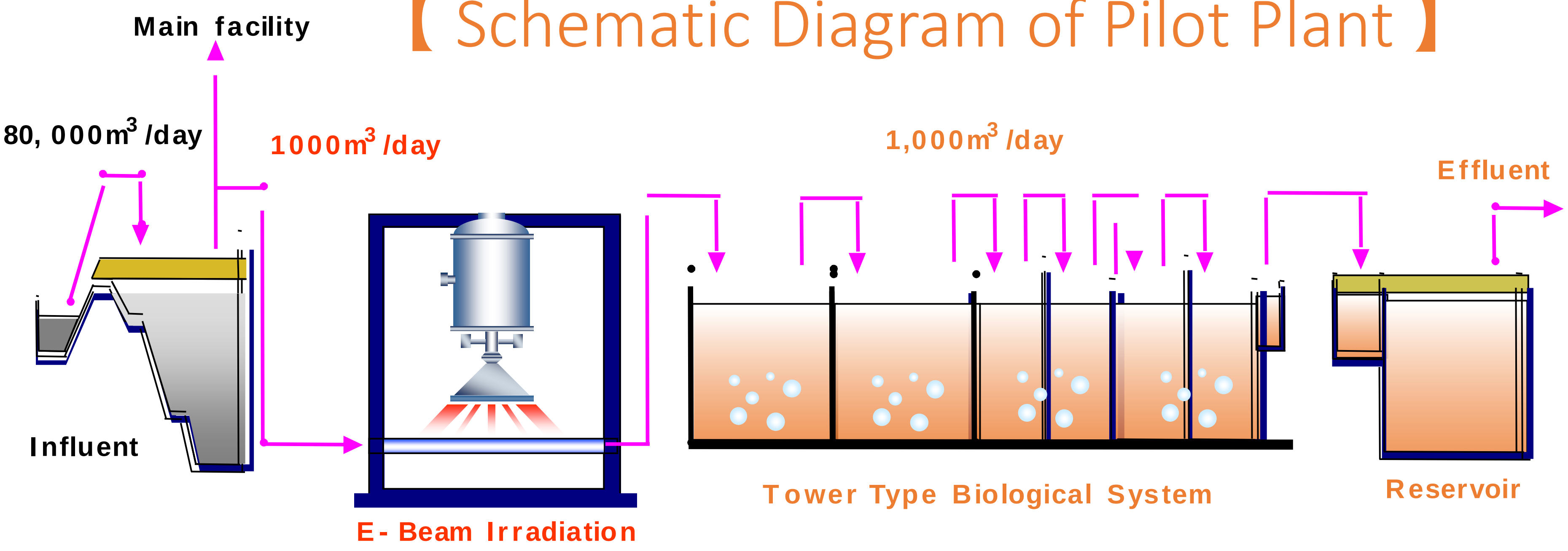
Wastewater Treatment Facility in Daegu Dyeing Industrial Complex

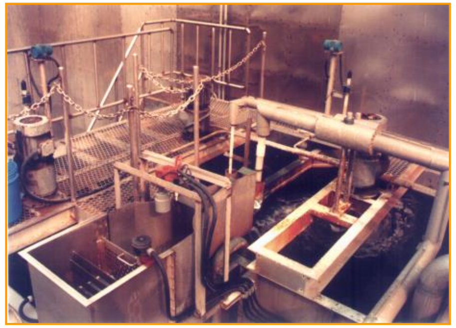
Location of Pilot Plant

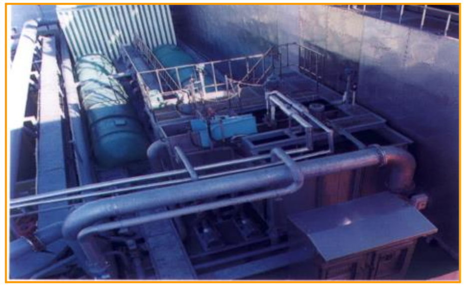
Wastewater treatment

Wastewater treatment

【 Schematic Diagram of Pilot Plant 】

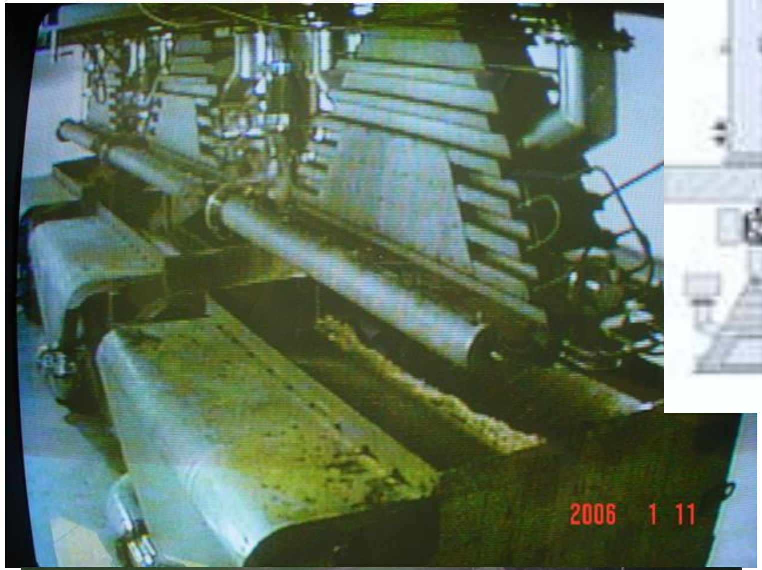


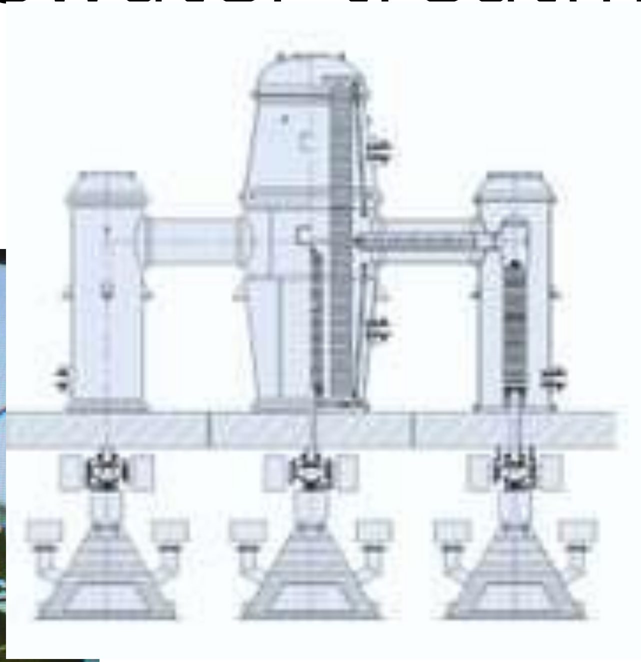


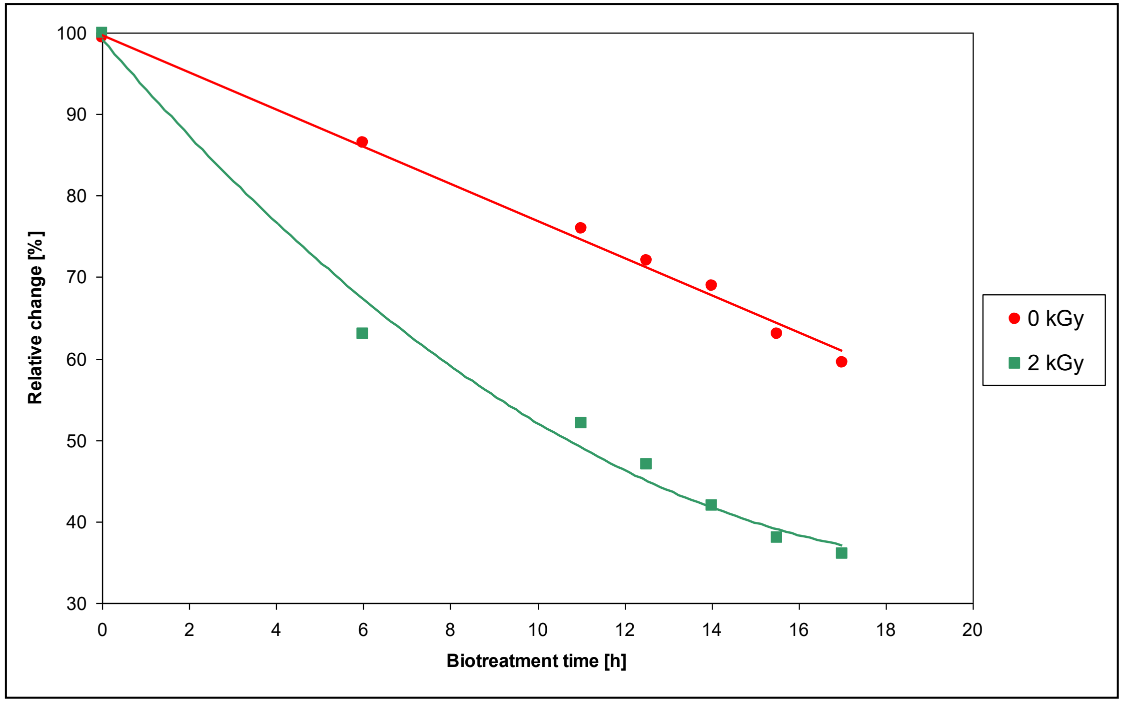


Wastewater treatment

Wastewater treatment







B. Han et al.: Rad. Phys. Chem. **64 (1)** (2002) 53

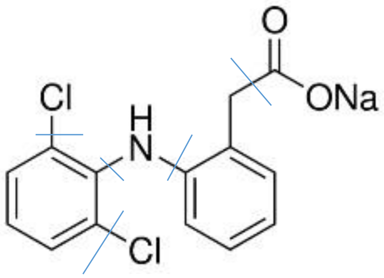
Total construction cost USD 4 M

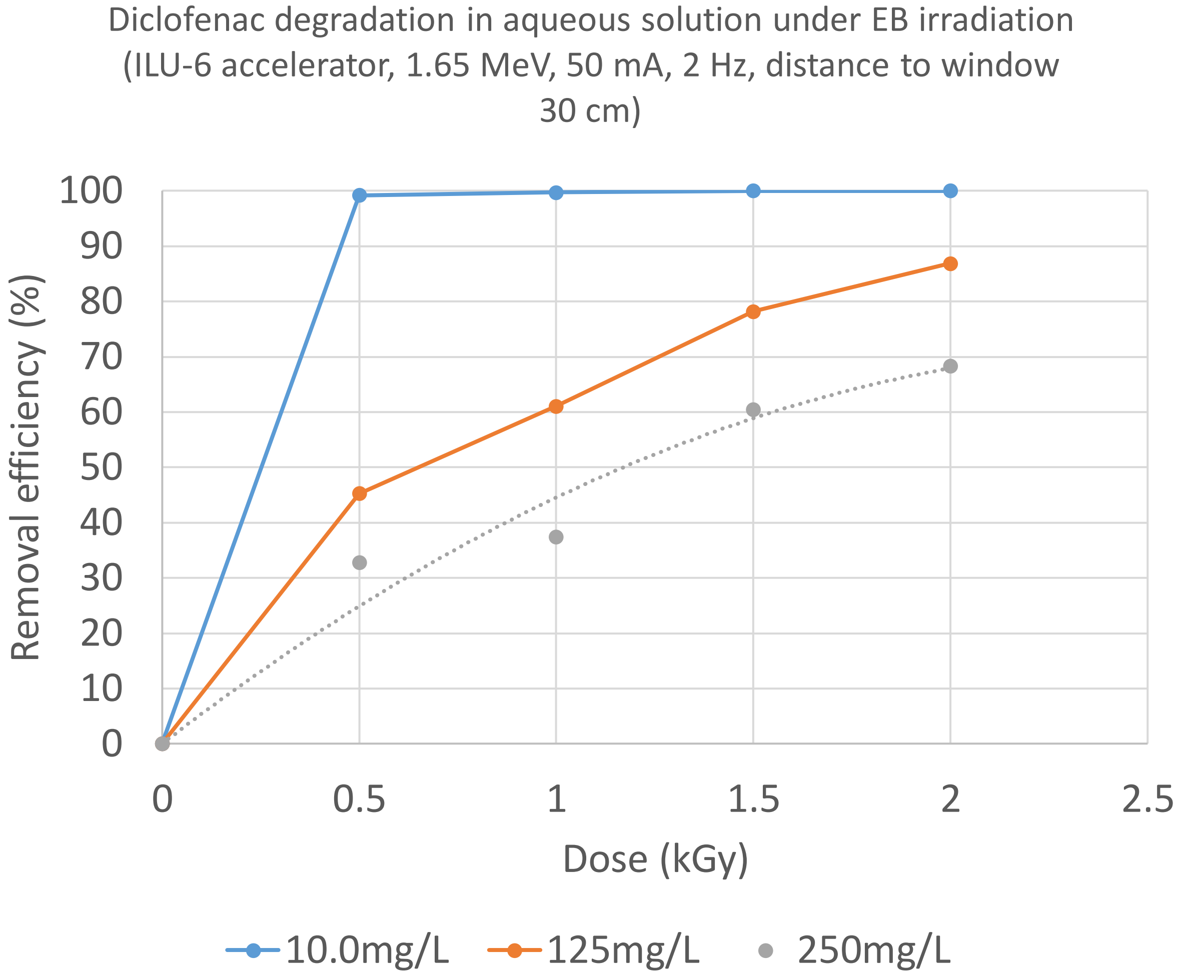
		Existing Facility	E-beam plant
Operating cost (k$)	Chemicals	1,367	580
	Sludge treatment	1,712	1,005
	Electricity	497	809

Wastewater treatment

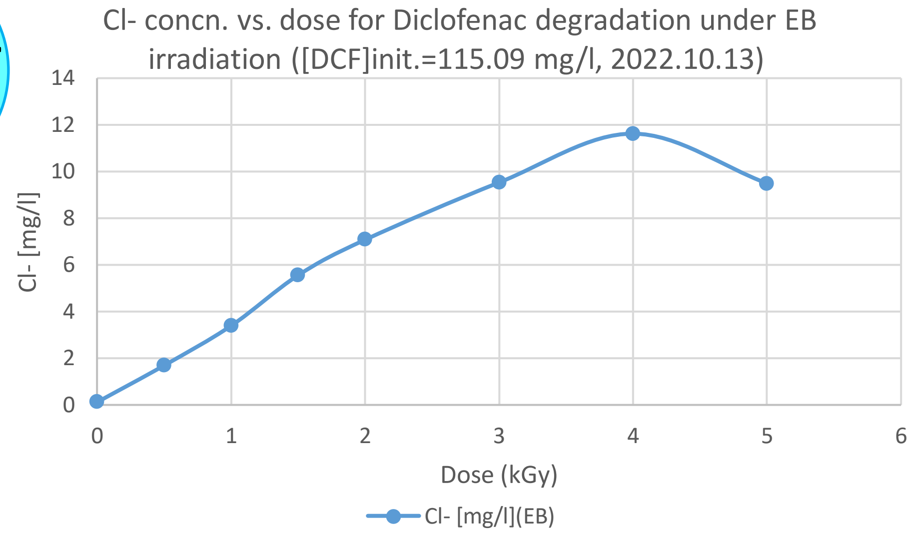
Diclofenac sodium salt

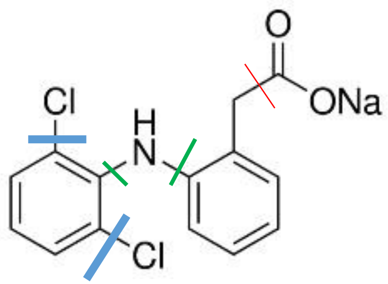
$C_{14}H_{10}Cl_2NNaO_2$, MW=318.13

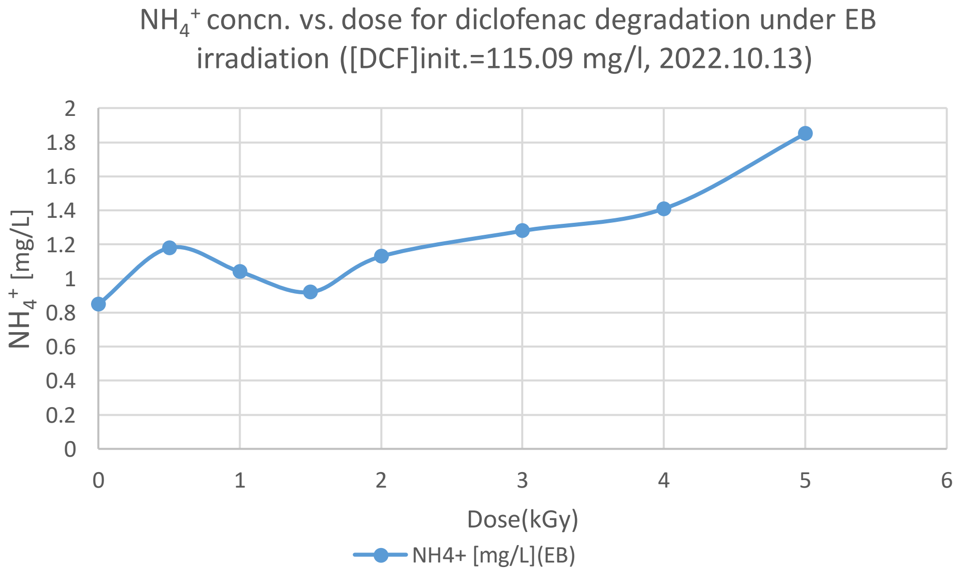




Wastewater treatment







	EB (5kGy)
DCF	96.27%
Cl-	45.24% , single Cl released 90.5%
NH_4^+	28.4%
CO_2	<1%

Ballast water treatment

Ballast water treatment

Motivation

In 2004 the International Maritime Organization (IMO) adopted the **International Convention for the Control and Management of Ships' Ballast Water and Sediments.** When the convention enters into force all ships in international traffic must eventually comply with the established discharge limits according to the **D-2 standard:**

Ships conducting ballast water management shall discharge:

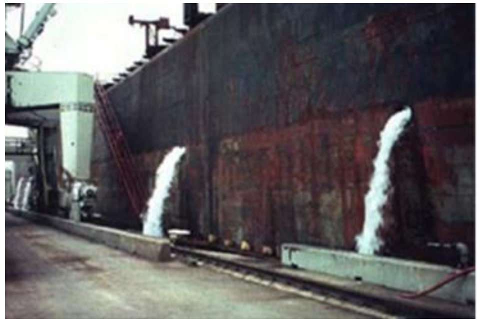
- less than 10 viable organisms per cubic metre greater than or equal to 50 micrometres in minimum dimension
- and less than 10 viable organisms per milliliter less than 50 micrometres in minimum dimension and greater than or equal to 10 micrometres in minimum dimension;
- and discharge of the indicator microbes shall not exceed the specified concentrations:

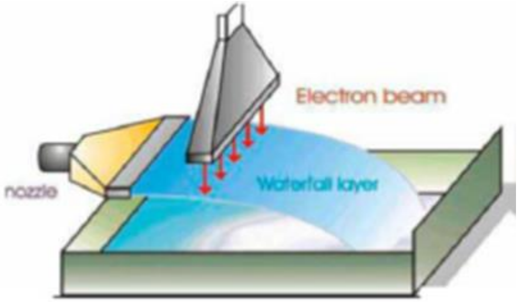
a. Toxicogenic Vibrio cholerae (O1 and O139) with less than 1 colony forming unit (cfu) per 100 milliliters;

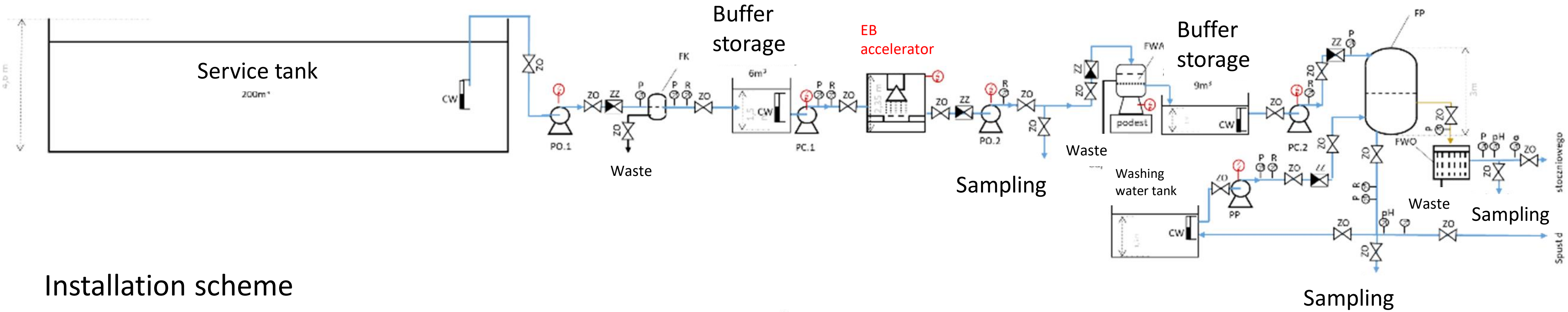
b. Escherichia coli less than 250 cfu per 100 milliliters;

c. Intestinal Enterococci less than 100 cfu per 100 milliliters.

Ballast water treatment



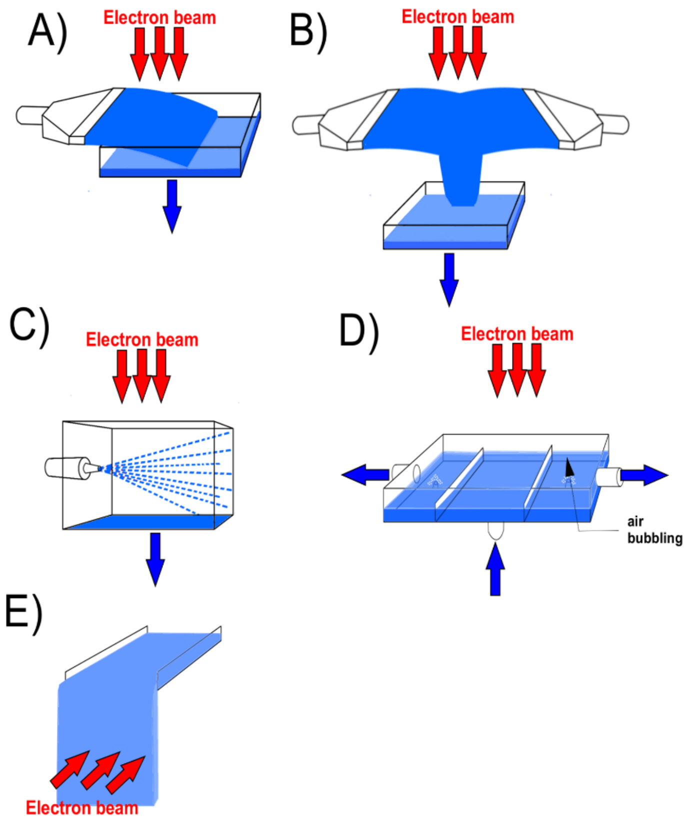




Installation scheme

Geometry of Technological Solution

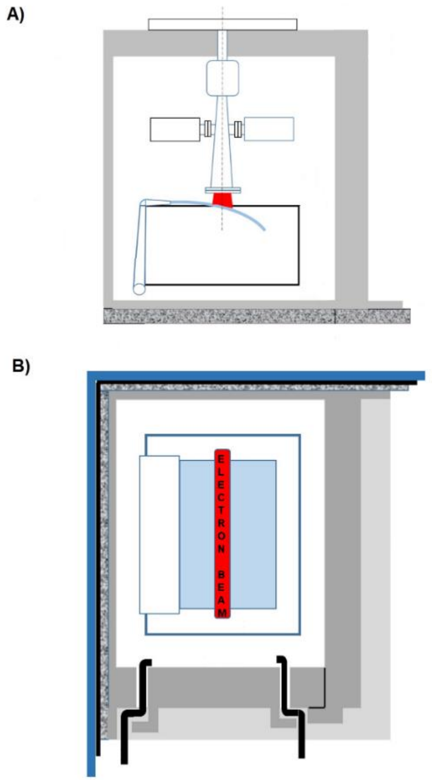
Ballast water treatment



The thickness of the irradiated layer of wastewater is correlated with the penetration of accelerated electrons which depends on accelerator energy. Irradiation of either falling film or up-flow mode or injected wastewater stream ensures the most efficient EB utilization.

Source: Urszula Gryczka, Zbigniew Zimek, Marta Walo, Dagmara Chmielewska-Śmietanko and Sylwester Bułka, „Advanced Electron Beam (EB) Wastewater Treatment System with Low Background X-ray Intensity Generation", Appl. Sci. 2021, 11(23), 11194; https://doi.org/10.3390/app112311194

Experimental set-up



ILU 6 (INP, Russia) accelerator energy ranging from 0.2 to 2 MeV, average beam power up to 20 kW.

The parameters of the beam in experiments: accelerating voltage—930 keV, beam current — 1 mA, sweep width—50 cm.

Ballast water treatment

Ballast water treatment

Number of the indicator microbes before and after irradiation (batch mode)

Ballast water

	Control samples (1,2,3)	1 kGy	2.5 kGy	5 kGy
E.Coli [MPN/100ml]	3730 4200 3120	410	<10	<10
Enterococci [MPN/100ml]	1690 2300 700	1940	<10	<10

Sediments

	Control samples	Control samples [average]	2 kGy	2 kGy [average]	5 kGy	5 kGy [average]
E.coli [MPN/1 g]	8600	6333,3	<1	<1	<1	<1
	4100		<1		<1	
	6300		<1		<1	
Enterococci [MPN/1 g]	2000	3433,3	<1	<1	<1	<1
	6300		<1		<1	
	2000		<1		<1	

MPN- the most probable number

Marine organisms

Nodularia spumigena : control sample (A), after irradiation (B)

Sludge treatment

Sludge treatment

Rich Source of organic carbon(20%-40%) and 3 times more than city compost organic fertilizers

Macro & Micro Nutrients

N, P, K, Zn, Fe, Cu

Pathogens, Virus, Bacteria, Weeds,

Chemical Contaminants

Heavy Toxic Metals

Lead, Arsenic, Cadmium, Chromium etc.

- Kills Pathogens
- Degrades Chemicals
- Allows Inoculation With Useful Bacteria
- Kills Weeds
- Reduces Smell

Sludge treatment

Biological threats in sewage sludge

- Pathogenic bacteria

(*Salmonella spp., Clostridium perfrigens, Escherichia Coli…*)

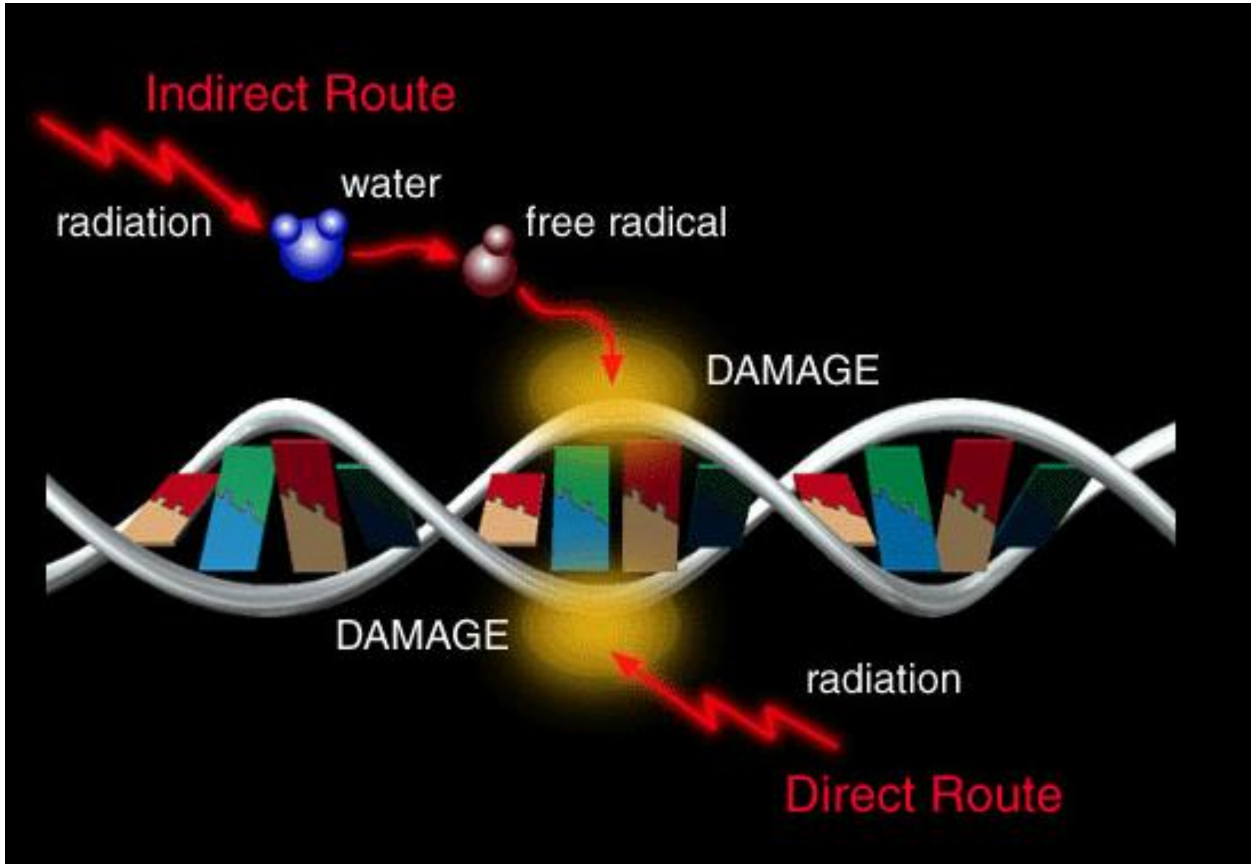
- Helminths eggs

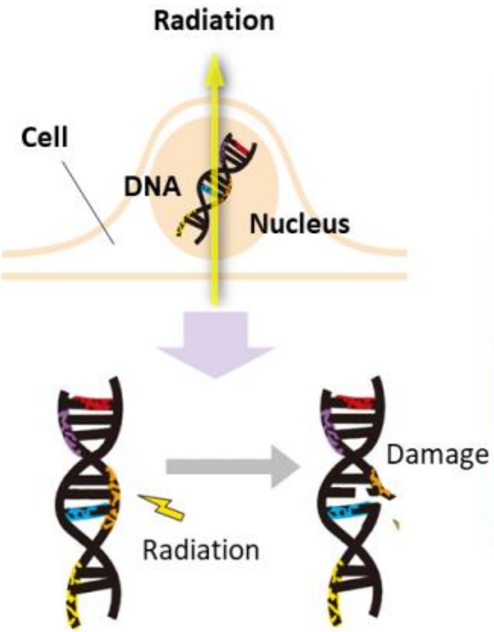
(*Toxocara spp., Trichuris spp., Ascaris spp, Taenia spp….*)

- Viruses
- Fungi

Sludge treatment

Influence of ionizing radiation on living organisms

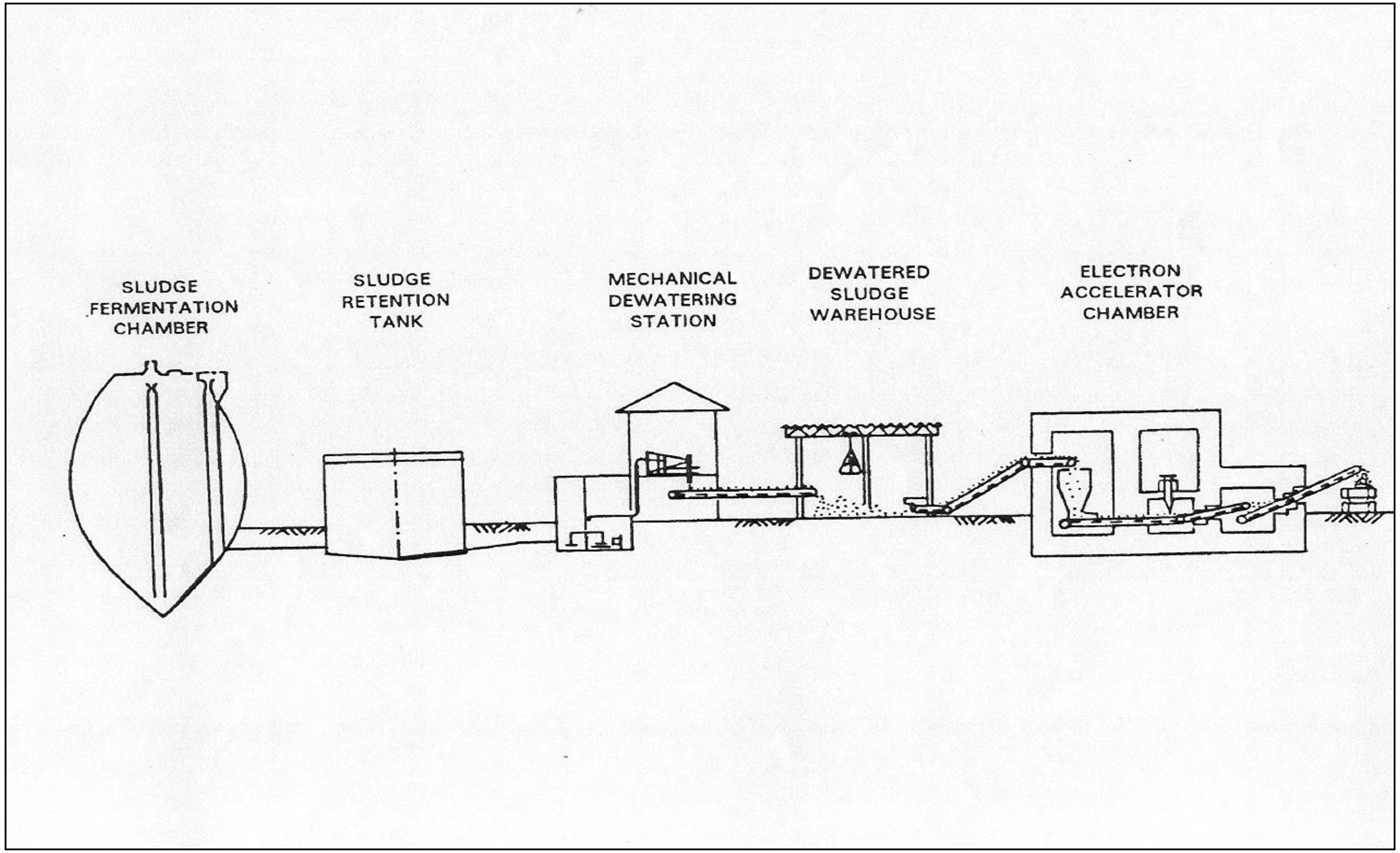




Damage per 1 mGy of X-rays (per cell)	
Base damage	2.5 locations
Single-strand break	1 location
Double-strand breaks	0.04 locations

Sludge treatment

Scheme of EB sewage sludge hygienization installation



Control

Sludge based biofertilizer

Sludge treatment

Sludge treatment

Dose (kGy)	Detected Species	Result (CFU)
0	*Escherichia coli,*	6.2×10^4
	Salmonella spp.	9.2×10^2
	Clostridium perfringens	1.1×10^2
2	*Escherichia coli,*	9.8×10^3
	Salmonella spp.	1.3×10^2
	Clostridium perfringens	0.9×10^2
3	*Escherichia coli,*	1.4×10^2
	Salmonella spp.	0.4×10^2
	Clostridium perfringens	ca.0.2×10^2
4	*Escherichia coli,*	none detected
	Salmonella spp.	none detected
	Clostridium perfringens	none detected
5	*Escherichia coli,*	none detected
	Salmonella spp.	none detected
	Clostridium perfringens	none detected

Dose (kGy)	Detected Species	Result (Number of Living Eggs)
0	*Ascaris* spp.	17
	Trichuris spp.	4
	Toxocara spp.	2
2	*Ascaris* spp.	11
	Trichuris spp.	1
	Toxocara spp.	none detected
3	*Ascaris* spp.	3
	Trichuris spp.	none detected
	Toxocara spp.	none detected
4	*Ascaris* spp.	none detected
	Trichuris spp.	none detected
	Toxocara spp.	none detected
5	*Ascaris* spp.	none detected
	Trichuris spp.	none detected
	Toxocara spp.	none detected

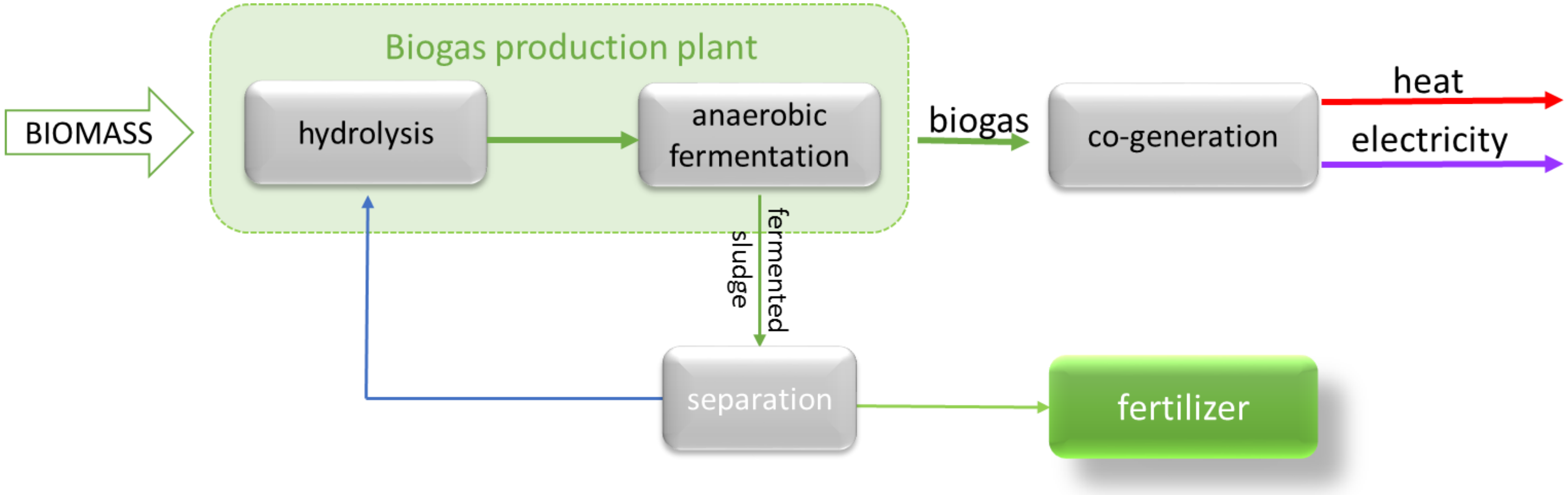
Source: Kim Y, Han B, Kim JK, Ben Yaacov N, Jeong KY, 2009. Design of electron beam sludge hygienization plant. In: International topical
meeting on nuclear research applications and utilization of accelerators.

Source: Sudlitz, M.; Chmielewski, A.G. A Method for WWTP Sludge Valorization through Hygienization by Electron Beam Treatment.
Fermentation 2021, 7, 302.
https://doi.org/10.3390/fermentation7040302

Sludge treatment

Biogas production using sewage sludge

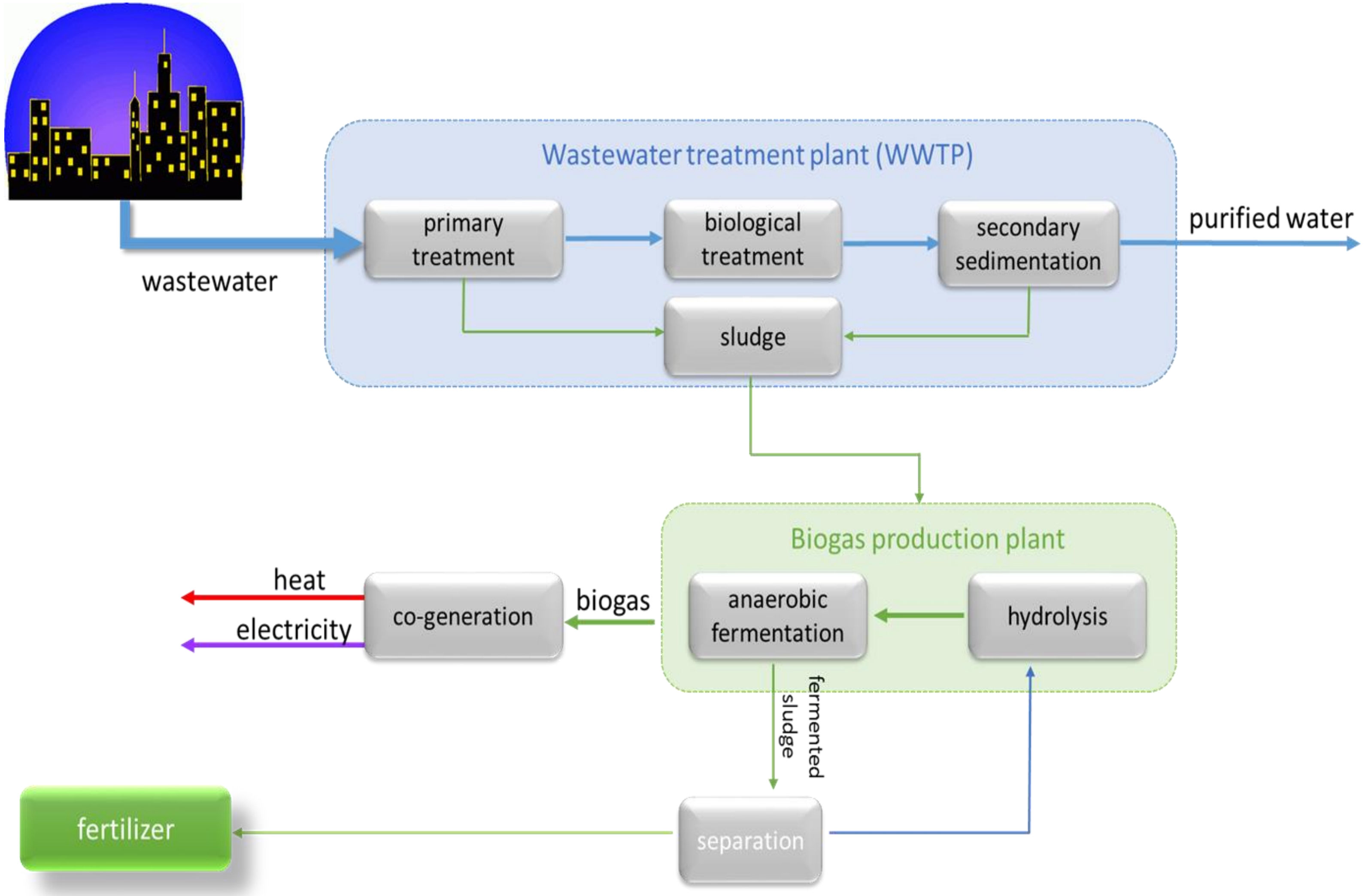
- The sludge is pumped into the anaerobic reactors where digestion takes place, usually at mesophilic temperature (35 – 39 °C). During a retention time of around 20 days, microorganisms break down part of the organic matter that is contained in the sludge and they produce biogas, which is composed of methane, carbon dioxide and trace gases. Biogas is used to feed cogeneration systems in order to simultaneously produce heat and electricity.



HYBRYD BIOGAS - EB SYSTEM

Advantage of proposed solution:

- **Environmental friendly technology**
- Biogas production is **disposal of problematic wastes**
- Production of **renewable power through combined heat and power cogeneration**
- Production of microbiologically safe organic fertilizer **due to electron beam hygenization**
- Technology can be applied in any place with sufficient biomass resources while there is **no need for external electric energy supply**



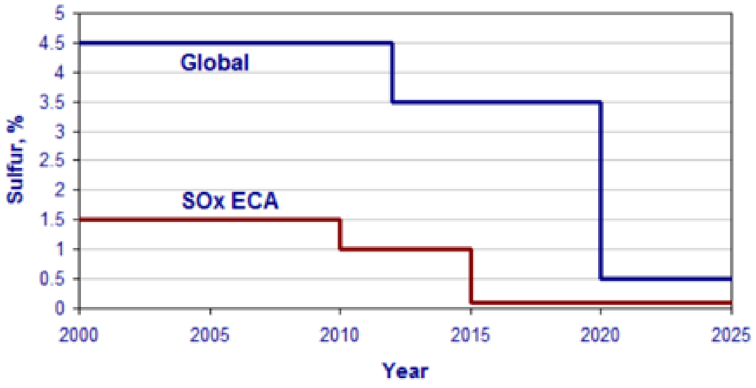
Economic analysis

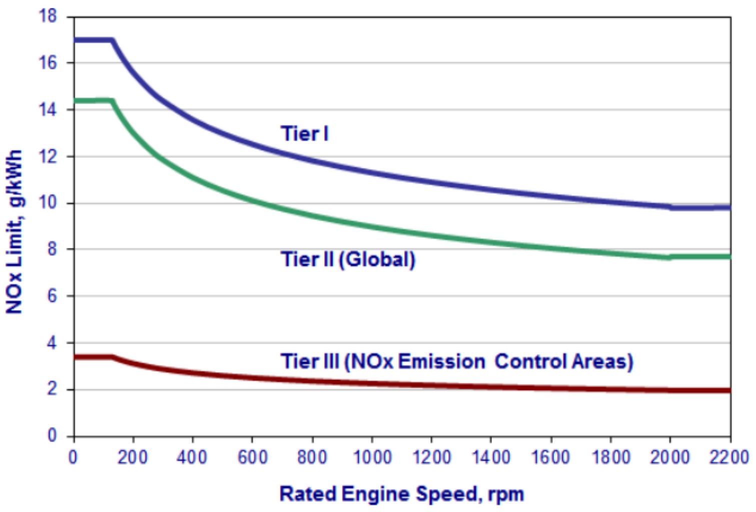
Wastewater treatment plant (Throughput: ~250 000 m³ annually. Sludge output ~1500 tons dry mass annually)	
I. E-beam technology for sludge hygenization	II. E-beam technology for sludge hygenization and biogas cogeneration
Accelerator specification	
100 kW, 2 MeV	100 kW, 2 MeV + biogas generation
Cost savings	
Savings from avoiding sludge disposal costs	
1500 tons @ 100 euros = 150 000 euros	1500 tons @ 100 euros = 150 000 euros
Potential revenue from biosolid-based fertilizer sales	
1500 tons @ 94.5 euros = 141 750 euros	1277.5 tons @ 94.5 euros = 120 723.75 euros
	Biogas production (1 022 000 m³ annually) Converted in co-generator in electricity and heat Generator power 350 kW Equivalent of electricity production: 350 kW × 8000 h × 0.13 euros/kWh = 354 000 euros
E-beam technology-associated operating costs	
Electricity consumption	
130 kW e-beam accelerator 70 kW wastewater plant equipment 10 kW heat generation	130 kW e-beam accelerator 70 kW wastewater plant equipment
Total cost	
210 kW × 8000 h × 0.13 euros/kwh = 218 400 euros	200 kW × 8000 h × 0.13 euros/kwh = 208 000 euros 1055 tons grass silage (annually) = 1 055 tons × 10 euros/ton = 10 055 euros
Net income and savings	
73 350 euros annually	271 668.75 euros annually

Source: Chmielewski, Andrzej G., Sudlitz, Marcin, Han, Bumsoo and Pillai, Suresh D.. "Electron beam technology for biogas and biofertilizer generation at municipal resource recovery facilities" Nukleonika, vol.66, no.4, 2021, pp.213-219.
https://doi.org/10.2478/nuka-2021-0031

Ship diesel off-gases treatment

Emission Control Areas & regulations





Ship diesel off-gases treatment

Ship diesel off-gases treatment

Exhaust gases vs regulations

Diesel engine exhaust gas composition	
NOx	50-1500 ppm
SO_2	Proportional to sulphur content in fuel; 500-2000 ppm
HC	50-500 ppm
CO	100-1000 ppm

Diesel engine:
6 MW,
85% engine load

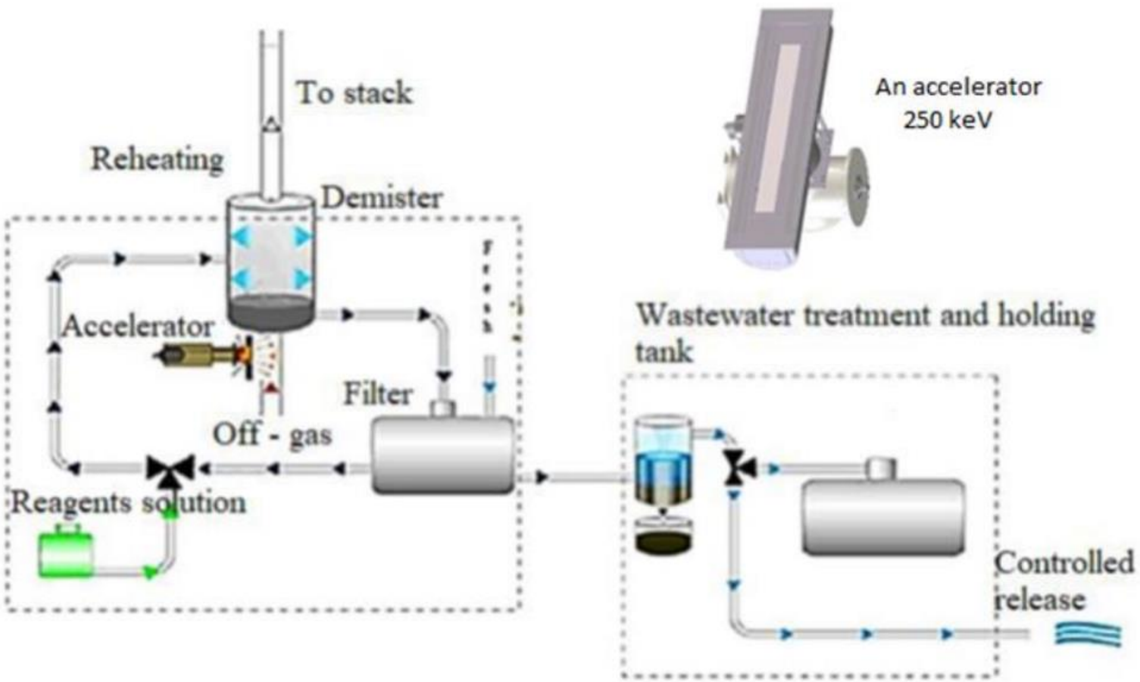
Exhaust gas:
4.727 Nm^3/kWh
NO: 1500 ppmv,
9.5g/kWh

Regulations of NOx emissions (Tier III)
315 ppmv,
2g/kWh

The removal has to be higher than 79%

Ship diesel off-gases treatment

Ship diesel off-gases treatment

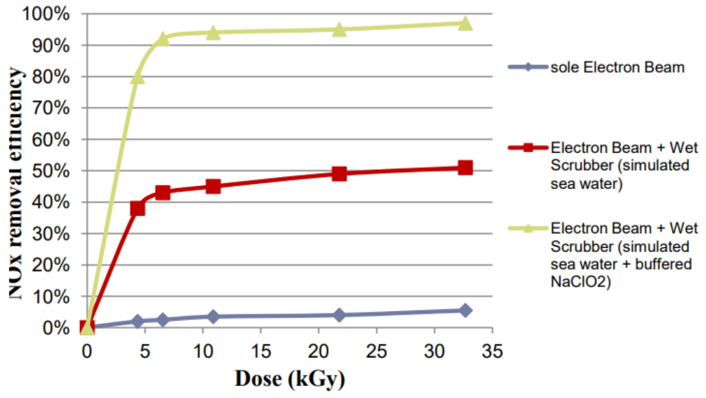


Diesel exhaust gases → Electron Beam → Wet Scrubbing → Clean gases

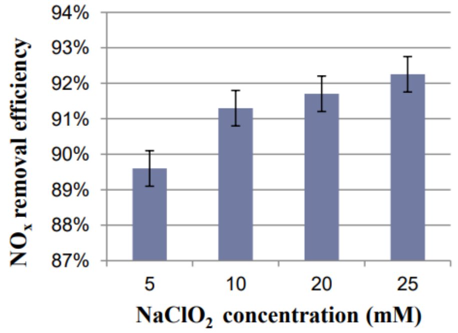
Ship diesel off-gases treatment

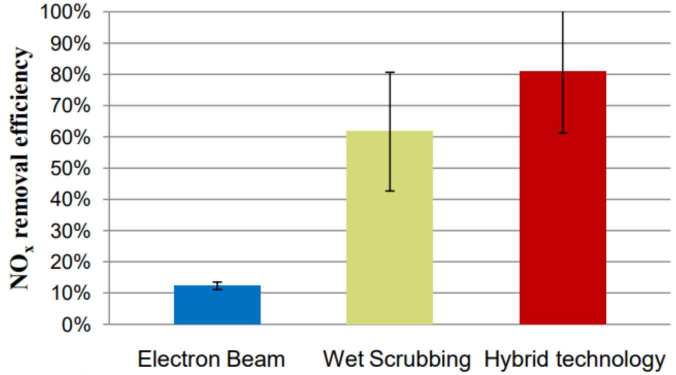
Ship diesel off-gases treatment

Hybrid technology



$NaClO_2$ solution





Average NO_x removal efficiency:

- 11,3% ± 1,2% for electron beam,
- 61,7% ± 19,1% for wet scrubbing
- 81,1% ± 19,5% for hybrid technology

Environment

- The electron beam is an important technique for environmental protection applications.

- Progress = not only a growing number of units but also lower cost, higier accelerator electrical efficiency, accelaretor reability, more compact size suitable for production lines, beams shaped adequately for the process, and other parameters that are important in the radiation-processing application