Electron beams for flue gas treatment

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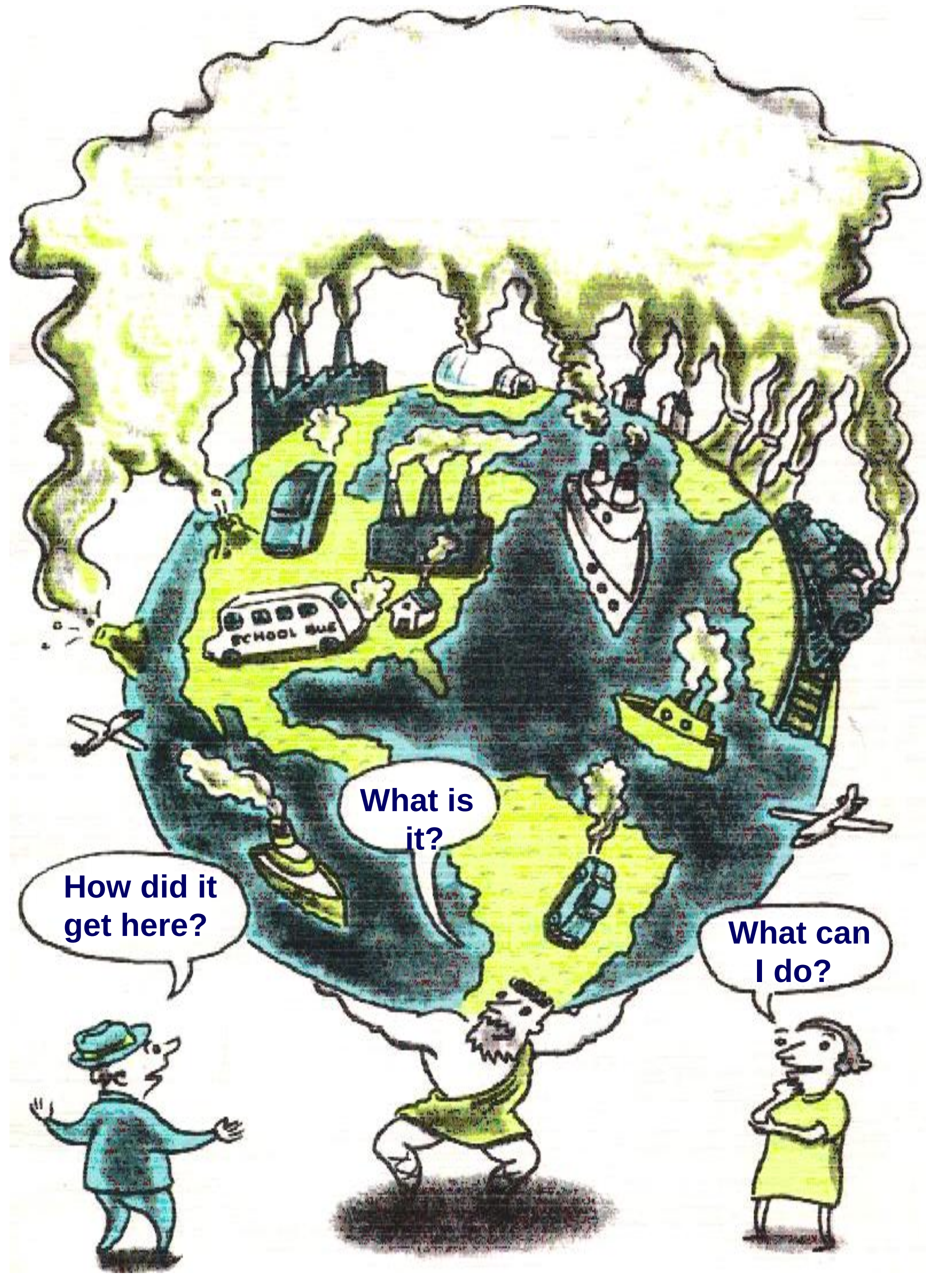
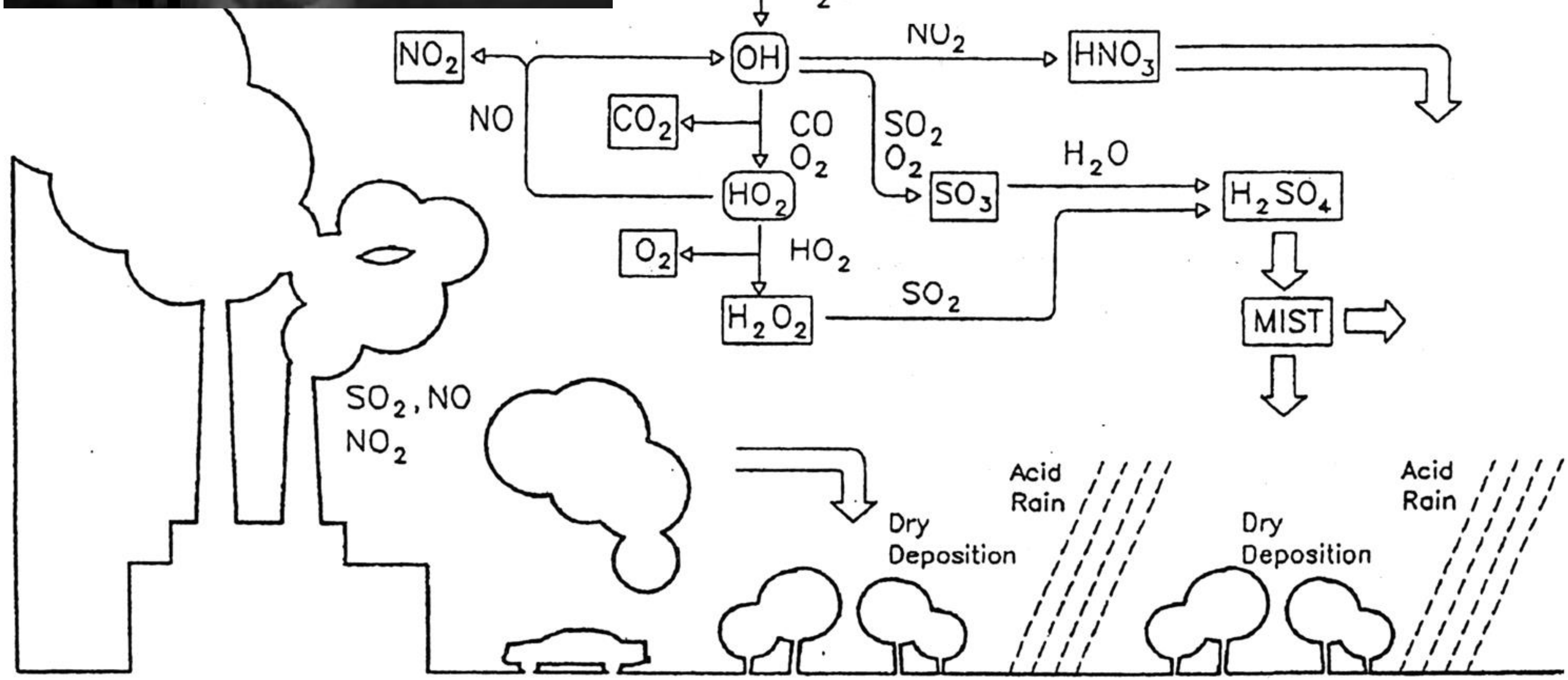


SCHEME OF ACIDIC RAIN FORMATION

Damage cost due to fossil fuel Combustion in European Union

Emission		Damage cost (1990)
SO_2	8330 kt	6000 \$/t
NO_x	2329 kt	5000 \$/t



Electron Beam Technology as 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 agriculture fertilizer;
- Technical advantages of electron beam process.

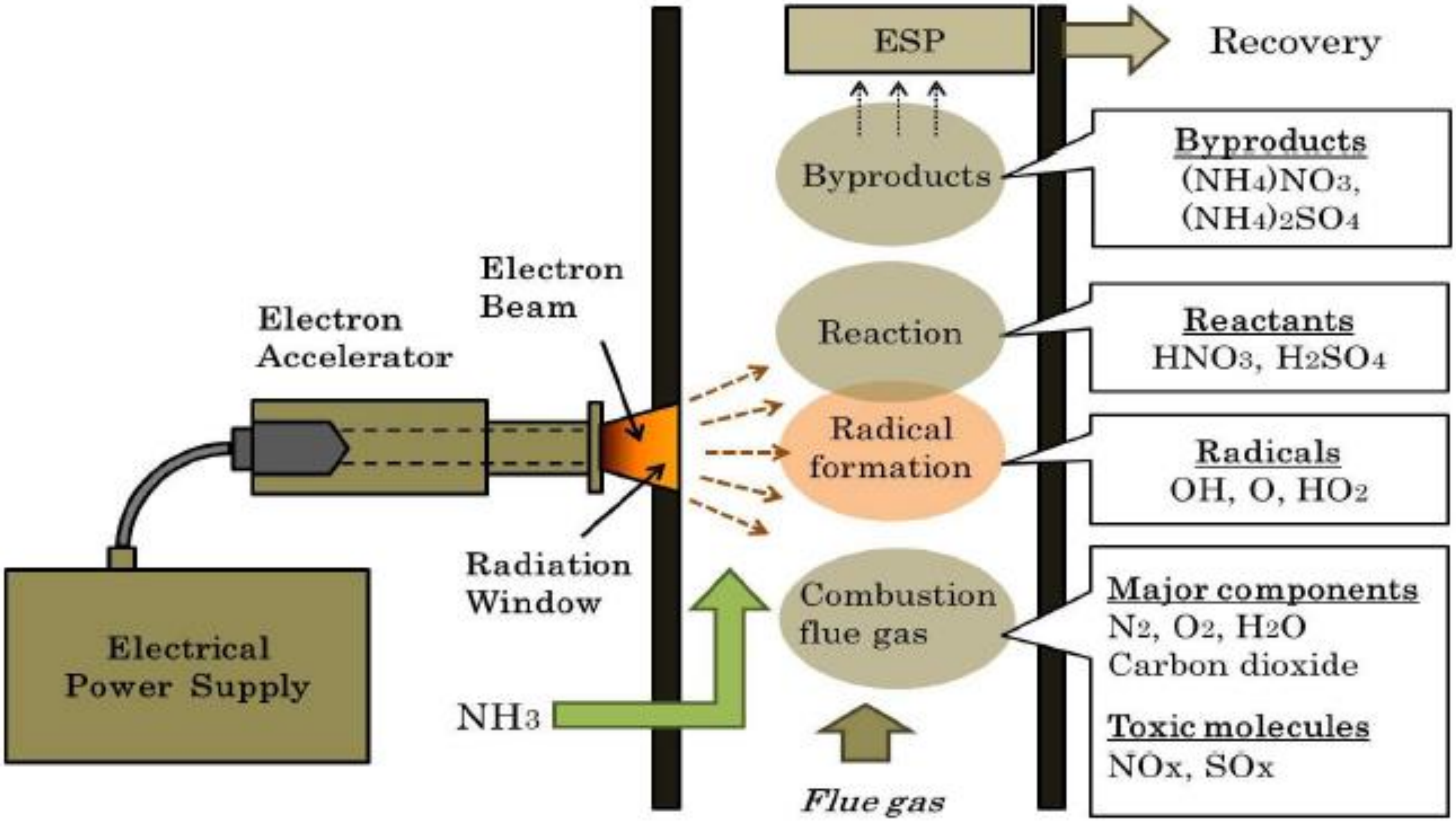
RADIATION TECHNOLOGY APPLIED IN ENVIRONMENT PROTECTION

Phase	Object	Additives	Process
Gas	Flue gas	SO_2; NO_x	Removal
	VOC	Organic compounds	Degradation, removal
Liquid	Drinking water	Chemical pollutants	Degradation, removal
	Wastewater	Bacteria; viruses; parasites	Hygenizataion
	Industrial wastes	Organic and nonorganic compounds	Degradation, removal
Solid	Sewage sludge	Bacteria; viruses; parasites	Hygenizataion
	Solid materials	Agriculture wastes	Transformation

TECHNOLOGY DEVELOPMENT

- Early phase (Japan, 1970's)
- Pilot plants phase (Japan, USA, Germany, Poland 1980's)
- Industrial plants phase (China, Poland, late 90's)
- Recent attempts (China, Bulgaria, Middle East)

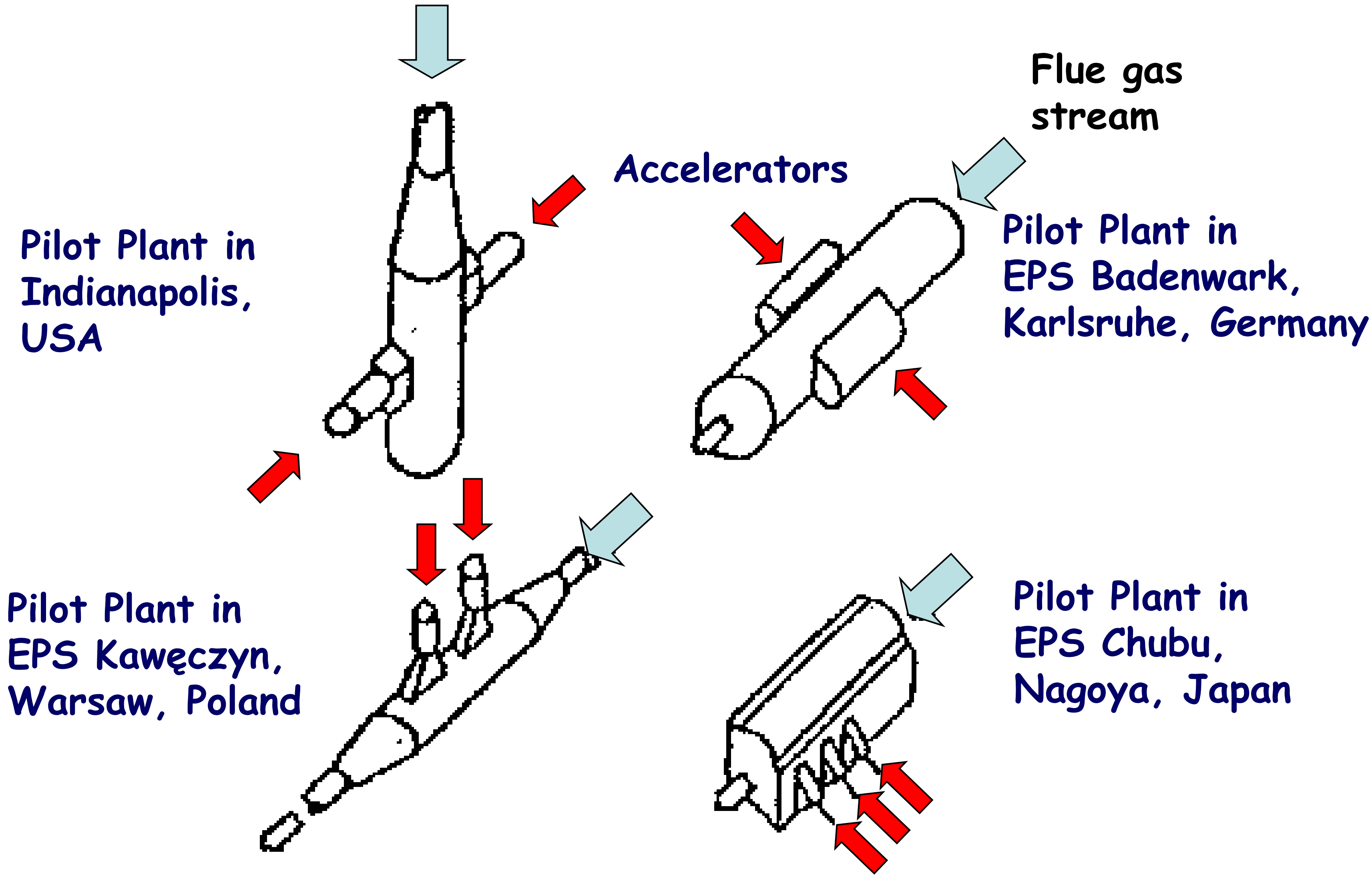
ELECTRON BEAM FLUE GAS TREATMENT PROCESS



Main advantages of the process

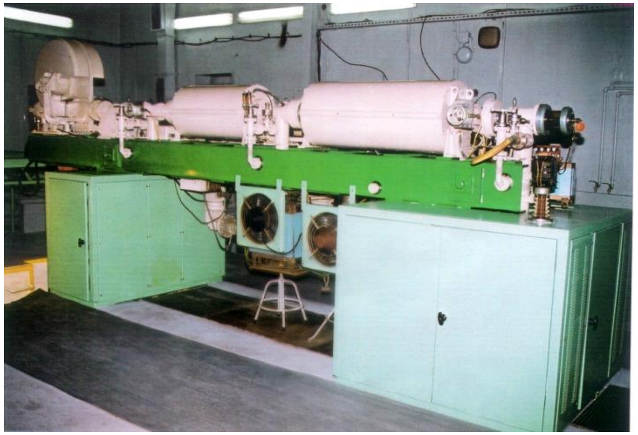
- Multipollution control technology;
- High efficiency of pollutants removal;
- High flexibility of installation;
- Usable byproduct creation;
- Dry and wasteless process;
- Simplicity of the installation;
- Ease of control and operation;
- Ease of retrofitting;
- Economically competitive process.

REACTION VESSELS CONSTRUCTION FOR FLUE GAS TREATMENT

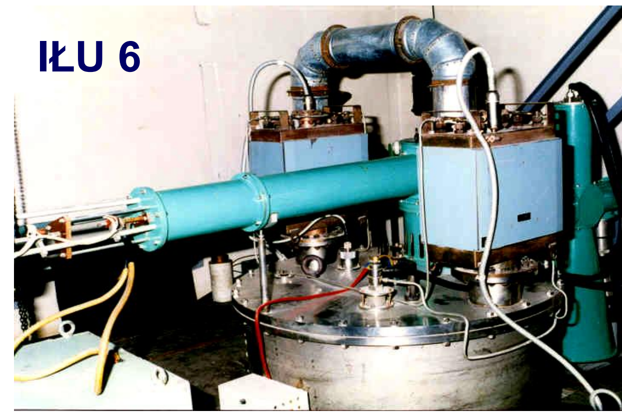


PILOT AND INDUSTRIAL FACILITIS FOR FLUE GAS TREATMENT

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



LAE 13/9   Elektronika 10/10



ELECTRON ACCELERATORS OF CENTRE FOR RADIATION RESEARCH AND TECHNOLOGY, INCT

Type of accelerator	Energy and Beam power	Remarks
LAE 13/9 **linac**	**5-13 MeV** **9 kW**	**R&D** **Radiation processing**
AS 2000 electrostatic	0,1-2 MeV 0,2 kW	R&D
IŁU 6 resonans	0,5 - 2 MeV 20 kW	R&D Pilot plant
Elektronika 10/10 **linac**	**10 MeV** **15 kW**	**Radiation processing** **(two units)**
LAE 10 linac	10 MeV	Basic research

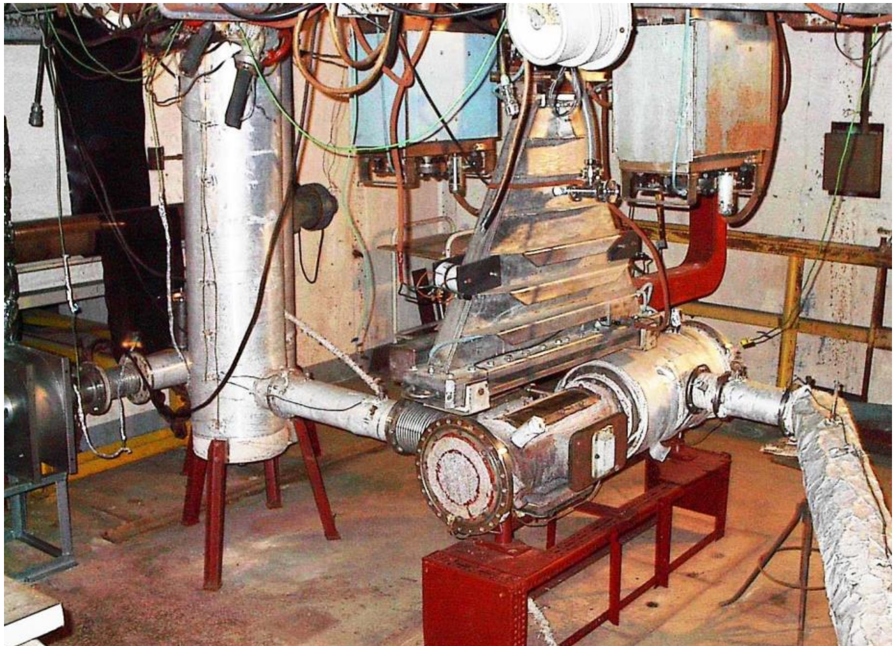
INSTITUTE OF NUCLEAR CHEMISTRY AND TECHNOLOGY
ul. Dorodna 16, 03-195 Warsaw, Poland

INCT pathway to EB Process Industrial Implementation

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

1990 – Pilot Plant PS Kawęczyn: 20 000 Nm^3/h,
accelerators: 2 x 50 kW, 700 keV

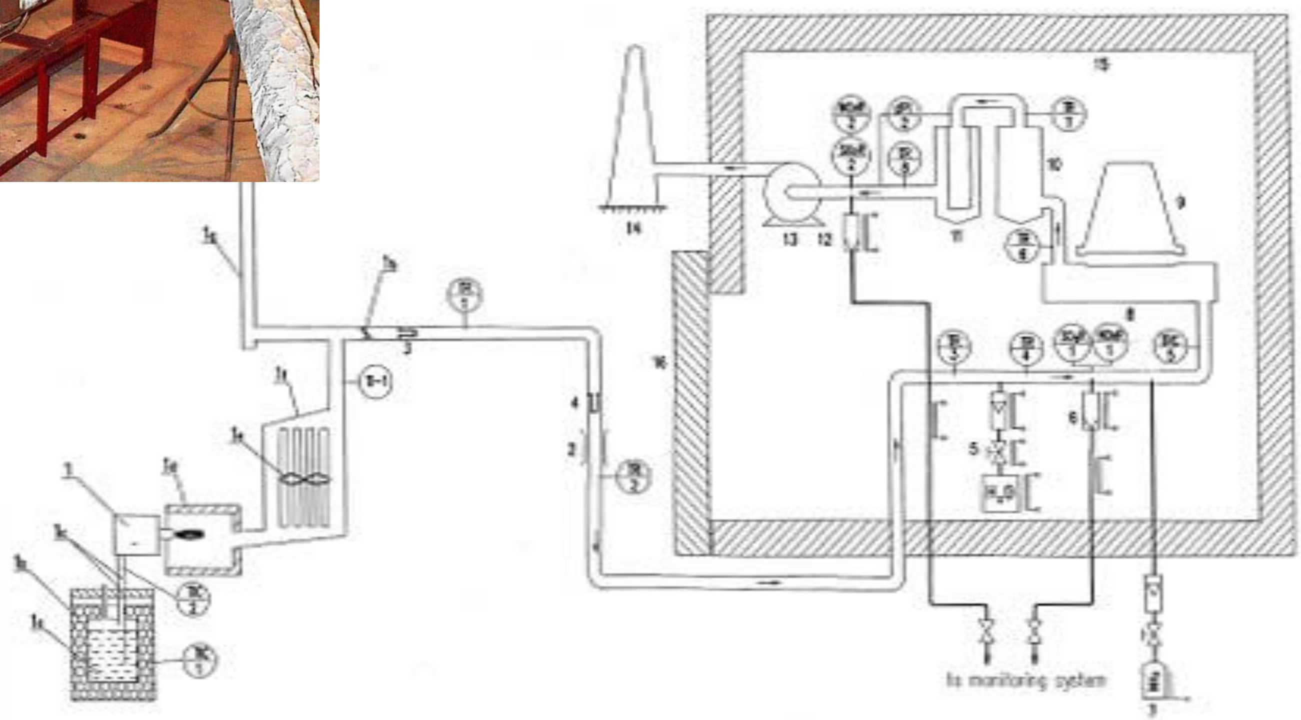
2002 – Industrial Plant PS Pomorzany;
270 000 Nm^3/h,
accelerators: 4 x 262.5 kW, 700 keV



ILU 6 ACCELERATOR

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

Oil burner



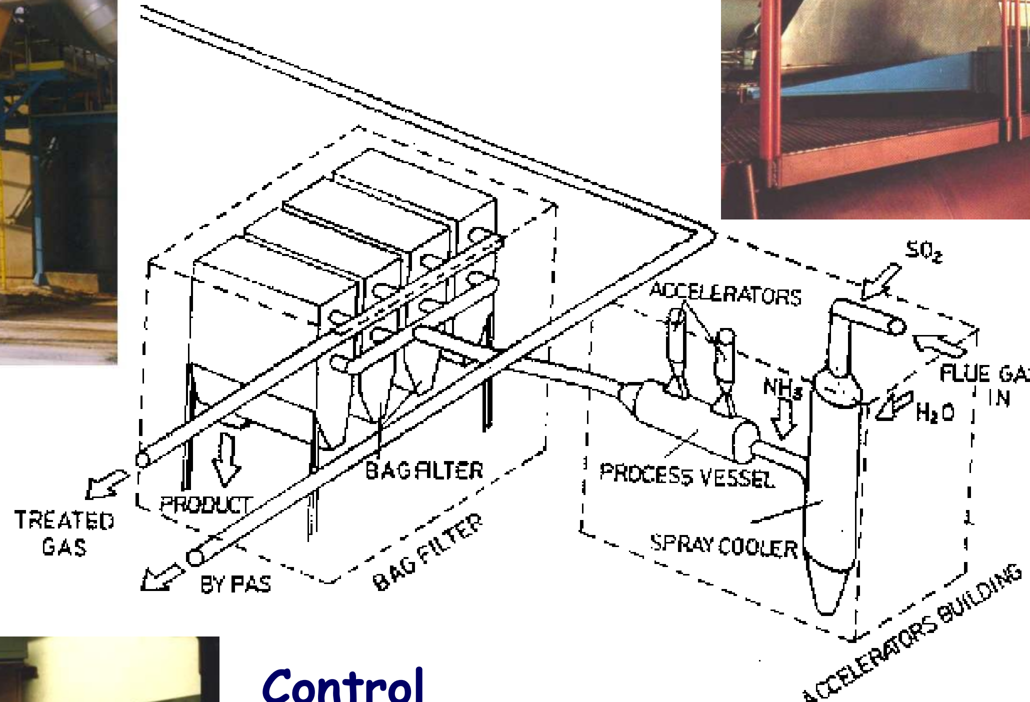
Schematic diagram of laboratory scale electron-beam flue gas treatment (EBFGT) installation

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

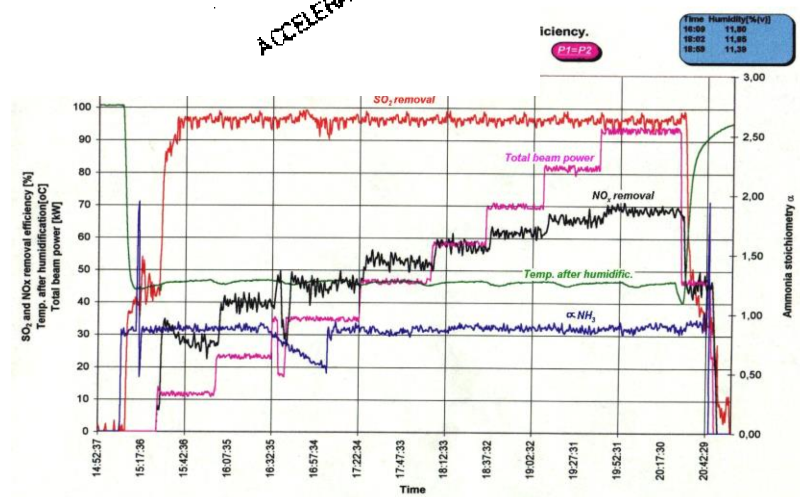
Two accelerators
Energy 0.7 MeV
Power 2 x 50 kW

Process vessel

Electrostatic precipitator



Control room



Empirical model of NO_x i SO_2 removal in pilot plant

Removal efficiency NO_x (η_{NOx}^m), [%]

$$\eta_{NOx}^m = 80.417\{1-\exp(-0.2587D)\}(1.03495-0.00007[NO_x]_0)$$

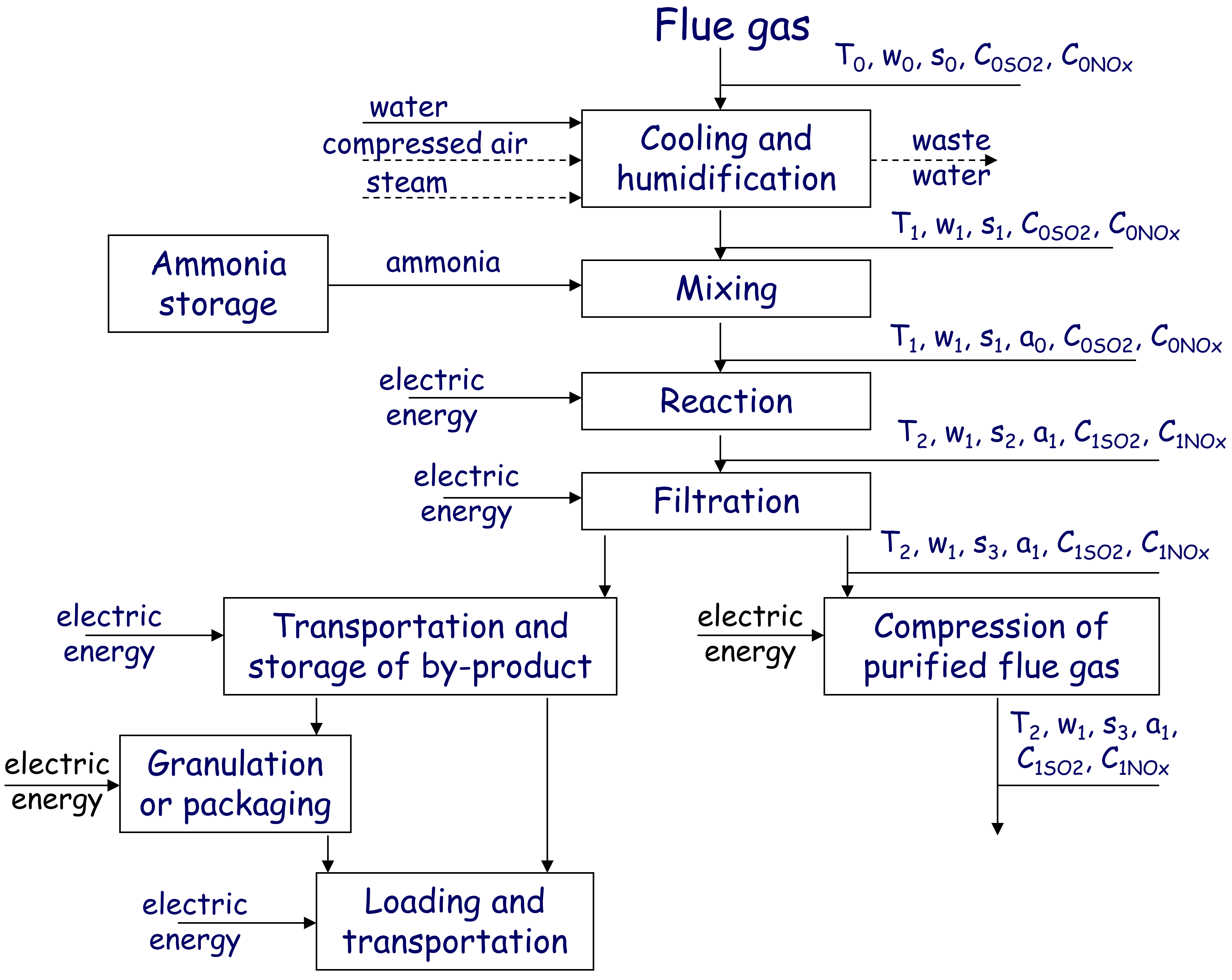
Removal efficiency SO_2 (η_{SO2}^m), [%]

$$\eta_{SO2}^m = 0.96(144.9787-1.12341T_{pn}+0.00267\,T_{pn}^2)(0.85732+0.01423H)(0.98528+0.00226D)(1.1777-0.79092/\tau)$$

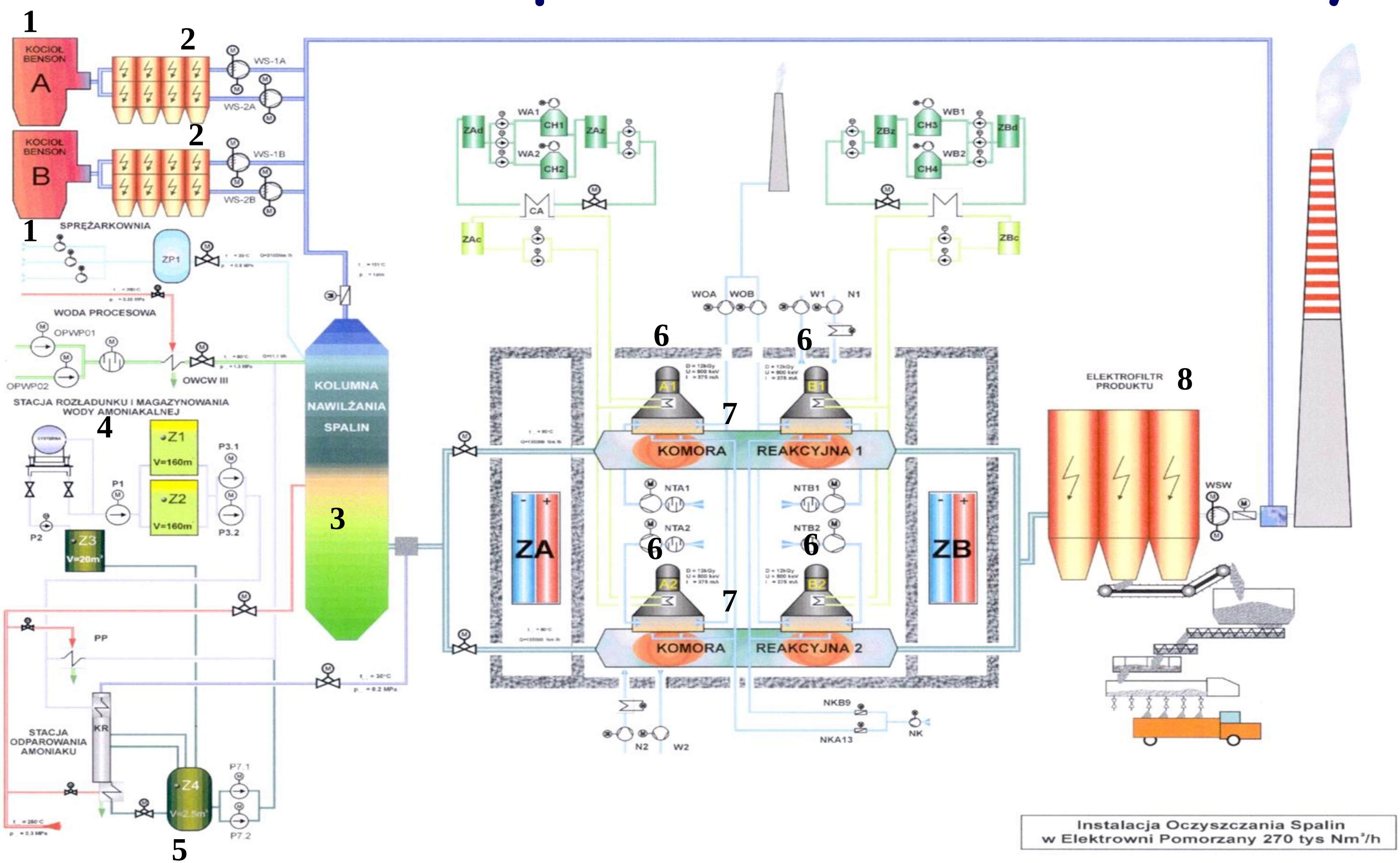
Inlet temperature T_{pn} [^{0}C]	Volume content of water vapor H [% vol]	Absorbed dose D [kGy]	Inlet NO_x concentr. $[NO_x]_0$ [ppm]	Average residence time τ [s]	Flue gas flow rate Q_{sp} [m^3/h]	Ammonia stoichiomet. α
54.9-78.8	6.7-12.4	2.8-12.7	127-216	3.56-14.43	4216-17082	0.87-0.93

A.G. Chmielewski et al.: Radiat. Phys. Chem. **57** (2000) 527

Control, monitoring and data management system

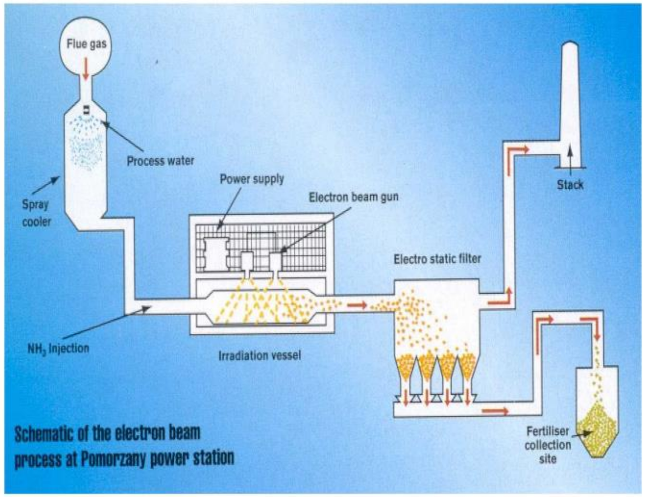


Electron beam process at EPS Pomorzany



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

Facility for flue gas treatment at EPS Pomorzany



Block diagram

Electrostatic precipitator

EPS Pomorzany

Cooling tower

Ammonia water container

Ammonia injection

Product collection

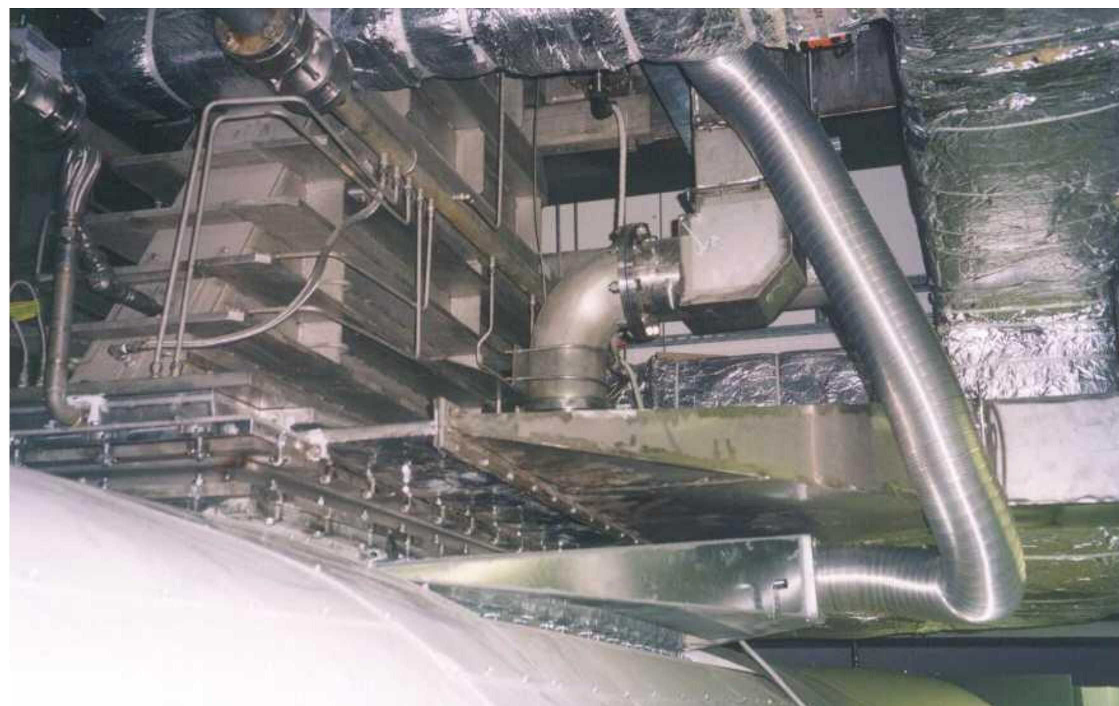
NHV, Japan

EPST-800-102
DC power supply

Frequency	50 Hz
Phase	3
Input voltage	1100 V
AC power	1300 kVA
Output voltage	800 kV
Load current	1000 mA
HV output	2
Oil volume	27000 l
Total mass	48000 kg
Volume of container	51 m^3
Dimensions	2.8x6.5x4.7 m

Nominal energy	700 keV
Nominal beam current	375 mA
Beam power	262.5 kW
Scan width	225 cm
Dose uniformity	± 5 %
3x380 V, 50 Hz, 460 kVA	
N° of accelerating heads	4
Total beam power	1050 kW
Producer:	Nissin High Voltage

Accelerating head (pressure tank)



Scanning horn and reaction vessel

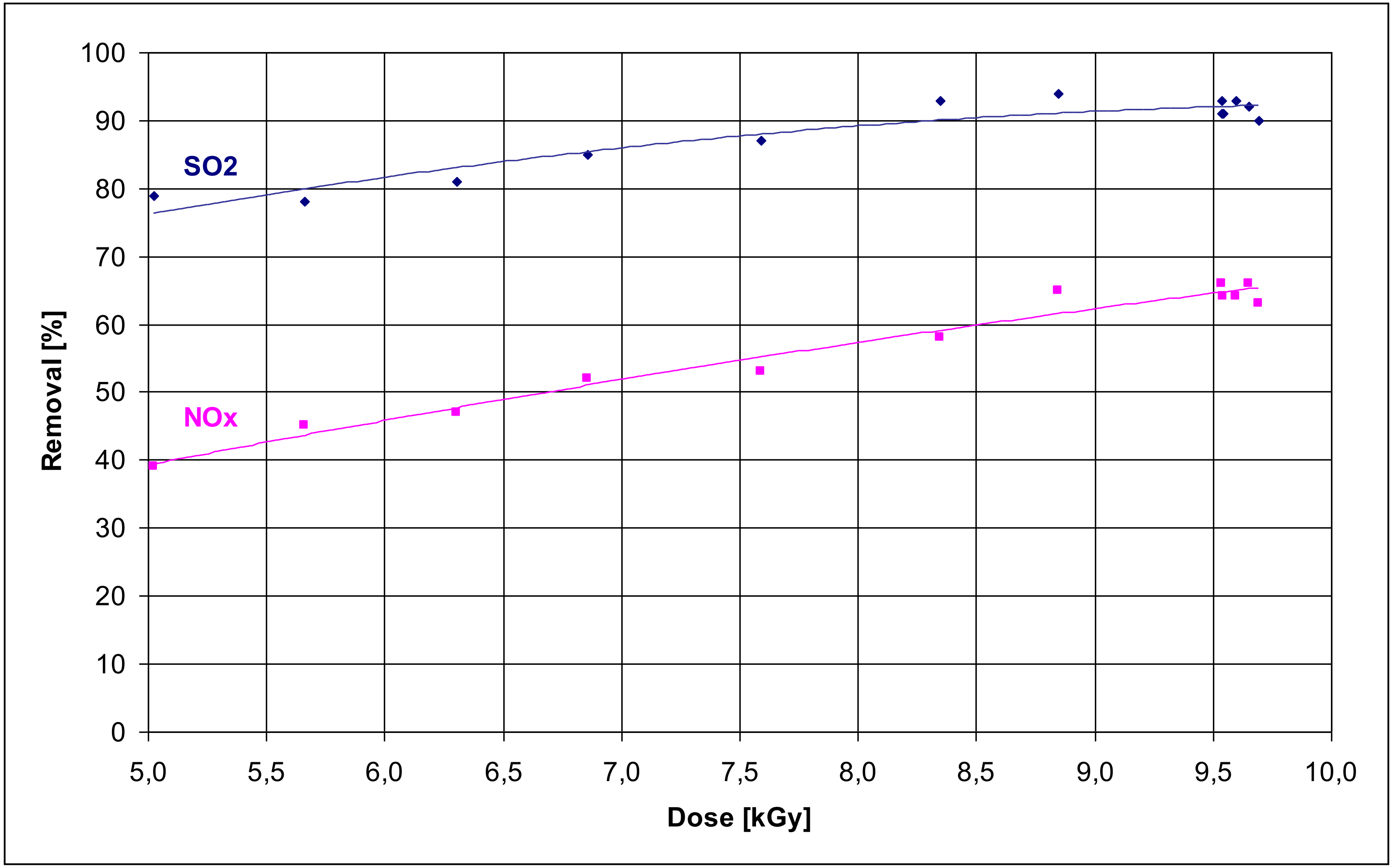
Reaction vessel window

Power Station Pomorzany, Szczecin

Industrial Facility for Flue Gas Treatment

The obtained results

The dependence of SO_2 and NO_x removal efficiency on dose



The by-product

Composition:

$(NH_4)_2SO_4$	45 - 60%
NH_4NO_3	22 - 30%
NH_4Cl	10 - 20%
moisture	0,4 - 1%
water insoluble parts	0,5 - 2%

by-product yield:up to 700 kg/h

Contents of heavy metals (mg/kg) in the byproduct and limits for heavy metals content in the NPK fertilizer established in some countries

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

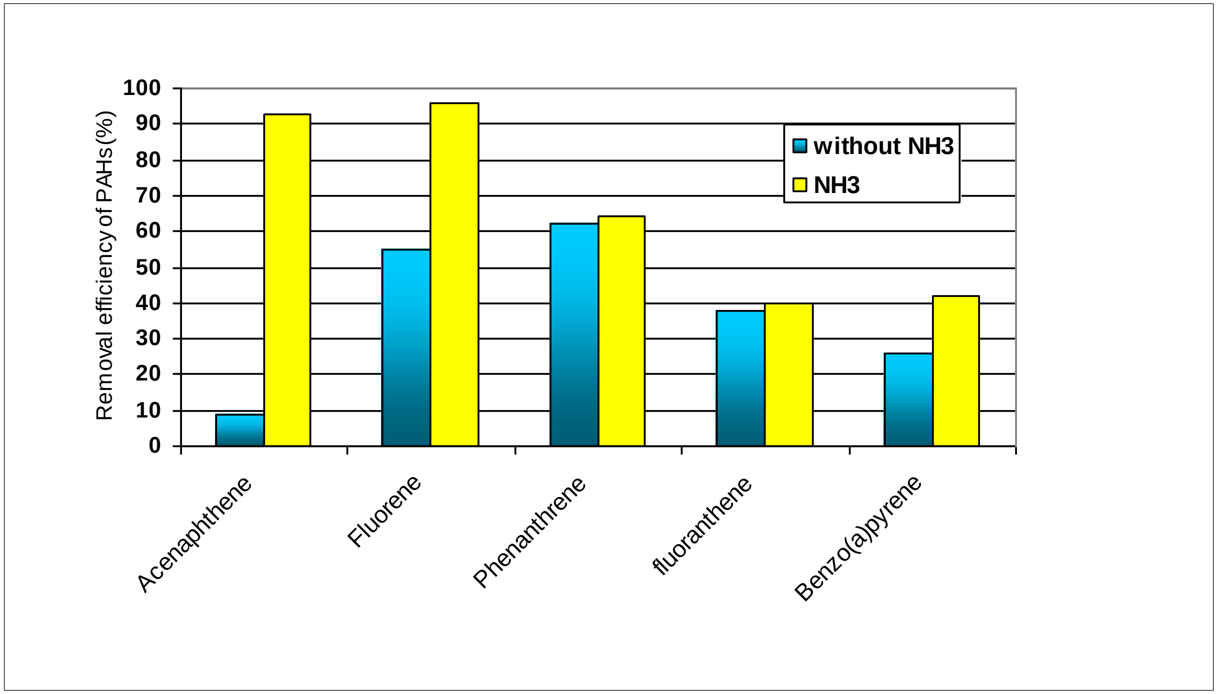
Different method comparison

Emission control method	Investment cost (USD/kW$_e$)	Annual operational cost (USD/kW$_e$)
Wet flue gas desulphurisation	120	3.0
Selective catalytic reduction	110	4.6
Wet FGD + SCR	230	7.6
Electron beam FGT	**160**	**7.35**

- Accelerators improvement,
- Adjustment for various pollutants - multipollutant control,
- Adjustment for various, technological processes,
- Costs lowering,
- New implementations.

Recent activity

VOC removal efficiency



Mercury removal

Mercury oxidation proceeds in reaction chamber

$$Hg^{o} \xrightarrow{\text{oxidation}} Hg^{2+} \xrightarrow{\text{removal}}$$

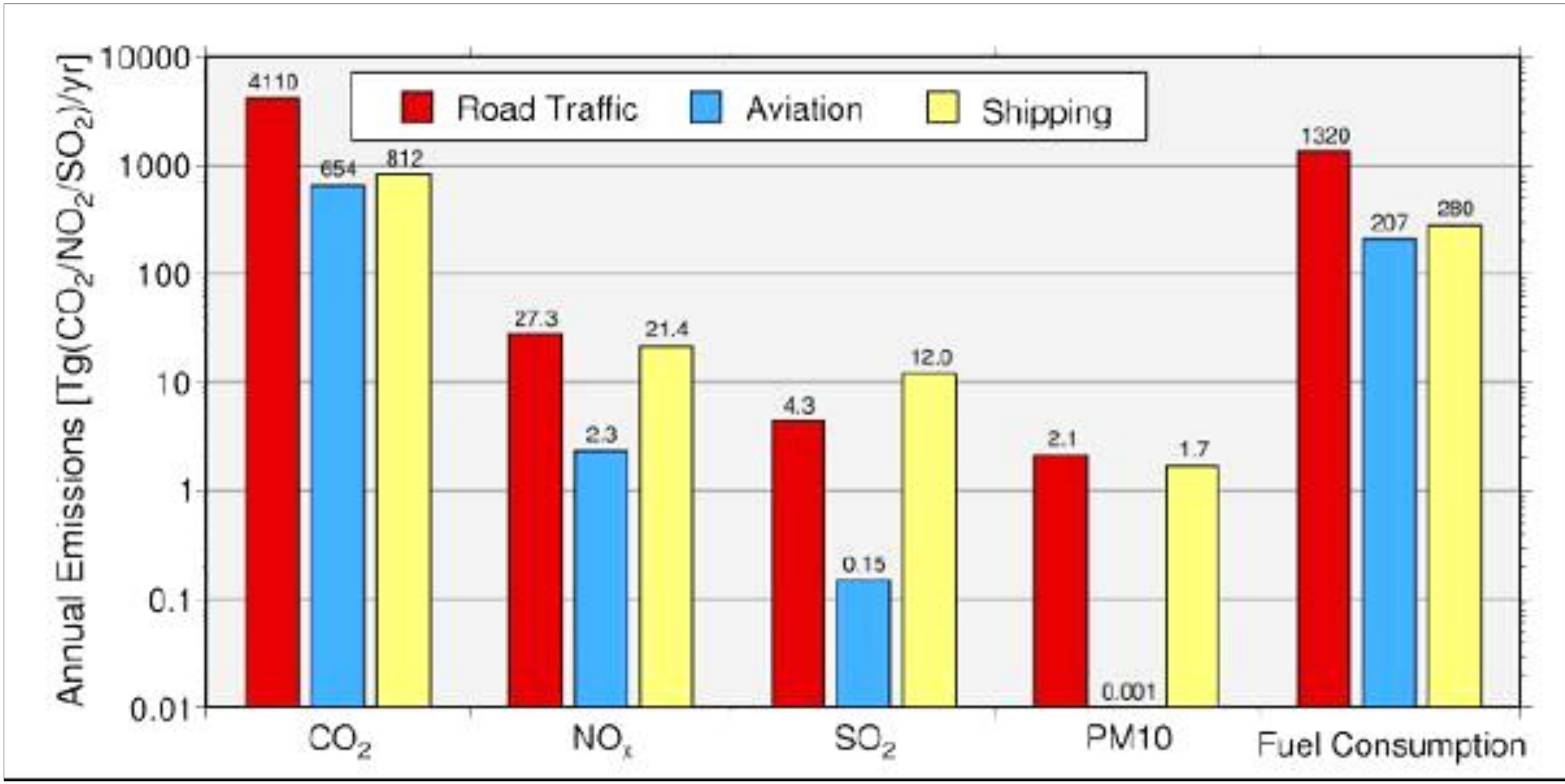
At medium energy levels, approximately 98% of gaseous mercury vapor was readily oxidized.

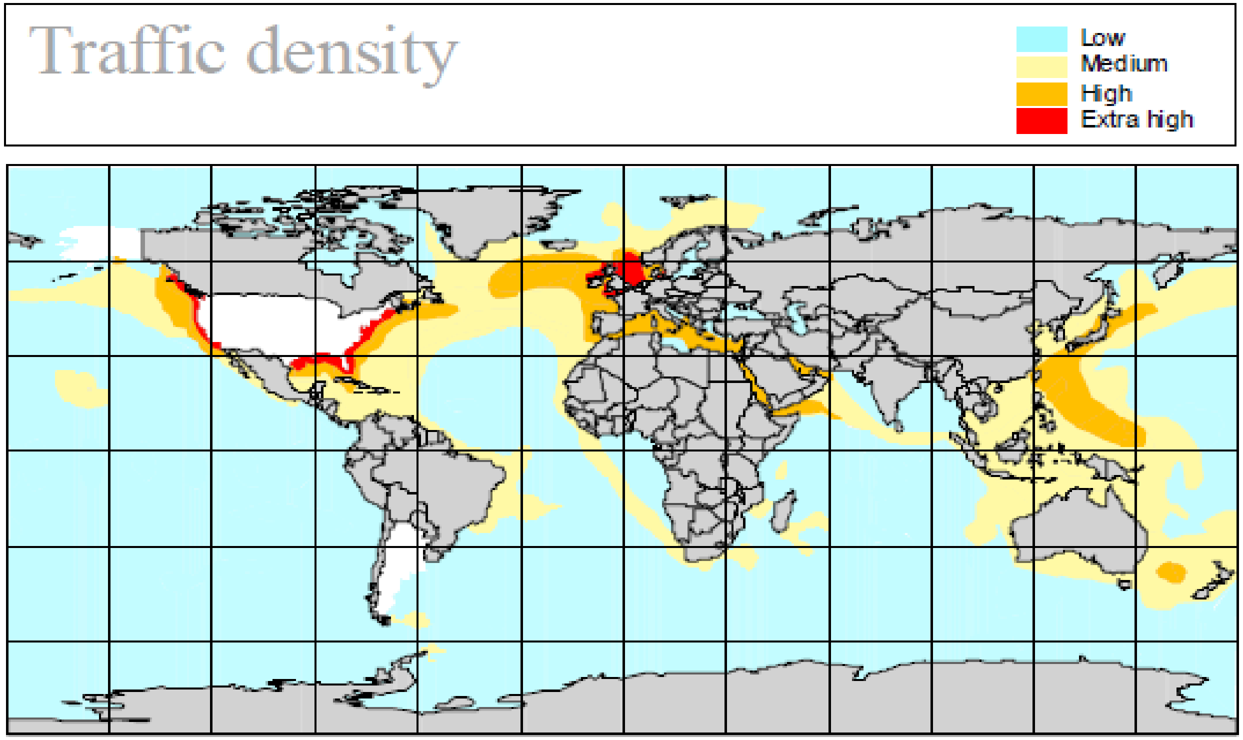
Experiments were performed for following parameters:

Hg concentration in gas	about 16 $\mu g/m^3$
applied doses of E-beam	2.5 – 10 kGy

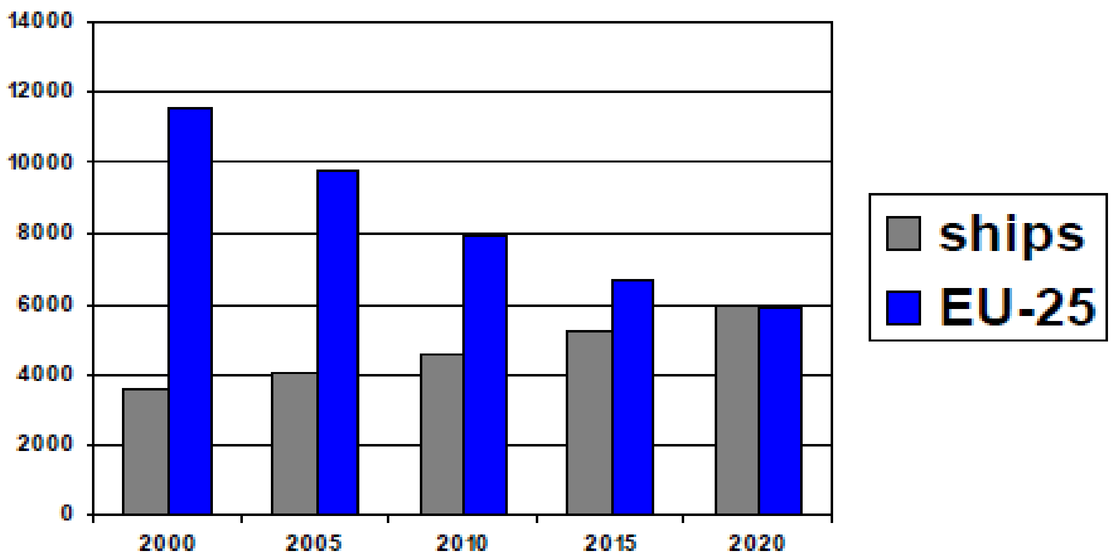
Jo-Chun Kim, Ki-Hyun Kim, Al Armendariz and Mohamad Al-Sheikhly: Electron Beam Irradiation for Mercury Oxidation and Mercury Emissions Control, J. Envir. Engrg. Volume 136, Issue 5, pp. 554-559 (May 2010)

ANNUAL POLLUTANTS EMISSIONS



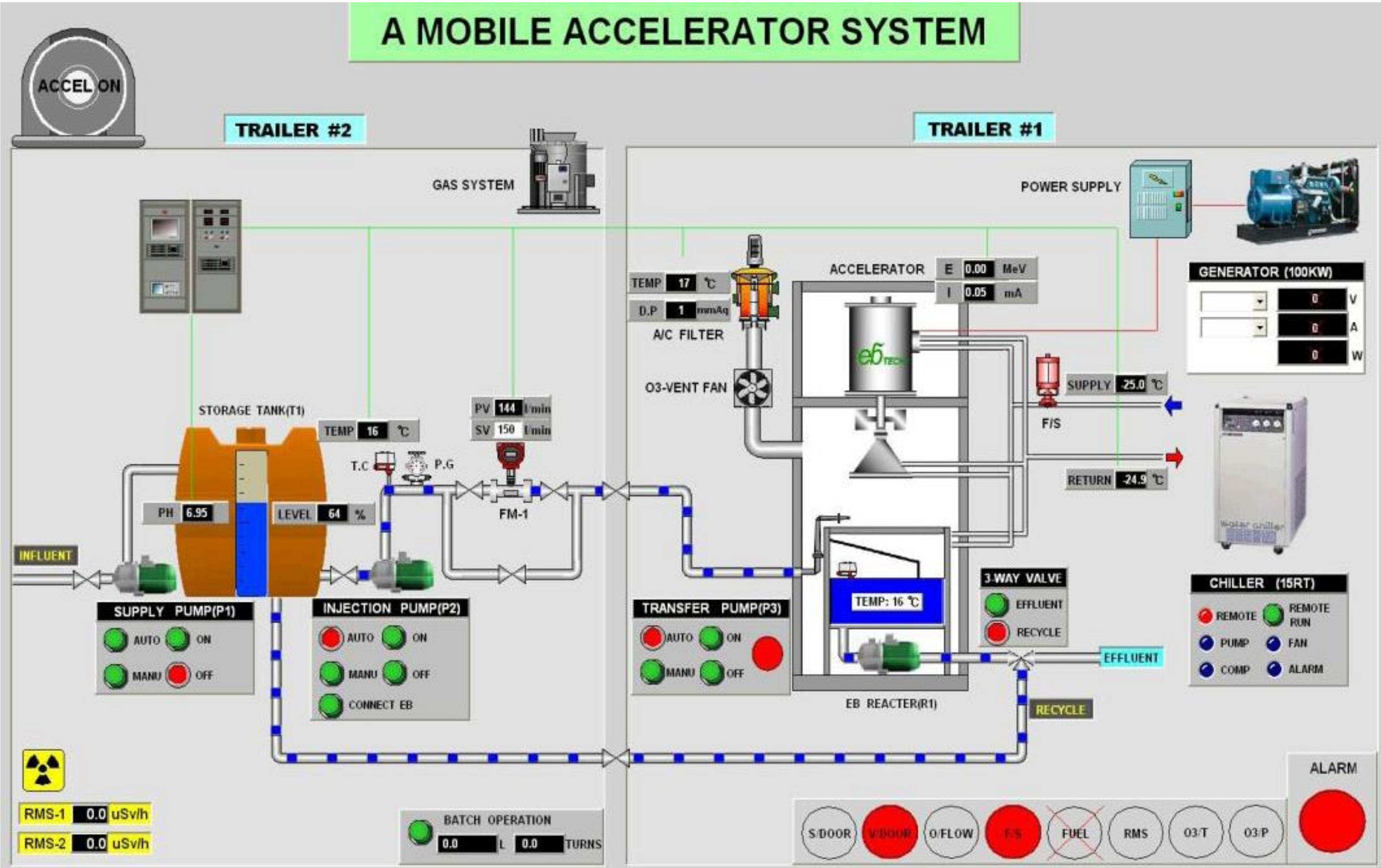

Traffic density
Low
Medium
High
Extra high

CARGO SHIPS


14000
12000
10000
8000
6000
4000
2000
0
2000
2005
2010
2015
2020
ships
EU-25

General view of the pilot plant in Saudi Arabia

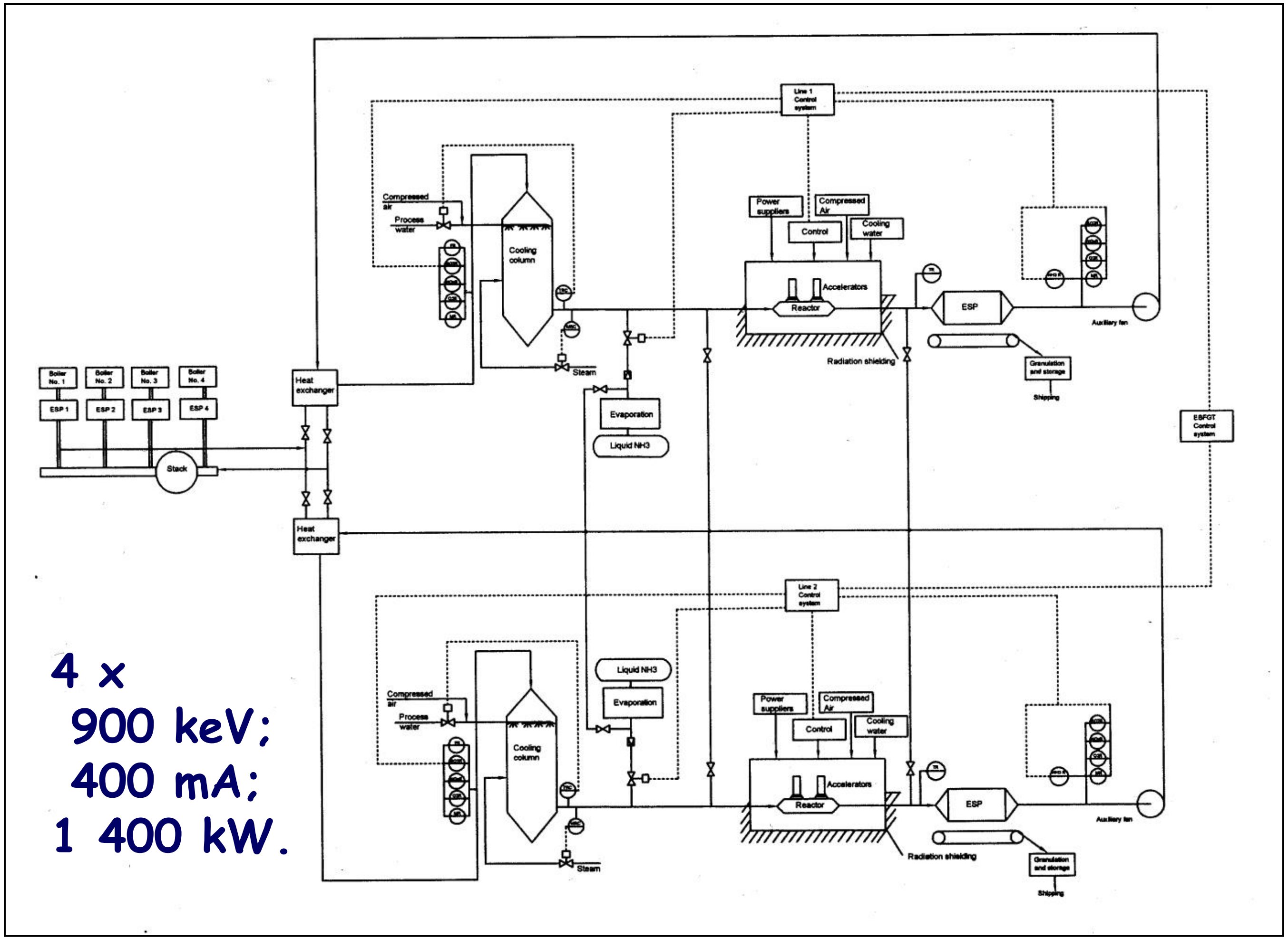
1 – stack of F 1001 boiler;
2 - boiler F1001;
3 - flue gas duct;
4 - control room;
5 - humidification unit;
6 - pilot plant stack;
7 - bag filter;
8 - insulated duct part;
9 – cyclone;
10 - ammonia storage and injection unit;
11 - EB mobile unit.



A MOBILE ACCELERATOR SYSTEM
ACCEL ON
TRAILER #2
TRAILER #1
GAS SYSTEM
POWER SUPPLY
ACCELERATOR
E 0.00 MeV
I 0.05 mA
GENERATOR (100KW)
V
A
W
TEMP 17 ℃
D.P 1 mmAq
A/C FILTER
O3-VENT FAN
STORAGE TANK(T1)
TEMP 16 ℃
PV 144 l/min
SV 150 l/min
T.C
P.G
FM-1
PH 6.95
LEVEL 64 %
INFLUENT
SUPPLY PUMP(P1)
AUTO
ON
MANU
OFF
INJECTION PUMP(P2)
AUTO
ON
MANU
OFF
CONNECT EB
TRANSFER PUMP(P3)
AUTO
ON
MANU
OFF
TEMP: 16 ℃
EB REACTER(R1)
SUPPLY -25.0 ℃
RETURN -24.9 ℃
F/S
3-WAY VALVE
EFFLUENT
RECYCLE
EFFLUENT
RECYCLE
CHILLER (15RT)
REMOTE
REMOTE RUN
PUMP
FAN
COMP
ALARM
RMS-1 0.0 uSv/h
RMS-2 0.0 uSv/h
BATCH OPERATION
0.0 L
0.0 TURNS
S/DOOR
V/DOOR
O/FLOW
F/S
FUEL
RMS
O3/T
O3/P
ALARM

MOBILE ACCELERATR SYSTEM

TPS Sviloza, Bulgaria



4 x
900 keV;
400 mA;
1 400 kW.

Thermal Power Station generate flue gases from all boilers – 600 000 Nm^3, with emission of SO2 → 2800 – 4800 mg/Nm^3, NOx → 1200 – 1600 mg/Nm^3 and dust → 200 – 1400 mg/Nm^3.

ACCELERATOR TECHNOLOGY FOR ENVIRONMENTAL APPLICATION

Best accelerator selection and radiation facility design with possibly:

- **Low electron energy,**
- **High beam power,**
- **High accelerator electrical efficiency,**
- **High beam utilization,**
- **High reliability/avalability level.**

Progress in accelerator technology development is based on new constructions and components,

Support of R&D study by governmental and international institutions is needed.

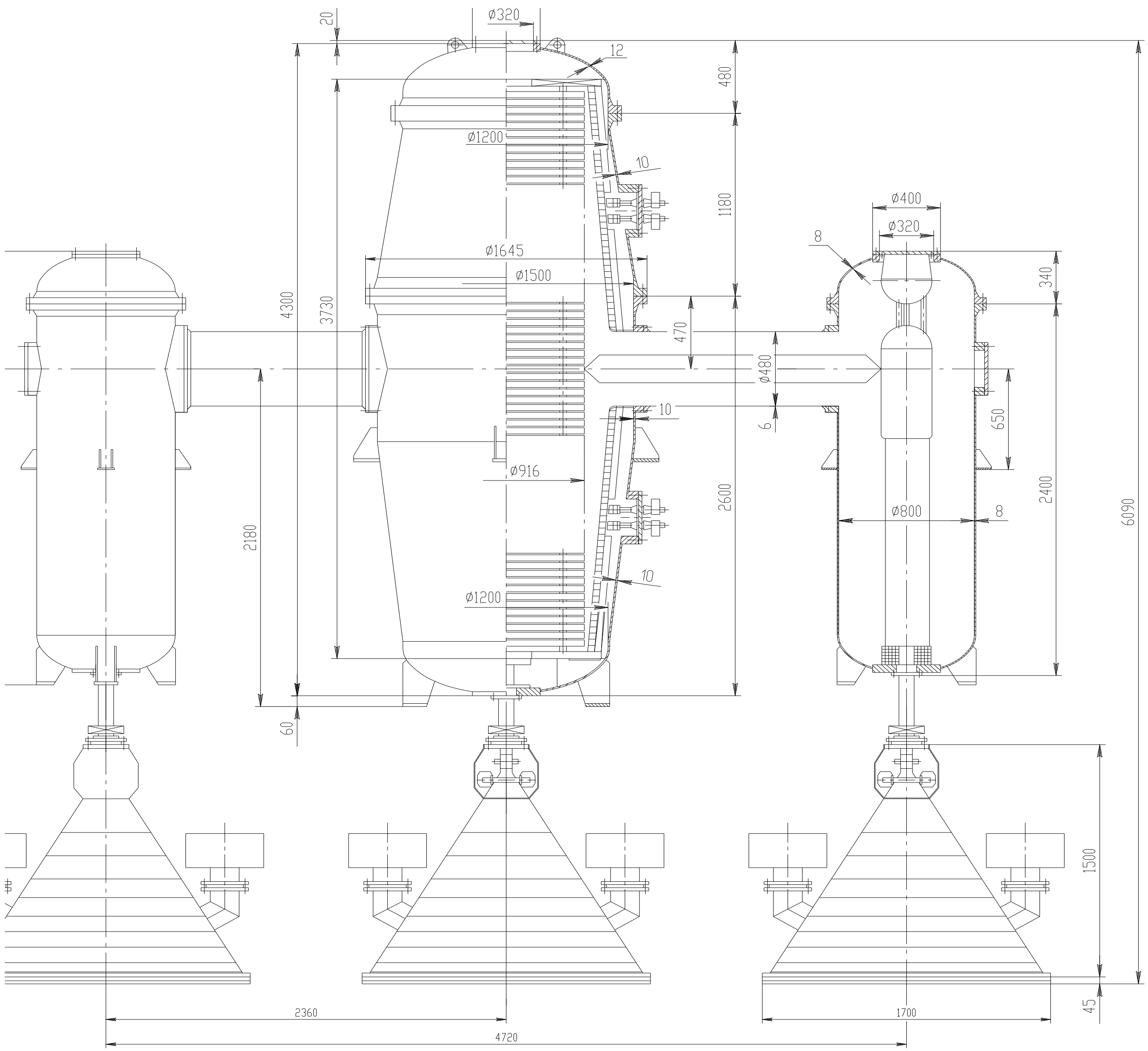
The principal parameters to be achieved for accelerators applied for flue gas treatment

- Electron energy 0.8 – 1.2 MeV;
- Beam power 300 – 500 kW;
- High reliability for long time operation (>6000 h/y);
- Availability above 95 %;
- Electron beam cost 1.5-2.5 $/W;
- Electrical efficiency >80 %;
- High current density, low level losses windows;
- Fault protection systems.

ELV 12

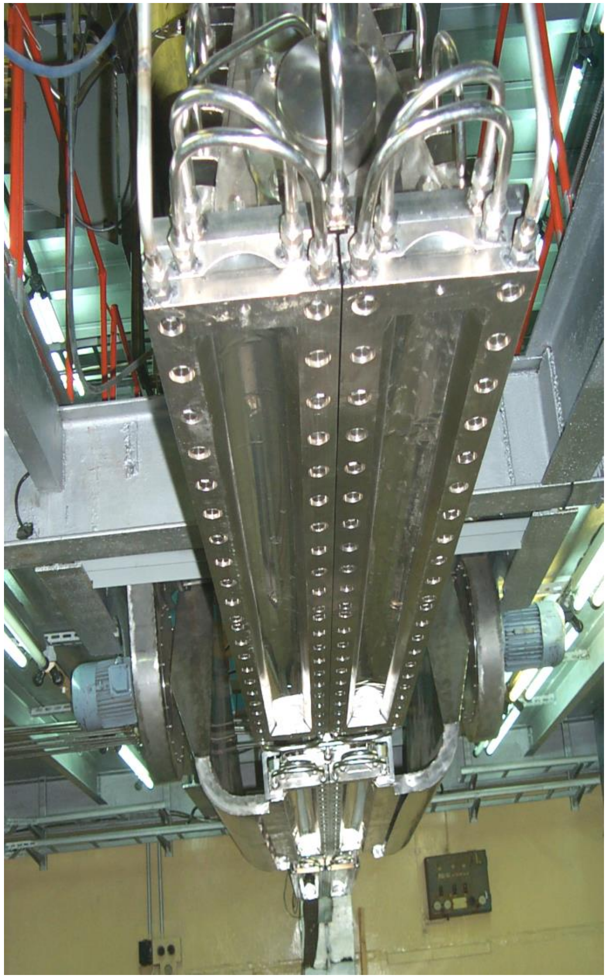
coreless transformer accelerator

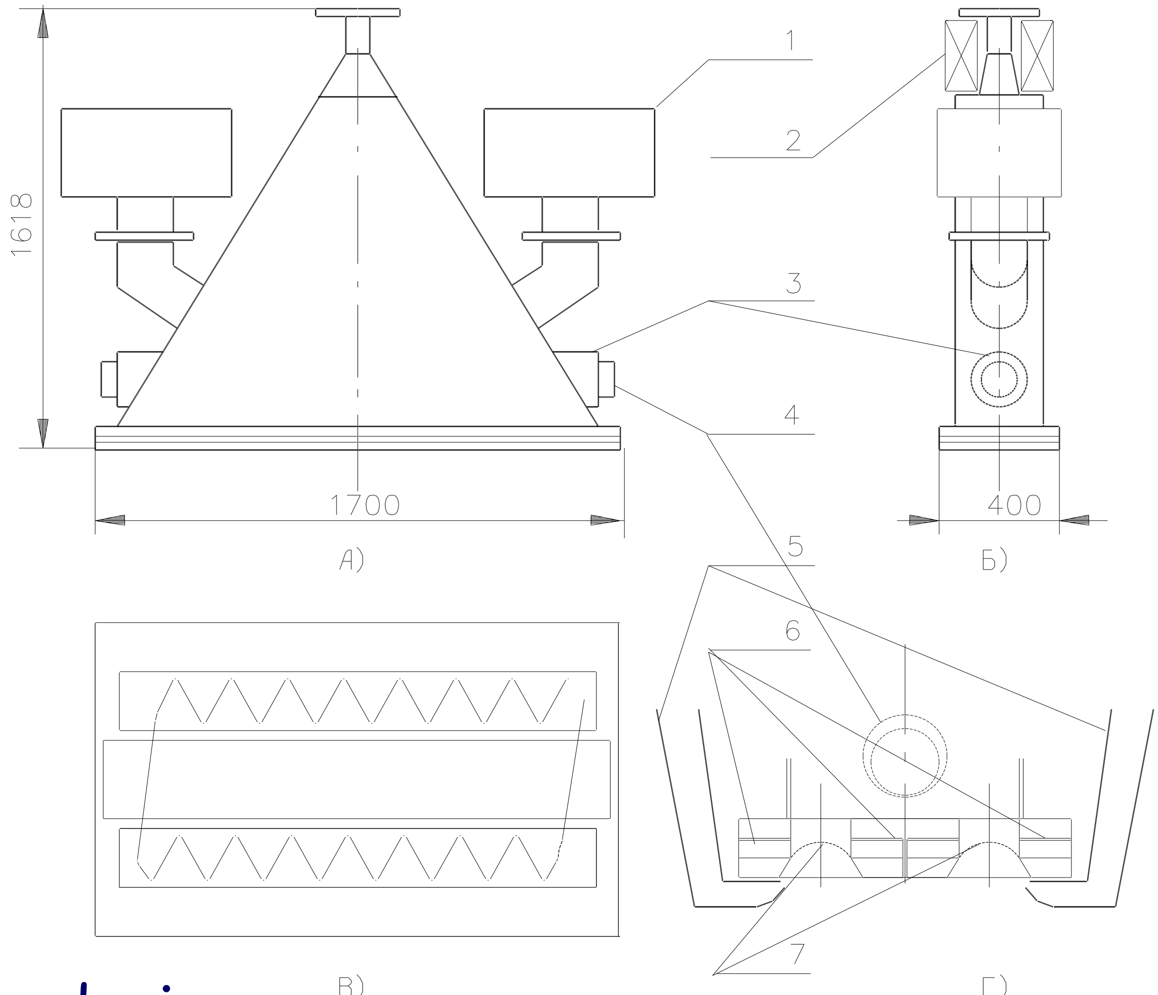
INP, Novosibirsk, Russia



Energy 0.6-1,0 MeV
Beam current 450 mA
Beam power 400 kW
Three scanners:
- 1600x75 mm;
- 200 mA (max beam current).

Double beam path scanning horn





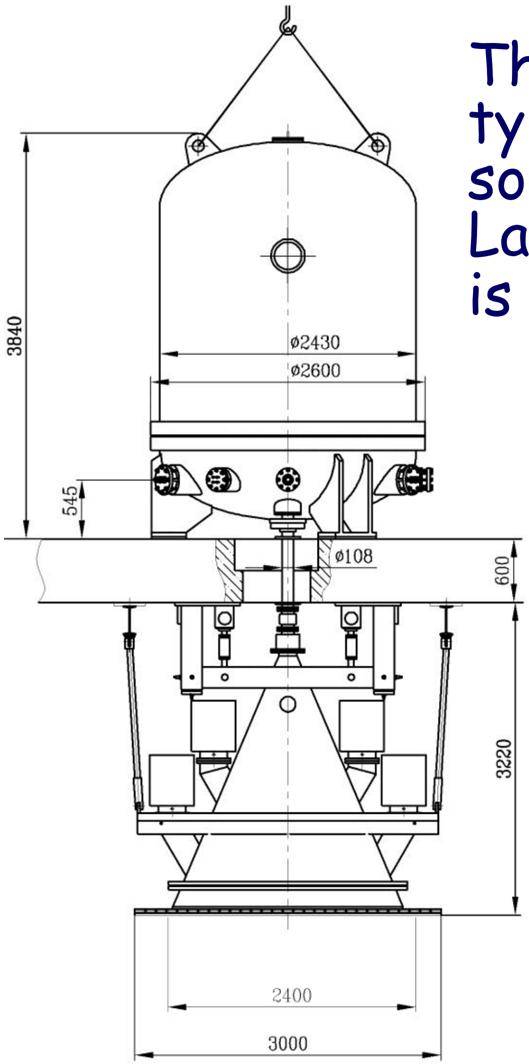
Two-windows extraction device:
1 – ion vacuum pumps, 2 - coils and cores of the beam scanning system, 3 - cylinder flange, 4 - foil blow, 5 - air jet cooling, 6 - frame for fixation of foil, 7 - extraction foils.

ELV 12

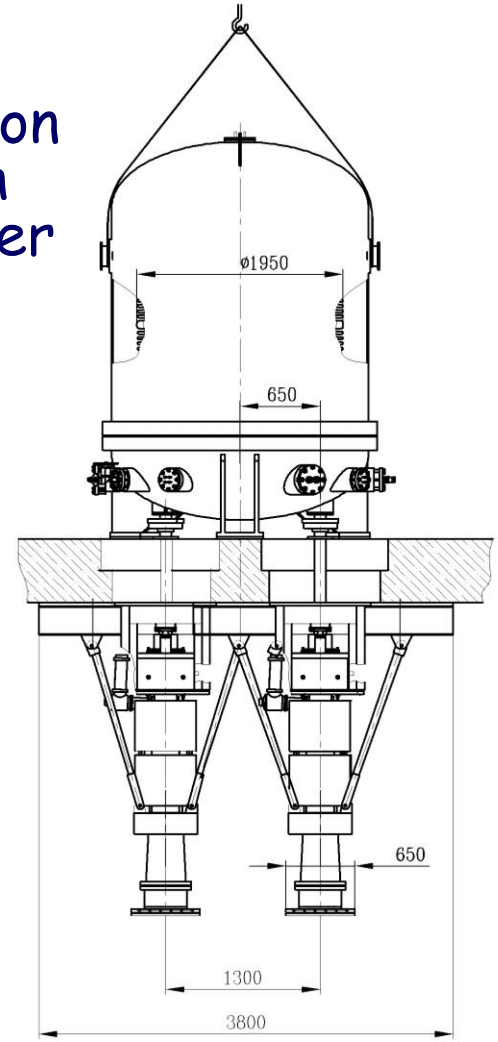
coreless transformer accelerator

Electron energy 1 MeV
Beam power 400 kW
Frequency 1000 Hz
One power supply
Three scanners


ELEKTRON 23
1 MeV, 500 kW



The diode type electron source with LaB6 emitter is used.



The DC high voltage is generated by three-phase cascade generator with inductive coupling.

NIIEFA, St Petersburg, Russia

HV electron accelerator Elektron-23

1. Accelerating voltage: 800-1000 kV;
2. Accelerating voltage instability during one hour of operation excluding ripples with frequency 50 Hz and more, not higher than: ± 2 %;
3. Beam current: 0-500 mA;
4. Electron beam current instability during one hour of operation, not higher than: ± 2 %;
5. Irradiation zone max length on the outlet window foil: 230 cm;
6. Linear beam current non-uniformity on the 10 cm distance from the outlet window foil on the irradiation zone max length, not higher than: ± 10 %;
7. AC/DC conversion efficiency, not less than: 90%.

Barriers for Industrial Application (why e-beam processes are not widely used?)

- Public acceptances:
  - Uneasy for the radiation safety;
  - New species formed by radiation.
- Technical problems:
  - Reliability for year-round operation;
  - Analysis of by-product (toxicity);
  - Scaling up from laboratory to industrial implementation.
- Competition with other processes (economics):
  - Difficult to beat the conventional processes;
  - High cost for pilot plant construction;
  - High investment cost and long returns;
  - No alternatives or by-passes for shut-down;
  - Not universal for all environmental plant.
- Regulation from Authorities.

CONCLUSIONS

Characteristics steps can be recognized in the past of accelerator development. Present stage of accelerator technology perfection includes: cost effectiveness, reliability, compactness and introduction of MW beam power level.

The electrical efficiency is very important parameter for high power accelerators. Special attention should be devoted to optimize electrical energy consumption for accelerator and auxiliary equipment installed in radiation facility.

New systems must be proven in an industrial confirmed acceptance, so introduction of a new accelerator technology can require a number of years for widespread market penetration.

Major industrial accelerator producers are located in USA, Russia, Japan, France and Belgium. Several other countries including Poland are capable to produce accelerators on limited scale.

The progress in accelerator technology is not a quick process but can be easily noticed in longer time scale.

Electron Beam Technology has been one of the promising process for environmental treatment, such as Flue gas/VOC, Water/ Wastewater, and Sludge from 1970s. Implementation of large scale plant has demonstrated the efficiency of system both in technically and economically.

Accelerators of high power (several hundreds kilowatt) are already available in the market, and some of them have proved their reliability in long term operation in Flue gas treatment and wastewater treatment.

The application of electron beam to the treatment of pollutants has emerged as one of effective methods and some of the newly developed electron beam technologies could be able to contribute to treatment of pollutants from the human activities.

Thank you for your attention