

# Electron beam treatment of marine diesel exhaust gases

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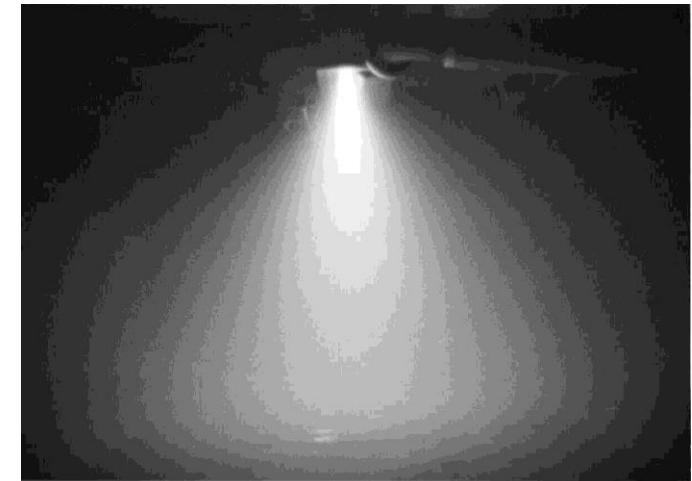
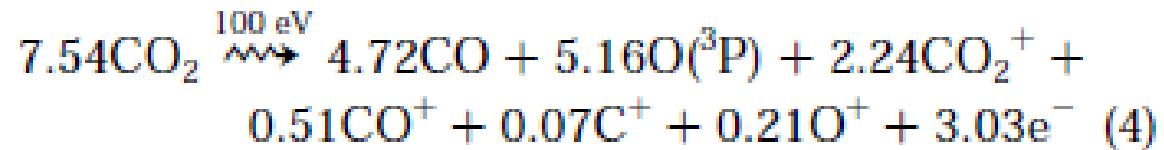
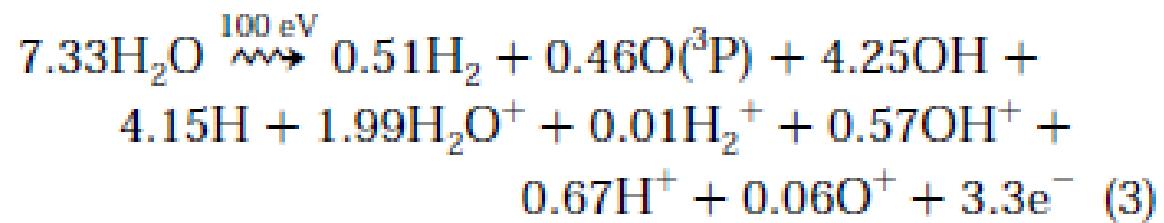
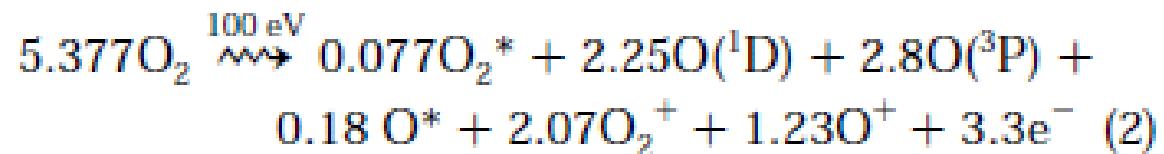
ARIES Meets Industry - accelerator application to the ship exhaust gases treatment  
1 Dec 2017,



TANGO 2



# Flue gas electron beam irradiation

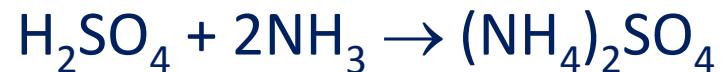


**SO<sub>2</sub>**

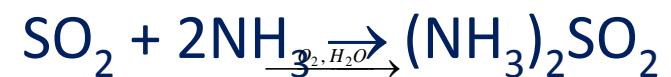
## REMOVAL MAIN REACTIONS



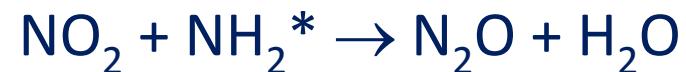
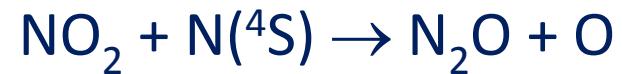
radiothermal



thermal



# NOx REMOVAL MAIN REACTIONS

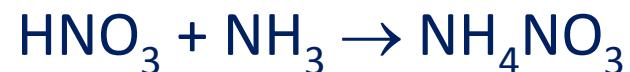


# NOx REMOVAL MAIN REACTIONS

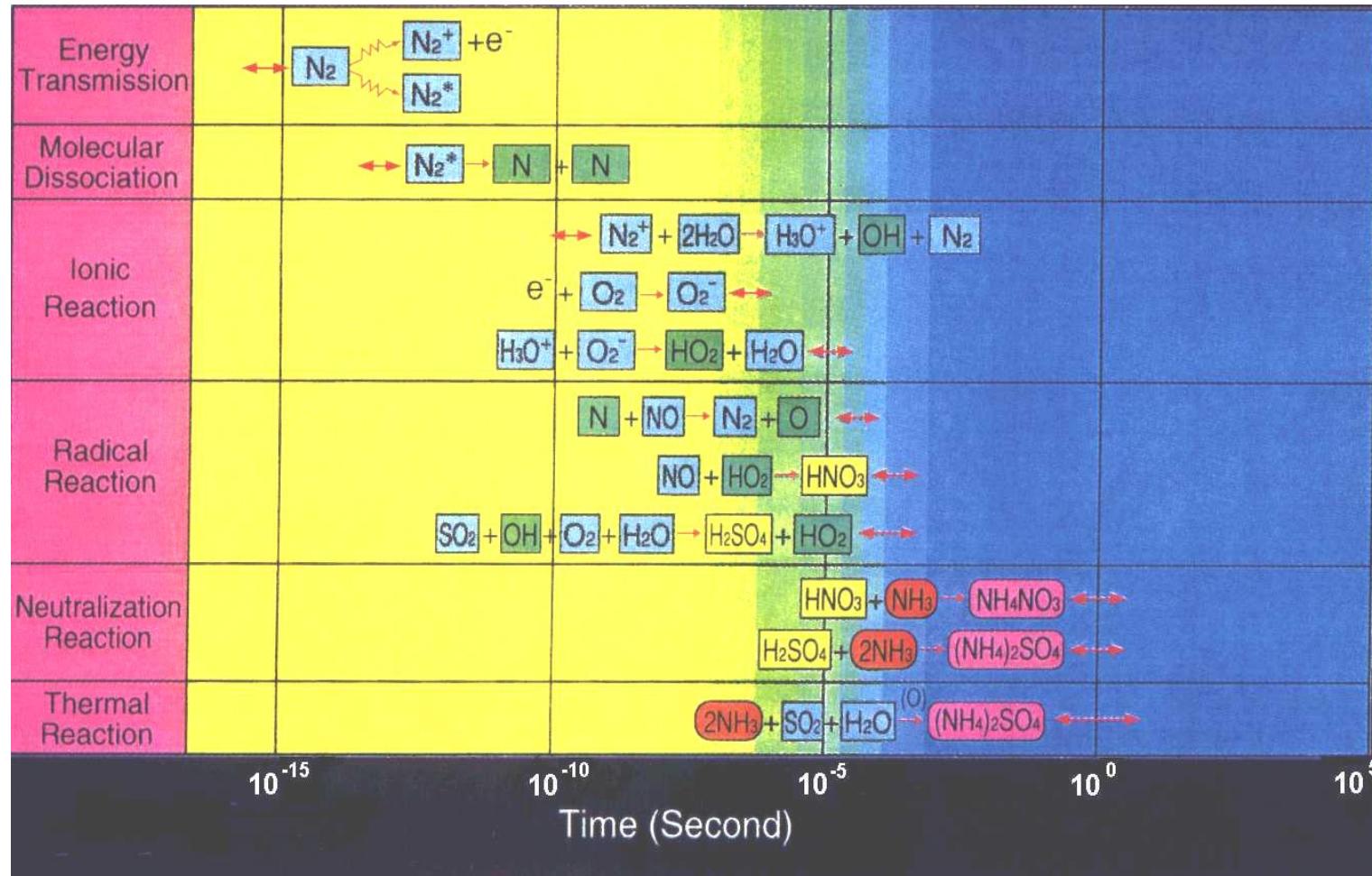
## NO oxidation



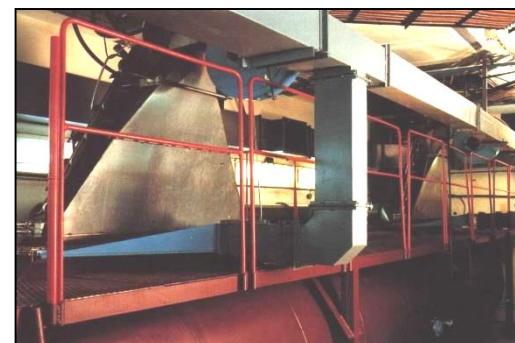
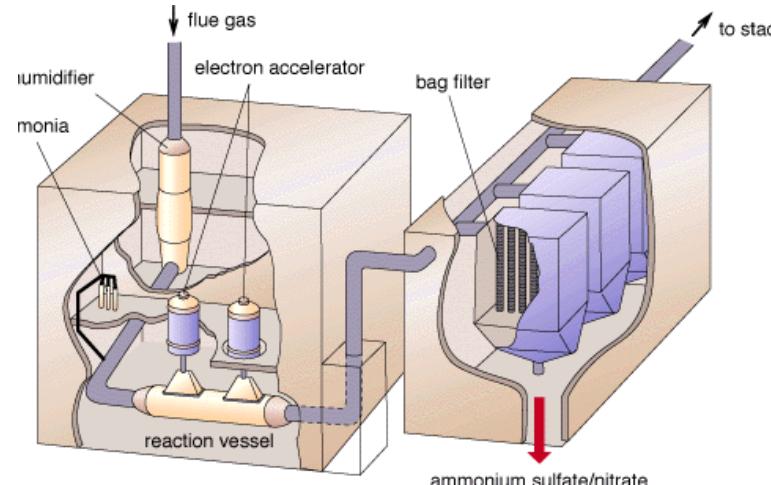
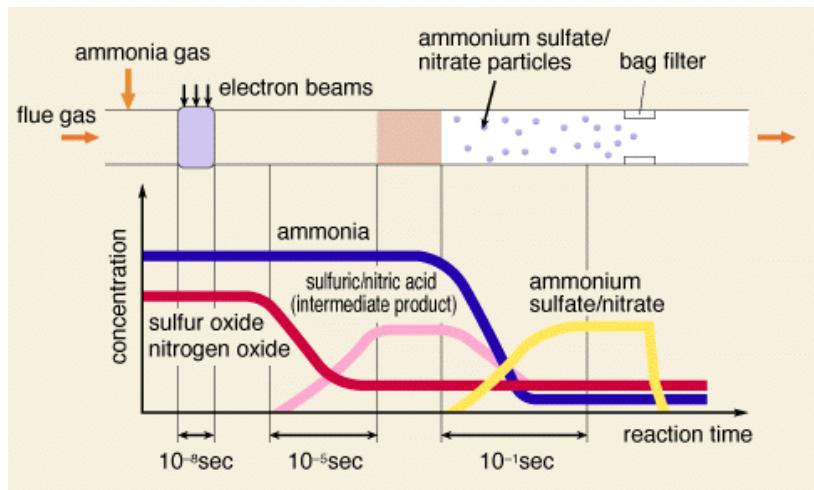
## NO<sub>2</sub> removal



# Reactions sequences

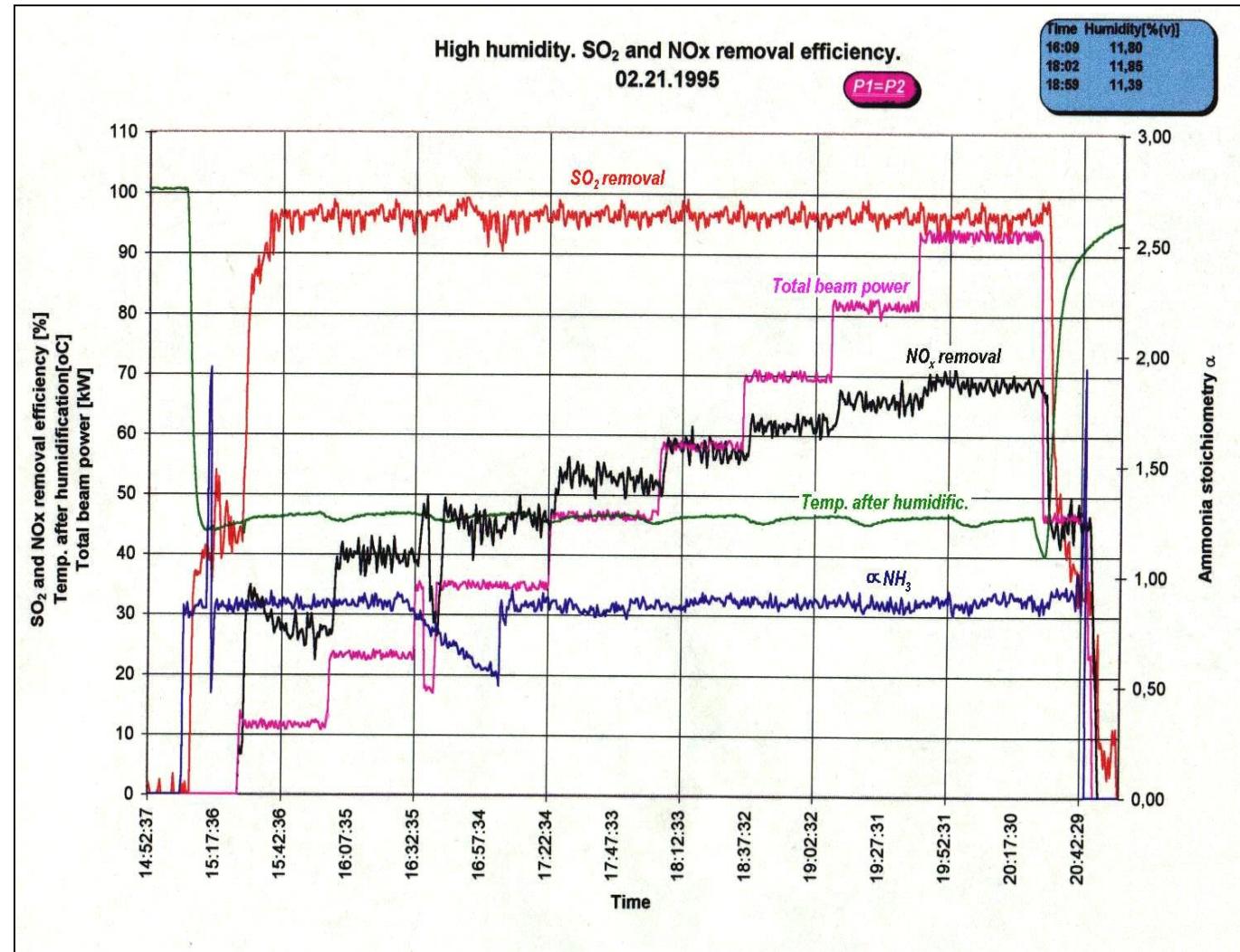


# Process and its engineering



Electron beam plant –common view

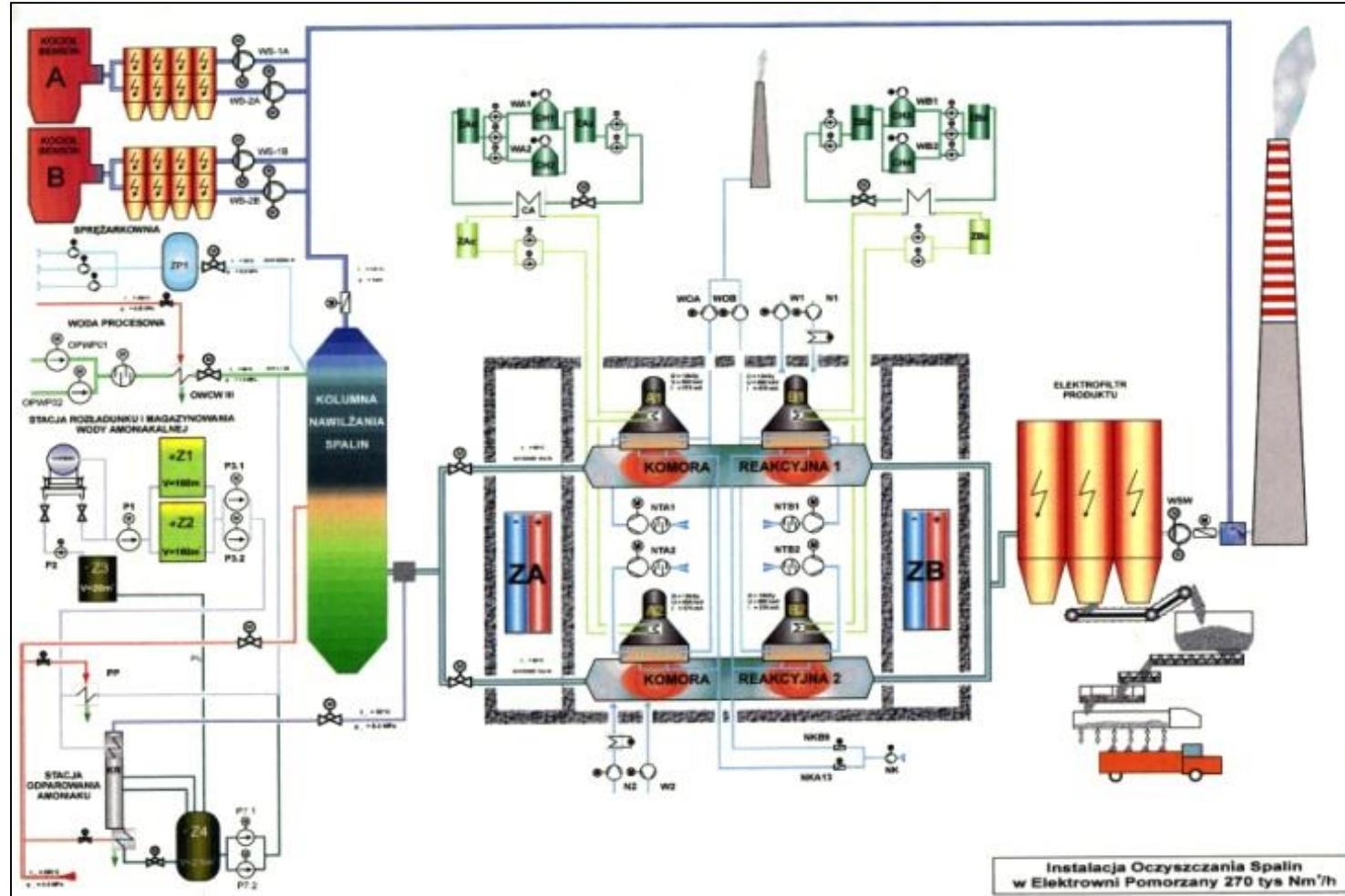
# The dependence of NOx removal on electron energy



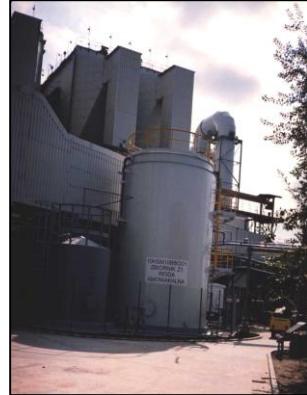
# Electron Beam Flue Gas Treatment Plant „Pomorzany”



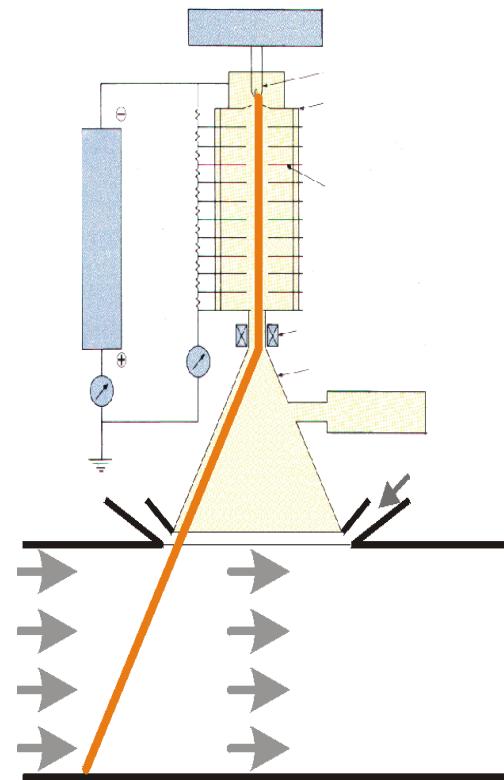
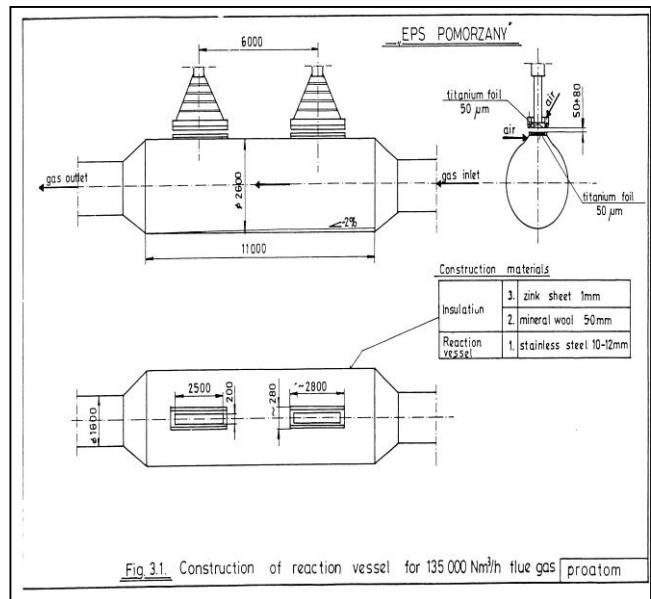
# EPS Pomorzany – EBFGT plant



# Main units of EBFGT plant

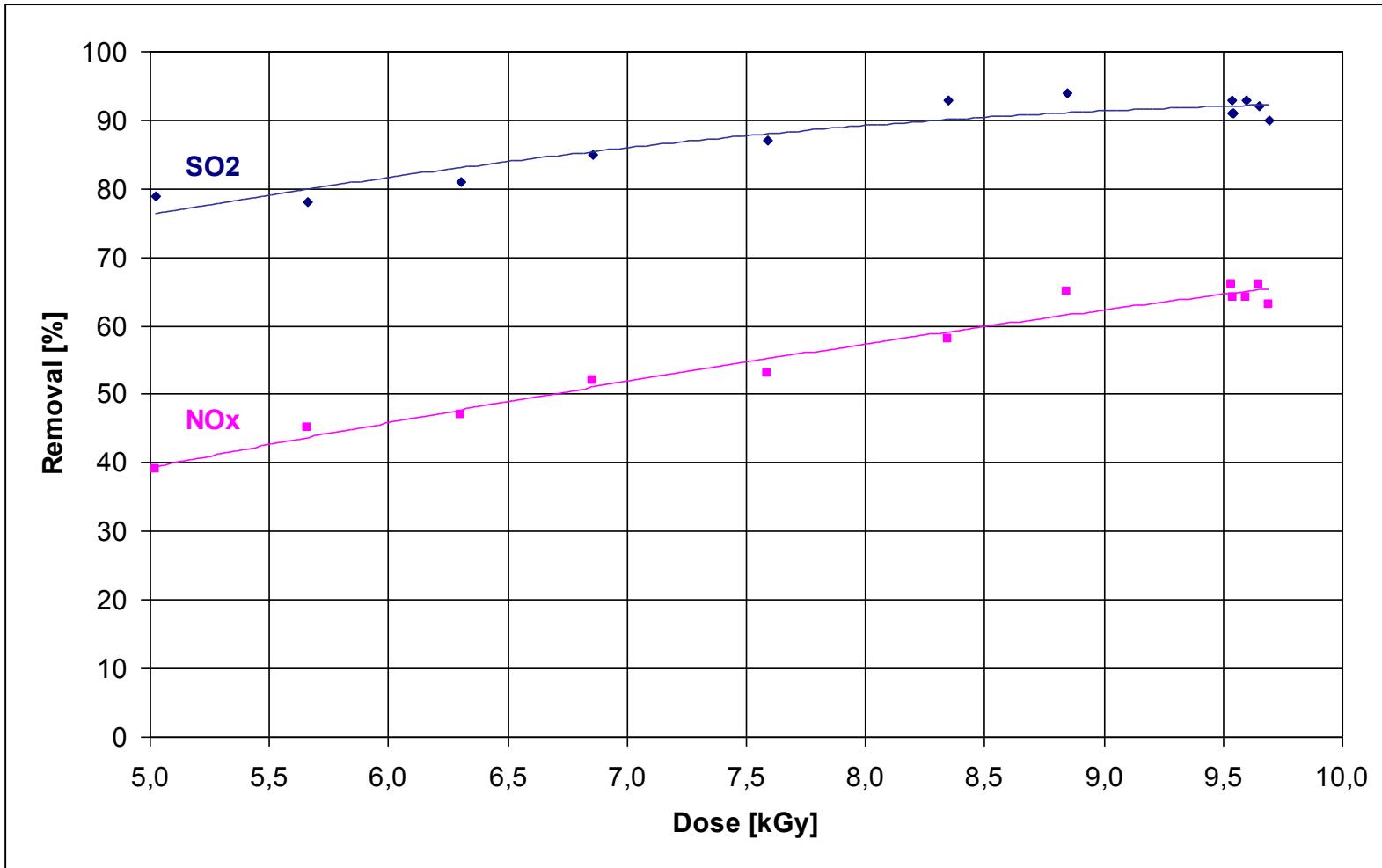


# Process vessel and electron beam scanning



# The obtained results

## The dependence of SO<sub>2</sub> and NO<sub>x</sub> removal efficiency on dose



# ESP byproduct collector and fertilizer



Emission control method	Investment cost (USD/kW <sub>e</sub> )	Annual operational cost (USD/MW <sub>e</sub> )
Wet flue gas desulphurisation	120	3000
Selective catalytic reduction	110	4600
Wet FGD + SCR	230	7600
<b>Electron beam FGT</b>	<b>160</b>	<b>7350</b>
EBFGT (low NOx removal)	130	4100

# Laboratory tests for heavy oil



# EBFGT – oil fired boiler



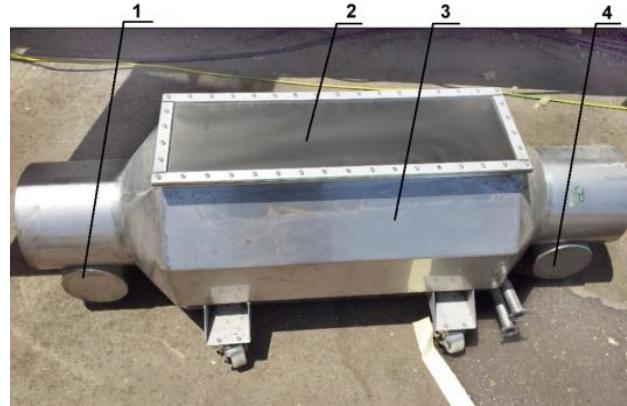
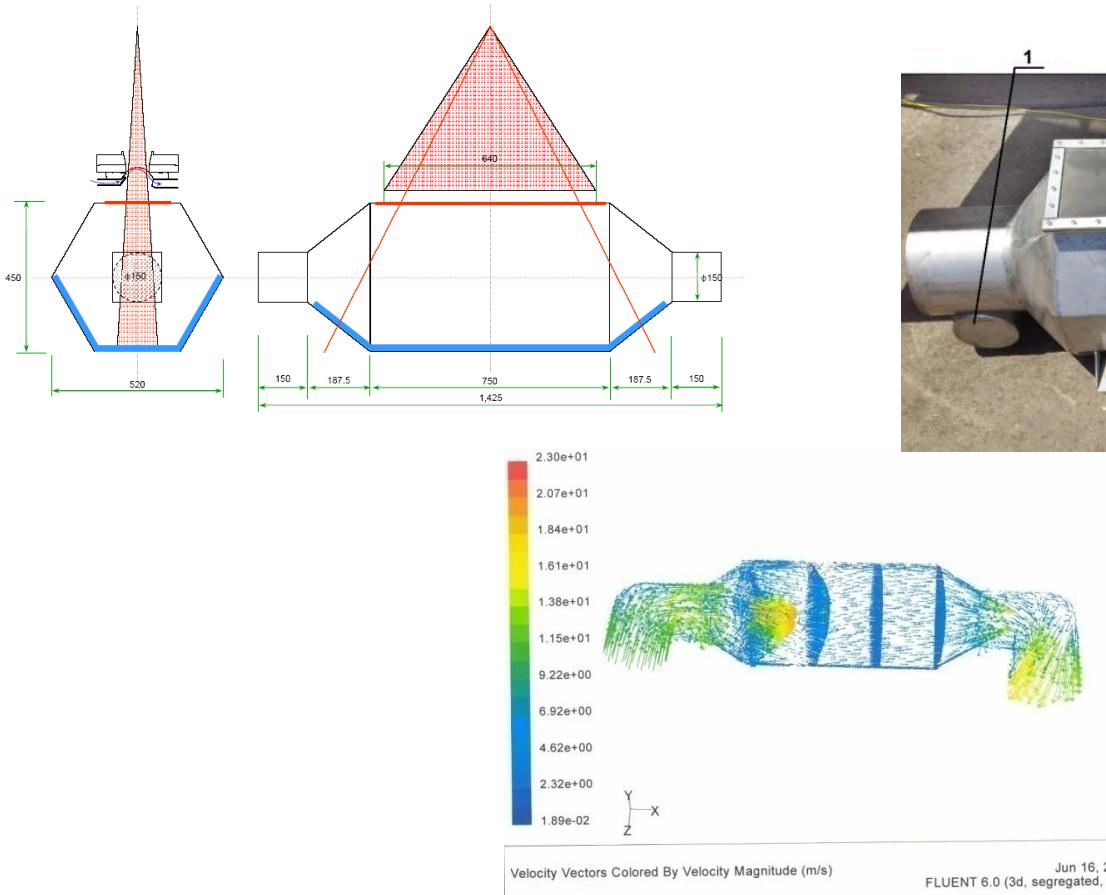
INCT + EBTech ROK

# *General view of the pilot plant.*

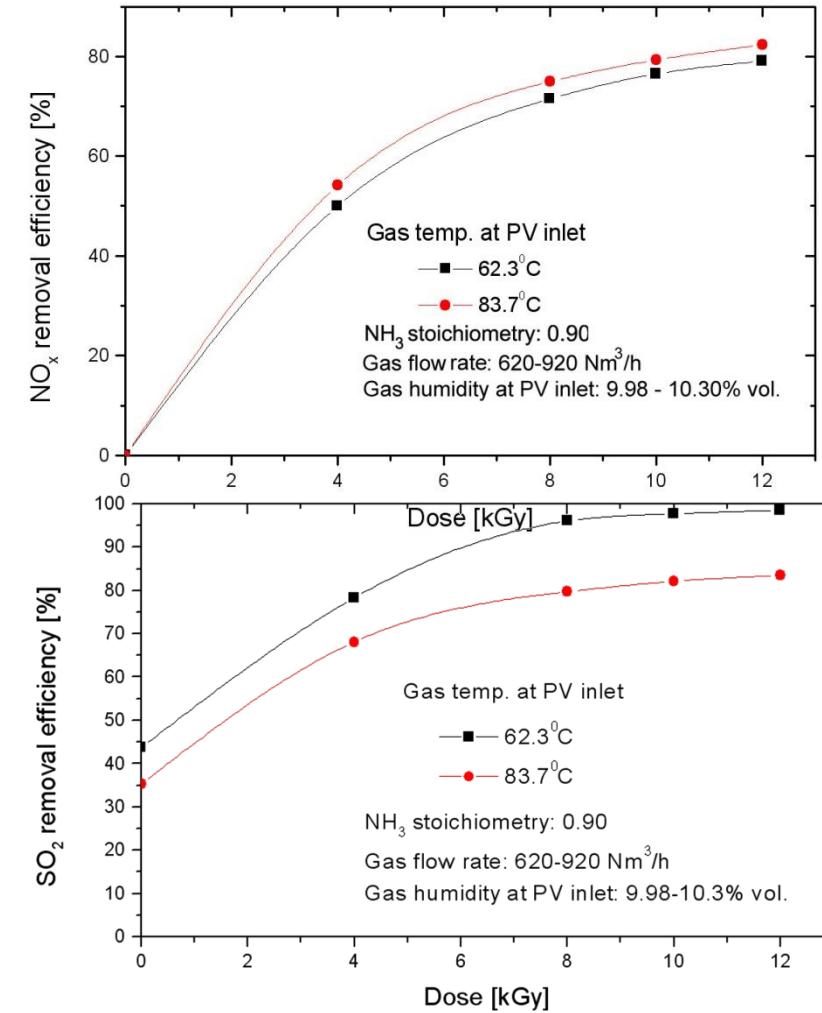
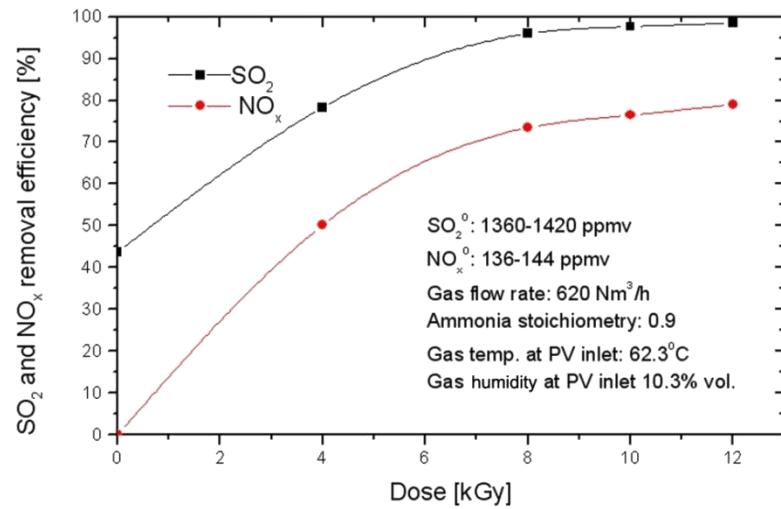


- |                                  |  |
|----------------------------------|--|
| <b>1- stack of F 1001 boiler</b> | <b>7-bag filter</b>                          |
| <b>2- boiler F1001</b>           | <b>8-insulated duct part</b>                 |
| <b>3-flue gas duct</b>           | <b>9-cyclone</b>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

# Process vessel



# $SO_2$ and $NO_x$ removal efficiency



# Product

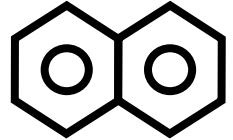
Cl <sup>-</sup>	0.0012	0.0068	0.0032
NO <sub>3</sub> <sup>-</sup>	0.35	0.44	0.34
SO <sub>4</sub> <sup>2-</sup>	78.19	79.24	79.63
NH <sub>4</sub> <sup>+</sup>	21.16	20.28	20.00
Na <sup>+</sup>	0.258	0.025	0.015
Mg <sup>2+</sup>	0.0047	0.0045	0.0012
Ca <sup>2+</sup>	0.027	0.014	0.012

Element	Concentration, mg/kg		
Arsenic	<0.02	<0.02	<0.02
Cadmium	<0.003	<0.003	0.023
Chromium	0.27	0.13	0.90
Cobalt	0.02	0.02	0.04
Lead	1.03	0.45	1.56
Mercury	<0.03	<0.03	<0.03
Nickel	29.8	58.5	102.3
Zinc	12.9	28.4	13.6

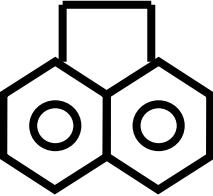
*Contents of heavy metals (mg/kg) in the byproduct and limits for heavy metals content in the NPK fertilizer established in some countries*

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
<b>Limits for heavy metals content in NPK fertilizer</b>								
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

# The structures of PAHs emitted from fossil fuels combustion



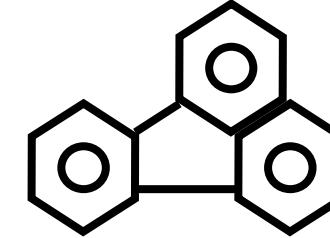
naphtalene



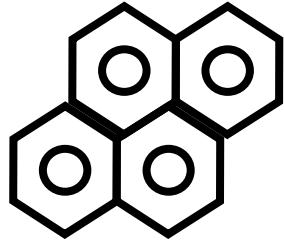
acenaphtene



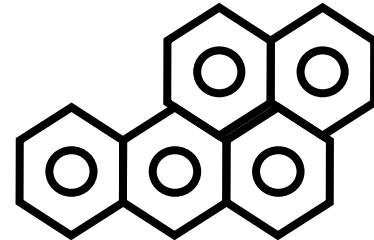
anthracene



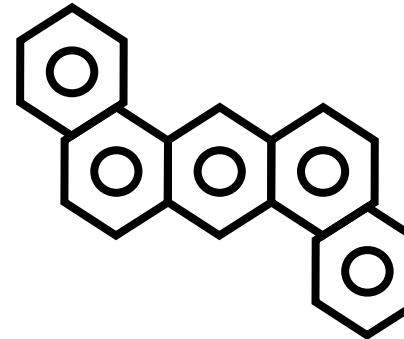
fluoranthene



pyrene

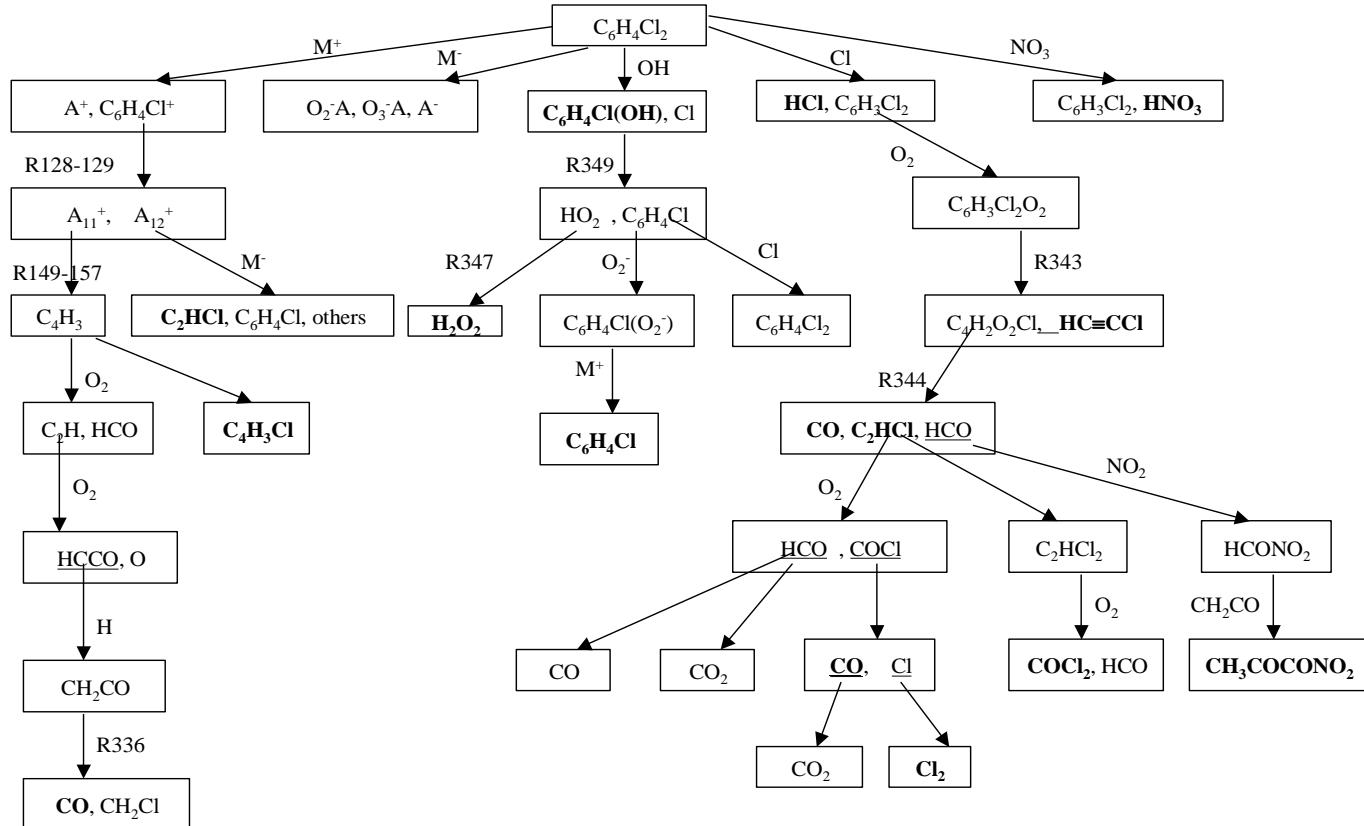


benzo(a)pyrene



dibenzo(a,h) anthracene

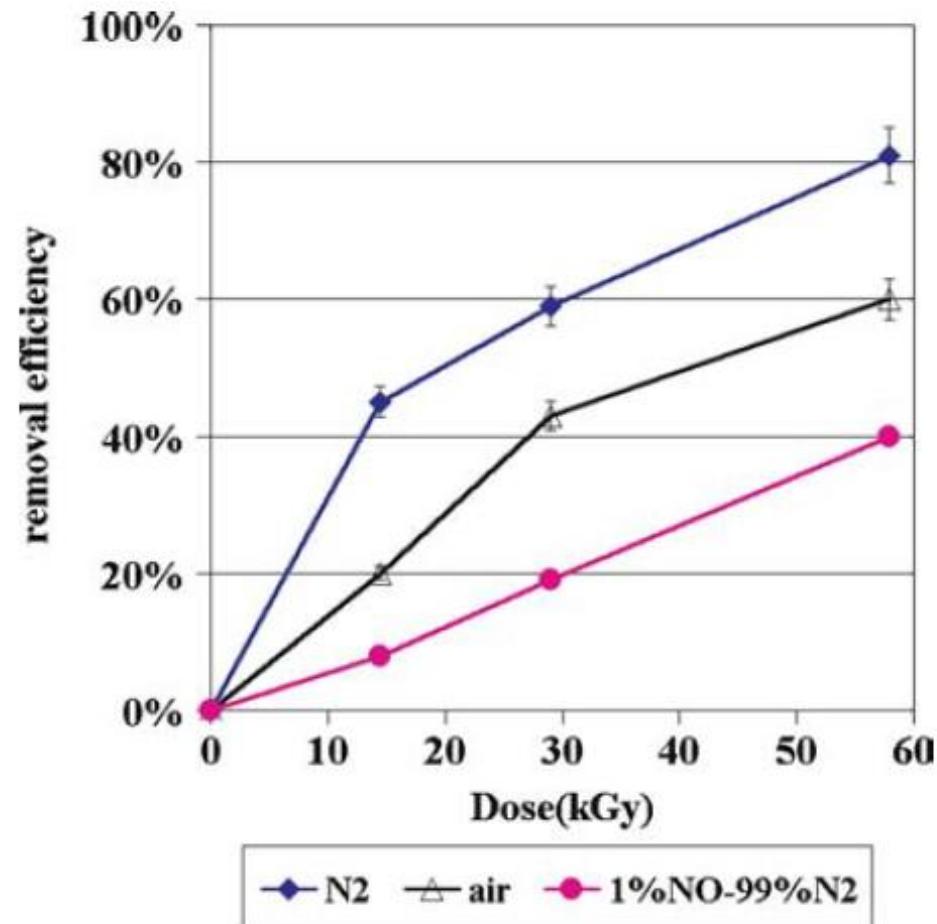
# Scheme of reaction pathways of 1,4-DCB decomposition and products formation



Yongxia Sun

# VOC Treatment

1,4 - dichlorobenzen



# *NOx removal from wet air in the presence of TiO<sub>2</sub> catalyst under electron beam radiation – chemical model description in INCT*



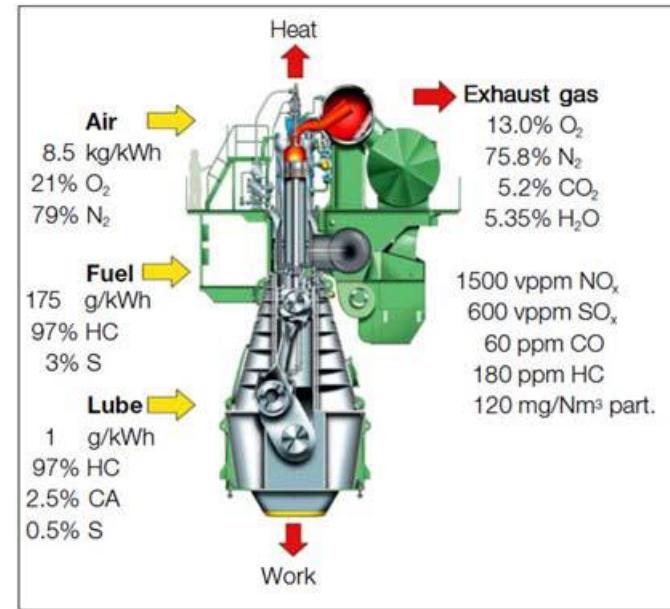
- TiO<sub>2</sub> + electron beam → e<sup>-</sup> + hole<sup>+</sup>
- h<sup>+</sup> + TiO<sub>2</sub> - H<sub>2</sub>O → OH• + H<sup>+</sup>
- e<sup>-</sup> + TiO<sub>2</sub> - O<sub>2</sub> → O<sub>2</sub><sup>-</sup>
- TiO<sub>2</sub> + NO → TiO<sub>2</sub> - NO
- TiO<sub>2</sub> - NO + OH• → TiO<sub>2</sub> - HNO<sub>2</sub>
- TiO<sub>2</sub> - HNO<sub>2</sub> + OH• → TiO<sub>2</sub> - NO<sub>2</sub> + H<sub>2</sub>O
- TiO<sub>2</sub> - NO<sub>2</sub> + OH• → HNO<sub>3</sub>(aq)

**Thus NO is removed from gas phase**

# Marine transportation

## EMISSION

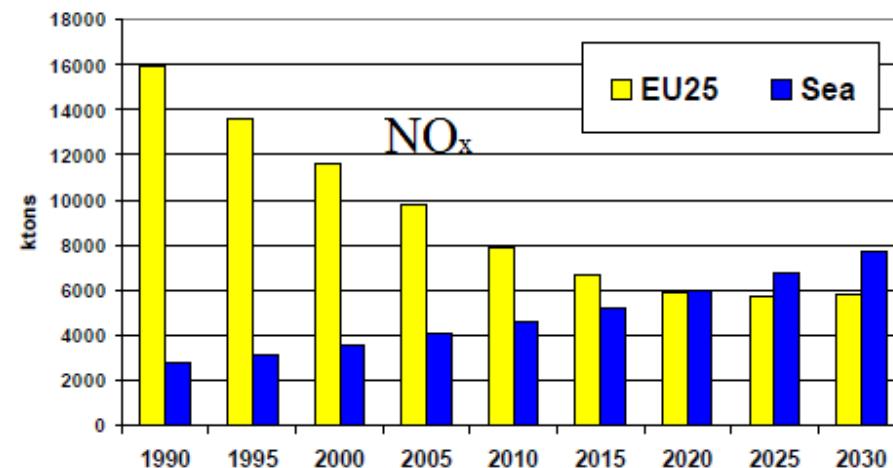
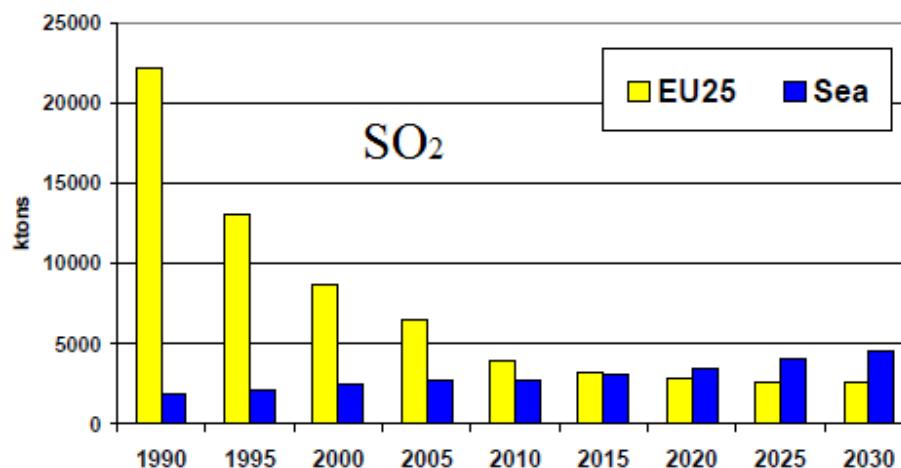
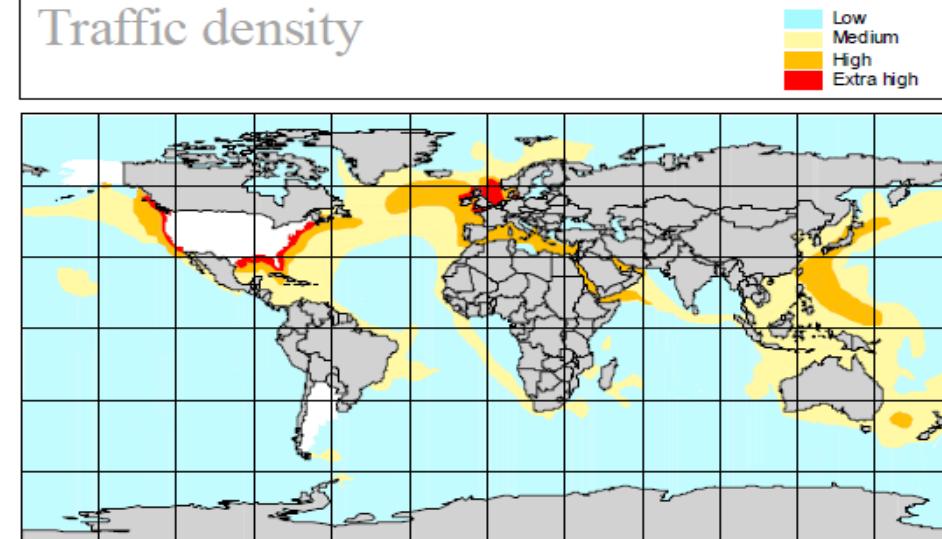
- ❖ Two stroke Diesel up to 81 MW
- ❖ 6 to 14 pistons ( each 1820 dm<sup>3</sup> )
- ❖ Heavy oil
- ❖ Consumption 250 ton per day
- ❖ Typical off-gases – 13 % O<sub>2</sub>, 5,2% CO<sub>2</sub>, 5,35% H<sub>2</sub>O,
- ❖ 1500ppmv NO<sub>x</sub>, 600ppmv SO<sub>x</sub>, 60 ppmv CO, 180 ppm VOC



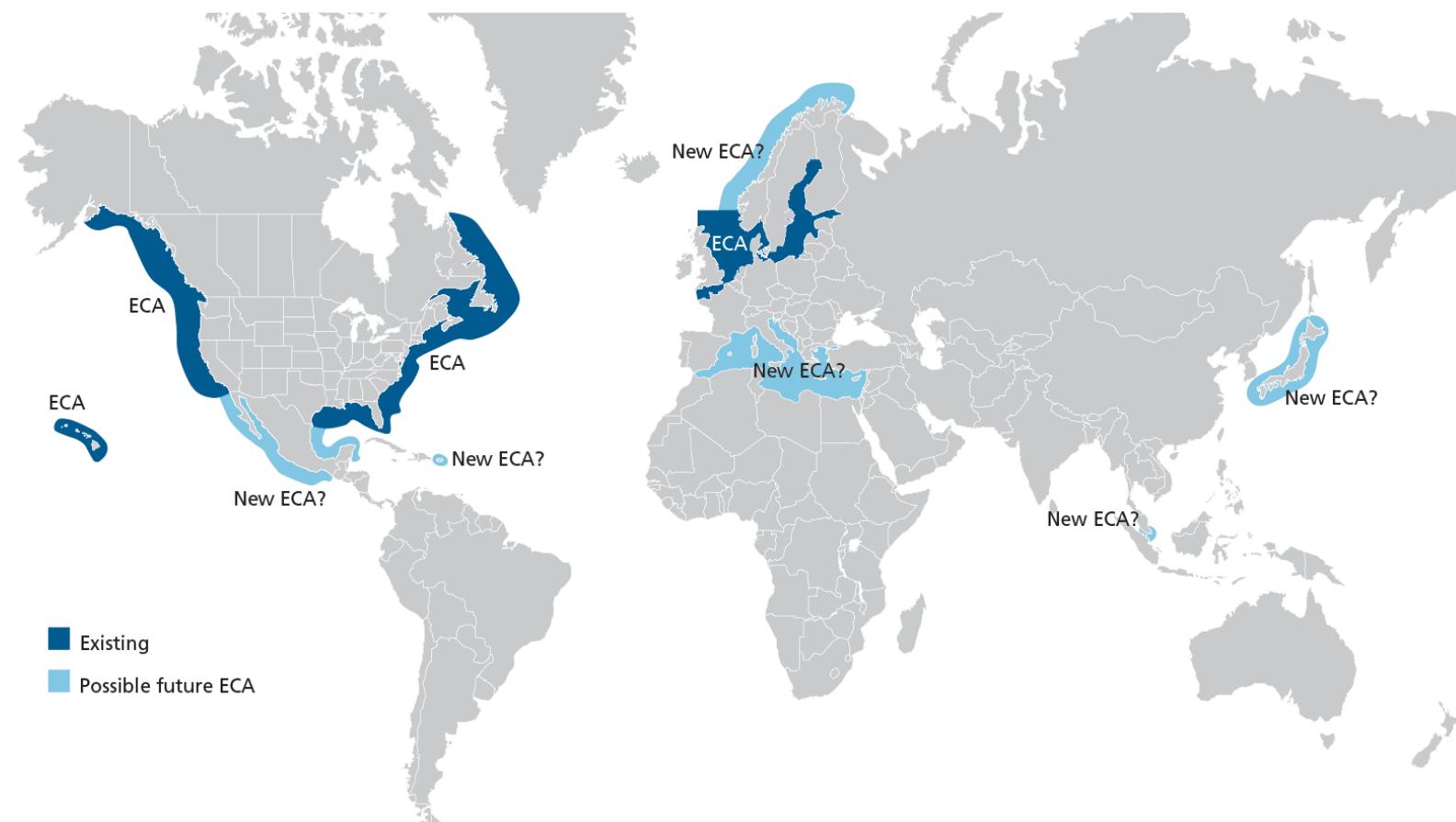
# Cargo ships – big emitters



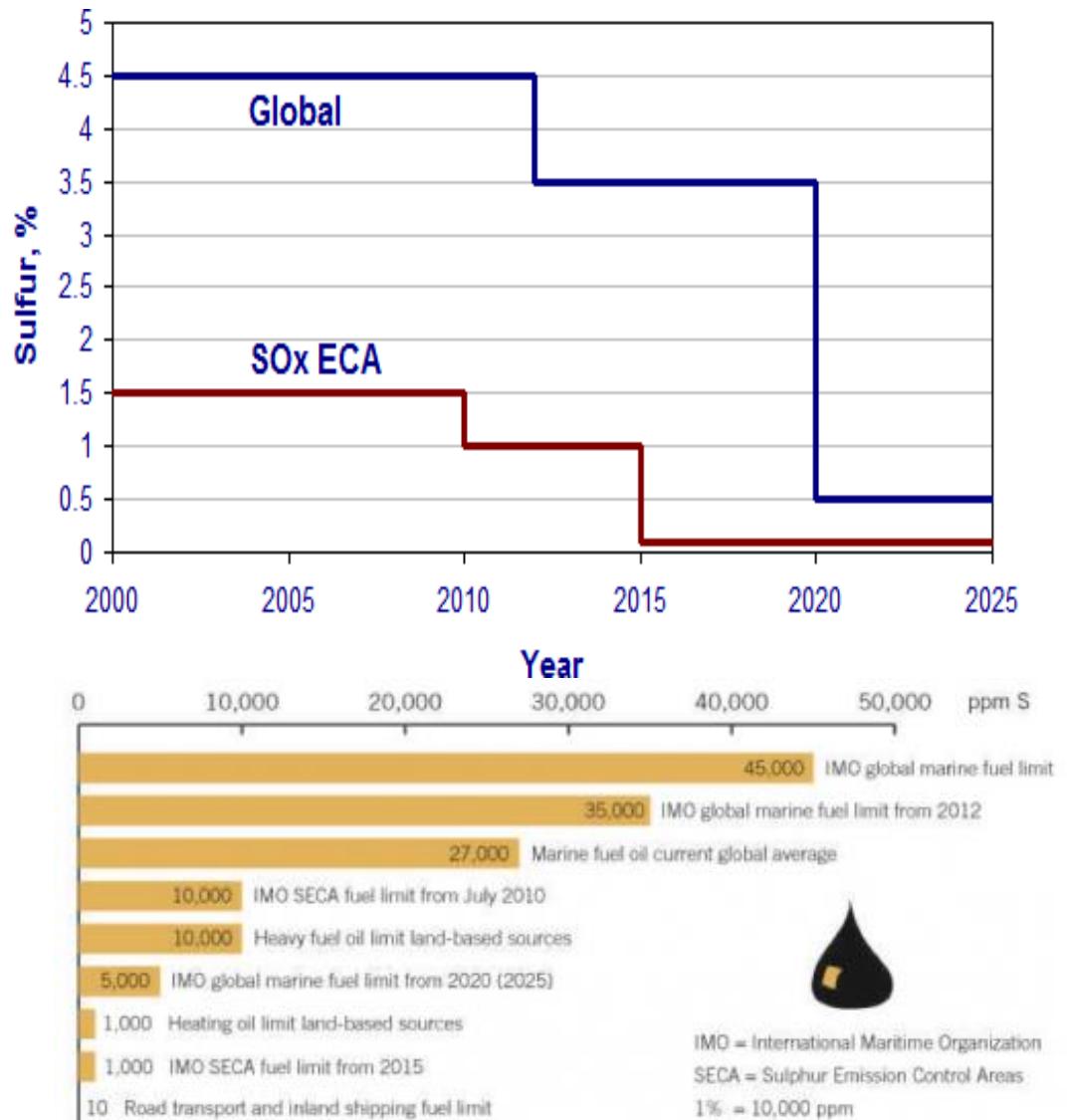
Traffic density



# Emission Control Areas

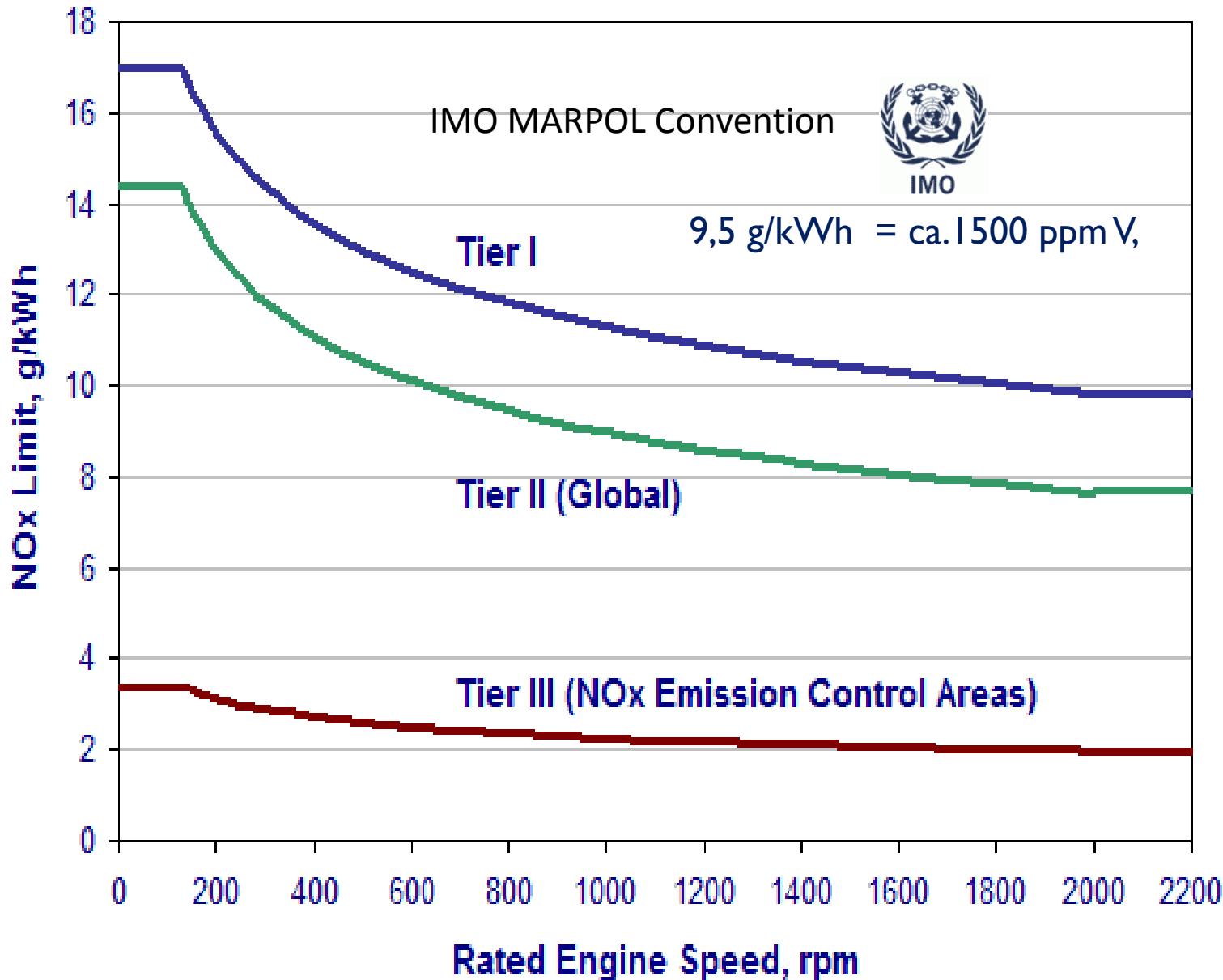


# MARPOL Annex VI Sulfur limits in fuel



- Approved alternative is off-gases purification (open sea and ECA). For 1,5% S in fuel for SOx ECAs, ship has to be equipped in FGT SOx  $\leq 6 \text{ g/kWh}$  (recalculated as SO<sub>2</sub>).

# Emission standards



## Fines at North America's SECAs - using high sulfur fuel( or lack of de-SOx unit)

**Table 3**

Actual Fuel Sulfur Content, % m/m <sup>14</sup>	Penalty over duration of violation, first offense – Table 3 (\$)	
	Violation of 1.00% sulfur limit (U = MT of fuel burned while in the U.S. ECAs )	Violation of 0.10% sulfur limit (U = MT of fuel burned while in the U.S. ECAs)
3.5 or higher	\$400*U	\$750*U
3.0	\$350*U	\$700*U
2.5	\$300*U	\$650*U
2.0	\$250*U	\$600*U
1.5	\$200*U	\$550*U
1.25	\$150*U	\$500*U
1.10	\$100*U	\$450*U
1.00	N/A	\$400*U
0.80		\$350*U
0.60		\$300*U
0.40		\$250*U
0.20		\$200*U
0.15		\$150*U
0.10		N/A

For \$ 400 over due and consumption of 50 ton daily:

\$ 400 \* 50 ton = \$ 20,000 /day; in the close future \$ 750 \* 50 ton =  
\$ 37,500 / day

# Is sense to use fuel like in cars ?

- Ship with engine 25 MW fire ca. 20 000 ton per year.
- Fuel with 0,1 % S increase cost by 3 - 5 millions \$US annually .
- And what about NOx ?
- And what in the future with VOC (PAH) ?

# Emission and standards

Diesel:  
6 MW,  
6 pistons,  
4 strokes,  
85% load

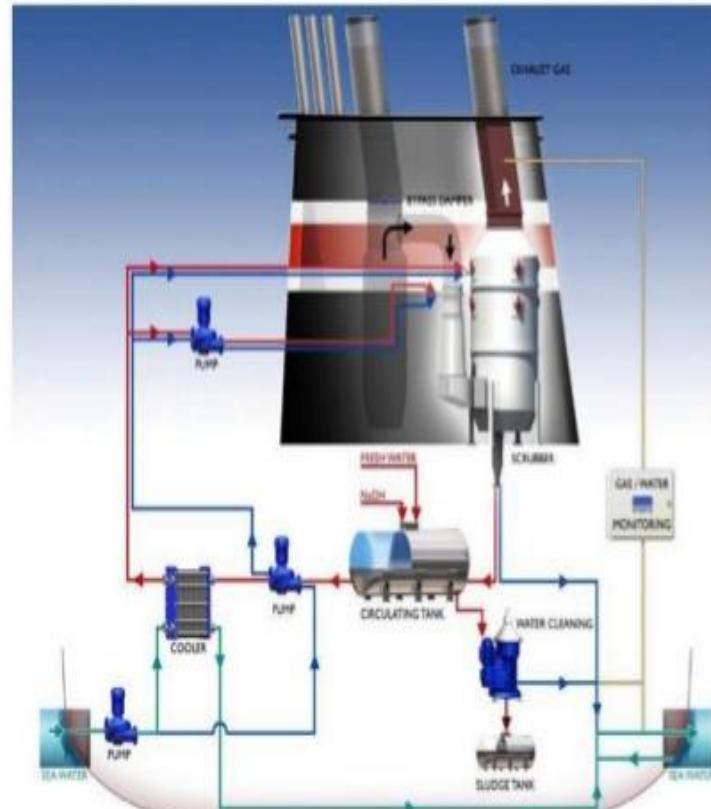
Off-gases:  
4.727  
 $\text{Nm}^3/\text{kWh}$   
1500 ppmv,  
9.5g/kWh

Limits for NOx  
315 ppmv,  
2g/kWh

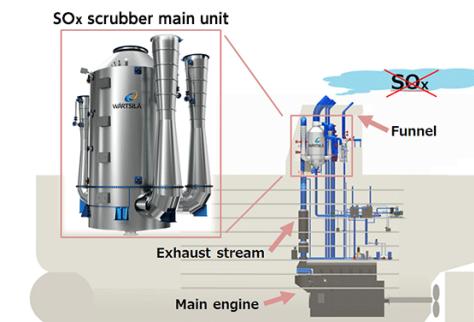
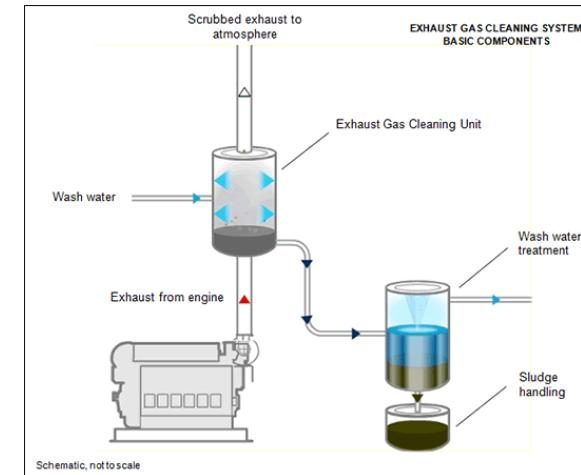
Requested.  
efficiency 79%

# Scrubber technology: How does it work?

- SOx is removed via using wash water.
- System includes:
  - Water supply
  - Water treatment
  - Exhaust gas and water monitoring
  - Supply to ship of treatment agent.
- Types
  - Freshwater
  - Sea water
  - Hybrid

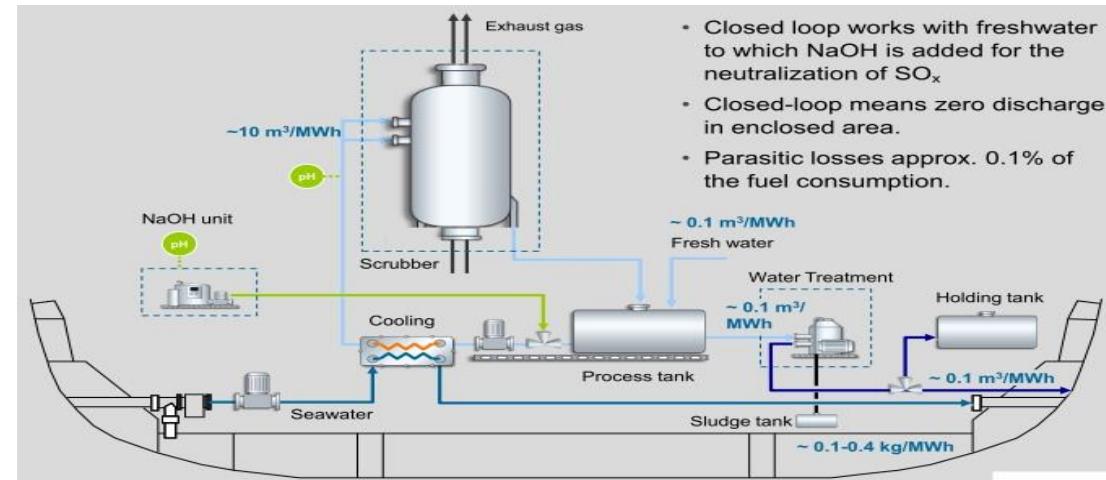
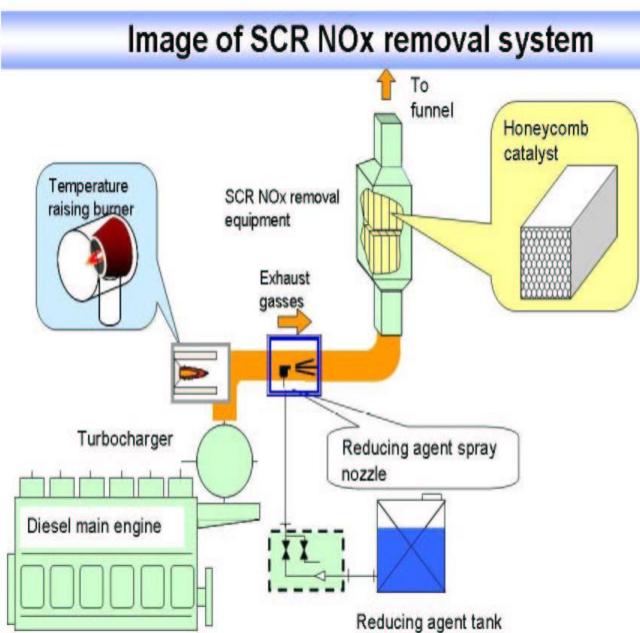


See: [http://www.youtube.com/watch?v=j8\\_D7ASh0\\_g](http://www.youtube.com/watch?v=j8_D7ASh0_g)

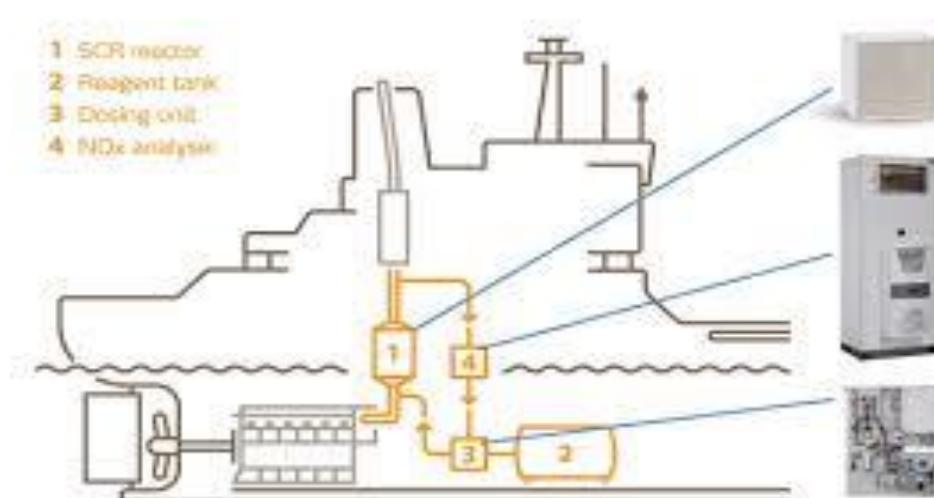


- Sea Water Scrubbing based on SO<sub>2</sub> in sea water
- Wash water is dumped into sea
- Removal of NOx is low due to low NO solubility in water.
- SCR has to be approved

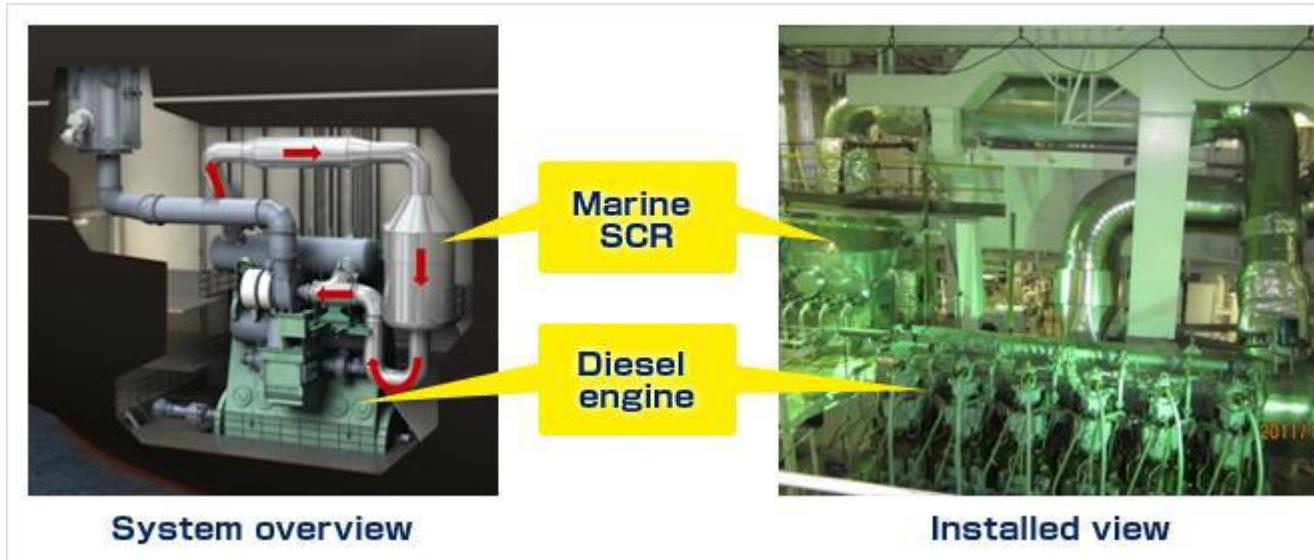
# FGD system (upper) + SCR (bottom) installed on the board



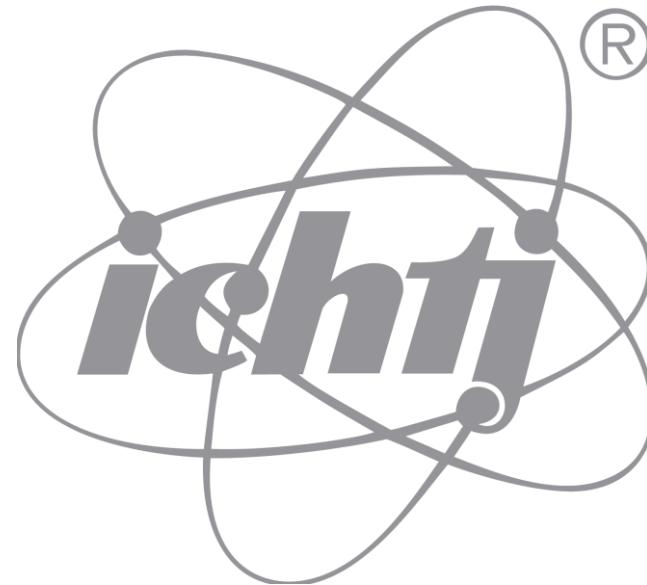
NOxCare SCR Systems



# catalyst of marine SCR in use is V2O5–WO3–TiO2.



- Catalyst
  - high NOX reduction could be above 90% at temperatures above 300.C
  - V2O5 is a kind of highly poisonous material
- Reagent
  - size of NH3-SCR system in use is a problem,
  - urea consumption of SCR system is 8.5% of the consumption of diesel oil
- Problems
  - NH3-slip is also important in SCR use



# Electron beam FGT

SOx and NOx removed in one step

# Laboratory set up

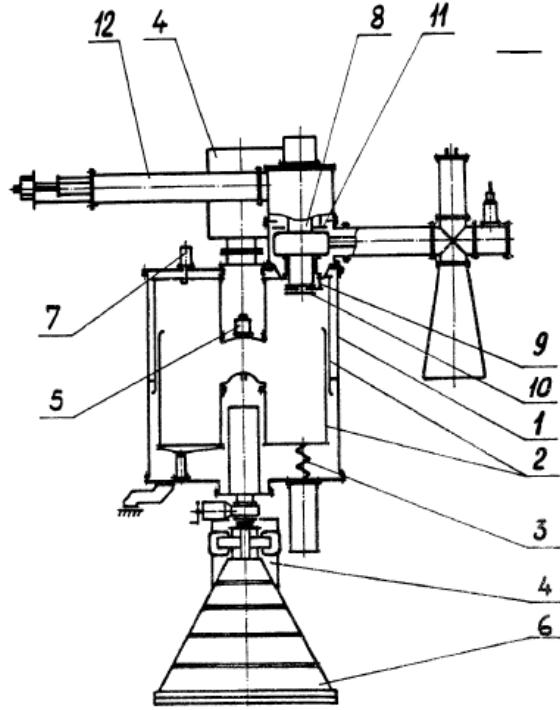
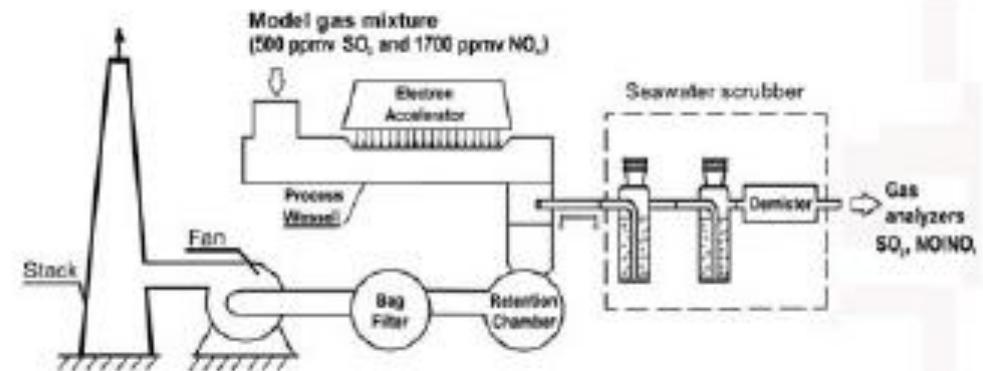


Figure 1: Main elements of ILU-6 electron accelerator: 1 – vacuum tank; 2 – RF cavity divided into 2 halves; 3 – input of constant bias voltage for lower cavity half; 4 – high vacuum pumps; 5 – electron injector; 6 – scanning horn; 7 – measuring loop; 8 – RF generator; 9 – coupling loop; 10 – coupling vacuum capacitor; 11 – feedback circuit, 12 – cathode circuit tuning line.

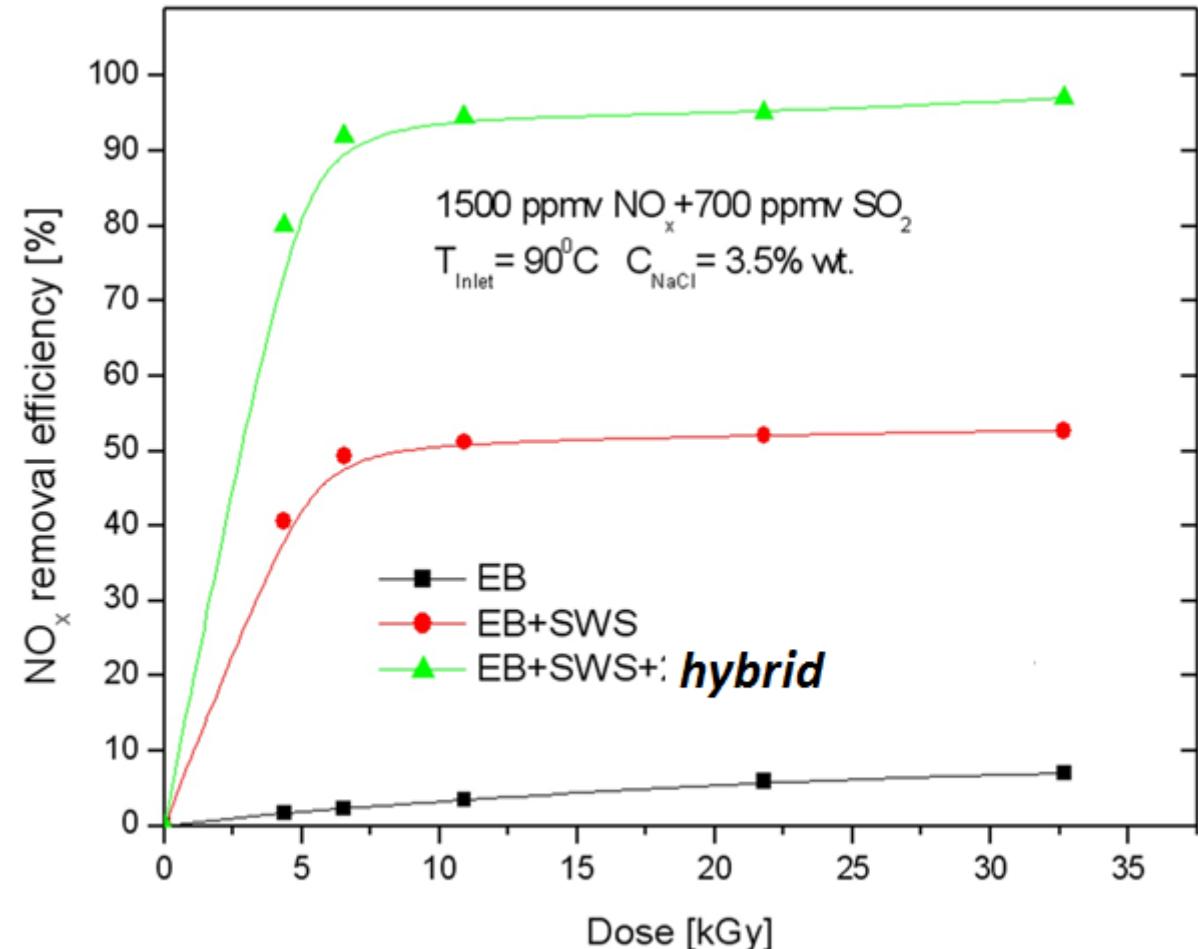


# Hybrid new solution ! Futher developments underway.

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Narodowe Centrum  
Badań i Rozwoju

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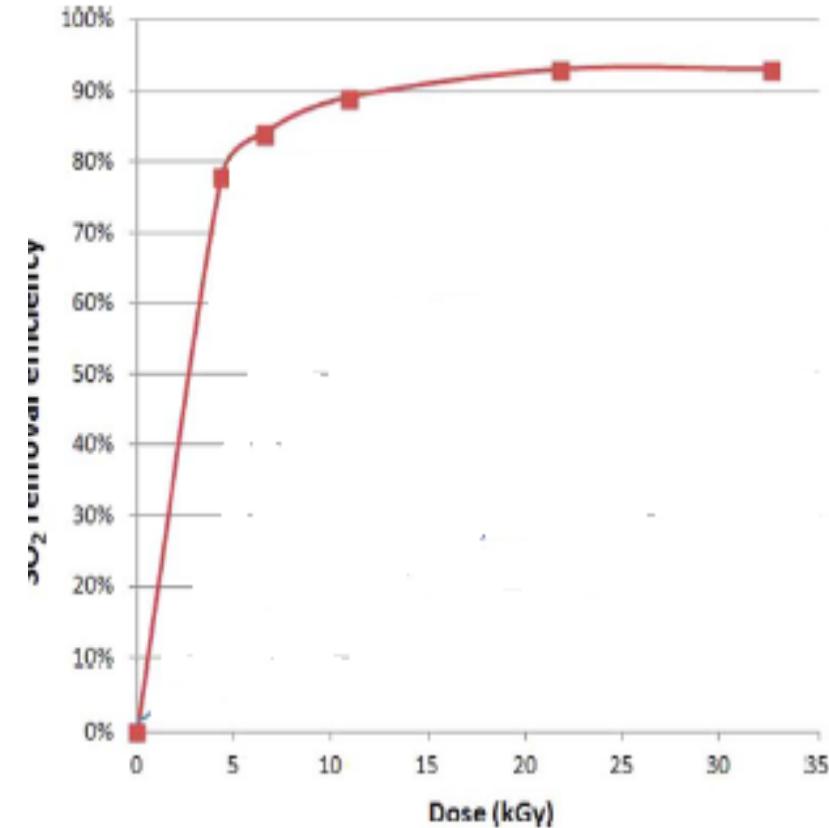
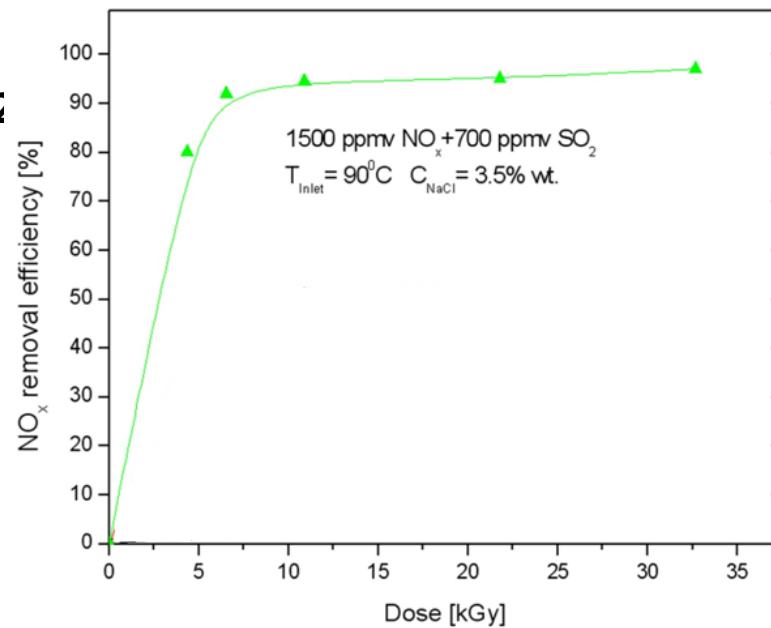
# Hybrid new solution ! Futher developments underway.



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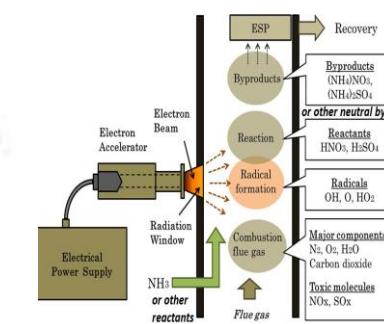
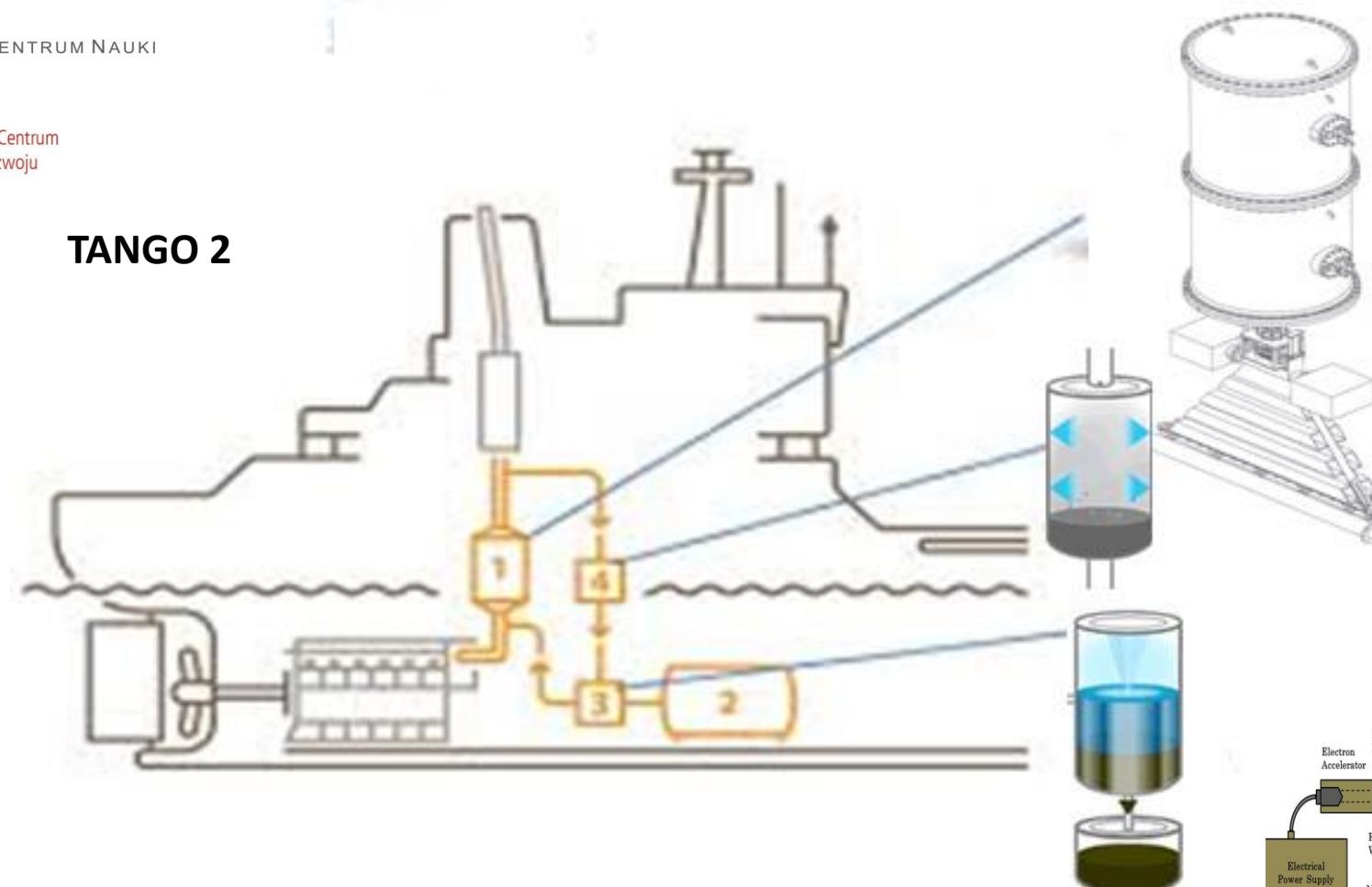
A.G.Chmielewski, J.Licki, Y.Sun, A.Pawełec, E.Zwolińska,  
S.Witman, Z.Zimek

# New application of EBFGT

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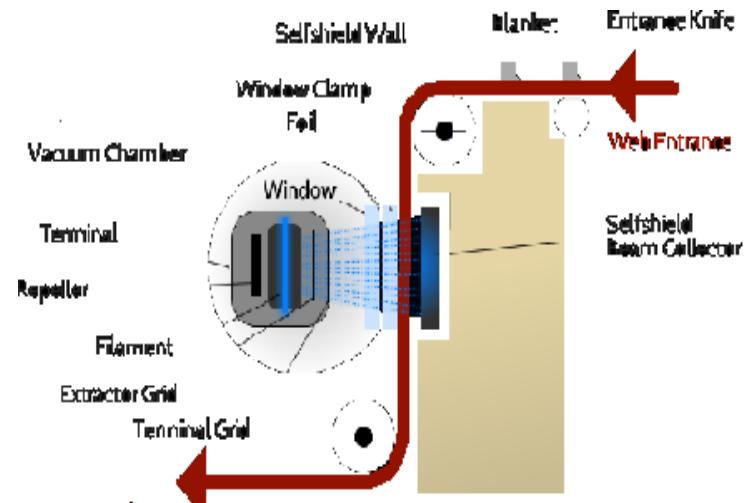
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# Low energy ebeams

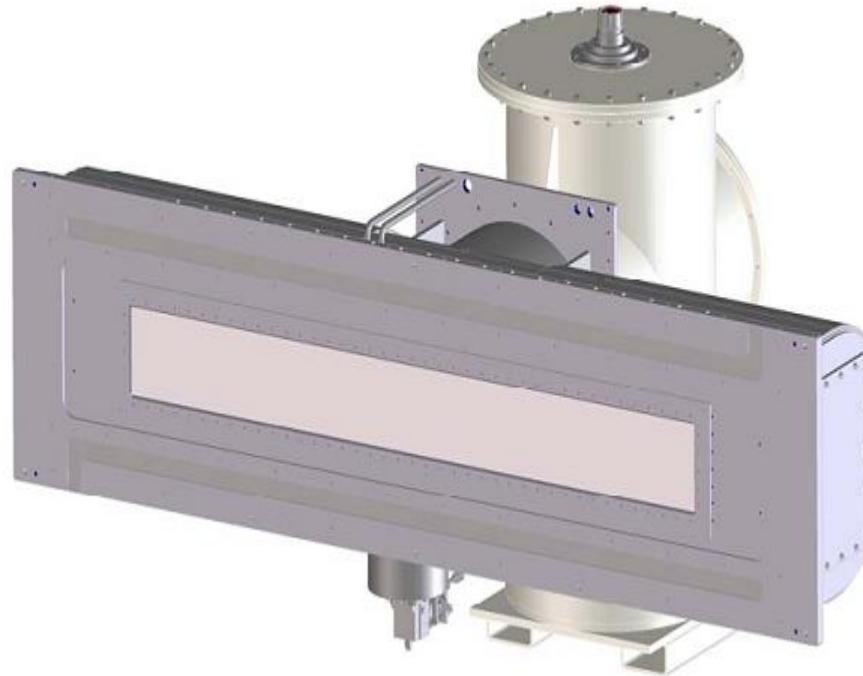
ESI – “EZCure®“

**Energy Science Inc.**



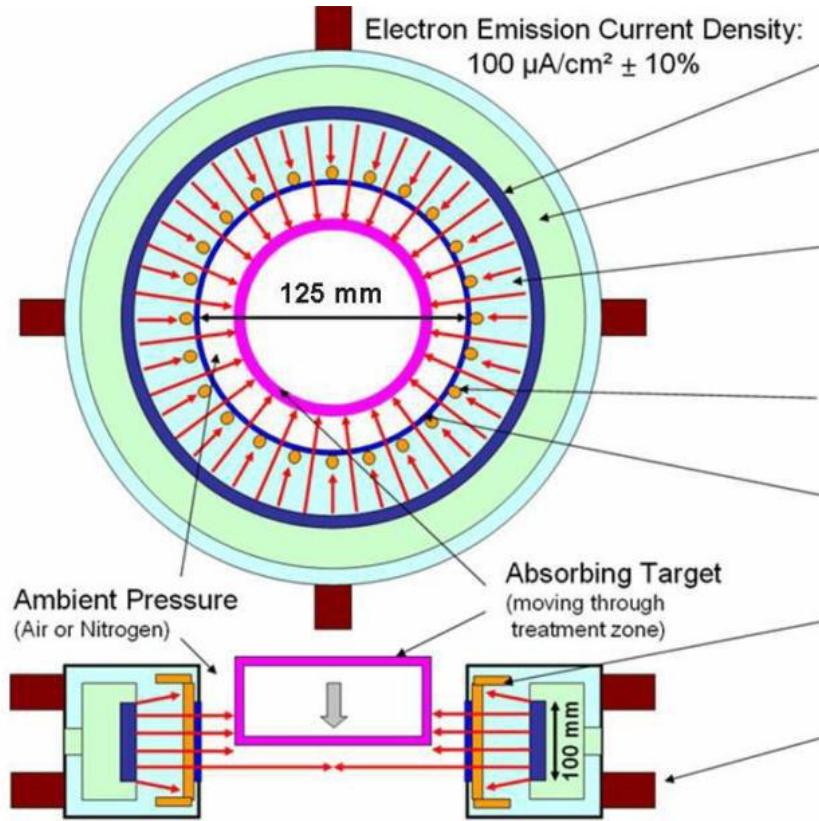
100 – 300 keV  
ESI CB-300

# Linear cathode eb machine

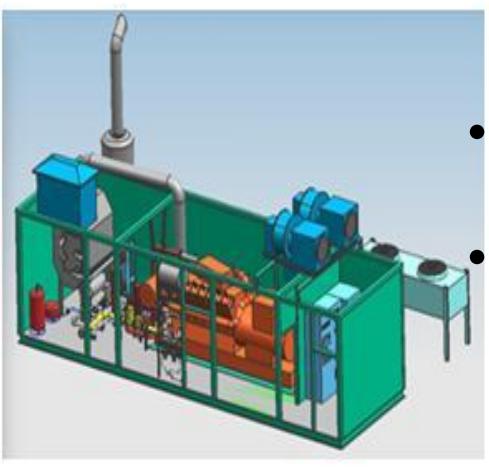
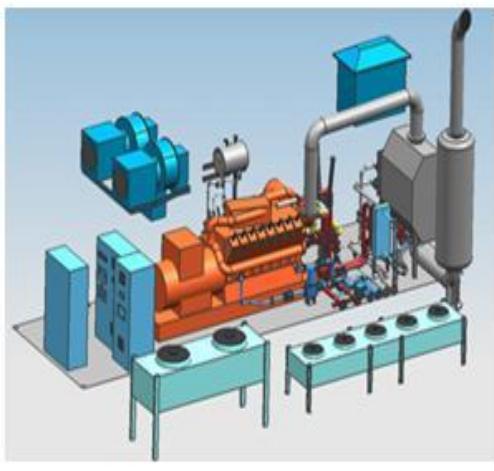
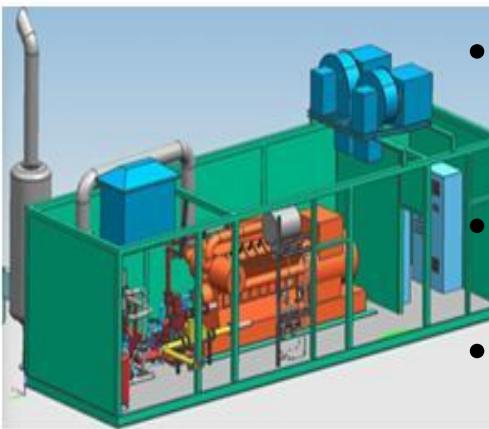
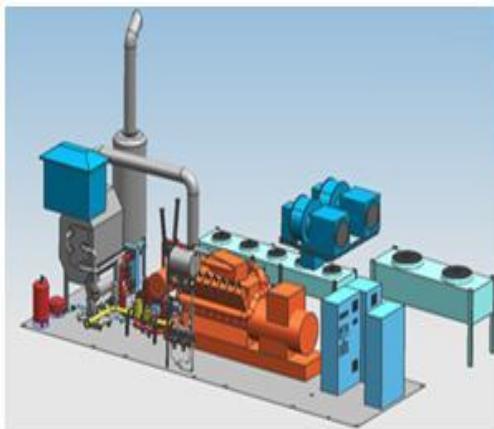


- Energy: 75 - 250 kV
- Current: 0 - 2000 mA
- EB width: 400 - 3000 mm
- Dose uniformity: < 10 %
- No window cooling needed.

# Development of the toroidal source



## On shore Diesel power stations



- Poland, Szpital Miejski Sochaczew – 412 kWe
- Poland, Huta Miedzi Głogów – 936 kWe
- Polska, Elektrownia Opole – 1058 kWe
- Poland, Elektrownia Bełchatów – 2106 kWe
- Greece, Andros – 3104 kWe
- Greece, Ikaria – 3104 kWe

# Scheme – 2 x 7K60MC-S

