FINAL REPORT

Development of Scaling Algorithms and Economic Evaluation for Non-Thermal Plasma Reactors – Adsorbant/Catalyzer Hybrid System for Control of NO_x Released During Army and Related U.S. Department of Defense (DOD) Operations

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EXECUTIVE SUMMARY

Objectives of the Project

The objective of this task is to develop economic evaluation and scaling algorithms for non-thermal plasma adsorbant/catalyzer hybrid systems which are used to remove NO_x from the air stream during army and related U.S. Department of Defense (DOD) operations. These systems need to be fully economically evaluated with respect to destruction efficiency, energy efficiency, electrical operating characteristics, and final product analysis based-on bench scale tests and numerical analyses so that the detailed models and experiments run at ARL can be correlated with the global apparatus behaviour and scale-up.

The specific original tasks are:

(1) Economic evaluations for the non-thermal plasma – adsorbant/catalyzer hybrid systems for jet engine test cell (JETC) conditions.

(2) Characterize non-thermal plasma – adsorbant/catalyzer hybrid systems proposed by ARL for operating behaviour with NO_x in air streams. Characterization tests will be performed for one selected type of each absorbant and catalyzer based on literature searches and manufacturer's data.

(3) Construct De-NO_x devices scale-up procedures for bench scale to pilot scale tests proposed by ARL.

Due to the request from DOD, the above original tasks are slightly modified as follows:

(1) Economic evaluations for the non-thermal plasma systems for JETC and cruise missile test cell (CMTC) condition must be conducted and compared with conventional wet-scrubber-SCR systems;

(2) Characterize non-thermal plasma-catalyzer hybrid system for NO_x and SO_2 treatment in air streams containing hydrocarbon. Conduct literature search for catalyst and adsorbents.

(3) Construct JETC/CMTC flue gas non-thermal plasma treatment system scale-up procedures and conduct preliminary conceptional design of pilot scale test system.

Conclusions and Recommendations

In order to develop scaling algorithms and economic evaluations for non-thermal plasma reactors with and without adsorbants/catalysts for the control of NO_x from jet engine and cruise missile test cells, an existing SUENTP code (Kim and Chang, 1998) was modified - SUENTP-J and the following conclusions and recommendations are obtained:

(1) For the jet engine test cell (JETC) condition of 10^6 scfm (1.62×10^6 Nm^3/h) flow rate, the conventional SCR/wet scrubber system costs 2 to 3 times more than any of the evaluated non-thermal plasma techniques. The cost of an electron-beam/electrostatic precipitator (ESP) system is 20-30% more than pulsed corona or corona shower system with ESP;

(2) For the JETC condition, SCR can be a stand-alone system without a wet scrubber if we do not remove SO_2. However, the life of SCR becomes shorter (less than half) with sulphur poisoning and an additional ESP system is required. Cost estimation for this SCR/ESP system is only slightly lower (~10%) compared with the SCR/wet scrubber system;

(3) For the cruise missile test cell (CMTC) condition of 6×10^4 scfm (10^5 Nm^3/h) flow rate, the conventional SCR/wet scrubber system costs 2 to 2.5 times more than pulsed corona/ESP or

corona shower/ESP system. However, the cost is 40% more than that of an electron beam/ESP system.

(4) In order to estimate more accurate non-thermal plasma system costs for JETC and CMTC conditions, much larger pilot plant tests, up to 200 to 1000 Nm^3/h, are required;

(5) In order to reduce more costs, a non-thermal plasma-adsorbant/catalyzer hybrid system should be tested. Based on preliminary experimental work, the cost reduction is as much as 20 to 30% of stand alone non-thermal plasma systems.

An experiment also conducted for non-thermal plasma (corona shower system)-catalyst hybrid system to treat simulated JETC flue gas and the following concluding remarks are obtained:

(1) SO_2 can be 100% removed by injections of NH_3, CH_4 or NH_3/CH_4 mixture generated radicals;

(2) SO_2 removal increases with increasing applied voltage and significant catalytic reduction/adsorption effects are observed;

(3) Heating of catalyst shows no significant effects on SO_2 removal for the NH_3 injections in the present range of gas temperature (T_g = 228K) but reduce capability of catalyst for CH_4 injections;

(4) NO_x removal significantly enhances NO_x removal for NH_3 injections at room temperature with catalyst due to the NO_2 reductions but NO_x removal decreases with gas temperature;

(5) NO_x removal increases with increasing applied voltage and up to 65% of NO_x removal rates are observed in hybrid systems with NH_3 injections;

(6) NO_x removal increases with increasing applied voltage under CH_3 or CH_4/NH_3 mixture injections and up to 42% removal rate is observed. However, no significant catalytic reaction or gas temperature effects were observed.

Based on the economic evaluations and an experimental test, the conceptual design of the pilot plant study was proposed as follows:

(1) Approximately 340 Nm^3/h JETC flue gas will be by-passed from the main flue gas and treated by non-thermal plasmas;

(2) Non-thermal plasma JETC flue gas treatment test facility consisted of corona shower reactor and electrostatic precipitator, where catalyst will be considered as options;

(3) Five-section corona shower system size is (140×60×120 cm) with 14 flow channels, and operated by 6 kW dc power supply (40 kV×150 mA maximum);

(4) Five-section ESP size is (150×60×80 cm) with 30 flow channels and operated by 6 kW dc power supply (40 kV×150 mA maximum); and

(5) Pressure drop, NO_x, SO_x, VOC concentrations will be monitored at inlet and exhaust of pilot plants.

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PART 1.

SUENTP-J CODE SIMULATIONS OF SCALE-UP AND ECONOMIC EVALUATION OF NON-THERMAL PLASMA TECHNOLOGY FOR EXHAUST GAS EMISSION CONTROL OF JET ENGINE TEST CELLS

ABSTRACT

Computer code (SUENTP-J) to predict scale-up and economic evaluation of several eligible non-thermal plasma processes for air pollution control – electron beam process, pulsed corona process, and corona radical shower process – was developed for a commercial power plant. This code was written in spread sheet type format (MS Excel) and visual basic for application and comprise a data input procedure, a scale-up (design) procedure, an economic calculation procedure, and an output procedure. Data obtained from pilot plant tests are input with general data so that they might lead to the conceptual design data of commercial plants by scale-up procedure. In the economic evaluation procedure, the total capital investment and the total annual cost are examined. The total capital investment comes into the indirect annual cost as the item of capital recovery. The levelized cost and the levelized busbar cost are shown in the output table. An example calculation was presented to evaluate the cost of three non-thermal plasma systems and the results were compared with a conventional wet-scrubber/selective catalytic reduction combined system.

1.1 INTRODUCTION

Several eligible non-thermal plasma technologies are in the stage of commercialization, and more recently, a several small scale commercial systems based on pulsed corona and electron beams are operating (Li et al, 1997). At this moment, their economic evaluation is requested not only for the selection of the most proper technology according to the subject facility, but also for the readjustment of future R&D direction of those technologies. In the past, there were a few economic evaluation works on NTPs. The Japanese Mechanical Industry Association and Energy Engineering Institute (1991) compared the types of De-SO_x and De-NO_x facilities from a coal fired power plant – the conventional wet-scrubber/selective catalytic reduction combined process, the electron beam process, and pulsed corona process. However, they evaluate their costs for only one case of 250MW power plant. Most other works are only for electron beams (Frank and Hirano, 1990; Tokunaga et al., 1995) or pulsed corona (Civitano, 1992) processes. Bartoszek et al. (1998) outlined economic evaluation methods for advanced reburning De-SO_x and De-NO_x processes based on thermal and non-thermal plasmas and proposed to use energy yield (reduced amount of acid gas [g]/input power [kWh]) for the accurate calculation of economic evaluations for plasma processes.

The non-thermal plasma (NTP) techniques are still not optimum and economic evaluations for commercial plants are rare. However, we have made an effort to estimate their economics as exactly as possible by using the most up-to-date information. The most important objective of an economic evaluation is to decide which system is most effective for the given conditions in terms of the flowrate of exhaust gas, initial concentration of NO_x, SO_x and the other emissions, space requirements, type of pollutant gases, etc. In this work, a simulation code named SUENTP-J is developed to evaluate and analyze scale-up procedures and economics for conceptual design of the three leading non-thermal technologies for commercial gas cleaning systems.

1.2 NON-THERMAL PLASMA TECHNOLOGY

Two different approaches are used for plasma gaseous pollution control. The first approach (direct method) is to treat flue gases directly by plasmas (mixture of electrons, ions and free radicals). The second approach (indirect method) is activating reducing or oxidizing gases by plasmas externally and injecting into flue gases. In the first approach, an input energy may be lost to activate unwanted flue gas components such as N_2, O_2, CO_2, etc., and the second approach requires suitable long life free radicals for pollutant gas treatment.

Non-thermal plasma direct treatment reactor an be divided into three different plasma sources as follows:

1. DC or pulsed corona reactor – (a) pin-plate; (b) corona torch; (c) capillary tube; and (d) wire-tube/wire-plate reactors.
2. Barrier discharge reactors – (a) silent discharge (b) surface discharge; (c) packed bed; and (d) superimposed barrier discharge reactors.
3. Electron beam reactors.

In order to avoid corona-to-spark discharge transitions, high gas flow or pulse applied voltage operations are used for corona devices, while a dielectric barrier is placed in the front of the electrodes in barrier discharges. The mean electron temperature for the corona or barrier discharge devices is 1 to 10 eV, while the electron beam devices are a few 100 keV. Indirect non-thermal plasma reactors currently developed are (a) corona radical injection devices and (b) corona shower system. DC or pulse power supplies are used for these retrofit devices and often these devices are used together with direct plasma treatment devices to enhance pollution gas treatment, i.e. hybrid concepts.

In this work, a wire-plate pulsed corona reactor, a corona shower system, and an electron beam reactor are selected for scale-up and economic evaluation algorithm development.

1.3 SCALE-UP AND ECONOMIC EVALUATION CODE

Features of the Code

The code SUENTP-J is written in Microsoft (MS) Excel and Visual Basic for Application (VBA). MS Excel is very convenient for treating considerable amounts of data and making charts from the results as a spread sheet type software. VBA is a kind of computer language, which might make this code more user-friendly interactive one. VBA is useful for the calculation of multiple conditions and the drawing of charts automatically.

This SUENTP-J code consists of an Input Data part, a Scale-up Calculation part, an Economic Calculation part, and an Output part VBA connects. Fig. 1.1 shows the simplified flow chart of this code This code can be used for various emission sources, but it is focused on the jet engine test cells in this work.

Data Input Procedure

The input data comprise two parts: common input data and input data from pilot plant tests. When the code file is opened first on MS Excel, a data sheet becomes available. This sheet includes common input data displayed in the first column of Table 1.1. Some of these input data, which are written in bold characters are some important parameters for sensitivity tests of each NTP system such as the capacity of the engine, initial NO or SO_2 concentration, removal rate of NO_x or SO_x, etc. Users can choose a variable with a set of values for a series of calculations. Then the calculations of scale-up and economic evaluation are carried out using those values. The others are general data for

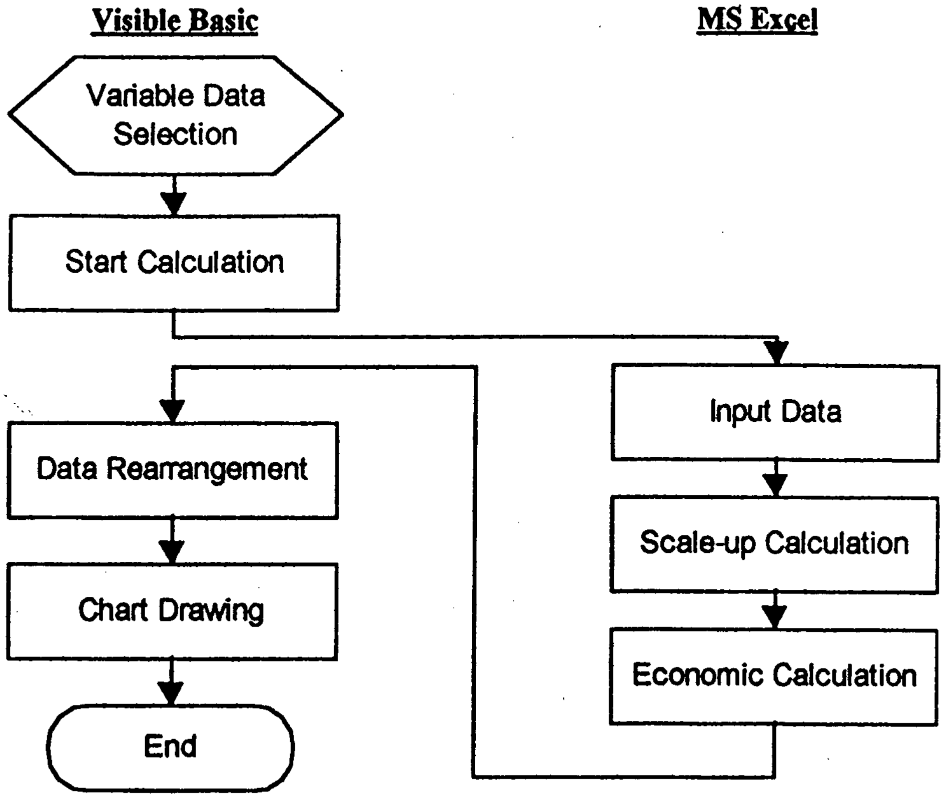

Fig 1.1 Flowchart of SUENTP

Source Data
- **Plant Power**
- Capacity Factor
- (Gas Flowrate)
- Gas Composition
- Temperture

Emission Data
- **NOx Initial Conc.**
- **NOx Removal Rate**
- **SOx Initial Conc.**
- **SOx Removal Rate**

Unit Price
- Electric Power
- NH3
- CH4
- Ar
- Water
- Fertilizer
- Personnel

Economic Data
- Depreciation Period
- Inflation Rate
- Real Interest Rate
- Nominal Interest Rate
- Salvage Rate

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Additional Gas
- Stoichiometric Ratio of
  - NH_3
  - HC(CH_4, $C2H_4$)

Spray Cooler
- Temperature

Reactor
- Reactor Geometry
- Flowrate of Mod.

Power Supply
- Max. Power of Unit/Gun
- Efficiency(In->Gas)
- Max. Peak Voltage

Energy Yield
- for NOx
- for SOx

Dust Collector
- Efficiency
- Migration Velocity
- Geometry
- Fertilizer Recovery

=>

Gas
- NOx Mass Flowrate
- SOx Mass Flowrate
- NH3 Consumption
- HC Consumption

Water Spray Cooler
- Cooler Volume
- Water Consumption

Reactor
- Geometry
- No. of Channel and Mod
- Area of Electrode
- Gas Velocity

Power Supply
- Total Input Power
- No. of Supply Unit/Gun

Fertilizer
- Ideal Total Production
- Recovery

Dust Collector (Module)
- Collecting Area
- Geometry

=>

Total Capital Investment

Total Direct Cost
- Water Spray Cooler
- Reactor
- Power Supply
- Dust Collector
- Instrumentation
- Other Equipment

Total Indirect Cost

Total Annual Cost

Direct Annual Cost
- Utilities
  - Electric Power
- Chemicals
  - NH3
  - HC
- Personnel Cost
- Laboratory Cost
- Maintenance Cost

Capital Recovery

Fertilizer Recovery

Levelized Annual Cost
- Levelization Factor
- Levelized Busbar Cost

Table 1.1 Data flow with input and output data emission source control, and unit prices, which are supposed to be adapted to all NTP processes. They must be input in this sheet by a user.

The Scale-up Procedure

Non-thermal plasma for emission control is accompanied by very complicated physical and chemical phenomena so that it is difficult to analyze theoretically. Therefore most design data should be obtained from experimental studies. In this work, the principal design data will be acquired from pilot plant experiments. Then these data are adopted as commercial plant design data directly.

Detailed design data as revealed in the second column of Table 1.1, which are obtained from the pilot plant experiments, and input into the sheet of the scale-up design procedure for each NTP process. These data are essential for the economic evaluations as well as for the scale-up design. Experimental values of energy are especially important since they affect not only the power supply capital cost, which is the most expensive among the capital costs, but also the electric power consumption cost which is one of the highest items in the annual cost. The consumption rate of power and chemicals such as NH_3 and hydrocarbons, are also quite important factors in the economic evaluation of non-thermal plasma systems for the removal of gaseous emissions.

This scale-up design sheet shows both of these input values and the calculated output values in the third column of Table 1.1. Some of output results are used to calculate the capital cost and the others the annual cost.

The Economic Calculation

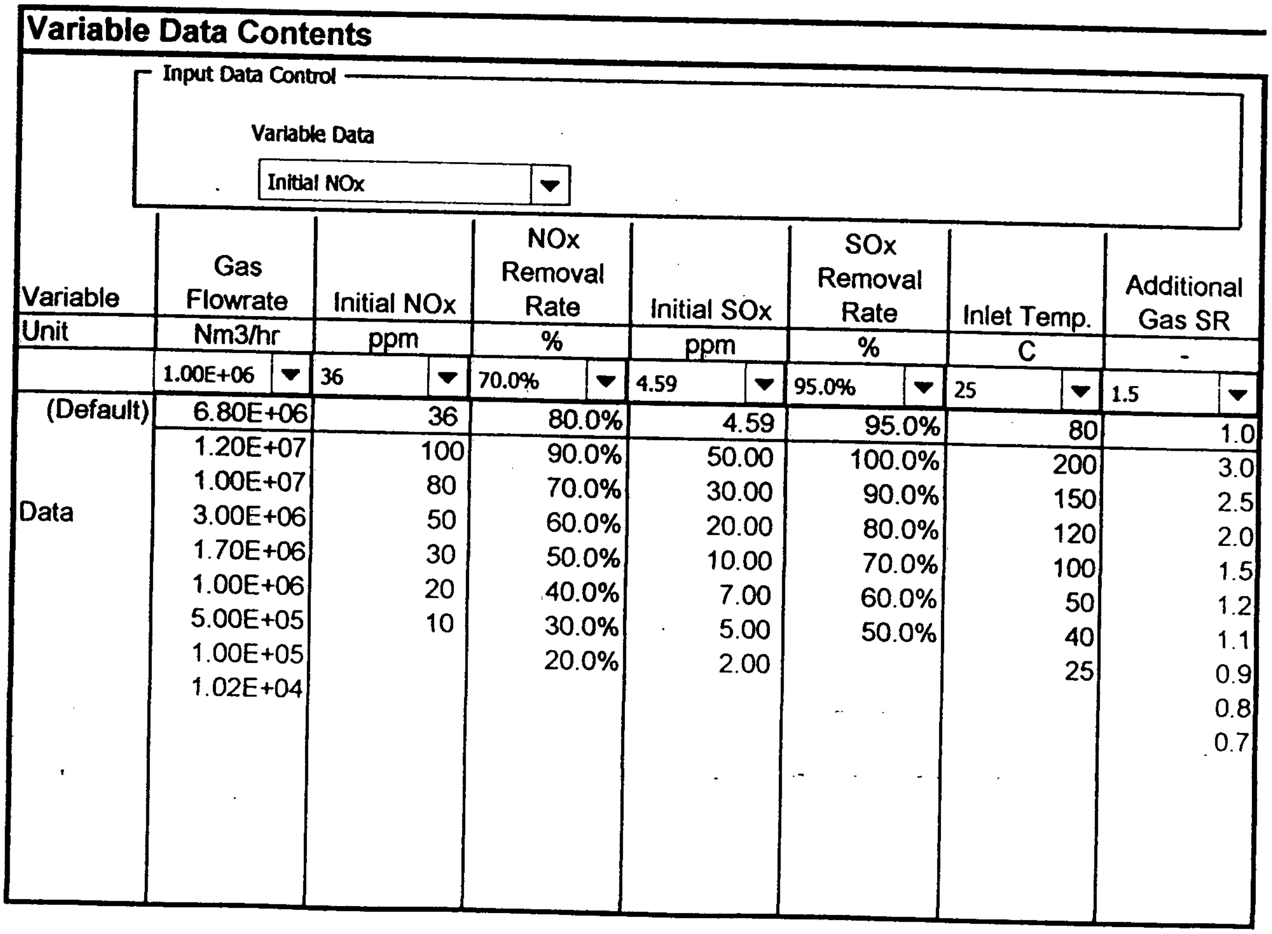
The economic evaluation follows Vatavuk's procedure (Vatavuk, 1990). The total capital investment is composed of depreciable and nondepreciable investment. The total annual cost is the sum of direct annual cost and indirect annual cost. If there is any recovery credit such as material and energy, the total annual cost could be reduced by this amount. The total capital investment comes into the indirect annual cost through the item of capital recovery. The important items of total capital investment and total annual cost are shown in Table 1.2. In this work, the period of construction is ignored, which is called "overnight construction". The inflation rate is considered as used in most utility cost evaluations. However, no tax is included.

As shown in Table 1.1, the calculated design values in the scale-up part for commercial power plant are related to estimated direct capital cost, and others are estimated direct annual cost. The direct capitals costs of primary equipment - reactor, power supply, and dust collector - are calculated using the input data obtained from existing bench, pilot or demonstration plants using the power factor model (Vatavuk, 1990; Bartoszek et al, 1998). The cost-capacity relationship in this estimate is based on the power factor model. The cost capacity factor is assumed in the range from 0.1 to 1.0. Generally, the factor is a round 0.6-0.7 for the large plants, and 0.3-0.4 for the pilot plants (Frank and Hirano, 1990; Bartoszek et al, 1998).

The economic estimation can allocate credits for the sale of by-products. It is expected that most of non-thermal plasma systems using NH_3 will produce a good fertilizer of ammonium sulfate and nitrate salts. As Frank and Hirano (1990) proposed, a system design which yields saleable sulfurous by-products may be essential to the application of flue gas treatment. Levelized costs or levelized busbar costs can be obtained from the total capital investment and the total annual costs being levelized by economic data such as a depreciation period, an interest, and salvage rate. The detailed economic procedure to get the levelized cost or levelized busbar cost can be obtained from EPRI Reports (EPRI, 1983; 1991).

Table 1.2. Items of Total Capital Investment and Total Annual Cost

Total Capital Investment (TCI)	Total Annual Cost (TAC)
Total Capital Investment (TCI) = DI + NDI **Depreciable Investment (DI)** Total Direct Cost - Site Preparation - Buildings - Purchased Equipment Cost - Direct Installation Cost Total Indirect Cost - Engineering and Supervision - Construction and Field Expense - Construction Fee - Start-up - Performance Test - Contingencies Offsite Facilities **Nondepreciable Investment (NDI)** - Land - Working Capital - Salvage	**Total Annual Cost (TAC) = DAC + IAC - RC** **Direct Annual Cost (DAC)** -Raw Materials -Utilities -Waste Treatment/Disposal -Labor -Maintenance Materials -Replacement Parts -Payroll Overhead **Indirect Annual Cost (IAC)** -Capital Recovery/Depreciation -Plant Overhead -Insurance -Administrative Charge **Recovery Credits (RC)** -Materials -Energy



Variable Data Contents

Input Data Control

Variable Data

Initial NOx ▼

Variable	Gas Flowrate	Initial NOx	NOx Removal Rate	Initial SOx	SOx Removal Rate	Inlet Temp.	Additional Gas SR
Unit	Nm3/hr	ppm	%	ppm	%	C	-
	1.00E+06 ▼	36 ▼	70.0% ▼	4.59 ▼	95.0% ▼	25 ▼	1.5 ▼
(Default)	6.80E+06	36	80.0%	4.59	95.0%	80	1.0
	1.20E+07	100	90.0%	50.00	100.0%	200	3.0
	1.00E+07	80	70.0%	30.00	90.0%	150	2.5
Data	3.00E+06	50	60.0%	20.00	80.0%	120	2.0
	1.70E+06	30	50.0%	10.00	70.0%	100	1.5
	1.00E+06	20	40.0%	7.00	60.0%	50	1.2
	5.00E+05	10	30.0%	5.00	50.0%	40	1.1
	1.00E+05		20.0%	2.00		25	0.9
	1.02E+04						0.8
							0.7

Output

The output of SUENTP-J consists of tables and charts. The table output including the items shown in Table 1.2 is very easy to use because it is a simple spread sheet. Another advantage of this type of output is that the output can be produced without running the program as soon as the input is changed. VBA produces charts as well as tables automatically carry out the calculation for a set of each important parameters.

1.4 AN EXAMPLE BASED ON EXISTING PILOT PLANT TESTS

Plant Test Data for Code Input

To obtain a set of pilot plant test data from non-thermal plasma technology for economic evaluations is difficult, since only electron beam (EB) technology has the experience of several pilot or commercial plants to provide baseline engineering data. Pulsed corona (PC) and corona shower (CS) technology do not have enough data for commercialization yet. Another reason is that even rare data from pilot or commercial plants will not be available to the public, since companies concerned the loss of important information to their competition.

Nevertheless, at this moment this economic evaluation must be made to inform the public about the possibility of which system is most profitable for a given emission resource. Therefore, this work tries to evaluate the cost of three non-thermal systems, compared with a conventional wet-scrubber/selective catalytic reduction and/or selective catalytic reduction/electrostatic precipitator systems although the experimental conditions of emission removal are slightly different as shown in Table 1.3.

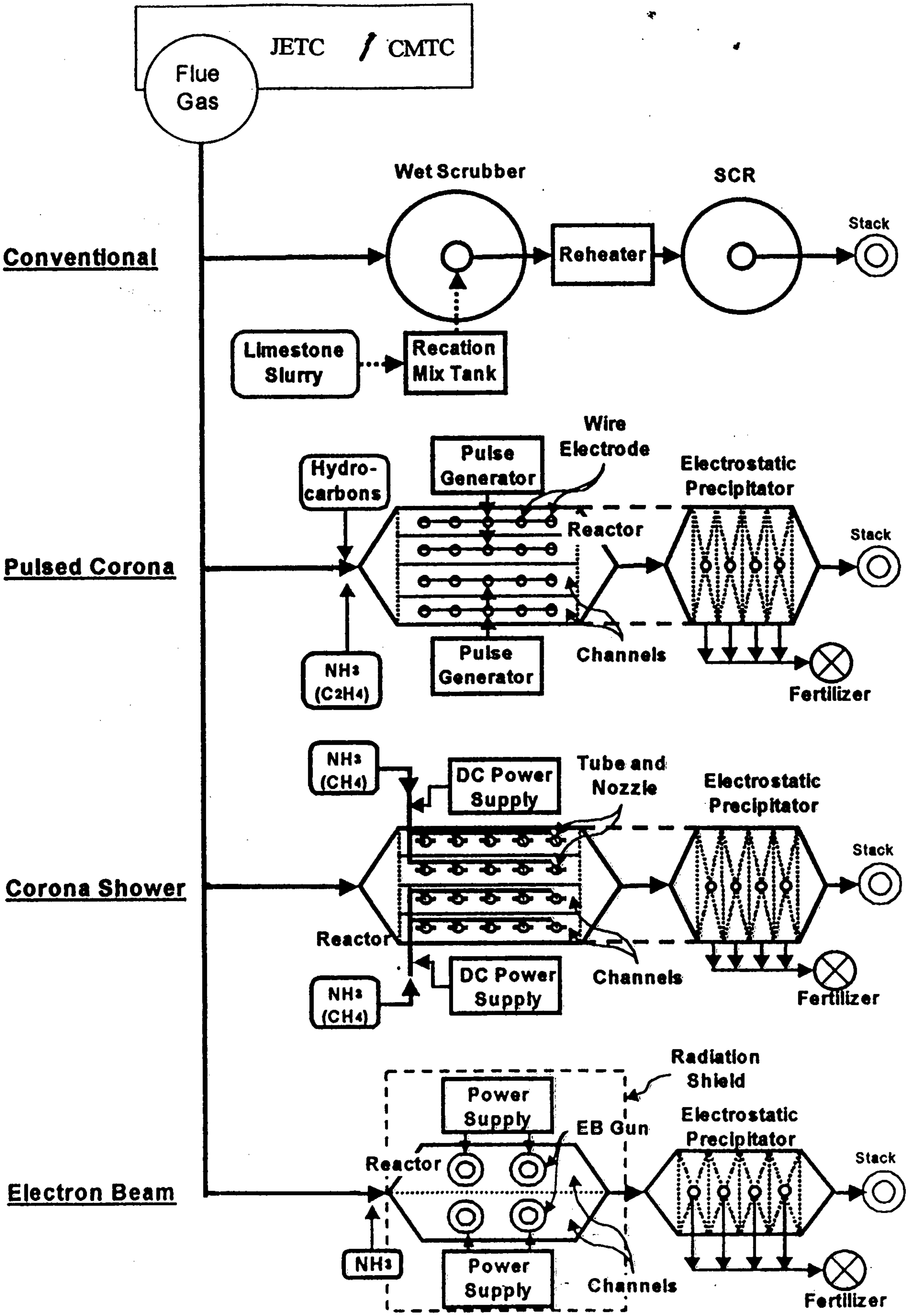


Fig 1.2 Block Diagram of Considered DeSOx and DeNOx Systems

Fig. 1.2 is the block diagram of the considered De-SO_x and De-NO_x systems, as mentioned above. It is assumed that the exhaust gas from the Jet engine test cell reaches thus plasma processes after passing through the main electrostatic precipitators.

Table 1.3 The emission removal conditions of each system for example calculation*.

ITEM	UNIT	Pulsed Corona[1]	Corona Shower[2]	Electron Beam[3]	Conventional[4]
Object		JETC	JETC	Undersea Tunnel	Coal Power Plant
Initial NO Concentration	ppm	36	40	10	300
NO_x Removal Rate	%	56	90	70	80
Initial SO_2 Concentration	ppm	4	4	1	3,050
SO_x Removal Rate	%	90	95	95	90
Energy Yield**	g-NO/kWh	20	1	19.1	-
Experimental Scale	Nm^3/h	600	12	40,000	1.9×10^6

* Data obtained from 1. Haythornthwaite et al, 1997; 2. Matsuoka et al, 1997; 3. Ebara Co., 1998; 4. EPRI, 1983; JMIA-EEI, 1991.

** Note : All electric power is assumed to contribute to the removal of NO_x.

Discussion

Fig. 1.3 displays the results of a sample calculation for various flue gas flow rates, where 10^6 scfm (1.62×10^6 Nm^3/h) and 6×10^4 scfm (10^5 Nm^3/h) are corresponding to JETC and CMTC flue gas flow rates, respectively. As mentioned above, it is very hard to compare the results of this sample calculation because the input conditions of each process are different from each other.

Although they are not disclosed in this figure, the costs of the electron beam guns and pulsed generators had the majority of the total capital costs of EB process and PC process, respectively.

Fig.1.3a Common Input Data of Scale-up and Economic Evaluation for Jet Engine Test Cells

Source Data

Plant Type			Jet Engine Test Cell	
Gas Flowrate	Qgas	Nm3/hr	**1.00E+06**	
Fuel			JP-5	
Capacity Factor	Ruse	%	80	
Gas Composition				
N2	C_{N2}	%	80.98	
CO2	C_{CO2}	%	0.50	
H2O	C_{H2O}	%	0.50	
O2	C_{O2}	%	18.00	
Density(Normal)	Dgas	kg/Nm3	1.283	
Exhaust GasTemp.	Tgas	C	**25**	
NTP In Temp.	T_{NTP}in	C	25	
Pressure	PRgas	mmAq	720	

Emisson Data

Emission	Inlet Concentration			Outlet Concentration			Removal Efficiency	
NOx	C_{NOx}	ppm	**36.00**	Cout_NOx	ppm	10.80	E_{NOx}	**70**
SO2	C_{SO2}	ppm	**4.59**	Cout_SO2	ppm	0.23	E_{SO2}	**95**
HC(VOC)	C_{HC}	ppm	60.00	Cout_HC	ppm	6.00	E_{HC}	90
CO	C_{CO}	ppm	53.36	Cout_CO	ppm	53.36	E_{CO}	0
Particle	Cpart	mg/Nm3		Cout_part	mg/Nm3		Epart	%
NH3 Stoichiometric Ratio(SR) to NO and SO_2				SR_{NH3}		**1.5**		

Labor Data

Supervisor	MP/year	0.5	On the basis of 400000Nm3/hr
Operator	MP/year	2.0	"
Yard-crew Worker	MP/year	2.0	"
Secretary	MP/year	0.5	"

Unit Price Data

Electrical Power	US$/kWh	*0.05*	*(Production Cost 0.02)*
Limestone	US$/ton	16	14*1.2
Lime	US$/ton	72	60*1.2
Gypsum	US$/ton	24	
NH3	US$/ton	180	(Retail : $356 for 150lb)
CH4	US$/ton	73.46	
Ar	US$/ton	100	(Retail : $91 for 331ft3 at 2490psi)
Water	US$/ton	0.2	
Steam	US$/ton	7	
Fertilizer	US$/ton	90	
Waste Treatment(Sludge)	US$/ton	10	
Personal			
Supervisor	US$/year	52,942	
Operator	US$/year	30,856	
Yard-crew Worker	US$/year	20,998	
Secretary	US$/year	24,583	

Economic Data

Depreciation Period	Years	10	
Inflation Rate	%	5.0	
Real Interest Rate	%	5.0	
Nominal Interest Rate	%	10.3	[Calculated, =(1+i)(1+e)-1]
Salvage Rate of Facilities	%	0.0	

Fig.1.3b Design of a Pulse Corona System

Input Data from Pilot Test				Calculated Data for Commercial Plant Design			
Dust Collector (Module)				**Dust Collector (Module)**			
Type : Wire-Plate Electrostatic Precipitator				**Collecting Area**	Aesp	m2	37
Efficiency	Eesp	%	95	Width	Wesp	m	0.90
Migration Velocity	VCmig	m/sec	0.125	Height	Hesp	m	1.15
Channel Width	Wespch	m	0.3	**No. of Channel**	Nespch		3
Gas Velocity	Vcesp	m/sec	1.5	Length	Lesp	m	11
No. of Module			2	**Volume**	VLesp	m3	11
				Residence Time	TMesp	sec	4
				Electric Power		kW	4
Flue Gas System				**Flue Gas System**			
Inlet Temperature	Tscin	C	25	Flowrate	Qmod	Nm3/hr	10,200
Outlet Temperture	Tscout	C	25	**Actual Flowrate**	Qacmod	m3/hr	11,134
				NOx Mass Flowrate	MF_{NOx}	kg/hr	0
				SOx Mass Flowrate	MF_{SOx}	kg/hr	0
				Electric Power		kW	16
Reagent Feed System				**Reagent Feed System**			
Limestone				Limestone Flowrate	Q_{CaCO3}	kg-mole/	0.00
Ratio to SO2 Removed	SR_{CaCO3}		1.15	**Limestone Consump**	MF_{CaCO3}	kg/hr	0
Fixative Lime				Electric Power		kW	0
Wet Scrubbing Absorber Tower				**Wet Scrubbing Absorber Tower (Module)**			
Reactor Type : Vertical Countcurrent Spray				No. of Reactor Module	Nmod	ea	1
Max. Flowrate of Mod	Qxmod	Nm3/hr	2.0E+06	Flowrate/Module	Qmod	Nm3/hr	10,200
Gas Velocity	VCrc	m/sec	1.5	Actual Flowrate/Mod	Qacmod	m3/hr	11,134
				Diameter of Module		m	1.6
				Height of Module		m	1.5
				Volume of Module		m3	3
				Water Consumption	MFscw	ton/hr	5
				Electric Power		kW	18
Reheat System				**Reheat System (Module)**			
Inlet Temperature	Trhin	C	25	Heat Flowrate	q_{rh}	MJ/hr	6,425
Outlet Temperture	Trhout	C	370	**Steam Consumption**	Qsteam	ton/hr	2.26
Flue Gas Specific Heat	Cpgas	kJ/kg	1.423				
Steam Inlet Temp.			233.3				
Steam Outlet Temp.			93.3				
Waste Handling System				**Waste Handling System**			
Recovery Rate	Erecov	%	-	Fly Ash		ton/hr	0.2
Ratio to Dry Sludge and Fly Ash			0.03	Waste Sludge		ton/hr	0.0
				Lime Consumption		ton/hr	0.0
				Total Waste		ton/hr	0.2
				Gypsum Recovery	Mfert	kg/hr	0.0
				Electric Power		kW	2
Power				**Power**			
				Total Power	Pin	MW	0.04
Selective Catalytic Reduction				**Selective Catalytic Reduction (Module)**			
NH_3				NH3 Flowrate	Q_{NH3}	Nm3/hr	0
Ratio to NO	SR_{NH3}		1.20	**NH3 Consumption**	MF_{NH3}	kg/hr	0
				Electric Power		kW	0

Fig.1.3c Design of a Pulse Corona System

Input Data from Pilot Test			
Additional Gas			
Additional Gas I			NH3
Ratio to NO and SO2	SR_{NH3}		**1.50**
Additional Gas II			CH4
Ratio to NO and SO2	SR_{CH4}		0.00
Additional Gas III			C2H4
Ratio to NO and SO2	SR_{C2H4}		0.00
Water Spray Cooler			
Inlet Temperature	Tscin	C	25
Outlet Temperture	Tscout	C	25
Gas Velocity	VCsc	m/sec	1.5
Residence Time	TMsc	sec	5
Reactor			
Reactor Type :	Wire-Plate Type Reactor		
Max. Flowrate of Mod	Qxmod	Nm3/hr	500,000
Flowrate/Channel	Qch	Nm3/hr	8,000
Volume of Channel	VLch	m3	20
Channel Width	Wch	m	0.2
Height of Module	Hmod	m	10
Pulse Generator (Unit)			
Power Supply Type :	Rotary Spark-Gap		
Max. Peak Voltage	Vmax	kV	120
Power of Unit	Pumax	MW	0.2
Efficiency(In->Gas)	Eps	%	60
Energy Yield			
for NOx (from Data)	Y_{NOx}	g/kWh	20.00
for SO2 (from Data)	Y_{SO2}	g/kWh	1.0E+06
(Spec. Energy Density)	ENden	J/L	6.08
(Power Density)	Pden	Wh/m3	1.69
Dust Collector (Module)			
Type :	Wire-Plate Electrostatic Precipitator		
Efficiency	Eesp	%	95
Migration Velocity	VCmig	m/sec	0.125
Channel Width	Wespch	m	0.3
Fertilizer Recovery	Efert	%	50

Calculated Data for Commercial Plant Design			
Gas			
NOx Mass Flowrate	MF_{NOx}	kg/hr	0
SOx Mass Flowrate	MF_{SOx}	kg/hr	0
NH3 Flowrate	Q_{NH3}	Nm3/hr	1
NH3 Consumption	MF_{NH3}	kg/hr	1
CH4 Flowrate	Q_{CH4}	Nm3/hr	0
CH4 Consumption	MF_{CH4}	kg/hr	0
Water Spray Cooler			
Residence Time	TMsc	sec	5.00
Cooler Volume	VLsc	m3	15.46
Inner Diameter	Dscin	m	2
Length (Height)	Lsc	m	9
Water Consumption	MFscw	ton/hr	0
Reactor			
No. of Reactor Module	Nmod	ea	1
Flowrate/Module	Qmod	Nm3/hr	10,200
Actual Flowrate/Mod	Qacmod	m3/hr	11,134
No. of Channel/Mod	Nch	ea	2
Volume of Module	VLmod	m3	40
Width of Module	Wmod	m	0.40
Length of Module	Lmod	m	10.00
Area of Electrode/Mod	Aelec	m2	200
Gas Velocity	VCrc	m/sec	0.77
Residence Time	TMres	sec	12.93
Power			
Total Corona Power	Pco	MW	0.02
Total Input Power	Pin	MW	0.03
No. of Supply Unit	Npsu	ea	1
Fertilizer			
Ideal Total Production	Midfert	kg/hr	1
Recovery	Mfert	kg/hr	1
Dust Collector (Module)			
Collecting Area	Aesp	m2	74
Width	Wesp	m	0.40
Height	Hesp	m	10.00
No. of Channel	Nespch		1
Length	Lesp	m	7.41
Volume	VLesp	m3	30
Residence Time	TMesp	sec	9.59
Gas Velocity	VCesp	m/sec	0.77

Fig.1.3d Design of Electron Beam Systems

Input Data			
Additional Gas			
Additional Gas I			NH3
Ratio to NO and SO2	MR_{NH3}		**1.50**
Additional Gas II			CH4
Ratio to NO and SO2	MR_{CH4}		0.00
Water Spray Cooler			
Inlet Temperature	Tscin	C	**25**
Outlet Temperture	Tscout	C	**25**
Gas Velocity	VCsc	m/sec	1.5
Residence Time	TMsc	sec	5
Reactor			
Reactor Type : Horizontal Square			
Max. Flowrate of Mod	Qxmod	Nm3/hr	400,000
Flowrate/Channel	Qch	Nm3/hr	200,000
Volume of Channel	VLch	m3	200
Channel Width	Wch	m	5
Height of Module	Hmod	m	5
Shield Thickness	Wshield	m	1
Shield Space	Lshield	m	5
E-Beam Gun			
Voltage of Gun	Vgun	kV	1000
Max. Current of Gun	Igun	mA	1500
(Max. Power of Gun)	Pxgun	kW	1500
Efficiency (Input->Gas)	Egun	%	80
Min. Power of Gun	Pmngun	kW	200
Energy Yield			
for NOx (from Data)	Y_{NOx}	g/kWh	19.1
for SO2 (from Data)	Y_{SO2}	g/kWh	1.0E+06
(Dosage)	ITeb	kGy	**(5.0)**
Dust Collector (Module)			
Type : Wire-Plate Electrostatic Precipitator			
Efficiency	Eesp	%	95
Migration Velocity	VCmig	m/sec	0.125
Channel Width	Wespch	m	0.3
Fertilizer Recovery	Efert	%	50

Calculated Data			
Gas			
NOx Mass Flowrate	MF_{NOx}	kg/hr	0
SOx Mass Flowrate	MF_{SOx}	kg/hr	0
NH3 Flowrate	Q_{NH3}	Nm3/hr	1
NH3 Consumption	MF_{NH3}	kg/hr	1
CH4 Flowrate	Q_{CH4}	Nm3/hr	0.00
CH4 Consumption	MF_{CH4}	kg/hr	0.00
Water Spray Cooler			
Cooler Volume	VLsc	m3	15.46
Inner Diameter	Dscin	m	2
Length (Height)	Lsc	m	8
Water Consumption	MFscw	ton/hr	0
Reactor			
No. of Reactor Module	Nmod	ea	1
Flowrate/Module	Qmod	Nm3/hr	10,200
Actual Flowrate/Mod	Qacmod	m3/hr	11,134
No. of Channel/Mod	Nch	ea	1
Volume of Module	VLmod	m3	200
Width of Module	Wmod	m	5.00
Length of Module	Lmod	m	8.00
Gas Velocity	VCrc	m/sec	0.12
Residence Time	TMres	sec	64.67
Shield Surface Area	Ashield	m2	1,530
E-Beam Gun			
EB Power/Module	Pmod	MW	0.02
Input Power/Module	Pmodin	MW	0.02
No. of EB Guns/Ch	Ngunch	ea	1
Gun Power	Pgun	kW	200
Total No. of EB Guns	Ngun	ea	1
Total EB Power	Peb	MW	0.02
Total Input Power	Pin	MW	0.20
Fertilizer			
Ideal Total Production	Midfert	kg/hr	1
Recovery	Mfert	kg/hr	1
Dust Collector (Module)			
Collecting Area	Aesp	m2	74
Width	Wesp1	m	0.40
Height	Hesp	m	10.00
No. of Channel	Nespch		2
Revised Width	Wesp	m	0.60
Length	Lesp	m	3.71
Volume	VLesp	m3	22
Residence Time	TMesp	sec	7.19
Gas Velocity	VCesp	m/sec	0.77

Fig.1.3e Design of Corona Radical Shower System

Input Data			
Additional Gas and Nozzle			
Additional Gas I			NH3
Ratio to NO + 2*SO2	MR_{NH3}		**1.50**
Additional Gas II			CH4
Ratio to NO + 2*SO2	MR_{CH4}		0.00
Water Spray Cooler			
Inlet Temperature	Tscin	C	**25**
Outlet Temperture	Tscout	C	**25**
Gas Velocity	VCsc	m/sec	1.5
Residence Time	TMsc	sec	5
Reactor			
Reactor Type :	Tube-Plate Type Reactor		
Max. Flowrate of Mod	Qxmod	Nm3/hr	500,000
Flowrate/Channel	Qch	Nm3/hr	8,000
Volume of Channel	VLch	m3	25
Channel Width	Wch	m	0.2
Height of Module	Hmod	m	10
Power Supply (Unit)			
Power Supply Type :	DC High Voltage		
Max. Voltage	Vmax	kV	120
Max. Power of Unit	Pumax	MW	10
Efficiency(In->Gas)	Eps	%	60
Energy Yield			
for NOx (from Data)	Y_{NOx}	g/kWh	17
for SO2 (from Data)	Y_{SO2}	g/kWh	1.0E+06
(Spec. Energy Density)	ENden	J/L	7.15
(Power Density)	Pden	Wh/m3	1.985
Dust Collector (Module)			
Type :	Wire-Plate Electrostatic Precipitator		
Efficiency	Eesp	%	95
Migration Velocity	VCmig	m/sec	0.125
Channel Width	Wespch	m	0.3
Fertilizer Recovery	Efert	%	50

Calculated Data			
Gas			
NOx Mass Flowrate	MF_{NOx}	kg/hr	0
SOx Mass Flowrate	MF_{SOx}	kg/hr	0
NH3 Flowrate	Q_{NH3}	Nm3/hr	1
NH3 Consumption	MF_{NH3}	kg/hr	1
CH4 Flowrate	Q_{CH4}	Nm3/hr	0.00
CH4 Consumption	MF_{CH4}	kg/hr	0.00
Water Spray Cooler			
Cooler Volume	VLsc	m3	15.46
Inner Diameter	Dscin	m	2
Length (Height)	Lsc	m	8
Water Consumption	MFscw	ton/hr	0
Reactor			
No. of Reactor Module	Nmod	ea	1
Flowrate/Module	Qmod	Nm3/hr	10,200
Actual Flowrate/Mod	Qacmod	m3/hr	11,134
No. of Channel/Mod	Nch	ea	2
Volume of Module	VLmod	m3	50
Width of Module	Wmod	m	0.40
Length of Module	Lmod	m	12.50
Area of Electrode/Mod	Aelec	m2	250
Gas Velocity	VCrc	m/sec	0.77
Residence Time	TMres	sec	16.17
Power			
Total Corona Power	Pco	MW	0.02
Total Input Power	Pin	MW	0.03
No. of Supply Unit	Npsu	ea	1
Power of Unit	Punit	MW	0.1
Fertilizer			
Ideal Total Production	Midfert	kg/hr	1
Recovery	Mfert	kg/hr	1
Dust Collector (Module)			
Collecting Area	Aesp	m2	74
Width	Wesp	m	0.40
Height	Hesp	m	10.00
No. of Channel	Nespch		1
Length	Lesp	m	7.41
Volume	VLesp	m3	30
Residence Time	TMesp	sec	9.59
Gas Velocity	VCesp	m/sec	0.77

Fig.1.3f

Gas Flow Rate 1.00E+05 Nm^3/h (5.89E+04 SCFM)

	Pulse	Corona	Corona	Shower	Electron	Beam	Wet Scrubb	+ SCR	ESP	+SCR
Capital Recovery	345		410		718		36		104	
Labor & Maintenance	218		246		377		273		273	
Electric Power	99		116		77		123		83	
Chemicals & Utilities	6		6		6		1,291		1,192	
Total Annual Cost		664		774		1,176		1,723		1,651
Fertilizer Recovery		4		4		4		0		0

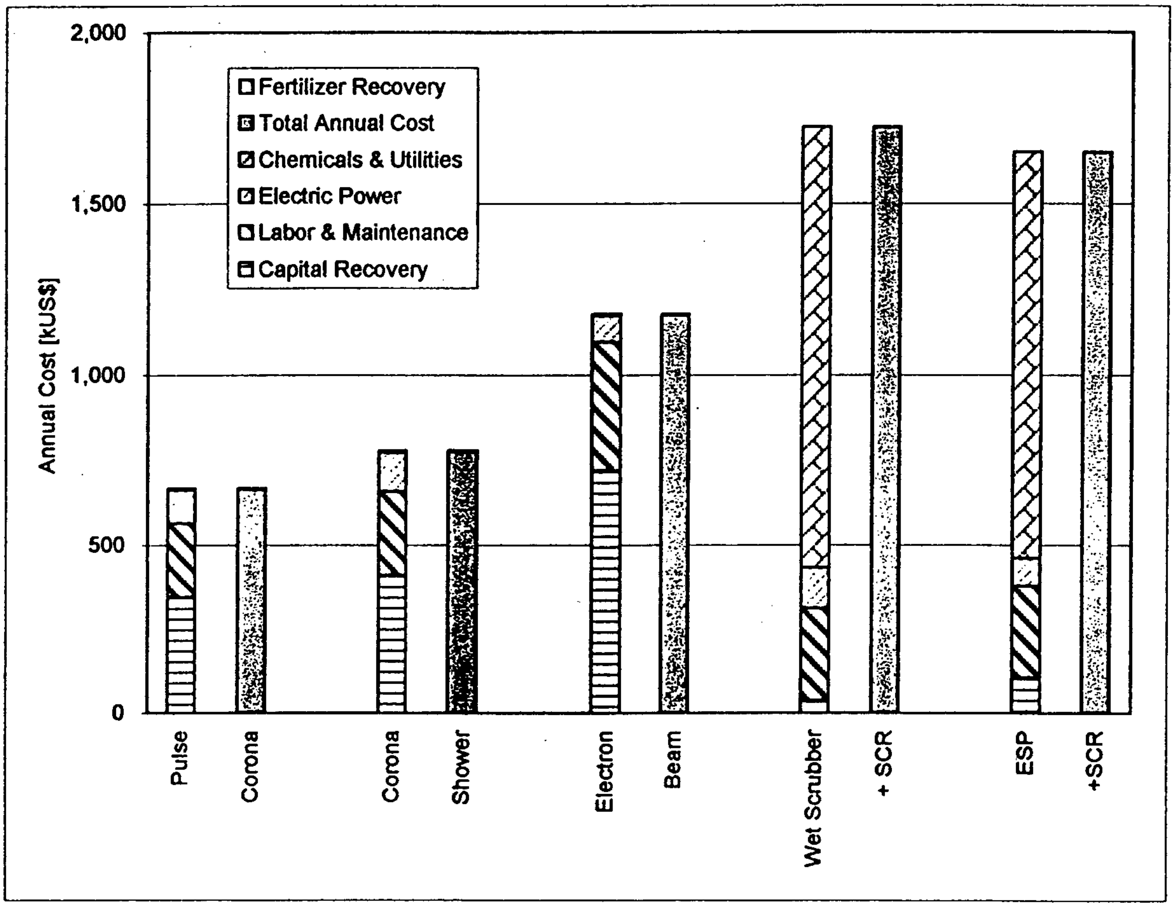


Fig.1.3 g Comparison of Important Factors and Results

Important Factors and Results	Unit	Pulse Corona	Corona Radical Shower	Electron Beam	Wet Scruber + SCR	SCR + ESP
Performance						
Additional Gas						
NH_3 Molar Ratio		1.50	1.50	1.50	1.20	1.20
NH_3 Consumption	kg/hr	5	5	5	3	4
Reactor						
No. of Reactor Module	ea	1	1	1	1	2
No. of Channel per Module	ea	13	13	1	0	10
Volume of Reactor Module	m^3	260	325	200	57	109
Area of Cathode Plates	m^2	1,300	1,625	-	-	-
Gas Velocity in Reactor	m/sec	1.17	1.17	1.21	1.50	1.50
Residence Time in Reactor	sec	8.57	10.72	6.60	0.00	3.59
Power Supply or EB Gun						
Voltage	kV	120	120	1,000	0	0
Max Current	mA	-	-	1,500	0	0
Power	MW	0.20	0.40	0.22	0.17	0.00
Efficiency (Input -> Gas)	%	60	60	80	95	0
No. of P/S or EB Gun	ea	2	1	1	0	0
Total Input Power	MW	0.28	0.33	0.22	0.35	0.24
Energy Yield						
for NOx	g/kWh	20.0	17.0	19.1	0.0	0.0
for SOx	g/kWh	1.0E+06	1.0E+06	1.0E+06	0.0	0.0
Total Capital Investment	**kUS$**	**2,095**	**2,491**	**4,367**	**221**	**630**
	US$/(kNm3/h)	**20,948**	**24,912**	**43,668**	**2,211**	**6,298**
Spray Cooler	kUS$	0	0	0	0	0
Reactor	kUS$	602	924	188	32	32
Power Supply or EB Gun	kUS$	326	241	1,094	31	0
Shield Costruction	kUS$	0	0	1,102	0	0
Dust Collector	kUS$	268	268	268	0	299
Instrumentation	kUS$	133	149	120	2	3
Others	kUS$	67	79	139	52	52
Direct Cost	kUS$	1,397	1,661	2,911	147	420
Indirect Cost	kUS$	698	830	1,456	74	210
Direct Annual Cost	**kUS$**	**323**	**368**	**461**	**1,687**	**1,547**
Electric Power	kUS$	99	116	77	123	83
Chemicals & Utilities	kUS$	6	6	6	1,291	1,192
Labor	kUS$	71	71	71	75	75
Maintenance	kUS$	147	174	306	198	198
Capital Recovery/Depreciation	**kUS$**	**345**	**410**	**718**	**36**	**104**
Fertilizer Recovery	**kUS$**	**4**	**4**	**4**	**0**	**0**
Total Annual Cost	**kUS$**	**664**	**774**	**1,176**	**1,723**	**1,651**
Levelized Annual Cost	**kUS$**	**750**	**873**	**1,299**	**2,179**	**2,069**

Gas Flow Rate **1.00E+05 Nm^3/h**
(5.89E+04 SCFM)

Fig. 1.3 h

Gas Flow Rate 1.00E+06 Nm^3/h (5.89E+05 SCFM)

	Pulse	Corona	Corona	Shower	Electron	Beam	Wet Scrubb	+ SCR	ESP	+SCR
Capital Recovery	2,089		2,321		3,954		1,489		1,496	
Labor & Maintenance	1,114		1,213		1,908		2,731		2,731	
Electric Power	986		1,159		776		1,225		826	
Chemicals & Utilities	65		65		65		12,910		11,917	
Total Annual Cost		4,217		4,722		6,666		18,356		16,970
Fertilizer Recovery		36		36		36		0		0

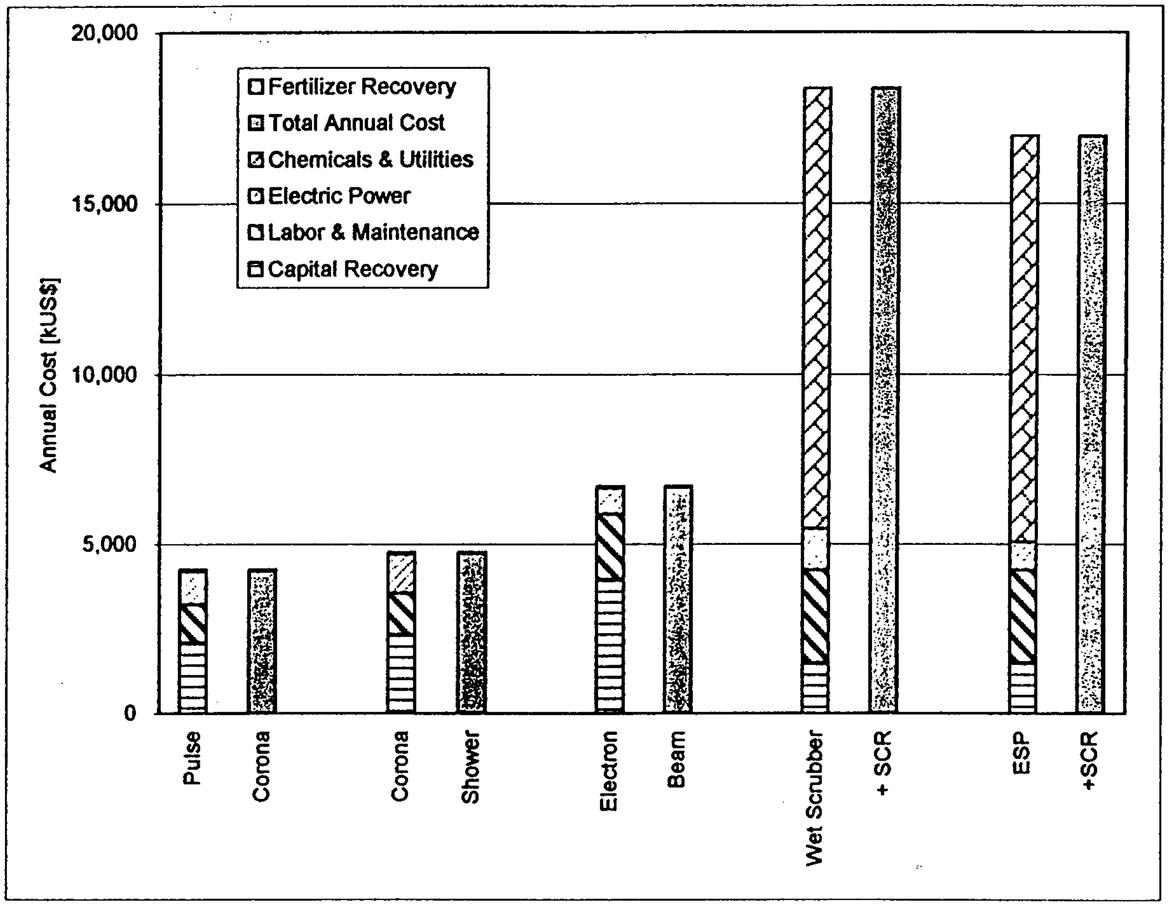


Fig. 1.3 i Comparison of Important Factors and Results

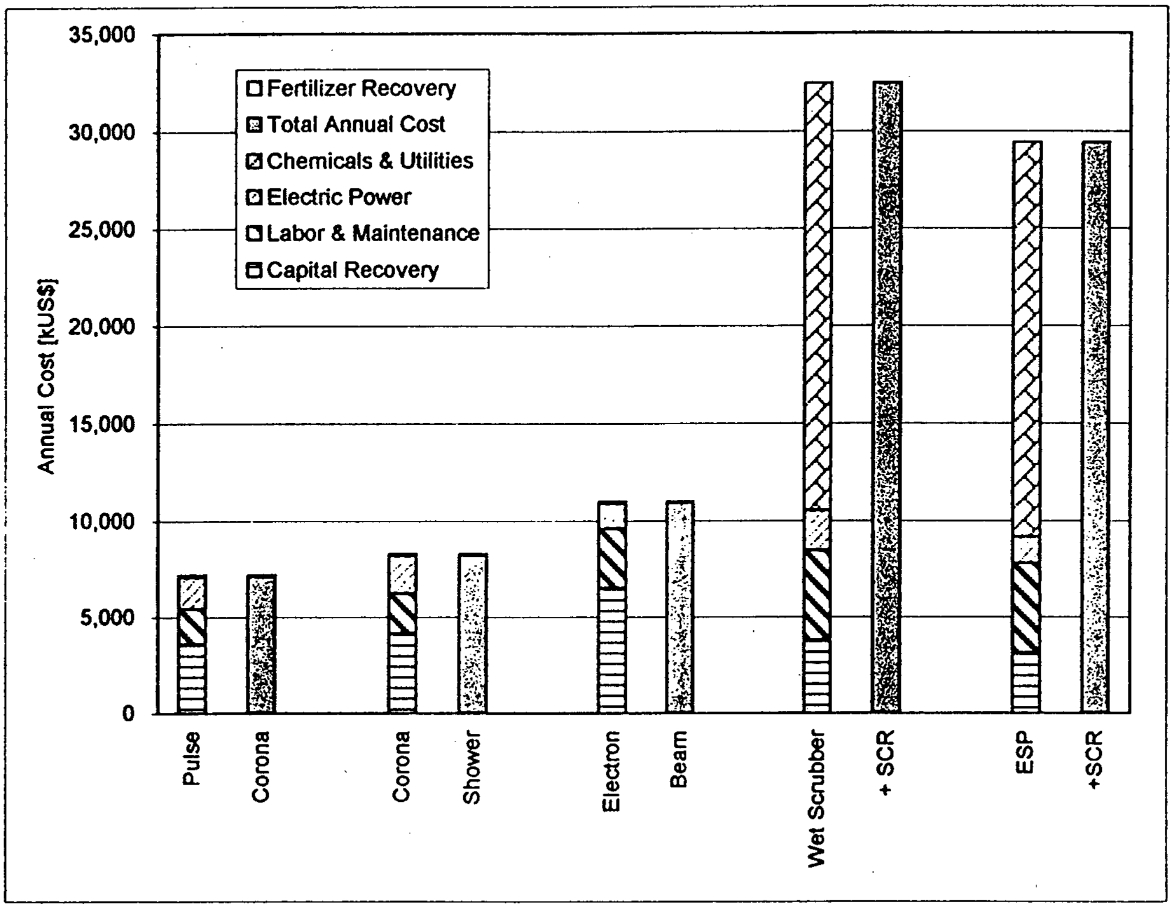
Important Factors and Results	Unit	Pulse Corona	Corona Radical Shower	Electron Beam	Wet Scruber + SCR	SCR + ESP
Performance						
Additional Gas						
NH_3 Molar Ratio		1.50	1.50	1.50	1.20	1.20
NH_3 Consumption	kg/hr	51	51	51	33	36
Reactor						
No. of Reactor Module	ea	2	2	3	1	2
No. of Channel per Module	ea	63	63	2	0	33
Volume of Reactor Module	m^3	1,260	1,575	400	2,121	1,090
Area of Cathode Plates	m^2	6,300	7,875	-	-	-
Gas Velocity in Reactor	m/sec	1.20	1.20	2.02	1.50	1.50
Residence Time in Reactor	sec	8.31	10.39	3.96	0.00	3.59
Power Supply or EB Gun						
Voltage	kV	120	120	1,000	0	0
Max Current	mA	-	-	1,500	0	0
Power	MW	0.20	1.70	0.37	1.74	0.00
Efficiency (*Input -> Gas*)	%	60	60	80	95	0
No. of P/S or EB Gun	ea	15	2	6	0	0
Total Input Power	MW	2.81	3.31	2.21	3.50	2.36
Energy Yield						
for NOx	g/kWh	20.0	17.0	19.1	0.0	0.0
for SOx	g/kWh	1.0E+06	1.0E+06	1.0E+06	0.0	0.0
Total Capital Investment	**kUS$**	**12,697**	**14,111**	**24,038**	**9,051**	**9,093**
	US$/(kNm3/h)	**12,697**	**14,111**	**24,038**	**9,051**	**9,093**
Spray Cooler	kUS$	0	0	0	0	0
Reactor	kUS$	3,245	4,977	884	1,624	1,624
Power Supply or EB Gun	kUS$	2,448	1,536	9,397	1,570	0
Shield Costruction	kUS$	0	0	2,523	0	0
Dust Collector	kUS$	2,082	2,082	2,219	0	2,082
Instrumentation	kUS$	287	364	238	83	166
Others	kUS$	403	448	763	520	520
Direct Cost	kUS$	8,465	9,407	16,025	6,034	6,062
Indirect Cost	kUS$	4,232	4,704	8,013	3,017	3,031
Direct Annual Cost	**kUS$**	**2,164**	**2,437**	**2,749**	**16,867**	**15,474**
Electric Power	kUS$	986	1,159	776	1,225	826
Chemicals & Utilities	kUS$	65	65	65	12,910	11,917
Labor	kUS$	225	225	225	754	754
Maintenance	kUS$	889	988	1,683	1,977	1,977
Capital Recovery/Depreciation	**kUS$**	**2,089**	**2,321**	**3,954**	**1,489**	**1,496**
Fertilizer Recovery	**kUS$**	**36**	**36**	**36**	**0**	**0**
Total Annual Cost	**kUS$**	**4,217**	**4,722**	**6,666**	**18,356**	**16,970**
Levelized Annual Cost	**kUS$**	**4,792**	**5,371**	**7,399**	**22,913**	**21,151**

Gas Flow Rate	1.00E+06 Nm^3/h
	(5.89E+05 SCFM)

Fig. 1.3j

Gas Flow Rate 1.70E+06 Nm^3/h (1.00E+06 SCFM)

	Pulse	Corona	Corona	Shower	Electron	Beam	Wet Scrubb	+ SCR	ESP	+SCR
Capital Recovery	3,594		4,151		6,504		3,802		3,123	
Labor & Maintenance	1,823		2,060		3,061		4,641		4,641	
Electric Power	1,674		1,970		1,318		2,082		1,403	
Chemicals & Utilities	110		110		110		21,935		20,247	
Total Annual Cost		7,139		8,230		10,931		32,459		29,414
Fertilizer Recovery		62		62		62		0		0



However the dc power supply was not the main part of CS process capital cost since it is much less inexpensive than an electron beam gun and pulsed generator. The most outstanding parameter which strongly affects both the capital cost and operating cost is energy yield. Low energy yield require less power supply capacity and less electric power consumed. This is another reason corona shower process has the low total annual cost including capital recovery. The total annual cost of pulsed corona system is almost the same with electron beam and corona shower system. All systems have slightly lower than the half of the total annual cost of conventional combined system.

Although only 50% of producible fertilizer is assumed to be recovered, the recovery credit can be high enough not to be negligible. If electrostatic precipitators are equipped at the both sides of each non-thermal system, good quality fertilizer of ammonia sulfate nitrate could be obtained. For the conventional system, gypsum could be recovered can if it is not significant amount.

All of the non-thermal plasma systems show 50 to 60% lower costs by comparison with conventional wet-scrubber/SCR or SCR/ESP systems for the present range of gas flow rates (10^5 to 10^7 Nm^3/h).

1.5 CONCLUDING REMARKS

The computer code SUENTP-J was developed to predict scale-up and economic evaluations of several eligible non-thermal plasma processes for Jet Engine Test Cell exhaust gas pollution controls. This code was written using a spread sheet (MS Excel) with Visual Basic for application and comprise a data input procedure, scale-up (design) procedure, economic calculation procedure, and output procedure.

This code has obtained the parametric economic evaluation of three non-thermal systems and has shown competitive with the conventional system. The result of the evaluation also shows that the

NTP system energy yield of NO_x and SO_x removal to be the most important parameter to affect the capital cost as well as the operating cost. Hence, any possible pilot study of non-thermal emission control systems should be clearly designed to present the value of the energy yield as well as De-NO_x and De-SO_x efficiency. In order to estimate more accurate non-thermal plasma system costs for JETC and CMTC conditions, much larger pilot plant tests, up to 200 to 1000 Nm^3/h, are required.

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PART 2.

ACID GAS REMOVAL CHARACTERISTICS OF CORONA RADICAL SHOWER-CATALYST HYBRID SYSTEM FOR TREATMENT OF STATIONARY ENGINE FLUE GAS

ABSTRACT

Acid gas removal experiments are carried out in a large bench scale corona radical shower reactor-catalyst hybrid system. A simulated stationary engine flue gas is air mixed with NO, SO_2 and CH_4. Optimizations for acid gas removal rates have been conducted in terms of the ammonia or methane to acid gas molar ratio, the applied voltage and the additional gas velocity. Both the removal efficiencies of NO and SO_2 increase with increasing applied voltage and decreasing initial NO concentration. It is also shown that high concentrations of CH_4 in flue gas have a negative effect on NO removal, where part of the NO is converted only to NO_2 but not to ammonium nitrate aerosol particles. The effect of catalytic reactions is larger with NH_3 injections but not significant for CH_4 injections for NO_x removal. However, SO_2 removal significantly enhanced by catalysts.

2.1 INTRODUCTION

NO_x and SO_x are air pollutants of concern and the major cause of acid rain. Many NO_x and SO_x conversion techniques such as wet scrubber, selective catalytic reactor, sorbent injection, low NO_x burner, etc., have been used. More recently, non-thermal plasma techniques have been used in commercial plants, however, the energy efficiency of the non-thermal plasma reactors have not yet been optimized. For example, the electron beam, barrier discharge and pulsed corona reactors, i.e.

direct plasma treatments of flue gases, may lose input energy to activate unwanted components of flue gases such as CO_2, N_2, etc. Hence, the corona discharge radical injection techniques have been developed. On the other hand, the treatment of an engine combustion flue gas by non-thermal plasmas have been investigated by many researchers [1-5]. In this work, an experimental investigation has been conducted to remove NO_x and SO_2 from stationary engine flue gases.

2.2 EXPERIMENTAL APPARATUS

The schematics of the experimental test loop and corona radical shower electrode are shown in Fig. 2.1. In stationary engine flue gas treatments, the combustion flue gas was normally diluted by air for cooling down to room temperature. In the present simulated flue gas test, the concentration ratio between NO and SO_2 or CH_4 are fixed at 0.128 or 1.667, respectively, and then NO initial concentration was varied from 30 to 100 ppm. NO, NO_2 and SO_2 concentrations were measured by a Green Line gas analyzer and the trace by-products are determined by Fourier Transform Infra-Red spectroscopy (FTIR). The aerosol particles generated by the acid gases and ammonia/methane related plasma processes were collected by the electrostatic precipitator operated at -19 kV dc downstream of the reactor. The size of the reactor is (10×30×100 cm) and three radical injectors are placed in series as shown in Fig. 2.1. The corona radical shower electrode used was a 6 mm o.d. tube equipped with 28 hollow electrodes (1.2 mm i.d./1.5 mm o.d.) as shown in Fig. 2.1b. Additional gas consisting of an air-NH_3 mixture was injected from these hollow electrodes to the reactor via the corona discharge generated by a positive dc high voltage at the edge of the hollow electrodes. Catalyst is placed 20 cm downstream of corona shower reactor and electrically heated by heating tapes.

2.3 EXPERIMENTAL RESULTS WITHOUT CATALYSTS

NO, NO_x and SO_2 removal rates as a function of applied voltage, ammonia-to-acid gas molecule ratio MR, additional gas superficial velocity and NO initial concentration are shown in Figs. 2.2, 2.3, 2.4 and 2.5, respectively, where the bar for each experimental point shows the minimum and maximum values observed during the transient tests. NO, NO_x and SO_2 removal rates increase with increasing applied voltage and decreasing NO initial concentration in flue gases as shown in Figs. 2.2 and 2.5, respectively, as expected from radical chemistry and heterogeneous reactions [5]. However, the acid gas removal rate has an optimum value in terms of MR and corona radical shower system additional gas velocity as shown in Figs. 2.3 and 2.4, respectively, where the NO and NO_x removal rate is maximum near molecule ratio between 1 to 1.5 and additional gas velocity near 8 m/s. Based on an analysis of Ohkubo et al [6], the effect of additional gas velocity can be explained by the better mixing of ammonia radicals to react with acid gases in lower velocity regions, where the mixing effect increases with increasing additional gas flow rates. For higher additional gas velocities, the ammonia radicals ejected from the hollow electrode may have shorter residence times in the reactor and only generate narrow flow channels to reduce reactions. Hence, the optimum additional gas flow velocity exists for the flue gas flow rate 6 Nm^3/h or reactor superficial velocity of 0.056 m/s.

Based on corona discharge gas phase and heterogeneous reactions with ammonia [5], the SO_2 removal rate increases with increasing MR as shown in Fig. 2.3. However, if we examined discharge by-products, ammonia and methane relative concentrations ($\propto$ absorbance of IR) as shown in Fig. 2.6, CH_4 and N_2O concentrations are minimized at molecule ratio near 1 to 1.5 where NH_3, H_2O and ϕ-CHO were determined by the IR absorptions at the wave length 964, 3017, 1304, 1551 and 1709 cm^{-1} in Fig. 2.6. For the molecule ratio below 1, NO and NO_x are removed by a reduction

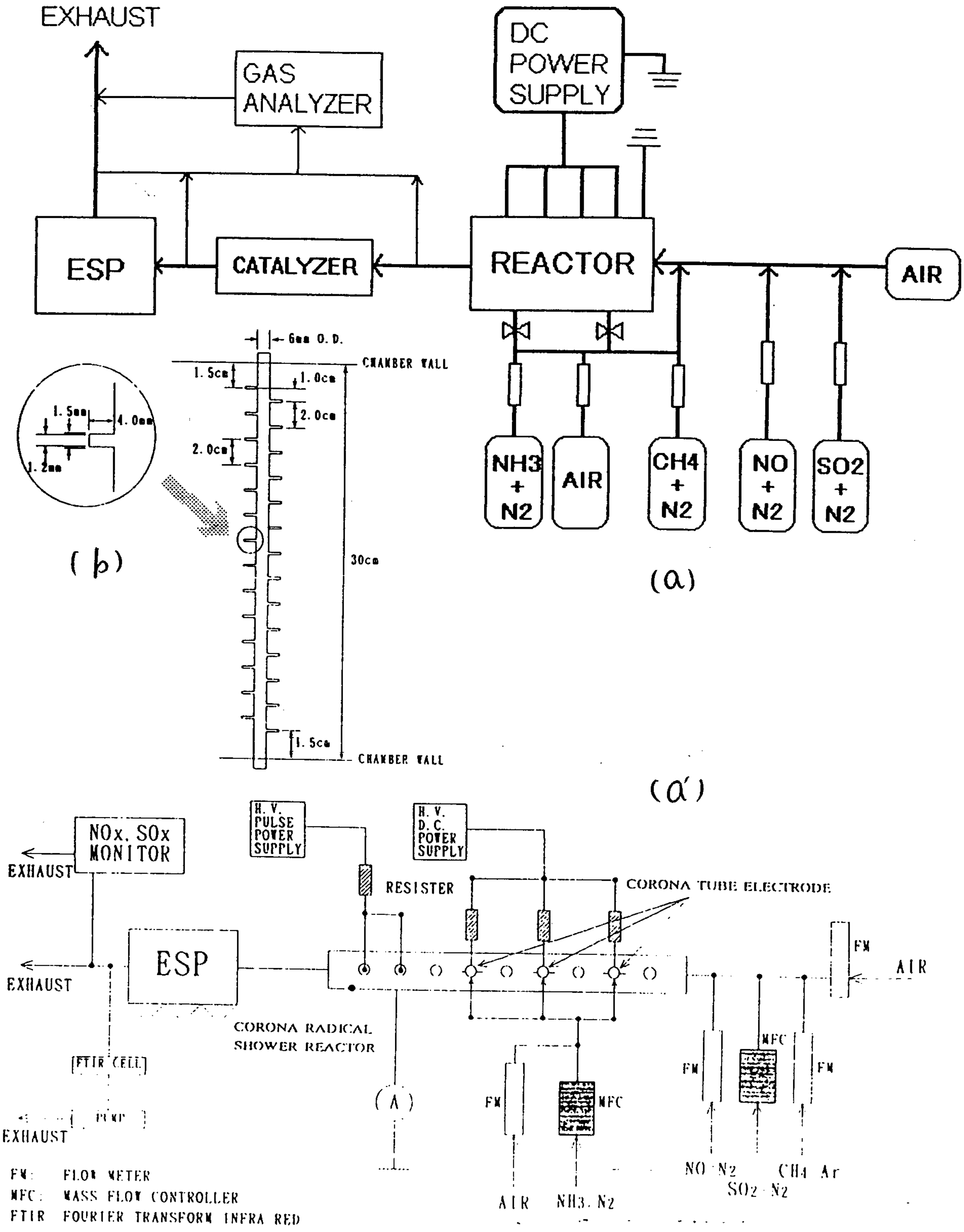
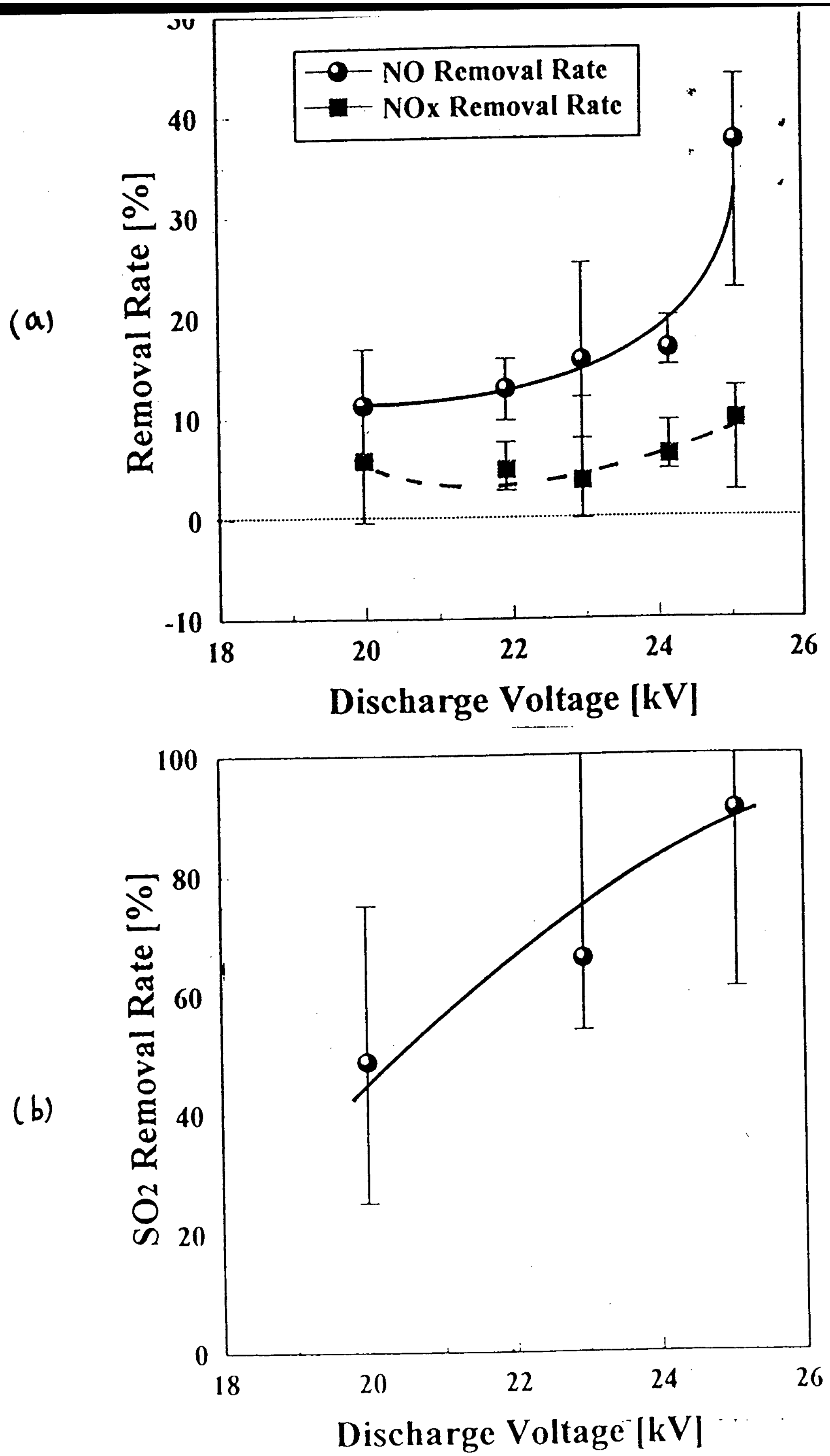
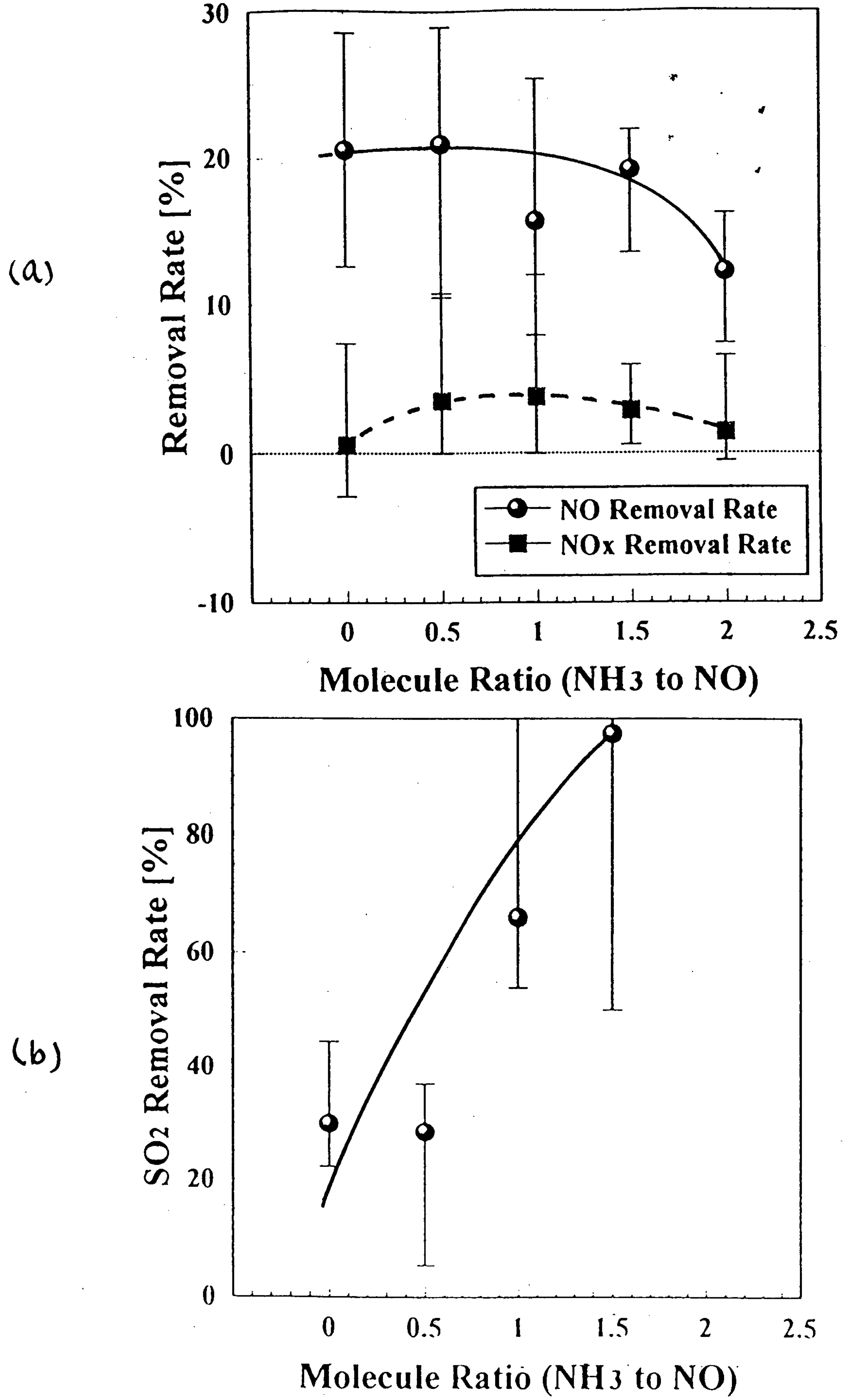


Fig. 2.1 Schematics of experimental flow loop (a) and corona radical shower electrode (b).



(Qmain=100L/min, vadd=5m/sec, M.R.=1, Initial NO=100ppm)

Fig. 2.2 Acid gas removal rate as a function of corona shower system applied voltage V, where bar in the each experimental points indicated minimum and maximum values. a) NO and NO_x and b) SO_2.



(Qmain=100L/min, vadd=5m/sec, V=23kV, Initial NO=100ppm)

Fig. 2.3 Acid gas removal rate as a function of ammonia to acid gas molecule ratio MR. a) NO and NO_x and b) SO_2.

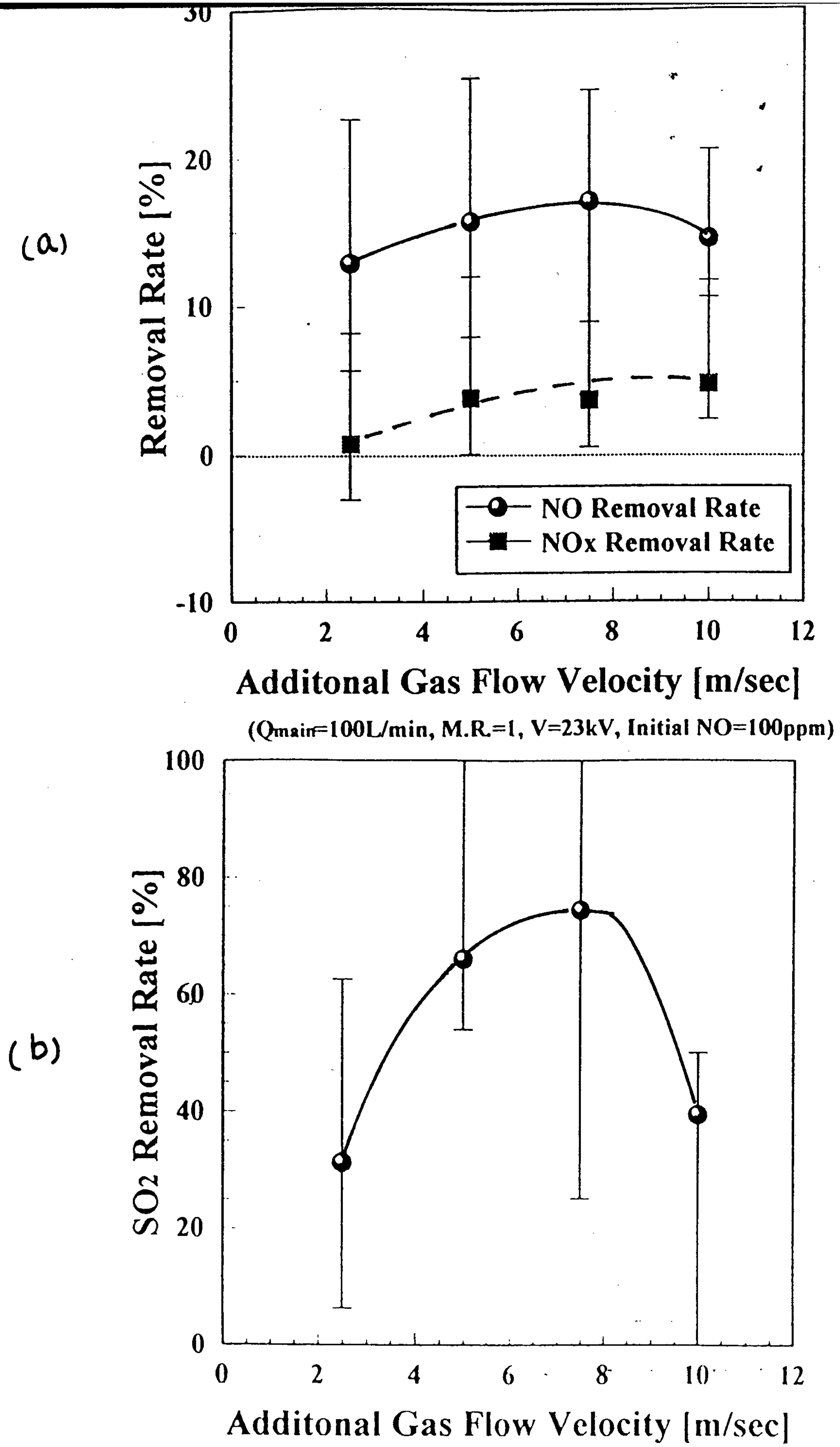
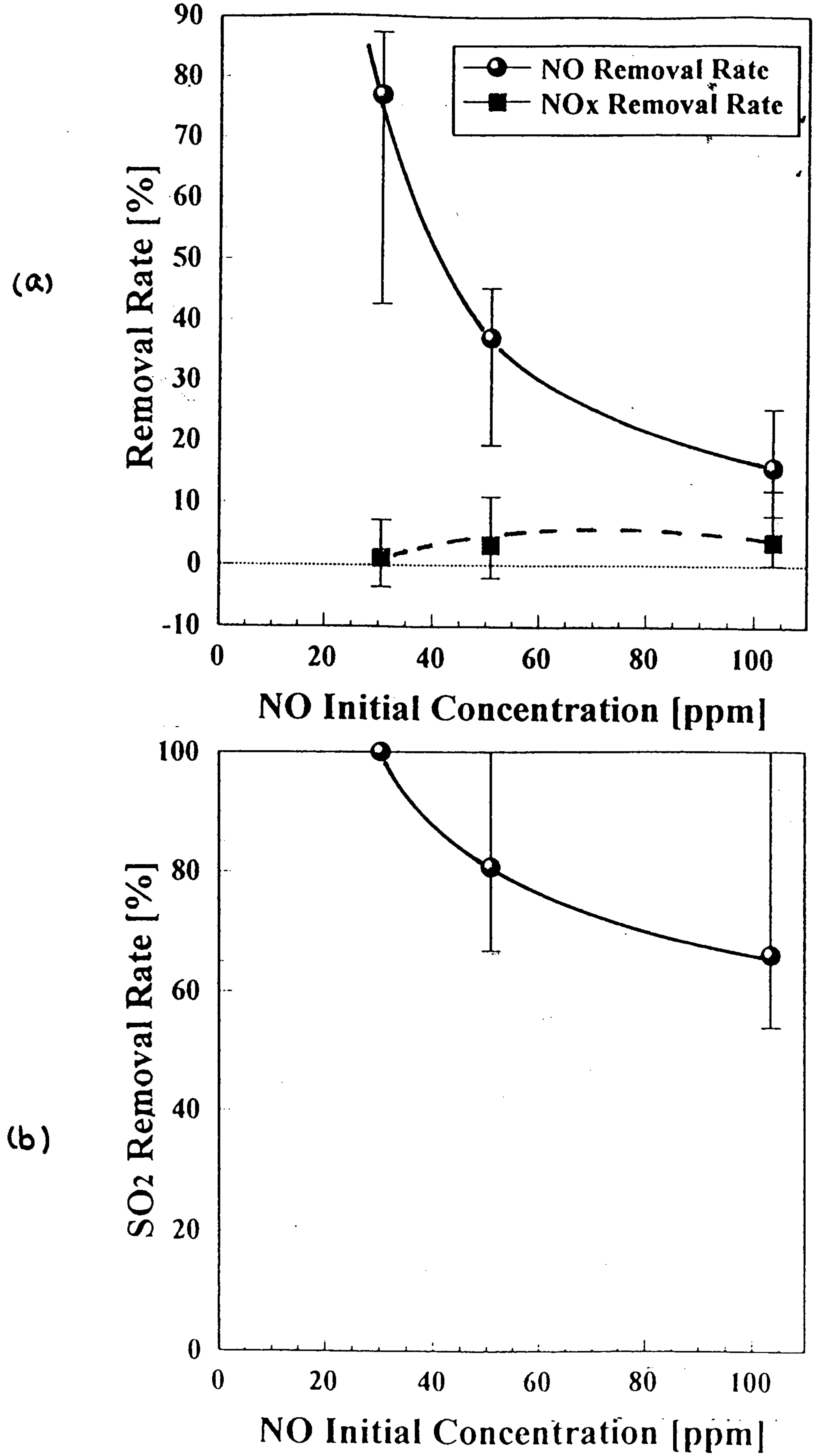


Fig. 2.4 Acid gas removal rate as a function of corona shower system hollow electrode additional gas flow velocity V_{add}. a) NO and NO_x and b) SO_2.



(Qmain=100L/min, vadd=5m/sec, M.R.=1, V=23kV)

Fig. 2.5 Acid gas removal rate as a function of NO initial concentration in flue gases $[NO]_0$. a) NO and NO_x and b) SO_2.

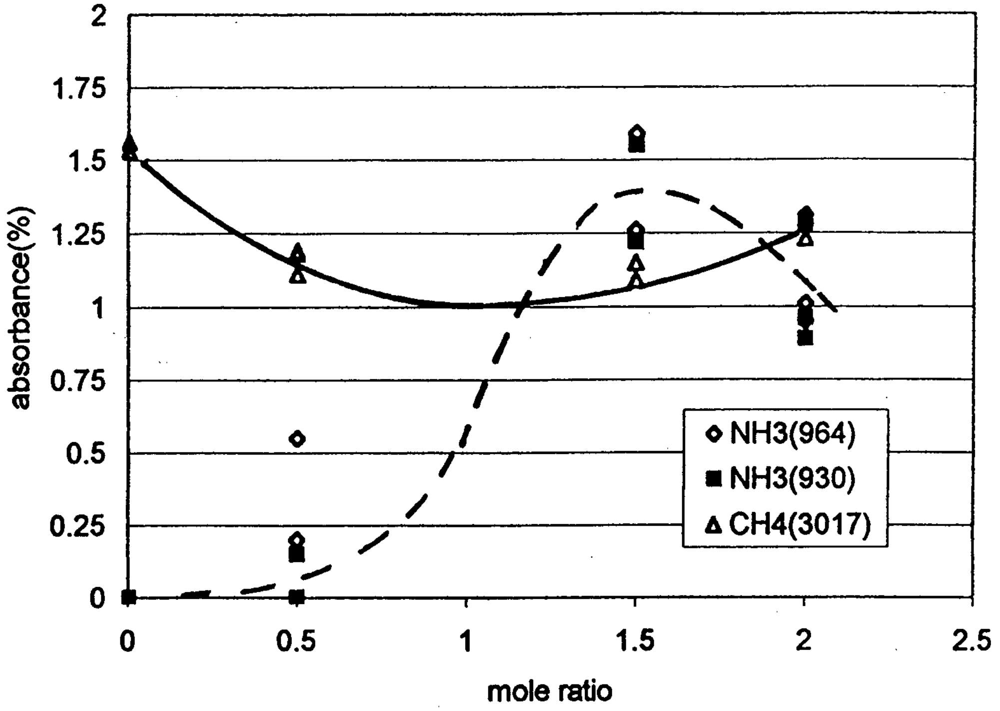


Fig. NH3 absorbance as a function of additional NH3
100ppm 100L/min 5m/sec 23kV

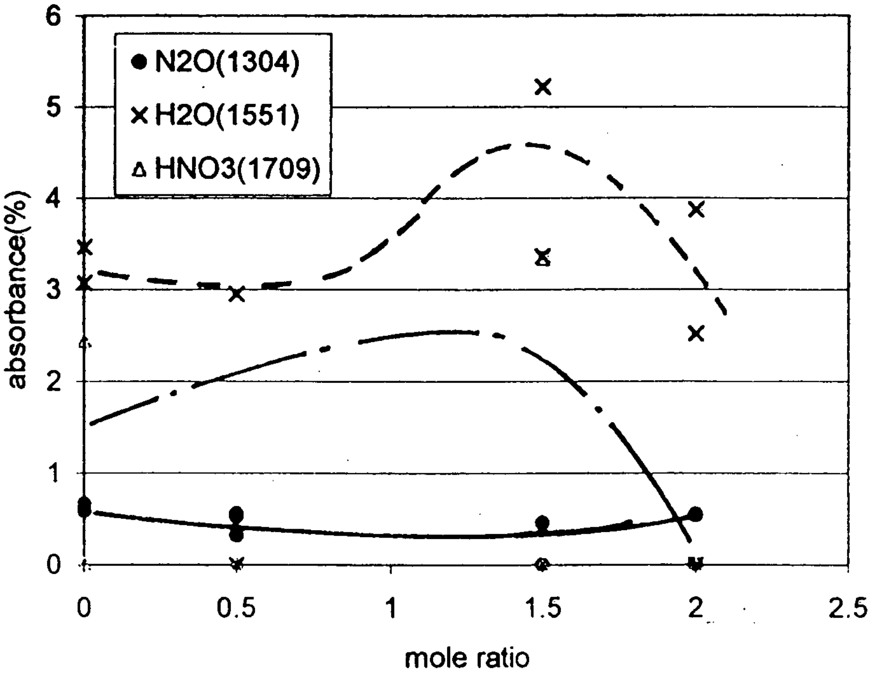


Fig. By-products as a function of additional NH3

Fig. 2.6 Relative concentration (∝ IR absorbance) of a) NH_3 and CH_4 and b) N_2O, H_2O and ϕ-CHO (aldehyde) as a function of ammonia to acid gas molecule ratio at flue gas flow rate $Q_f = 6\ Nm^3/h$ (100 L/min), V =23 kV, $[NO]_0$ = 100 ppm and V_{add} = 5 m/s.

reaction of methane and ammonia radicals, hence, the removal rates of NO, NO_x, N_2O and CH_4 increase with increasing molecule ratio. However, for the molecule ratio larger than 1, ammonia and their radicals may be mainly consumed for SO_2 removal and ϕ-CHO formations hence NO, NO_x, N_2O and CH_4 removals may be reduced.

By comparison with combustion generated flue gas (without large methane concentration), the removal rate of NO_x is much lower, as has been observed for other engine-generated flue gas plasma treatments [1-4] in spite of effective NO oxidations. The role played by the hydrocarbon under non-thermal plasma treatment should be investigated in detail.

2.4 EXPERIMENTAL RESULTS WITH HYBRID SYSTEM

Acid gas (NO_x, NO and SO_2) removal efficiency as a function of corona shower system applied voltage for NH_3 or CH_4, and gas temperature at catalyst exist $T_g = 293$ or 234 K are shown in Figs. 2.7 to 2.10. Figure 2.7 shows that acid gas removal efficiencies increase with increasing applied voltage and up to 100% of SO_2 and 62% of NO_x can be removed by the current hybrid system with NH_3 injections. By compared with Figs. 2.2 and 2.7a, the catalyst even operated at room temperature can significantly enhance SO_2 and NO_x removal due to the NH_3 radical generated by the corona shower reactor as has been observed by various investigator using pulsed corona or barrier discharge non-thermal plasma reactor [4,7,8,9]. For the NO_x removal, the role of catalyst is mainly NO_2 catalytic reductions (see Figs. 2.7a and 2.7b) and adsorption/catalytic reactions for SO_2 . By comparison between Figs. 2.7 and 2.8, the effect of heating catalyst (monitored by catalyst exist gas temperatures) shows slightly negative effects on NO_x removal but no effects on SO_2 removals.

Figures 2.9 and 2.10 show the effects of heating catalyst on the CH_4 injection cases. The results show that the acid gas removal efficiency increases with increasing applied voltage but no

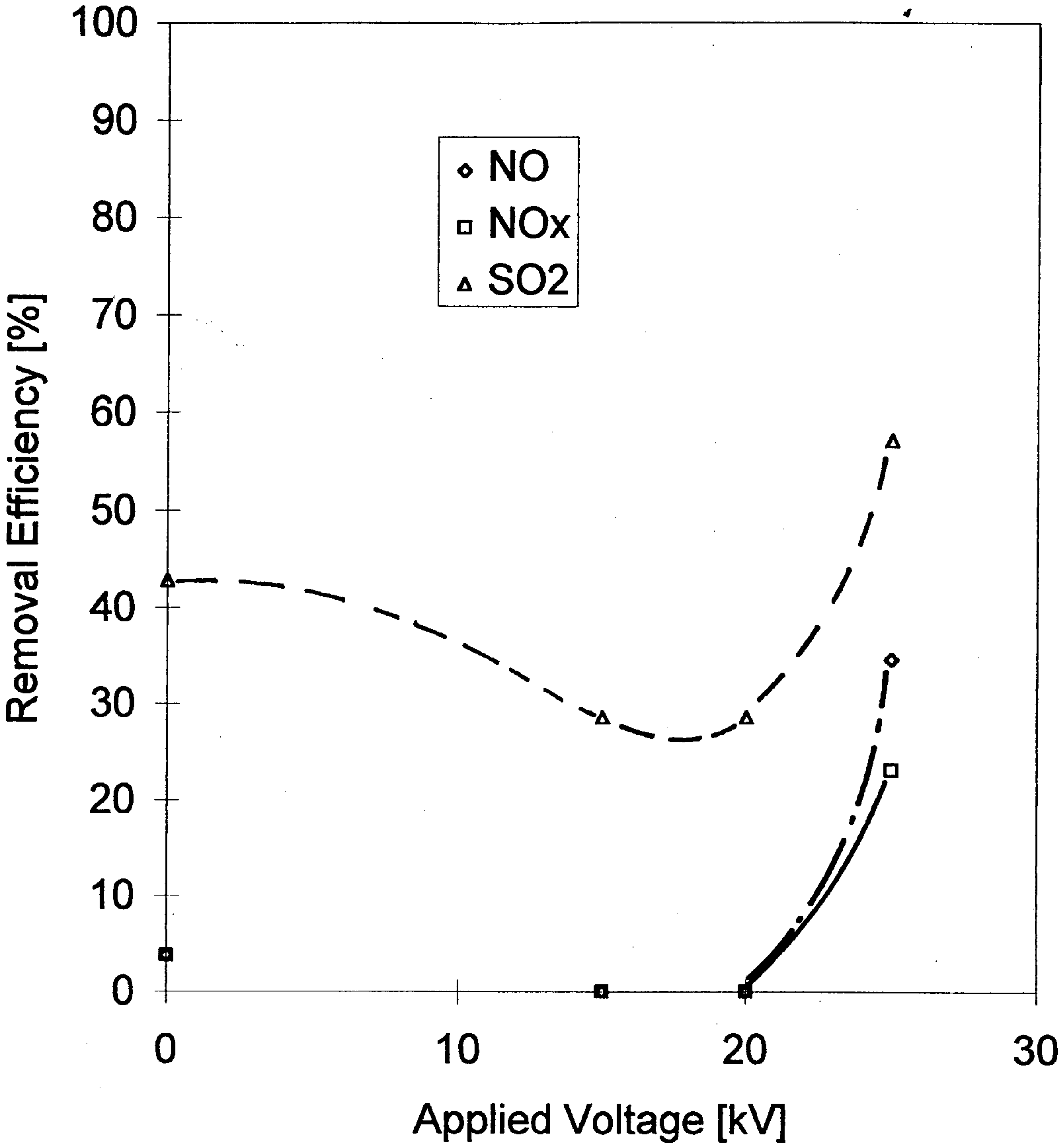


Fig.a Removal efficiency as a function of applied voltage without heating and NH3 injection (before Catalysis)

Fig. 2.7 Acid gas removal efficiency as a function of applied voltage for NH_3 injections in hybrid systems at $T_g = 293K$. a) After corona shower reactor; b) after catalyst; and c) after ESP.

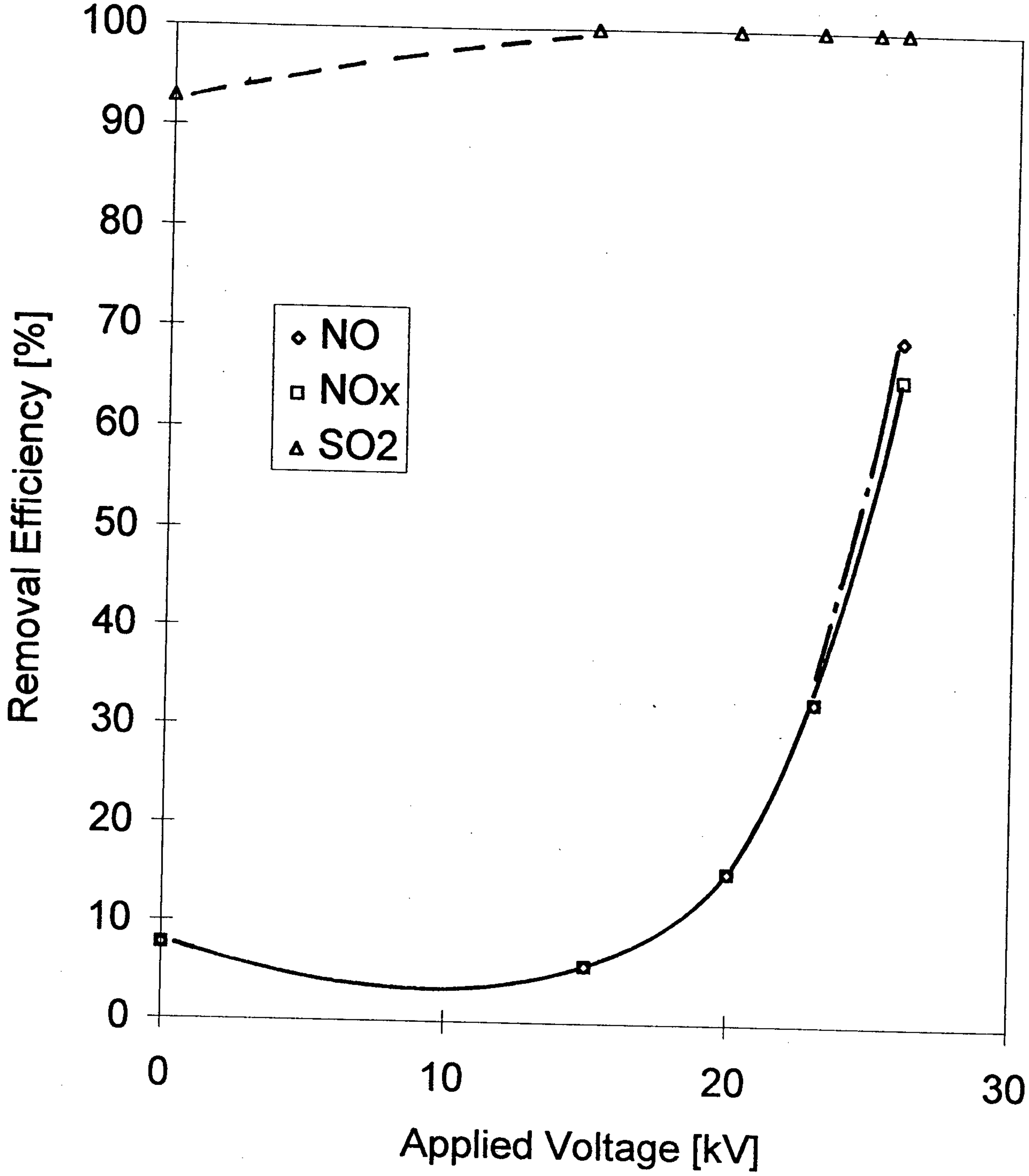


Fig.b Removal efficiency as a function of applied
2.7 voltage without heating
and NH3 injection (after Catalysis)

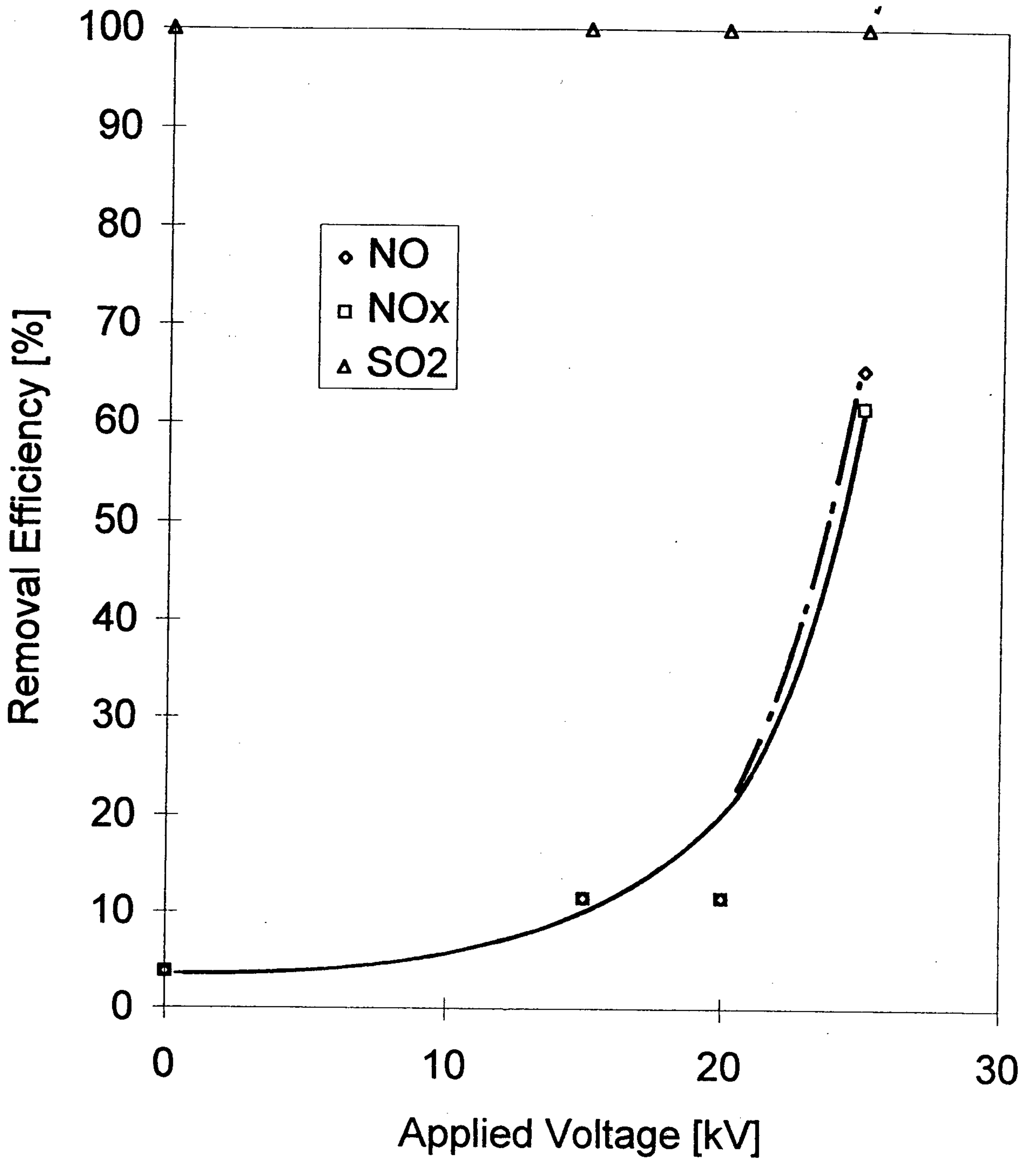


Fig. C Removal efficiency as a function of applied voltage without heating and NH3 injection (after ESP)

2.7

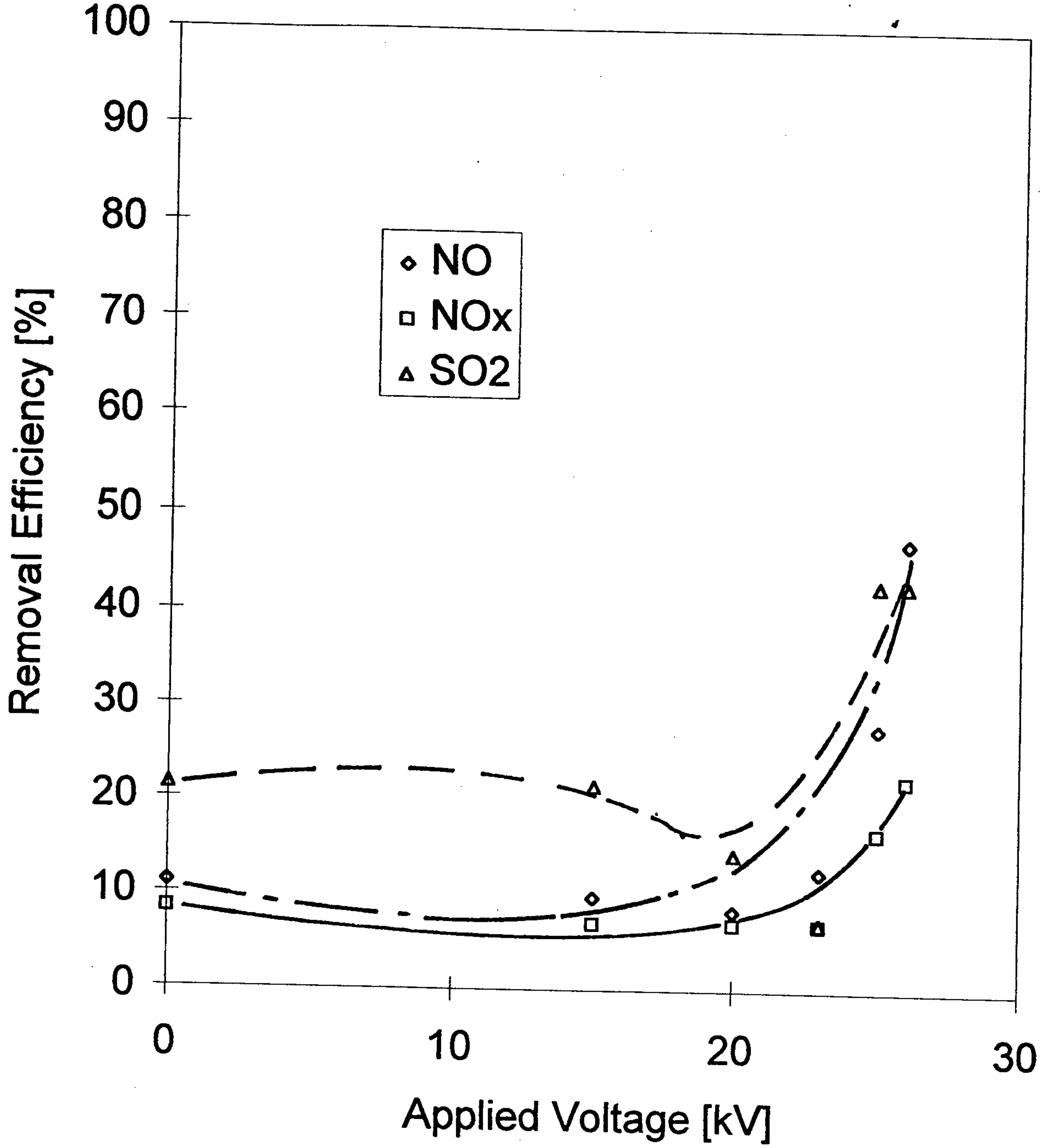


Fig.28a Removal efficiency as a function of applied voltage with two heating tape and NH3 injection (before Catalysis)

Fig. 2.8 Acid gas removal efficiency as a function of applied voltage for NH_3 injections in hybrid systems at $T_g = 324K$. a) After corona shower reactor; b) after catalyst; and c) after ESP.

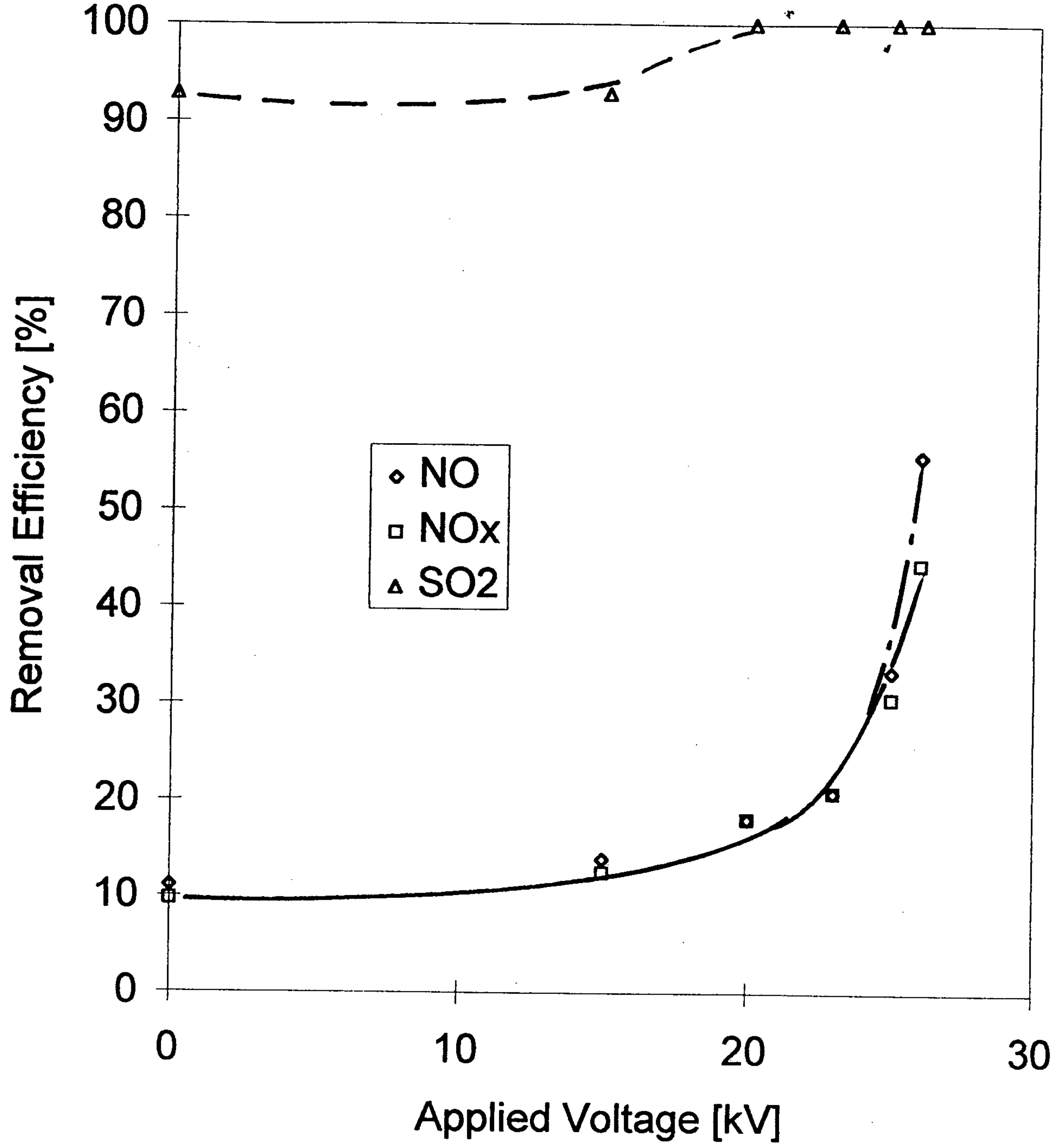


Fig.28b Removal efficiency as a function of applied voltage with two heating tape and NH3 injection (after Catalysis)

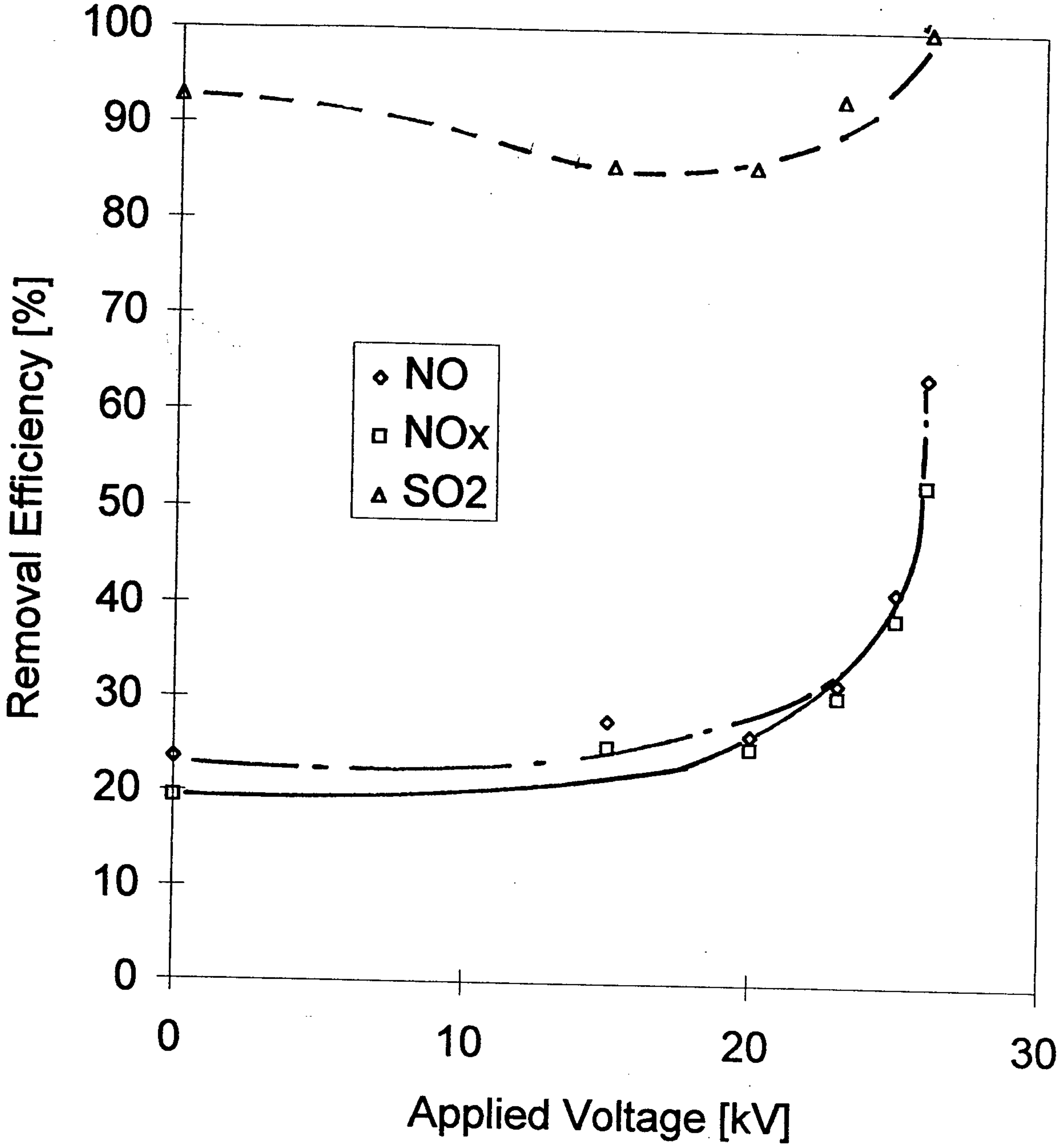


Fig.2ec Removal efficiency as a function of applied voltage with two heating tape and NH3 injection (after ESP) significant catalyst and heating effects on the NO_x removals. However, SO_2 removal efficiency is significantly enhanced by the adsorption effect of catalyst, where SO_2 removal efficiency decreases with increasing catalyst heating due to the decreasing adsorption capability of ceramic catalyst under higher temperature. Maximum SO_2 removal efficiency is same for NH_3 or CH_4 injections but NO_x removal with NH_3 injections is much higher compared with CH_4 injections. 50–50% mixture of NH_3 and CH_4 is also used as an injection gas to the corona shower system, however, the results are only slightly better compared with CH_4 injection cases.

2.5 CONCLUDING REMARKS

An experimental investigation has been conducted to remove acid gases from stationary engine flue gas and the following concluding remarks are obtained: 1) NO, NO_x and SO_2 removal rates increase with increasing applied voltage and decrease with increasing NO initial concentration in the flue gases; (2) NO, NO_x and SO_2 removal rates non-monotonically depend on corona shower system additional gas flow velocity due to the mixing effects where the maximum removal rates are observed near 8 m/s; (3) SO_2 removal rates increase with increasing ammonia to acid gas molecule ratio while NO and NO_x non-monotonically depend on molecule ratio; (4) Ammonia and methane slips non-monotonically depend on ammonia to acid gas molecule ratio; (5) Trace unwanted discharge by-products significantly depend on ammonia to acid gas molecule ratio and only N_2O and ϕ-CHO (aldehydes) are observed; (6) Significant amounts of aerosol particles are formed during the acid gas removal processes; (7) The effects of catalytic reactions even in room temperature is significant with NH_3 injections but not significant for CH_4 injections for NO_x removals; and (8) SO_2 removal efficiency is significantly enhanced by adsorption/catalytic reactions of catalyst.

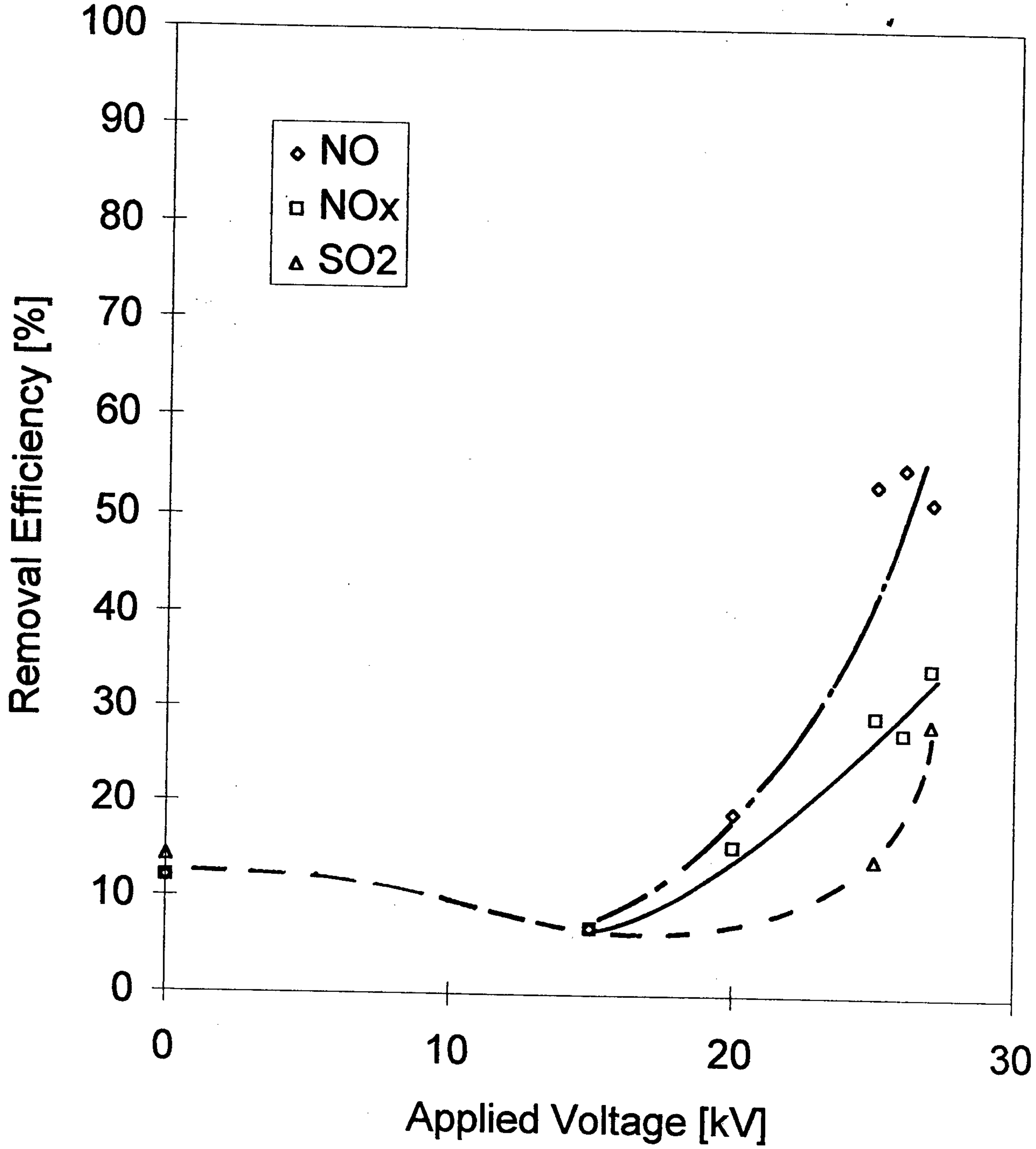


Fig.4 Removal efficiency as a function of applied voltage without heating and CH4 injection (before Catalysis)

Fig. 2.9 Acid gas removal efficiency as a function of applied voltage for CH_4 injections in hybrid systems at $T_g = 293K$. a) After corona shower reactor; b) after catalyst; and c) after ESP.

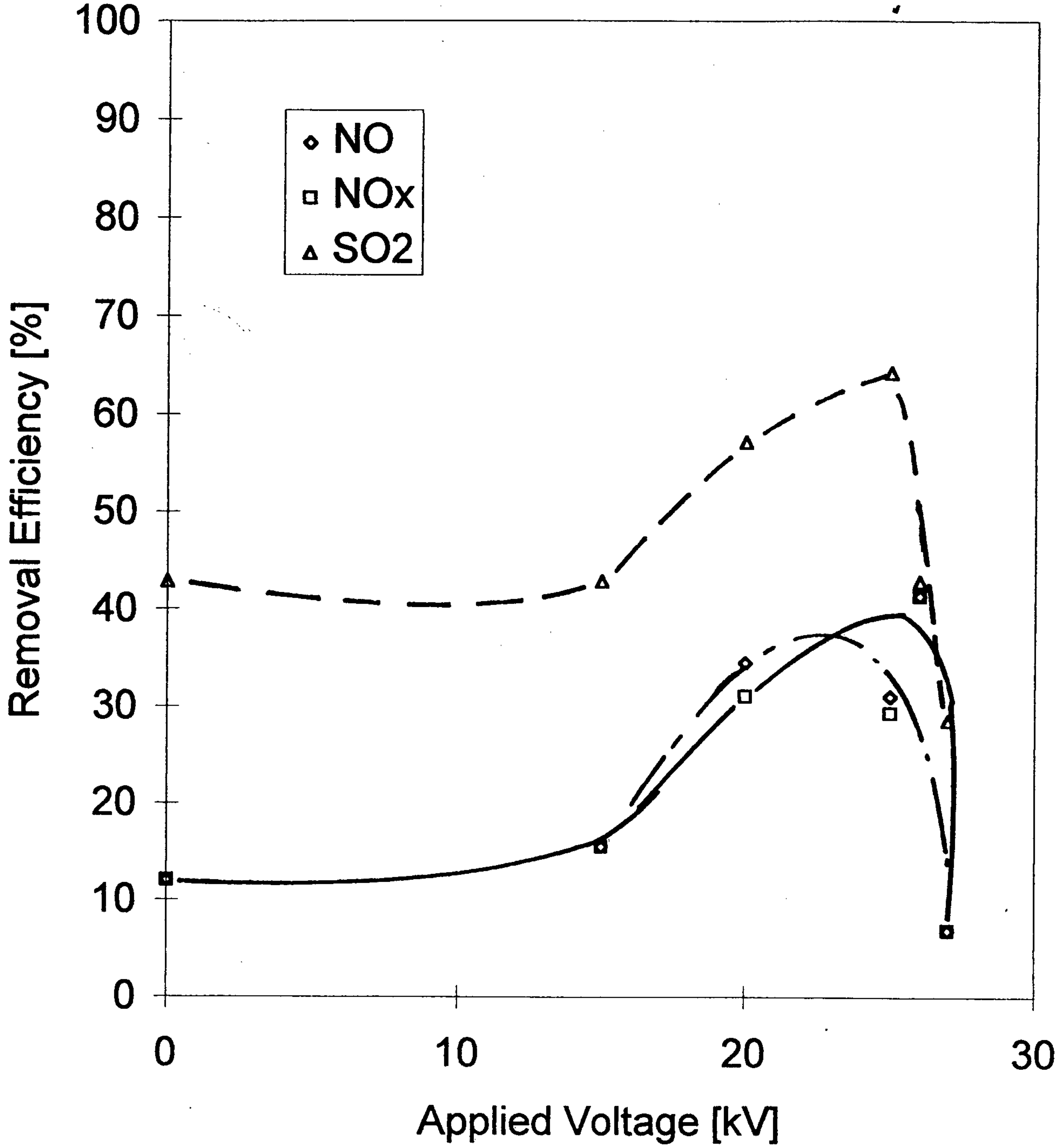


Fig.b Removal efficiency as a function of applied
2.9 voltage without heating
and CH4 injection (after Catalysis)

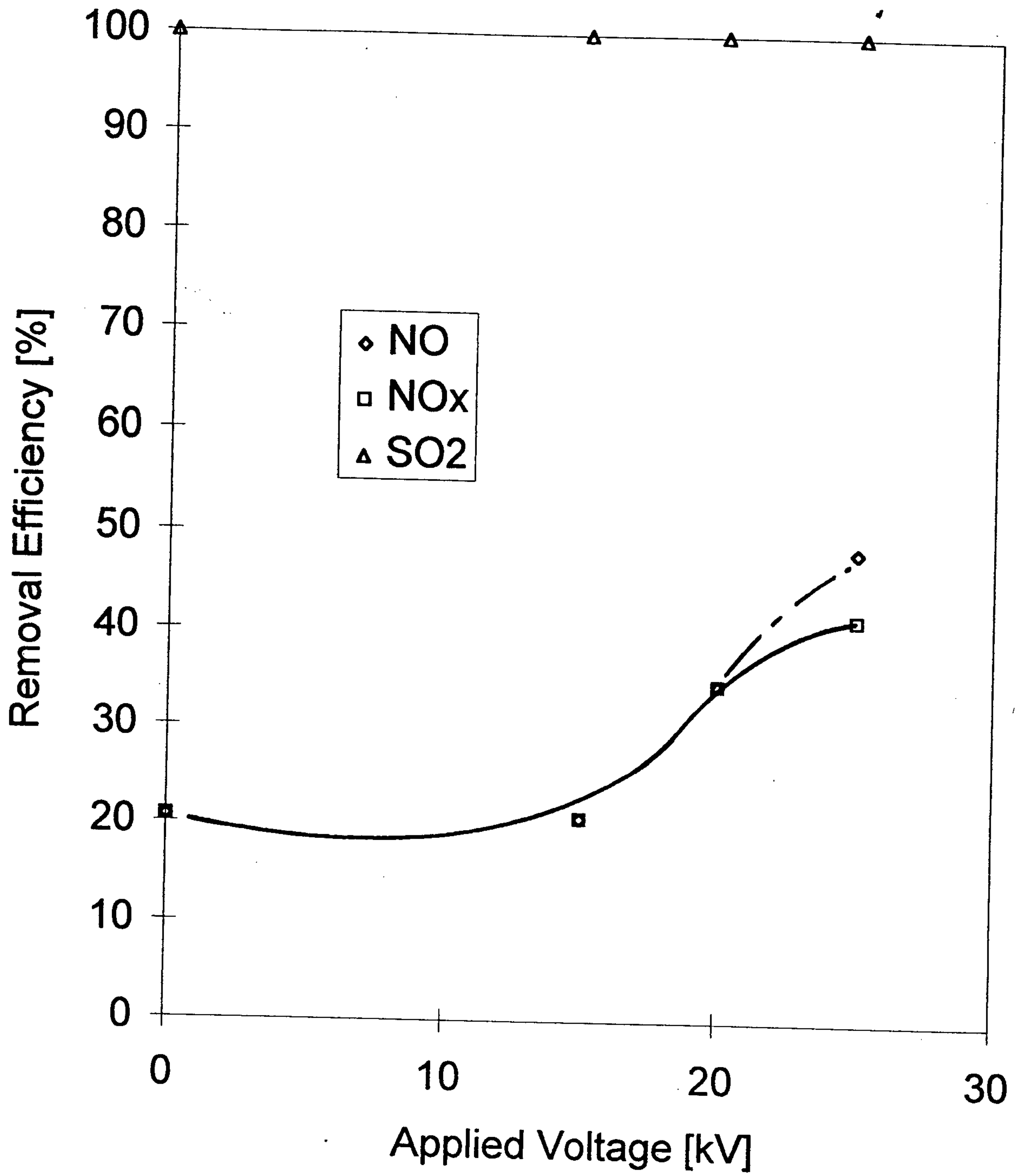


Fig.C 2.9 Removal efficiency as a function of applied voltage without heating and CH4 injection (after ESP)

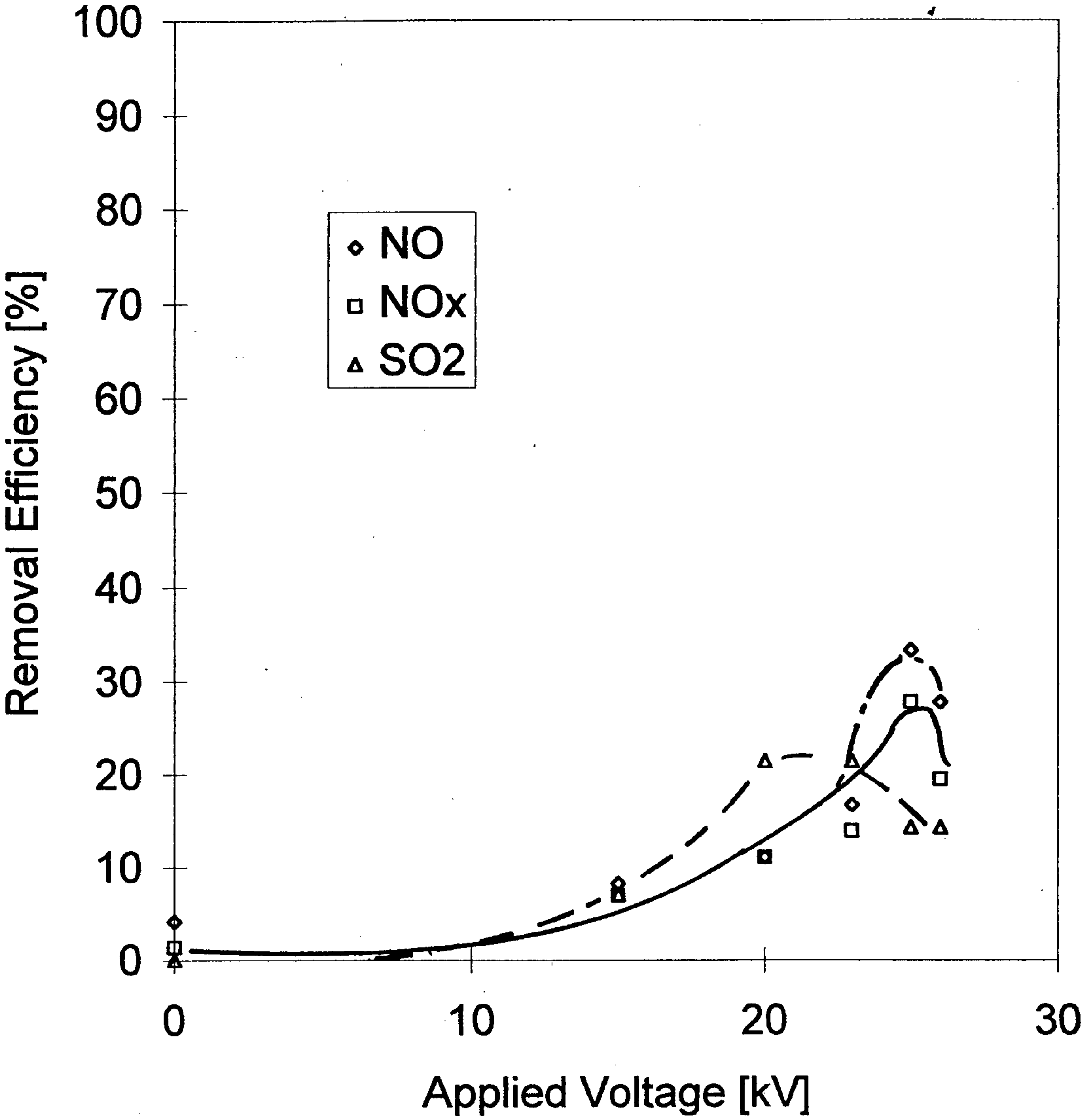


Fig2.10a Removal efficiency as a function of applied voltage with two heating tape and CH4 injection (before Catalysis)

Fig. 2.10 Acid gas removal efficiency as a function of applied voltage for CH_4 injections in hybrid systems at $T_g = 324K$. a) After corona shower reactor; b) after catalyst; and c) after ESP.

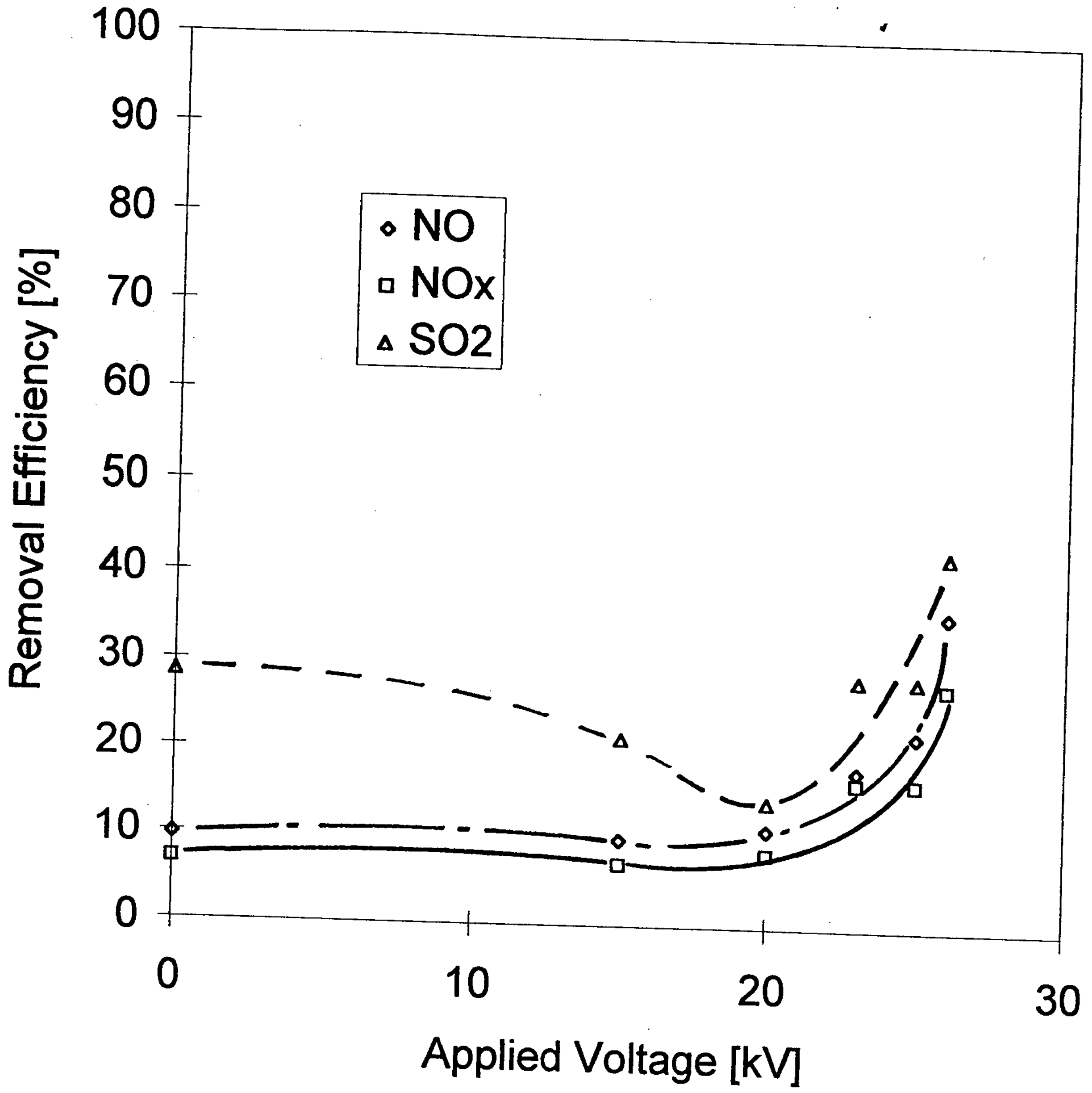


Fig.20 b Removal efficiency as a function of applied voltage with two heating tape and CH4 injection (after Catalysis)

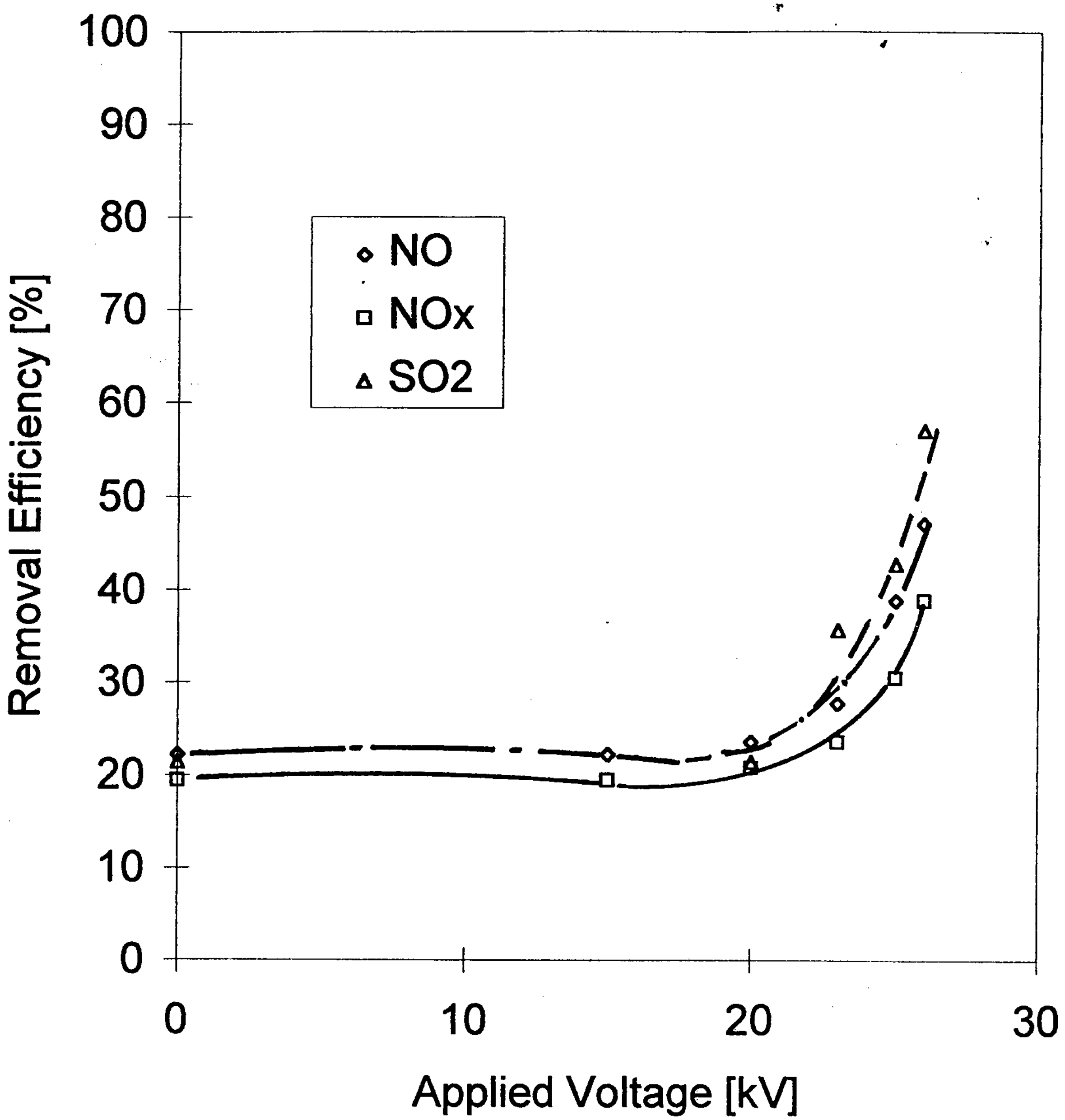


Fig.2.10c Removal efficiency as a function of applied voltage with two heating tape and CH4 injection (after ESP)

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PART 3.

PRELIMINARY CONCEPTUAL DESIGN OF PILOT PLANT TEST FOR PLASMA JET ENGINE TEST CELL FLUE GAS TREATMENTS

ABSTRACT

Preliminary conceptual design has been conducted for the pilot plant test cell flue gas cleaning in DOE facilities. Pilot plant will be directed 340 Nm^3/h of flue gases from the main jet engine test cell exhaust duct by 20 cm i.d. flow tubes. Fourteen flow channel corona shower reactor (140×60×120 cm) and 30 flow channel–5 section electrostatic precipitator are required for the acid gas treatments.

3.1 INTRODUCTION

In order to treat the jet engine (JETC) and the cruise missile test cells (CMTC), 10^4–10^6 scfm (or 2×10^4 to 2×10^6 Nm^3/h), flue gas flow rate must be treated. Hence, 10^2 to 10^3 scfm level pilot plant must be constructed. In this section, a preliminary conceptual design has been conducted for the pilot plant for the JETC/CMTC flue gas treatments.

3.2 PROPOSED DESIGN AND SPECIFICATIONS

Based on the large bench scale tests (LBS) conducted at 12 Nm^3/h, the simple scale-up pilot test selected in 340 Nm^3/h flue gas flow rate. Under this condition, the length of LBS corona shower system can be used with slightly larger height and length with multi-flow channel. Schematics of proposed pilot test facility is shown in Fig. 3.1. The part of JETC flue gas will be diverted to the pilot plant through the 20 cm i.d. flow tube with electromagnetic gate valves (EMGV). In order to obtain near fully developed flow, the corona shower reactor (CSR) will be installed 4 m downstream of the EMGV and electrostatic precipitator (ESP) will be installed again 4 m downstream of CSR. Independent NO_x, SO_x and VOC meters will be installed 1 m downstream of CSR and 1 m downstream of ESP.

A detail of corona shower reactor is shown in Fig. 3.2. Corona shower reactor dimension is (140×60×120 cm) with 14 flow channels. Five 60 cm long corona shower electrodes/channel will be installed. Corona shower system will be driven by 6 kW dc power supply (40 kV×150 mA) or by seven 1 kW power supplies (40 kV×25 mA). Air-NH_3 mixture gas will be fed through the corona shower electrodes via flow controllers (FC).

A detail of the wire-plate type electrostatic precipitator is shown in Fig. 3.3. The dimension of the five section ESP is (150×60×80 cm) and 30 flow channels. ESP is driven by the 6 kW dc power supply.

3.3 RECOMMENDATION

In order to conduct pilot plant tests, the site visit must be conducted before the conceptual design stage. The conceptual design for the plant will take one month, and the following detailed design will require two months. Construction of corona shower reactor and electrostatic precipitator will take two to three months. Integration of the system into the pilot plant site will take one to two months. In total, 8 to 10 months are required to construct this pilot plant. If we plan to conduct this pilot plant test, 12 to 18 months are required for the project.

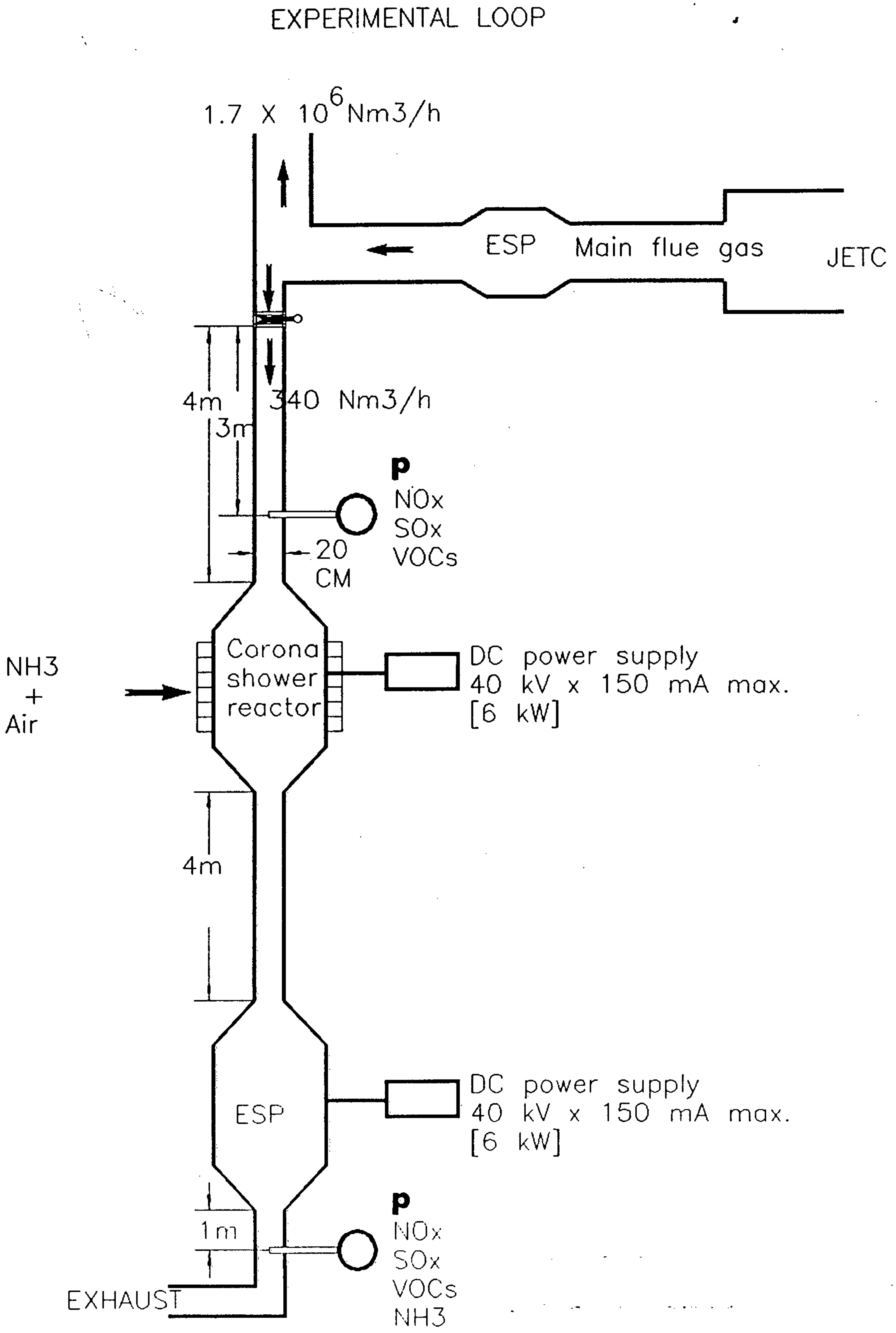
EXPERIMENTAL LOOP

Fig. 3.1 Schematics of pilot plant test loop.

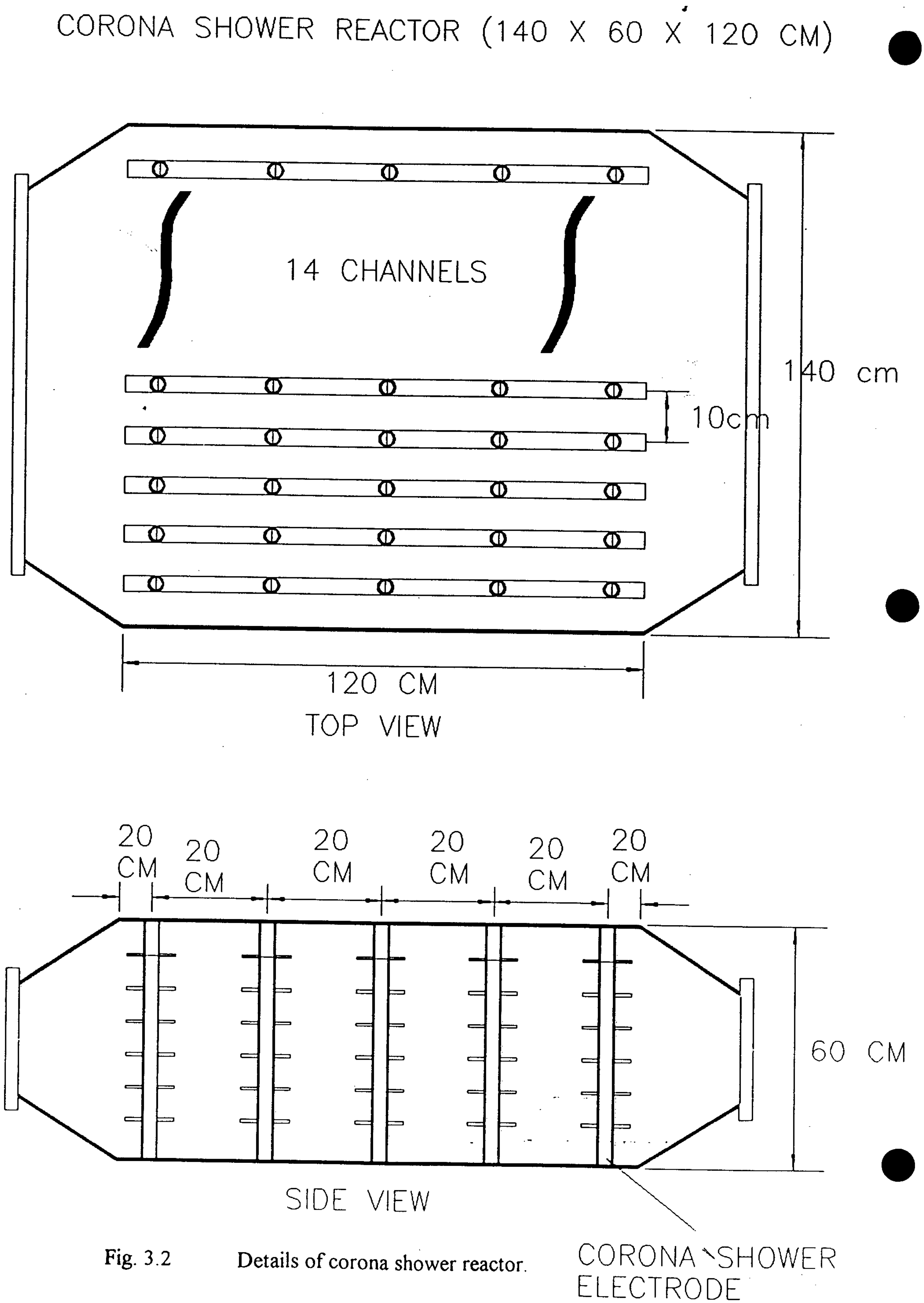

Fig. 3.2 Details of corona shower reactor.

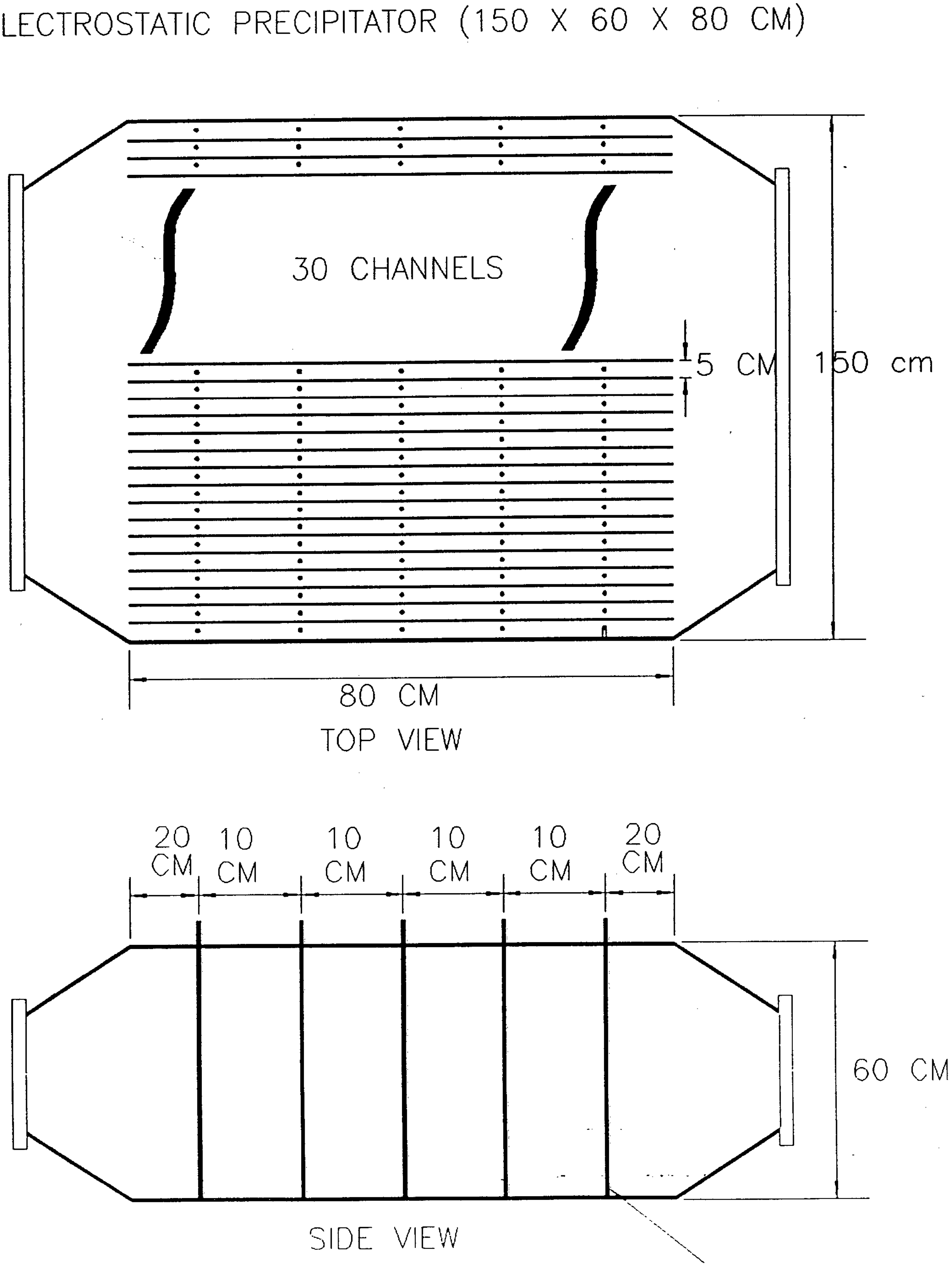

Fig. 3.3 Details of electrostatic precipitator.

APPENDIX

REVIEW OF CATALYSTS/ADSORBENTS FOR GASEOUS POLLUTION CONTROL IN JETC

ABSTRACT

Review of existing catalysts and adsorbents for gaseous pollution control has been conducted. Several ceramic base and three-way metal base catalysts were tested and used in diesel flue gas emission control, however, only $Sr_xLaIxCoO_3$ catalysts were small-scale tested in JETCs at U.S. Air Force Armstrong Laboratory. Based on bench-scale tests, most of the catalysts require operations above 300°C, hence gas reheaters are required for the JETC/CMTC applications. No detailed sulphur poison problems and particulate matter effects were discussed in references.

A.1 INTRODUCTION

Catalysts are widely used in the treatment of NO_x in automobile exhaust and coal/oil/natural gas-fired power plant flue gases. The operation of catalysts required normally operated at higher gas temperatures (>300°C) or moderate gas temperature with additives such as ammonia (>250°C). More recently, a major effort for R&D in gaseous pollution control is lowering the catalyst operation temperature and the application to diesel engine flue gases. In this section, the review of existing catalysts has been conducted and applications to JETC examined.

A.2 LIST OF CATALYSTS

A list of catalysts recently developed for the control of gaseous pollutant is shown in Table A, where the absorbent for the gaseous pollution control also listed in this table. Ceramic base and three-way metal base catalysts were mainly used and applications to diesel engine flue gases were tried. However, most of the catalysts studied are still operating in higher gas temperatures (>250°C) and no detailed sulphur poison problems are conducted. An application to JETCs only conducted by U.S. Air Force Armstrong Laboratory in small scale using metal perovskite catalysts ($Sr_xLaIxCoO_3$) for NO_x in N_2. However, no effects of VOCs, SO_2 and particulate matter in flue gas were well investigated.

A.3 CONCLUDING REMARKS

Since JETC/CMTC flue gas contains SO_2 and VOCs, an application of existing catalysts must be carefully studied. Hence, three different options are proposed as follows:

1. Using wet scrubber-reheater-catalysts system;
2. Using electrostatic precipitator-reheater-catalysts system;
3. Using plasma reactor-catalyst system.

Based on the economic evaluations in Section 1, Options 1 and 2 are much more expensive compared with the plasma system. Hence, the third option without gas reheater should be tested.

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Table A List of Catalysts for Pollution Control

Company	Sourses	Materials	Gases	Flow rate	De-%	Date	Commer.	Ref.	Comment
ACCEL Catalysts, Inc., USA	automobile	metal-Pt-Rh	NOx, HC, CO	?	-	94	N/A	5	Metal-Supported Metal(MSM), $50,000 contract
Air Force, Armstrong Lab., USA	JETCs	SrxLal-xCoO3	NO, NO2, N2	?	90, -, -	94	N/A	4	
Allis Mineral Systems, USA & ISGS Appli. Reser. Lab.	waste incinerator	activated carbon	SOx, NOx	?	90, 80	July'95	N/A	16	Hg, dioxins, furans
AVL-LIST, USA	diesel (fuel)	Zeolite	NOx	?	17-30	Jul.96	engine fuel system	12	modified fuel system fuel economy not given
Caralytica Combustion systems, USA	gas turbine engine	SCRs	NOx	?	80	98	yes	3	XONON®
Catalytica Combustion system Inc. & Allison Engine Co., USA	power generation, 4.5-11MW		NOx, CO, HC	?	5ppm	Apr.96	N/A	2	$3.5mill. contract, $82.5 mill.for 5-7 years
Cosmo Research Institute, Japan	diesel	Al2O3(A)	NOx (1000ppm)-O2(10%)-CH3OH (1000ppm)-C3H6 (330ppm)	200kW (7200h-1)	10-70 (250-300°C)	97	yes	23	
	diesel	Al2O3(B)	NOx (1000ppm)-CH3OH (1000ppm)	200kW (7200h-1)	45-90 (375-440°C)	97	yes	23	

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List of Catalysts for Pollution Control

Company	Sourses	Materials	Gases	Flow rate	De-%	Date	Commer.	Ref.	Comment
Cycle-Thermal, Inc & Advanced Environmental System, Inc., USA	solvent laden fumes	thermal/ catalytic oxidizer	Cl-VOCs		>99		yes	13	VOC concentrators, Fiberbed Mist Collection System
Degussa, Germany	Synthetic gas	zeolite impregnated with IB and VIII elements	C3H6 / C3H8	40,000h-1	10-85 (unaged), 10-55 (aged)	Jul.96	N/A	12	HC/NOx=2400ppmC/270ppm
	stationary	ceramic and metal-Pt-Rh	NOx, CO, HC	-			yes	11	HDC, PCE, TCE, MCl, MBr
	diesel	Pt-Zeolite	800ppm C4H8/C4H10(2/1) + exhaust HC	transient space velocity	19 (unaged) 23 (aged)	Jul.96	N/A	12	vehicle test, 50hr catalyst aging
Hokkaido Univ., Japan	diesel	Cu-ZSM-5	ehylene	20,000	25/50(without/with ethylene)	Jul.96	bottle	12	water and paticulate removed
	diesel (light oil)	Cu-ZSM-5	NOx	20,000	80	Jul.96	drip	12	
Honda Tech. Inst. Co., Japan	2 cycle engine	SUS-Pt-Rh	CO, HC, NOx	50 & 100 cc	1/2, 1/3, 1/2	Jan.98	yes	10	
KSE, Inc., USA	stationary	SCR	NOx	1,000,000 h-1	90	94	N/A	6	$49,975 contract, for European
Mazda Moter Co., Ltd., Japan	automobile	Pt-Ir-Rh-H-MFI(SiO2-Al2O3)	NOx	?	48.1-51.7%	97	yes	22	
Nippon Puretec Co., Ltd., Japan	clean room	Clean Sorb chem. filter	VOC, O3, NO2 (10 to 50ppb)	?	90-94%	Nov'97	yes	17	O-type

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List of Catalysts for Pollution Control

Company	Sourses	Materials	Gases	Flow rate	De-%	Date	Commer.	Ref.	Comment
Nippon Puretec Co., Ltd., Japan	clean room	Clean Sorb chem. filter	HNO3,HF (10 to 50 ppb)	?	90-94%	Nov'97	yes	17	H-type
Nippon Shokubai Co., Ltd., Japan	gas turbin	SCR	NOx (30-150ppm), SOx (0-30ppm)	?	-, 90	Jan'96	yes	18	gas temp. 180-450°C
	diesel engine	SCR	NOx (800-1500ppm), SOx (20-500ppm)	?	-, 90	Jan'96	yes	18	gas temp. 300-480°C SOF(Soluble Organic Fraction) catalyst
	oil boiler	SCR	NOx (100-200ppm), SOx (100-1500ppm)	?	-, 80	Jan'96	yes	18	gas temp. 280-400°C
	Industries air	STH catalyst	TCE	2,000hr-1	50-100	Jan'96	yes	18	gas temp. 250-350°C, inicial conc.1,000-2,500ppm
	Lean-Burn Gasoline engine	Cu-ZSM-5	HC/NO=5-10	45,000h-1	40-80	96	N/A	19	350-450°C
	diesel engine	Cu-ZSM-5	HC/NOx=5	55,000h-1	5-20	96	N/A	19	300-500°C
	diesel engine	TiO2-SiO2-V2O5	urea/NOx=0.8mol	70,000h-1	50	96	N/A	19	300-500°C honeycomb type
	diesel engine(3% light oil)	Pt-Rh-Al2O3	NOx	55,000h-1	20	96	N/A	19	200°C
	diesel engine(3% light oil)	Pd-Rh-Al2O3	NOx	55,000h-1	20	96	N/A	19	350°C

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Company	Sourses	Materials	Gases	Flow rate	De-%	Date	Commer.	Ref.	Comment
Osaka Gas Co., Ltd., Japan	gas turbine (city gas)	Cu-ZSM-5 (SiO2/Al2O3=50, M^{2+}/Al2= 106%)	NO (500ppm) C3H8 (1000ppm) O2(10%) CO2(6%) CO (1000ppm) H2 (660ppm)	?	40-70	96	N/A	25	300-600°C
	gas turbine (city gas)	Co-ZSM-5 (50,111%)	NO (500ppm) C3H8 (1000ppm) O2(10%) CO2(6%) CO (1000ppm) H2 (660ppm)	?	40-100	96	N/A	25	300-600°C
	gas turbine (city gas)	Co-SiO2/Al2O3	NO (500ppm) CH4 (2500ppm) O2(3.2%) CO2(8.4%) H2O (15.4%)	10,000h-1	57	96	N/A	25	550-570°C honeycomb type

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Company	Sourses	Materials	Gases	Flow rate	De-%	Date	Commer.	Ref.	Comment
Osaka Gas Co., Ltd., Japan, & Eniricerche Co., Italy	gas turbine (city gas)	Co(3wt%)-Beta-(SiO2/Al2O3=22.3)	NO (500ppm) C3H8 (1000ppm) O2(10%) CO2(6%) CO (1000ppm) H2 (660ppm) H2O(9%)	15,000h-1	54.7-83.7	96	N/A	25	400-600°C
Osaka Gas Co. & N-E-ChemCat Co., Japan	gas engine	Pt-Rh-Al2O3	NOx, CO, HC	?	?	May.96	yes	9	30,000hr no changeable
Riken, Japan	C3H6	Cu-Al2O3	synthetic gas	15,000	30 (o% water), 10 (10% water)	Jul.96	bottle	12	bench test, HC/NOx=5100ppmC/800ppm
	diesel fuel	Cu-Al2O4	synthetic gas	15,000	30 (fuel), 50 (incresed fuel)	Jul.96		12	bench test, 10% water, Max. Fuel/NOx mass ratio=5
	diesel fuel	Cu-Al2O5	diesel	?	30	Jul.96	spray system	12	Fuel/NOx mass ratio=5
	deisel engine	Ag-Al2O3	NO (800ppm) SO2 (30ppm) O2(10%) EtOH/NO (=3w/w) H2O(10%)	40000h-1	8-80	97	N/A	24	250-450°C, honeycom type(2), by-products (THC = 25 ppm>, CH3CHO=0,NH3 +other N-compounds=0, CO =10ppm>)

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List of Catalysts for Pollution Control

Company	Sourses	Materials	Gases	Flow rate	De-%	Date	Commer.	Ref.	Comment
Riken, Japan	diesel (light oil, S<0.2%)	EtOH over the Ag-Al2O3	NOx (1300ppm) SO2 (20ppm)	50,000h-1	23-88	97	N/A	24	320-470°C honeycomb type
Selective Adsorption Associates, Inc., USA	Indesties air, hydrogen & other gases	carbons	Hg	10sec/area	<1 micg-Hg/Nm3	?	yes	14	MERSORB®, Hg capacity 20Wt.% and Moisture content 3Wt.%Max.
	Industries water	carbon with chemical	Hg	?	ppMw of Hg	?	yes	14	MERSORB®, ref. show typical physical and chemical properties
SiemensAG, Germany	diesel , car	SCR	NOx, HC	?	70, 50-70	Dec.97	yes	1	SINOX system
South Coast Clean Air, Inc., USA	Industries air	catalytic oxidizers	VOC	?	?	?	?	15	
	Industries air	quench/scrub systems	NOx, SOx, HCl, H2S	?	?	?	?	15	
Southwest Research Inst., USA	diesel	Cu-ZSM-5	adsorbed exhaust HC	20,000	50	Jul.96	N/A	12	no increased total HC emission
Southwest Research Inst., USA	diesel	Cu-Zeolite	Ethylene + exhaust HC	up to 30,000	50	Jul.96	bottle	12	particulate removal
	diesel	Cu-Mordenite	adsorbed exhaust HC	20,000	?	Jul.96	N/A	12	exhaust HCs can be used as reductants
Steuler, Germany	diesel	Zeolite-molecular sieves	?	?	?	82	100units	20	300-480°C
TDA Research, Inc.,USA	automobile	metal oxide	HCs, CO	?	98	94	N/A	7	$50,000 contract
	automobile	SCR-CH4	NO, NOx	?	100	94	N/A	8	$50,000 contract
Toyota Moter Co., Ltd, Japan	automobile	Pt(1.8wt%)-Ba-Al2O3	NO (570ppm)	?	35-70%	94	yes	21	NSR catalyst

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List of Catalysts for Pollution Control

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13. ABSTRACT ***(Maximum 200 Words)***

Computer code (SUENTP-J) to predict scale-up and economic evaluation of several eligible non-thermal plasma processes for air pollution control – electron beam process, pulsed corona process, and corona radical shower process – was developed for a commercial power plant. This code was written in spread sheet type format (MS Excel) and visual basic for application and comprise a data input procedure, a scale-up (design) procedure, an economic calculation procedure, and an output procedure. Data obtained from pilot plant tests are input with general data so that they might lead to the conceptual design data of commercial plants by scale-up procedure. In the economic evaluation procedure, the total capital investment and the total annual cost are examined. The total capital investment comes into the indirect annual cost as the item of capital recovery. The levelized cost and the levelizd busbar cost are shown in the output table. An example calculation was presented to evaluate the cost of three non-thermal plasma systems and the results were compared with a conventional wet-scrubber/selective catalytic reduction combined system.

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