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Economic Assessment of Proposed Electric-Discharge Non-Thermal Plasma Field-Pilot Demonstration Units for NO_x Removal in Jet-Engine Exhaust: White Paper for SERDP Project CP-1038

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Executive Summary

This project is currently evaluating non-thermal plasma (NTP) technologies for treating jet-engine exhaust arising from DoD test facilities. In the past, some economic analyses for NTP de-NO_x have shown that it is not economical, compared to other techniques. The main reasons for this conclusion was that the previous analyses examined stand-alone, or less mature electrical-discharge reactors, or electron-beam based systems that incorporated both chemical additives and quite expensive (both in terms of capital and maintenance costs) electron accelerators. Also, in contrast to more recent developments, both the discharge and electron-beam techniques of the past did not extensively incorporate methods to increase the yields (energy efficiency) of active NO_x-decomposing species. In an earlier White Paper and a Project Report, we have analyzed the costs of more mature NTP systems incorporating chemical additives and new-concept NTP technologies (namely, hybrid systems) for jet-engine emissions control and have shown lower exhaust-gas treatment costs for NTP systems compared to baseline standard de-NO_x technologies like Selective Catalytic Reduction (SCR) combined with a wet scrubber or SCR combined with an electrostatic precipitator (ESP). In this paper, we will examine our most-promising candidate NTP reactor systems for a field-pilot demonstration on jet-engine exhaust and discuss the economic analyses for these hybrid units, which show that the economics of the proposed candidate systems are more favorable than earlier NTP reactor economic-assessment conclusions for NO_x removal.

**Economic Assessment of Proposed Electric-Discharge Non-Thermal Plasma
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Background

The purpose of SERDP project CP-1038 is to evaluate and develop non-thermal plasma (NTP) reactor technology for Department of Defense (DoD) air emissions control applications. The primary focus is on oxides of nitrogen (NO_x) and a secondary focus on hazardous air pollutants (HAPs), especially volatile organic compounds (VOCs). Example NO_x sources are jet engine test cells (JETCs), Cruise Missile test cells (CMTCs), and diesel-engine powered electrical generators. Example VOCs are organic solvents used in painting, paint-stripping, and parts cleaning.

In the feedback from the May 1997 SERDP Compliance In Process Review (IPR) for this project, guidance was supplied to resolve some issues associated with the potential cost of implementing non-thermal plasma technology for the control of jet-engine emissions – particularly oxides of nitrogen, NO_x . A previous White Paper [1] covered two of the issues in the guidance: an economic analysis of NTP de- NO_x technology prior to go ahead on a field test and, because previous work on NTP economics has shown non-favorable economics for this technology, carrying out an analysis comparing the process economics with previous work.

In this White Paper, we will examine our most promising candidate NTP reactor systems for a field-pilot demonstration on jet-engine exhaust and discuss their relative merits and costs, which show that the economics of the proposed systems, for which we have data that can be reasonably extrapolated, are more favorable than earlier NTP reactor economic-assessment conclusions for NO_x removal.

De- NO_x Technologies - Conventional and Emerging

Conventional de- NO_x Technologies

The process of combustion, using a fuel such as coal (in a coal-fired electrical power plant) or diesel fuel (in diesel engines, including jet engines) can generate substantial quantities of oxides of nitrogen (NO_x) and sulfur (SO_x). SO_x emissions can be easily controlled by using low-sulfur-content fuels. However, NO_x emissions still pose a problem (we are concentrating on emissions from jet-engine test cells (JETCs) and Cruise Missile test cells (CMTCs), which also employ jet engines, albeit smaller ones.

Our earlier economics White Paper [1] discussed the conventional technologies of granular activated carbon (GAC) and mature processes incorporating catalysts (e.g., selective catalytic absorption - SCR).

Because these conventional de- NO_x processes must be closely matched to the combustion device, sometimes make use of high-temperature catalysts (which suffer sulfur poisoning, deterioration), and are often quite complicated and expensive, searches for newer technologies have been undertaken during the past 20 or 25 years. Some of the most promising of the emerging technologies are based on NTP methods.

Emerging de- NO_x Technologies - NTPs

The roots of treating hazardous and/or toxic chemicals with NTPs go back over two decades to military applications for destroying toxic chemical warfare agents with electric discharge reactors and civilian applications for treating flue gases (SO_x and NO_x) from electric power plants

and other installations (e.g., steel mills) with electron beams. More details about the history and applications of these early systems can be found in the earlier-referenced economics White Paper.

Several non-thermal plasma technologies for dc-NO_x are in the commercialization stage and, more recently, several small scale commercial systems based on pulsed corona and electron beams are operating (Li et al 1998 [2], and a full-scale, flue-gas demonstration plant which is under construction by Chubu Electric Power in Japan for a 220 MW power plant). Economic evaluations are needed not only for the selection of the best-matched technology for the operating facility, but also for providing guidance for future research and development on those technologies. In this paper, we will show that present NTP-based processes are currently showing favorable economic trends.

Exhaust Stream Addressed by This Project

There are several studies and reports that address jet-engine emissions arising from engine test facilities (Spicer et al 1988 [3], 1990 [4]; Walker 1996 [5]). Representative emissions of the major compounds of concern are shown in Table 1 for F101 and F110 jet engines operated in jet engine test cells (JETCs) at Tinker Air Force Base, Oklahoma [4].

Table 1: Measured emissions for Tinker AFB JETCs (F101 & F110 engines) [4].

Power setting	Test No.	THC (ppmC)	NO _x (ppm)	NO (ppm)	CO (ppm)	CO ₂ (%)
F101 Engine						
Idle	TAFB-1-6-17	6.5	6.9	5.0	50.0	0.50
44%	TAFB-2-6-17	3.5	28.5	25.5	8.0	0.98
75%	TAFB-3-6-17	2.5	68.0	62.0	8.0	1.52
Intermediate	TAFB-4-6-17	3.0	140.0	133.0	11.0	2.02
Augmentation (Stage 1)*	TAFB-5-6-17	287.0	21.8	7.2	110.0	0.32
F110 Engine						
Idle	TAFB-1-6-15	7.0	13.8	11.2	85.0	0.98
30%	TAFB-2-6-15	6.0	30.0	28.0	23.0	1.25
63%	TAFB-3-6-15	3.0	97.0	92.0	13.0	2.35
Intermediate	TAFB-4-6-15	3.5	243.0	227.0	15.0	3.17
Augmentation (Stage 1)*	TAFB-5-6-15	335.0	21.5	3.7	178.0	0.41
Intermediate (Roof-top)*	---	< 7.0	26.0	25.0	6.0	0.28

* Measurements made with ~ 20-50:1 diluted exhaust.

Table 2 shows a summary emissions inventory for Tinker AFB JETCs 1-12 for the year 1995; when 3,414,836 gallons of JP-5 fuel were consumed in a time period of 4420 hours of

operation [5]. The emissions were calculated on the basis of fuel consumption but not directly measured.

Table 2: Calculated emissions inventory for twelve JETCs at Tinker AFB for CY1995 [5].

Compound	Emission Inventory (ton/yr)
NO _x	113.01
SO _x	30.71
Aggregate hydrocarbons	100.45
CO	156.34
Particulates	26.72
PM-10	4.45

Based on the data taken from Spicer 1990 [4] and that supplied by Walker 1996 [4], a model emissions profile for a representative JETC can be defined. However, our plans for a field-pilot demonstration for this project call for testing NTP jet-engine emissions treatment on a Cruise Missile Test Cell (CMTC) at Tinker AFB (which employs F107 and F112 engines). In contrast to the Tinker JETCs, the actual emissions from the CMTCs have not been characterized. Therefore, our approach is to: 1) work with Tinker to have the emissions characterized for a CMTC; 2) formulate a model emissions profile, based on the measured and calculated profiles for JETCs. Item #1 will be used in setting the final operating parameters for the field-pilot equipment, while item #2 will be used in making cost-analysis and economic projections for the treatment of jet-engine emissions by NTP systems and in making comparisons with the most commonly employed conventional flue-gas treatment technology: Selective Catalytic Reduction (SCR) plus wet scrubbers or SCR plus electrostatic precipitators (ESPs).

NTP technology probably has applications for treating air emissions from other sources of interest to the DoD; e.g., industrial boilers and furnaces; Aerospace Ground Equipment (AGE), including diesel-powered electrical generators, compressors, hydraulic test stands, and weapons loading units; and emergency electrical power generators. Means of calculating inventories for air pollutants arising from such sources have been formulated and documented by Jagielski et al 1994 [6].

Candidate NTP Reactor Systems for Field Demonstration

We have chosen five initial candidate NTP reactor systems (all based on electric discharges) for the field-pilot demonstration:

- Pulsed Corona Plasma Reactor System
- Dielectric-Barrier (Silent Discharge) Plasma Reactor System
- Hybrid/NTP Reactor-Adsorber System
- Hybrid Corona Radical Shower Plasma Reactor System
- Hybrid Plasma-Catalytic System.

Because the cost and logistics of using an electron-beam NTP reactor are, respectively, too high and too complicated for this project, we have limited our candidate systems to those based on

electric-discharge-driven NTP reactors (which previous economic analyses have shown to be more cost effective, Kim & Chang 1998 [7], Rosocha et al 1998 [1]).

Active species/radicals capable of decomposing NO_x , SO_x , and hydrocarbons are created in all four of the above-mentioned reactors. However, some have particular advantages. Each type of NTP reactor system will be discussed in greater detail further below.

As a rough estimate, we assume that the production of radicals is the same for all four reactors listed above (which is not explicitly true) so that we can provide an estimate of the required plasma power for a given removal fraction of NO. The specific plasma energy for a one e-fold removal (~ 63%) of NO - the figure for which we are planning - is approximately 50 J/L in electric discharge reactors. The average plasma power requirement is calculated from the equation

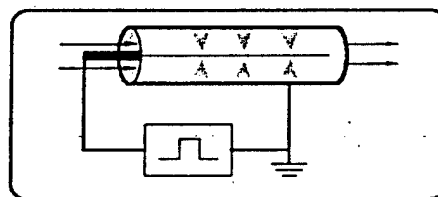
$$P = \bar{E} Q,$$

where P is the power, \bar{E} is the plasma energy density (50 J/L for our case), and Q is the gas flow rate through the reactor. For 100 and 500 SCFM (59 and 294 Nm³/h) gas flow rates, the average plasma powers are 2.4 kW and 11.8 kW, respectively.

Depending on the exhaust-gas conditions (e.g., humidity and hydrocarbon content) and the potential use of additives, the overall de- NO_x removal chemistry in our candidate NTP reactor systems can be either oxidative or reductive. This will influence the final byproduct effluent distributions. In the oxidative case under humid conditions, the most prevalent byproduct is nitric acid (HNO_3), which dictates the use of base scrubbers to neutralize the acid. Under dry conditions, the formation of NO_2 is favored. However NO_2 is more easily adsorbed by activated carbon and can be captured and subjected to further treatment. With additives such as ammonia (NH_3), methane (CH_4), ethylene (C_2H_4), or part of the actual exhaust gas, the product distribution can be shifted to particles (e.g., useful agricultural fertilizer like ammonium nitrate - NH_4NO_3) which can be collected with an electrostatic precipitator.

Pulsed Corona Plasma Reactor System

A generic pulsed or DC corona reactor is shown in Figure 1 below. In pulsed corona, the combination of a fine wire and a short, high-voltage pulse provides a gas breakdown electric field that is enhanced over the normal DC breakdown field. Several wires in a planar geometry or parallel combinations of reactors can be used to provide a larger active gas-treatment volume.



Pulsed or DC corona

Figure 1: Schematic diagram of a generic wire-tube pulsed or DC corona NTP reactor.

A schematic diagram illustrating a more specific pulsed corona reactor system is shown in Figure 2. In this system, ammonia (NH_3) or ethylene (C_2H_2) can be supplied as additives to enhance the production of useful reactive species. Similarly, a small portion of the actual engine exhaust can be injected at the reactor intake to use hydrocarbons entrained in the exhaust gas for active-species enhancement.

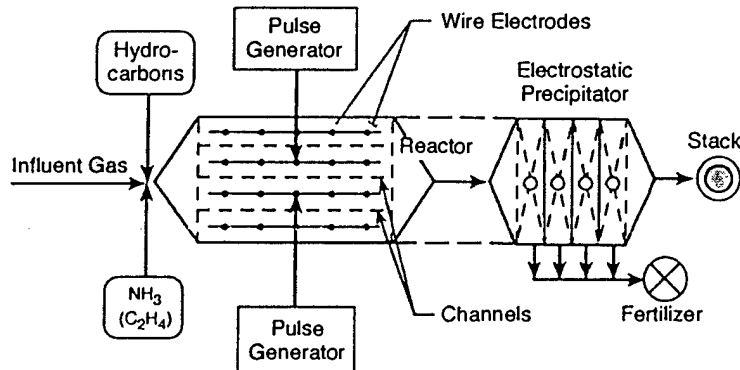
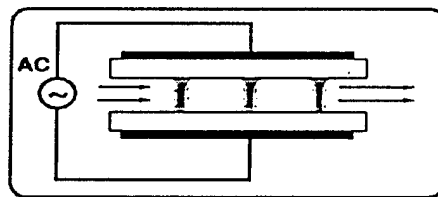


Figure 2: Schematic diagram of pulsed corona reactor system for exhaust-gas emission treatment, including electrostatic precipitator for particulate collection.

Dielectric-Barrier Discharge Plasma Reactor System

A generic dielectric-barrier (silent discharge) reactor is shown in Figure 3 below. In an AC-driven barrier discharge, the buildup of charge on the dielectric automatically terminates the microdischarge streamers, thus producing a short, electron-energetic pulse and eliminating the need for more expensive and/or more complicated pulsed power supplies.



**Silent discharge
(dielectric-barrier discharge)**

Figure 3: Simple schematic diagram for a dielectric-barrier discharge reactor.

At Los Alamos, the dielectric-barrier reactor has been extensively studied for the decomposition of VOCs (especially chlorinated hydrocarbons) and four field-pilot demonstrations have been carried out with modular reactors. Reactor banks with average plasma power as much as 10 kW have been employed in such tests (Rosocha 1997 [8]). Commercialization of the technology for VOC/air toxics treatment under specific fields of use is now in progress with a commercial partner.

An example of a silent-discharge NTP reactor that has already been commercialized for flue-gas treatment is the Tecolytic™ modified dielectric-barrier reactor + lime scrubber system (from Thermo-Power Corp., Bittenson & Breault 1998 [9]). The company's stated objective is to

“develop a zero discharge NO_x control process using no hazardous reagents or catalysts”. Figure 4 shows a schematic diagram of the system. The NTP reactor consists of a housing to hold a large array of metal rods covered by ceramic-dielectric insulators and to hold the associated high-voltage insulated feedthroughs. The rods are essentially arranged such that a high-voltage electrode is surrounded by four grounded nearest-neighbor rods. The high-voltage “corona” rods are connected to a HV/AC power supply to supply the necessary voltage and current to produce an electrical discharge in the gas space between the rods. Flue gas is flown across the electrodes, entering the reactor housing at one end and exiting the opposite end. The NTP-treated gas is then sent to a wet scrubber, using $\text{Mg}(\text{OH})_2$ and slaked Mg-enhanced lime, which scrubs out SO_2 to make gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), which is a salable commodity. In humid flue gas, much of the NO_x is converted in nitrate products (e.g., acids which can be neutralized or collected as products). Clean effluent gas is vented to the atmosphere.

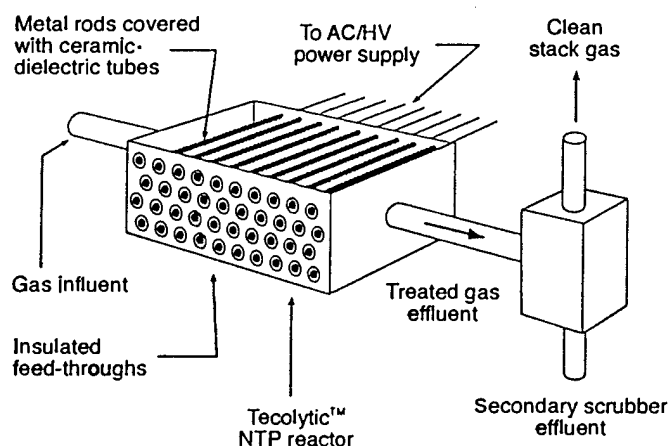


Figure 4: Schematic diagram of commercial Tecolytic™ [9] modified dielectric-barrier NTP reactor system for de- NO_x/SO_x (flue-gas treatment).

Within the past few months, one of these systems has been installed on the Miami Fort power-plant facility and field tests are in progress. Data from these tests will be highly useful in establishing further benchmarks for the economic model and in lending further credence for the acceptance of NTP technology as an alternative to conventional de- NO_x methods.

Hybrid-Systems

The NTP + Adsorber Hybrid Concept

We define a hybrid NTP emissions-control system as a combination of one or more NTP reactors with an adsorber, a catalyst, or another NTP reactor. Our interest in hybrid systems arises from a major conclusion drawn from the points made in the section on GAC of our earlier economics White Paper: if the operating lifetime and/or effectiveness of GAC can be improved, the treatment costs will decrease.

There are two simple ways to combine an NTP stage with a GAC stage: place the NTP stage in series with the GAC stage, thus lessening the load on the GAC; or place the NTP stage in

parallel with the GAC stage and use it to regenerate the GAC under more favorable conditions than the heat/steam regeneration methods typically employed.

The expected advantages of such an NTP-GAC hybrid system are:

- Prolonged life of GAC filters (with an associated operating cost reduction)
- Application to a broader range of exhaust-gas flow rates, types of pollutants, and pollutant concentrations
- Potential for reducing the dependence of treatment cost on pollutant concentration
- Pollutants are destroyed by the NTP stage, rather than simply captured
- NTP system can incorporate feedback to aid in optimizing the treatment efficiency and costs.

For many applications, end-of-pipe emissions treatment is the norm. However, one can also conceive of restricting the treatment closer to the point-of-use, or integrating the emissions treatment equipment directly into the process which produces the emissions. For the purposes of this report, an end-of-pipe application will sufficiently illustrate the hybrid system concept.

Serial-Mode NTP Reactor Hybrid Architecture

In a serial-mode hybrid system, an NTP reactor precedes an adsorber bank (see Figure 5). As mentioned earlier, adsorbers such as activated carbon, are commonly-employed but cost-intensive treatment methods (mainly because of regeneration, reactivation, or disposal costs). For the serial-mode hybrid, the load on the adsorber stage can be possibly reduced by 50-75% by the pretreatment action of the NTP reactor. This results in a significant change in the overall treatment economics because the useful adsorber lifetime can be greatly increased, while the NTP reactor does not have to operate in an energy-demanding, high-removal regime (as the removal equation shows, the energy cost per pollutant molecule destroyed is a logarithmic function of the degree of removal). Additionally, one can envision tailoring the adsorber to better match the compounds which the NTP reactor produces, thereby increasing the overall process effectiveness. That is, one is not necessarily constrained to the use of GAC - superior adsorbents are most likely available and adsorber technology is expected to advance in the next few years.

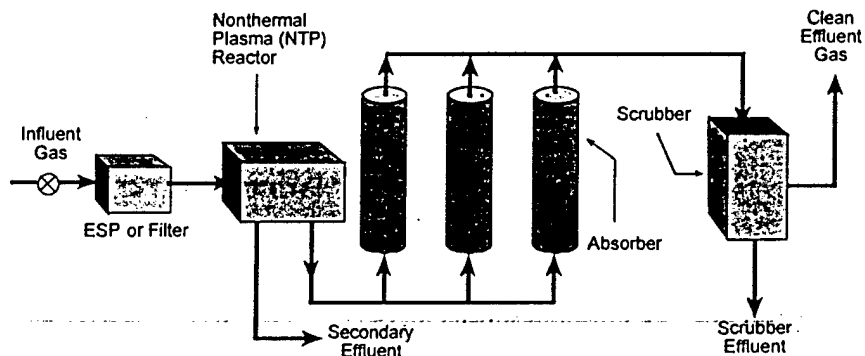


Figure 5: Serial-mode NTP-absorber architecture. Disposal and/or regeneration economic advantage comes from reducing the load on the absorber. Treatment effectiveness can also be increased if the NTP reactor converts the initial pollutant into more easily-absorbed compounds.

Regenerative-Mode NTP Reactor Hybrid Architecture

In a regenerative-mode (or 'trap and treat') hybrid system, an NTP reactor is used to regenerate a pollutant-adsorber bank (see Figure 6). Here the adsorber traps the pollutants (NO_x or VOCs) while operating at a high off-gas flow rate, but is regenerated off-line at more economical conditions. Such conditions can be a lower flow rate and, hence, a lower power demand (and associated lower power cost when operating at electrical utility off-peak times). This architecture is particularly attractive for episodic emissions (e.g., JETCs and CMTCs), where high-flow operation and regeneration can be easily divided into separate functions.

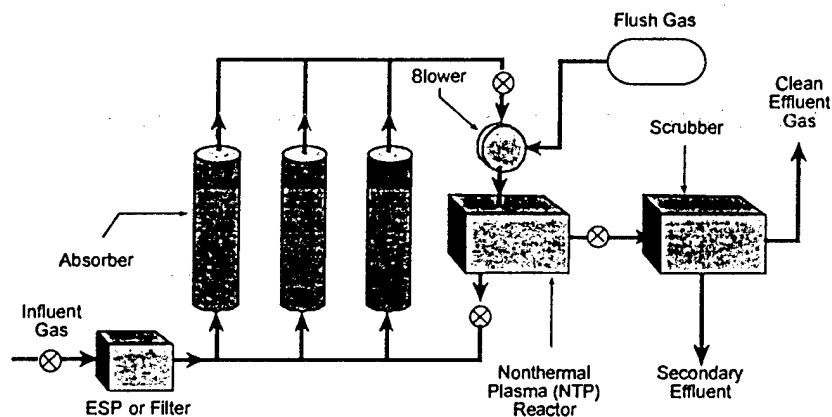


Figure 6: Regeneration-mode NTP-absorber architecture. Economic and performance advantages may be gained by regenerating the absorbers off-line from pollutant capture, but employing on-site, rather than off-site handling.

Two additional key advantages of the NTP regenerative hybrid are: the ability to incorporate electronic feedback into the process, thereby operating the system at more optimal treatment conditions and costs; and the ability to flush the adsorbent with a tailored gas mixture, thereby more effectively controlling the destruction chemistry, the formation of undesirable byproducts, and the overall effectiveness and treatment costs.

Dual-NTP Reactor Hybrid System (Corona Radical Injection/Shower)

There are several ways to combine one or more NTP reactors with other NTP stages. A promising, novel corona reactor called the Corona Radical Shower (CRS) or radical injector, that employs a small NTP reactor to inject beneficial active species into the main NTP reactor, has been demonstrated by (Kanazawa et al 1997 [10] and Chang et al 1998 [11]). This device is more fully described in an earlier report to SERDP (Matsuoka et al 1997 [12]). Here, a brief summary of the system will be presented.

In the CRS system (see Figure 7), arrays of small nozzles or showers, each with a small bleed-gas flow, are introduced into a wire-plate DC corona reactor. The purpose of the nozzles is to create desirable active species and inject them into the larger main corona treatment region, which enhances the overall pollutant-removal effectiveness. The injected active species can be tailored to the particular pollutant stream being treated by selecting the shower-injector bleed-gas

so that it produces active species that are particularly effective in decomposing the target pollutant.

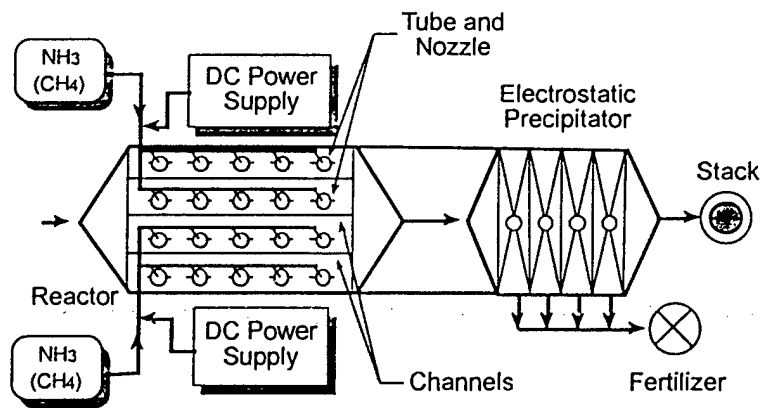


Figure 7: Schematic diagram of CRS reactor. Ammonia (NH_3) or methane (CH_4) are added to generate radicals that drive reactions leading to the formation of particulates; these particulates are then captured by the electrostatic precipitator. Some of the captured products are useful for agricultural fertilizer (e.g., ammonium nitrate, NH_4NO_3).

Experiments by our collaborators at McMaster University have shown that, for NO removal, ammonia (NH_3) or a hydrocarbon like methane (CH_4) are useful injector-gas additives [12]. It is interesting to note that McMaster has also shown that, for JETC de- NO_x , normally-present hydrocarbons in the exhaust stream can enhance the de- NO_x process. In this case, air or a slipstream of the JETC exhaust itself is effective as a shower-injector gas, without requiring additional external additives (like NH_3). The economic advantages of the CRS system will be described further below.

Plasma-Catalyst Hybrids

In either the serial-mode hybrid or the regenerative-mode hybrid, the use of catalysts, rather than sorbents, is also considered. Recently, there has been considerable interest in combining non-thermal plasmas and catalysts for de- NO_x applications (Penetrante et al 1997 [13], Tonkyn et al 1997 [14], Wander & Penetrante 1997 [15]). Much of this work has been focused on lean-burn diesel engines, whose oxygen-rich exhaust streams tend to enhance the oxidative conversion path $\text{NO} \rightarrow \text{NO}_2$ when only plasma treatment is employed. With plasma-assisted catalysis, the goal is to develop a de- NO_x system that favors the reductive path $\text{NO} \rightarrow \text{N}_2 + \text{O}_2$ (or other products which are not oxides of nitrogen).

In oxygen-rich environments, several types of catalytic materials can promote the selective catalytic reduction (SCR) of NO_x by hydrocarbons normally present in the exhaust stream. Combining an NTP with a catalyst has been shown to enhance the SCR process. Additionally, one can conceive of multi-stage plasma-catalytic systems, whereby either a catalytic material or an NTP is applied to enhance particular reaction steps in the SCR process. For example, the

highly-efficient, yet undesirable reaction $\text{NO} \rightarrow \text{NO}_2$ can be used to advantage if the plasma stage which produces the NO_2 is followed by an efficient catalytic stage for converting the NO_2 to a more-desirable terminal product: $\text{NO}_2 + \text{catalyst} + \text{hydrocarbon} \rightarrow \text{N}_2 + \text{CO}_2 + \text{H}_2\text{O}$. Such systems are being explored by other researchers in fundamental, benchtop studies and are expected to be tested at pilot-stage under another SERDP project (Wander & Penetrante [15]). Our experimental evaluation of plasma-catalytic systems for DoD applications (in particular JETCs and diesel motor-generator exhausts) has been started at McMaster University using bench-scale ($6 \text{ Nm}^3/\text{h}$ gas flow) serial hybrid NTP-catalytic apparatus as shown in Figure 8.

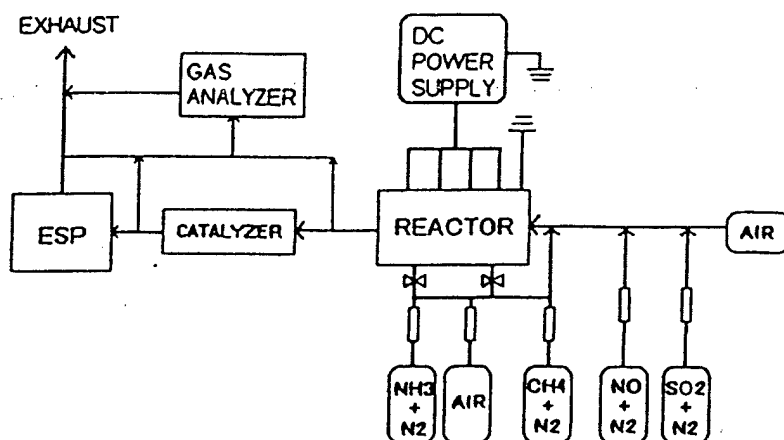


Figure 8: Schematic diagram of bench-scale plasma-catalytic system tested at McMaster University.

The following conclusions have been drawn from the bench-scale tests of a corona radical shower reactor followed by a catalytic converter and ESP (Urashima et al 1998 [16]):

- NO , NO_x , and SO_2 removal fractions increase with increasing applied NTP-reactor voltage (plasma specific energy) and decrease with increasing NO initial concentration;
- NO , NO_x , and SO_2 removal fractions non-monotonically depend on the velocity of the gas added to the corona radical shower unit (due to gas-mixing effects);
- SO_2 removal fractions increase with increasing ammonia-to-acid-gas molecular ration, while NO and NO_x removal non-monotonically depend on the ammonia ratio;
- NH_3 and CH_4 slips depend non-monotonically on the ammonia ratio;
- Trace, unwanted discharge byproducts significantly depend on the ammonia-to-acid-gas ratio and only N_2O and $\phi\text{-CHO}$ (aldehydes) are observed;
- Significant amounts of aerosol particles are formed during the acid-gas removal process;
- The effects of catalytic reactions on de- NO_x are significant, even at room temperature, with NH_3 injection but not significant for CH_4 injection;
- SO_2 removal is significantly enhanced by adsorption/catalytic reactions in the catalytic converter.

Additional plasma-catalytic hybrid systems, such as a non-thermal plasma in close physical proximity to a catalytic material, remain to be evaluated, although there is some work in the literature on this subject.

Previous Cost Analyses for NTP De-NO_x

Historical Perspective

Few works in the past dealt with the economic evaluation of NTP air-pollution technologies. One past economic evaluation carried out by the Japanese Mechanical Industry Association and Energy Engineering Institute (Masuda 1993 [17]) compared three types of de-SO_x and de-NO_x facilities for a coal-fired power plant - the conventional, combined wet-scrubber - selective catalytic reduction process, the electron beam process, and the pulsed corona process. The results of this study (for a 250 MW power plant) showed that the pulsed corona process was more economical than the others. Most other works have been on electron beams (Frank & Hirano 1993 [18], Frank 1993 [19]) or pulsed corona (Civitano 1993 [20]). Bartoszek et al, 1998 [21] outlined economic evaluation methods for advanced reburning de-SO_x and de-NO_x processes based on thermal and non-thermal plasmas and used the energy yield (removed amount of acid gas g / input power kWh) as a figure of merit for the economic evaluation of plasma processes.

The work of Frank [19] pointed out that cost analyses of e-beam de-NO_x have been carried out by several groups and that it is extremely difficult to compare the various estimates because different assumptions have been made by those carrying out the work. Primary among the assumptions is the cost of the heart of the system: the electron-beam accelerator. As of 1992 (with assumptions about the development of lower-cost, modular accelerators), an estimate of \$200/kW of power plant output is proposed for an installed flue-gas de-SO_x/NO_x system on a 500 MW power plant module. This is based on an accelerator cost of \$2/W and a \$50/ton by-product credit (gypsum and/or fertilizer). Frank concluded that such a cost makes e-beam de-NO_x cost competitive with more conventional processes. Frank & Hirano [18] also refer to a study conducted by the Electric Power Research Institute (EPRI) and subcontractors (Radian Corp. and Sargent & Lundy) that evaluated over 70 processes for air pollution control. The e-beam process was highly rated for combined SO_x/NO_x removal: the EPRI report stated, that for power plant flue-gas treatment retrofits, the e-beam process was rated as equivalent or preferable to the combined Flue Gas Desulfurization (FGD)/Selective Catalytic Reduction (SCR) process - the most often employed flue-gas treatment method at that time (and, largely, still the case).

For the pulsed corona process, Civitano et al [20] calculate the cost for a de-SO_x/NO_x flue gas system to be installed on a 320 MW power plant. However, they do not compare the cost with conventional technologies but simply state that it is less expensive. Other studies on the economics of de-NO_x by pulsed corona (Haythornthwaite et al 1997 [21]) have concluded that, using a spark gap-switched pulsed corona reactor (which converts NO to higher oxides of nitrogen that are treated by a sodium thiosulfate wet scrubber) the cost of such a system is unreasonable for a full-scale JETC (e.g., ~ \$17 M per year operation and maintenance cost for 50 hours of operation per week). Clearly their conclusion about direct treatment of the exhaust stream, followed by wet scrubbing, is reasonable (as demonstrated by sub-scale and field tests). Therefore, we conclude that other architectures, as suggested in this White Paper, should be considered instead.

Studies of the economics of de-NO_x by dielectric barrier discharges (silent discharge plasma) are very rare at scales larger than benchtop. Further below, we will discuss a commercial modified dielectric-barrier system that shows promising cost projections for flue-gas treatment.

Example of Previous De-NO_x Systems and Cost Analysis Cost-Analysis Methodology

Historically, in formulating costs for NTP de-NO_x and comparisons with other technologies (even one type of NTP with others), there are “apples & oranges problems”, i.e., workers did not use consistent measurement techniques and parameters. This makes it hard to compare one plasma system with another and with conventional methods.

Most previous estimates of the cost of NTP-based air pollution control have basically examined only two very closely related NTP architectures: namely, a stand-alone NTP reactor or an NTP reactor coupled to some type of post-reactor gas-treatment equipment (e.g., a scrubber or electrostatic precipitator - ESP). It is clear that, for very high gas flow applications (e.g., JETCs) or energy-intensive applications (e.g., hard-to-decompose VOCs), a stand-alone NTP reactor is both operationally and economically unfeasible. Byproducts like acids and particulates are produced in treating air pollutants; these cannot simply be vented to the atmosphere without further treatment.

These simple economic conclusions are illustrated in Table 3 below for de-NO_x. To render NTP technology viable, one must consider the addition of chemical additive to the exhaust stream (e.g., NH₃ is commonly used to create additional reactive species) or coupling the NTP reactor to another stage (e.g., an adsorber and/or catalyzer).

Table 3: Simple economic estimates for one e-fold (63%) removal, stand-alone NTP de-NO_x reactor (assuming power supply and electricity usage dominates cost for electric-discharge reactor equipment and accelerator and its electricity usage dominates cost for e-beam reactors).

	Small Source	Large Source
Exhaust-gas flow rate	100 SCFM (170 Nm ³ /hr)	1.0 x 10 ⁶ SCFM (1.7 x 10 ⁶ Nm ³ /hr)
Plasma power	472 W (e-beam), 2.4 kW (dis)	4.7 MW (e-beam), 23.6 MW (dis)
Cost of power supply or accelerator	\$18.8 k (e-beam), \$5.6 k (dis)	\$18.9 M (e-beam), \$13.9 M (dis)
Cost/ton NO removed (5,000 hrs operation)	\$248,286 (e-beam), \$77,273 (dis)	\$27,665 (e-beam), \$26,909 (dis)

Assumptions: Specific plasma energy for one e-fold removal is 10 J/liter for e-beam and 50 J/liter for electric discharges. Stand-alone electric-discharge reactors are considered to give similar removal fractions at a given specific energy (i.e., their efficiencies are essentially the same, which has been shown in the literature (Penetrante 1995 [22], Korzekwa & Rosocha 1997 [23]). Cost of e-beam accelerator estimated at \$20/W for small systems and \$2/W for large systems; coupling efficiency from power supply to accelerator to plasma power estimated at 50%. Cost of electric-discharge power supply estimated at \$2/W for small systems and \$0.5/W for large systems; coupling efficiency from power supply to plasma power estimated at 85% (these figures are characteristic of dielectric barrier discharge reactors - pulsed corona reactors will have a higher power supply cost and a lower coupling efficiency). [NO] = 100 ppm. Cost of electricity = 5 ¢/kWh.

Note: 5000 hours is approximately the yearly operating time for the Tinker JETCs.

Clearly, following this example analysis, the small source the stand-alone NTP reactor costs per ton are prohibitive. The scaling becomes more favorable for larger sources. However, for a smaller source (like an electric generator or other AGE equipment), the estimated costs in Table ?? (power supply cost plus electrical power consumption) may not be prohibitive for electric-discharge reactors. For example, if the source only emits a fraction of a ton of NO_x over one year of operation - a realistic case is a diesel-turbine powered emergency electrical generator, which emits about 678 lb NO_x/yr [6], one year of operation (assuming a stand-alone NTP reactor unit) would cost about \$26 k. Because conventional NO_x -removal technologies are not cost effective for low exhaust-gas flow rates and low NO_x concentrations, an NTP reaction could fit this niche economically.

Recent Economic Calculations for NTP De- NO_x

Subject to the best available interpretable data, we have attempted the best economic comparisons possible. Our practice has been to use the plasma energy density (and the associated electrical coupling efficiency from power supply to plasma) and the removal fraction of the pollutant as key parameters in the analyses.

The non-thermal plasma (NTP) techniques are still not optimum and economic evaluations for commercial plants are rare. However, more recently, Kim & Chang 1998 [7] estimated the economics as closely as possible by using 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 flow rate of exhaust gas, initial concentration of NO_x , SO_x , *other emissions*, and facility requirements.

Recent Work by Kim and Chang - Summary of the Model

This section presents a summary of computer-code simulation results which predict scale-up and economic evaluations of several NTP technologies employed for a commercial electric power plant (mainly NO and SO_2 emissions) and a comparison of several NTP technologies with the conventional technologies of Selective Catalytic Reduction (SCR) and Wet Scrubbers, taken from our SERDP Project collaborators at McMaster University [7, 12]. It should be noted that power plant emissions of NO_x are similar to those of jet-engine exhausts (our primary target for this project).

The computer code (SUENTP) 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. Non-thermal plasma technology for emissions control is very complicated in terms of both physical and chemical phenomena, so it is difficult to analyze theoretically. Therefore most design data should be obtained from experimental studies. In the model work, the principal design data are acquired from pilot-plant experiments. Then these data are adopted as design data for commercial plants. The data obtained from pilot-plant tests are input with general data to provide information for the conceptual design of scaled-up commercial plants. The economic evaluation procedure deals with the total capital investment and the total annual cost. 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 also calculated. In the Kim & Chang paper [7], an example calculation is presented to evaluate the cost of three non-thermal systems and the results compared with a conventional wet-scrubber/selective catalytic reduction combined system. In a

more-recent report by Urashima et al 1998 [16], a plasma-catalyst hybrid system has been analyzed from the point of view of bench-scale performance.

Benchmark design data shown in Table 4, which are obtained from pilot-plant experiments, are used in the scale-up design procedure of each NTP process. These data are essential for the economic evaluation as well as for the scale-up design. Experimental values of energy yield are most important, since this parameter affects 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 electric power and chemicals such as NH₃ and hydrocarbons, are also quite important factors in the economic evaluation. Several eligible non-thermal plasma technologies are in the stage of commercialization and, more recently, several small scale commercial systems based on pulsed corona and electron beam are operating (Tamaki et al 1998 [24], Song et al 1997 [25]), Li et al 1998 [2]). Economic evaluations are needed not only for the selection of the best-matched technology for the operating facility, but also for providing guidance for future R&D on those technologies and to provide guidance to the DoD on viable, alternative NTP air-pollution control technologies.

Table 4: Benchmark de-NO_x pilot-plant data (aimed at 500 MW coal-fired power plants)*.

Item	Units	Pulsed Corona	Corona Shower	Electron Beam	Plasma + Catalyst	Conventional
[NO] ₀	ppm	300	200	230	30-100	300
NO _x Removal	%	60	70	80	62	80
[SO ₂] ₀	ppm	1,000	800	1,000	~ 200-800	3,050
SO ₂ Removal	%	90	95	95	> 90	90
Energy Yield**	g-NO _x /kWh	20	374	56	> CS	-
Scale	Nm ³ /h	600	12	20,000	6	1.9 x 10 ⁶

* Data from Dinelli et al 1990 [26], Bartosek et al 1998 [21], EPRI 1983 [27], Masuda 1993 [17], Ebara Company 1998 [28], and Urashima et al 1998 [16]. ** All electric power assumed to contribute to NO_x removal.

Model Results and Comparison with Conventional-Process Economics Using Data from Existing NTP Flue-Gas Treatment Pilot Plant Tests

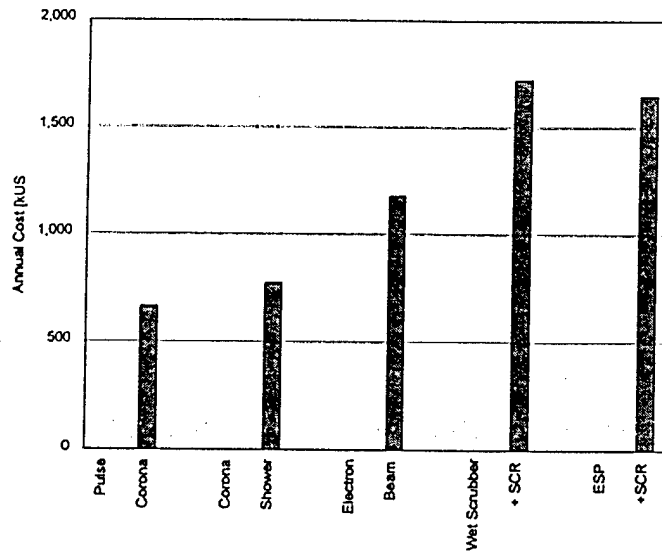
Obtaining a set of non-thermal plasma technology pilot plant test data for economic evaluations is difficult, because only electron beam (EB) technology has the experience of several pilot or commercial plants to provide baseline engineering data. Pulsed corona (PC), dielectric-barrier, and corona shower (CS) technology do not yet have enough data for commercialization. Another reason is that even rare data from pilot or commercial plant tests will not be open to the public because of competitive concerns of the involved companies.

Nevertheless, at this time an economic evaluation must be made to provide information about which system is most suitable for a given JETC or CMTC emissions source. Therefore this work has tried to evaluate the cost of three non-thermal systems and compare these with a conventional, combined wet-scrubber/selective catalytic reduction system (although the experimental conditions of emissions removal are slightly different, as shown in Table 4). The calculations are based on the input data shown in Table 5 below.

Table 5: Common input data for economic calculations.

Source Data for JETC				
	Variable	Units	Value	Value
Gas Flow	Q _{gas}	Nm ³ /h	1.0E+05	1.7E+06
Fuel			JP-5	
Capacity factor	R _{use}	%	80	
Gas Composition				
N ₂	C _{N2}	%	80.98	
O ₂	C _{O2}	%	18.00	
CO ₂	C _{CO2}	%	0.50	
H ₂ O	C _{H2O}	%	0.50	
Density (Normal)	D _{gas}	kg/Nm ³	1.283	
Exhaust Gas Temperature	T _{gas}	C	25	
NTP Inlet Temperature	T _{NTPin}	C	25	
Pressure	P _{rgas}	mm H ₂ O	720	
Emission Data				Removal (%)
NO _x	C _{NOx}	ppm	36.00	70
SO ₂	C _{SO2}	ppm	4.59	95
HC (VOC)	C _{HC}	ppm	60.00	90
CO	C _{CO}	ppm	53.36	0
Particles	C _{part}	mg/Nm ³	-	-
	Variable	Units	Value	
NH ₃ Stoichiometric Ratio to NO and SO ₂			1.5	
Economic Data				
Depreciation Period		Years	10.0	
Inflation rate		%	5.0	
Real Interest Rate		%	5.0	
Nominal Interest rate		%	10.3	
Salvage Rate of Equipment		%	0.0	

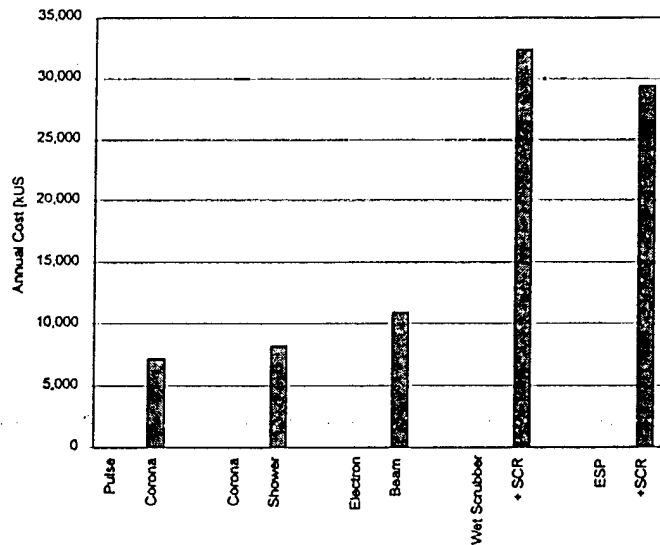
Figure 9 shows a comparison of annual cost for three example non-thermal plasma air pollution control systems compared with conventional technology for a JETC with an exhaust-gas flow rate of 1×10^5 Nm³/h (5.89×10^4 SCFM). Figure 10 shows a comparison of these plasma systems with conventional technology for model emissions for a JETC with a higher exhaust flow rate of 1.7×10^6 Nm³/h (1.0×10^6 SCFM).



Gas Flow Rate: $1.0 \times 10^5 \text{ Nm}^3/\text{h}$ ($5.89 \times 10^4 \text{ SCFM}$)

(k\$)	Pulsed Corona	Corona Shower	Electron Beam	Wet Scrubber + 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

Figure 9: Comparison of annual costs for three example NTP air pollution control systems compared with conventional technology for a JETC with an exhaust-gas flow rate of $1 \times 10^5 \text{ Nm}^3/\text{h}$ ($5.89 \times 10^4 \text{ SCFM}$).



Gas Flow Rate: $1.70 \times 10^6 \text{ Nm}^3/\text{h}$ ($1.0 \times 10^6 \text{ SCFM}$)

(k\$)	Pulsed Corona	Corona Shower	Electron Beam	Wet Scrubber + 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

Figure 10: Comparison of three example NTP systems with conventional technology for a JETC with a higher exhaust flow rate of $1.7 \times 10^6 \text{ Nm}^3/\text{h}$ ($1.0 \times 10^6 \text{ SCFM}$).

Although not disclosed in these figures, the costs of the electron accelerator and pulse generator comprise the majority of the total capital costs of the EB process the PC process, and the dielectric-barrier process, respectively. However, the DC power supply was not the main part of the CS process capital cost because it is much less expensive (by factors of 2-10) than an electron accelerator or a pulse generator. The most outstanding parameter which affects both the capital cost and operating cost is energy yield. Low energy yield implies a need for a lower capacity power supply and less electric power consumed. This is another reason that the corona shower process has the lowest total annual cost, including capital recovery. The total annual cost of a pulsed corona system is almost the same as an electron beam system. Both systems have slightly higher than the half of the total annual cost of a conventional combined system.

Although 50% of the produced fertilizer is assumed to be recovered, the recovery credit can be non-negligible. If electrostatic precipitators are used at both sides of each non-thermal

system, good quality fertilizer (ammonia sulfate/nitrate) could be obtained. For the conventional system, gypsum could be recovered, even if it is not a significant amount.

Recent Commercial Development in NTP De-NO_x

A cost analysis for the earlier-mentioned, modified dielectric-barrier Tecolytic™ system has been presented in reference [9]. The projected de-NO_x costs are reasonable and competitive with conventional catalytic technologies (see Figure 11).

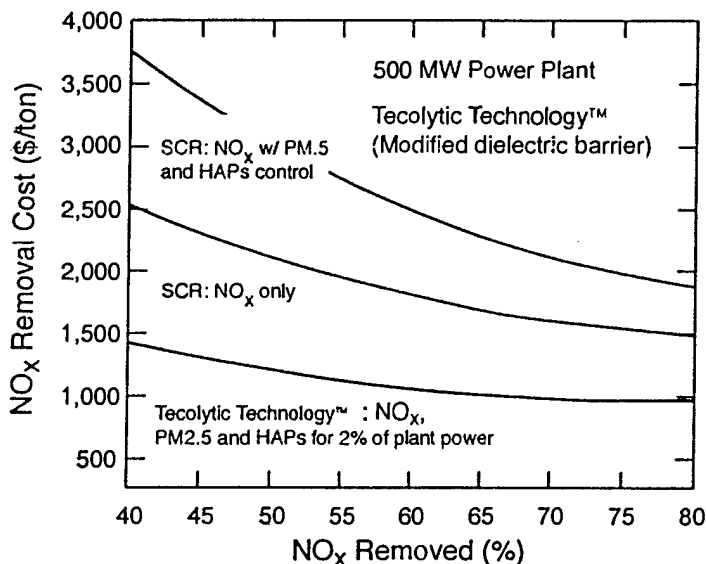


Figure 11: De-NO_x/particulate/HAP removal cost for commercial Tecolytic™ modified dielectric-barrier NTP reactor system [9]. The cost of this technology is quite low because it uses power supplies that are not capital-intensive (e.g., , 0.5-1.0 \$/W).

Conclusions/Summary

To a large extent, the present body of technical literature describing the treatment of air emissions with non-thermal plasmas (NTPs) mainly presents phenomenological descriptions of NTP reactor performance and, consequently in most cases, does not provide a consistent way to compare and/or predict the scaling and optimization properties of different NTP reactors. In a previous cost-analysis/economics White Paper, we presented a simple basis for comparing different types of NTP reactors, based on the concepts of: the plasma specific energy (electrical energy per unit volume deposited in the reactor active volume) required to remove a particular pollutant to a prescribed level in a defined exhaust-gas mixture and the associated yield (electrical energy cost per mass of pollutant removed).

In this report, we have shown the economics conclusions for candidate field-pilot demonstration systems and have also concentrated on pointing out the reasons that some cost assessments carried out in the past showed less favorable economic trends for de-NO_x by NTP technology. The main reasons for this were:

- Previous analyses examined stand-alone, or less mature electrical-discharge reactors, or electron-beam based systems that incorporated both chemical additives and quite expensive (both in terms of capital and maintenance costs) electron accelerators;
- Earlier analyses were based on systems which did not extensively incorporate methods to increase the yields (energy efficiency) of active NO_x-decomposing species.
- More mature NTP systems incorporating chemical additives and new-concept NTP technologies (namely, hybrid systems) did not then exist.

It should be emphasized that NTP is an emerging air-emissions control technology. Very few commercial systems exist. Also, for many emissions applications, the present forms of NTP technology are expected to be expensive (in terms of electrical power consumption) - and ancillary equipment (e.g., scrubbers) that may be necessary to handle treatment byproducts.

Realizing the performance and economic shortcomings of stand-alone NTP reactors, some workers in this discipline have proposed the use of staged or hybrid systems to better match particular air-emissions control applications. In this case, overall system scaling must be considered in terms of the separate parts of the emissions-control system - that is the NTP reactor itself and the other major components. Comparing different hybrid systems is considerably more complicated and was not treated in this report because no field-pilot or large-scale performance data are available for comparing different hybrids.

We have shown that the present trends for emerging NTP de-NO_x technologies are favorable. However, rigorous pilot-plant tests are required to provide further data and operating experience to more fully evaluate economic and performance projections. The demonstration of a small-scale, field-pilot unit remains a key goal of this project.

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