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Cost Analysis and Economic Assessment of Proposed Electric-Discharge Non-Thermal Plasma Processes for NO_x Removal in Jet-Engine Exhaust: White Paper for SERDP Project CP-1038

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Abstract

Incentives for implementing new pollution-control technologies are both regulatory and economic. Given considerable regulatory pressure (e.g., the promulgation of a NESHAPS for NO_x emissions in CY 2000), new de-NO_x technologies are being explored. One major reason for this is that conventional de-NO_x methods (like wet scrubbers plus Selective Catalytic Reduction - SCR) will not work effectively for the low NO concentrations (e.g., < 50 ppm), high exhaust-gas flow rates, and low gas temperatures characteristic of Jet Engines Test Cells (JETCs). This project is currently evaluating non-thermal plasma (NTP) technologies for treating jet-engine exhaust. In the past, economic analysis for NTP de-NO_x has shown that it is not cost effective, compared to other techniques. One might accept a high-cost system, if it can provide a function or functions that other (conventional) technologies cannot. However, it would certainly be better if a new technology could function as well or better than a conventional technology and do so at competitive costs. In this White Paper, we have analyzed the costs of some NTP technologies for jet-engine emissions control. In some cases, these analyses have shown lower exhaust-gas treatment costs for NTP systems compared to a baseline standard de-NO_x technology like SCR combined with wet scrubbing. Therefore, the main conclusion of this White Paper is that completing this project's work through the small field-pilot demonstration phase should proceed to provide further data and operating experience to more fully evaluate economic and performance projections for NTP de-NO_x technology.

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Introduction (Purpose and Topics of This White Paper)

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 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). This White Paper will cover 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. These two issues will be largely combined in this White Paper.

Economic evaluations are needed not only for the selection of the best-matched technology for a given practical application, but also for providing guidance for future R&D on candidate technologies.

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 quanties 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.

Conventional Activated Carbon Adsorbers

A very common post-combustion air-emissions control technique (for NO_x and other compounds) is to pass an exhaust stream through an adsorber system, thus capturing the entrained pollutants. Granular activated carbon (GAC) is the most commonly-employed adsorber medium for many air pollutants because it has a relatively low capital cost, has a very high surface area to volume ratio, and can adsorb a wide variety of compounds (Cummings & Booth 1996 [1], Vercammen et al 1997 [2]). However, when the GAC loses its ability to easily adsorb pollutants, it must be regenerated, reactivated, or disposed of as waste. In the processes of regeneration or reactivation, heated gases and/or steam are usually employed to desorb or strip the pollutants from the granules. These processes usually do not restore all of the adsorption capacity and the GAC must eventually be replaced, typically within five to ten cycles. If hazardous chemical pollutants are involved, handling, transportation, and permitting issues come into play - which can significantly increase costs. In summary [1, 2], GAC has the following properties:

- Simple and inexpensive at low exhaust-gas flow rates and low pollutants concentrations
- Can be used as a concentrator and, if product is recovered, this can offset the annual operating cost
- Desorbed compounds require ultimate disposal or further treatment
- GAC cartridges are sensitive to plugging and poisoning (deactivation)
- GAC must be periodically regenerated; at moderate to high flow rates and pollutant concentrations, the costs of off-site regeneration tend to outweigh the advantages of simplicity of use
- The adsorber deactivates over time
- The cost of treatment largely depends on the pollutant concentration
- GAC is best suited for short-term, low mass-flow applications
- GAC adsorber equipoment has a relatively high pressure drop
- Over a 10-year life cycle, about 90% of the cost of a GAC system is associated with operating expenses.

Conventional Catalytic Systems

For post-combustion NO_x control, the best presently available technologies (from a summary by Penetrante 1993 [3]) are Selective Catalytic Reduction (SCR), Selective Non-Catalytic Reduction (SNCR), RAPRENOx, and Non-Selective Catalytic Reduction (NSCR). SCR, which has been under development for over thirty years, employs ammonia injection into the emissions stream and the subsequent reduction of NO to N_2 on a catalyst. SNCR, which has been used for almost 25 years, does not use a catalyst but employs a combination of ammonia or urea-based reducing reagents and higher operating temperature (~ 370 C). The RAPRENOx process is similar to SNCR and surface catalysis; however, it uses isocyanic acid, rather than ammonia or urea, as an additive. NSNR uses hydrocarbon additives to reduce NO in the presence of a catalyst and was developed over fifty years ago. Choosing a process can be quite complicated because of a strong dependence on the particular characteristics of the combustion unit.

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.

The first civilian applications of NTPs for pollution control were focused on the removal of oxides of nitrogen and sulfur (NO_x, SO_x) with electron-beam reactors. The scrubbing of flue gases with electron-beam systems was initiated in 1970 in Japan by the Ebara Corporation (Frank & Hirano 1993 [4]) and extensively studied during that decade by Japanese scientists (Kawamura et al 1978 [5]), and, later, by others (Pearson & Ham 1988 [6]). A study on the decomposition of an organic compound (vinyl chloride) was published in the early 1980s by Slater & Douglas-

Hamilton 1981 [7] and, more recently, extensive work on VOCs has been done by the Karlsruhe group (Paur et al 1993 [8]).

Based on laboratory and small-scale studies of de-SO_x and de-NO_x, pilot plants and larger demonstration facilities were constructed and tested in Japan, the United States, and Germany (Kawamura et al 1979 [9], Frank et al 1987 [10], Fuchs et al 1987 [11], Jordan & Schikarski 1987 [12]). Chemical models to describe the process in reasonable agreement with experiments were first published by (Tokunaga et al 1984 [13], Busi et al 1985 [14], and Matzing 1991 [15]). Unfortunately, for the early scale-up demonstrations, a lack of commercial acceptance and unfavorable economics (especially the capital and maintenance cost of electron accelerators at that time) compared to conventional systems contributed to a loss of interest in the technology. This interest seems to have been renewed recently, as evidenced by the construction and operation of large-scale flue-gas treatment facilities in Europe (Chmielewski et al 1995 [16]).

The removal of SO_x and NO_x from gaseous media was also investigated at laboratory scale using electrical-discharge reactors (pulsed corona) in the 1980s - with pioneering experimental work performed for NO_x by Masuda & Nakao 1990 [17] and for SO_x by Mizuno et al 1986 [18]; and modeling work performed by Gallimberti 1988 [19]. Following these basic investigations, scale-up of the pulsed corona process for flue gases emitted from a coal-burning electrical power plant was carried out at pilot-plant and demonstration levels (Dinelli et al 1990 [20], Civitano et al 1993 [21]). The larger pilot-plant demonstrations appeared to show favorable economics ([21], Tamaki et al 1998 [22], Song et al 1997 [23]).

It should be noted that most electric-discharge NTP reactors mainly drive oxidative chemistry (using O-atom and OH-radicals), while most electron-beam NTP reactors drive reductive chemistry (using N-atoms). However, either type of reactor can be made to operate in a reductive mode by adding chemicals which enhance the production of reducing radicals (e.g., NH_3). Hydrocarbons can also be added to change the final product distributions of the effluent gas.

Several non-thermal plasma technologies for de-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 [24], 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 [25], 1990 [26]; Walker 1996 [27]). 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 [26].

Table 1: Measured emissions for Tinker AFB JETCs (F101 & F110 engines)

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 (Rooftop)*	——	< 7.0	26.0	25.0	6.0	0.28

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

Figure 1 shows a schematic diagram which illustrates the jet-engine exhaust-gas sampling methods employed to acquire the data in Table 1 [26].

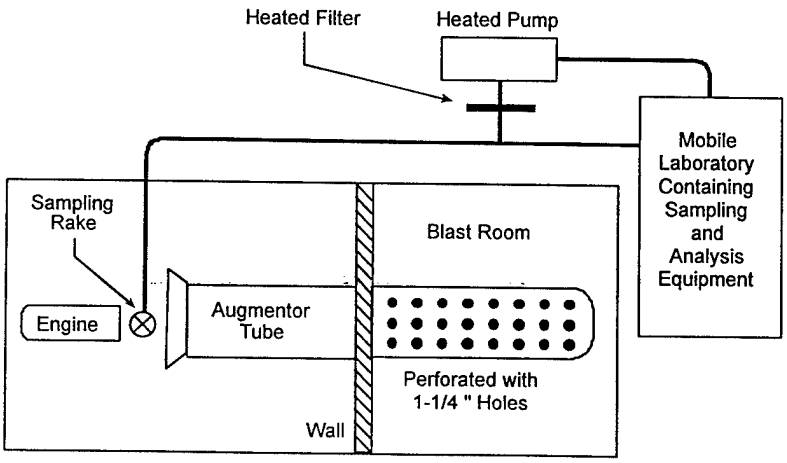


Figure 1: Schematic diagram of jet-engine emissions sampling methods [26].

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 [27]. 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.

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 [26] and Walker 1996 [27], 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.

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 [28].

Limitations on and Advantages of Feasible NTP Architectures

In our context, the term architecture refers to the way in which an NTP reactor system is configured to treat a gaseous-emissions stream (exhaust gas, stack/flue gas). A previous report [29] discusses the concepts of monolithic and modular scaling architectures. In this present report, we will not be concerned with the type of scale-up architecture - emphasis will be given to generic "black box" NTP reactors.

Stand-Alone NTP Reactor Systems

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-NOx. To render NTP technology viable, one must consider the addition of chemical additive to the exhaust stream (e.g., NH_3 is commonly used to create additional reactive species) or coupling the NTP reactor to another stage (e.g., an adsorber).

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 [30], Korzekwa & Rosocha 1997 [31]). 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, for 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 3 (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 [28], 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.

Another potential economical niche for NTP de-NO_x technology is the intermediate flow regime, characterized by CMTCs (5,000-10,000 SCFM). However, we believe that this will require NTP reactors in combination with other systems. Two promising candidates for this

application are the NTP + adsorber system and the corona radical shower reactor system, which will be discussed in greater detail below.

Figure of Merit and Optimization

Optimizing the performance (degree of removal of the pollutant, decomposition products, energy consumption, etc.) of an NTP reactor is a complicated process. NTP processing can be quite energy intensive (especially for chlorinated/fluorinated VOCs). Therefore, in this section, we will concentrate on a discussion of reactor electrical energy consumption, because preliminary economic analysis indicates that the major cost of an NTP reactor system resides in the cost of the electrical power supply, assuming one uses readily-available power supplies - which are usually not well-matched to a plasma load. In some cases the power supply might be 75-90% of the plasma reactor cost. This cost is expected to fall with the development of better-matched, state-of-the-art power supplies and operation of the plasma reactor at more optimal treatment conditions.

For many compounds for which the removal is not too sensitive to the initial pollutant concentration, the removal can be described by [32]

$$(1) \qquad [X] = [X]_0 \exp(-\bar{E}/\beta),$$

where $[X]_0$ is the initial pollutant concentration, $[X]$ is the resulting concentration, $\bar{E}$ is the applied specific energy (or plasma power divided by gas flow rate, P/Q), and β is the e-fold energy density. Supplying one β to the reactor reduces the concentration by 1/e, 2β by $1/e^2$, and so on.

A useful figure of merit for the decomposition of pollutants is defined by the energy delivered to the plasma per hazardous molecule removed from the gas stream. At any instant, this can be expressed as the following quantity obtained by solving Equation 1 for $\bar{E}$ and taking the derivative:

$$(2) \qquad \gamma_i = -\frac{d\bar{E}}{d[X]} = -\frac{d[-\beta \ln(\frac{[X]}{[X]_0})]}{d[X]} = \frac{\beta}{[X]}.$$

This is the instantaneous energy cost per molecule removed; a more practically-useful parameter is the integral, or average, energy cost γ

$$(3) \qquad \gamma = \frac{\bar{E}}{[X]_0 - [X]} = \frac{-\beta \ln(\frac{[X]}{[X]_0})}{[X]_0(1-\frac{[X]}{[X]_0})}.$$

Here, the energy cost per molecule is expressed in terms of the β-value, the degree of removal, and the initial concentration. As an example, Figure 2 gives $\bar{E}$ (same as power/gas flow, P/Q) and γ (number of eV of deposited energy per NO molecule removed) for an NO-in-air mixture. The γ-value translates into an actual electrical energy cost for the process. Another convenient unit for the figure of merit is the number of kilowatt-hours required to remove a kilogram of hazardous compound (i.e., kW-h/kg). For a γ-value of 100 eV/molecule (a reasonable

estimate for some electric-discharge reactors), approximately 125 kWh/kg of NO are required. At an electrical energy cost of 5¢/kWh and the above γ-value, NO removal costs about $6.25 per kg ($27,500/ton), based only on the cost of energy into the plasma and neglecting other efficiency factors like those for the power supply and the cost of ancillary equipment).

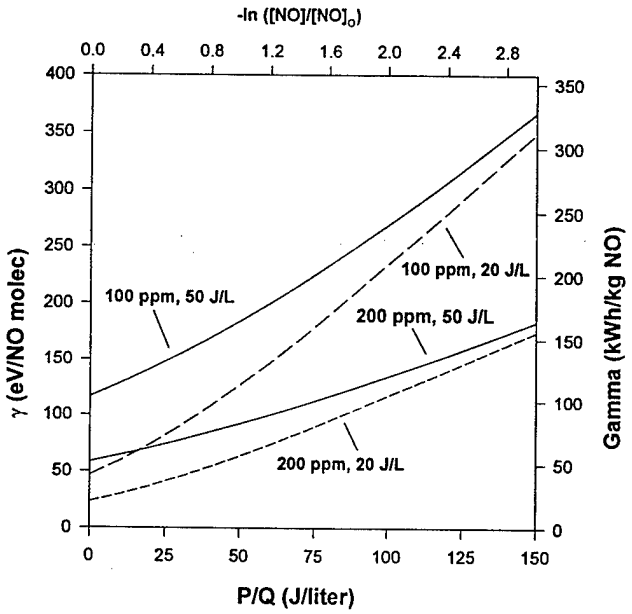


Figure 2: Energy costs and degree of removal for NO removal in an NO-air mixture with one e-fold plasma specific energies of 50 J/liter and 20 J/liter. NO is one of several compounds whose β-value is not very sensitive to the initial concentration; therefore, the removal energy costs decrease as the concentration increases (note 200 ppm case vs 100 ppm case).

Recently-presented work (Penetrante 1997 [33]) on the fundamental limits for the removal of NO from engine exhaust gases (without adding NH_3 or hydrocarbons), based on gaseous electronics and plasma chemistry considerations (without heterogeneous reactions at aerosol particle surfaces), has shown that the energy costs are 40 eV/NO molecule when reductive chemistry dominates and 18 eV/NO molecule when oxidative chemistry is dominant. Using the γ-value of 18 eV/molecule, approximately 15.7 kW-hr/kg NO removed are required. At an electricity cost of 5 ¢/kW-h, the NO-removal electrical cost is about 79 ¢/kg (about $3,500/ton). It should be noted that the oxidative channel principally results in the conversion of NO to NO_2, which does not change the total NO_x concentration a great deal. The reductive channel, which leads to $N_2 + O_2$ is preferable because less ancillary equipment (like an NO_2 trap/scrubber) is required in the de-NO_x system.

What Equation 2 tells us is that the instantaneous energy cost per pollutant molecule removed is lower when the pollutant concentration is high. This makes intuitive sense because, at high concentration, active species always have a high probability of reacting with a target molecule. Equation 3 tells us that the average energy cost per removed molecule is lower at lower degrees of pollutant removal. In optimizing reactor performance, one can conceive of somehow

adjusting the active species concentrations so that the ratio of pollutant concentration to active-species concentration is always relatively large. This way the probability of attack is high, while both the specific energy $\bar{E}$ and the degree of removal ($[X]/[X]_0 \sim 1$) are low.

Two possible ways of achieving this optimization are constructing a continuous-flow reactor whose energy density decreases as the residence time of the treated gas in the reactor increases or constructing a serial train of reactors, each having optimal plasma energy density. One might even construct the first reactor such that it contains individual, segmented excitation regions (like a serial train within a single reactor).

Alternative NTP Reactor Architectures - 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 GAC section above: 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 3). 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 Equation 1 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.

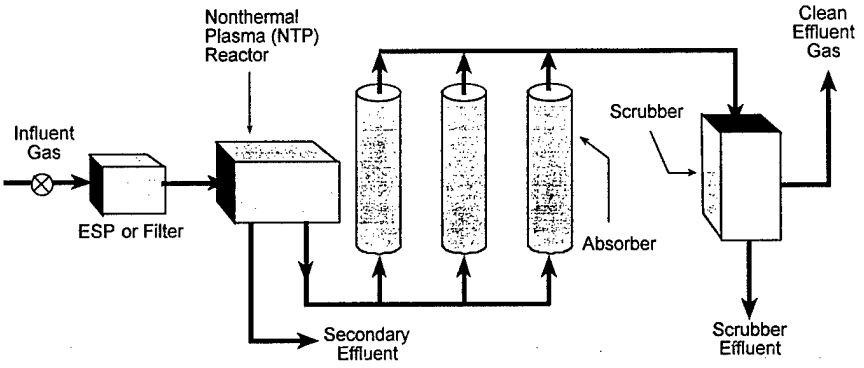


Figure 3: Serial-mode NTP-absorber architecture. Disposal and/or regeneration economic advantage comes from reducing the load on the absorber. Treatment effectiveness can also be increased if the NTP reactor converts the initial pollutant into more easily-absorbed compounds.

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 4). 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.

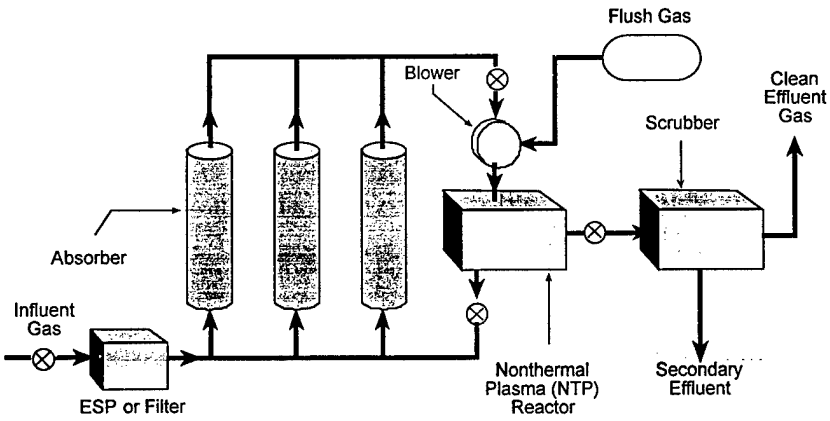


Figure 4: Regeneration-mode NTP-absorber architecture. Economic and performance advantages may be gained by regenerating the absorbers off-line from pollutant capture, but employing on-site, rather than off-site handling.

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.

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 [34], Tonkyn et al 1997 [35], Wander & Penetrante 1997 [36]). Much of this work has been focused on lean-burn diesel engines, whose oxygen-rich exhaust streams tend to enhance the oxidative conversion path $NO \rightarrow NO_2$ 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 $NO \rightarrow N_2 + O_2$ (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 $NO \rightarrow NO_2$ 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: NO_2 + catalyst + hydrocarbon $\rightarrow N_2 + CO_2 + H_2O$. Such systems are being explored by other researchers in fundamental, benchtop studies and are expectred to be tested at pilot-stage under another SERDP project (Wander & Penetrante [36]). In our future work, we intend to more fully evaluate plasma-catalytic systems for DoD applications (in particular JETCs and diesel motor-generator exhausts).

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 [37] and Chang et al 1998 [38]). This device is more fully described in an earlier report to SERDP (Matsuoka et al 1997 [39]). Here, a brief summary of the system will be presented.

In the CRS system (see Figure 5), 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.

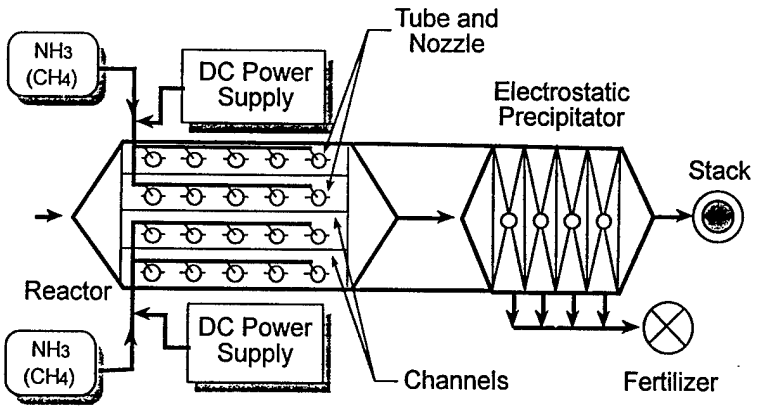


Figure 5: Schematic diagram of CRS reactor. Ammonia (NH_3) or methane (CH_4) are added to generate radicals that drive reactions leading to the formation of particulates; these particulates are then captured by the electrostatic precipitator. Some of the captured products are useful for agricultural 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. 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.

Historical Cost Analysis for NTP De-NO_x and Associated Problems

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 [40]) 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 [4], Frank 1993 [41]) or pulsed corona (Civitano 1993 [21]). Bartoszek at al, 1998 [42] 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 [41] 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 [4] 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 [21] 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 [43]) 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 subscale 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.

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. We will do the best we can in making comparisons using the best available interpretable data. Our practice will be 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 [44] 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 Economic Calculations for NTP De-NO_x

Recent Work by Kim and Chang

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 [39, 44]. Future reports will provide more detailed economic and cost-benefit analyses for NTP processing. 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. 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 [44], 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.

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 [22], Song et al 1997 [23]), Li et al 1998 [24]). 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.

Summary of the Model

Scale-Up Procedure

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.

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 NH_3 and hydrocarbons, are also quite important factors in the economic evaluation.

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	Conventional
$[NO]_0$	ppm	300	200	230	300
NOx Removal	%	60	70	80	80
$[SO_2]_0$	ppm	1,000	800	1,000	3,050
SO_2 Removal	%	90	95	95	90
Energy Yield**	g-NO_x/kWh	20	374	56	-
Scale	Nm^3/h	600	12	20,000	1.9×10^6

* Data from Dinelli et al 1990 [20], Bartosek et al 1998 [42], EPRI 1983 [45], Masuda 1993 [40], Ebara Company Commercial Catalogue CC3402J 1998. ** All electric power assumed to contribute to NO_x removal.

The input and output data parameters included in the model are shown in Table 5; these data cover technical parameters like emissions data, as well as economic parameters. Some of output results are used to calculate the capital cost and others the annual cost.

Table 5: Input and calculated output data parameters used in the model.

Common Input Data	Pilot-Test Input Data	Scale-Up Calculated Data	Output Data
Source Data Plant Power Capacity Factor Gas flow rate Gas Composition Temperature **Emissions Data** $[NO]_0$ NO_x Removal $[SO_2]_0$ SO_2 Removal **Unit Price** Electric Power NH3 CH4 Ar Water Fertilizer Personnel **Economic Data** Depreciation Period Inflation Rate Real Interest rate Nominal Interest Rate Salvage Rate	**Added Gas** Stoichiometric Ratios of NH_3 HC (CH_4, C_2H_4) **Water-Spray Cooler** Temperature **NTP Reactor** Reactor Geometry Module Flow Rate **Power Supply** Max. Power of Unit Efficiency (Input → gas) Max. Peak Voltage **Energy Yield** for NO_x for SO_x **Dust Collector** Efficiency Migration Velocity Geometry Fertilizer Recovery	**Exhaust Gas** NO_x Mass Flow Rate SO_x Mass Flow Rate NH_3 Consumption HC Consumption **Water-Spray Cooler** Cooler Volume Water Consumption **NTP Reactor** Geometry No. Channels/Modules Electrode Area Gas Velocity **Power Supply** Total Input Power No. of Supply Units **Fertilizer** Ideal Total Production Recovery **Dust Collector Module** Collecting Area Geometry	**Total Capital Investment** **Total Direct Cost** Water-Spray Cooler NTP Reactor Power Supply Dust Collector Instrumentation Other Equipment **Total Indirect Cost** **Total Annual Cost** **Direct Annual Cost** Utilities (Power) Chemicals NH_3 HC Personnel Cost Laboratory Cost Maintenance Cost Capital Recovery Fertilizer Recovery **Levelized Annual Cost** Levelization Factor Levelized Busbar Cost

Economic Calculations - Including Cost Categories and Breakdowns

The economic evaluation follows Vatavuk's procedure (Vatavuk 1990 [46]). The total capital investment is composed of depreciable and nondepreciable investments. 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 can then be reduced. The total capital investment enters into the indirect annual cost as the item of capital recovery. The important items of total capital investment and total annual cost are shown in Table 6 below.

Table 6: Total capital investment and total annual costs.

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

For these calculations, the period of construction is ignored - so called "overnight construction". The inflation rate is that typically used in most utility cost evaluations. But any taxes are not included.

As shown in Table 6, some calculated design values in the scale-up part for commercial power plants are related to the estimated direct capital costs, and others are estimated direct annual costs. 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 [46]; Bartoszek et al 1998 [42]). The cost capacity factor is assumed to be in the range 0.1- 1.0. Generally, the factor is around 0.6 - 0.7 for large plants, and 0.3 - 0.4 for pilot plants (Frank and Hirano 1990 [47], Bartoszek et al 1998 [42]).

The economic estimate can also allocate credits for the sale of any useful by-products. It is expected that most of non-thermal plasma systems using NH_3 will produce good fertilizers (ammonium sulfate and nitrate salts). As Frank and Hirano proposed, a system design which yields a salable sulfurous by-product 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 cost being levelized by economic data such as a depreciation period, an interest, and a salvage rate. The detail economic procedure to get the levelized costs or levelized

busbar costs can be found in reports from the Electric Power Research Institute (EPRI 1983 [45], 1991 [48]).

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.

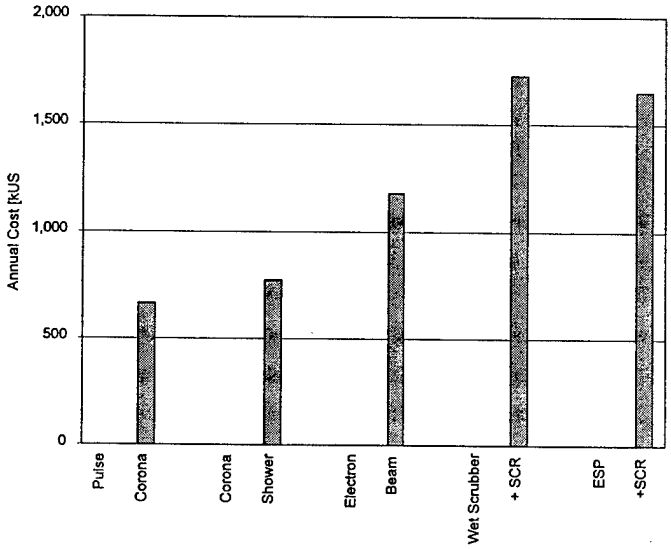
Nevertheless, at this time an economic evaluation must be made to provide information about which system is most suitable for a given JETC or CMTC emissions source. Therefore this work has tried to evaluate the cost of three non-thermal systems and compare these with a conventional, combined wet-scrubber/selective 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 7 below.

Table 7: Common input data for economic calculations.

Source Data				
Plant Type: JETC				
	Variable	**Units**	**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_2O	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	Pr_{gas}	mm H_2O	720	
Emission Data				**Removal (%)**
NOx	C_{NOx}	ppm	36.00	70
SO2	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	

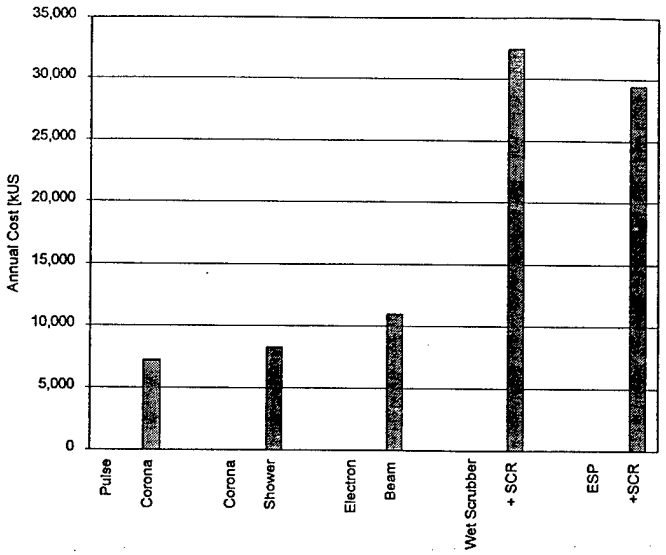
Figure 6 shows a comparison of annual cost for the three non-thermal plasma air pollution control systems compared with conventional technology for a JETC with an exhaust-gas flow rate of $1x10^5$ Nm^3/h ($5.89x10^4$ SCFM). Figure 7 shows a comparison of the three plasma systems with conventional technology for model emissions for a JETC with a higher exhaust flow rate of $1.7x10^6$ Nm^3/h ($1.0x10^6$ SCFM).



Gas Flow Rate: 1.0×10^5 Nm^3/h (5.89×10^4 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 6: Comparison of annual costs for three NTP air pollution control systems compared with conventional technology for a JETC with an exhaust-gas flow rate of $1x10^5$ Nm^3/h ($5.89x10^4$ SCFM).



Gas Flow Rate: 1.70 x 10^6 Nm^3/h (1.0 x 10^6 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 7: Comparison of four plasma systems with conventional technology for a JETC with a higher exhaust flow rate of $1.7x10^6$ Nm^3/h ($1.0x10^6$ 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.

A summary of important input factors and calculated results are shown in Tables A-1 and A-2 in the Appendix.

Other Recent Commercial Development in NTP de-NO_x

An example of an NTP reactor that has been commercialized for flue-gas treatment is the Tecolytic™ modified dielectric-barrier reactor + lime scrubber system (from Thermo-Power Corp., Bittenson & Breault 1998 [49]). The company's stated objective is to "develop a zero discharge NO_x control process using no hazardous reagents or catalysts". Figure 8 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 $Mg(OH)_2$ and slaked Mg-enhanced lime, which scrubs out SO_2 to make gypsum ($CaSO_4 \cdot 2H_2O$), 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.

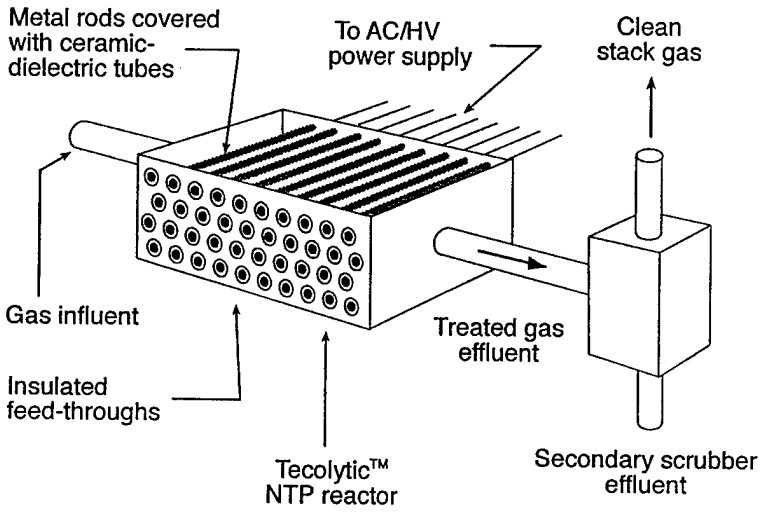


Figure 8: Schematic diagram of commercial Tecolytic™ modified dielectrc-barrier NTP reactor system for de-NO_x/SO_x (flue-gas treatment).

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.

A cost analysis for the Tecolytic™ system has been presented in the above reference [49]. The projected de-NO_x costs are reasonable and competitive with conventional catalytic technologies (see Figure 9).

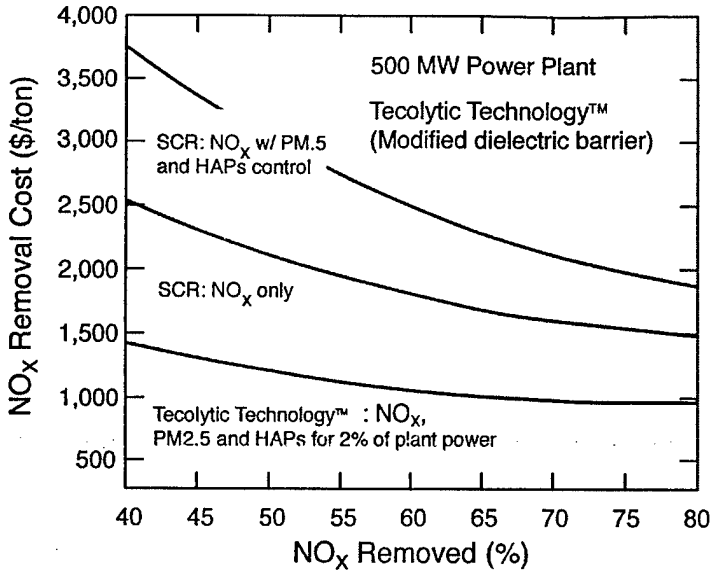


Figure 9: De-NO_x/particulate/HAP removal cost for commercial Tecolytic™ modified dielectric-barrier NTP reactor system.

Conclusions/Summary

The largest share of 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 this report, we have attempted to present a simple basis for comparing different types of NTP reactors, based on the concept 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.

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.

We have shown that the present trends for emerging NTP de-NOx 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 is a key goal of this project.

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Appendix

Table A-1: Important factors and results for JETC exhaust gas flow rate of 1.0×10^5 Nm^3/h (5.89×10^4 SCFM)

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	0.4	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
Economic Results	Input 1 for kUS$, 2 for MUS$					
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	388	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)					