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Power Consumption and Byproducts in Electron Beam and Electrical Discharge Processing of Volatile Organic Compounds

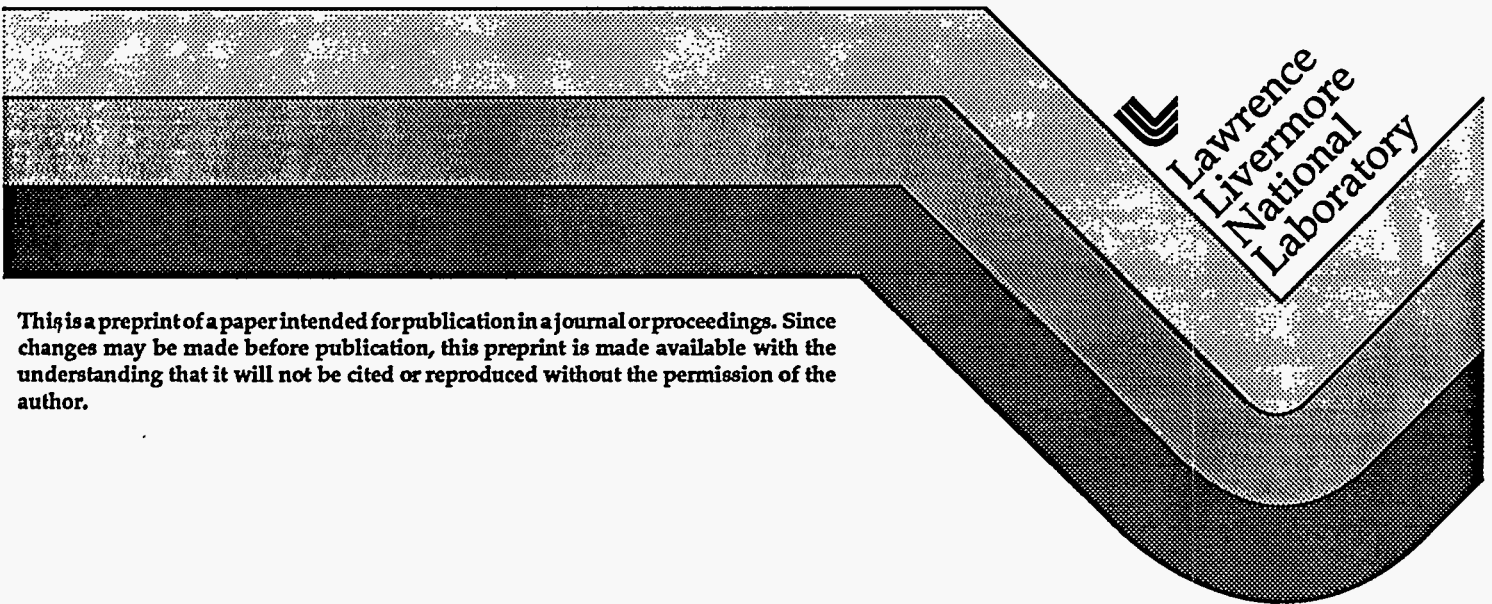B. M. Penetrante, M. C. Hsiao, J. N. Bardsley
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POWER CONSUMPTION AND BYPRODUCTS IN ELECTRON BEAM AND ELECTRICAL DISCHARGE PROCESSING OF VOLATILE ORGANIC COMPOUNDS

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Abstract

Among the new methods being investigated for the post-process reduction of volatile organic compounds (VOCs) in atmospheric-pressure air streams are based on non-thermal plasmas. Electron beam, pulsed corona and dielectric-barrier discharge methods are among the more extensively investigated techniques for producing non-thermal plasmas. In order to apply non-thermal plasmas in an industrial scale, it is important to establish the electrical power requirements and byproducts of the process. In this paper we present experimental results using a compact electron beam reactor, a pulsed corona and a dielectric-barrier discharge reactor. We have used these reactors to study the removal of a wide variety of VOCs. The effects of background gas composition and gas temperature on the decomposition chemistry have been studied. We present a description of the reactions that control the efficiency of the plasma process. We have found that pulsed corona and other types of electrical discharge reactors are most suitable only for processes requiring O radicals. For VOCs requiring copious amounts of electrons, ions, N atoms or OH radicals, the use of electron beam reactors is generally the best way of minimizing the electrical power consumption. Electron beam processing is remarkably more effective for all of the VOCs we tested. For control of VOC emissions from dilute, large volume sources such as paint spray booths, cost analysis shows that the electron beam method is cost-competitive to thermal and catalytic methods that employ heat recovery or hybrid techniques.

INTRODUCTION

Volatile organic compounds (VOCs) are emitted from numerous manufacturing processes. In most of these processes, either for raw materials, intermediates, or finished products, VOC-containing materials are present as

chemicals, solvents, release agents, coatings, and decomposition products that eventually must be disposed of.

The control of VOC emissions from dilute, large volume sources such as paint spray booths is a challenging problem. Conventional technologies, such as carbon adsorption/solvent recovery or catalytic/thermal oxidation have high annual costs per ton of VOC emissions controlled. With a large gas flow rate (50,000 to 250,000 cfm) and low solvent concentrations (100 ppm or less) of no possible reuse value, operating costs for conventional systems over five years can greatly exceed the installed capital cost.

In order to reduce the operating cost, novel low-temperature (ambient to 125°C) treatment technologies are being sought. The emerging technologies include low-temperature catalysts, biofiltration and non-thermal plasmas. Catalysts easily suffer from plugging, fouling or poisoning by particulates and non-VOC materials in the exhaust stream (Ref. 1); this results in high maintenance costs. The major disadvantage of biofilters is their large specific footprint, typically 100-400 square feet per 1,000 cfm of treated gas (Ref. 2). Biofilter systems and filter materials may also require costly maintenance and replacement.

Non-thermal plasma processing is an emerging technology for the abatement of dilute concentrations of VOCs (Ref. 3). Either electrical discharge or electron beam methods can produce these plasmas. The basic principle that these techniques have in common is to produce a plasma in which a majority of the electrical energy goes into the production of energetic electrons, rather than into gas heating. Through electron-impact dissociation and ionization of the background gas molecules, the energetic electrons produce free radicals, ions and additional electrons which, in turn, oxidize, reduce or decompose the pollutant molecules. This is in contrast to the use of plasma furnaces or torches and several chemical techniques in which the whole gas is heated in order to break up the undesired molecules.

Electrical discharge and electron beam methods can both be implemented in many ways. There are many types of electrical discharge reactors, the variants depending on the electrode configuration and electrical power supply (pulsed, AC or DC). Some of the types of electrical discharge reactors that have been investigated for VOC abatement include the pulsed corona (Refs. 4-5), ferroelectric packed bed (Ref. 4), dielectric-barrier discharge (Refs. 5-8), surface discharge (Ref. 9), gliding arc (Ref. 10) and microwave discharge (Ref. 11). Two of the more extensively investigated types of discharge reactors are based on the pulsed corona and dielectric-barrier discharge. In the pulsed corona method, the reactor is driven by very short pulses of high voltage, thus creating short-lived discharge plasmas that consist of energetic electrons, which in turn produce the free radicals responsible for the decomposition of the undesirable molecules. In a dielectric barrier discharge reactor, one or both of the electrodes are covered with a dielectric layer, such as glass or alumina. Whereas in the pulsed corona method the transient behavior of the plasma is controlled by the applied voltage pulse, the plasma that takes place in a dielectric-barrier discharge self-extinguishes when charge build-up on the dielectric layer reduces the local electric field. Dielectric-barrier discharge reactors, also referred to as silent discharge reactors, are now routinely used to produce commercial

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quantities of ozone. Unfortunately, the plasma conditions suitable for the generation of ozone are not the same plasma conditions optimum for the destruction of most VOCs.

The electron beam method has been applied to the removal of vinyl chloride (Ref. 12), trichloroethylene (Refs. 13-15), trichloroethane (Ref. 15), carbon tetrachloride (Refs. 16-18) and other types of volatile hydrocarbons encountered in industrial off-gases (Refs. 18-19). In the past, the high capital cost and x-ray hazard associated with conventional MeV-type electron beam accelerators have discouraged the use of electron beam processing in many pollution control applications. Recently, however, compact low-energy (<200 keV) electron accelerators have been developed to meet the requirements of industrial applications such as crosslinking of polymer materials, curing of solvent-free coatings, and drying of printing inks. Special materials have also been developed to make the window thin and rugged. Some of these compact electron beam sources are already commercially available and could be utilized for many pollution control applications.

In this paper we will present a comparative assessment of various non-thermal plasma reactors. The thrust of our work has been two-fold: (1) to understand the scalability of various non-thermal plasma reactors by focusing on the energy efficiency of the electron and chemical kinetics, and (2) to identify the byproducts to ensure that the effluent gases from the processor are either benign or much easier and less expensive to dispose of compared to the original pollutants. We will present experimental results using a compact electron beam reactor, pulsed corona reactor and dielectric-barrier discharge. We have used these reactors to study the removal of a wide variety of VOCs. We have studied the effects of background gas composition and gas temperature on the decomposition chemistry. For all of the pollutants investigated, we find that electron beam processing is remarkably more energy efficient than pulsed corona or dielectric-barrier discharge processing. Preliminary cost analysis based on these data show that the electron beam method is cost-competitive to advanced thermal and catalytic methods that employ heat recovery or hybrid techniques.

TEST FACILITY

All of our experiments were performed in a flow-through configuration. To characterize the energy consumption of the process for each VOC, the composition of the effluent gas was recorded as a function of the input energy density. The input energy density, Joules per standard liter, is the ratio of the power (deposited into the gas) to gas flow rate at standard conditions (25°C and 1 atm). The amount of VOC was quantified using an FTIR analyzer and a gas chromatograph.

Our electron beam reactor, shown schematically in Figure 1, used a cylindrical electron gun designed to deliver a cylindrically symmetric electron beam that is projected radially inward through a 5 cm wide annular window into a 17 cm diameter flow duct. An electron beam of 125 keV energy was introduced into the reaction chamber through a 0.7 mil thick titanium window. The electron beam current was produced from a low-pressure helium plasma in an annular vacuum

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chamber surrounding the flow duct. This novel design facilitates highly uniform (efficient) irradiation of the flowing gas. The non-plasma produced by the electron beam is capable of decomposing the VOCs in polluted gas streams at high flow rates.
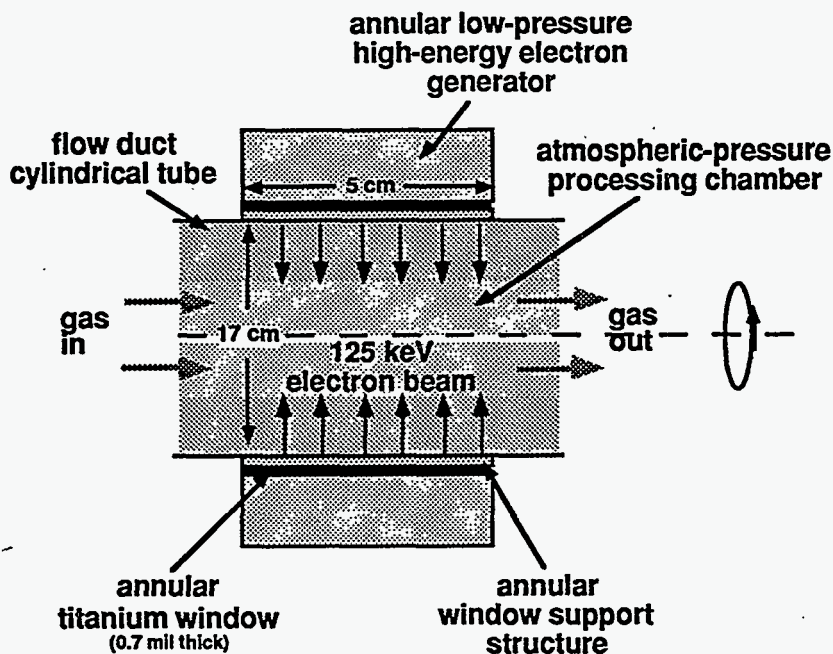

Figure 1. Schematic of the compact electron beam reactor developed by First Point Scientific, Inc. The cylindrical electron gun is designed to deliver a cylindrically-symmetric highly-uniform electron beam that is projected radially inward into the gas flow duct.

Our pulsed corona reactor is a 1.5 mm diameter wire in a 60 mm diameter metal tube 300 mm long. The power supply is a magnetic pulse compression system capable of delivering up to 15-35 kV output into 100 ns FWHM pulses at repetition rates from 15 Hz to 1.5 kHz. The power input to the processor was varied by changing either the pulse energy or pulse repetition frequency. For the same energy density input, either method produced almost identical results. The gas mixtures were set with mass flow controllers. The gas and processor temperatures can be maintained at a temperature that can be controlled from 25°C to 300°C.

We investigated whether it is possible to improve the processing efficiency by taking advantage of transient high electric fields during the formation of the streamer plasma. To do this, the voltage pulse should be very fast-rising, but with a pulse length short enough so that most of the radical production occurs only during streamer propagation. One way of achieving this condition is by combining the fast-rising, strongly non-uniform applied electric field of a corona reactor with the self-extinguishing microdischarge pulses of a dielectric-barrier discharge reactor. We therefore used a reactor that is a form of hybrid between a pulsed corona reactor and a dielectric-barrier discharge reactor. The reactor consisted of a wire (1.5 mm

diameter) in a 300 mm long dielectric (alumina) tube with inner and outer diameters of 28 mm and 35 mm, respectively. The middle 150 mm of the dielectric tube has aluminum foil coating the outside to form the outer electrode.

RESULTS AND DISCUSSION

Whatever the type of reactor, the plasma can induce three basic types of reactions with the VOC molecules, as shown in Figure 2. The electron mean energy in a plasma reactor is very important because it determines the types of radicals produced in the plasma and the input electrical energy required to produce those radicals. Figure 3-(a) shows the dissipation of the input electrical power in a dry air discharge. Note that at low electron mean energies (< 5 eV) a large fraction of the input electrical energy is consumed in the vibrational excitation of N_2. Electron mean energies around 5 eV are optimum for the electron-impact dissociation of O_2, which is important for the production of O radicals. These oxidizing radicals play a key role in the generation of ozone and the initial decomposition of some types of VOCs. For VOCs that take advantage of electron-induced or ion-induced decomposition, high electron mean energies are required to efficiently implement the ionization of the background gas.

The rate coefficients for electron-impact dissociation and ionization reactions strongly depend on the electron energy distribution in the plasma. In pulsed corona and dielectric-barrier discharge reactors, the non-thermal plasma is produced through the formation of statistically distributed microdischarges. The electrons dissociate and ionize the background gas molecules within nanoseconds in the narrow channel formed by each microdischarge. The electron energy distribution in the plasma is complicated because the electric field is strongly non-uniform (e.g. because of strong space-charge field effects) and time dependent. However, most of the species responsible for the chemical processing are generated in the microdischarge channels already established during the main current flow. In each microdischarge column, the electrons acquire a drift velocity, v_d, and an average energy corresponding to an effective E/n, i.e., the value of the electric field E divided by the total gas density n. The efficiency for a particular electron-impact process can be expressed in terms of the G-value (number of dissociation or ionization reactions per 100 eV of input energy) defined as
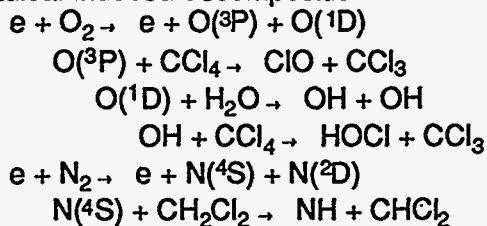
$$G\text{-value} = 100\, k\, /\, (v_d\, E/n) \qquad (1)$$

where k is the rate coefficient (cm^3/molec-s). The rate coefficient k represents the number of reactions in a unit volume per unit time. The quantity v_d E/n represents the amount of energy expended by the electrons in a unit volume per unit time. In Figure 3-(b) the calculated G-values for various electron-impact dissociation and ionization processes in dry air are shown as functions of the electron mean energy in the discharge plasma.

Under most conditions encountered in pulsed corona or dielectric-barrier discharge processing, the effective E/n is close to the value for breakdown (Paschen field) (Refs. 20-21). For dry air, the effective E/n is around 130 Td (1 Td = 10^{-17} V-cm^2), which corresponds to an electron mean energy of about 4 eV. This analysis
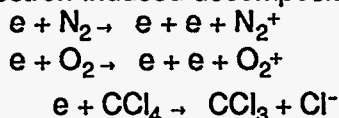
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suggests that the attainable electron mean energy in electrical discharge reactors is rather limited and cannot be significantly enhanced by changing the electrode configuration or voltage pulse parameters.

Radical-induced decomposition

$$e + O_2 \rightarrow e + O(^3P) + O(^1D)$$
$$O(^3P) + CCl_4 \rightarrow ClO + CCl_3$$
$$O(^1D) + H_2O \rightarrow OH + OH$$
$$OH + CCl_4 \rightarrow HOCl + CCl_3$$
$$e + N_2 \rightarrow e + N(^4S) + N(^2D)$$
$$N(^4S) + CH_2Cl_2 \rightarrow NH + CHCl_2$$

Electron-induced decomposition

$$e + N_2 \rightarrow e + e + N_2^+$$
$$e + O_2 \rightarrow e + e + O_2^+$$
$$e + CCl_4 \rightarrow CCl_3 + Cl^-$$

Ion-induced decomposition

$$N_2^+ + CH_3OH \rightarrow CH_3^+ + OH + N_2$$

Figure 2. There are three basic types of chemical reactions responsible for the decomposition of volatile organic compounds: (a) decomposition via oxidation by O and OH free radicals or reduction by N atoms, (b) electron-induced decomposition via dissociative electron attachment, and (c) ion-induced decomposition via dissociative charge exchange.
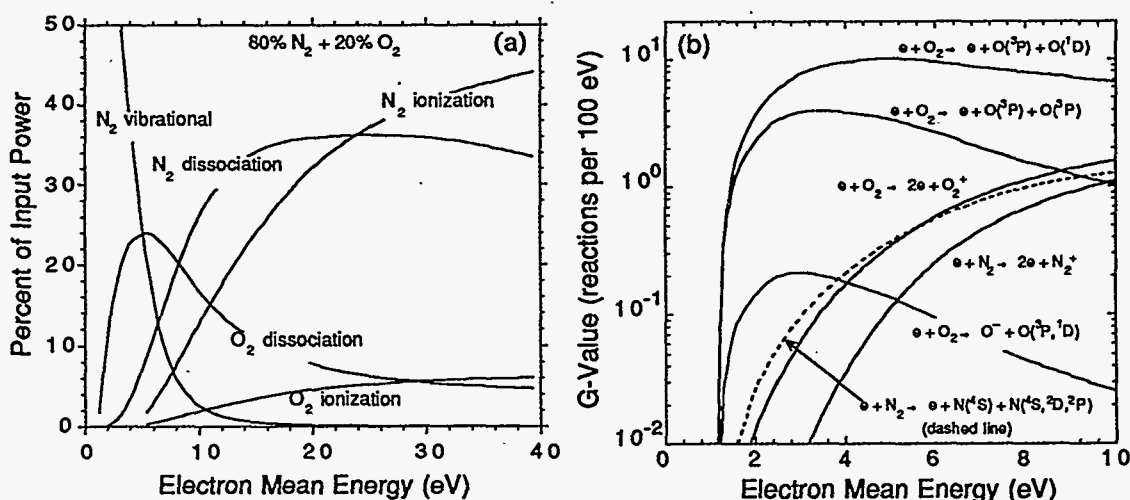

Figure 3. (a) Electrical power dissipation in a dry air discharge, showing the percent of input power consumed in the electron-impact processes leading to vibrational excitation, dissociation and ionization of N_2 and O_2. (b) Calculated G-values (number of reactions per 100 eV of input energy) for dissociation and ionization processes in dry air, shown as functions of the electron mean energy in a discharge plasma.
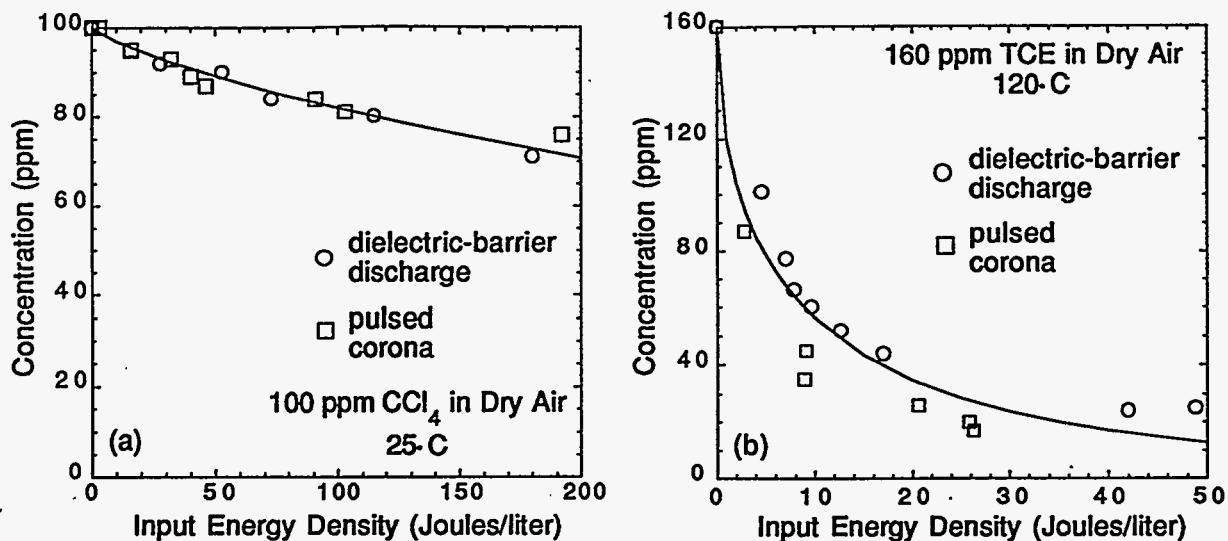
Figure 4. Pulsed corona and dielectric-barrier discharge processing of (a) 100 ppm carbon tetrachloride in dry air at 25°C and (b) 160 ppm trichloroethylene in dry air at 120°C. There is no significant difference in the performance of different types of electrical discharge reactors.
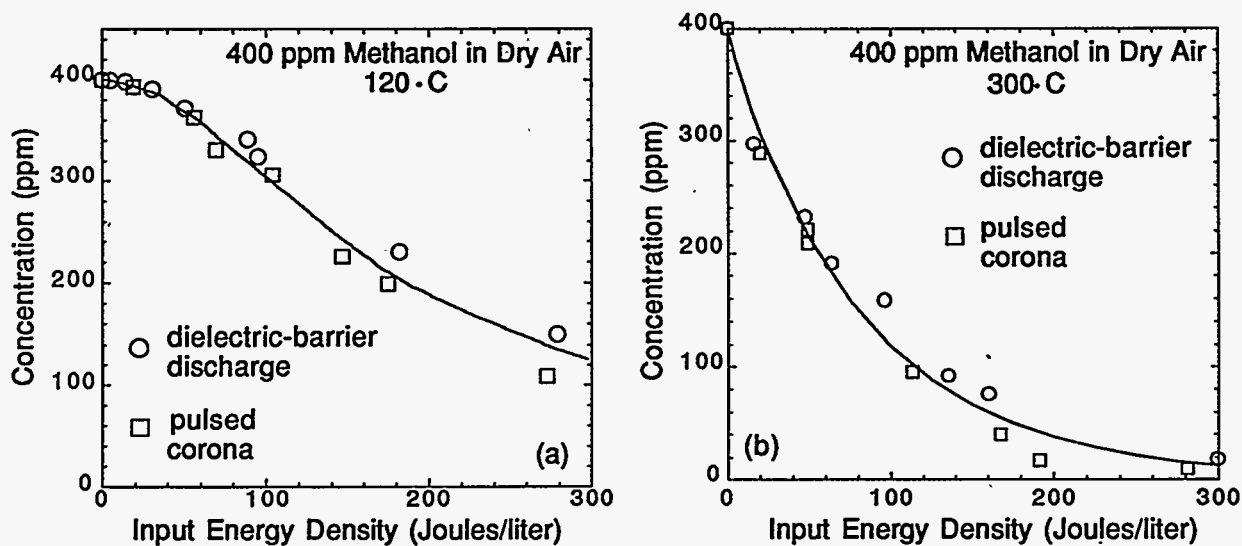

Figure 5. Pulsed corona and dielectric-barrier discharge processing of 400 ppm methanol in dry air at (a) 120°C and (b) 300°C. There is no significant difference in the performance of different types of electrical discharge reactors.

Under identical gas conditions (gas composition and gas temperature), we see no significant difference in the energy efficiency of various types of electrical discharge reactors. Figure 4-(a) shows the comparison between pulsed corona and dielectric-barrier discharge processing of carbon tetrachloride in dry air at 25°C. Figure 4-(b) shows the comparison between pulsed corona and dielectric-barrier

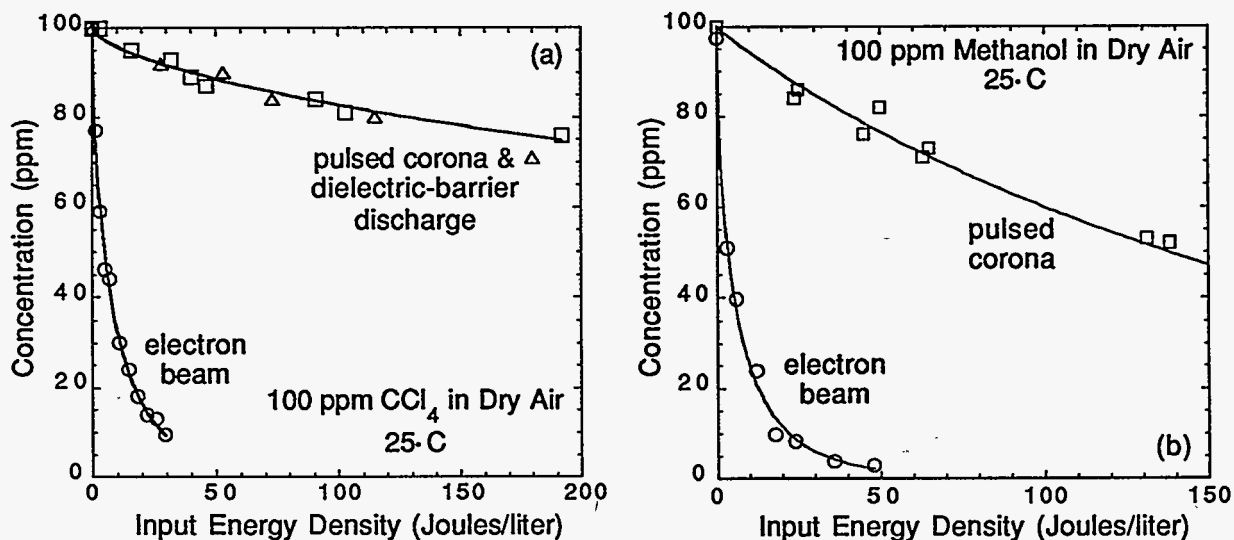discharge processing of trichloroethylene in dry air at 120·C. Figures 5-(a) and 5-(b) shows the comparison between pulsed corona and dielectric-barrier discharge processing of methanol in dry air at 120·C and 300·C. We now have considerable experimental evidence showing that all discharge reactors have the same energy consumption for identical gas conditions (Refs. 5,21).

Figure 6-(a) shows a comparison between electron beam, pulsed corona and dielectric-barrier discharge processing of 100 ppm carbon tetrachloride (CCl_4) in dry air at 25·C. The rate limiting step in the decomposition of CCl_4 is determined by the dissociative attachment of CCl_4 to the thermalized electrons in the created plasma (Refs. 16,17):

$$e + CCl_4 \rightarrow Cl^- + CCl_3. \qquad (2)$$
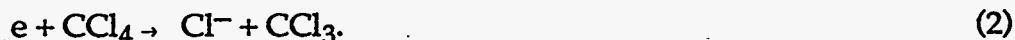
During the creation of the plasma, electron-ion pairs are produced through primary electron-impact ionization of the bulk molecules, such as $e + N_2 => e + N_2^+$ and $e + O_2 => e + O_2^+$, and the corresponding dissociative ionization processes for N_2 and O_2. An analysis of the rates of the reactions discussed above suggests that the energy consumption for CCl_4 removal is determined by the energy consumption for creating electron-ion pairs. The energy density required to decompose CCl_4 by 90% is around 20 Joules/liter and 1270 Joules/liter by electron beam and electrical discharge processing, respectively. This result demonstrates that for VOCs requiring copious amounts of electrons for decomposition, electron beam processing is much more energy efficient than electrical discharge processing. The main products in the plasma processing of CCl_4 in air are Cl_2, $COCl_2$ and HCl. These products can be easily removed from the gas stream; e.g. they dissolve and/or dissociate in aqueous solutions and combine with $NaHCO_3$ in a scrubber solution to form NaCl (Ref. 22).
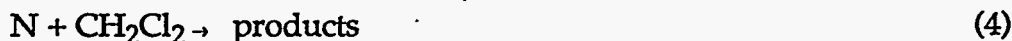

Figure 6. (a) Electron beam, pulsed corona and dielectric-barrier discharge processing of 100 ppm carbon tetrachloride in dry air at 25·C. (b) Electron beam and pulsed corona processing of 100 ppm methanol in dry air at 25·C. Electron beam processing is much more energy efficient compared to electrical discharge processing.

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Figure 6-(b) shows a comparison between electron beam and pulsed corona processing of 100 ppm methanol in dry air at 25·C. For the case of methanol, the electron beam method is more efficient because the decomposition proceeds mainly via a dissociative charge exchange reaction

$$N_2^+ + CH_3OH \rightarrow CH_3^+ + OH + N_2 \qquad (3)$$
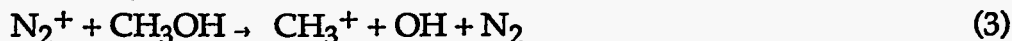
The OH radicals resulting from the initial decomposition reaction (3) in turn may lead to additional decomposition of methanol via OH + CH_3OH. To verify that the primary decomposition during electron beam processing does not proceed through an oxidation pathway using O radicals, we performed the experiment using N_2 as the background gas; the specific energy consumption for electron beam processing in dry air is almost identical to that in N_2.

Not all compounds have strong dissociative electron attachment or dissociative ion charge exchange rates. Figure 7-(a) shows a comparison between electron beam and pulsed corona processing of 100 ppm methylene chloride (CH_2Cl_2) in dry air at 25·C. For methylene chloride, the dissociative attachment rate to electrons is many orders of magnitude lower compared to carbon tetrachloride. In this case, the electron beam method is also more efficient because the initial decomposition proceeds via a reaction with the N atom

$$N + CH_2Cl_2 \rightarrow products \qquad (4)$$

The energy efficiency for dissociation of N_2 to produce N atoms is much higher in an electron beam reactor.
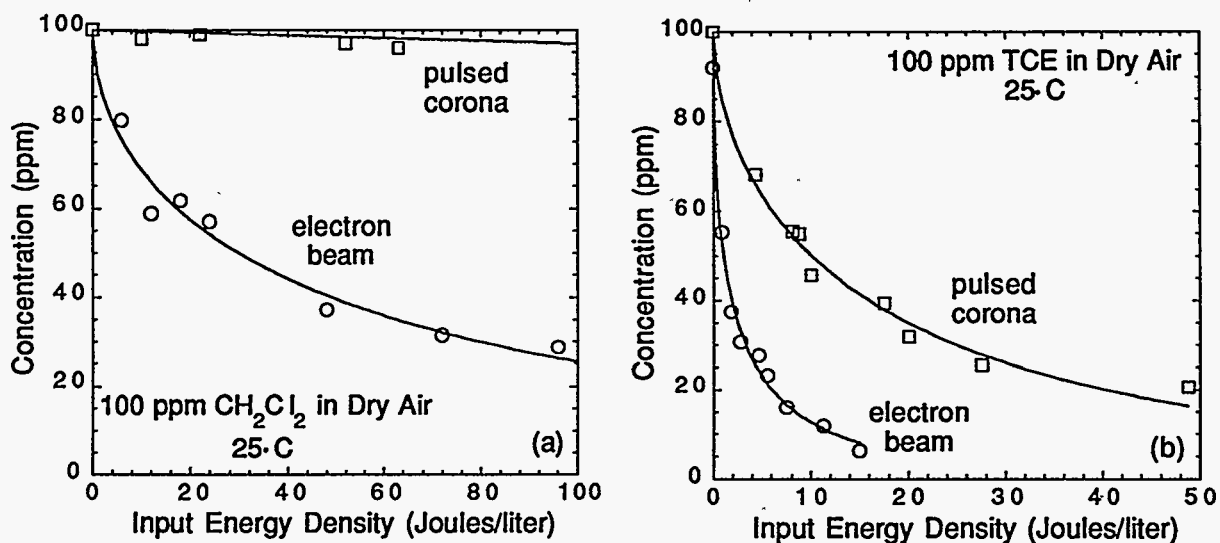

Figure 7. Comparison between electron beam and pulsed corona processing of 100 ppm of (a) methanol and (b) trichloroethylene in dry air at 25·C. Electron beam processing is much more energy efficient compared to electrical discharge processing.

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For the case of trichloroethylene (C_2HCl_3 or TCE), the initial decomposition pathway can proceed efficiently by reactions with either electrons (in the electron beam method) or O radicals (in the electrical discharge method). Figure 7-(b) compares electron beam and pulsed corona processing of 100 ppm trichloroethylene in dry air at 25·C. The energy consumption for TCE removal is relatively small using either electron beam or electrical discharge methods. This is because of a chain reaction mechanism involving chlorine (Cl) radicals. The reaction of TCE with electrons or O radicals initiates the detachment of Cl radicals. Other TCE molecules then decompose by Cl radical addition to the carbon-carbon double bond

$$Cl + CHClCCl_2 \rightarrow products \tag{5}$$
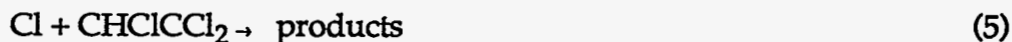
The decomposition pathway (5) regenerates more Cl radicals, which react with other TCE molecules, causing a chain reaction. Our byproduct measurements and material balance analysis point to significant amounts of dichloroacetyl chloride (DCAC), phosgene, and hydrochloric acid in addition to smaller amounts of CO and CO_2 in the effluent.

The case of trichloroethane ($C_2H_2Cl_3$ or TCA) is interesting in comparison to TCE. TCA and TCE have very similar electron attachment cross sections, yet the energy required for decomposition of TCE by electron beam processing is more than 10 times less than for TCA. The TCA molecule decomposes primarily through hydrogen abstraction by chlorine and oxygen radicals, whereas the TCE molecule decomposes through chlorine and oxygen radical addition to the carbon-carbon double bond. The carbon-carbon single bond in TCA is not susceptible to chlorine radical attack. The chain reaction mechanism possible with chlorinated ethylenes therefore does not occur with chlorinated ethanes (Ref. 15).

The above decomposition mechanisms provide examples of how the chemistry could strongly affect the economics of the process. In some cases it will be necessary to experimentally or theoretically obtain fundamental information on rate constants and branching ratios in order to understand the energy consumption and byproduct formation in the plasma process. Computer modeling of the plasma chemical kinetics serves as an important design tool for minimizing the energy consumption of the process and identifying all possible byproducts.

Tables I and II show why electron beam processing is much more effective than electrical discharge processing in decomposing VOCs. Table I shows a comparison of the calculated G-values (number of reactions per 100 eV of input energy) for dissociation processes in dry air using an electron beam and a discharge reactor. Discharge plasma conditions are optimum for the dissociation of O_2, whereas electron beam conditions are optimum for the dissociation of N_2. Table II shows a comparison of the calculated G-values for ionization processes in dry air using an electron beam and a discharge reactor. The efficiency for production of electron-ion pairs is much higher in an electron beam reactor compared to that in electrical discharge reactor.

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Table I. Calculated G-values for dissociation processes in dry air using an electron beam and an electrical discharge reactor.

REACTION	Electron Beam	Discharge
$e + N_2 \rightarrow e + N(^4S) + N(^4S, ^2D, ^2P)$	1.2	0.17
$e + O_2 \rightarrow e + O(^3P) + O(^3P)$	1.3	4.0
$e + O_2 \rightarrow e + O(^3P) + O(^1D)$	2.65	10.0
$e + O_2 \rightarrow O^- + O(^3P, ^1D)$	0.11	0.19

Table II. Calculated G-values for ionization processes in dry air using an electron beam and an electrical discharge reactor.

REACTION	Electron Beam	Discharge
$e + N_2 \rightarrow 2e + N(^4S, ^2D) + N^+$	0.69	$< 10^{-6}$
$e + N_2 \rightarrow 2e + N_2^+$	2.27	0.044
$e + O_2 \rightarrow 2e + O_2^+$	2.07	0.17
$e + O_2 \rightarrow 2e + O(^1D) + O^+$	1.23	0.0016

COST ESTIMATES

Table III shows the comparison between pulsed corona and electron beam processing of various VOCs in dry air at room temperature. As mentioned previously, we observe no significant difference in the performance of pulsed corona and dielectric-barrier discharge reactors. For all the compounds we tested, electron beam processing is more energy efficient than either pulsed corona or dielectric-barrier discharge processing.

Assuming a nominal energy cost of 10 Joules/liter to decompose a mixture of volatile organic compounds from 100 ppm to 10 ppm, the electron beam power required for an 80,000 cfm total gas flow rate application is 380 kilowatts. Some commercial electron beam generators now cost as low as $2 per beam watt. A 380 kilowatt electron beam system would therefore have a capital cost of $760,000. This corresponds to a capital cost of less than $10 per cfm. This is cheaper than thermal oxidation methods that use advanced heat recovery. Similarly, the five year operating cost (based on $0.05/kWh electricity cost with 4,000 hours operation/year) is less than $5 per cfm. Again the operating cost of the electron beam method is much lower than those of advanced thermal oxidation or carbon adsorption.

Straightforward engineering is the major advantage of electrical discharge methods. However, the electrical energy consumption of electrical discharge reactors are excessive, as can be deduced from Table III. If we assume that a pulsed corona or dielectric-barrier discharge reactor consumes only 5 times more energy per VOC

molecule, i.e., 50 Joules/liter to decompose the VOC from 100 ppm to 10 ppm, then the power required is 1.9 megawatts. Even though the capital cost for discharge reactors may be low, the operating costs over several years can greatly exceed the capital cost because of the large electrical energy consumption.

Table III. Comparison between pulsed corona and electron beam processing of 100 ppm VOC in dry air at room temperature. Energy density (Joules per standard liter) required for 90% decomposition of the VOC. Based on experimental data taken at Lawrence Livermore National Laboratory and First Point Scientific, Inc.

VOC	Electron Beam	Pulsed Corona
Trichloroethylene	6	38
O-Xylene	10	370
Ethylene	15	83
Methanol	15	450
Carbon Tetrachloride	20	1277
Toluene	34	1586

Table IV shows nominal air pollution control costs using various VOC control technologies. An energy cost in the range of 10-30 Joules/liter was assumed to decompose 100 ppm of VOC using electron beam processing. A pulsed corona or dielectric-barrier discharge reactor consumes at least 5 times more energy per VOC molecule. For the capital costs, it was assumed that $2/watt for electron beam, $1/watt for pulsed corona, and $0.20/watt for dielectric-barrier discharge are required. The five year operating cost is based on $0.05/kWh electricity cost with 4,000 hours operation/year. For control of emissions from dilute, large volume sources of VOCs, this preliminary cost estimates show that

(1) the operating cost of electrical discharge methods such as pulsed corona or dielectric-barrier discharge is excessive,.

(2) the electron beam method is the preferable non-thermal plasma technique, and

(3) the electron beam method is cost-competitive to thermal and catalytic methods that employ heat recovery or hybrid techniques.

A realistic comparison between different VOC control technologies must include all factors. These include: (1) energy costs; (2) capital costs; (3) operating costs; (4) maintenance costs; (5) pollutant removal efficiency; (6) generation of secondary pollutants; (7) plugging/fouling/poisoning; (8) reliability/downtime; (9) safety; and (10) equipment life.

Table IV. Cost comparison of various VOC control technologies for the case of a paint spray booth operating at a gas flow rate of 80,000 cfm containing 70 ppm MEK and 30 ppm toluene.

System	Capital Cost*	Operating Cost**	Total Five Year Cost***
Regenerative Thermal Oxidizer	$1,200,000	$240,000 / year	$2,400,000
Carbon Concentrator + Catalytic Oxidizer	$1,600,000	$54,000 / year	$1,870,000
Electron Beam	$760,000	$76,000 / year	$1,140,000
Pulsed Corona	$1,900,000	$380,000 / year	$3,800,000
Dielectric-Barrier Discharge	$380,000	$380,000 / year	$2,280,000

*Assumes $2/watt for electron beam, $1/watt for pulsed corona, and $0.2/watt for dielectric-barrier discharge.
**Based on $4/million BTU fuel cost and $0.05/kWh electricity cost with 4,000 hours operation/year.
***Total capital cost plus five-year operating costs.

CONCLUSIONS

There are basically two types of non-thermal atmospheric-pressure plasma reactors: (1) electrical discharge reactors and (2) electron beam reactors. Many different variants of electrical discharge reactor have been proposed. Two of the more extensively investigated types of discharge reactors are based on the pulsed corona and dielectric-barrier discharge. The most mature discharge reactor is the dielectric-barrier discharge reactor used for ozone generation. However, the optimum conditions for ozone generation are not the optimum conditions for VOC destruction. There is now considerable experimental evidence showing that all discharge reactors have similar energy consumption under identical gas conditions. We have found that pulsed corona and other types of electrical discharge reactors are most suitable only for processes requiring O radicals. For VOCs requiring copious amounts of electrons, ions, N atoms or OH radicals, the use of electron beam reactors is generally the best way of minimizing the electrical power consumption. Electron beam processing is remarkably more effective for all of the VOCs we tested. Cost analysis shows that the electron beam method is cost-competitive to thermal and catalytic methods that employ heat recovery or hybrid techniques.

ACKNOWLEDGMENTS

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