DESTRUCTION EFFICIENCY AND POWER USAGE

FOR A SINGLE DIELECTRIC BARRIER

DISCHARGE PLASMA REACTOR

By

AMANDA KATHLEEN BENSON

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PLASMA REACTOR

Thesis Approved:

Dr. John Veenstra

Thesis Adviser
Dr. Arland Johannes

Dr. Dee Anne Sanders

Dr. A. Gordon Emslie

Dean of the Graduate College

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1. Introduction

Project Background

Currently, Tinker Air Force Base (TAFB) operations include the maintenance of U.S. military, Air Force, and Navy airplanes. The act of surface coating the airplanes in a paint booth produces effluent gas that contains hazardous air pollutants which are regulated under Subpart GG of 40 Code of Federal Regulations (CFR) Part 63 for Aerospace Manufacturing and Rework Facilities source category. TAFB switched to low volatile organic compound (VOC) and paint in order to meet the stationary major source threshold of 10 tons per year required by the Clean Air Act (CAA). Expensive end-of-process treatment technology would have been required to meet the standards required by the CAA if the switch to low solids/low VOC paint had not been made. However, the new paint has required more frequent applications due to poor performance and weathering (Hall 2005); therefore, TAFB requires a new treatment technology that will allow a return to the higher VOC and solid content paint.

Typical VOCs found in TAFB paint include: ketones, aromatic hydrocarbons, and isocyanates. Since painting is typically conducted in 1 to 2

hours, in periods typically lasting 12 to 25 minutes, per 8-hour shift or 3 to 6 hours per day, the technology would need to incorporate an "instant-on" and "instant off" feature. It should not require continuous operation in order to meet the 90% reduction requirement of which current treatment technologies are capable. Oklahoma State University has been researching the ability of plasma reactors to destroy VOC pollutants such as tetrachloroethylene, trichloroethylene, and toluene for over ten years (Veenstra, Johannes et al. 2005).

Purpose

TAFB has sponsored multiple phases of development for the plasma technology to treat the VOC emissions from their paint booth operations. Previous phases of the project have focused on designing a reactor with ability to scale-up, modeling the process, and understanding the applications for the technology. The initial phase of the project studied the scalability of the reactor by analyzing ozonators and a straw-like packing system. Phase two calculated scale-up properties and analyzed specific flow rates for the system. The third phase built a scaled-up reactor, but was unable to determine cost data and actually test the new scaled reactor. In this, the final stage of the project, the scaled-up reactor was tested for operational information such as destruction efficiency, power usage, and cost. Toluene was used as a representative compound because it is relatively safe, compared to other compounds found in exhaust, and is readily available (Veenstra, Johannes et al. 2005).

2. Literature Review

Volatile Organic Compounds

General Health Issues

Volatile organic compounds or VOCs can be a serious air pollution problem that can adversely affect human health. In 1990, following the promulgation of the Clean Air Act Amendments, certain pollutant sources were required to treat hazardous air pollutants (HAPs), including VOCs, to maximum control technology (MACT) standards (Agnihotri, Cal et al. 2004). The various chemicals that fall under the category of VOCs can cause minor problems such as headaches, sore throats, and dizziness. However, some forms of cancer, liver and kidney diseases, and paralysis of the nerve centers are also attributed to long-term VOC exposure (Chen, Tzeng et al. 2004).

Tinker Air Force Base falls under the source category of Aerospace Manufacturing and Rework Facilities under Subpart GG of 40 Code of Federal Regulations (CFR) Part 63. Paint booth operations are required to limit the emissions of the VOCs found in the paint emissions to under the stationary major source threshold of 10 tons per year required by the Clean Air Act. Current abatement technologies meet a 90% reduction of emissions; therefore, in order

to be competitive, any new technologies should reach this level (Veenstra, Johannes et al. 2005).

Toluene Related Health Issues

Toluene ($C_6H_5CH_3$) is a VOC found in the emission from the Tinker paint booth (Hall 2005) and was used in this study because it is easily accessible, and therefore less costly, and safer to work with compared to other VOCs found in the paint booth exhaust. Humans can be exposed to toluene through contact with skin and eyes, inhalation, and ingestion. Typical symptoms associated with toluene exposure are eye and nose irritation, weakness or exhaustion, confusion, euphoria, dizziness, headache, pupil dilation, anxiety, muscle fatigue, insomnia, paresthesia, dermatitis, lacrimation, and liver or kidney damage. These problems occur when toluene affects the respiratory system, central nervous system, eyes, skin, liver, and the kidneys of a person (CDC 2005). Table 2.1 gives the reference doses set by the United States Environmental Protection Agency (EPA) for toluene:

Table 2.1 Reference Doses

Exposure Route	Reference Dose (RfD)	Adverse Effect
Oral	0.08 mg/kg-day	Increased kidney weight
Inhalation	5 mg/m3	Neurological effects (i.e. Headache, dizziness, impaired vision and hearing, etc.)

(EPA 2005)

Toluene has been classified as a Group D contaminant by EPA's Integrated Risk Management System (IRIS) which indicates it is "not classifiable as to human

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carcinogenicity," or there is not enough data to verify whether it is or is not a carcinogen (EPA 2005).

Treatment Options

There are many treatment alternatives for the removal of VOCs; a few commonly used options include oxidation, adsorption, scrubbing, biofiltration, and other new technologies.

Oxidation

Thermal oxidation attempts to completely combust contaminants to water and carbon dioxide. This is accomplished by raising the temperature of the material above the autoignition point. Many factors contribute to the total efficiency of thermal oxidation such as time, temperature, turbulence, and available oxygen. There are various types of thermal oxidizers but all have a flame produced from a nozzle stabilization unit that requires fuel combined with the waste stream and additional air. Some examples of various thermal incinerators include: direct flame, recuperative, and regenerative systems.

Design residence times are usually around one second, with temperatures ranging from 650 to 1,100 degrees Celsius (°C). Specific temperature and residence time varies with the specific pollutant to reach destruction efficiencies as high as 99.9999%. Since designs are specific to each pollutant stream, the treatment system is not easily changed once it has been built. Consequentially, the influent gas stream should remain consistent for the system to work

properly. Some pollutants such as halogenated organics may require additional

treatment such as a caustic scrubber or a post-oxidation water scrubber to

remove corrosive effluent gases (Moretti 2002).

Catalytic oxidation is similar to thermal oxidation with the addition of a

catalyst bed after the combustion chamber. The catalyst, which is usually a

metal oxide or precious metal such as palladium or platinum, allows for much

lower temperatures in the combustion chamber. Catalyst exhaust temperatures

are no higher than 540 to 675 degrees Celsius. After being mixed, heated, and

passed through a heat exchanger, waste gas is sent to the catalyst bed, where

diffusion of the pollutant onto the catalyst material occurs. The pollutants are

then oxidized, and their products are released back into the waste stream.

Catalysts must be monitored to prevent coating by particulate matter which can

hinder the oxidation process. Advantages of catalytic oxidation include lower

temperatures and less fuel required, which leads to a smaller overall footprint

(Moretti 2002).

Adsorption

Adsorbers are designed based on the specific pollutant characteristics and

the properties of the adsorbent used. Waste gas first passes through a filter to

prevent particle deposits from contaminating the system. Next, the waste

stream passes onto the adsorber bed at a determined optimum temperature.

The bed needs to be regenerated periodically after saturation has occurred.

Regeneration usually consists of heating or vacuum cleaning to desorb the

waste. Fans then dry the system and direct vapors to a vapor recovery system such as a condenser. Since periodic cleaning is required, duplicate beds must be provided to ensure continual system operation. Activated carbon is a commonly used adsorption material, but polymers and zeolite can also be used. Adsorption can handle variations in concentration and can reach a removal efficiency of 95% (Moretti 2002).

Scrubbing

Scrubbing or absorption is used on high concentration waste streams by passing the stream through an appropriate solvent. How soluble the pollutant is and what solvents are available affect the potential efficiency of the system. Water and mineral oils are commonly used solvents. The solvent must be cleaned after use and other treatment such as a water treatment system or a stripping technique may be required after the scrubber system. This could produce many potential problems and additional costs (Moretti 2002). A common type of absorption is the "wheel absorption and incineration type" which can reach efficiencies greater than 90%. However, the wheel part of the system has the potential to be blocked by VOCs with high boiling points which lowers the efficiency. This blockage could cause a fire hazard in the incineration step (Chen, Tzeng et al. 2004).

Biofiltration

Biofiltration utilizes a natural material, continually moistened, in which microorganisms reside. The waste stream passes through the material and the biofilter converts the pollutants into non-hazardous compounds. Some designs incorporate a closed system so that the temperature and humidity may be more easily monitored. Since the system utilizes microbial growth, it is very important that temperature, humidity, pH, and nutrient levels are carefully monitored. Biofiltration works the best for low molecular weight compounds and can reach removal efficiencies better than 90%. The filter bed must be replaced after a few years, when it becomes too clogged to work properly. Pilot testing is necessary prior to use, so that proper parameters can be determined for the specific waste stream (Moretti 2002).

Emerging Technologies

Two emerging technologies in the treatment of VOCs include ultraviolet oxidation (UV) and plasma technology. UV oxidation utilizes strong oxygen based oxidants such as ozone, peroxide, and hydroxyl free radicals combined with UV radiation to excite the oxidants. Excited oxidants then destroy the VOCs. Some post treatment may be necessary such as a wet scrubber to remove acids formed or a carbon adsorber for unreacted VOCs. UV oxidation is advantageous since pollutant byproducts are not formed, and they are energy efficient for low concentration waste streams (Moretti 2002).

Plasma

Definition

Plasma is considered the fourth state of matter found in space and in nature. Some examples of plasma in space include solar winds and nebula, while examples in the natural environment include lightening bolts and auroras. Examples of current plasma technology include fluorescent lights, computer applications, and thin plasma televisions. Plasma systems may also be used in research and industry to treat surfaces and for the destruction of VOCs (Fridman and Kennedy 2004).

Plasma works by electrically heating gas to a high ionization state which initiates dissociation in the pollutants by the formation of free-radicals (Moretti 2002). There are two distinct types of plasma that can be formed: equilibrium or thermal plasma and nonequilibrium or cold plasma. Whether the plasma is in equilibrium is based on the kinetic energy of the particles. If the kinetic energy of the ions is higher than those of the neutral molecules, the plasma is not in equilibrium. When the kinetic energies are the same, the plasma is said to be in equilibrium. Equilibrium plasma may also be called thermal plasma due to higher temperatures increasing the likelihood of the energies to find equilibrium. An advantage of a cold plasma is that smaller portions of a volume may be excited at a time, leaving a large portion of the gas intact (Eliasson and Kogelschatz 1991a). Nonthermal plasmas are also advantageous for their lower energy cost compared to incineration techniques and for low potential pressure drops compared to adsorption and absorption techniques. Another advantage is the

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potential to destroy organics, such as VOCs, and inorganics, such as NO and SO_2, through the same reactor (Cal and Schluep 2001).

Within nonequilibrium plasmas, there are five types of discharges distinguished by how the plasma is generated, the operation pressure, and the geometry of their electrodes. They are as follows: glow discharge, corona discharge, microwave discharge, radio frequency (RF) discharge, and silent discharge (Eliasson and Kogelschatz 1991a).

Types of Cold Plasma

Glow Discharge

Typical glow discharge plasma can be seen in fluorescent light bulbs used for neon signs and energy efficient indoor light bulbs. Glow discharge is practical for this application as opposed to chemical production due to the low pressure and therefore low mass flow of the system. Standard pressures for this system are below 10 mbar which produces high electron energy and a distinct homogeneous glow for each specific gas used. An advantage to this system is the low current and voltage required to produce the plasma. Commonly used setups for glow discharge plasma include a tube system encasing two flat electrodes with a space between them for the plasma to form (Eliasson and Kogelschatz 1991a).

Corona Discharge

Corona discharge plasma is characterized by the small volume usable for dissociation. Inhomogeneous electrodes such as the most common, a pointed electrode directed toward a flat electrode, form a dome-shaped discharge unique to corona type plasma. The plasma is more effective closer to the pointed electrode and less effective closer to the plate electrode. Very low pressures are required for stable formation, but higher pressures (1 bar) such as atmospheric pressure can be used if the field is increased to compensate. There are two types of corona discharge, positive and negative. Depending on the geometry of the point electrode, a specific voltage is required to produce the corona and a positive discharge. If this voltage is exceeded, a negative corona is formed; however, breakdown of the corona plasma occurs if too high a voltage is used. Common uses for corona discharge include electrostatic precipitators, copy machines, dry-ore separators, radiation detection, and treatment of polymer surfaces (Eliasson and Kogelschatz 1991a).

Microwave Discharge

Microwave discharge plasma works well over a large pressure range, 1 mbar to atmospheric pressure, and the microwave region of wavelengths 0.3 to 10 GHz. Due the wavelength of the electromagnetic field being similar in size to the discharge vessel, a resonate cavity or waveguide structure is preferred to produce the plasma. Microwave discharge plasmas produce homogeneous plasma. Some setups use a dielectric tube and the electromagnetic wave to

induce plasma formation in a column similar to a positive column in glow

discharge plasmas. Examples of microwave discharge applications include

elemental analysis and lasing media, though there is potential for use in

plasmachemical investigations (Eliasson and Kogelschatz 1991a).

Radio Frequency Discharge

Radio frequency discharge or RF is commonly used in laboratories for

optical emission spectroscopy, spectroscopic analysis, semiconductor etching,

and plasmachemical investigations. Common frequencies used in RF discharge

range from 2 to 60 Hz. A key distinguishing feature of RF discharge is that the

electrodes do not need to be inside the volume where the plasma is formed.

This is beneficial because the electrodes do not corrode and produce metal

vapors that could contaminate the plasma field. RF discharges produce

homogeneous plasmas with wavelengths longer than the length of the container.

Low pressures are frequently utilized; however, RF plasmas can still be formed at

atmospheric pressure, where they behave more like thermal or hot plasma

(Eliasson and Kogelschatz 1991a).

Silent Discharge

Silent discharge plasma formation is also called dielectric barrier discharge

(DBD) because one or both of the electrodes are covered in a dielectric material.

Some examples of material with a high dielectric strength include glass, quartz or

ceramic (Been and Chun-Cheng 1997). The dielectric material is important to

the good formation of the plasma because it limits the current from energy produced by fast electrons, which is transferred to the surrounding atoms, and prevents sparks and arcs from forming. In a silent discharge, microdischarges are formed in the space between the electrodes by a sinusoidal voltage of specific amplitude. The microdischarges occur at random, but with the use of a dielectric material, they are more evenly situated over the electrodes and are limited to the amount of charge they can hold.

Plasma can be formed at a high range of pressures and can produce a large active volume (Eliasson and Kogelschatz 1991a). Pressure ranges from 0.1 to 10 bar, but pressures of 1 bar or higher are more commonly used (Eliasson and Kogelschatz 1991b). The frequency of the applied AC current can also vary from 50 to thousands of hertz (Agnihotri, Cal et al. 2004).

Silent discharge is primarily used for the breaking of chemical bonds due to an ideal electron energy range of 1-10 electron volts. In order to initiate disassociation, the bond energy of the molecule must be exceeded by the reactor. For a silent discharge reactor, this is accomplished by changing the product of the gap width "d" and the gas density "n". A higher product produces a streamer breakdown which is more effective for disassociating molecules.

Other than disassociation, silent discharge is very important for the formation of ozone. Due to many factors such as control over pressure, electron energy and density, gas temperature, and the production of ozone, silent discharge plasma is more likely to be economical and effective for destroying

unwanted compounds. Less money will be required to implement secondary

conditions such as an elevated temperature or pressure, which can add

substantial additional operation cost. Simpler control over the electron energy

and density allow for easier optimization of the plasma, and the production of

ozone is a secondary destruction technique that adds to the overall efficiency of

the system (Eliasson and Kogelschatz 1991a). Research conducted by Kim,

Kobara, et. al. showed that under the same conditions, dielectric barrier

discharge had the highest destruction efficiency for a nonthermal plasma with

the exception of a plasma driven catalyst system (Kim, Kobara et al. 2005).

Reactions in Silent Discharge

Ozone

Ozone formation in silent discharge can contribute to potential byproduct

formation and the destruction of pollutants in an air stream. The formation of

ozone is impacted by the amount of power and the configuration of the reactor.

Typical ozone generators utilized at water treatment plants consume 0.1-0.5 MW

(100-500 kW) and produce 10-50 kg O_3/hr (10,000-50,000 gO_3/hr) with

approximately 1,000 tubes. Silent discharge experimental ozone measurements

have shown 250 g/kW-hr production while the maximum efficiency calculations

showed the potential for 400 g/kW-hr (Eliasson and Kogelschatz 1991b).

In a pure oxygen system, ozone is produced by the following reaction

where M represents a third collision partner: $O + O_2 + M \rightarrow O_3 + M$. Breakdown

occurs by: $O + O_3 \rightarrow 2O_2$. The addition of humidity decreases the efficiency of

ozone production, changes the surface conductivity of the dielectric, and increases the strength of the microdischarges in silent discharge reactors. Nitrogen also impacts the formation of ozone. If ozone is formed in air, nitrogen oxides (NO_x) such as NO, N_2O, NO_2, NO_3, and N_2O_5 will be formed, but at a lower magnitude. The following equations show examples of the formation of NO_x:

$$N + O_2 \rightarrow NO + O \tag{1}$$

$$N + NO \rightarrow N_2 + O \tag{2}$$

$$N_2(A) + O_2 \rightarrow N_2O + O \tag{3}$$

Ozone production can breakdown and NO_x formation can take over if the specific energy is too high. Formation of ozone can also stop if the concentration of NO_x increases too high, and it is removed by the following equation: $NO + O_3 \rightarrow NO_2 + O_2$ (Eliasson and Kogelschatz 1991b).

Chemical Reactions Associated with Toluene

With effective oxidation, complex hydrocarbons, such as toluene, can be completely broken down to CO_2 and H_2O after multiple intermediary reactions (Agnihotri, Cal et al. 2004). Toluene usually oxidizes in the following pathway: toluene ($C_6H_5CH_3$) $\rightarrow$ benzyl alcohol ($C_6H_5CH_2OH$) $\rightarrow$ benzaldehyde (C_6H_5CHO) $\rightarrow$benzoic acid (C_6H_5COOH) $\rightarrow CO_2 + H_2O$. Oxidation in the presence of metallic catalysts can produce other byproducts such as phenol depending on the catalyst type (Hancock 1982). Toluene has the following reactions when in a plasma reactor:

$$C_6H_5CH_3 + O \rightarrow C_6H_5CH_2O + H \qquad (4)$$

$$C_6H_5CH_3 + O_3 \rightarrow C_6H_5CHO_2 + H_2O \qquad (5)$$

$$C_6H_5CH_3 + OH \rightarrow C_6H_5CH_2 + H_2O \qquad (6)$$

$$C_6H_5CH_3 + O_2 \rightarrow C_6H_5CHO + HO_2 \qquad (7)$$

The products from the above reactions react again with OH, HO_2, and O to generate CO_2 and H_2O as final products. Reaction number 6 with OH tends to be the biggest factor leading to destruction of the toluene (Been and Chun-Cheng 1997). Formation of the OH radical comes from the ionization of the toluene, water, and O_2, which implies that higher oxygen content and higher humidity content will increase the destruction efficiency (Chai-Hsin and Hsunling 2001). If the power in the plasma reactor is not efficient, which can occur when power is set at higher frequencies, byproducts such as CO, NO, and NO_2 can be formed when destroying toluene (Chen, Tzeng et al. 2004). For the VOC benzene, researchers noticed that the production of CO from a silent discharge plasma reactor decreased considerably with the presence of humidity (Cal and Schluep 2001).

Silent Discharge Plasma Examples

Over the years, research has been conducted of various setups utilizing silent discharge plasma reactors to destroy different VOCs.

Single Dielectric

One type of silent discharge reactor utilizes a dielectric material to cover only one of the electrodes. Chang and Chang in 1997 from the National Central University in Taiwan looked at the removal of toluene and methyl ethyl keytone (MEK) with the use of a single dielectric silent discharge reactor. Ozone production was also analyzed in this experiment. A gas stream was simulated by the use of a nitrogen and oxygen tank and a mass flow measurement system. Contaminants were generated by bubbling the tank stream though glassware containing liquid sample in a controlled temperature water bath. The reactor was comprised of Pyrex glass tubes 40 cm in length, 0.2 cm thick with an inner diameter of 3.6 cm. A 0.24 cm molybdenum rod passed through the center of the Pyrex tube while a stainless-steel wire mesh covered the outside of the Pyrex tube. The entire system was encompassed by a hot air jacket to maintain the temperature of the gas while in the plasma system.

Toluene was tested at 200 ppmv with a 21% volume of O_2 and nitrogen as the carrier gas. The gas residence time was approximately 4 seconds at a flow of 3 standard liters per minute through a volume of 202 cm^3. Removal of the toluene was shown to increase as the applied voltage increased. Oxygen levels were varied to determine the effect on destruction, and the higher levels of oxygen in the system showed the best destruction efficiency. When humidity was added to the system (0 – 2.8 % relative humidity), ozone production decreased but the destruction efficiency increased. Humidity runs were conducted varying voltage at a constant retention time. The best destruction at

their chosen retention time was approximately 65%. Since the most important reaction for destruction of toluene was the reaction with OH, it was determined that the addition of humidity increased the generation of OH in the gas stream.

Residence time was also varied from 3 to 12 seconds at dry conditions. The best destruction efficiency of 80% was found at a residence time of 12 seconds, 19 kV, and 21% oxygen content. Despite finding a better percent removal at higher residence times, higher mass removal was found at lower retention times. Optimum mass removal conditions were found at 20 W, 19kV, and a 3 s retention time, with an energy removal efficiency of 5.21 g/kWh or a toluene removal rate of 1.7 mg/min. A removal efficiency of 80% was found for MEK at 19 kV, 125 ppmv, dry conditions, 21% oxygen, and a flow of 1.5 standard liters per minute. The energy efficiency for MEK was 1.6g/kWh and total power consumption was 18 W. Energy efficiency was calculated based on the mass destroyed per minute and the total power measured from the power meter. Frequency for this setup was assumed to be 60 Hz, since no mention was made of altering the standard outlet conditions. A layer of particulate matter was found deposited on the inner wall of the reactor after hours of operation when humidity was present (Been and Chun-Cheng 1997).

Packed Bed

Another commonly used form of dielectric barrier discharge reactors incorporate catalyst in the plasma volume called a packed bed. In a packed bed reactor, a glass tube is filled with pellets made from a high dielectric material.

Different packing materials can increase the efficiency of a silent discharge system by a catalytic effect of the material and by increasing the intensity of the microdischarges. Changes in the shape of the packing material can change the conductance and the intensity of the discharge. The microdischarges in a packed bed reactor form around the pellets creating a small volume with a high surface area.

Chai-Hsin and Hsunling in 2001 conducted an experiment using a packed bed reactor for the destruction of toluene analyzing oxygen concentration, relative humidity, the packing material, size of the reactor, flow rate, concentration of the inlet gas, and temperature. Oxygen content was kept at 20% and humidity was set at 95%. Nitrogen was bubbled through an impinger to provide the concentration of pollutant, and then mixed with an air stream which could be independently bubbled through water to provide humidity. The setup included a glass tube with an inner diameter of 2 cm and an outer diameter of 2.4 cm filled with 0.5 cm diameter spherical glass pellets for 15 cm of its length. A stainless steel rod with a 0.2 cm diameter provided the inner electrode while a stainless steel wire mesh encased the glass tube as the outer electrode (Chai-Hsin and Hsunling 2001).

A maximum of 11.7 kV rms was applied with an AC power source at 60 Hz. The study showed that the power used by the reactor was less than the power of the entire system, but the relationship to the decomposition efficiency was the same. As the power increased, the efficiency increased. At low power

usage, the increase in efficiency was very steep, but as the efficiency reached 90%, more power was required for the same increase in efficiency. At high efficiencies and voltages, the system required more power for the same amount of increase as seen at lower voltages. The total system required more power because of losses in the transformer of up to 60%.

At a concentration of 500 ppmv, an applied voltage of 8.5 kV, and a gas flow rate of 500 cm^3/min, the destruction efficiency of the reactor was 90%. A variety of concentrations ranging from 250 to 1,000 ppmv and flow rates from 500 to 2,000 cm^3/min (0.5 to 2 L/min) were also analyzed for their effects on destruction efficiency. It was shown that the higher concentrations and high flow rates decreased the destruction efficiency possible for the reactor. At lower removal efficiencies, the power efficiency was shown to increase.

This study also compared a non-packed bed reactor to a packed bed reactor with the same geometry. A flow rate of 1 L/s was used with retention times of 2.7 s for the packed bed and 4.7 s for the non-packed bed reactor. The packed bed reactor was shown to have higher destruction efficiency, lower power consumption, and better energy efficiency. At 11.6 kV the packed bed reactor had a 91% destruction efficiency, while the non-packed bed reactor had a 66% destruction efficiency. The packed bed reactor was also shown to have higher mass removal compared to power usage, or cost effectiveness, but there are disadvantages from a higher pressure drop and for potential by-product formation from the packing material such as N_2O.

Power was specifically analyzed for cost effectiveness by looking at the relationship between the g toluene removed per kW-hr and the applied voltage. This analysis showed that the packed bed reactor had a higher energy efficiency compared to the non-packed bed reactor. However, the general trend for both reactors showed that the efficiency increased at low voltages, but that a maximum efficiency was reached (approximately 6.5 kV for non-packed and 7.5 kV for packed bed) quickly and at a fairly low applied voltage. After this point, the efficiency dropped off dramatically and continued to decrease.

This implies that there is a specific applied voltage that will produce the maximum mass removal efficiency and that the energy use becomes less efficient if voltage is applied past this point. The same trend is shown in the destruction efficiency versus applied voltage. After a certain point, a rise in destruction efficiency or a rise in mass removed does not increase enough to balance the required rise in voltage or power. Under optimum conditions, the power consumption was analyzed for multiple tubes connected in parallel. Power consumption was also shown to increase linearly as the number of tubes increased (Chai-Hsin and Hsunling 2001).

Catalyst Systems

Catalysts such as MnO_2, NiO, CoO, Al_2O_3, and CuO, and combinations of catalysts, can be introduced into a silent discharge system to increase the destruction efficiency (Zeng, Ye et al. 2004). The addition of certain catalysts, such as platinum, placed after the plasma reactor can also remove unwanted

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byproducts such as carbon monoxide from the waste stream (Demidiouk and Chae 2004).

A system studied by Ronghui, Daiqi, Jiancong, and Bichun (2004) analyzed two different setups of a dielectric system for the destruction of toluene: wire-to-plate and plate-to-plate. The wire-to-plate system used a tungsten filament electrode through the center of two plates comprised of stainless steel nets coated in epoxy resin. Conglutinated on the epoxy coating with 704 silicone rubber, was a catalyst powder containing MnO_2, NiO, CoO, Al_2O_3, and CuO powder in a 40:15:20:15:10 percent weight ratio. The plate-to-plate system utilized a single plate with the same plate setup as the wire to plate system but had the catalyst placed on a foamed nickel ground electrode where the other stainless steel plate would have been.

From the experiments run, the catalyst was proven to increase the destruction efficiencies for both systems. The wire-to-plate reactor formed more ozone at respective voltages than the plate-to-plate reactor, and ozone production was decreased with the addition of the catalysts. When a catalyst was present, the plate-to-plate reactor had better removal efficiencies (36.8% compared to 25.8% at 16.4 kV), but when a catalyst was added, wire to plate reactor showed a better efficiency (62.1% compared to 61.5% at 16.4 kV) (Zeng, Ye et al. 2004).

Issues with Plasma/Silent Discharge

Like other treatment options, plasma reactors can have associated problems that interfere with their efficiencies. One issue is the relative energy efficiency between different types of reactors and different types of pollutants. In one study, pulsed corona discharge and dielectric barrier discharge plasmas were considered in the treatment of NO_x compounds. No noticeable difference was found in the energy efficiency between the two plasma reactors (Penetrante, Mc C. Hsiao et al. 1995); however, another study showed that a pulsed power supply was more energy efficient in destroying NO in diesel emissions. It is important to find the most appropriate, energy efficient, plasma when determining the best treatment method, so that cost can be optimized (Hammer 2000). It appears, however, that the type of pollution as well as the type of plasma generated has a bearing on how energy efficient the final reactor is. Some pollutants may have similar energy efficiencies with different types of plasma, where others may favor a specific type (Young-Hoon, Suk et al. 2004).

Another issue to consider is water soluble aerosol deposits on the surface of the electrodes from the treatment of VOCs. These deposits can hinder the formation of the plasma and make it unstable. Specifically, toluene has been observed to cause aerosol deposits even at dilute concentrations. Dielectric barrier discharge plasmas have the capability to oxidize and destroy deposits by operating the reactor for a short period of time at a high power density. If the aerosols are not treated, then the potential for arcing to cause a dangerous failure in the system increases. This ability to clean itself is an advantage over

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other plasma formation methods. Other types of plasma may require a filter prior to the reactor to prevent deposit formation (Young-Hoon, Suk et al. 2004). Another possible disadvantage is the production of byproducts such as carbon monoxide, ozone, and aerosol particles that require additional treatment (Chae, Demidiouk et al. 2004).

3. Materials and Methods

Electronic Experiments

Before any of the experiments for destruction or ozone analysis could be organized, information regarding the electronics and the formation of the plasma in the reactor was determined. As previously mentioned, the reactor used in this research was a silent discharge plasma, single dielectric barrier discharge. Variables that were analyzed included voltage, current, the number of tubes in the reactor, and the temperature.

Multiple 4 ft long, 12.2 mm diameter quartz glass tubes (dielectric strength of 5 x 10^7 V/m and max operating temperature 1,120 °C) wrapped in ¼ in. copper tape, excluding 4 inches on each end, and containing a 1.4 in. diameter stainless steel rod with Teflon spacers through the center were used in the reactor (Veenstra, Johannes et al. 2005). The tubes can be seen in Figure 3.1 and Figure 3.2 below.
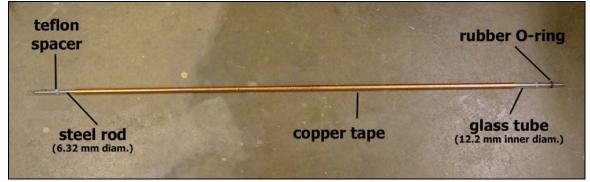
Figure 3.1 Individual Tube
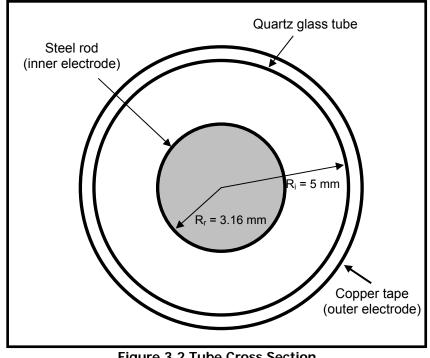
Figure 3.2 Tube Cross Section

An AC, adjustable hertz power source by California Instruments, model 1001TC, and a transformer with a scale up of 120 volts in to 15,000 volts out were used for the experiments. Both the transformer and the power source can be seen in Figure 3.3 below.
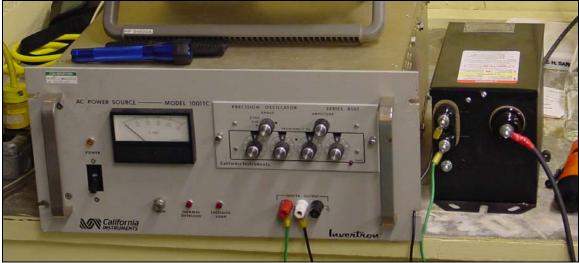
Figure 3.3 Power Source and Transformer

The power source was powered by building power which varied from 120 to 123 V and 4 to 7 amps. Copper electrical wires connected the power source to the transformer, and high voltage wire (spark plug wire) was used to connect the transformer to the reactor. High voltage wires were connected to the end of the metal rods by hose clamps and by an alligator clip to the copper tape on the outside of a single tube. When multiple tubes were connected at a time, a hose clamp was used to connect the copper tape between the tubes. Tubes were numbered in order to differentiate between each.

In this setup, readings could be taken for current at the wall from the building power outlet (prior to the power source), primary (between the power source and the transformer), and the secondary (between the transformer and the reactor) as seen in Figure 3.4 below.
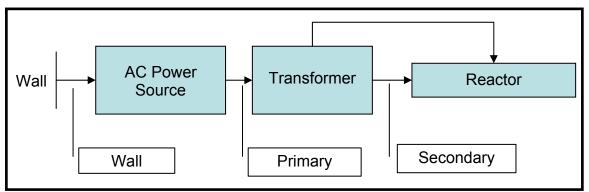
Figure 3.4 Electrical Reading Locations

Current was measured at each location with the clamp-on ammeter. Voltage was measured with the clamp-on ammeter (Extech Instruments model 380942), seen in Figure 3.5 below, at the building outlet and at the primary. Building outlet voltage was measured at the beginning of the run before any of

the electronics were turned on and after each primary voltage was set. The

power source dial began at zero and was increased to reach the desired primary

voltage for the experimental run. Secondary voltage was calculated by the scale

of the transformer (120 volts in to 15,000 volts out).

Figure 3.5 Clamp-on Ammeter

The Plexiglas reactor consists of three separate parts: two end pieces and

a central cylinder. Each end of the cylinder was connected to a square flange

which allowed for stability and contained aligned holes for the tubes to be

supported from each end. Both end pieces consisted of a cylinder closed on one

end and connected to a square flange on the other. On the closed end, there

was a connection to the steel piping, and a hole which allowed wire to pass

through in order to turn the unit on. The flange contained eight holes which

could be screwed together (plastic screws for safety) with the flange on the main

cylinder of the unit. A cork gasket was used between the flanges. Rubber

stoppers were used to plug all open holes, and O-rings were used around each

end of the tubes in order to create an air-tight seal. The reactor may be seen in Figure 3.6 below.

Figure 3.6 Reactor

Experimental runs were conducted to determine how the voltage and current interacted between the different measurement points. Different numbers of tubes were connected and values were measured. The tubes were checked for consistency and the change in temperature was noted at different primary voltages.

Reactor Setup for Ozone and Destruction Experiments

The following equipment was used for the ozone measurement experiments and the destruction experiments in addition to the above mentioned equipment:

A SRI 8610C gas chromatograph with a 15 meter long, 0.53 mm inner diameter capillary column from Restek, serial # 504796 was used to measure toluene samples in the experiments. The gas chromatograph can be seen below in Figure 3.7.
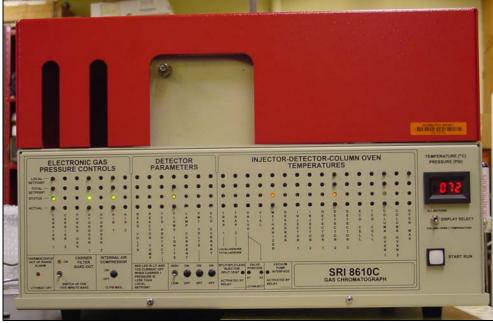
Figure 3.7 SRI 8610C Gas Chromatograph

The electrical setup and the 26-tube reactor were the same as found in the previous section with one exception. In order to determine the exact secondary current, which could not be determined with the clamp-on ammeter, a 100 ohm resistor was spliced into the high voltage wire connecting the transformer to the reactor. A Fluke 23 multi-meter was connected to the two sides of the resister so that the change in voltage over the resistor could be determined. The Fluke multimeter can be seen in Figure 3.8 below.

Figure 3.8 Fluke Multimeter 23

Secondary current was calculated using the following equation:

$$e = IR \tag{8}$$

where

e = the change in voltage

I = the secondary current

R = the resistance (100 ohms)

In order to have air and contaminants flow through the system, ¾ inch stainless steel tubing was used to connect the system. Air was piped through a flow meter from a compressed air or toluene tank. After the flow meter, piping continued to a pressure gauge and two other T-intersections. The first T-intersection was used to monitor air temperature (kitchen temperature probes) and the second to take samples of the base air stream prior to the plasma (septum were placed in the T-intersection).

The piping connected to the inlet end of the 26-tube reactor after the temperature and sample ports. Air flowed through the tubes, which contained

plasma when the unit was powered up, and continued through the other end and into more piping. The piping connected to another pressure gauge and two more T-intersections: another sampling port, and another temperature port. After the temperature port, the piping was connected to another flow meter and then continued outside of the building for release into the atmosphere through a piece of flexible Teflon tubing. A compressed air tank provided flow throughout the system for ozone testing, and a compressed toluene tank provided the concentration of contaminant to the system. Figure 3.9 represents the entire setup of the experimental system.
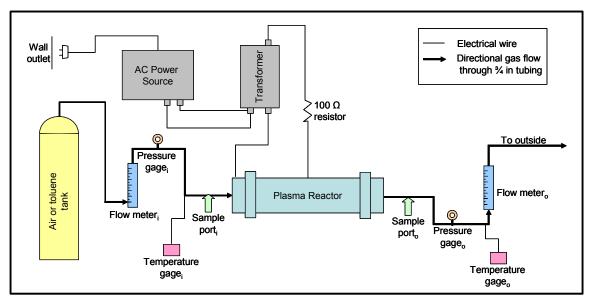
Figure 3.9 Schematic of Experimental System

Samples were taken from either the inlet or outlet sample ports. The inlet sample port was located prior to the plasma reactor while the outlet sample port was located after the reactor. Most samples were taken at the outlet sample port in order to show complete distribution of the toluene through the system,

and to show the destruction of the toluene after it has passed through the reactor. Samples were taken at the inlet port while the reactor was turned on to prove that the amount of toluene prior to the plasma reactor stayed the same during the entire experiment.

Samples were taken using the same procedure every time. A Hamilton 2.5 mL #1002 gas-tight syringe with a 26 gauge needle and a Luer lock was utilized as seen in Figure 3.10 below. The syringe was inserted into the desired sampling port penetrating the septum, so that the tip was midway into the air/toluene stream within the piping. With the Luer lock set to "open," the plunger was pulled all the way to the 2.5 mL mark then pushed until all the gas was expelled from the needle. The procedure was repeated five times, and then the plunger was pulled to the 2.5 mL mark again. Without closing the Luer lock, the syringe was pulled out of the septum in the sampling port. As quickly as possible, the plunger was pushed down to the desired sample size, and then the Luer lock was closed. After closing the Luer lock, the syringe was placed into the sampling port on the gas chromatograph. The Luer lock was then opened and the plunger pushed in, so that the sample was injected into the gas chromatograph.

Figure 3.10 Hamilton Gas-tight Series #1002 Syringe

The gas chromatograph was set at a temperature of 70 °C and allowed to run for 6 minutes for each sample. At Tinker Air Force Base (TAFB), the paint booth runs for a short duration of up to 30 minutes at a time. The duration of the runs was chosen as approximately 30 minutes to mimic the operations at TAFB. A 70 degree temperature allowed a reasonably quick run for all of the toluene to pass completely through the column. This also set the 8 minute interval between sample times for the experimental runs resulting in a 42 minutes, with 32 minutes while the reactor was turned on.

Statistical Analysis Method

In order to analyze the efficacy of the plasma reactor, multiple parameters need to be tested. Each parameter under consideration may have an impact on how effectively the reactor works. Three different variables were initially chosen to test with a minimum of three different values each in order to have a line. If the three variables were tested in this manner, a minimum of twenty seven experiments would have been required to determine the relationship between each parameter and the measured value ($3^3 = 3 \times 3 \times 3 = 27$). With the twenty seven different experiments, there would not be a direct way to create an equation which finds a relationship between all of the variables since each parameter would be analyzed separately. A lot of gas would also be required to run the 27 experiments.

Due to time and cost constraints, a 2^k factorial design including center points was used to lessen the total required runs and to analyze the system. In

a 2^k factorial design, parameters are assumed to have a linear relationship. Center points were added to the design as a check point for the calculated regression line. The two represents the highs and lows of the desired parameters ranges, while the k represents the number of independent variables to be tested. For example, if three independent variables are tested, 8 experiments (2^3 = 2 x 2 x 2 = 8) will be able to give an equation to predict the desired value with the tested parameters. The addition of three center points brings the total number of experiments to 11 (Montgomery 2001). For the following tests, only 11 experiments were conducted.

Once the experiments were completed, a Tukey's test and analysis of variance (ANOVA) test were conducted to determine whether the parameters were non-additive. The null hypothesis was that there was interaction between the parameters, or they were non-additive. If the parameters were proven to be additive or show no interaction, a regression model could be applied to the data based on the effect estimates, the average observed value, and the experimental error (Kirk 1995).

Ozone Experiments

In order to conduct testing for ozone production measurement, 11 experiments were conducted using the 2^k factorial method with three parameters and three center points to determine the test conditions. The parameters of the experiment included the number of tubes in the reactor (2-8), the primary voltage (70-117 volts), and retention time (1.32-1.8 s to 3.61-4.9 s) for flow

traveling through the reactor. Retention time was difficult to set since the flow

meter utilized did not have the sensitivity required to have the same high and

low retention times for the variations in tube number. Therefore, flows were

chosen that were as close as possible to the same high and low retention times

among all the experiments. A breathing quality air tank was used to analyze

ozone production with no toluene present. Table 3.1 below shows the 11

different experiments that were conducted and their specific parameters. The

three varied parameters primary voltage, retention time and reactor

configuration are shown with secondary voltage and flow as well.

Table 3.1 List of Experiments

Experiment	Number of Tubes	Primary Voltage (Volts)	Secondary Voltage (Volts)	Retention Time (sec)	Flow (mL/min)
1	8	72	8,750	4.3	5,321
2	8	117	14,625	4.3	5,321
3	8	72	8,750	1.8	12,283
4	8	117	14,625	1.8	12,283
5	2	72	8,750	4.9	1,164
6	2	117	14,625	4.9	1,164
7	2	72	8,750	1.4	3,936
8	2	117	14,625	1.4	3,936
9	5	96	11,250	2.7	5,321
10	5	96	11,250	2.7	5,321
11	5	96	11,250	2.7	5,321

Ozone testing followed section 402 Ozone (Residual) from the 15th edition

of the *Standard Methods for the Examination of Water and Wastewater*, 2005.

The following solutions were required for ozone testing:

1. *Potassium Iodide solution* (KI)-Prepared by adding 20 g KI in 1 liter of

    freshly boiled and cooled distilled water. The solution was made at least

one night prior and stored in a brown bottle in a refrigerator before testing.

2. Sulfuric Acid (H_2SO_4)-1.0N

3. *Standard Sodium thiosulfate* ($Na_2S_2O_3$)-0.1N prepared by adding 25 g $Na_2S_2O_3$ in 1 liter of freshly boiled distilled water. The titrant (0.005N $Na_2S_2O_3$) was prepared by adding 50 mL of the 0.1N solution to 1 liter of distilled water. The titrant was standardized daily.

4. *Starch indicator solution*-Prepared by adding 5 g soluble starch to 800 mL of boiled distilled water. The solution was diluted to 1 liter and allowed to settle overnight. Only the supernate of the settled solution was used. It was preserved with a few drops of toluene.

5. *Standard iodine solution*-0.1N solution purchased from Hach (Loveland, Colorado) and used to create a 0.005N solution. 50 mL of the 0.1N solution was added to 1 liter of distilled water. This solution was standardized daily (APHA, AWWA et al. 2005).

Section 408A Idometric Method I from the 15th edition of the *Standard Methods for the Examination of Water and Wastewater*, 2005 was used to standardize the titrant solution and to check the "blank" contributed by impurities to the system.

For each experiment, 400 mL of the KI solution was measured into two glass gas washing bottles (200 mL in each bottle). Only 400 mL was used instead of the suggested 800 mL because the average flows present in our

experiments were higher than the flow rates recommended by the standards for ozone testing. Lower volume in the gas washing bottles insured fewer potential problems such as overflow or turbulence due to full bottles. Parameters for the desired experimental system were set up and the effluent air flow from the reactor was connected to the two bottles, which were connected in series. The reactor was allowed to run, and then the effluent flexible Teflon® tubing was connected to the bottles. As soon as the effluent flow was connected to the bottles, a stopwatch was started to record the time in which the ozone was collected. As ozone contacted the KI solution in the bottles, the solution changed from a clear color to a yellow and then to a dark amber color. The reactor was allowed to run until the second bottle had turned a slight yellowish color.

The solutions from both gas washing bottles were then mixed together after the run, and 20 mL of sulfuric acid was added to reduce the pH of the solution. In order to test the constancy of the titration, the solution was separated into three samples of 100 mL each and one of approximately 120 mL. Each sample was titrated with the 0.005N sodium thiosulfate solution until the yellow color almost disappeared. Next, 4 mL of starch was added as an indicator to turn the solution blue. More titrant was added until the blue color turned clear. The final amount of titrant was recorded to calculate the amount of ozone produced. Each measured volume of titrant from the separated samples was added together to determine the final amount of titrant required for the entire

experimental run. The total mg/L of ozone produced from an experiment can be

calculated from the following equation:

$$mgO_3 \, / L = \frac{(A \pm B) \times N \times 24{,}000}{mL \quad Sample} \qquad\qquad (9)$$

where:

    A = mL titrant for sample

    B = mL of titrant for the blank run (+/- depending)

    N = normality of sodium thiosulfate (APHA, AWWA et al. 2005)

All chemicals used for analysis were reagent grade. The data collected

from the experimental runs can be found in Appendix C, and the results are

discussed Chapter 4: Results and Discussion.

Destruction Experiments

The same three variables used to analyze the ozone production were used

to analyze how well the plasma reactor destroyed toluene and the optimum set

of conditions for destruction. All 11 experiments conducted for destruction

analysis had the same experimental parameters chosen for the 11 ozone

experiments (Table 3.1).

Each experiment followed the same experimental protocol. First, the

required number of tubes was placed in the reactor. Then the primary voltage

was set, but not kept on, and all gauges, such as the voltmeter, were switched

to the "on" position. Toluene flow was initiated and allowed to stabilize for two

minutes. The short two minute stabilization period was chosen to conserve the toluene gas but still account for potential equalization after flow was initiated. After two minutes, the first sample was taken at the outlet port. Official time for the experimental run began at the first sample, labeled as -8 minutes. Due to the time required for the gas chromatograph to run a toluene sample, each of the following runs were 8 minutes apart, and a complete series of samples for 1 experiment were labeled as -8, 0, 8, 16, 24, and 32 minutes. Power was turned on slightly prior to the zero time and turned off just after the 24 minute sample was taken. A total of 6 samples were taken; each experimental run lasted approximately 50 minutes.

The first three samples and the last two samples were taken at the outlet port, while the sample at 16 minutes was taken at the inlet port. The zero point is representative of the instant-on feature that is possible with a plasma reactor. An inlet sample at sixteen minutes showed that the influent toluene concentration did not change during the course of the experiment compared to the initial sample at -8 minutes, prior to the reactor being initiated, and the final sample at 32 minutes, after the reactor was turned off. Electrical readings for voltage and current were taken after the power was turned on. Full results are listed in Appendix A and discussed in detail in Chapter 4: Results and Discussion.

Humidity and Concentration Variation

In order to test the system for the effects of the variation of toluene concentration and the humidity of the sample, three more tests were conducted.

First, three different experimental parameters were chosen to represent the spectrum of information found by initial testing. Samples were chosen based on destruction efficiency and range of parameters. The experiments chosen were 7 (two tubes), 8 (two tubes), and 9 (10 and 11) (five tubes). Experiments 9, 10, and 11 were the center point experiments with all middle values of the parameters represented. Experiment 7 had the lowest voltage and the lowest retention time, while experiment 8 had the lowest retention time and the largest voltage.

Since a pressurized tank was used to run the system, it was assumed that no humidity was present in the initial experimental setup. A Cooper SRH774 temperature/humidity probe (with a range of 10-95% RH), as seen in Figure 3.11 below, was added to the system after the second flow meter. Flexible Teflon tubing was used to connect the outlet flow from the second flow meter to a steel pipe inserted in a rubber stopper at the mouth of the Erlenmeyer flask. The humidity probe was inserted through the rubber stopper as well, while the flow exited through the side arm of the flask and was directed outside the building.
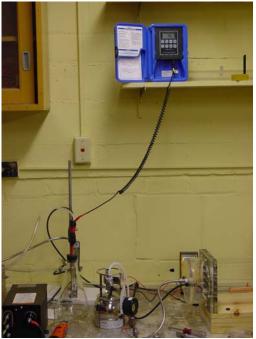
Figure 3.11 Cooper Humidity Probe

In order to provide humidity to the system, an air tank was set up to run through three Erlenmeyer flasks filled with water and kept at a constant temperature (approximately 25° Celsius) by immersion in a hot water bath. Quarter inch stainless steel piping through rubber stoppers was used to connect the flasks to each other in series and to the rest of the system. Air was bubbled through the water and entered the system to mix with the toluene gas through a T-connection located just after the first flow meter. Mixing provided an approximate relative humidity of 30-50%.

A tank of toluene containing a 100 ppmv concentration was chosen to provide toluene to the system, but due to mixing with uncontaminated humidified air, a decreased toluene concentration actually entered the system. The concentration of toluene in the system varied depending on the amount of

air required to reach the desired humidity range. The experiments were run following the same procedure identified in the destruction experiment section, with the exception of an ozone test being conducted prior to the initiation of each experiment. Ozone sampling followed the same procedure outlined above. An ozone sample for experiment 7 was taken without humidity added to the system for comparison purposes. Complete results can be found in Appendix B and the results are discussed in Chapter 4: Results and Discussion.

Summa Canisters

A contracted lab was retained to analyze the end products from the plasma. Summa canisters were ordered from Pace Analytical Labs located in Minneapolis, Minnesota, in order to determine what products were created when the toluene was passed through the plasma. The summa canisters are vacuum sealed 1 liter tanks that can easily be connected to a piping system in order to draw an instantaneous sample. After the samples were taken, the canisters were shipped back to Pace Analytical Labs for analysis using their TO-15 method testing for VOCs in air.

Figure 3.12 Summa Canister

A sample was taken using the humidity setup described above, with a 240 ppmv tank instead of the 100 ppmv tank of toluene. The configuration for experiment 8 was used. A single influent and a single effluent sample were taken at an approximate relative humidity of 30%. Results from the summa canister test are discussed in more detail in Chapter 4: Results and Discussion and the data are provided in Appendix F.

Power Measurements

Power can be calculated in an alternating current (AC) power system by multiplying the current (amps), the voltage, and the cosine of the phase angle (Ramakumar 2007). In order to correctly calculate power used by the different parts of the experimental system, the phase angle was measured under the three different tube arrangements, the three different voltages, and for the three different places in the experimental setup: wall, primary, and secondary. A HP

3575A gain-phase meter capable of operating from 1 Hz to 13 mHz, a ½ ohm

resister capable of carrying 300 watts of power, and two voltage probes with a

10:1 step-up were utilized to measure the phase angle. The ½ ohm resistor was

placed in the neutral wire between the outlet and the power source. One probe

was connected to the hot wire coming from the outlet to the power source, while

the second probe was connected to neutral wire between the power source and

the ½ ohm resister. Both probes were grounded and connected to the gain-

phase meter.

Phase angles were digitally read for 2, 5, and 8 tubes at 72, 96, and 117

volts primary. Measurements were also read at the three voltages with the

reactor disconnected and while the reactor and the transformer were

disconnected. By disconnecting the reactor, the effect of the power source and

the transformer on the system was determined. With both the transformer and

the reactor disconnected, the effect of the power source was determined

independent of the transformer. This allowed the individual parts of the setup to

be analyzed.

4. Results and Discussion

Electrical Determinations

Tubes

Before experiments were run to determine the destruction capability, ozone production, and overall power usage, each tube was verified, by testing, to behave in approximately the same manner in an electrical basis. In order to verify the similarities between tubes, current readings were taken for each tube at 30, 50, and 70 volts (primary). The power source dial began at zero and was increased to reach each of the mentioned points. Readings were taken when the desired primary voltage was reached; then the voltage was increased to the next measurement point. The following graphs (Figure 4.1, Figure 4.2 and, Figure 4.3) represent the spread of current readings at the primary, secondary, and wall for each of the set primary voltages.
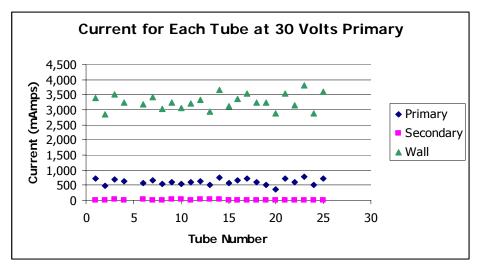
Figure 4.1 Current Variation at 30 Volts Primary
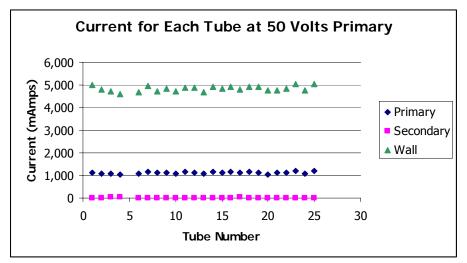
Figure 4.2 Current Variation at 50 Volts Primary
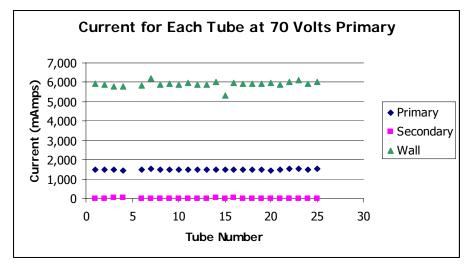
Figure 4.3 Current Variation at 70 Volts Primary

As seen in the above graphs, there is very little variation between each tube. Therefore, it was assumed that each tube was essentially the same and that varying a tube from experiment to experiment should have little to no bearing on the outcome of the electrical measurements.

There is also a relation between the primary voltage and the amount of current measured at each location. As would be expected, as more voltage is applied, the current increased. Considering the use of a transformer to increase the voltage applied on the secondary side and for power to be maintained, the secondary current had to be significantly lower than that measured at the primary. Secondary current was shown to follow closely to this ratio. Six tubes were randomly selected and tested at five different voltages to assess the linearity of each current reading and verify the increase seen for all tubes at three voltages.

During the course of this experimentation, it was determined that the power source was unable to fully light the 26 tubes the reactor was capable of holding. At a maximum primary voltage of 117 produced by the power source, only eight tubes could be sufficiently energized to a glowing state. The primary voltage was capped at slightly under the average reading from the outlet found at the wall due to safety issues from past experimentation with the transformer used in these experiments. Therefore, future experiments only tested up to eight tubes in the reactor.

Temperature

Experiments were conducted that determined the maximum temperature reached by connecting a tube at certain primary voltages without air flowing through the tube. Table 4.1 below shows the temperature increase for one tube at a primary voltage of 30. The tubes were allowed to run until the temperature stabilized. Temperatures were measured using a PE1 Thermometer which measured the surface temperature of the copper tape on the outside of the tubes.

Table 4.1 Temperature Evaluation

Tube Number	Max Temp. ($^\circ$ C)	Time (min)	Min. Temp ($^\circ$ C)
3	30.0	26	21.8
4	25.8	16	22.3
3-1st repeat	28.4	26	23.3
3-2nd repeat	31.0	28	23.1
All	*31.0*	*28*	*21.8*

As seen above, the temperature did not increase drastically above room temperature (approximately 25° C). Minimum temperatures were found in the first two readings of each run. The tubes were warm to the touch, but not too hot to pick up. More measurements were taken to gauge the effect an increase in voltage would have on the temperature of the tubes. Maximum temperatures reached for 40, 50 and 60 volts primary were approximately 37, 41, and 45° C respectively. This demonstrated an increase in tube exterior temperature as the applied voltage increased; however, the temperature did not increase drastically with the increase in voltage. Since air was not flowing through the tubes, the resultant stabilized temperatures may be lower with flow to circulate the heated air inside the tubes. Varying the airflow could change the stabilization temperature and the time it would take to reach a stable point.

Reynolds numbers for the various air flows used in the experiments were calculated assuming an average room temperature of 25 °C and using the following equation:

$$R = \frac{DV}{v} \tag{10}$$

where:

D = effective diameter of a single tube

V = the velocity of airflow

v = kinematic viscosity

Actual calculations were corrected for the number of tubes in each experiment. Reynolds numbers ranged from 103 to 350. The critical Reynolds

number is 2,000; flow is laminar below this point (Finnemore and Franzini 2002).

For the Reynolds numbers calculated for these experiments, flow was well below

this point and was therefore laminar. Full calculations may be found in Appendix

E.

Pressure drop across the system was measured at various flows at the

various experimental conditions. Gages read in lbs/in^2 gage (psig) or the

pressure in psi above atmospheric pressure. Although readings varied, the

maximum value shown at the effluent side of the reactor was 3 psi. The front

pressure gage usually read 0, but under some conditions 2.5 psi was seen.

Pressure drop varied from 1 to 0.4 psi, indicating that a pressure drop of 0.5 was

seen on average over the reactor. The very low readings also show that the

reactor ran approximately at atmospheric pressure.

Power

As mentioned in chapter 3: Materials and Methods, power calculations

were performed measuring phase angle at the wall reading. Power at the

secondary was calculated by subtracting power calculated from the phase angle

measured with the reactor disconnected. Total system power was calculated

from the measured voltage and current for each experimental run. Power losses

for the power source and the transformer combined were calculated based on a

wall voltage of 120 volts, a current read at the specific primary voltage (72, 96,

or 117 volts) and the phase angle read at the specific primary voltage.

Average phase angle readings were -40, -41.5, and -41.6 degrees for the total system, the system with the power source and the transformer only, and the power source alone, respectively. The lack of change in the phase angle indicates the majority of the losses are due to the power source. Calculated power loss due to the transformer and the power source were 0.195, 0.206, and 0.217 kW at 72, 96, and 117 V respectively. Compared to a total power range from 0.664-.0454 kW, the losses due to the power source and the transformer are significant. This loss may be minimized by finding a more efficient power source for the 300 Hz frequency used in these experiments. Phase angle readings and power calculations may be found in Appendix A.

Ozone Production

Basic Production

Initial ozone experiments were conducted using a compressed air tank following the experimental parameters discussed in the previous chapter. Ozone measurement techniques only looked at the formation of ozone, not byproducts from the presence of nitrogen in the system. However, nitrogen was present at normal levels found in air, which will be similar to the conditions found at Tinker Air Force Base. Therefore, measured numbers will be comparable to those found under normal operation conditions. The effect of the presence of toluene in the system is discussed later in this chapter. Table 4.2 shows the ozone produced per hour and per kW of total energy applied to the system and per hour. Energy

applied to the system was calculated by taking total power drawn from the outlet minus power required by the power source and the transformer.

Table 4.2 Ozone Results

Experiment	gO$_3$/hr	gO$_3$/kW-hr
1	0.54	1.9
2	1.59	4.0
3	0.69	2.7
4	0.57	1.4
5	0.17	0.5
6	0.75	1.6
7	1.19	4.1
8	2.24	4.8
9	1.43	4.0
10	1.66	4.7
11	1.53	4.2

As seen above, the highest production of ozone per hour was the found in the same experiment, 8, as the highest produced per kilowatt hour. Other experiments that produce high removal per kW are not necessarily the highest when only looking at ozone produced per hour. The amount of ozone produced per kW-hr represents a cost effective production. Power is the major cost of the plasma reactor; therefore, ozone production should be optimized with regards to the operation costs. Further analysis will consider ozone produced per kW-hr in order to look at the optimum production with respect to cost.

For the same conditions, with different applied voltages, the ozone produced increased as the voltage increased, and the efficiency of ozone production increased except for one experiment. The same conditions were present for experiment 3 and 4 except that 4 had a higher applied voltage and produced ozone less efficiently than experiment 3. Zeng, Ye, et al. (2004) also

showed an increase in ozone production, not with respect to power, in their reactors with an increase in applied voltage.

An analysis of variance and Tukey test with no repetition were conducted to analyze the effects of change in voltage, number of tubes, and retention time through the reactor and to determine additivity. The tests were run with a null hypothesis of non-additivity for the ozone produced per hour and the cost effective ozone produced per kW-hour based on the total power supplied to the system.

The calculated F-values of non-additivity were -0.787 for g O_3/hr and -0.977 for g O_3/kW-hr, while the significance was $F_{\alpha = 0.25,1,2} = 2.57$. Since $F_{non-additivity}$ is less than the significance of 2.57, the null hypothesis was disproved. It can be assumed that the parameters are additive and there is no interaction between the retention time, number of tubes, and the voltage. A regression line for the data were then calculated based on the equation $Y = \mu + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3$, where μ is the average value of the observations, and β represents the normalized value of a parameter, and x is half of the effects estimate. Parameters were normalized by the following equation:

$$\beta = \frac{parameter - average}{(high - low)/2} \tag{11}$$

The high and low values in the equation represent the high and low values for each parameter in the 2^k factorial design. Normalized values, β, vary from -1 to +1 for the low and high values respectively. Middle values represent potential other values for the parameters under study. After analyzing the data,

regression equations produced numbers too different from the actual results to be helpful in analysis of the system. It was therefore concluded that more data must be collected to create a useful linear relationship among the parameters (Kirk 1995). Detailed statistical and regression calculations may be found in Appendix D.

Since a full comparison by statistical analysis was not possible, and only two points are available for the varying parameters, a direct relationship cannot be determined from the current data. Correlations, however, can be seen at reactor setups of 8 and 2 tubes in relation to the secondary voltage in Figure 4.4 and Figure 4.5.
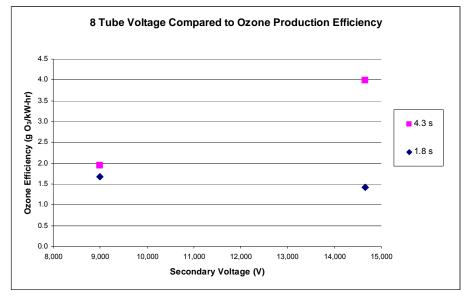
Figure 4.4 Ozone Efficiency Compared to Secondary Voltage for 8 Tubes

2 Tube Voltage Compared to Ozone Production Efficiency
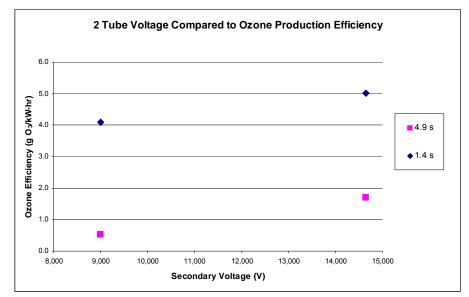
Figure 4.5 Ozone Efficiency Compared to Secondary Voltage for 2 Tubes

For all of the two tube experiments and for the eight tube experiment at the slowest retention time (4.3 s), ozone efficiency increased as the voltage increased. At the shortest retention time (1.8 s) for the eight tube configuration, the efficiency decreased with the increase in voltage, experiments 3 and 4. This result could be due to the fact that the amount of power applied to the system was not offset by the amount of toluene destroyed, or measurements may have had associated error which skewed the results. In most situations it appears that a higher voltage does yield a higher efficiency. Figure 4.6 and Figure 4.7 below show the ozone production efficiency with respect to the retention time.

8 Tube Retention Time Compared to Ozone Production Efficiency
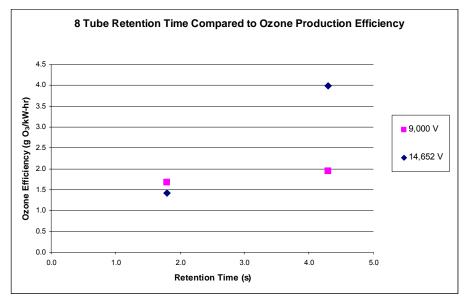
Figure 4.6 Ozone Efficiency vs. Retention Time for 8 Tubes

2 Tube Retention Time Compared to Ozone Production Efficiency
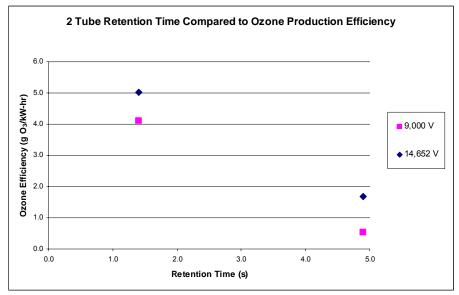
Figure 4.7 Ozone Efficiency vs. Retention Time for 2 Tubes

For the eight tube reactor configuration, an increase in retention time showed a decrease in the ozone production efficiency, but for the two tube setup, the reactor showed a decrease in ozone production efficiency with an increase in retention time. The same relationships are shown when related to

the volume of the plasma reactor. Not enough information is available to show a

correlation between ozone efficiency and retention time.

Effects of Other Parameters

Other experiments were conducted looking at variation of concentration

and variation of humidity. Due to the application of humidity through an

additional air stream, no direct comparisons were possible between the

concentration of toluene with and without humidity. Table 4.3 following shows

the data collected for each experiment run.

Table 4.3 Ozone Experiments with Varied Parameters

Experimental Conditions	Toluene Concentration (ppmv)	Humidity (% RH)	Ozone Production (gO$_3$/hr)	Ozone Production (gO$_3$/kW-hr)
2	240	0	0.4	1.1
	0	0	1.6	4.0
7	100	0	0.4	1.2
	34.77	30-50	0.3	1.1
	0	0	1.2	4.1
8	240	0	0.3	0.9
	37.53	30-50	0.2	0.5
	0	0	2.2	4.8
9, 10, 11	240	0	0.4	0.7
	145	30-50	0.5	1.2
	9.62	30-50	0.2	0.6
	0	0	1.5	4.3

When only looking at experiments without humidity, ozone production and

ozone production efficiency increased as the concentration of toluene decreased.

The addition of humidity to the system, even with a decrease in toluene

concentration showed a reduction in the ozone produced for most of the

experiments. Although more data would be necessary to fully understand the

relationship, it appears that the addition of water into the air stream consumes some of the power that would have gone into the creation of ozone. The decrease seen with the addition of humidity is consistent with the findings of Eliasson and Kogelschatz which recommended that air used for ozone production be dried below the dew point or to -60° C because humidity could interfere with the production of ozone (Eliasson and Kogelschatz 1991b).

When looking at the ozone production efficiency, there is not a direct relationship with humidity and toluene concentration. For example, in experiments 9, 10, 11 the reactor was less efficient at a toluene concentration of 9.62 ppmv than at 145 ppmv. However, when no toluene was present and no humidity was in the system, each experiment showed the highest ozone production and energy efficiency. If ozone production were the purpose of the reactor, then no humidity or excess compounds should be present in the system.

Comparison to ozone generators

Silent discharge ozone generators tend to be constructed of 1 to 2 meter long glass tubes with an inner metal coating and an outer electrode of stainless steel tubing.   Tubes are typically 50 mm (1.97 in) in diameter. Air or oxygen is passed between the stainless steel tube and the glass tube to create the ozone. Typical large ozone generators hold as much as 1,000 tubes which can produce 10 to 50 kg O_3/hr with 0.1 to 0.5 MW of power consumption. From these values, power per tube can be calculated as approximately 0.1 to 0.5 kW per tube and ozone production can be calculated 0.01 to 0.05 kg O_3/hr per tube (0.1 to 0.5 kg

O_3/kW-hr) (Eliasson and Kogelschatz 1991b). If the tubes are 1 meter long, then they can be directly compared to the tubes used in the reactor currently being studied.

The maximum ozone production for the new reactor was seen in experiment 8 with 2.2 g O_3/hr (0.0022 kg O_3/hr) and maximum efficiency in experiment 8 with 4.8 g O_3/kW-hr (0.0048 kg O_3/kW-hr). The plate-to-plate and wire-to-plate reactor from research conducted by Zeng, Ye, et. al. (2004) had an approximate ozone production of 0.0015 g O^3/hr calculated from 90 mg/m^3 ozone production at a flow of 280 mL/min. Ozone production for both reactors was very low when compared to ozone producers in use today, but the new reactor produces substantially more ozone per hour than the plate-to-plate and wire-to-plate reactors. Maximum destruction efficiencies for the plate-to-plate and wire-to-plate reactor were around 62% while the new reactor showed much higher removal efficiencies. If ozone aids the destruction of toluene, the larger amount produced by the new reactor could contribute to the better destruction efficiency, though more testing would be necessary to show a direct correlation (Zeng, Ye et al. 2004).

The ozone produced in dry conditions would be the largest concentration of ozone that could be produced by the system (Table 4.2). Since ozone emissions are regulated, it is important to know the maximum concentration of ozone that would be exhausted by the reactor. More testing would be necessary to understand the emissions of ozone while toluene is actually being destroyed.

Destruction Efficiency

Instant-on Feature

As mentioned in the materials and methods section of the paper,

measurements were taken from -8 to 32 minutes showing how the system

reacted over the course of time. Samples taken at 16 minutes were from the

inlet injection port to verify that inlet concentration had not changed and that

destruction was due to the reactor, not to other sources. Figure 4.8 below is the

mass verses time plot for experiment 9. Other experimental plots and data can

be found in Appendix A.
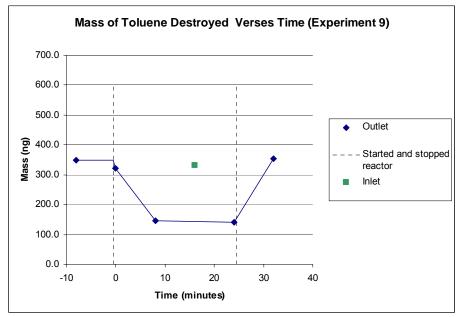
Figure 4.8 Example Experimental Run

As seen in the plot above, the setup did not achieve the desired instant-on

feature. A certain amount of time was necessary to reach an equilibrium

destruction. However, when the system was measured at 8 minutes after the

power was initiated, stability was achieved. Measurements to determine the

exact time equilibrium was achieved were not possible with the available

equipment. Although not instantaneous, the system did respond relatively

quickly. The instant-off feature was also not completely analyzed; however, the

system did show stability consistent with the original influent air 8 minutes after

the power was turned off.

Basic Destruction

Table 4.4 following shows the mass removed per minute and the

destruction efficiency, for the experiments listed in Chapter 3: Materials and

Methods of this thesis.

Table 4.4 Destruction Measurements

Exp.	Number of Tubes	Actual Retention Time (s)	Primary Voltage (V)	Destruction Efficiency (%)	Mass Removed (mg/min)
1	8	4.3	72	31.7	0.58
2	8	4.3	117	77.6	1.48
3	8	1.8	72	19.8	0.81
4	8	1.8	117	43.2	1.98
5	2	4.9	72	98.8	0.42
6	2	4.9	117	100.0	0.39
7	2	1.4	72	85.4	1.52
8	2	1.4	117	98.4	1.36
9	5	2.7	96	59.4	1.00
10	5	2.7	96	60.5	1.15
11	5	2.7	96	62.2	1.22

The best destruction efficiency was seen in experiment 6, but experiments

5 and 8 also exceeded the desired goal of 90%. All three experiments had two

tubes placed in the reactor, but the retention time and the applied voltage

varied. The best mass removal was seen in experiment 4 followed by

experiments 7, 2, and 8, but their destruction efficiencies did not meet the required 90%. Experiments 2, 8, and 4 all had the highest voltages but of the four, only experiment 2 had the high retention time. Mass removal increases for experiments with the same number of tubes and the same voltage as the retention time decreased. When the retention times were kept the same, the mass removed per time increased with the increase in voltage for eight tubes, but the opposite effect was shown for two tubes. This could indicate that an optimum voltage might not be the highest voltage able to be applied.

Table 4.5 below shows the power used for the total system drawn from the wall outlet and the cost effective destruction in g toluene removed/kW-hr. Cost efficiency is based on the calculated secondary power discussed in more detail earlier in this chapter. Calculations may be seen in Appendix A. Cost calculations are based on 10 ¢ per kW-hr as a conservative number for research.

Table 4.5 Destruction Power Results

Exp.	Secondary Power (kW)	Destruction Cost Efficiency (g/kW-hr)	Cost of Removal ($/g)
1	0.279	0.126	0.80
2	0.401	0.222	0.45
3	0.259	0.189	0.53
4	0.421	0.283	0.35
5	0.316	0.079	1.26
6	0.469	0.049	2.02
7	0.291	0.313	0.32
8	0.470	0.173	0.58
9	0.360	0.167	0.60
10	0.353	0.196	0.51
11	0.364	0.201	0.50

The best mass removal per power and time was seen in experiment 7 which had 2 tubes, 1.4 second retention time, and 117 volts primary.   This also

equates to less cost for removal. Experiments 2, and 4 also had high cost

efficient mass removal using 8 tubes in the reactor, but they did not meet the

required 90% removal efficiency. For each experiment with the same voltage

and the same number of tubes, the cost efficiency increased as the retention

time decreased, but the percent destruction decreased. The highest voltage was

used in experiments 2 and 4, but the minimum voltage was used in experiment

7. Even though experiment 7 has a much lower applied voltage, there is still

more voltage per volume than with experiments 2 and 4. This could account for

the increased efficiency. There does not appear to be one factor that determines

how well the system works, rather there is input from all three variables to

determine the final destruction. Further analysis of the parameters and their

interaction through statistical analysis would show the relationship with the

removal.

The destruction information was statistically analyzed using the same 3-

way ANOVA with no repetition and Tukey test used for ozone calculations.

Destruction was analyzed with respect to destruction efficiency, and best

destruction with respect to power. Power and destruction efficiency have also

been standardized for a single tube in order to compare values on the same

volume of plasma formed. The test was also run with a null hypothesis of non-

additivity for both sets of data.

The calculated F-value of non-additivity was -0.65 for % destruction and -

0.773 for g toluene/kW-hr, while the significance was $F_{\alpha = 0.25, 1, 2} = 2.57$. The null

hypothesis was disproved because $F_{\text{non-additivity}}$ for each data set was less than the

significance of 2.57. Parameters were therefore additive and there was no

interaction between the retention time, number of tubes, and the voltage. The

following regression line that excludes interaction terms may be used: $Y = \mu +$

$\beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3$, where μ is the average value of the observations, and β

represents the normalized value of a parameter, and x is half of the effects

estimate. Parameters were normalized by the same equation given in the ozone

analysis. Regression equations for destruction also showed too much deviation

from measured values to be useful in analyzing the system (Kirk 1995). More

data are required to determine a useful linear relationship among the

parameters.

Although complete relationships between experimental parameters cannot

be determined, correlations can be seen among the two points for each

parameter. Figure 4.9 and Figure 4.10 below show the destruction efficiency

based on power for eight and two tubes compared to the secondary voltage of

the system.

8 Tube Comparison of Voltage and Destruction Cost Efficiency
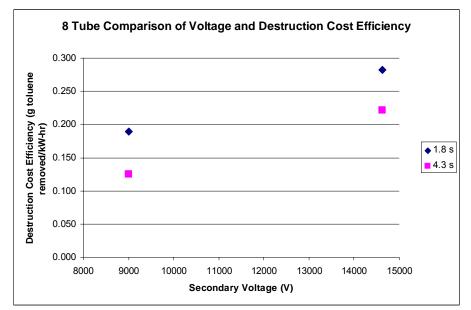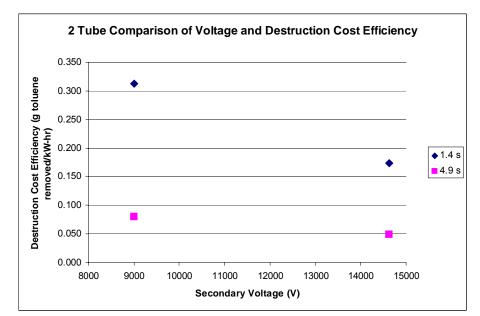
Figure 4.9 Toluene Destruction Cost Efficiency vs. Secondary Voltage for 8 Tubes

2 Tube Comparison of Voltage and Destruction Cost Efficiency

Figure 4.10 Toluene Destruction Cost Efficiency vs. Secondary Voltage for 2 Tubes

Destruction efficiency appears to decrease with an increase in the applied voltage, except at eight tubes and 1.8 s where it increased. This indicates that power increased at the higher voltages more than the amount of toluene was destroyed. Even though an increase in actual mass might be present, the power required for the increase in removal is too high compared to the increased

benefit.   Figure 4.11 and Figure 4.12 below show the destruction efficiency

based on power for eight and two tubes compared to the retention time.

8 Tube Comparison of Retention Time and Destruction Cost Efficiency
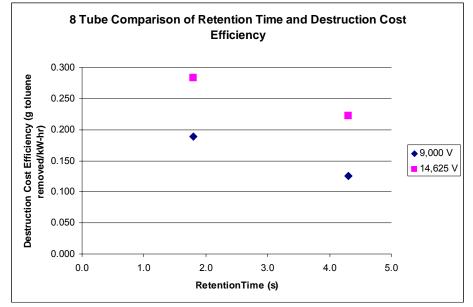
Figure 4.11 Toluene Destruction Cost Efficiency vs. Retention Time for 8 Tubes

2 Tube Comparison of Retention Time and Destruction Cost Efficiency
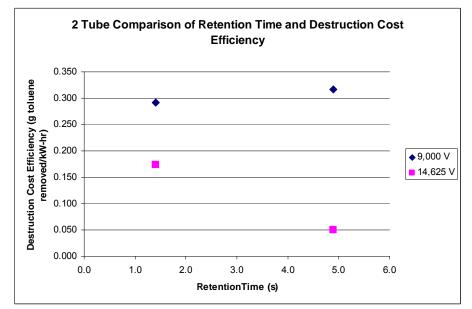
Figure 4.12 Toluene Destruction Cost Efficiency vs. Retention Time for 2 Tubes

For the two tube configurations, the efficiency increased at the lower

voltages and decreased for the higher voltages, but at eight tubes, both voltages

67

showed a decrease as retention time increased. As discussed above, there may

be more interaction with voltage. Figure 4.13 below shows the destruction cost

efficiency compared to the voltage per tube at the maximum and minimum

retention times.
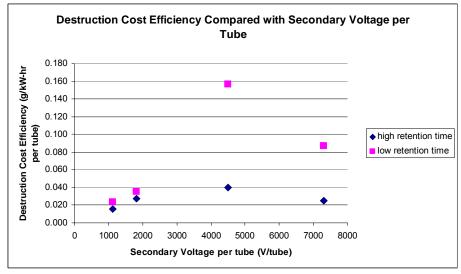
Figure 4.13 Comparison With Voltage Per Tube

The above graph indicates an optimum voltage per tube which would

provide the most efficient cost removal. However, the shorter retention time

always had higher cost efficiencies when the same voltage per tube was applied.

This graph shows that shorter retention times should be utilized with an

intermediate voltage for optimum cost removal. A longer retention time may

show a higher percentage destruction, but the shorter times show optimum

destruction efficiencies. This indicates the importance of retention time as a

factor in effective destruction. More research would be necessary to determine

the exact relationship for complete optimization.

Analysis of experimentation error can be seen by looking at

experiments 9, 10, and 11 which are the same experiment repeated three times.

Figure 4.14 below is a graphical display of the average value of the runs and their standard deviations. One point of high deviation was at the 0 minute mark, which had a standard deviation of 46.1 ng from the mean of 287.1 ng. It was very difficult to be consistent at this point because power had just been applied to the system and large experimental error while sampling was possible.

As seen in the figure, a large error of 29.5 and 52.4 ng from the mean values 241 and 285.4 ng respectively was seen in the initial and final mass values at -8 and 32 minutes. This represented the baseline concentration applied to the system. At the points of destruction, 8 and 24 minutes, the standard deviation is much smaller at 5.4 and 11.6 ng from the mean values of 151 and 153.3 ng respectively. Small error was also seen at the influent check point, 16 minutes, as 7.2 ng from the mean value of 332.1 ng.
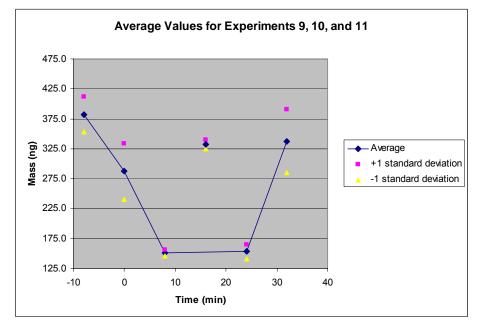
Figure 4.14 Graphical Mean and Standard Deviation for Experiments 9, 10, and 11

Inconsistencies in the analysis above could be attributed to the

experimental error found at the baseline point at -8 minutes, especially when

looking at the percent destruction. Mass removed was based on the starting

mass for each experiment; therefore, the potential error for the initial

measurements is a source for error in the mass removed calculation. The

influent values measured at 16 minutes had very low error compared to the

baseline effluent measurements at -8 and 32 minutes. The reason for a

decrease in the deviation for the influent mass is unknown with current testing.

More experimentation would be required to better understand the reason for the

variation in the error among the different points.

Comparison to Other Systems

Considering the difference in volume size for each reactor, comparisons

were made showing the amount of destruction per volume space. Table 4.6

below shows the difference in reactor setups mentioned in the literature

compared to the new system, while Table 4.7 below shows the relative volumes

of different types of dielectric barrier discharge reactors from current research

compared to the new reactor.

Table 4.6 Comparison of Reactor Materials

Reactor type	Ground electrode	Discharge electrode	Dielectric	Other
wire-to-plate with catalyst[a]	stainless steel net (100 mm x 16 mm)	tungsten filaments (D = 1.5 mm)	epoxy dielectric over steel (x mm between plates)	catalytic powder
plate-to-plate with catalyst[a]	foamed nickel (100 mm x 19 mm)	stainless steel net (100 mm x 12 mm)	epoxy dielectric over steel (6 mm between plates)	catalyst on foamed nickel
packed column[b]	stainless steel rod (0.2 cm)	stainless steel mesh	glass dielectric tube (D_i = 2 cm)	spherical glass pellets (D = 0.5 cm)
tube[b]	stainless steel rod (0.2 cm)	stainless steel mesh	glass dielectric tube (D_i = 2 cm)	-
tube[c]	molybdenum rod (0.24 cm)	stainless steel wire mesh	Pyrex glass dielectric tube (D_i = 3.6 cm)	-
new tube reaction	stainless steel rod (0.63 cm)	copper tape	glass dielectric tube (D_i = 1 cm)	-

a. (Zeng, Ye et al. 2004)
b. (Chai-Hsin and Hsunling 2001)
c. (Been and Chun-Cheng 1997)

Table 4.7 Volume Comparison

Reactor type	Reactor volume (cm^3)	Number of new tubes
wire-to-plate with catalyst[a]	9.6	0.2
plate-to-plate with catalyst[a]	7.2	0.2
packed column[b]	45.0	0.9
tube[b]	78.4	1.7
tube[c]	202.0	4.3
new tube reaction	47.4	-

a. (Zeng, Ye et al. 2004): calculated from dimensions (Ye 2007)
b. (Chai-Hsin and Hsunling 2001): Calculated from given information (1 L/min has a 2.7 s retention time in the packed bed reactor and 4.7 s in non-packed bed)
c. (Been and Chun-Cheng 1997): calculated from dimensions

Comparisons were made with respect to the volume of each reactor in order to standardize the amount of destruction shown by each. The best destruction found for each system was compared to the voltage required, the concentration, retention time, and humidity in Table 4.8.

Table 4.8 Best Destruction Comparison

Reactor type	Best destruction efficiency (%)	Best energy efficiency (g toluene/kW-hr)	Concentration (ppmv)	Flow rate (L/min)	Reactor volume (cm^3)	Retention time (s)
wire-to-plate with catalyst[a]	62.10%	8.28	159	1	9.6	0.6
plate-to-plate with catalyst[a]	62.50%	5.17	159	0.28	7.2	1.5
packed column[b]	42.00%	11.5	500	1	45.0	2.7
tube[b]	27.00%	8	500	1	78.4	4.7
tube[c]	42.00%	5.1	320	4.04	202.0	3
new tube reaction[d]	85.00%	0.313	100	3.9	94.8	1.4

a. (Zeng, Ye et al. 2004): concentration converted from mg/m^3 and retention times computed from dimensions (Ye 2007)
b. (Chai-Hsin and Hsunling 2001)
c. (Been and Chun-Cheng 1997)

Only the packed column reactor was able to break the desired 90%
efficiency. In the new system, at 100 ppmv, which is less than the packed
column tested at, experiments 5, 6, and 8 were also able to meet the 90%
breakdown. Table 4.9 below shows the parameters for the experiments and
compares the percent destruction compared to the total volume of plasma.

Table 4.9 Comparison of Experiments With > 90% Destruction

Experiment	Best Destruction Efficiency (%)	Concentration (ppmv)	Voltage (kV)	Retention time (s)	Humidity (% RH)	Destruction per volume (%/cm^3)
packed column[a]	91.00%	500	11.6	2.7	95	0.020
5	98.40%	100	14.6	1.4	0	0.010
6	100.00%	100	14.6	4.9	0	0.011
8	98.80%	100	9.0	4.9	0	0.010

a. (Chai-Hsin and Hsunling 2001)

Although the percent destruction is higher for the newer experiments,
when compared to the size of the reactor, the packed column appeared to have
an advantage, although there may be other factors that affect the efficiency.
The packed bed reactor did have humidity in the system, which has been shown

through other experimentation to improve destruction and ran at 60 Hz. The

effect of humidity on the current research is discussed later in this chapter.

Voltage in experiments 5 and 6 were higher than that of the packed

column, but experiment 8 did not require as much voltage. Retention time was

much longer for experiments 6 and 8, but shorter for experiment 5 than the

packed column. It should also be noted that the new experiments had a lower

concentration and considering that they showed almost 100% destruction, they

could potentially show the same destruction percentage with a single tube. The

packed bed experiment only used one tube while experiments 5, 6, and 8 all

used two of the new system tubes. A comparison of total mass of toluene

destroyed would be beneficial, but no information is available from the packed

column research.

The best comparison would be to analyze the efficiency with respect to

power. Table 4.10 below shows the energy efficiency with respect to applied

power.

Table 4.10 Energy Efficiency Comparison

Reactor type	Power (W)	Voltage (kV)	Best Energy Efficiency (g toluene/kW-hr)	Efficiency per volume (g/kW-hr-cm3)
wire-to-plate with catalyst[a]	2.7	-	8.28	0.863
plate-to-plate with catalyst[a]	1.2	-	5.17	0.718
packed column[b]	4.0	7.2	11.5	0.256
tube[b]	2.5	6.4	8	0.102
tube[c]	20.0	19.0	5.1	0.025
new tube reaction	291.0	9.0	0.313	0.003

a. (Zeng, Ye et al. 2004)
b. (Chai-Hsin and Hsunling 2001)
c. (Been and Chun-Cheng 1997)

As seen above, although the new reactor was capable of high destruction efficiencies, the destruction energy efficiency was much lower than that of other systems in literature. The primary difference can be attributed to the extreme range of power required by the different systems over a very similar range in voltage. Even when compared to the relative volumes of plasma, the new system requires substantially more power. More research would be necessary to determine how the other systems utilized the low currents that would be required to run at high voltages and achieve the required power.

Effects of Other Parameters

The same experiments tested for ozone production at varied toluene concentrations and humidity were tested for destruction as seen in Table 4.11.

Table 4.11 Destruction Experiments at Varied Parameters

Experimental Conditions	Concentration (ppmv)	Humidity (% RH)	Destruction (%)	Destruction (mg/min)	Destruction Efficiency (g/kW-hr)
2	240	0	39.7	1.08	0.16
	100	0	77.6	1.48	0.22
7	100	0	85.4	1.52	0.31
	34.77	30-50	109.1[a]	0.56	0.11
8	240.0	0	93.8	1.98	0.26
	100	0	98.4	1.36	0.17
	37.53	30-50	112.6[a]	0.51	0.07
9, 10, 11	240	0	57.7	1.42	0.20
	145	30-50	68.2	1.06	0.15
	100	0	60.7	1.12	0.19
	9.62	30-50	111.9[a]	0.27	0.04

a. Destruction over 100% likely due to experimental error

With the new parameters a few experiments showed increases in the destruction above the desired 90%. Experiment 7 showed a large increase with the addition of humidity and a decrease in the initial concentration. For

experiment 8, which had good destruction efficiency with the initial conditions, the increase in concentration showed a drop in efficiency, but not below the desired level. With the increase in humidity and decrease in concentration, the efficiency also increased. In each experiment tested, the lowest concentration showed the best destruction efficiency. However, the addition of humidity for experiments 9, 10, 11, showed a higher efficiency at 145 ppmv than at 100 ppmv. The difference was an addition of humidity for 145 ppmv experimental run. This could be an indication that humidity can improve the destruction efficiency, but further testing would be required to conclusively prove this.

Through experimentation with humidity, Been and Chun-Cheng (1997) showed an increase in destruction efficiency when humidity was increased (0 to 2.8% by volume). Destruction efficiency was higher, approximately 65%, at the same conditions, when 2.8% humidity was applied compared to no humidity at approximately 45% (Been and Chun-Cheng 1997). Reactors tested by Chai-Hsin and Hsunling were always operated at a relative humidity of 95% (Chai-Hsin and Hsunling 2001). Considering the improvement shown by the addition of humidity in Been and Chun-Cheng and the large relative humidity chosen and high destruction achieved by Chai-Hsin and Hsunling, humidity for the new system should be further analyzed and will probably show an increase the capabilities of the new system.

Effluent Product Evaluation

Summa canister samples were taken from an experimental run following the parameters of experiment 1 from the materials and methods with the addition of humidity. Since an undetermined amount of air was added to the system in order to reach the desired retention time, the amount of toluene added to the system was calculated from the calibration curve and the known sample size. A tank of 240 ppmv provided the influent toluene, but with the addition of humidity and air, a concentration of approximately 169 ppmv was measured in the system compared to approximately 113 ppmv determined by Pace laboratories. Samples taken and tested in the lab with the gas chromatograph were compared to those sent to Pace laboratories for analysis. The following Table 4.12 represents the amount of chemicals found by Pace labs in the two samples taken at the above stated conditions. Simple calculations of percent destruction between the influent and effluent samples are also shown in the table.

Table 4.12 Summa Canister Results

Chemical	Influent (ID:8953) (ppbv)	Effluent (ID:5973) (ppbv)	Destruction [(ppbv in- ppbv out)/(ppbv in)]
Acetone (C_3H_6O)	129	26.2	79.7%
Chloromethane (CH_3Cl)	-	15.9	-
n-Hexane (C_6H_{14})	39.1	5.8	85.2%
Methylene Chloride (CH_2Cl_2)	197	222	-12.7%
Toluene (C_7H_8)	113,000	7.3	100.0%

Toluene was found as expected in the influent stream, but acetone, n-hexane, and methylene chloride were also found. Acetone is commonly used as a solvent in laboratories which may have been present in the OSU laboratories or

the Pace laboratories. Since the difference between the influent and effluent

measurements indicates that acetone is also destroyed in the system, the

presence of acetone, another VOC, indicates the ability of the system to destroy

contaminants other than toluene at fairly high efficiencies (79.7%).

The presence of methylene chloride, also at very small amounts, could be

due to various reasons. Methylene chloride is a very common solvent used in

chemical analysis, and this would very likely be present in the air at the analytical

laboratory. Since it is present in such small amounts, it is likely that it was not

added into the system by direct means. However, since there is an increase in

the effluent sample, other potential entry points must be considered. Methylene

chloride could be part of soft Teflon tubing used to connect some of the stainless

steal tubing in the system setup, or it could be used in the construction of the

Plexiglas. Either material could have been broken down by the formation of

ozone.   The increase in the effluent sample could also be considered negligible

and only present due to analytical error. A difference of 25 ppbv or

approximately 13% does not represent a significant change in concentration.

N-hexane is also found in negligible amounts in the influent and effluent

samples at 39.1 and 5.8 ppbv respectively. Since it is in such small amounts, it

could be disregarded as potential error in testing or due to background

concentrations at Pace laboratories. Chloromethane also found in the effluent,

was detected in such small amounts as to be considered negligible. The use of

air as the carrier gas for the toluene limits the possible nitrogen byproducts

formed, and the presence of the strong oxidant ozone, limits any carbon

monoxide from potentially being formed. Essentially, there is no byproduct

formation detected that could require more treatment or consideration.

The toluene was shown to be entirely destroyed except for trace amounts

(less than 10 ppbv). This destruction was verified by the measurements taken at

the same time with analyzed by the gas chromatograph at OSU. Table 4.13

below compares the relative concentrations measured by Pace labs and the gas

chromatograph as well as the relative destruction efficiencies.

Table 4.13 Comparison Between Summa Canister Sample and Syringe Sample

Toluene Sample	Influent (ppbv)	Effluent (ppbv)	Destruction [(ppbv in- ppbv out)/(ppbv in)]
Summa Canister	113,000	7.3	100.0%
GC sample	169,762	3,599	97.9%

Destruction efficiencies of 100% and 97.9% are approximately the same

number considering human error and error due to measurement and sampling

techniques. The gas chromatograph does not have the capability to detect

concentrations in the ppbv range that Pace laboratories does. Pace laboratory

results can be seen in Appendix F.

5. Conclusions

The purpose of this experiment was to analyze a scaled reactor for destruction efficiency, cost efficiency, and instant-on features for a single dielectric silent discharge plasma reactor. This project was conducted for Tinker Air Force Base in response to problems associated with painting their airplanes. New air pollution requirements prevent excess emission of volatile organic compounds (VOC) into the atmosphere. In response to the new laws, Tinker changed from a high solids, high VOC paint to a low solids, low VOC paint. However, the new paint was weathering poorly and required more maintenance. The plasma reactor currently tested was a potential treatment technology for the emissions from the Tinker painting booths.

Eleven experiments were conducted to analyze the relationship between parameters and how they affected the overall efficiency of the reactor. Unfortunately, statistical analysis was unable to provide the regression relationship due to insufficient data. Correlations between increased voltage, volume, and retention time were possible, but not complete relationships. Ozone production was shown to be typical of silent discharge systems, and effluent products, other than carbon derivatives, were shown to be minimal. Destruction efficiency greater than the required 90% was reached, but when the system was

compared with other reactors, the mass removal per kW-hr was significantly less than comparative literature. This was due to lower power required by the systems in literature compared to that drawn by the OSU system. The system was not able to produce an instant-on feature, but the reactor did stabilize within 8 minutes of power being applied to the system.

A more thorough analysis of the system with more experimental points for voltage, retention time, and tube number would be recommended to obtain a better understanding of the operation and scale-up of the system. Experiments should be repeated at least once to obtain more reliable statistical analysis. More precise equipment would be necessary to measure flow and therefore the retention time. Humidity should be tested at the same flow rates and concentrations to obtain a true grasp of its potential beneficial properties. A new power source would be necessary to run a larger scaled-up reactor that may provide a more true-life industrial application. More efficient transformers and power sources may also be available. A full analysis of the power produced and of why the new system had a low power efficiency compared to other reactors in literature should also be studied. Other testing should also look into the production of carbon monoxide and other regulated effluent products that were not tested for in this experiment.

6. References

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7. Appendix A

100 ppm Experimental Runs

Experiment 1   6-Dec-06

Conditions

Concentration into reactor =	100	ppm
Number of Tubes =	8	tubes
Volume per tube =	47.30	mL per tube
Flow Through Reactor =	5,321	mL/min
retention time =	4.3	sec
Wall Voltage =	123.1	Volts
Primary Voltage =	72	Volts
Secondary Voltage =	9,000	Volts
Wall Current =	5.06	amps
Primary Current =	1.20	amps
Resistor =	100	ohms
Measured ΔVolts =	0.987	Volts
Secondary Current =	10	mamps
Wall Power =	622.886	volt-amps
Primary Power =	86.4	volt-amps
Secondary Power =	88.83	volt-amps
Temperature =	25	˚C
MW Toluene =	92.14	

Calibration Curve 12/6/06

$y = 7.9809x - 146.14$

$R^2 = 0.999$

Influent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
16	1.1	3,293	394.3	3,160	414.3	95.17
-	1.1	-	-	3,160	414.3	-

*Expected value determined by concentration and calibration curve
*Measured mass calculated by calibration curve

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
-8	1.1	3,179	380.1	3,160	414.3	91.74
0	1.1	2,530	298.6	184	41.4	72.09
8	1.1	2,217	259.5	184	41.4	62.63
24	1.1	2,276	266.9	184	41.4	64.42
32	1.1	3,224	385.6	3,160	414.3	93.08

*Blue cells indicate reactor is running
*Expected values in bluebased on 90% destruction
*Time zero is approximately 30 seconds after reactor is on
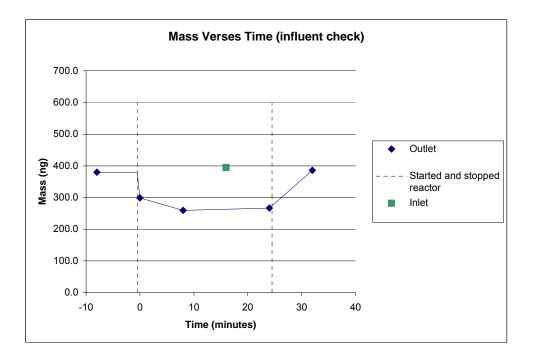
Concentration verses time

Time (min)	Mass (ng)
-8	380.1
0	298.6
8	259.5
24	266.9
32	385.6
16	394.3

green is the inlet sample

Destruction Efficiency (with influent)

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
380.1	298.6	81.4	21.4%	0.0
380.1	259.5	120.6	31.7%	8.0
380.1	266.9	113.2	29.8%	24.0

*values are compared with -8 minutes

Mass Verses Time (influent check)
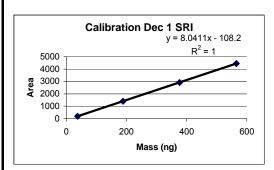
Experiment 2   1-Dec-06

Conditions

Concentration into reactor =	100	ppm
Number of Tubes =	8	tubes
Volume per tube =	47.30	mL per tube
Flow Through Reactor =	5,321	mL/min
retention time =	4.3	sec
Wall Voltage =	122.1	Volts
Primary Voltage =	117	Volts
Secondary Voltage =	14,625	Volts
Wall Current =	6.59	amps
Primary Current =	1.77	amps
Resistor =	100	ohms
Measured ΔVolts =	1.472	Volts
Secondary Current =	15	mamps
Wall Power =	804.639	volt-amps
Primary Power =	207.09	volt-amps
Secondary Power =	215.28	volt-amps
Temperature =	25	˚C
MW Toluene =	92.14	

Calibration Dec 1 SRI

$y = 8.0411x - 108.2$

$R^2 = 1$

Influent Samples

Time (min)	Sample Size (mL)	Measured Value Area	Measured Value Mass (ng)	Expected Value Area	Expected Value Mass (ng)	Measured concentration (ppm)
16	1.1	2,442	290.3	3,223	414.3	70.07
-	1.1	-	-	3,223	414.3	-

*Expected value determined by concentration and calibration curve

*Measured mass calculated by calibration curve

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value Area	Measured Value Mass (ng)	Expected Value Area	Expected Value Mass (ng)	Measured concentration (ppm)
-8	1.1	3,280	394.4	3,223	414.3	95.20
0	1.1	2,593	309.1	225	41.4	74.60
8	1.1	818	88.2	225	41.4	21.29
24	1.1	1,219	138.2	225	41.4	33.35
32	1.1	3,233	388.5	3,223	414.3	93.79

*Blue cells indicate reactor is running

*Expected values in bluebased on 90% destruction

*Time zero is approximately 30 seconds after reactor is on

Time (min)	Mass (ng)
-8	394.4
0	309.1
8	88.2
24	138.2
32	388.5
16	290.3

green is the inlet sample

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
394.4	309.1	85.3	21.6%	0.0
394.4	88.2	306.2	77.6%	8.0
394.4	138.2	256.2	65.0%	24.0

*values are compared with -8 minutes

Mass Verses Time (influent check)

87
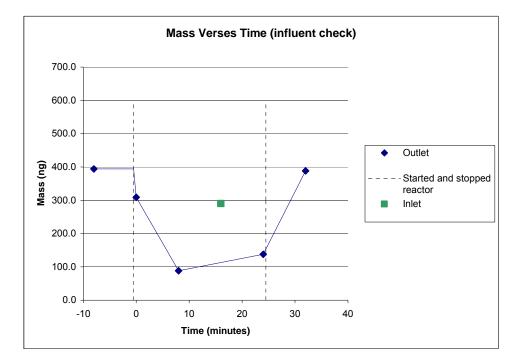
Experiment 3   4-Dec-06

Conditions

Concentration into reactor =	100	ppm
Number of Tubes =	8	tubes
Volume per tube =	47.30	mL per tube
Flow Through Reactor =	12,283	mL/min
retention time =	1.8	sec
Wall Voltage =	121.5	Volts
Primary Voltage =	72	Volts
Secondary Voltage =	9,000	Volts
Wall Current =	4.91	amps
Primary Current =	1.19	amps
Resistor =	100	ohms
Measured ΔVolts =	0.996	Volts
Secondary Current =	10	mamps
Wall Power =	596.565	volt-amps
Primary Power =	85.68	volt-amps
Secondary Power =	89.64	volt-amps
Temperature =	25	˚C
MW Toluene =	92.14	

Calibration Curve 12/4/06

$y = 7.608x - 163.5$
$R^2 = 0.998$

Influent Samples

Time (min)	Sample Size (mL)	Measured Value Area	Measured Value Mass (ng)	Expected Value Area	Expected Value Mass (ng)	Measured concentration (ppm)
16	1.1	2,785	344.5	2,988	414.3	83.16
-	1.1	-	-	2,988	414.3	-

*Expected value determined by concentration and calibration curve
*Measured mass calculated by calibration curve

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value Area	Measured Value Mass (ng)	Expected Value Area	Expected Value Mass (ng)	Measured concentration (ppm)
-8	1.1	2,962	367.8	2,988	414.3	88.78
0	1.1	2,873	356.1	152	41.4	85.95
8	1.1	2,522	310.0	152	41.4	74.83
24	1.1	2,407	294.9	152	41.4	71.18
32	1.1	2,889	358.2	2,988	414.3	86.46

*Blue cells indicate reactor is running
*Expected values in bluebased on 90% destruction
*Time zero is approximately 30 seconds after reactor is on

Concentration verses time
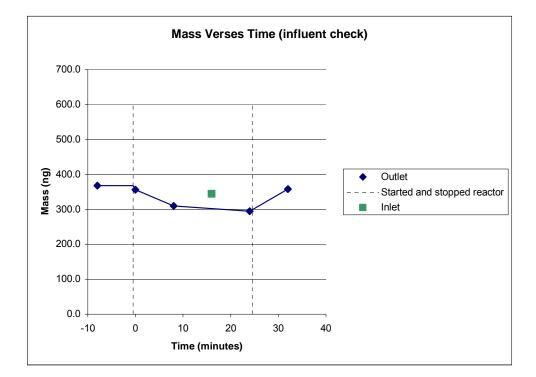
Time (min)	Mass (ng)
-8	367.8
0	356.1
8	310.0
24	294.9
32	358.2
16	344.5

green is the inlet sample

Destruction Efficiency (with influent)

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
367.8	356.1	11.7	3.2%	0.0
367.8	310.0	57.8	15.7%	8.0
367.8	294.9	72.9	19.8%	24.0

*values are compared with -8 minutes

Mass Verses Time (influent check)
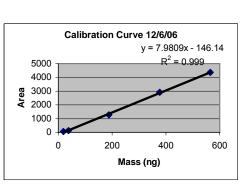
Experiment 4   6-Dec-06

Conditions

Concentration into reactor =	100	ppm
Number of Tubes =	8	tubes
Volume per tube =	47.30	mL per tube
Flow Through Reactor =	12,283	mL/min
retention time =	1.8	sec
Wall Voltage =	121.5	Volts
Primary Voltage =	117	Volts
Secondary Voltage =	14,625	Volts
Wall Current =	6.60	amps
Primary Current =	1.75	amps
Resistor =	100	ohms
Measured ΔVolts =	1.478	Volts
Secondary Current =	15	mamps
Wall Power =	801.9	volt-amps
Primary Power =	204.75	volt-amps
Secondary Power =	216.1575	volt-amps
Temperature =	25	˚C
MW Toluene =	92.14	

Calibration Curve 12/6/06
$y = 7.9809x - 146.14$
$R^2 = 0.999$

Influent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
16	1.1	3,135	374.5	3,160	414.3	90.39
-	1.1	-	-	3,160	414.3	-

*Expected value determined by concentration and calibration curve
*Measured mass calculated by calibration curve

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
-8	1.1	3,429	411.3	3,160	414.3	99.28
0	1.1	2,039	237.1	184	41.4	57.23
8	1.1	2,013	233.9	184	41.4	56.45
24	1.1	2,012	233.8	184	41.4	56.42
32	1.1	3,068	366.1	3,160	414.3	88.37

*Blue cells indicate reactor is running
*Expected values in bluebased on 90% destruction
*Time zero is approximately 30 seconds after reactor is on

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Concentration verses time
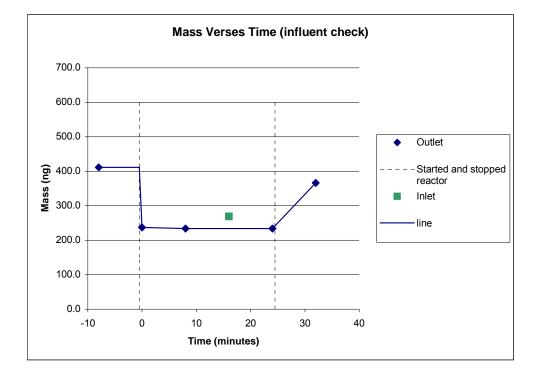
Time (min)	Mass (ng)
-8	411.3
0	237.1
8	233.9
24	233.8
32	366.1
16	374.5

green is the inlet sample

Destruction Efficiency (with influent)

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
411.3	237.1	174.2	42.4%	0.0
411.3	233.9	177.5	43.1%	8.0
411.3	233.8	177.6	43.2%	24.0

*values are compared with -8 minutes

Mass Verses Time (influent check)
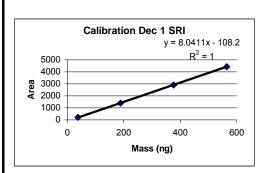
Experiment 5   1-Dec-06

Conditions

Concentration into reactor =	100	ppm
Number of Tubes =	2	tubes
Volume per tube =	47.30	mL per tube
Flow Through Reactor =	1,164	mL/min
retention time =	4.9	sec
Wall Voltage =	122	Volts
Primary Voltage =	72	Volts
Secondary Voltage =	9,000	Volts
Wall Current =	5.51	amps
Primary Current =	1.34	amps
Resistor =	100	ohms
Measured ΔVolts =	1	Volts
Secondary Current =	10	mamps
Wall Power =	672.22	volt-amps
Primary Power =	96.48	volt-amps
Secondary Power =	93.96	volt-amps
Temperature =	25	˚C
MW Toluene =	92.14	

Calibration Dec 1 SRI

$y = 8.0411x - 108.2$

$R^2 = 1$

Influent Samples

Time (min)	Sample Size (mL)	Measured Value Area	Mass (ng)	Expected Value Area	Mass (ng)	Measured concentration (ppm)
16	1.1	3,272	393.4	3,223	414.3	94.97
-	1.1	-	-	3,223	414.3	-

*Expected value determined by concentration and calibration curve
*Measured mass calculated by calibration curve

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value Area	Mass (ng)	Expected Value Area	Mass (ng)	Measured concentration (ppm)
-8	1.1	3,320	399.4	3,223	414.3	96.41
0	1.1	2,893	346.3	225	41.4	83.58
8	1.1	146	4.7	225	41.4	1.13
24	1.1	167	7.3	225	41.4	1.77
32	1.1	2,730	326.0	3,223	414.3	78.69

*Blue cells indicate reactor is running
*Expected values in bluebased on 90% destruction
*Time zero is approximately 30 seconds after reactor is on
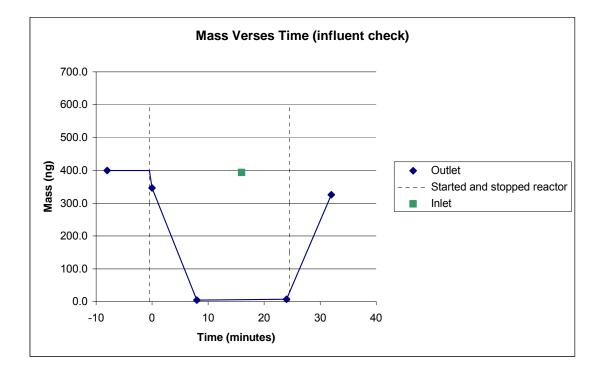
Concentration verses time

Time (min)	Mass (ng)
-8	399.4
0	346.3
8	4.7
24	7.3
32	326.0
16	393.4

green is the inlet sample

Destruction Efficiency (with influent)

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
399.4	346.3	53.2	13.3%	0.0
399.4	4.7	394.7	98.8%	8.0
399.4	7.3	392.1	98.2%	24.0

*values are compared with -8 minutes

Mass Verses Time (influent check)

93

Experiment 6   6-Dec-06

Conditions

Concentration into reactor =	100	ppm
Number of Tubes =	2	tubes
Volume per tube =	47.30	mL per tube
Flow Through Reactor =	1,164	mL/min
retention time =	4.9	sec
Wall Voltage =	121	Volts
Primary Voltage =	117	Volts
Secondary Voltage =	14,625	Volts
Wall Current =	7.10	amps
Primary Current =	1.95	amps
Resistor =	100	ohms
Measured ΔVolts =	1.600	Volts
Secondary Current =	16	mamps
Wall Power =	856.97	volt-amps
Primary Power =	228.15	volt-amps
Secondary Power =	234	volt-amps
Temperature =	25	˚C
MW Toluene =	92.14	

Calibration Curve 12/6/06

$y = 7.9809x - 146.14$

$R^2 = 0.999$

Influent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
16	1.1	3055.95	364.6	3,160	414.3	88.01
-	1.1	-	-	3,160	414.3	-

*Expected value determined by concentration and calibration curve
*Measured mass calculated by calibration curve

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
-8	1.1	2,652	314.0	3,160	414.3	75.80
0	1.1	1,664	190.1	3,160	414.3	45.90
8	1.1	13	-16.7	3,160	414.3	-4.04
24	1.1	8	-17.3	3,160	414.3	-4.19
32	1.1	3,153	366.3	3,160	414.3	88.40

*Blue cells indicate reactor is running
*Expected values in bluebased on 90% destruction
*Time zero is approximately 30 seconds after reactor is on

Concentration verses time

Time (min)	Mass (ng)
-8	314.0
0	190.1
8	-16.7
24	-17.3
32	366.3
16	364.6
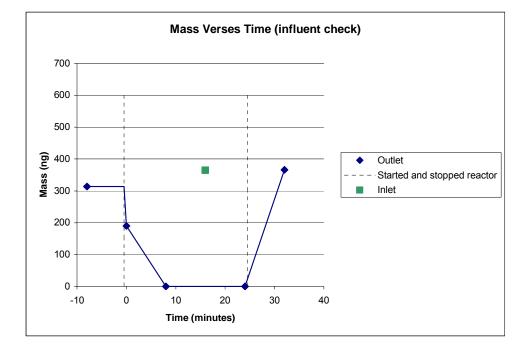
green is the inlet sample

Destruction Efficiency (with influent)

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
364.6	190.1	174.5	47.8%	0.0
364.6	0.0	364.6	100.0%	8.0
364.6	0.0	364.6	100.0%	24.0

*values are compared with 16 minutes

*values zeroed to account for error producing > 100% destruction

Mass Verses Time (influent check)

Mass (ng) vs Time (minutes)

Legend:
- ◆ Outlet
- --- Started and stopped reactor
- ■ Inlet
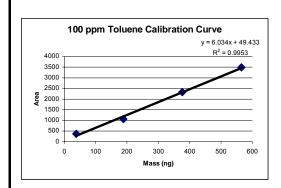
Experiment 7   27-Nov-06

Conditions

Concentration into reactor =	100	ppm
Number of Tubes =	2	tubes
Volume per tube =	47.30	mL per tube
Flow Through Reactor =	3,936	mL/min
retention time =	1.4	sec
Wall Voltage =	122	Volts
Primary Voltage =	72	Volts
Secondary Voltage =	9,000	Volts
Wall Current =	5.240	amps
Primary Current =	1.310	amps
Resistor =	100	ohms
Measured ΔVolts =	1.065	Volts
Secondary Current =	11	mamps
Wall Power =	641.38	volt-amps
Primary Power =	94.32	volt-amps
Secondary Power =	95.85	volt-amps
Temperature =	25	˚C
MW Toluene =	92.14	

100 ppm Toluene Calibration Curve

$y = 6.034x + 49.433$
$R^2 = 0.9953$

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value Area	Measured Value Mass (ng)	Expected Value Area	Expected Value Mass (ng)	Measured concentration (ppm)
-8	1.1	3,052	497.6	2,549	414.3	120.11
0	1.1	1,815	292.7	299	41.4	70.64
8	1.1	510	76.4	299	41.4	18.44
16	1.1	488	72.7	299	41.4	17.56
24	1.1	496	74.1	299	41.4	17.88
32	1.1	1,526	244.6	2,549	414.3	59.05
41	1.1	2,896	471.7	2,549	414.3	113.86

*Blue cells indicate reactor is running

*Expected values in blue based on 90% destruction

*Time zero is approximately 30 seconds after reactor is on

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Concentration Verses Time
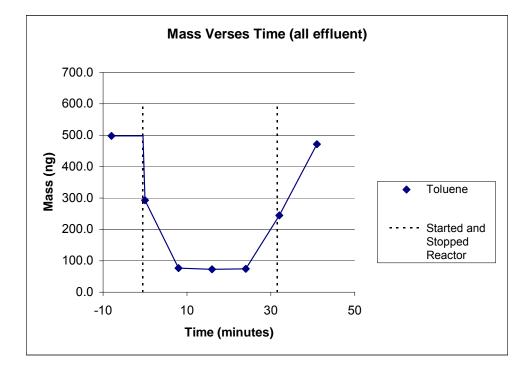
Time (min)	Mass (ng)
-8	497.6
0	292.7
8	76.4
16	72.7
24	74.1
32	244.6
41	471.7

Destruction Efficiency (all effluent)

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
497.6	292.7	204.9	41.2%	0.0
497.6	76.4	421.2	84.6%	8.0
497.6	72.7	424.9	85.4%	16.0
497.6	74.1	423.5	85.1%	24.0

*all compared with -8 min

Mass Verses Time (all effluent)

Experiment 8   1-Dec-06

Conditions

Concentration into reactor =	100	ppm
Number of Tubes =	2	tubes
Volume per tube =	47.30	mL per tube
Flow Through Reactor =	3,936	mL/min
retention time =	1.4	sec
Wall Voltage =	122.4	Volts
Primary Voltage =	117.0	Volts
Secondary Voltage =	14,625	Volts
Wall Current =	7.05	amps
Primary Current =	1.91	amps
Resistor =	100	ohms
Measured ΔVolts =	1.569	Volts
Secondary Current =	16	mamps
Wall Power =	862.92	volt-amps
Primary Power =	223.47	volt-amps
Secondary Power =	229.4663	volt-amps
Temperature =	25	˚C
MW Toluene =	92.14	

Calibration Dec 1 SRI

$y = 8.0411x - 108.2$

$R^2 = 1$

Influent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
16	1.1	3,292	395.9	2,549	414.3	95.57
-	1.1	-	-	2,549	414.3	-

*Expected value determined by concentration and calibration curve
*Measured mass calculated by calibration curve

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
-8	1.1	3,203	384.9	3,223	414.3	92.89
0	1.1	1,620	188.0	225	41.4	45.38
8	1.1	176	8.5	225	41.4	2.05
24	1.1	157	6.1	225	41.4	1.47
32	1.1	3,184	382.5	3,223	414.3	92.32

*Blue cells indicate reactor is running
*Expected values in bluebased on 90% destruction
*Time zero is approximately 30 seconds after reactor is on

Concentration verses time
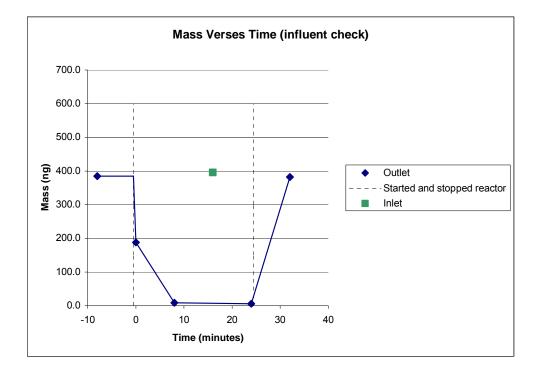
Time (min)	Mass (ng)
-8	384.9
0	188.0
8	8.5
24	6.1
32	382.5
16	395.9

green is the inlet sample

Destruction Efficiency (with influent)

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
384.9	188.0	196.8	51.1%	0.0
384.9	8.5	376.4	97.8%	8.0
384.9	6.1	378.8	98.4%	24.0

*values are compared with -8 minutes

Mass Verses Time (influent check)

Experiment 9 1-Dec-06

Conditions

Concentration into reactor =	100	ppm
Number of Tubes =	5	tubes
Volume per tube =	47.30	mL per tube
Flow Through Reactor =	5,321	mL/min
retention time =	2.7	sec
Wall Voltage =	122.4	Volts
Primary Voltage =	96	Volts
Secondary Voltage =	12,000	Volts
Wall Current =	5.94	amps
Primary Current =	1.55	amps
Resistor =	100	ohms
Measured ΔVolts =	1.270	Volts
Secondary Current =	13	mamps
Wall Power =	727.056	volt-amps
Primary Power =	148.8	volt-amps
Secondary Power =	152.4	volt-amps
Temperature =	25	˚C
MW Toluene =	92.14	

Calibration Dec 1 SRL $y = 8.0411x - 108.2$
$R^2 = 1$

[Chart: Area vs Mass (ng)]

Influent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration
		Area	Mass (ng)	Area	Mass (ng)	(ppm)
16	1.1	2,768	330.7	3,223	414.3	79.83
-	1.1	-	-	3,223	414.3	-

*Expected value determined by concentration and calibration curve
*Measured mass calculated by calibration curve

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration
		Area	Mass (ng)	Area	Mass (ng)	(ppm)
-8	1.1	2,914	349.0	3,223	414.3	84.23
0	1.1	2,685	320.5	225	41.4	77.35
8	1.1	1,274	144.9	225	41.4	34.98
24	1.1	1,247	141.6	225	41.4	34.19
32	1.1	2,962	354.9	3,223	414.3	85.66

*Blue cells indicate reactor is running
*Expected values in bluebased on 90% destruction
*Time zero is approximately 30 seconds after reactor is on

Concentration verses time
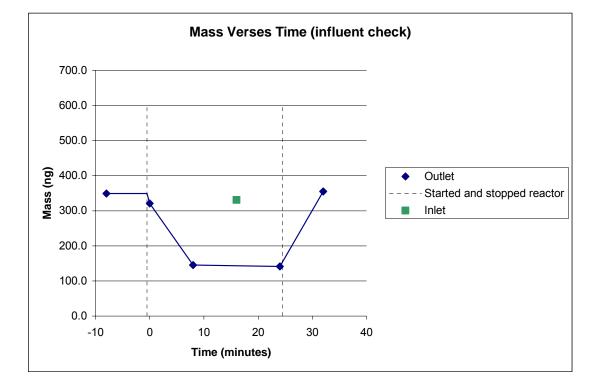
Time (min)	Mass (ng)
-8	349.0
0	320.5
8	144.9
24	141.6
32	354.9
16	330.7

green is the inlet sample

Destruction Efficiency (with influent)

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
349.0	320.5	28.5	8.2%	0.0
349.0	144.9	204.0	58.5%	8.0
349.0	141.6	207.3	59.4%	24.0

*values are compared with -8 minutes

Mass Verses Time (influent check)

Experiment 10   6-Dec-06

Conditions

Concentration into reactor =	100	ppm
Number of Tubes =	5	tubes
Volume per tube =	47.30	mL per tube
Flow Through Reactor =	5,321	mL/min
retention time =	2.7	sec
Wall Voltage =	121.8	Volts
Primary Voltage =	96	Volts
Secondary Voltage =	12,000	Volts
Wall Current =	5.88	amps
Primary Current =	1.57	amps
Resistor =	100	ohms
Measured ΔVolts =	1.274	Volts
Secondary Current =	13	mamps
Wall Power =	716.184	volt-amps
Primary Power =	150.72	volt-amps
Secondary Power =	152.88	volt-amps
Temperature =	25	˚C
MW Toluene =	92.14	

Calibration Curve 12/6/06

$y = 7.9809x - 146.14$

$R^2 = 0.999$

Influent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
16	1.1	2,859	339.9	3,160	414.3	82.04
-	1.1	-	-	3,160	414.3	-

*Expected value determined by concentration and calibration curve

*Measured mass calculated by calibration curve

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
-8	1.1	3,258	393.6	3,160	414.3	95.02
0	1.1	1,988	234.5	184	41.4	56.61
8	1.1	1,356	155.3	184	41.4	37.49
24	1.1	1,431	164.7	184	41.4	39.76
32	1.1	2,342	278.9	3,158	414.3	67.33

*Blue cells indicate reactor is running

*Expected values in bluebased on 90% destruction

*Time zero is approximately 30 seconds after reactor is on

Concentration verses time
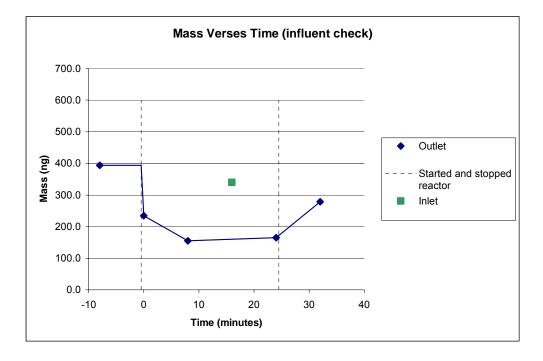
Time (min)	Mass (ng)
-8	393.6
0	234.5
8	155.3
24	164.7
32	278.9
16	339.9

green is the inlet sample

Destruction Efficiency (with influent)

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
393.6	234.5	159.1	40.4%	0.0
393.6	155.3	238.3	60.5%	8.0
393.6	164.7	228.9	58.2%	24.0

*values are compared with -8 minutes

Mass Verses Time (influent check)

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Experiment 11   1-Dec-06

Conditions

Concentration into reactor =	100	ppm
Number of Tubes =	5	tubes
Volume per tube =	47.30	mL per tube
Flow Through Reactor =	5,321	mL/min
retention time =	2.7	sec
Wall Voltage =	122.1	Volts
Primary Voltage =	96	Volts
Secondary Voltage =	12,000	Volts
Wall Current =	5.98	amps
Primary Current =	1.53	amps
Resistor =	100	ohms
Measured ΔVolts =	1.278	Volts
Secondary Current =	13	mamps
Wall Power =	730.158	volt-amps
Primary Power =	146.88	volt-amps
Secondary Power =	153.36	volt-amps
Temperature =	25	˚C
MW Toluene =	92.14	

Calibration Dec 1 SRI $y = 8.0411x - 108.2$
$R^2 = 1$

Influent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
16	1.1	2,727	325.7	3,223	414.3	78.61
-	1.1	-	-	3,223	414.3	-

*Expected value determined by concentration and calibration curve
*Measured mass calculated by calibration curve

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
-8	1.1	3,362	404.6	3,223	414.3	97.66
0	1.1	2,571	306.3	225	41.4	73.94
8	1.1	1,336	152.7	225	41.4	36.87
24	1.1	1,343	153.5	225	41.4	37.06
32	1.1	3,159	379.4	3,223	414.3	91.57

*Blue cells indicate reactor is running
*Expected values in blue based on 90% destruction
*Time zero is approximately 30 seconds after reactor is on

Concentration verses time
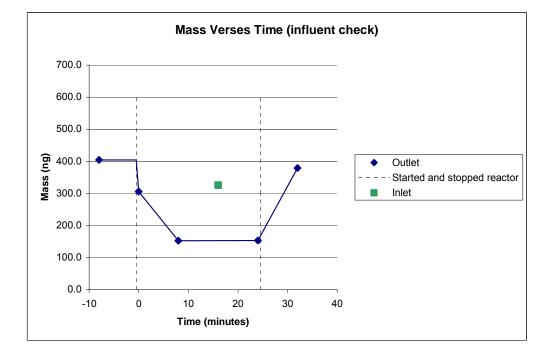
Time (min)	Mass (ng)
-8	404.6
0	306.3
8	152.7
24	153.5
32	379.4
16	325.7

green is the inlet sample

Destruction Efficiency (with influent)

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
404.6	306.3	98.3	24.3%	0.0
404.6	152.7	251.9	62.2%	8.0
404.6	153.5	251.1	62.1%	24.0

*values are compared with -8 minutes

Mass Verses Time (influent check)

Cumulative Experimental Results

Exp.	Reactor Config.	Actual Retention Time (s)	Secondary Voltage (V)	Primary Voltage (V)	Flow (mL/min)	voltage per tube	Mass Removed (ng)	Best Destruction Efficiency (%)	Mass removed per time (mg/min)	Wall current (amps)	Wall Voltage (Volts)	Wall power (kW)	Secondary Power[a] (kW)	Destruction Cost Effeciency (g/kW-hr)
1	8	4.3	9000	72	5321	9000	120.6	31.7	0.58	5.06	123.1	0.474	0.279	0.126
2	8	4.3	14625	117	5321	7312.5	306.2	77.6	1.48	6.59	122.1	0.617	0.401	0.222
3	8	1.8	9000	72	12283	3000	72.9	19.8	0.81	4.91	121.5	0.454	0.259	0.189
4	8	1.8	14625	117	12283	3656.3	177.6	43.2	1.98	6.60	121.5	0.615	0.421	0.283
5	2	4.9	9000	72	1164	1800	394.7	98.8	0.42	5.51	122	0.511	0.316	0.079
6	2	4.9	14625	117	1164	2437.5	364.6	100	0.39	7.10	121	0.663	0.469	0.049
7	2	1.4	9000	72	3936	1285.7	424.9	85.4	1.52	5.24	122	0.486	0.291	0.313
8	2	1.4	14625	117	3936	1828.1	378.8	98.4	1.36	7.05	122.04	0.664	0.470	0.173
9	5	2.7	12000	96	5321	1333.3	207.3	59.4	1.00	5.94	122.04	0.555	0.360	0.167
10	5	2.7	12000	96	5321	1200	238.3	60.5	1.15	5.88	121.8	0.549	0.353	0.196
11	5	2.7	12000	96	5321	1090.9	251.9	62.2	1.22	5.98	122.1	0.559	0.364	0.201

a) Secondary power = Wall power -power without tubes connected

Wall
Phase angle in degrees

	Voltage		
# tubes	72	96	117
2	-40.50	-39.90	-39.50
5	-40.20	-40.00	-39.90
8	-40.50	-40.20	-39.90
without tubes	-41.50	-41.40	-41.70
current	2.17	2.29	2.42
power source only	-41.60	-41.70	-41.60
current	2.03	1.90	1.92

wall voltage = 120 V

Phase angle in radians

# tubes	Voltage		
	72	96	117
2	-0.71	-0.70	-0.69
5	-0.70	-0.70	-0.70
8	-0.71	-0.70	-0.70
without tubes	-0.72	-0.72	-0.73
	-	-	-
power source only	-0.73	-0.73	-0.73
	-	-	-

Power Calculation (example experiment # 1)

total system power:
(5.06 amps)*(123.1 volts)*cos(-0.72)/1000 = 0.474 kilowatts

power drawn by the power source and transformer:
(120 volts)*(2.17 amps)*cos(-0.72) = 0.195 kilowatts

secondary power = (0.474-0.195) = 0.279 kilowatts

8. Appendix B
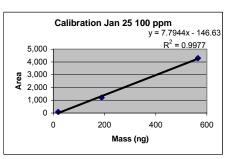
Varied Concentration and Humidity Experimental Runs

100 ppm With Humidity
Experiment 7   25-Jan-07

Conditions

Concentration into reactor =	34.77	ppm
Number of Tubes =	2	tubes
Volume per tube =	47.30	mL per tube
Flow Through Reactor =	3,936	mL/min
retention time =	1.4	sec
Wall Voltage =	122	Volts
Primary Voltage =	72	Volts
Secondary Voltage =	9,000	Volts
Wall Current =	5.470	amps
Primary Current =	1.360	amps
Resistor =	100	ohms
Measured ΔVolts =	1.083	Volts
Secondary Current =	11	mamps
Wall Power =	666.79	volt-amps
Primary Power =	97.92	volt-amps
Secondary Power =	97.47	volt-amps
Temperature =	25	˚C
Humidity =	30-50	%
MW Toluene =	92.14	

Calibration Jan 25 100 ppm
$y = 7.7944x - 146.63$
$R^2 = 0.9977$

Influent Samples

Time (min)	Sample Size (mL)	Measured Value Area	Mass (ng)	Expected Value Area	Mass (ng)	Measured concentration (ppm)
16	1.1	1,098	122.1	976	144.1	29.48
-	1.1	-	-	976	144.1	

*Expected value determined by concentration and calibration curve
*Measured mass calculated by calibration curve

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value Area	Mass (ng)	Expected Value Area	Mass (ng)	Measured concentration (ppm)
-8	1.1	1,363	156.1	976	144.1	37.67
0	1.1	666	66.6	-34	14.4	16.08
8	1.1	36	0.0	-34	14.4	0.00
24	1.1	45	0.0	-34	14.4	0.00
32	1.1	1,347	154.0	976	144.1	37.17

*Blue cells indicate reactor is running
*Expected values in bluebased on 90% destruction
*Time zero is approximately 30 seconds after reactor is on

Concentration Verses Time
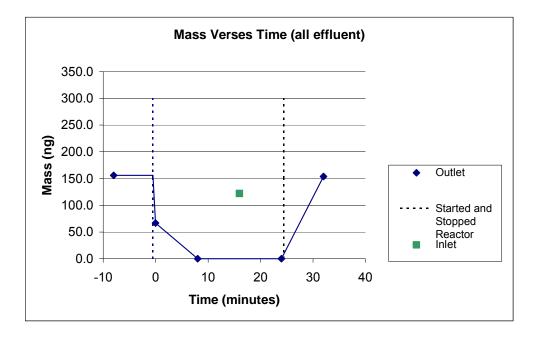
Time (min)	Mass (ng)
-8	156.1
0	66.6
8	0.0
24	0.0
32	154.0
16	122.1

Destruction Efficiency (all effluent)

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
156.1	66.6	89.4	57.3%	0.0
156.1	0.0	156.1	100.0%	8.0
156.1	0.0	156.1	100.0%	24.0

*all compared with -8 min

Mass Verses Time (all effluent)

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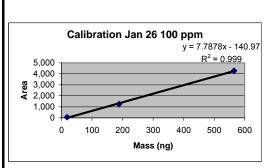
Experiment 8   26-Jan-07

Conditions

Concentration into reactor =	37.53 ppm
Number of Tubes =	2 tubes
Volume per tube =	47.30 mL per tube
Flow Through Reactor =	3,936 mL/min
retention time =	1.4 sec
Wall Voltage =	122 Volts
Primary Voltage =	117 Volts
Secondary Voltage =	14,625 Volts
Wall Current =	7.060 amps
Primary Current =	1.970 amps
Resistor =	100 ohms
Measured ΔVolts =	1.606 Volts
Secondary Current =	16 mamps
Wall Power =	859.20 volt-amps
Primary Power =	230.49 volt-amps
Secondary Power =	234.88 volt-amps
Temperature =	25 ˚C
Humidity =	30-50 %
MW Toluene =	92.14

Calibration Jan 26 100 ppm

$y = 7.7878x - 140.97$
$R^2 = 0.999$

Influent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
16	1.1	1,416	179.9	1,070	155.5	43.43
-	1.1	-	-	1,065	155.5	-

*Expected value determined by concentration and calibration curve
*Measured mass calculated by calibration curve

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
-8	1.1	1,260	143.7	1,070	155.5	34.68
0	1.1	326	23.7	-20	15.5	5.72
8	1.1	0	0.0	-20	15.5	0.00
24	1.1	0	0.0	-20	15.5	0.00
32	1.1	1,254	142.9	1,070	155.5	34.48

*Blue cells indicate reactor is running
*Expected values in bluebased on 90% destruction
*Time zero is approximately 30 seconds after reactor is on
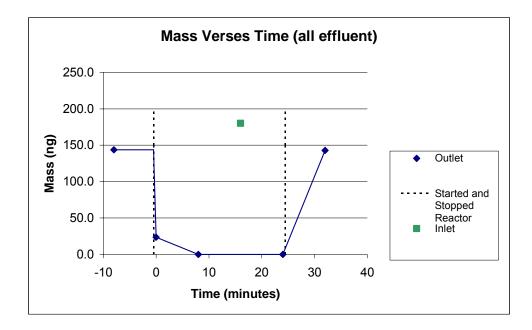
Concentration Verses Time

Time (min)	Mass (ng)
-8	143.7
0	23.7
8	0.0
24	0.0
32	142.9
16	179.9

Destruction Efficiency (all effluent)

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
143.7	23.7	120.0	83.5%	0.0
143.7	0.0	143.7	100.0%	8.0
143.7	0.0	143.7	100.0%	24.0

*all compared with -8 min

Mass Verses Time (all effluent)
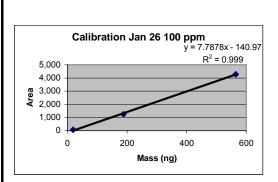
Experiment 9,10,11   26-Jan-07

Conditions

Concentration into reactor =	9.62	ppm
Number of Tubes =	5	tubes
Volume per tube =	47.30	mL per tube
Flow Through Reactor =	5,321	mL/min
retention time =	2.7	sec
Wall Voltage =	123	Volts
Primary Voltage =	96	Volts
Secondary Voltage =	12,000	Volts
Wall Current =	6.220	amps
Primary Current =	1.590	amps
Resistor =	100	ohms
Measured ΔVolts =	1.296	Volts
Secondary Current =	13	mamps
Wall Power =	761.95	volt-amps
Primary Power =	152.64	volt-amps
Secondary Power =	155.52	volt-amps
Temperature =	25	˚C
Humidity =	30-50	%
MW Toluene =	92.14	

Calibration Jan 26 100 ppm

$y = 7.7878x - 140.97$
$R^2 = 0.999$

Influent Samples

Time (min)	Sample Size (mL)	Measured Value Area	Mass (ng)	Expected Value Area	Mass (ng)	Measured concentration (ppm)
16	1.1	355	27.5	169	39.9	6.65
-	1.1	-	-	290	39.9	-

*Expected value determined by concentration and calibration curve
*Measured mass calculated by calibration curve

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value Area	Mass (ng)	Expected Value Area	Mass (ng)	Measured concentration (ppm)
-8	1.1	574	55.7	169	39.9	13.43
0	1.1	299	20.3	-110	4.0	4.91
8	1.1	90	0.0	-110	4.0	0.00
24	1.1	89	0.0	-110	4.0	0.00
32	1.1	424	36.4	169	39.9	8.78

*Blue cells indicate reactor is running
*Expected values in bluebased on 90% destruction
*Time zero is approximately 30 seconds after reactor is on

Concentration Verses Time
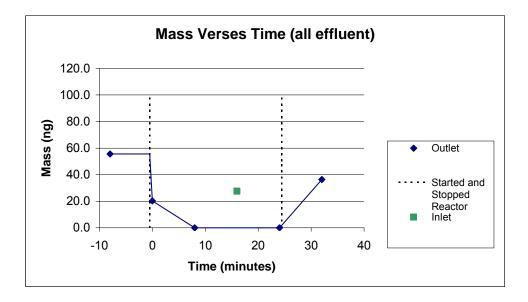
Time (min)	Mass (ng)
-8	55.7
0	20.3
8	0.0
24	0.0
32	36.4
16	27.5

Destruction Efficiency (all effluent)

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
55.7	20.3	35.3	63.5%	0.0
55.7	0.0	55.7	100.0%	8.0
55.7	0.0	55.7	100.0%	24.0

*all compared with -8 min

Mass Verses Time (all effluent)
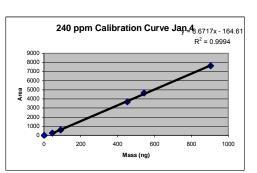
240 ppm
Experiment 8   4-Jan-07

Conditions

Concentration into reactor =	240	ppm
Number of Tubes =	2	tubes
Volume per tube =	47.30	mL per tube
Flow Through Reactor =	3,936	mL/min
retention time =	1.4	sec
Wall Voltage =	121.6	Volts
Primary Voltage =	117	Volts
Secondary Voltage =	14,625	Volts
Wall Current =	7.09	amps
Primary Current =	1.94	amps
Resistor =	100	ohms
Measured ΔVolts =	1.580	Volts
Secondary Current =	16	mamps
Wall Power =	862.144	volt-amps
Primary Power =	226.98	volt-amps
Secondary Power =	231.075	volt-amps
Temperature =	25	˚C
MW Toluene =	92.14	

240 ppm Calibration Curve Jan 4

$y = 8.6717x - 164.61$
$R^2 = 0.9994$

note: 15 on second flow meter to insure proper flow.

Influent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
16	0.6	4,085	490.0	4,703	542.3	216.8
-	0.6	-	-	4,703	542.3	-

*Expected value determined by concentration and calibration curve
*Measured mass calculated by calibration curve

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
-8	0.6	4,951	589.9	4,538	542.3	261.1
0	0.6	373	62.0	306	54.2	27.4
8	0.6	254	48.3	306	54.2	21.4
24	0.6	153	36.6	306	54.2	16.2
32	0.6	3,914	470.3	4,538	542.3	208.1

*Blue cells indicate reactor is running
*Expected values in bluebased on 90% destruction
*Time zero is approximately 30 seconds after reactor is on

Concentration verses time
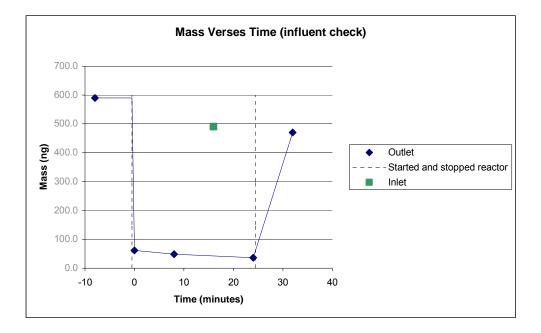
Time (min)	Mass (ng)
-8	589.9
0	62.0
8	48.3
24	36.6
32	470.3
16	490.0

green is the inlet sample

Destruction Efficiency (with influent)

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
589.9	62.0	527.9	89.5%	0.0
589.9	48.3	541.7	91.8%	8.0
589.9	36.6	553.3	93.8%	24.0

*values are compared with -8 minutes

Mass Verses Time (influent check)

Experiment 9, 10, 11   5-Jan-07

Conditions

Concentration into reactor =	240	ppm
Number of Tubes =	5	tubes
Volume per tube =	47.30	mL per tube
Flow Through Reactor =	5,321	mL/min
retention time =	2.7	sec
Wall Voltage =	121.7	Volts
Primary Voltage =	96	Volts
Secondary Voltage =	12,000	Volts
Wall Current =	6.75	amps
Primary Current =	1.86	amps
Resistor =	100	ohms
Measured ΔVolts =	1.498	Volts
Secondary Current =	15	mamps
Wall Power =	821.475	volt-amps
Primary Power =	178.56	volt-amps
Secondary Power =	179.76	volt-amps
Temperature =	25	˚C
MW Toluene =	92.14	

240 ppm Calibration Jan 5

$y = 8.6285x - 178.26$
$R^2 = 0.9999$

Influent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
16	0.6	3,812	448.5	4,639	542.3	198.5
-	0.6	-	-	4,639	542.3	-

*Expected value determined by concentration and calibration curve
*Measured mass calculated by calibration curve

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
-8	0.6	4,356	510.2	4,639	542.3	225.8
0	0.6	3,115	369.4	338	54.2	163.4
8	0.6	1,763	215.9	338	54.2	95.5
24	0.6	2,196	265.1	338	54.2	117.3
32	0.6	4,478	524.0	4,639	542.3	231.9

*Blue cells indicate reactor is running
*Expected values in bluebased on 90% destruction
*Time zero is approximately 30 seconds after reactor is on

Concentration verses time
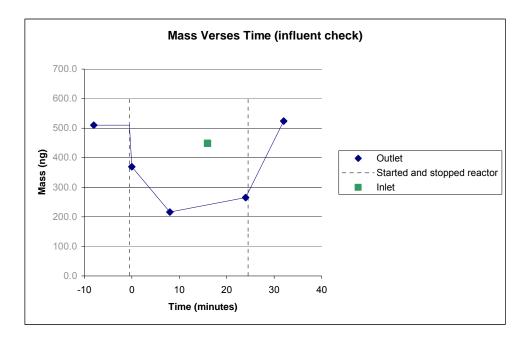
Time (min)	Mass (ng)
-8	510.2
0	369.4
8	215.9
24	265.1
32	524.0
16	448.5

green is the inlet sample

Destruction Efficiency (with influent)

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
510.2	369.4	140.9	27.6%	0.0
510.2	215.9	294.3	57.7%	8.0
510.2	265.1	245.2	48.1%	24.0

*values are compared with -8 minutes

Mass Verses Time (influent check)

Experiment 2   5-Jan-07

Conditions

Concentration into reactor =	240	ppm
Number of Tubes =	8	tubes
Volume per tube =	47.30	mL per tube
Flow Through Reactor =	5,321	mL/min
retention time =	4.3	sec
Wall Voltage =	121.9	Volts
Primary Voltage =	117	Volts
Secondary Voltage =	14,625	Volts
Wall Current =	6.65	amps
Primary Current =	1.76	amps
Resistor =	100	ohms
Measured ΔVolts =	1.476	Volts
Secondary Current =	15	mamps
Wall Power =	810.635	volt-amps
Primary Power =	205.92	volt-amps
Secondary Power =	215.865	volt-amps
Temperature =	25	˚C
MW Toluene =	92.14	

240 ppm Calibration Jan 5

$y = 8.6285x - 178.26$
$R^2 = 0.9999$

Influent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
16	0.6	4,260	499.4	4,639	542.3	221.0
-	0.6	-	-	4,639	542.3	-

*Expected value determined by concentration and calibration curve
*Measured mass calculated by calibration curve

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value		Expected Value		Measured concentration (ppm)
		Area	Mass (ng)	Area	Mass (ng)	
-8	0.6	4,816	562.5	4,639	542.3	248.9
0	0.6	3,216	380.8	338	54.2	168.5
8	0.6	2,945	350.1	338	54.2	154.9
24	0.6	2,849	339.2	338	54.2	150.1
32	0.6	4,363	522.1	4,538	542.3	231.0

*Blue cells indicate reactor is running
*Expected values in bluebased on 90% destruction
*Time zero is approximately 30 seconds after reactor is on

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Concentration verses time
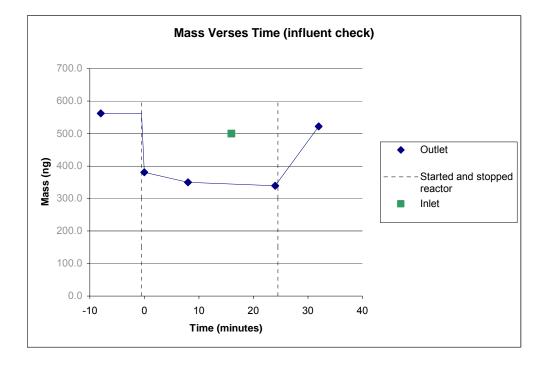
Time (min)	Mass (ng)
-8	562.5
0	380.8
8	350.1
24	339.2
32	522.1
16	499.4

green is the inlet sample

Destruction Efficiency (with influent)

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
562.5	380.8	181.6	32.3%	0.0
562.5	350.1	212.4	37.8%	8.0
562.5	339.2	223.3	39.7%	24.0

*values are compared with -8 minutes

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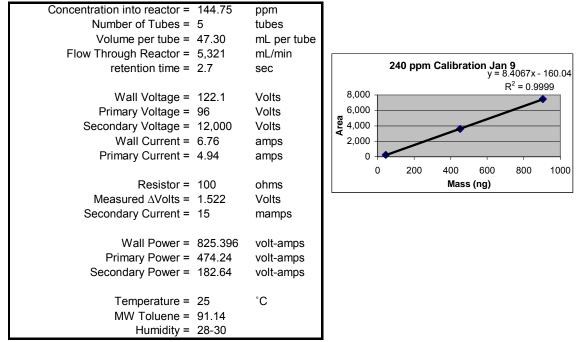
240 ppm With Humidity
Experiment 9, 10, 11　　9-Jan-07

Conditions

Concentration into reactor =	144.75	ppm
Number of Tubes =	5	tubes
Volume per tube =	47.30	mL per tube
Flow Through Reactor =	5,321	mL/min
retention time =	2.7	sec
Wall Voltage =	122.1	Volts
Primary Voltage =	96	Volts
Secondary Voltage =	12,000	Volts
Wall Current =	6.76	amps
Primary Current =	4.94	amps
Resistor =	100	ohms
Measured ΔVolts =	1.522	Volts
Secondary Current =	15	mamps
Wall Power =	825.396	volt-amps
Primary Power =	474.24	volt-amps
Secondary Power =	182.64	volt-amps
Temperature =	25	˚C
MW Toluene =	91.14	
Humidity =	28-30	

240 ppm Calibration Jan 9

$y = 8.4067x - 160.04$

$R^2 = 0.9999$

Influent Samples

Time (min)	Sample Size (mL)	Measured Value Area	Measured Value Mass (ng)	Expected Value Area	Expected Value Mass (ng)	Measured concentration (ppm)
16	0.6	2,975	334.8	2,560	323.5	149.8
-	0.6	-	-	2,560	323.5	-

*Expected value determined by concentration and calibration curve
*Measured mass calculated by calibration curve

Effluent Samples

Time (min)	Sample Size (mL)	Measured Value Area	Measured Value Mass (ng)	Expected Value Area	Expected Value Mass (ng)	Measured concentration (ppm)
-8	0.6	2,859	321.0	2,560	323.5	143.6
0	0.6	1,881	204.8	2,560	323.5	91.6
8	0.6	1,019	102.2	2,560	323.5	45.7
24	0.6	1,279	133.1	2,560	323.5	59.6
32	0.6	2,807	314.8	2,560	323.5	140.8

*Blue cells indicate reactor is running
*Expected values in bluebased on 90% destruction
*Time zero is approximately 30 seconds after reactor is on

Concentration verses time
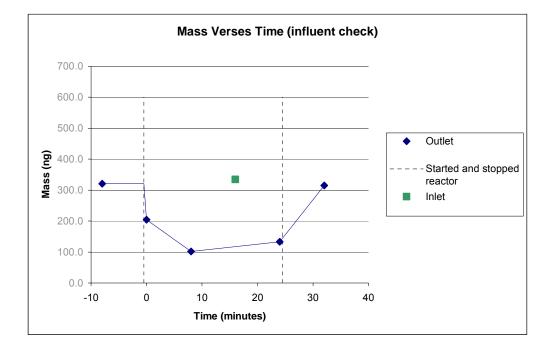
Time (min)	Mass (ng)
-8	321.0
0	204.8
8	102.2
24	133.1
32	314.8
16	334.8

green is the inlet sample

Destruction Efficiency (with influent)

Mass Without Destruction (ng)	Effluent Mass (ng)	Change in Mass (ng)	Destruction (influent-effluent)/ influent*100	Sample time (min)
321.0	204.8	116.3	36.2%	0.0
321.0	102.2	218.8	68.2%	8.0
321.0	133.1	187.9	58.5%	24.0

*values are compared with -8 minutes

Mass Verses Time (influent check)

Cumulative Experimental Results

Parameters	Exp.	Reactor Config.	Actual Retention Time (s)	Flow (mL/min)	Secondary Voltage (V)	Mass Removed (ng)	Wall power (kW)	Secondary Power (kW)	Mass removed per time (mg/min)	Actual concentration (ppm)	mass removed (mg/min)
240 ppm	2	8	4.3	5321	14625	223.3	0.622	0.405	0.160	240	1.08
no humidity	8	2	1.4	3936	14625	553.3	0.665	0.449	0.265	240	1.98
	9	5	2.7	5321	12000	294.3	0.629	0.423	0.202	240	1.42
240 ppm	9h	5	2.7	5321	12000	218.8	0.632	0.426	0.149	145	1.06
100 ppm	7h	2	1.4	3936	9000	156.1	0.508	0.313	0.107	35	0.56
humidity	8h	2	1.4	3936	14625	143.7	0.665	0.448	0.069	38	0.51
	9h	5	2.7	5321	12000	55.7	0.586	0.380	0.043	10	0.27

9. Appendix C

Ozone Calculations

Experiment	Secondary Voltage	Flow (mL/min)	Na2S2O3 (ml)	mg O3/L air	g O3/h	W. C. (Amp)	W.V. (V)	Wall Power	Seconda y Power	g O3/Kw·h
1	9,000	5,321	135.4	1.7	0.5	5.06	123.1	473.8	278.7	1.9
2	14,652	5,321	161.5	5.0	1.6	6.59	122.1	617.5	400.6	4.0
3	9,000	12,283	78.7	0.9	0.7	4.91	121.5	610.0	414.9	1.7
4	14,652	12,283	84.8	0.8	0.6	6.6	121.5	615.4	398.5	1.4
5	9,000	1,164	22.3	2.4	0.2	5.51	122	511.3	316.2	0.5
6	14,652	1,164	43.1	10.8	0.8	7.1	121	663.1	446.2	1.7
7	9,000	3,936	153.8	5.1	1.2	5.24	122	486.3	291.2	4.1
8	14,652	3,936	151.5	9.5	2.2	7.05	122	664.1	447.2	5.0
9	12,000	5,321	110.7	4.5	1.4	5.94	122	555.5	349.3	4.1
10	12,000	5,321	87.6	5.2	1.7	5.88	121.8	548.8	342.6	4.8
11	12,000	5,321	99.3	4.8	1.5	5.98	122.1	559.5	353.3	4.3

Experiment	Sample 1 100 ml	Sample 2 100ml	Sample 3 100ml	Sample 4 120ml	Total Experim	Sample Time (min)	Sample air Volume (ml)	mg O3/L solution
1	31.2	32.2	32.5	39.5	135.4	1.71	9101	38.6
2	40.1	40.2	38.0	43.2	161.5	0.70	3718	46.4
3	16.6	18.3	19.2	24.6	78.7	0.75	9192	21.6
4	18.0	21.1	20.6	25.1	84.8	0.99	12156	23.4
5	3.8	5.1	6.2	7.2	22.3	0.68	790	4.7
6	9.2	10.2	10.7	13.0	43.1	0.35	404	10.9
7	33.0	36.1	38.0	46.7	153.8	0.89	3495	44.1
8	34.3	34.7	36.9	45.6	151.5	0.46	1828	43.4
9	24.0	25.6	27.2	33.9	110.7	0.52	2791	31.2
10	19.6	20.3	22.1	25.6	87.6	0.35	1869	24.3
11	20.1	23.6	22.8	32.8	99.3	0.44	2325	27.8

Other Experimental Parameters

ppm	Experiment	Secondary Voltage	Flow (mL/min)	Humidity (%)	Na2S2O3 (ml)	mg O3/L air	g O3/h	Secondary Power (kW)	g O3/Kw·h
	2	14,625	5,321	0	84.7	1.4	0.4	0.405	1.1
	9	12,000	5,321	0	84.9	1.3	0.4	0.449	0.9
240	8	14,625	3,936	0	77.6	1.2	0.3	0.423	0.7
240	9h	12,000	5,321	30-50	154.4	1.6	0.5	0.426	1.2
	7h	9,000	3,936	30-50	154.4	1.5	0.3	0.313	1.1
	8h	14,625	3,936	30-50	96.6	1.0	0.2	0.448	0.5
100	9h	12,000	5,321	30-50	123.5	0.7	0.2	0.380	0.6
100	7	9,000	3,936	0	145.6	1.5	0.4	0.291	1.2

ppm	Experiment	Sample 1 100 ml	Sample 2 100ml	Sample 3 100ml	Sample 4 120ml	Total Experiment	Sample Time	Sample air Volume (ml)	mg O3/L solution
	8	17.4	18.8	19.4	29.1	84.7	0.28	1463	23.8
	9	17.4	18.9	21.0	27.6	84.9	0.29	1563	23.9
240	2	15.5	17.1	19.2	25.8	77.6	0.35	1359	21.7
240	2	23.0	35.0	26.1	28.5	112.6	0.44	2326	32.2
	7h	33.6	35.5	39.5	45.8	154.4	1.21	4754	44.7
	8h	26.8	26.0	30.8	39.9	123.5	0.83	4403	35.4
100	9h	25.3	22.6	23.8	24.9	96.6	0.94	3716	27.4
100	7	35.8	34.6	17.9	57.3	145.6	0.76	4022	42.1

10. Appendix D
Statistics Calculations

Destruction Efficiency ANOVA & Tukey Test

Exp.	Actual Retention Time, A (s)	Reactor Config., B	Primary Voltage, C (V)	Best Destruction Efficiency (%)
1	4.3	8	72	0.317
2	4.3	8	117	0.776
3	1.8	8	72	0.198
4	1.8	8	117	0.432
5	4.9	2	72	0.988
6	4.9	2	117	1
7	1.4	2	72	0.854
8	1.4	2	117	0.984
9	2.7	5	96	0.594
10	2.7	5	96	0.605
11	2.7	5	96	0.622

avg observation = 0.69
sum Yjkl = 5.55
avg Y... = 1.39
0.607 [Y] = 7.70

ABC Summary Table

		B, Number of Tubes (k)						
		2 (b1)		8 (b2)				
		C, Primary Voltage (l)		C, Primary Voltage (l)				
	A, Retention Time (j)	72 (c1)	117 (c2)	72 (c1)	117 (c2)	Yj..	avg Yj..	dj..=Yj..-Y...
a1	1.4	0.854	0.984	0.198	0.432	2.468	0.617	-0.770
a2	4.9	0.988	1.000	0.317	0.776	3.081	0.770	-0.617
	Y..l	2.357		3.192				
	avg Y..l	0.921	0.992	0.258	0.604			
	d..l = Y..l-Y...	-0.466	-0.395	-1.130	-0.783			
	avg d..l	-0.798		-0.589				
		c1		c2				

B Summary Table

	Y.k.	avg Y.k.	dk = avg Y.k. - avg Y...
b1	3.826	0.957	-0.431
b2	1.723	0.431	-0.957

α = 0.25

if F nonadditive < 2.57 system is additive
rejects null hypothesis of non-additive

dijk Summary Table (dj..*d.k.*d..l)

	B, Number of Tubes (k)			
	2 (b1)		8 (b2)	
	C, Primary Voltage (l)		C, Primary Voltage (l)	
A, Retention Time (j)	72	117	72	117
1.4	-0.265	-0.196	-0.588	-0.434
4.9	-0.212	-0.157	-0.471	-0.348

parameter	[parameter]	SS	df	mean square	Fo	Effects Estimate
A	7.792	0.094	1	0.09	-0.03	0.217
B	8.804	1.106	1	1.11	-0.33	0.744
C	7.872	0.174	1	0.17	-0.05	0.295
ABC	4.602	-4.470	1	-4.47	1.35	-
rem	-	-6.625	2	-3.31	-	-
nonadd	-	**2.155**	**1**	**2.16**	**-0.65**	-
total	-	-7.565	7	-	-	-

Equation
Y = u + ax + by + cz

Exp.	Observations	A	a = (A-3.15)/(1.75)	B	b = (B-5)/3	C	c = (C-94.5)/22.5	Eq results	error
1)	0.317	4.3	0.66	8	1	72	-1	0.989	-0.672
2)	0.776	4.3	0.66	8	1	117	1	1.284	-0.508
3)	0.198	1.8	-0.77	8	1	72	-1	0.834	-0.636
4)	0.432	1.8	-0.77	8	1	117	1	1.129	-0.697
5)	0.988	4.9	1.00	2	-1	72	-1	0.283	0.705
6)	1	4.9	1.00	2	-1	117	1	0.578	0.422
7)	0.854	1.4	-1.00	2	-1	72	-1	0.066	0.788
8)	0.984	1.4	-1.00	2	-1	117	1	0.361	0.623
9)	0.607	2.7	-0.26	5	0	96	0.07	0.676	-0.069

u = average of observations

a,b,c = the normalized parameters retention time, tubes, and voltage respectively

x,y,z = effects/2 for the respective parameters

	A	B	C
high	4.9	8	117
low	1.4	2	72
average	3.15	5	94.5
(high-low)/2	1.75	3	22.5

y =   0.69 +   0.11 a +   0.37 b +   0.15 c

Destruction Cost Efficiency ANOVA & Tukey Test

Exp.	Actual Retention Time, A (s)	Reactor Config., B	Primary Voltage, C (V)	Destruction Cost Effeciency (g/kW-hr)
1	4.3	8	72	0.126
2	4.3	8	117	0.222
3	1.8	8	72	0.189
4	1.8	8	117	0.283
5	4.9	2	72	0.079
6	4.9	2	117	0.049
7	1.4	2	72	0.313
8	1.4	2	117	0.173
9	2.7	5	96	0.167
10	2.7	5	96	0.196
11	2.7	5	96	0.201

avg observation = 0.18
sum Yjkl = 1.43
avg Y... = 0.36
0.187862462   [Y] = 0.51

ABC Summary Table

		B, Number of Tubes (k)						
		2 (b1)		8 (b2)				
		C, Primary Voltage (l)		C, Primary Voltage (l)				
	A, Retention Time (j)	72 (c1)	117 (c2)	72 (c1)	117 (c2)	Yj..	avg Yj..	dj..=Yj..-Y...
a1	1.4	0.313	0.173	0.189	0.283	0.958	0.240	-0.119
a2	4.9	0.079	0.049	0.126	0.222	0.476	0.119	-0.240
	Y..l	0.707		0.727				
	avg Y..l	0.196	0.111	0.157	0.252			
	d..l = Y..l-Y...	-0.162	-0.247	-0.201	-0.106			
	avg d..l	-0.182		-0.177				
		c1		c2				

B Summary Table

	Y.k.	avg Y.k.	dk = avg Y.k. - avg Y...
b1	0.615	0.154	-0.205
b2	0.819	0.205	-0.154

α = 0.25

if F nonadditive < 2.57 system is additive

rejects null hypothesis of non-additive

dijk Summary Table   (dj..*d.k.*d..l)

		B, Number of Tubes (k)			
		2 (b1)		8 (b2)	
		C, Primary Voltage (l)		**C, Primary Voltage (l)**	
A, Retention Time (j)		72	117	72	117
1.4		-4.4E-03	-4.3E-03	-3.3E-03	-3.2E-03
4.9		-8.9E-03	-8.7E-03	-6.7E-03	-6.5E-03

parameter	[parameter]	SS	df	mean square	Fo	Effects Estimate
A	0.572	0.058	1	0.058	-0.269	0.170
B	0.525	0.010	1	0.010	-0.048	0.072
C	0.514	0.000	1	0.000	0.000	0.007
ABC	0.317	-0.265	1	-0.265	1.227	-
rem	-	-0.432	2	-0.216	-	-
nonadd	-	**0.167**	1	**0.167**	**-0.773**	-
total	-	-0.462	7	-	-	-

125

Equation
Y = u + ax + by + cz

Exp.	Observations	A	a = (A-3.15)/(1.75)	B	b = (B-5)/3	C	c = (C-94.5)/22.5	Eq results	error
1)	0.126	4.3	0.66	8	1	72	-1	0.268	-0.142
2)	0.222	4.3	0.66	8	1	117	1	0.275	-0.053
3)	0.189	1.8	-0.77	8	1	72	-1	0.146	0.043
4)	0.283	1.8	-0.77	8	1	117	1	0.153	0.130
5)	0.079	4.9	1.00	2	-1	72	-1	0.225	-0.146
6)	0.049	4.9	1.00	2	-1	117	1	0.232	-0.183
7)	0.313	1.4	-1.00	2	-1	72	-1	0.054	0.259
8)	0.173	1.4	-1.00	2	-1	117	1	0.062	0.112
9)	0.188	2.7	-0.26	5	0	96	0.07	0.158	0.030

u = average of observations
a,b,c = the normalized parameters retention time, tubes, and voltage respectively
x,y,z = effects/2 for the respective parameters

	A	B	C
high	4.9	8	117
low	1.4	2	72
average	3.15	5	94.5
(high-low)/2	1.75	3	22.5

y =   0.18 +   0.09 a +   0.04 b +   0.00 c

Ozone Production ANOVA & Tukey Test

Exp.	Actual Retention Time, A (s)	Reactor Config., B	Primary Voltage, C (V)	g O3/h
1	4.3	8	72	0.542
2	4.3	8	117	1.595
3	1.8	8	72	0.693
4	1.8	8	117	0.568
5	4.9	2	72	0.166
6	4.9	2	117	0.755
7	1.4	2	72	1.193
8	1.4	2	117	2.245
9	2.7	5	96	1.428
10	2.7	5	96	1.659
11	2.7	5	96	1.526

avg observation = 0.97
sum Yjkl = 7.76
avg Y... = 1.94
1.537340002   [Y] = 15.04

ABC Summary Table

		B, Number of Tubes (k)						
		2 (b1)		8 (b2)				
		C, Primary Voltage (l)		C, Primary Voltage (l)				
	A, Retention Time (j)	72 (c1)	117 (c2)	72 (c1)	117 (c2)	Yj..	avg Yj..	dj..=Yj..-Y...
a1	1.4	1.193	2.245	0.693	0.568	4.699	1.175	-0.764
a2	4.9	0.166	0.755	0.542	1.595	3.057	0.764	-1.175
	Y..l	2.593		5.162				
	avg Y..l	0.679	1.500	0.617	1.082			
	d..l = Y..l-Y...	-1.260	-0.439	-1.322	-0.857			
	avg d..l	-1.291		-0.648				
		c1		c2				

B Summary Table

	Y.k.	avg Y.k.	dk = avg Y.k. - avg Y...
b1	4.358	1.089	-0.849
b2	3.398	0.849	-1.089

dijk Summary Table   (dj..*d.k.*d..l)

	B, Number of Tubes (k)			
	2 (b1)		8 (b2)	
	C, Primary Voltage (l)		C, Primary Voltage (l)	
A, Retention Time (j)	72	117	72	117
1.4	-0.84	-0.42	-1.07	-0.54
4.9	-1.29	-0.65	-1.65	-0.83

α = 0.25

if F nonadditive < 2.57 system is additive
rejects null hypothesis of non-additive

parameter	[parameter]	SS	df	mean square	Fo	Effects Estimate
A	15.710	0.674	1	0.674	-0.119	0.580
B	15.267	0.230	1	0.230	-0.041	0.339
C	16.687	1.651	1	1.651	-0.290	0.908
ABC	10.699	-6.893	1	-6.893	1.213	-
rem	-	-11.367	2	-5.683	-	-
nonadd	**-**	**4.474**	**1**	**4.474**	**-0.787**	-
total	-	-11.230	7	-	-	-

Equation

$Y = u + ax + by + cz$

Exp.	Observations	A	a = (A-3.15)/(1.75)	B	b = (B-5)/3	C	c = (C-94.5)/22.5	Eq results	error
1)	0.542	4.3	0.66	8	1	72	-1	0.876	-0.334
2)	1.595	4.3	0.66	8	1	117	1	1.784	-0.189
3)	0.693	1.8	-0.77	8	1	72	-1	0.461	0.232
4)	0.568	1.8	-0.77	8	1	117	1	1.369	-0.801
5)	0.166	4.9	1.00	2	-1	72	-1	0.636	-0.470
6)	0.755	4.9	1.00	2	-1	117	1	1.544	-0.790
7)	1.193	1.4	-1.00	2	-1	72	-1	0.055	1.138
8)	2.245	1.4	-1.00	2	-1	117	1	0.964	1.281
9)	1.537	2.7	-0.26	5	0	96	0.07	0.925	0.612

u = average of observations

a,b,c = the normalized parameters retention time, tubes, and voltage respectively

x,y,z = effects/2 for the respective parameters

	A	B	C
high	4.9	8	117
low	1.4	2	72
average	3.15	5	94.5
(high-low)/2	1.75	3	22.5

y =   0.97 +   0.29 a +   0.17 b +   0.45 c

Ozone Efficiency ANOVA & Tukey Test

Exp.	Actual Retention Time, A (s)	Reactor Config., B	Primary Voltage, C (V)	g O3/Kw·h
1	4.3	8	72	1.944
2	4.3	8	117	3.982
3	1.8	8	72	2.678
4	1.8	8	117	1.350
5	4.9	2	72	0.523
6	4.9	2	117	1.610
7	1.4	2	72	4.097
8	1.4	2	117	4.780
9	2.7	5	96	3.965
10	2.7	5	96	4.694
11	2.7	5	96	4.190

avg observation = 2.62
sum Yjkl = 20.96
avg Y... = 5.24
4.282798913 [Y] = 109.87

ABC Summary Table

		B, Number of Tubes (k)						
		2 (b1)		8 (b2)				
		C, Primary Voltage (l)		C, Primary Voltage (l)				
	A, Retention Time (j)	72 (c1)	117 (c2)	72 (c1)	117 (c2)	Yj..	avg Yj..	dj..=Yj..-Y…
a1	1.4	4.097	4.780	2.678	1.350	12.905	3.226	-2.015
a2	4.9	0.523	1.610	1.944	3.982	8.059	2.015	-3.226
	Y..l	9.242		11.722				
	avg Y..l	2.310	3.195	2.311	2.666			
	d..l = Y..l-Y…	-2.931	-2.046	-2.930	-2.575			
	avg d..l	-2.931		-2.311				
		c1		c2				

B Summary Table

	Y.k.	avg Y.k.	dk = avg Y.k. - avg Y…
b1	11.011	2.753	-2.488
b2	9.954	2.488	-2.753

dijk Summary Table   (dj..*d.k.*d..l)

	B, Number of Tubes (k)			
	2 (b1)		8 (b2)	
	C, Primary Voltage (l)		C, Primary Voltage (l)	
A, Retention Time (j)	72	117	72	117
1.4	-14.69	-11.58	-16.25	-12.81
4.9	-23.53	-18.55	-26.03	-20.52

α = 0.25

if F nonadditive < 2.57 system is additive
rejects null hypothesis of non-additive

parameter	[parameter]	SS	df	mean square	Fo	Effects Estimate
A	115.746	5.871	1	5.871	-0.129	1.713
B	110.154	0.279	1	0.279	-0.006	0.374
C	111.412	1.537	1	1.537	-0.034	0.877
ABC	71.127	-46.435	1	-46.435	1.023	-
rem	-	-90.808	2	-45.404	-	-
nonadd	**-**	**44.373**	**1**	**44.373**	**-0.977**	-
total	-	-85.183	7	-	-	-

Equation
Y = u + ax + by + cz

Exp.	Observations	A	a = (A-3.15)/(1.75)	B	b = (B-5)/3	C	c = (C-94.5)/22.5	Eq results	error
1)	1.944	4.3	0.66	8	1	72	-1	2.932	-0.988
2)	3.982	4.3	0.66	8	1	117	1	3.809	0.173
3)	2.678	1.8	-0.77	8	1	72	-1	1.708	0.970
4)	1.350	1.8	-0.77	8	1	117	1	2.585	-1.235
5)	0.523	4.9	1.00	2	-1	72	-1	2.852	-2.329
6)	1.610	4.9	1.00	2	-1	117	1	3.729	-2.118
7)	4.097	1.4	-1.00	2	-1	72	-1	1.139	2.958
8)	4.780	1.4	-1.00	2	-1	117	1	2.015	2.765
9)	4.283	2.7	-0.26	5	0	96	0.07	2.429	1.853

u = average of observations
a,b,c = the normalized parameters retention time, tubes, and voltage respectively
x,y,z = effects/2 for the respective parameters

	A	B	C
high	4.9	8	117
low	1.4	2	72
average	3.15	5	94.5
(high-low)/2	1.75	3	22.5

y =   2.62 +   0.86 a +   0.19 b +   0.44 c

11.   Appendix E

Reynolds Number Calculations

$$R = \frac{DV}{\nu}$$

(inner) D_{tube} = 10 mm
D_{rod} = 6.32 mm

$D_{effective}$ = $(D_{tube}^2 - D_{rod}^2)^{1/2}$ = 7.7 mm = <u>0.77 cm</u>

A = $(\Pi\, D_{effective}^2)/4$ = <u>47.3 cm^3</u>

$$V = \frac{Q}{A * tubes}$$

ν = 1.55 x 10^{-5} m^2/s = 9.3 cm^2/min
at 25 °C from:
 Finnemore, E. John and Franzini, Joseph B., Fluid Mechanics. McGraw Hill 2002.
10th ed.

Exp.	Tubes	Actual Retention Time (s)	Q (mL/min)	R (DV/v)/tubes
1	8	4.3	5321	117.6
2	8	4.3	5321	117.6
3	8	1.8	12283	271.4
4	8	1.8	12283	271.4
5	2	4.9	1164	102.9
6	2	4.9	1164	102.9
7	2	1.4	3936	347.8
8	2	1.4	3936	347.8
9	5	2.7	5321	188.1
10	5	2.7	5321	188.1
11	5	2.7	5321	188.1

12. Appendix F
Tank Certifications and Lab Results

PRAXAIR

4/13/2006

Praxair Distribution, Inc.
37256 Highway 30
Geismar, LA 70734
Tel (225) 677-7700
   888-495-4356
Fax (225) 673-3531
ISO 9001 Registered

Oklahoma State University
207 Engineering South Annex
Stillwater, OK 74078
c/o Civil and Enviromental Eng.;
Attn. Dr. John Leenstra

COPY

Praxair Order No.	824466-00	Praxair Part No.	NI BW105X1C-AS
P.O. No.	613640 HN Leenstra		

CERTIFICATE OF ANALYSIS
Certified Standard

Component	Requested Concentration	Certified Concentration	Analytical Principle	Analytical Accuracy
2-Butanol	105 ppm	106 ppm	D	+/-2 %
n-Butylacetate	105 ppm	106 ppm	D	+/-2 %
Methyl isobutyl ketone	105 ppm	106 ppm	D	+/-2 %
Toluene	106 ppm	107 ppm	D	+/-2 %
Nitrogen	Balance	Balance		

Analytical Instruments: **Hewlett Packard 6890**

Cylinder Style:	**AS**	Filling Method:	**Gravimetric**
Cylinder Pressure @70F:	**230 psig**	Date of Fill:	**4/5/2006**
Cylinder Volume:	**17.4 ft3**	Expiration Date:	**4/5/2007**
Valve Outlet Connection:	**350 SS**		

Cylinder No. **CC217657**

Analyst: James Dobson - Chemist   QA Reviewer: Ramon Gonzalez

The gas calibration cylinder standard prepared by Praxair Distribution is considered a certified standard. It is prepared by gravimetric, volumetric, or partial pressure techniques. The calibration standard provided is certified against Praxair Reference Materials which are either prepared by weights traceable to the National Institute of Standards and Technology (NIST) or by using NIST Standard Reference Materials where available.

Note: All expressions for concentration (e.g., % or ppm) are for gas phase, by volume (e.g., ppmv) unless otherwise noted.

Key to Analytical Techniques:

A	Flame Ionization with Methanizer	B	Gas Chromatography with Discharge Ionization Detector	C	Gas Chromatography with Electrolytic Conductivity Detector	D	Gas Chromatography with Flame Ionization Detector
E	Gas Chromatography with Flame Photometric Detector	F	Gas Chromatography with Helium Ionization Detector	G	Gas Chromatography with Methanizer Carbonizer	H	Gas Chromatography with Photoionization Detector
I	Gas Chromatography with Reduction Gas Analyzer	J	Gas Chromatography with Thermal Conductivity Detector	K	Gas Chromatography with Ultrasonic Detector	L	Infrared - FTIR or NDIR
M	Mass Spectrometry - MS or GCMS	N	Proprietary	O	Paramagnetic	P	Specific Water Analyzer
Q	Total Hydrocarbon Analyzer	R	Wet Chemical	S	Detector Tube	T	Odor
J	Gas Chromatography with Chemiluminescence Detector	V	Electrochemical	W	Hygrometer		

IMPORTANT
The information contained herein has been prepared at your request by personnel within Praxair Distribution. While we believe the information is accurate within the limits of the analytical methods employed and is complete to the extent of the specific analyses performed, we make no warranty or representation as to the suitability of the use of the information for any particular purpose. The information is offered with the understanding that any use of this information is at the sole discretion and risk of the user. In no event shall liability of Praxair Distribution, Inc. arising out of the use of the information contained herein exceed the fee established for providing such information.

Pg. 1 of 1

CERTIFIED WORKING CLASS

Single-Certified Calibration Standard

Scott Specialty Gases
9810 BAY AREA BLVD, PASADENA, TX 77507

Phone: 281-474-5800   Fax: 281-474-5857

CERTIFICATE OF ACCURACY: Certified Working Class Calibration Standard

Product Information
Project No.: 04-50145-001
Item No.: 04023912   TAL
P.O. No.: TFANCHER 120406

Cylinder Number: ALM052781
Cylinder Size: AL
Certification Date: 19Dec2006
Expiration Date: 01Jan2009

Customer

OKLAHOMA STATE UNIVERSITY
TAMYRA FANCHER/ENV ENG.
DEPT OF CIVIL ENG.
207 ENGINEERING SOUTH
STILLWATER, OK   74078

CERTIFIED CONCENTRATION

Component Name	Concentration (Moles)		Accuracy (+/-%)
TOLUENE	240.	PPM	5
AIR		BALANCE	

TRACEABILITY

Traceable To

Scott Reference Standard

APPROVED BY: _Susan J Brandon_
SUSAN BRANDON

DATE: 12-19-06

Page   1 of 2

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CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Pace Analytical®

Page: _____ of _____

10931

1044833

Section A
Required Client Information:

Company: Oklahoma State Univ.
Address: 207 Engineering South
Stillwater, OK 74078
Email To: veenst@okstate.edu
Phone: (405) 744-5190 Fax: 744-7554
Requested Due Date/TAT:

Section B
Required Project Information:

Report To: John Veenstra
Copy To:
Purchase Order No.:
Project Name: Please
Project Number:

Section C
Invoice Information:

Attention:
Company Name: Pay w/
Address: Credit + Card
Pace Quote Reference: Cell 405-744-9300
Pace Project Manager:
Pace Profile #:

REGULATORY AGENCY
- ☐ NPDES
- ☐ UST
- ☐ GROUND WATER
- ☐ RCRA
- ☐ DRINKING WATER
- ☐ Other

SITE LOCATION
- ☐ GA ☐ IL ☐ IN ☐ MI ☐ MN ☐ NC
- ☐ OH ☐ SC ☐ WI ☑ OTHER OK

Pace Project Number Lab I.D.: 001 / 002

Section D Required Client Information

SAMPLE ID
One Character per box.
(A-Z, 0-9 / . -)
Samples IDs MUST BE UNIQUE

Valid Matrix Codes:
DRINKING WATER — DW
WATER — WT
WASTE WATER — WW
PRODUCT — P
SOIL/SOLID — SL
OIL — OL
WIPE — WP
AIR — AR
OTHER — OT
TISSUE — TS

# ITEM	SAMPLE ID	MATRIX CODE	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED COMPOSITE START / COMPOSITE END/GRAB DATE/TIME	# OF CONTAINERS	TD-15
1	59713	AR	G	1/9/07 6:52	1	X
2	59753	AR	G	1/9/07 6:57	1	X
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						

Preservatives: Unpreserved / H2SO4 / HNO3 / HCl / NaOH / Na2S2O3 / Methanol / Other

Filtered (Y/N)
Requested Analysis:
Residual Chlorine (Y/N)

Additional Comments:

RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME
John Veenstra/OSU	1/9/07		B. Flexu	1/5/07	7:00

SAMPLER NAME AND SIGNATURE
PRINT Name of SAMPLER: John Veenstra
SIGNATURE of SAMPLER:
DATE Signed (MM/DD/YY): 01/09/07

SAMPLE CONDITION
Temp in °C / Received on Ice / Custody Sealed Cooler / Samples Intact

Y/N	Y/N	Y/N	Y/N

ORIGINAL

SEE REVERSE SIDE FOR INSTRUCTIONS

ALL-Q020rev.3.31Mar05

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Sample Condition Upon Receipt

Pace Analytical

Client Name: Oklahoma St. Univ   Project # 1044833

Courier: ☐ Fed Ex ☒ UPS ☐ USPS ☐ Client ☐ Commercial ☐ Pace Other _____

Tracking #: 1Z374E4039675699I

Custody Seal on Cooler/Box Present: ☐ yes ☒ no   Seals intact: ☐ yes ☒ no

Packing Material: ☒ Bubble Wrap ☐ Bubble Bags ☐ None ☐ Other _____

Thermometer Used   230194010   Type of Ice: Wet Blue (None)   ☐ Samples on ice, cooling process has begun

Cooler Temperature   Amb   Biological Tissue is Frozen: Yes No

Temp should be above freezing to 6°C

Date and initials of person examining contents: _____

		Comments:
Chain of Custody Present:	☒ Yes ☐ No ☐ N/A	1.
Chain of Custody Filled Out:	☒ Yes ☐ No ☐ N/A	2.
Chain of Custody Relinquished:	☒ Yes ☐ No ☐ N/A	3.
Sampler Name & Signature on COC:	☒ Yes ☐ No ☐ N/A	4.
Samples Arrived within Hold Time:	☒ Yes ☐ No ☐ N/A	5.
Short Hold Time Analysis (<72hr):	☐ Yes ☒ No ☐ N/A	6.
Rush Turn Around Time Requested:	☐ Yes ☒ No ☐ N/A	7.
Sufficient Volume:	☒ Yes ☐ No ☐ N/A	8.
Correct Containers Used:	☒ Yes ☐ No ☐ N/A	9.
-Pace Containers Used:	☒ Yes ☐ No ☐ N/A	
Containers Intact:	☒ Yes ☐ No ☐ N/A	10.
Filtered volume received for Dissolved tests	☐ Yes ☐ No ☒ N/A	11.
Sample Labels match COC:	☒ Yes ☐ No ☐ N/A	12.
-Includes date/time/ID/Analysis Matrix: Aur CAH		
All containers needing preservation have been checked.	☐ Yes ☐ No ☒ N/A	13.
All containers needing preservation are found to be in compliance with EPA recommendation.	☐ Yes ☐ No ☒ N/A	
exceptions: VOA, coliform, TOC, O&G, WI-DRO (water)	☐ Yes ☒ No	Initial when completed / Lot # of added preservative
Samples checked for dechlorination:	☐ Yes ☐ No ☒ N/A	14.
Headspace in VOA Vials (>6mm):	☐ Yes ☒ No ☐ N/A	15.
Trip Blank Present:	☐ Yes ☒ No ☐ N/A	16.
Trip Blank Custody Seals Present	☐ Yes ☒ No ☐ N/A	
Pace Trip Blank Lot # (if purchased): _____		

Client Notification/ Resolution: Field Data Required?   Y / N

Person Contacted: _____   Date/Time: _____

Comments/ Resolution: _____

_____

_____

_____

_____

_____

Project Manager Review: SDO   Date: 01/15/07

Note: Whenever there is a discrepancy affecting North Carolina compliance samples, a copy of this form will be sent to the North Carolina DEHNR Certification Office (i.e out of hold, incorrect preservative, out of temp, incorrect containers)

F-ALLC003rev.3, 11September2006

Pace Analytical®
www.pacelabs.com

January 30, 2007

John Veenstra
Oklahoma State University
207 Engineering South
Stillwater, OK 74078

RE: Project: PLASMA
      Pace Project No.: 1044833

Dear John Veenstra:

Enclosed are the analytical results for sample(s) received by the laboratory on January 15, 2007.
Results reported herein conform to the most current NELAC standards, where applicable, unless
otherwise narrated in the body of the report.

If you have any questions concerning this report, please feel free to contact me.

Sincerely,

Daryl Peterson

daryl.peterson@pacelabs.com
Project Manager

Illinois Certification #: 200011
Iowa Certification #: 368
Minnesota Certification #: 027-053-137
Wisconsin Certification #: 999407970

Enclosures

cc: Artie Southern, Oklahoma State University School of Civil
      and Env. Engin.

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SAMPLE SUMMARY

Project: PLASMA
Pace Project No.: 1044833

Lab ID	Sample ID	Matrix	Date Collected	Date Received
1044833001	5973	Air	01/09/07 06:52	01/15/07 09:00
1044833002	5953	Air	01/09/07 06:57	01/15/07 09:00

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
1700 Elm Street, Suite 200
Minneapolis, MN 55414

Phone: (612)607-1700
Fax: (612)607-6444

SAMPLE ANALYTE COUNT

Project: PLASMA
Pace Project No.: 1044833

Lab ID	Sample ID	Method	Analytes Reported
1044833001	5973	TO-15	57
1044833002	5953	TO-15	57

ANALYTICAL RESULTS

Project: PLASMA
Pace Project No.: 1044833

Sample: 5973			Lab ID: 1044833001	Collected: 01/09/07 06:52		Received: 01/15/07 09:00	Matrix: Air	
Parameters	Results	Units	Report Limit	DF	Prepared	Analyzed	CAS No.	Qual
TO15 MSV AIR		Analytical Method: TO-15						
Acetone	**26.2** ppbv		4.6	8.36		01/25/07 23:23	67-64-1	IC
Benzene	ND ppbv		4.3	8.36		01/25/07 23:23	71-43-2	
Bromodichloromethane	ND ppbv		4.3	8.36		01/25/07 23:23	75-27-4	
Bromoform	ND ppbv		4.3	8.36		01/25/07 23:23	75-25-2	
Bromomethane	ND ppbv		4.3	8.36		01/25/07 23:23	74-83-9	
1,3-Butadiene	ND ppbv		4.3	8.36		01/25/07 23:23	106-99-0	
2-Butanone (MEK)	ND ppbv		4.6	8.36		01/25/07 23:23	78-93-3	
Carbon disulfide	ND ppbv		4.2	8.36		01/25/07 23:23	75-15-0	
Carbon tetrachloride	ND ppbv		4.3	8.36		01/25/07 23:23	56-23-5	SS
Chlorobenzene	ND ppbv		4.3	8.36		01/25/07 23:23	108-90-7	
Chloroethane	ND ppbv		4.3	8.36		01/25/07 23:23	75-00-3	
Chloroform	ND ppbv		4.3	8.36		01/25/07 23:23	67-66-3	
Chloromethane	**15.9** ppbv		4.2	8.36		01/25/07 23:23	74-87-3	
Cyclohexane	ND ppbv		4.3	8.36		01/25/07 23:23	110-82-7	
Dibromochloromethane	ND ppbv		4.4	8.36		01/25/07 23:23	124-48-1	
1,2-Dibromoethane (EDB)	ND ppbv		4.3	8.36		01/25/07 23:23	106-93-4	
1,2-Dichlorobenzene	ND ppbv		4.3	8.36		01/25/07 23:23	95-50-1	
1,3-Dichlorobenzene	ND ppbv		4.3	8.36		01/25/07 23:23	541-73-1	
1,4-Dichlorobenzene	ND ppbv		4.3	8.36		01/25/07 23:23	106-46-7	
Dichlorodifluoromethane	ND ppbv		4.3	8.36		01/25/07 23:23	75-71-8	
1,1-Dichloroethane	ND ppbv		4.3	8.36		01/25/07 23:23	75-34-3	
1,2-Dichloroethane	ND ppbv		4.3	8.36		01/25/07 23:23	107-06-2	
1,1-Dichloroethene	ND ppbv		4.3	8.36		01/25/07 23:23	75-35-4	
cis-1,2-Dichloroethene	ND ppbv		4.3	8.36		01/25/07 23:23	156-59-2	
trans-1,2-Dichloroethene	ND ppbv		8.4	8.36		01/25/07 23:23	156-60-5	
1,2-Dichloropropane	ND ppbv		4.3	8.36		01/25/07 23:23	78-87-5	
cis-1,3-Dichloropropene	ND ppbv		4.3	8.36		01/25/07 23:23	10061-01-5	
trans-1,3-Dichloropropene	ND ppbv		4.3	8.36		01/25/07 23:23	10061-02-6	
Dichlorotetrafluoroethane	ND ppbv		4.8	8.36		01/25/07 23:23	76-14-2	
Ethyl acetate	ND ppbv		4.3	8.36		01/25/07 23:23	141-78-6	
Ethylbenzene	ND ppbv		4.3	8.36		01/25/07 23:23	100-41-4	
4-Ethyltoluene	ND ppbv		4.4	8.36		01/25/07 23:23	622-96-8	
n-Heptane	ND ppbv		4.3	8.36		01/25/07 23:23	142-82-5	
Hexachloro-1,3-butadiene	ND ppbv		4.2	8.36		01/25/07 23:23	87-68-3	IC
n-Hexane	**5.8** ppbv		4.4	8.36		01/25/07 23:23	110-54-3	
2-Hexanone	ND ppbv		4.6	8.36		01/25/07 23:23	591-78-6	
Methylene Chloride	**222** ppbv		86.5	166.4		01/25/07 22:48	75-09-2	SS
4-Methyl-2-pentanone (MIBK)	ND ppbv		4.6	8.36		01/25/07 23:23	108-10-1	
Methyl-tert-butyl ether	ND ppbv		8.4	8.36		01/25/07 23:23	1634-04-4	
Propylene	ND ppbv		16.7	8.36		01/25/07 23:23	115-07-1	
Styrene	ND ppbv		4.6	8.36		01/25/07 23:23	100-42-5	
1,1,2,2-Tetrachloroethane	ND ppbv		4.3	8.36		01/25/07 23:23	79-34-5	
Tetrachloroethene	ND ppbv		4.3	8.36		01/25/07 23:23	127-18-4	
Tetrahydrofuran	ND ppbv		4.3	8.36		01/25/07 23:23	109-99-9	
Toluene	**7.3** ppbv		4.3	8.36		01/25/07 23:23	108-88-3	
1,2,4-Trichlorobenzene	ND ppbv		4.3	8.36		01/25/07 23:23	120-82-1	
1,1,1-Trichloroethane	ND ppbv		4.3	8.36		01/25/07 23:23	71-55-6	

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REPORT OF LABORATORY ANALYSIS

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Fax: (612)607-6444

ANALYTICAL RESULTS

Project: PLASMA
Pace Project No.: 1044833

Sample: 5973		Lab ID: 1044833001	Collected: 01/09/07 06:52	Received: 01/15/07 09:00	Matrix: Air		
Parameters	Results	Units	Report Limit	DF	Prepared	Analyzed	CAS No.	Qual

TO15 MSV AIR Analytical Method: TO-15

Parameters	Results	Units	Report Limit	DF	Prepared	Analyzed	CAS No.	Qual
1,1,2-Trichloroethane	ND	ppbv	4.3	8.36		01/25/07 23:23	79-00-5	
Trichloroethene	ND	ppbv	4.3	8.36		01/25/07 23:23	79-01-6	SS
Trichlorofluoromethane	ND	ppbv	4.2	8.36		01/25/07 23:23	75-69-4	CC
1,1,2-Trichlorotrifluoroethane	ND	ppbv	4.3	8.36		01/25/07 23:23	76-13-1	
1,2,4-Trimethylbenzene	ND	ppbv	4.3	8.36		01/25/07 23:23	95-63-6	
1,3,5-Trimethylbenzene	ND	ppbv	4.3	8.36		01/25/07 23:23	108-67-8	
Vinyl acetate	ND	ppbv	4.6	8.36		01/25/07 23:23	108-05-4	
Vinyl chloride	ND	ppbv	4.3	8.36		01/25/07 23:23	75-01-4	
m&p-Xylene	ND	ppbv	8.4	8.36		01/25/07 23:23	1330-20-7	
o-Xylene	ND	ppbv	4.3	8.36		01/25/07 23:23	95-47-6	

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ANALYTICAL RESULTS

Project: PLASMA
Pace Project No.: 1044833

Sample: 5953   Lab ID: 1044833002   Collected: 01/09/07 06:57   Received: 01/15/07 09:00   Matrix: Air

Parameters	Results	Units	Report Limit	DF	Prepared	Analyzed	CAS No.	Qual
TO15 MSV AIR	Analytical Method: TO-15							
Acetone	129	ppbv	34.3	62.4		01/25/07 23:54	67-64-1	IC
Benzene	ND	ppbv	32.4	62.4		01/25/07 23:54	71-43-2	
Bromodichloromethane	ND	ppbv	31.8	62.4		01/25/07 23:54	75-27-4	
Bromoform	ND	ppbv	32.4	62.4		01/25/07 23:54	75-25-2	
Bromomethane	ND	ppbv	31.8	62.4		01/25/07 23:54	74-83-9	
1,3-Butadiene	ND	ppbv	32.4	62.4		01/25/07 23:54	106-99-0	
2-Butanone (MEK)	ND	ppbv	34.3	62.4		01/25/07 23:54	78-93-3	
Carbon disulfide	ND	ppbv	31.2	62.4		01/25/07 23:54	75-15-0	
Carbon tetrachloride	ND	ppbv	31.8	62.4		01/25/07 23:54	56-23-5	SS
Chlorobenzene	ND	ppbv	32.4	62.4		01/25/07 23:54	108-90-7	
Chloroethane	ND	ppbv	31.8	62.4		01/25/07 23:54	75-00-3	
Chloroform	ND	ppbv	31.8	62.4		01/25/07 23:54	67-66-3	
Chloromethane	ND	ppbv	31.2	62.4		01/25/07 23:54	74-87-3	
Cyclohexane	ND	ppbv	32.4	62.4		01/25/07 23:54	110-82-7	
Dibromochloromethane	ND	ppbv	33.1	62.4		01/25/07 23:54	124-48-1	
1,2-Dibromoethane (EDB)	ND	ppbv	32.4	62.4		01/25/07 23:54	106-93-4	
1,2-Dichlorobenzene	ND	ppbv	31.8	62.4		01/25/07 23:54	95-50-1	
1,3-Dichlorobenzene	ND	ppbv	31.8	62.4		01/25/07 23:54	541-73-1	
1,4-Dichlorobenzene	ND	ppbv	31.8	62.4		01/25/07 23:54	106-46-7	
Dichlorodifluoromethane	ND	ppbv	31.8	62.4		01/25/07 23:54	75-71-8	
1,1-Dichloroethane	ND	ppbv	32.4	62.4		01/25/07 23:54	75-34-3	
1,2-Dichloroethane	ND	ppbv	32.4	62.4		01/25/07 23:54	107-06-2	
1,1-Dichloroethene	ND	ppbv	32.4	62.4		01/25/07 23:54	75-35-4	
cis-1,2-Dichloroethene	ND	ppbv	32.4	62.4		01/25/07 23:54	156-59-2	
trans-1,2-Dichloroethene	ND	ppbv	62.4	62.4		01/25/07 23:54	156-60-5	
1,2-Dichloropropane	ND	ppbv	32.4	62.4		01/25/07 23:54	78-87-5	
cis-1,3-Dichloropropene	ND	ppbv	31.8	62.4		01/25/07 23:54	10061-01-5	
trans-1,3-Dichloropropene	ND	ppbv	32.4	62.4		01/25/07 23:54	10061-02-6	
Dichlorotetrafluoroethane	ND	ppbv	35.6	62.4		01/25/07 23:54	76-14-2	
Ethyl acetate	ND	ppbv	31.8	62.4		01/25/07 23:54	141-78-6	
Ethylbenzene	ND	ppbv	32.4	62.4		01/25/07 23:54	100-41-4	
4-Ethyltoluene	ND	ppbv	33.1	62.4		01/25/07 23:54	622-96-8	
n-Heptane	ND	ppbv	32.4	62.4		01/25/07 23:54	142-82-5	
Hexachloro-1,3-butadiene	ND	ppbv	31.2	62.4		01/25/07 23:54	87-68-3	IC
n-Hexane	39.1	ppbv	33.1	62.4		01/25/07 23:54	110-54-3	
2-Hexanone	ND	ppbv	34.3	62.4		01/25/07 23:54	591-78-6	
Methylene Chloride	197	ppbv	32.4	62.4		01/25/07 23:54	75-09-2	SS
4-Methyl-2-pentanone (MIBK)	ND	ppbv	34.3	62.4		01/25/07 23:54	108-10-1	
Methyl-tert-butyl ether	ND	ppbv	62.4	62.4		01/25/07 23:54	1634-04-4	
Propylene	ND	ppbv	125	62.4		01/25/07 23:54	115-07-1	
Styrene	ND	ppbv	34.3	62.4		01/25/07 23:54	100-42-5	
1,1,2,2-Tetrachloroethane	ND	ppbv	32.4	62.4		01/25/07 23:54	79-34-5	
Tetrachloroethene	ND	ppbv	32.4	62.4		01/25/07 23:54	127-18-4	
Tetrahydrofuran	ND	ppbv	32.4	62.4		01/25/07 23:54	109-99-9	
Toluene	113000	ppbv	4160	7999		01/26/07 14:10	108-88-3	A3
1,2,4-Trichlorobenzene	ND	ppbv	32.4	62.4		01/25/07 23:54	120-82-1	
1,1,1-Trichloroethane	ND	ppbv	32.4	62.4		01/25/07 23:54	71-55-6	

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REPORT OF LABORATORY ANALYSIS

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Minneapolis, MN 55414

Phone: (612)607-1700
Fax: (612)607-6444

ANALYTICAL RESULTS

Project: PLASMA
Pace Project No.: 1044833

Sample: 5953			Lab ID: 1044833002	Collected: 01/09/07 06:57	Received: 01/15/07 09:00	Matrix: Air	

Parameters	Results	Units	Report Limit	DF	Prepared	Analyzed	CAS No.	Qual
TO15 MSV AIR	Analytical Method: TO-15							
1,1,2-Trichloroethane	ND	ppbv	32.4	62.4		01/25/07 23:54	79-00-5	
Trichloroethene	ND	ppbv	32.4	62.4		01/25/07 23:54	79-01-6	SS
Trichlorofluoromethane	ND	ppbv	31.2	62.4		01/25/07 23:54	75-69-4	CC
1,1,2-Trichlorotrifluoroethane	ND	ppbv	32.4	62.4		01/25/07 23:54	76-13-1	
1,2,4-Trimethylbenzene	ND	ppbv	31.8	62.4		01/25/07 23:54	95-63-6	
1,3,5-Trimethylbenzene	ND	ppbv	32.4	62.4		01/25/07 23:54	108-67-8	
Vinyl acetate	ND	ppbv	34.3	62.4		01/25/07 23:54	108-05-4	
Vinyl chloride	ND	ppbv	31.8	62.4		01/25/07 23:54	75-01-4	
m&p-Xylene	ND	ppbv	62.4	62.4		01/25/07 23:54	1330-20-7	
o-Xylene	ND	ppbv	32.4	62.4		01/25/07 23:54	95-47-6	

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REPORT OF LABORATORY ANALYSIS

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QUALITY CONTROL DATA

Project: PLASMA
Pace Project No.: 1044833

QC Batch:	AIR/5105	Analysis Method:	TO-15
QC Batch Method:	TO-15	Analysis Description:	TO15 MSV AIR
Associated Lab Samples:	1044833001, 1044833002		

METHOD BLANK: 305269

Associated Lab Samples: 1044833001, 1044833002

Parameter	Units	Blank Result	Reporting Limit	Qualifiers
1,1,1-Trichloroethane	ppbv	ND	0.52	
1,1,2,2-Tetrachloroethane	ppbv	ND	0.52	
1,1,2-Trichloroethane	ppbv	ND	0.52	
1,1,2-Trichlorotrifluoroethane	ppbv	ND	0.52	
1,1-Dichloroethane	ppbv	ND	0.52	
1,1-Dichloroethene	ppbv	ND	0.52	
1,2,4-Trichlorobenzene	ppbv	ND	0.52	
1,2,4-Trimethylbenzene	ppbv	ND	0.51	
1,2-Dibromoethane (EDB)	ppbv	ND	0.52	
1,2-Dichlorobenzene	ppbv	ND	0.51	
1,2-Dichloroethane	ppbv	ND	0.52	
1,2-Dichloropropane	ppbv	ND	0.52	
1,3,5-Trimethylbenzene	ppbv	ND	0.52	
1,3-Butadiene	ppbv	ND	0.52	
1,3-Dichlorobenzene	ppbv	ND	0.51	
1,4-Dichlorobenzene	ppbv	ND	0.51	
2-Butanone (MEK)	ppbv	ND	0.55	
2-Hexanone	ppbv	ND	0.55	
4-Ethyltoluene	ppbv	ND	0.53	
4-Methyl-2-pentanone (MIBK)	ppbv	ND	0.55	
Acetone	ppbv	ND	0.55	IC
Benzene	ppbv	ND	0.52	
Bromodichloromethane	ppbv	ND	0.51	
Bromoform	ppbv	ND	0.52	
Bromomethane	ppbv	ND	0.51	
Carbon disulfide	ppbv	ND	0.50	
Carbon tetrachloride	ppbv	ND	0.51	SS
Chlorobenzene	ppbv	ND	0.52	
Chloroethane	ppbv	ND	0.51	
Chloroform	ppbv	ND	0.51	
Chloromethane	ppbv	ND	0.50	
cis-1,2-Dichloroethene	ppbv	ND	0.52	
cis-1,3-Dichloropropene	ppbv	ND	0.51	
Cyclohexane	ppbv	ND	0.52	
Dibromochloromethane	ppbv	ND	0.53	
Dichlorodifluoromethane	ppbv	ND	0.51	
Dichlorotetrafluoroethane	ppbv	ND	0.57	
Ethyl acetate	ppbv	ND	0.51	
Ethylbenzene	ppbv	ND	0.52	
Hexachloro-1,3-butadiene	ppbv	ND	0.50	IC
m&p-Xylene	ppbv	ND	1.0	
Methyl-tert-butyl ether	ppbv	ND	1.0	
Methylene Chloride	ppbv	ND	0.52	

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1700 Elm Street, Suite 200
Minneapolis, MN 55414

Phone: (612)607-1700
Fax: (612)607-6444

QUALITY CONTROL DATA

Project: PLASMA
Pace Project No.: 1044833

METHOD BLANK: 305269

Associated Lab Samples: 1044833001, 1044833002

Parameter	Units	Blank Result	Reporting Limit	Qualifiers
n-Heptane	ppbv	ND	0.52	
n-Hexane	ppbv	ND	0.53	
o-Xylene	ppbv	ND	0.52	
Propylene	ppbv	ND	2.0	
Styrene	ppbv	ND	0.55	
Tetrachloroethene	ppbv	ND	0.52	
Tetrahydrofuran	ppbv	ND	0.52	
Toluene	ppbv	ND	0.52	
trans-1,2-Dichloroethene	ppbv	ND	1.0	
trans-1,3-Dichloropropene	ppbv	ND	0.52	
Trichloroethene	ppbv	ND	0.52	SS
Trichlorofluoromethane	ppbv	ND	0.50	CC
Vinyl acetate	ppbv	ND	0.55	
Vinyl chloride	ppbv	ND	0.51	

LABORATORY CONTROL SAMPLE: 305270

Parameter	Units	Spike Conc.	LCS Result	LCS % Rec	% Rec Limits	Qualifiers
1,1,1-Trichloroethane	ppbv	10.6	8.6	81	60-134	
1,1,2,2-Tetrachloroethane	ppbv	10.6	10.1	95	55-141	
1,1,2-Trichloroethane	ppbv	10.7	8.8	83	64-129	
1,1,2-Trichlorotrifluoroethane	ppbv	10.9	9.6	88	55-137	
1,1-Dichloroethane	ppbv	10.7	10.5	98	59-136	
1,1-Dichloroethene	ppbv	10.8	12.0	112	60-137	
1,2,4-Trichlorobenzene	ppbv	10.4	13.8	133	50-150	
1,2,4-Trimethylbenzene	ppbv	10.4	10.3	99	63-137	
1,2-Dibromoethane (EDB)	ppbv	10.5	9.5	91	61-136	
1,2-Dichlorobenzene	ppbv	10.4	10.6	102	60-139	
1,2-Dichloroethane	ppbv	10.6	9.3	88	56-141	
1,2-Dichloropropane	ppbv	10.5	9.3	88	57-131	
1,3,5-Trimethylbenzene	ppbv	10.4	9.9	95	61-134	
1,3-Butadiene	ppbv	10.7	8.6	80	53-140	
1,3-Dichlorobenzene	ppbv	10.5	10.6	101	59-136	
1,4-Dichlorobenzene	ppbv	10.5	10.4	99	59-130	
2-Butanone (MEK)	ppbv	10.4	10.9	105	54-133	
2-Hexanone	ppbv	10.4	9.0	86	54-139	
4-Ethyltoluene	ppbv	10.3	10.4	101	61-138	
4-Methyl-2-pentanone (MIBK)	ppbv	10.4	9.1	87	53-139	
Acetone	ppbv	10.3	9.4	92	50-139	IC
Benzene	ppbv	10.6	8.3	78	64-125	
Bromodichloromethane	ppbv	10.4	8.7	84	61-131	
Bromoform	ppbv	10.4	9.4	90	66-138	
Bromomethane	ppbv	10.1	9.6	95	55-135	
Carbon disulfide	ppbv	10.4	10.2	98	50-150	
Carbon tetrachloride	ppbv	10.7	8.4	78	58-135	SS

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QUALITY CONTROL DATA

Project: PLASMA
Pace Project No.:   1044833

LABORATORY CONTROL SAMPLE: 305270

Parameter	Units	Spike Conc.	LCS Result	LCS % Rec	% Rec Limits	Qualifiers
Chlorobenzene	ppbv	10.6	8.2	78	62-139	
Chloroethane	ppbv	10	9.6	96	56-140	
Chloroform	ppbv	9.8	12.2	125	50-150	CC
Chloromethane	ppbv	9.9	11.6	117	56-144	
cis-1,2-Dichloroethene	ppbv	10.7	10	93	62-135	
cis-1,3-Dichloropropene	ppbv	10.5	10.1	96	64-133	
Cyclohexane	ppbv	10.2	8.3	82	54-139	
Dibromochloromethane	ppbv	10.4	9.9	95	50-150	
Dichlorodifluoromethane	ppbv	10.1	10	99	60-130	
Dichlorotetrafluoroethane	ppbv	9.9	9.0	91	59-130	
Ethyl acetate	ppbv	9.8	10.3	105	60-132	
Ethylbenzene	ppbv	10.5	10.3	98	65-140	
Hexachloro-1,3-butadiene	ppbv	10.4	13.6	131	50-150	IC
m&p-Xylene	ppbv	20.8	20.1	97	60-132	
Methyl-tert-butyl ether	ppbv	10.2	9.9	97	50-150	
Methylene Chloride	ppbv	10.8	12.6	117	56-138	
n-Heptane	ppbv	10.2	9.5	93	62-135	
n-Hexane	ppbv	10.1	11.2	111	62-134	
o-Xylene	ppbv	10.6	10.0	94	64-132	
Propylene	ppbv	10.6	10.3	97	56-125	
Styrene	ppbv	10.5	10.1	96	69-134	
Tetrachloroethene	ppbv	10.5	8.5	81	60-137	
Tetrahydrofuran	ppbv	10.2	11.2	109	52-139	
Toluene	ppbv	10.6	9.3	88	69-130	
trans-1,2-Dichloroethene	ppbv	10	9.7	97	50-150	
trans-1,3-Dichloropropene	ppbv	11	9.8	89	70-142	
Trichloroethene	ppbv	10.4	8.3	80	60-134	SS
Trichlorofluoromethane	ppbv	10.2	6.7	66	56-141	CC
Vinyl acetate	ppbv	10.6	9.8	92	61-142	
Vinyl chloride	ppbv	10	8.8	88	66-132	

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REPORT OF LABORATORY ANALYSIS

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QUALIFIERS

Project: PLASMA
Pace Project No.: 1044833

DEFINITIONS

DF - Dilution Factor, if reported, represents the factor applied to the reported data due to changes in sample preparation, dilution of the sample aliquot, or moisture content.

ND - Not Detected at or above adjusted reporting limit.

J - Estimated concentration above the adjusted method detection limit and below the adjusted reporting limit.

MDL - Adjusted Method Detection Limit.

S - Surrogate

1,2-Diphenylhydrazine (8270 listed analyte) decomposes to Azobenzene.

Consistent with EPA guidelines, unrounded data are displayed and have been used to calculate % recovery and RPD values.

LCS(D) - Laboratory Control Sample (Duplicate)

MS(D) - Matrix Spike (Duplicate)

DUP - Sample Duplicate

RPD - Relative Percent Difference

NC - Not Calculable.

ANALYTE QUALIFIERS

A3   The sample was analyzed by serial dilution.

CC   The continuing calibration for this compound is outside of method control limits. The result is estimated.

IC   The initial calibration for this compound was outside of method control limits. The result is estimated.

SS   This analyte did not meet the secondary source verification criteria for the initial calibration. The reported result should be considered an estimated value.

REPORT OF LABORATORY ANALYSIS

QUALITY CONTROL DATA CROSS REFERENCE TABLE

Project: PLASMA
Pace Project No.: 1044833

Lab ID	Sample ID	QC Batch Method	QC Batch	Analytical Method	Analytical Batch
1044833001	5973	TO-15	AIR/5105		
1044833002	5953	TO-15	AIR/5105		

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REPORT OF LABORATORY ANALYSIS

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nelac

VITA

Amanda Kathleen Benson

Candidate for the Degree of

Master of Science

Thesis: DESTRUCTION EFFICIENCY AND POWER USAGE FOR A SINGLE
DIELECTRIC BARRIER DISCHARGE PLASMA REACTOR

Major Field: Environmental Engineering

Biographical:

Personal Data: Daughter of James and Kathy Benson, and born in
Columbus, Ohio on July 30, 1983.

Education: Graduated from Deer Creek High School in Edmond,
Oklahoma in 2001; earned a Bachelor of Science degree in Civil
Engineering in December 2005 from Oklahoma State University;
completed requirements for a Master of Science in May 2007 at
Oklahoma State University.

Experience: Civil engineering internship at Poe and Associates in Tulsa,
Oklahoma; Environmental engineering internship for Cardinal
Engineering in Oklahoma City, Oklahoma; lab assistant for
Oklahoma State University in Stillwater, Oklahoma.

Professional Memberships: American Society of Civil Engineers

Name: Amanda Kathleen Benson   Date of Degree: May 2007

Institution: Oklahoma State University   Location: Stillwater, Oklahoma

Title of Study: DESTRUCTION EFFICIENCY AND POWER USAGE FOR A SINGLE
                DIELECTRIC BARRIER DISCHARGE PLASMA REACTOR

Pages in Study: 147   Candidate for the Degree of Master of

                                                Science

Major Field: Environmental Engineering

Scope and Method of Study: This study was intended to understand a scaled up
        plasma reactor for the destruction of volatile organics from paint booth
        emissions. Electrical and power system requirements were studied in
        order to understand the cost of running a system in industry. Ozone
        production and effluent products were also analyzed. The plasma reactor
        being studied was a single dielectric barrier discharge with a cylindrical
        geometry. Three parameters were varied in order to understand their
        interaction with the efficiency of the system. The number of tubes,
        retention time, and applied voltage were studied in this experiment.

Findings and Conclusions: The system was capable of high destruction
        efficiencies and but was not competitive when compared to other reactors
        recently studied. Ozone production was small compared to ozone
        generators, and essentially no effluent products were created. The
        reactor was not capable of an instant-on feature, but did not take more
        than 8 minutes to be effective. Not enough data was collected to fully
        understand the interaction among the parameters varied under this study.
        More research is required for a more complete analysis of the system.

ADVISER'S APPROVAL: Dr. John Veenstra