DESTRUCTION OF TRICHLOROETHYLENE AND TOLUENE IN AN ALTERNATING CURRENT PLASMA REACTOR

BY

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IN AN ALTERNATING CURRENT
PLASMA REACTOR

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CHAPTER 1

INTRODUCTION

The most comprehensive air pollution control legislation since the Clean Air Act of 1970 was passed by the United States Congress on October 26, 1990, and signed by the President on November 15, 1990. The Clean Air Act Amendments (CAAA) of 1990 added many new provisions of extreme significance to industry.

The Environmental Protection Agency (EPA) had a program for regulating toxic air pollutants outlined in the Clean Air Act of 1970. Title III of the Clean Air Act Amendments created a list of 189 compounds that are considered hazardous air pollutants and contained a new approach to regulating hazardous air pollutants (1). The strategy in the CAAA is based on the control-technology approach similar to the Clean Water Act (CWA). Through this new idea of control-technology Congress is hoping to achieve its environmental goals through the use of novel approaches. This research involves the novel approach of destroying or detoxifying trichloroethylene (TCE) and toluene in an Alternating Current Plasma Reactor (ACPR). Both TCE and toluene are on the list of hazardous air pollutants (1).

Trichloroethylene (TCE) is an industrial solvent mainly (85-90%) used for the vapor degreasing and cold cleaning of fabricated metal parts. In addition it has been used as a solvent for waxes, fats, resins, and oils and as an anaesthetic for medical and dental use. It can be found in printing inks, varnishes, adhesives, paints, lacquers, spot removers, rug cleaners, disinfectants, and cosmetic cleansing fluids (2).

Toluene is produced both in isolated form and as a component of mixtures. When produced in the form of a mixture it is used to back blend gasoline. Toluene in isolated form is used in: (1) the production of other chemicals; (2) as a solvent carrier in paints, thinners, adhesives and inks; and (3) as an additive in cosmetic products (3).

Trichloroethylene is a moderately toxic substance. In terms of acute toxicity, LC_{50} values in rodent test species range from 45 to 260 mg/m^3, and oral LD_{50} values range from 2400 to 4920 mg/kg body weight (2). The toxic effects of exposure are related to a depressant action on the central nervous system that can lead to coma and death (2). Liquid TCE has an irritant effect on the skin and eyes. Toxic effects on the kidneys have been produced in rats by long-term oral administration (2).

Toluene inhalation LC_{50} values in mice range from 26,000 to 200,000 mg/m^3, and oral LD_{50} values range from 2.6

to 7.5 g/Kg body weight(3). In human beings the primary effect is on the central nervous system. This effect may be depressant or excitatory (3). Single, short-term exposure to toluene (750 mg/m^3 for eight hours) has reportedly caused transient eye and respiratory tract irritation. Repeated long term exposure in this range, on the other hand, have caused neurological damage (3).

There is clear evidence that trichloroethylene is carcinogenic in mice with lifetime (2-year) exposures to 1620 mg/m^3 by inhalation or oral administration of 700-1200 mg/Kg of body weight per day (2). The signs and symptoms of over-exposure in human beings are mainly related to the central nervous system, for example, headache, drowsiness, hyperhidrosis, tachycardia, and in more severe cases, stupor and coma (2).

As practiced in this research, both trichloroethylene and toluene in the gas phase can be detected through gas chromatography using a flame ionization detector (FID) that yields good sensitivity. Methods are available for the determination of trichloroethylene and toluene in blood, fat, tissues, food, and water (2,3).

The current methods of removal of air phase trichloroethylene include: thermal oxidation, thermal catalytic oxidation, carbon adsorption, on-site solvent recovery, and solar detoxification (4). The most widely used conventional methods of destruction for toluene include:

thermal incineration, catalytic incineration, carbon adsorption, and packed-bed corona (5). The goal of this research was to determine if an alternating current plasma reactor can be used for the removal of both trichloroethylene and toluene from a contaminated air stream.

For the purpose of this thesis the word "destruction" as used in the title and the body of this document implies the conversion of TCE and toluene into simpler compounds after passage through the plasma reactor under controlled conditions. Chapter II discusses the possible compounds that make up the effluent.

The specific objectives of this research are:

1. To perform a bench scale study to confirm the feasibility of removing air phase TCE and toluene using plasma reactor.
2. Select an optimum frequency and primary voltage for maximum destruction and minimal cost in terms of power used.
3. Determine the effect of process parameters (residence time, and humidity) on the removal efficiency of TCE and toluene.
4. Determine the performance of plasma when a mixture of two compounds are sent through the plasma reactor. Also to find which of the gases' parameter the plasma

reactor would need to be tuned to achieve maximum destruction for both chemicals.

CHAPTER II

LITERATURE REVIEW

ALTERNATING CURRENT PLASMA

The passage of an electric current or charge through a medium, often accompanied by luminous effects is called discharge (6). In 1929, Langmuir associated the word "plasma", which is the greek word for "to mold" to the discharge taking place in the closed container due to the electric field (4). A region of ionized gas in a gas discharge tube that contains approximately equal numbers of electrons and positive ions and provides a conducting path for the discharge is called plasma (6). Nowadays "plasma" is the term usually used for discharge taking place in a nonhomogeneous field such as between two coaxial cylinders and is considered the fourth state of matter (4). The discharge is also called "corona" discharge. The old Greeks noticed sulphur-like odors accompanying strokes of lightning. One can find references to these observations in Homeric songs of both Iliad and Odyssey (7). The smell was most likely due to ozone, and the remarks of Homer are probably the earliest reference to this substance and to reactions initiated by electrical agents (7).

Normally gas is a poor electrical conductor but sufficiently high electric field causes ionization of its molecules and atoms. Application of an electric field on a gas leads to the action of large forces on any free charges that are already present in the gas due to the natural ionization caused by cosmic rays or radioactive contamination. These gaseous ions are attracted to the charged electrodes and current flows through the plasma. When an electrical discharge passes through a gas it splits the neutral gas molecules into positively charged ions, negatively charged ions, free radicals, and randomly occurring free electrons. The total sum of the charged entities makes the plasma neutral. Current flows as a result of a multiple collision of ions within the tube. Collisions between ions cause excitation and further ionization, light being produced when excited atoms and ions return to the ground state or when the positive and negative ions recombine (6). Soon the two processes of ion formation and the rate of recombination establish equilibrium. The positive ions do not contribute much to the discharge as these ions travel with very low drift velocities (4).

All matter shows intrinsic electrical conductivity due to the ionization produced in the molecules of the material medium by the cosmic rays. This conductivity can be discovered by means of a device delicate enough to permit the measurement of the current flowing between two conducting surfaces as a function of the applied voltage or by means of an electroscope when one can observe its discharge (7).

Certain mixtures of molecules such as the components of air are usually inert and do not react with one another under normal conditions. For the components of air to react with one another they must be in an abnormal, excited or energy-rich state. From such observations it is learned that there is needed a definite amount of energy of activation to cause the chemical reaction to continue (7). The activation energy that is required by the molecules of the chemical systems for reaction can be applied in other forms. The study of one of these forms is called the science of photochemistry which deals with the reactions that have been initiated by radiation fields. Similarly any form of electrical discharge produces activated species of molecules and hence may be expected to yield chemical reactions in systems which ordinarily are unreactive (7).

Besides the electrical discharge due to thunderbolts in the air that cause air to lose its non-conductivity for electricity, artificial methods have been developed through which electrical conditions can be induced in an otherwise neutral medium. One of these artificial methods of inducing electrical transport accompanied by light production in the gas phase is the self-sustaining electrical discharge. Neon signs, used extensively for advertising purposes, are a good example of the practical use of a self sustained plasma.

Glockler and Lind (7) has suggested the following impacts in the electrical discharges.

(a) ELASTIC IMPACTS

The impacts are called elastic between electrons (E^-) and molecules (M) when neither impact partner suffers a great change in energy and where at most only changes in direction of motion result. These interchanges are of no significance in the production of the activated state leading to chemical reaction.

(b) IONIZATION IMPACTS

Ionization impacts are represented by:

$$E^- \text{ (fast)} + M \rightarrow M^+ + 2E^{--} \text{ (slow)}$$

These impacts resulting in the production of positive ions (M^+) and another electron. The positive ions created will travel towards the cathode if they are produced in a region where a potential gradient exists.

Some impacts may result in the formation of clusters:

$$M^+ + M \rightarrow (M \, . \, M)^+$$

(c) EXCITATION IMPACTS

Some impacts are of the type:

$$E^- \text{ (fast)} + M \rightarrow M^* + E^- \text{ (slow)}$$

whereby the molecule is brought into an excited, energy-rich state. From this higher quantum state (M^*) the molecule will return to normal condition after a short average life (10^{-7} sec.) with the emission of radiation (**hν**):

$$M^* \rightarrow M + h\nu$$

(d) DISSOCIATION IMPACTS

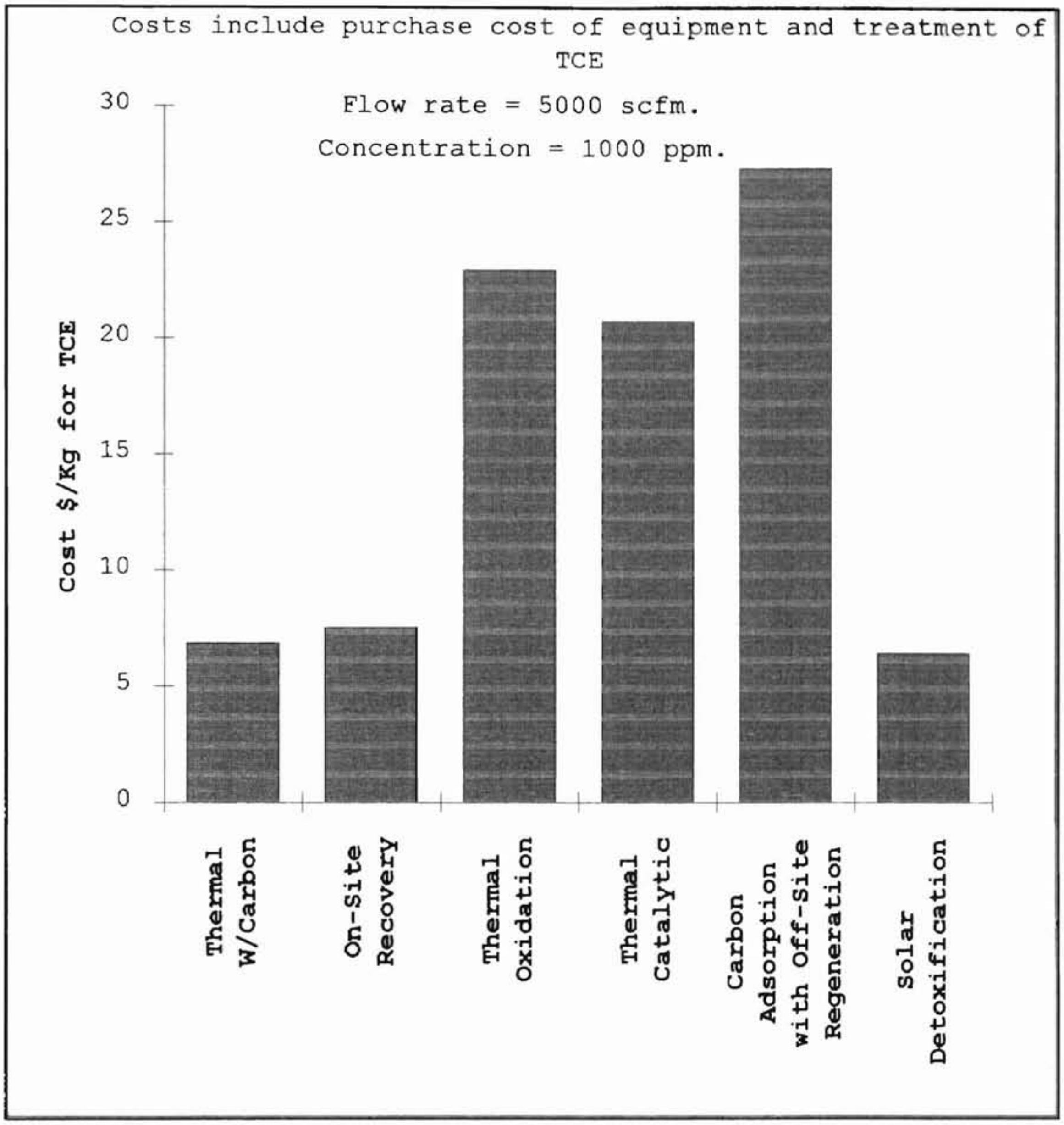
One would not expect direct dissociation by electron impact to occur to any extent. For example, the reaction

$$H_2 \rightarrow 2H, \text{ at } 4.34 \text{ e.v.}$$

has not been observed, although, many investigators have looked for the effect.

ALTERNATIVE METHODS OF TRICHLOROETHYLENE DESTRUCTION

Figure 1 shows the cost in \$/Kg (1992 dollars) of TCE for widely used methods of thermal oxidation, thermal catalytic oxidation, carbon adsorption with off-site regeneration, on-site solvent recovery and solar detoxification. The mass is based on TCE in the air phase. The cost reported in this figure include purchase cost of the equipment and the actual treatment cost of the contaminant. The importance of this figure lies in its depiction of the large variation in the treatment costs for different removal and destruction methods. It does not include destruction of TCE through plasma. As Figure 1 shows solar detoxification had the lowest cost of 6.8 dollars per kilogram and the carbon adsorption with off-site regeneration proved to be the most expensive at 27.34 dollars per kilogram.



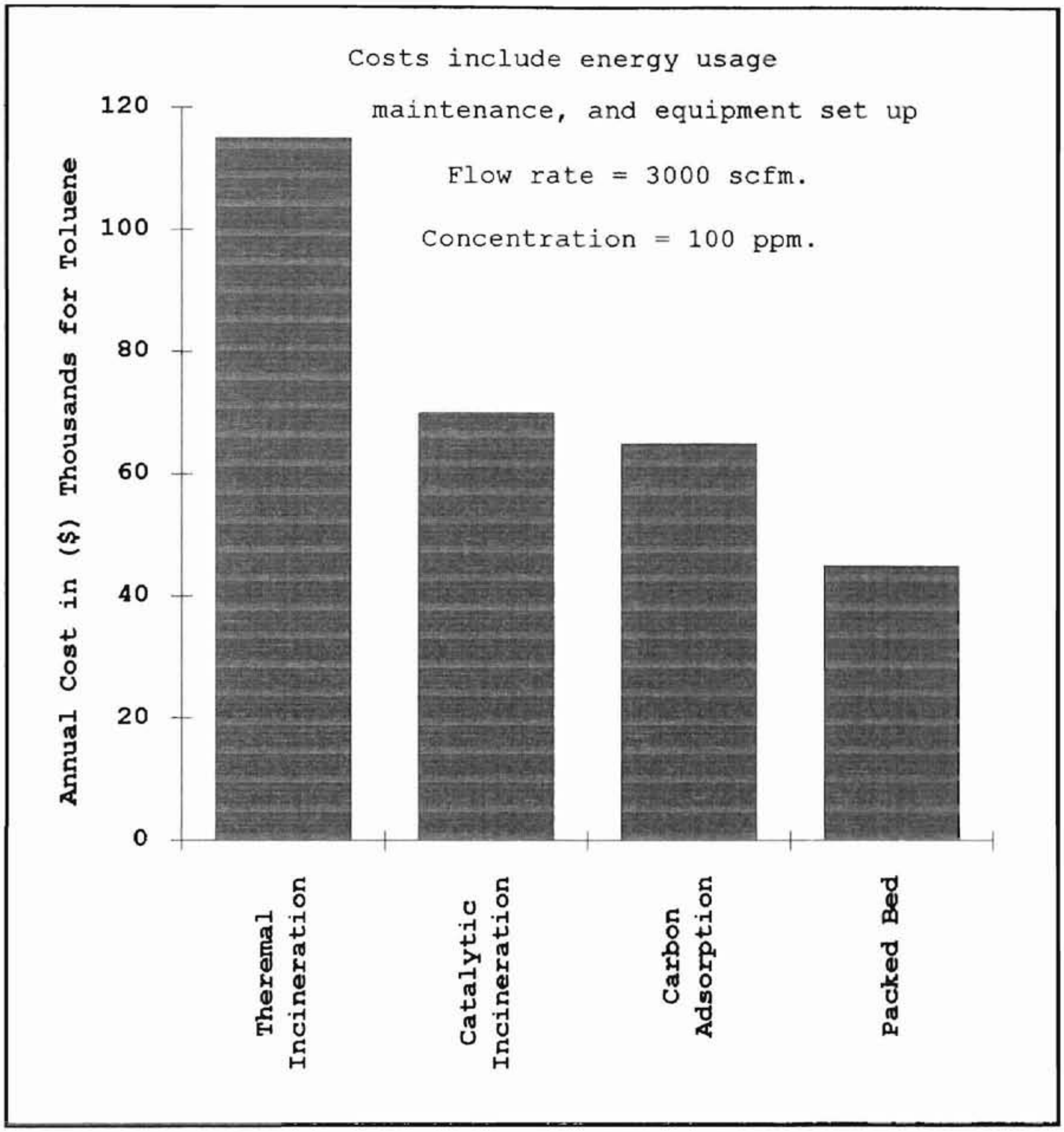
Source: Glatzmaier (1992)

Figure 1: Cost (in US $) Comparison of Removal and Destructive Methods of Trichloroethylene

Kushner *et al.* reported the cost of treating TCE in terms of power used per Kg of TCE in the air phase in a silent discharge plasma reactor (8). A silent discharge plasma reactor (SDP) is different than an alternating current plasma reactor due to different reactor geometry and its glass coating of the electrodes. They calculated the cost to be slightly less than a dollar (1993 dollars) per kilogram of TCE. Their reported cost is not included in Figure 1 because it was based on kilogram of TCE removed and not the cost of equipment and treatment.

ALTERNATIVE METHODS OF TOLUENE DESTRUCTION AND REMOVAL

Figure 2 shows the cost in $/lb (1992 dollars) of toluene for widely used destructive methods of thermal incineration, catalytic incineration, carbon adsorption, and packed-bed corona. This cost includes energy usage, normal maintenance, and equipment setup averaged over ten years. As indicated by Figure 2 the packed-bed corona proved to be the cheapest method of treating toluene (45,000 dollars per year). The thermal incineration method carried the highest cost of treatment (115,000 dollars per year). The packed-bed corona uses a plasma detoxification process. It is different than an alternating current plasma reactor because of its rectangular geometry and the fact that it uses ferroelectric pellets across its bed. In addition sparking occurs across the bed which is non-existent in an alternating current plasma reactor.



Source: Nunez *et al.* (1993)

Figure 2: Cost Comparison (in US $) Of Removal Methods of Toluene

TRICHLOROETHYLENE CORONA CHEMISTRY

Trichloroethylene or C_2HCl_3 reacts with atomic oxygen and hydroxyl radicals, which are efficiently produced in a low temperature plasma containing O_2 and H_2O to give the following reactions (8):

$$C_2HCl_3 + 4\ OH \rightarrow CO_2 + 3HCl + H_2$$

$$C_2HCl_3 + 4\ O \rightarrow 2\ CO_2 + HCl + Cl_2$$

The CO_2 and H_2 can be exhausted into the atmosphere, while HCl and Cl_2 can be readily removed from the gas stream. Research has been conducted to detoxify TCE in a silent discharge plasma (SDP) where one or both electrodes were covered with dielectric layers (e.g. glass) that separated them from the gas (8). It was found that the ClO radical is an important intermediate that oxidizes TCE and its consumption by OH radicals is largely responsible for the lower removal efficiencies in wet mixtures compared to dry mixtures (8).

The following intermediate reactions have been reported for TCE reactions inside a plasma reactor (8).

(a) In dry Ar/O_2/TCE mixtures:

$$C_2HCl_3 + O \rightarrow CHOCl + CCl_2$$

$$CCl_2 + O_2 \rightarrow ClO + COCl$$

$$CHOCl + \begin{matrix} O \\ Cl \end{matrix} \rightarrow COCl + \begin{matrix} OH \\ HCl \end{matrix}$$

$$CHOCl + \begin{matrix} O \\ Cl \end{matrix} \rightarrow CO + \begin{matrix} ClO \\ Cl_2 \end{matrix}$$

$$COCl + O_2 \rightarrow CO_2 + ClO$$

The ClO radical is an important intermediate and readily reacts with TCE to form phosgene ($COCl_2$) and methyldichloride ($CHCl_2$) which reacts with oxygen to form chlorine.

$C_2HCl_3 + ClO \rightarrow COCl_2 + CHCl_2$

$CHCl_2 + O \rightarrow CHOCl + Cl$

(b) In Wet Ar/O_2/TCE mixtures:

$C_2HCl_3 + OH \rightarrow C_2Cl_3 + H_2O$

$ClO + OH \rightarrow HCl + O_2$

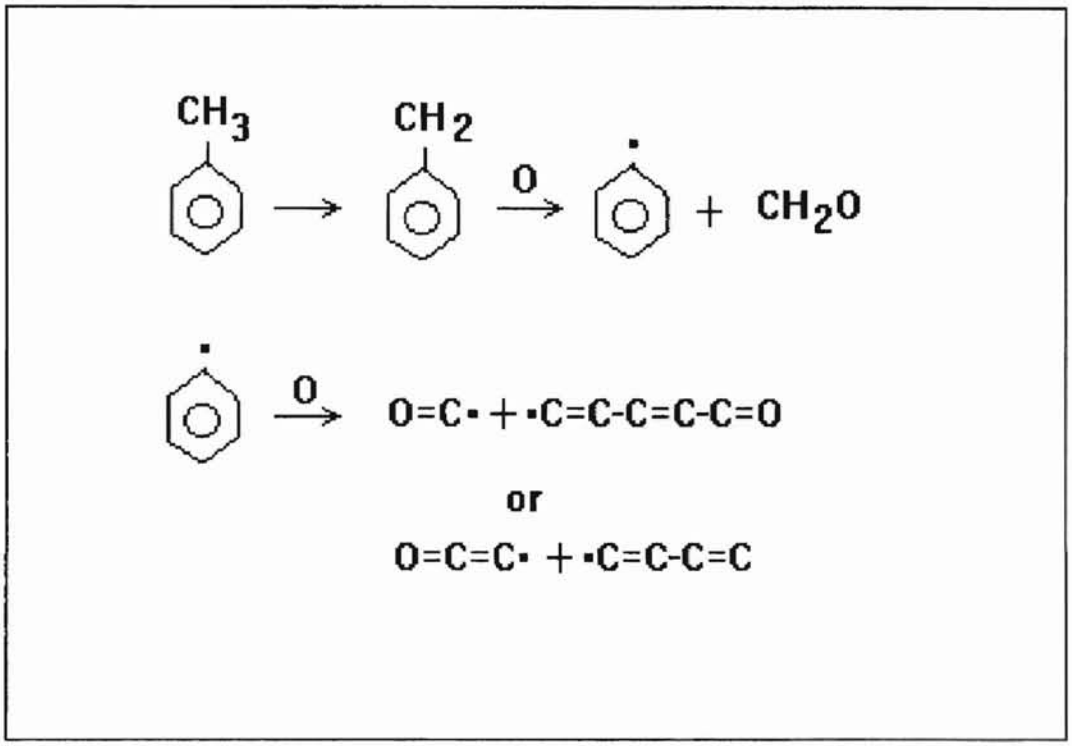
$COCl_2 + OH \rightarrow COCl + HOCl$

Wet mixtures reactions are different than those in the dry mixtures. In wet mixtures the formation of the hydroxyl ion and its reaction with the ClO ion lowers the destruction efficiency of TCE because the ClO ion helps oxidize the TCE molecule (8).

TOLUENE CORONA CHEMISTRY

According to Nunez *et al* (9) during the plasma destruction of toluene the methyl group of the toluene molecule undergoes oxidation and the reactions shown in Figure 3 occur.

Toluene has a resonance structure where a proton is lost or gained at the methyl group (CH_2-) which should result in a more reactive site. The methyl group serves as an electron donor to the phenyl group. When an excited oxygen molecule attacks the methyl group it forms a benzene and a CH_2O radical. The CH_2O radical rapidly reacts to form a CHO radical which goes to CO. The benzene radical reacts as shown in Figure 3 and form O=C or O=C=C. Either O=C or O=C=C radical reacts with oxygen to form CO_2. The other radical oxidizes rapidly to CHO and then to CO_2. At low temperatures the reaction to form CO rather than CO_2 is favored while high temperatures favor formation of CO_2. The formation of the CO_2 molecule occurs at the breakdown of the benzene ring, but the CO reaction is favored in the remainder of bond destruction reactions (9).



Source: Nunez *et al.* (1993)

Figure 3: Toluene Breakdown Inside Plasma Reactor

DESTRUCTION STUDIES IN THE LITERATURE

Several studies have been performed on the destruction of different chemical species when exposed to plasma. The results of these studies are summarized in Table 1. The trichloroethylene and toluene destruction results in the Table 1 were obtained using a different type of plasma reactor than the one used in this research. The one used for carbon tetrachloride destruction by Hurst (12) was similar to the one used in this work.

TCE has been detoxified in a silent discharge plasma reactor but not in an alternating current plasma reactor. Also, toluene has been altered in a packed-bed corona reactor but not in an alternating current plasma reactor. Both the silent discharge plasma reactor and packed-bed corona reactor are briefly described on page 12 of this study. One of the goals of this study was to investigate frequency and humidity effects on toluene and TCE destruction in an ACPR. In addition this study was conducted to evaluate the differences in destruction efficiency of a chlorinated aliphatic (TCE) as compared to an aromatic compound (toluene). One of the other major objectives of this study was to determine the effect of a mixture of gases on the tuning of the plasma reactor.

Table 1

Results of Plasma Destruction Tests

Test Species	**Destruction Efficiency**	**Frequency (Hz)**	**Temperature (K)**	**Concent-ration (PPM)**	**Reactor Type**	**Residence Time (Seconds)**
Trichloroethylene (1)	>99.9	4500	300-500	100-1000	Silent Discharge Plasma	1.6
Carbon tetrachloride (2)	90	60	298	10-700	Electron-beam	3
Toluene (3)	100	60	323.15	50-250	Packed Bed Corona	0.48-1.43
Nitrogen Oxide (4)	100	50-250	423.15	200	Pulse Corona-induced	2
Carbon tetrachloride (5)	94.2	550	298	19-83	ACPR	8-70

-Sources:
(1) Kushner et al (8)
(2) Koch et al (10)
(3) Nunez *et al.* (9)
(4) Masuda S. (11)
(5) Hurst M. (12)

CHAPTER III

EXPERIMENTAL APPARATUS, METHODS, AND DESIGN

This chapter is devoted to describing and explaining the experimental procedures, data analysis, and the design used in this research. This chapter has been divided into two parts to discuss the above components of the research; 1. Experimental apparatus, 2. Experimental design.

EXPERIMENTAL APPARATUS

There were three major components of the apparatus used in this research.

1. Electrical System
2. Plumbing System
3. Analysis System

Electrical System

The electrical system was the driving force of this experimental setup. Contaminant destruction was accomplished through the formation of a plasma that needs a constant supply of electricity to induce an electric field between the electrodes of the alternating current plasma reactor. A schematic of the electrical system is shown in Figure 4.

The three basic components of this system were the transformer, oscillator, and three Fluke meters. A John

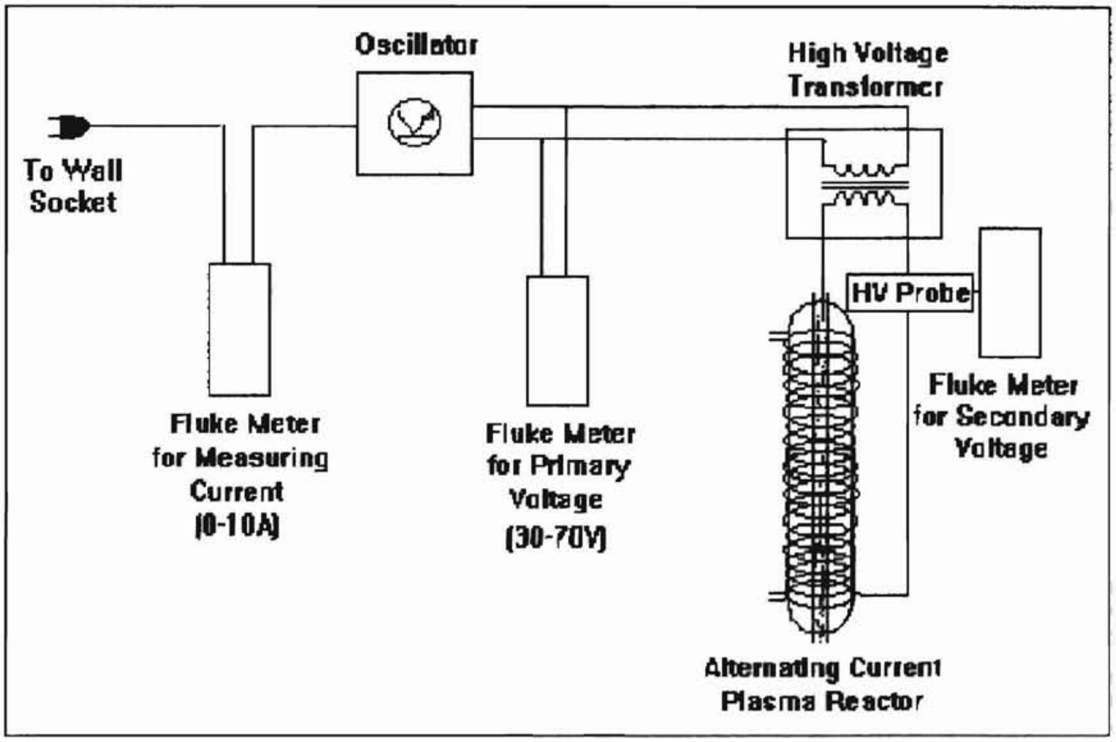


Figure 4: Schematic of Electrical System

Fluke digital fluke meter Model 83 (Everret, CA 94538) was used to read current in amperes going from the socket to the oscillator. The oscillator was a California Instruments Series 800T Oscillator. The oscillator's available range was from 40 to 5000 Hertz. It was used to change the frequency of the current. A John Fluke Multimeter Model 8010A Digital (Everett, WA 98206) was used to read the primary voltage leading to the transformer. A high voltage Magnetic Jefferson Electric Luminous Tube Transformer was used to create an electric potential across the electrodes in the plasma reactor. This transformer had a range from 0 to 120 rms and drew current from the oscillator. It was center-taped and rated at 15,000 volts. This transformer was connected to the two electrodes of the reactor by 8 mm multi-thread silicone coated wires (Taylor Prowire, OK). One of these electrodes was placed in the central annular space of the reactor and the other was wrapped around its outside surface. To measure the secondary voltage a John Fluke Multimeter Model 8010A Digital was connected to the transformer by means of a high voltage probe. This probe was built by John Fluke Manufacturing Co., Inc. (Everett, WA 98206) and was rated at 45,000 volts and 60 hertz.

Plumbing System

A schematic of the plumbing system is shown in Figure 5. The air from a compressed air gas cylinder was regulated through a Linde FM4575 Mass Flow Meter/Flow Controller. The

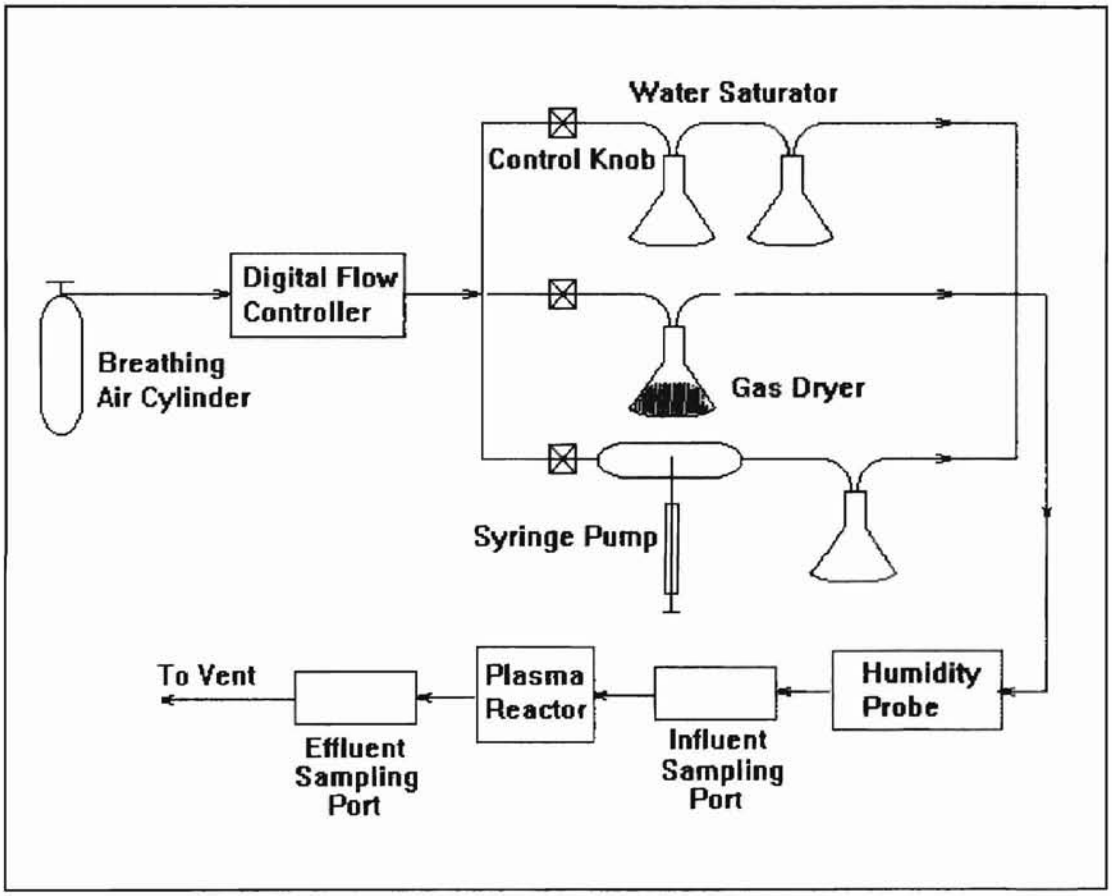


Figure 5: Schematic of Plumbing System

mass flow controller had four different modules which could provide a range of flow rates. This research used only one module (channel 1) that could provide up to a 1000 ml per minute of gas flow. As shown in the Figure 5, the compressed air line was divided into three lines. Each of these three lines had control valves to increase or decrease the gas flow through the line. One of these lines served the purpose of adding humidity to the air flow by passing it through a water saturator consisting of two 500 ml Erlenmeyer flasks. The first of these flasks was half filled with water with the inlet tube immersed in the liquid and the outlet at the top. The second flask was used to make sure no water droplets from the first flask proceeded into the line.

The second line passed through an Erlenmeyer flask half filled with Drierite (anhydrous $CaSO_4$, Fischer Scientific) to act as a gas drier. This set-up allows different humidities in the composite gas stream to be created.

The third line lead to a 100 ml gas sampling bulb. This glass bulb had an inlet and an outlet at the ends. In addition it had a sampling port in the middle sealed with a rubber cap. Liquid trichloroethylene and toluene were injected through this sampling port. For the purpose of liquid injection a syringe-pump model 1002 Syringe pump (Houston Atlas Inc.) was used. This syringe pump contained state of the art digital circuitry to control the motor's speed. A useful feature included in the syringe pump was the automatic drive limit. The drive limit circuit automatically prevented the micro-jector thrust plate from travelling past the front most limit to avoid possible damage to the syringe. The thrust plate of the syringe pump is driven by a linear motion stepper motor which provides precise step-wise linear motion using a minimum of mechanical parts. The syringe pump was fitted with a 25 microliter Hamilton 710RN Syringe (Supelco Inc., Bellefonte, PA).

The concentration of trichloroethylene and toluene in the composite gas stream were controlled by injecting only a certain amount of these chemicals per unit time. The calculations for the required injection volume of both toluene and TCE are given in Appendix C. These calculations show the volume of these chemicals injected to acquire a 300 ppm concentration in the air phase inside the glass bulb.

Humidity was monitored using a Davis Instrument Model DTH-1 Digital Hygrometer/Thermometer. The humidity probe had an accuracy range between 20-80 percent humidity. As shown in Figure 5, a sampling port was placed in line immediately following the humidity probe. The sampling bulb was a Fischerbrand Septum-Port Gas Sampling Tube made of Pyrex glass with a volume of 200 ml. This influent sampling bomb had a rubber septum through which samples were drawn. The rubber septum was changed after every run. Figure 6 shows the dimensions of the sampling bulb. The samples were taken using a gas-tight syringe and injected into the Gas

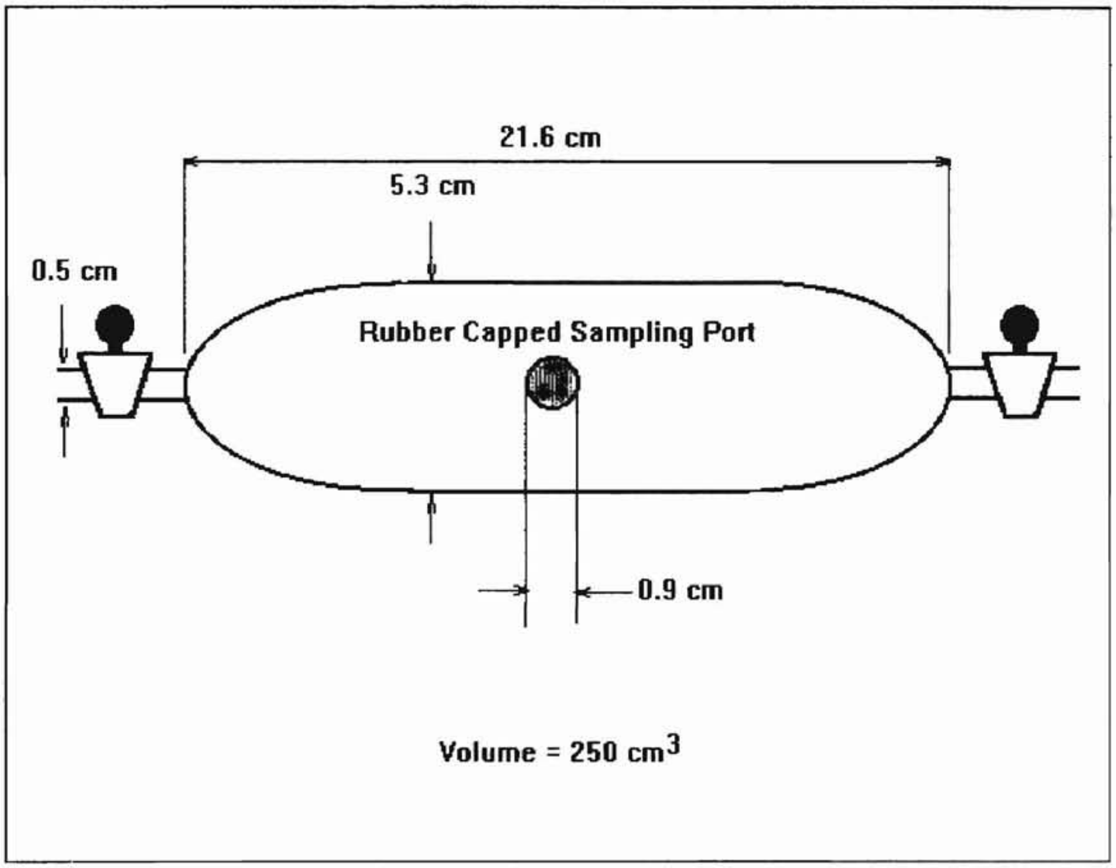


Figure 6: Schematic of Gas Sampling Bomb

Chromatograph (GC) in the next room. As shown in Figure 5, the plasma reactor was located immediately behind the sampling bomb. The length of tubing between the sampling bomb and plasma reactor was 3.3 meters.

The main component of experimental apparatus used in the research was the alternating current plasma reactor. The plasma reactor was connected to the electrical system as described above. The plasma reactor dimensions are shown in Figure 7. The effective volume of the reactor was 19.6 ml. and was determined by filling the reactor with water. The reactor was made of Pyrex glass, 1.11 cm. thick, and consisted of two concentric cylinders forming an annulus through which the reactant gas flowed. The Pyrex glass is Corning code 7440 chemical-resistant borosilicate glass with a dielectric constant of 4.6 at 25°C (12). One electrode was situated in the center of the reactor. The second electrode was wrapped around the outside of the reactor. The inner electrode consisted of a number 40 mesh copper sheet wrapped in a cylinder and inserted into the inner glass cylinder. The outer electrode consisted of a molybdenum wire (1 mm diameter) wrapped 18 times around the outside of the outer glass cylinder. When current was supplied, this allowed a plasma to be formed in the annulus. The electrodes were situated in this manner for two reasons. First, so that there can be no corrosion of the electrodes by the reactant gas, since the gas never comes in contact with the

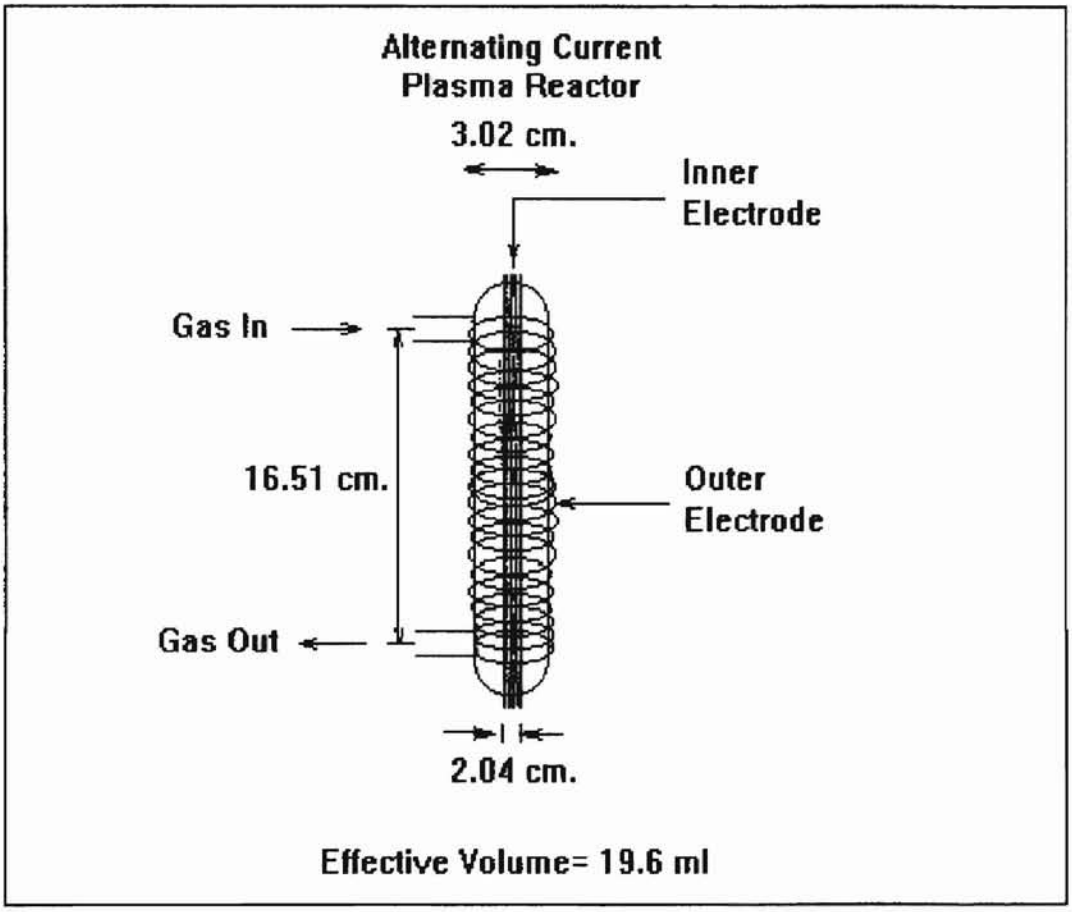


Figure 7: Schematic of Alternating Current Plasma Reactor

electrodes. Second, the glass barrier helps create a diffuse glow throughout the entire annulus region instead of a bright arc between the two electrodes. The plasma reactor was located in an outside bay at Oklahoma State University's Hazardous Materials Lab. This bay was separated from the other equipment rooms by a thick concrete wall. The plasma was mounted using iron brackets and clamps. The clamps were enclosed and fitted with 0.5 cm. thick teflon covering to prevent stray current from exiting the reactor. This effluent sampling bulb was of the same type as the influent sampling bulb.

The entire piping system was made of welded stainless steel, and teflon tubing. The steel tubing had an inner diameter of 0.635 cm. and the thickness of tube material was 0.0889 cm. Two different sizes of teflon tubing was used. One had an inner diameter of 2 cm. and the other had an inner diameter of 0.635 cm. The thickness of teflon tube material was 0.159 cm. The teflon tubing was used because of its flexible characteristics (as compared to steel), non-reactivity with TCE and toluene gas and any by-products of the plasma, such as ozone.

ANALYSIS SYSTEM

To analyze the polluted air stream and to determine the concentration of the pollutant in the gas a Gas Chromatograph (GC) was used. The GC produces an area count. To decode these areas in terms of recognizable units like parts per millions the GC needs to be calibrated. The GC was calibrated using standards of known concentration.

A Perkin-Elmer Sigma 3B gas chromatograph (Flame Ionization Detector) with data station was used for the analysis of samples obtained from the gas stream. A 6 feet and 1/8 inches column packed with 1% SP-2100 on 100/120 mesh Supelcoport (Supelco Inc.) was used.

The carrier gas for the GC was nitrogen. Hydrogen and oxygen were used for combustion in the GC. The isothermal zone temperatures used were:

Detector temperature = 110 C°
Injection temperature = 120 C°
Oven temperature = 110 C°

The calibration standards were made by injecting a known volume of the liquid TCE or toluene, using a 50 µL gas tight syringe into large glass bottles. This 50 µL gas tight syringe was manufactured by Dynatech Precision Sampling Corporation of Baton Rouge, LA. The volume of the glass bottles ranged from 25 to 27 liters in volume. The volume of these bottles were determined by measuring the volume of water contained by these bottles.

The trichloroethylene used was purchased from Fisher Scientific and was 99.9 percent pure with a residue of 0.0003 percent. The toluene was purchased from J. T. Baker chemical. It was 99.9 percent pure with a residue of 0.0001 percent.

The following two-step strategy was adopted for the construction of calibration curves:

(1) Each calibration curve was composed of at least four sample data points. For example a curve of 10, 200, 250, 300, 350, and 400 parts per million.

(2) Three calibration curves were created for trichloroethylene and three for toluene. Each of these calibration curves were checked for accuracy by injecting a known concentration of the contaminant gas into the GC and comparing the area with the area predicted by the standard calibration curve.

The following steps were taken to obtain one data point on a calibration curve:

(1) The opening of the five separate glass bottles were covered with parafilm. The parafilm was checked against a teflon and rubber cap for its ability to prevent leaks. It was found that both parafilm and teflon caps worked equally well (tests are included in the results on page 98) at containing the gas inside the bottles. These bottles were kept at room temperature of 75 F°.

(2) With a syringe a known volume of the liquid contaminant was injected though the parafilm. These volumes ranged from 2 microliter to 49 microliter.

(3) Immediately after the contaminant was injected into the bottle the opening was covered with another two pieces of parafilm to ensure the opening made by the syringe needle did not leak any gas.

(4) These bottles were left at room temperature for 45 minutes so that the contaminant gas that was created by evaporation of the injected liquid could diffuse in the air inside the bottles. Tables 9 and 10 (Appendix H) contain the data of concentrations of TCE and toluene in the bottles over a 45 minutes duration. These concentration are in terms of the areas obtained from the GC. Both these tables are plotted in Figures 8 and 9, respectively. These plots were developed by sampling the same bottle at 5 minute intervals. For each curve it was noticed that after a duration of 20-25 minutes the maximum concentration had been reached. Thus 45 minutes diffusion time was considered sufficient for the complete diffusion of contaminant in the air inside the bottle.

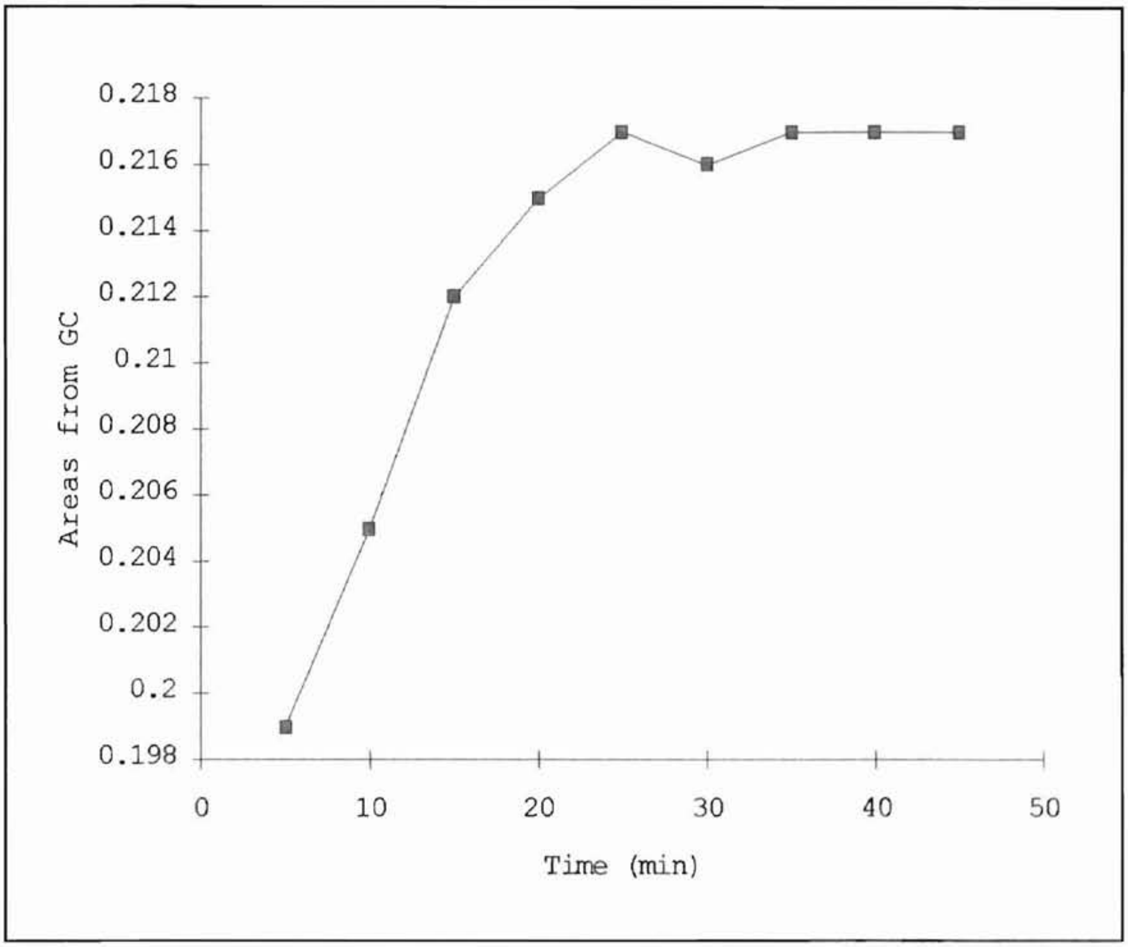


Figure 8: A Plot of Areas Obtained From the GC Against Time for TCE

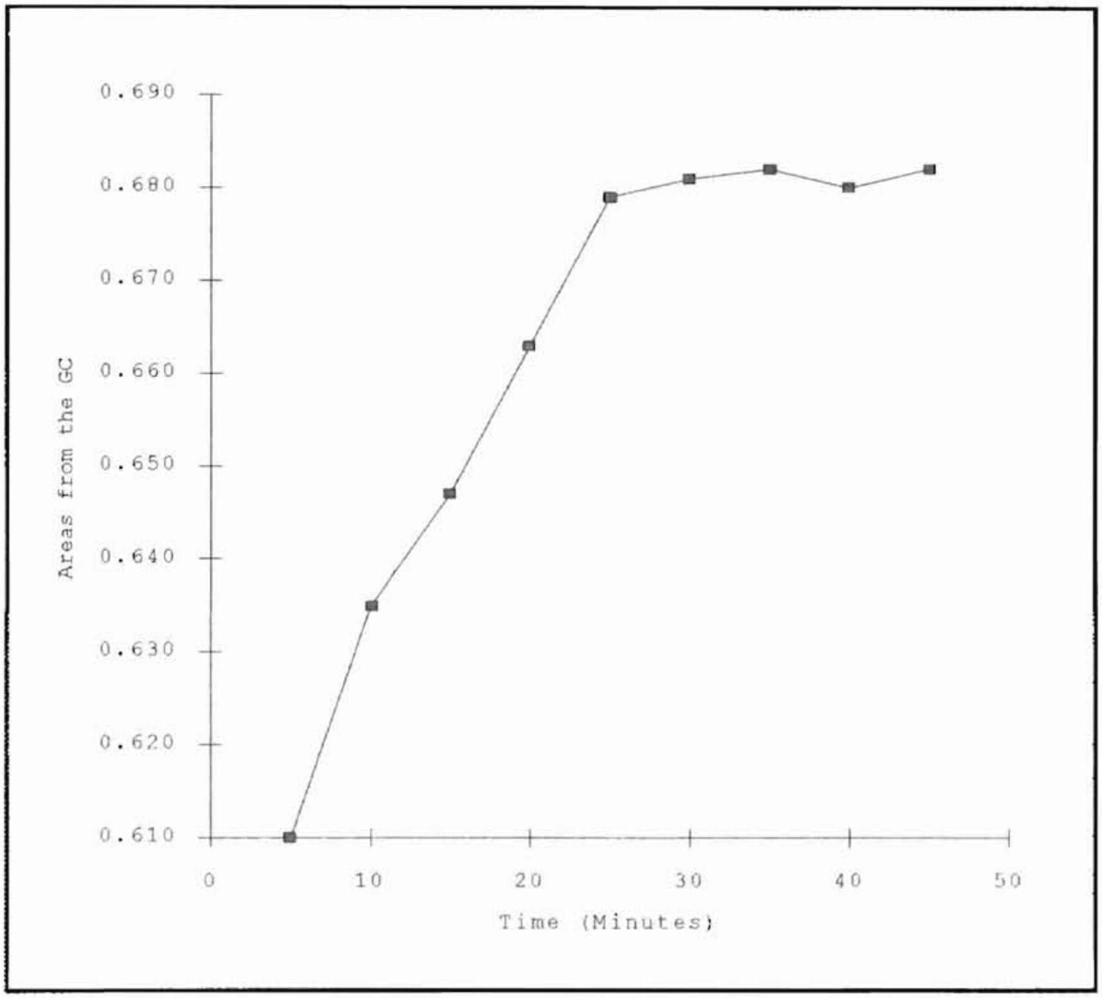


Figure 9: A Plot of Areas Obtained From the GC Against Time for Toluene

(5) With a syringe 5 ml of contaminated air was extracted from the bottle and then injected immediately in the GC.

(6) Data obtained from the GC integrator were used to plot the calibration curve. The areas under the curves were related to the known concentrations of the contaminant inside the bottle as shown in Figure 10.

This study was conducted during the months of September, October, and November of 1994 at Stillwater, Oklahoma. The three spreadsheets included in Appendix F report the data for pressure in inches of Hg for Stillwater (Oklahoma) area. This data was reported by the MESONET System of the Department of Agriculture of Oklahoma State University at Stillwater, Oklahoma. The maximum value of pressure was 29.59 inches and the minimum value was 28.7 inches with an average of 29.15 inches. During the three months of September, October, and November the pressure changed only 1.5 percent with respect to the average value of 29.15 inches. This pressure change was not significant enough to have an effect on calibration data.

The results of the calibration data are discussed in the results section in Chapter IV. The calculations for the theoretical values are shown in the Appendix C. Figures 11 to 18 show different equipment discussed in this chapter.

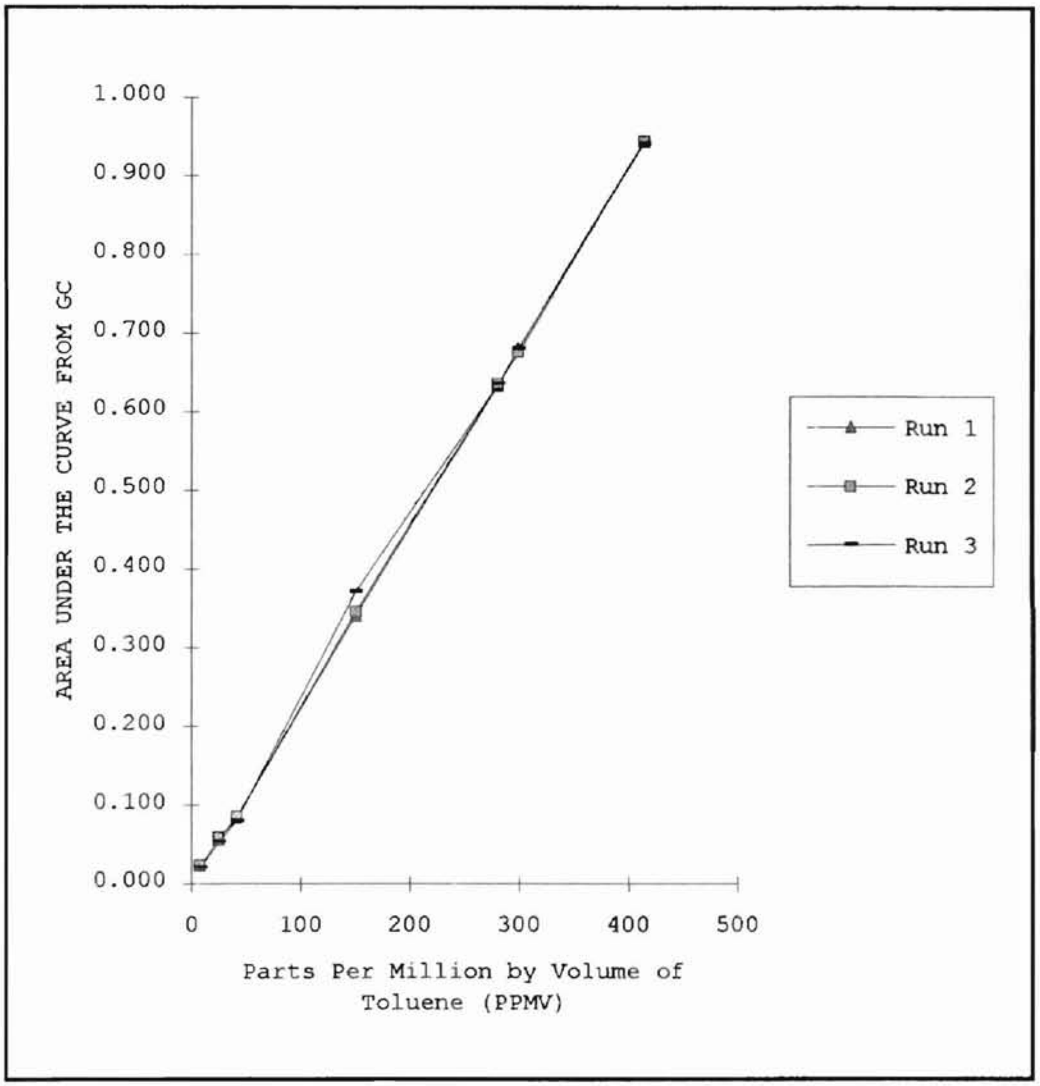


Figure 10: A Sample Calibration Curve Showing Five Injections (Identical in Volume of Contaminant) of Toluene from Three Separate Bottles

Figure 11: Gas Chromatograph Unit

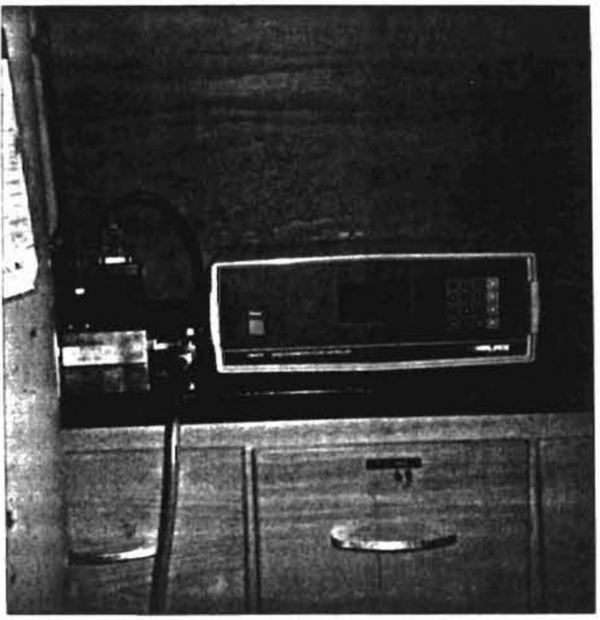


Figure 12: Mass Flow Controller

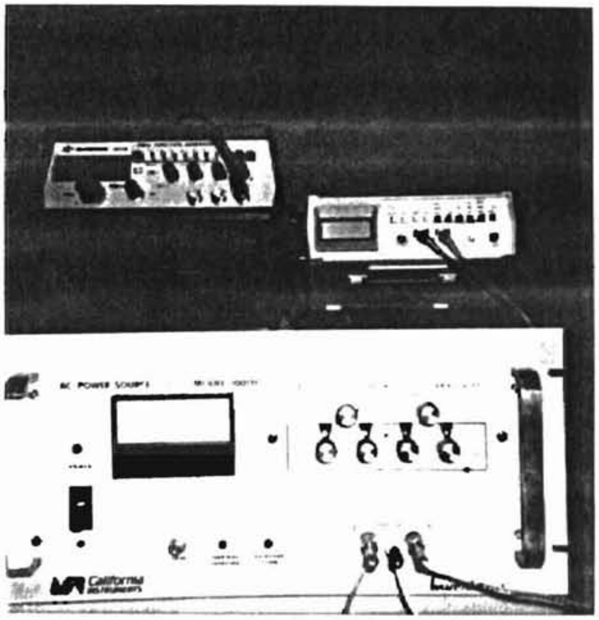


Figure 13: Oscillator with Function Generator

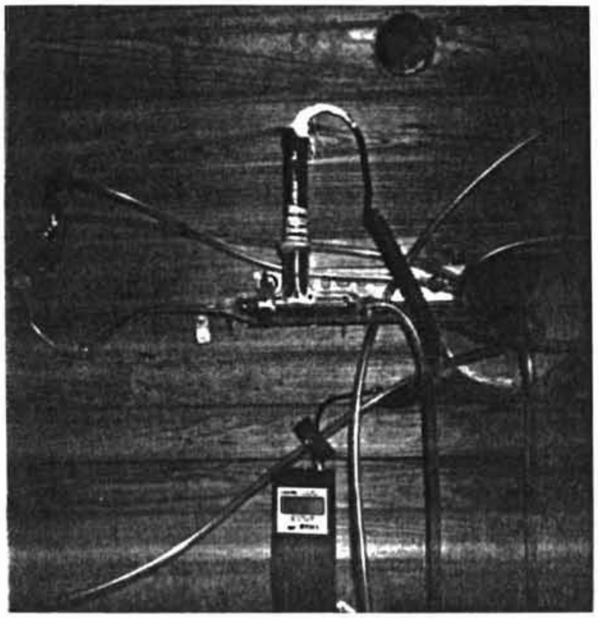


Figure 14: Humidity Meter

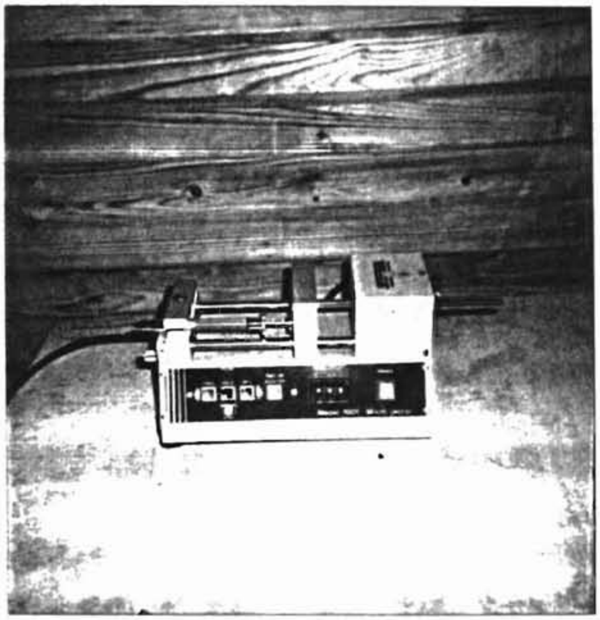


Figure 15: Syringe Pump

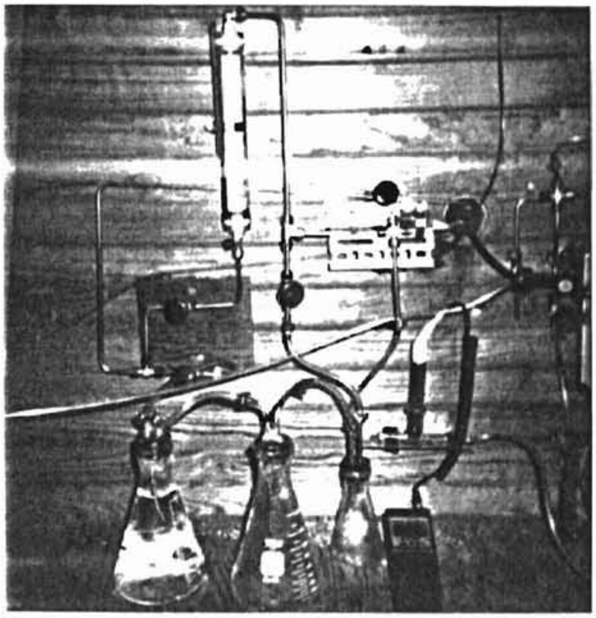


Figure 16: Water Saturator and Drierite System

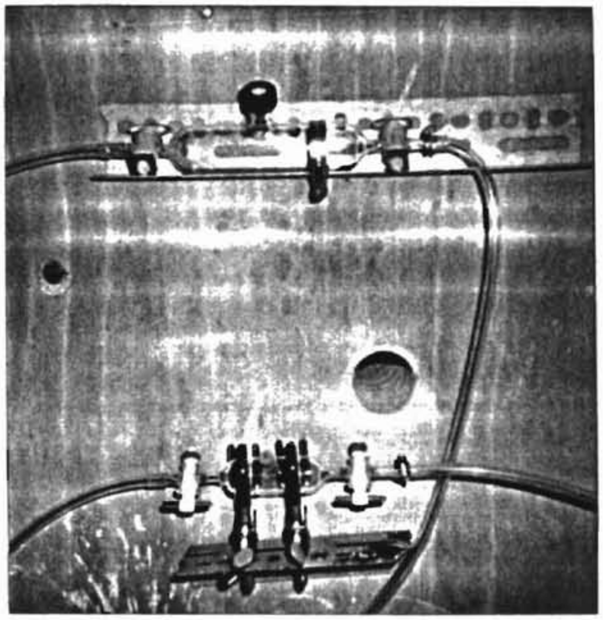


Figure 17: Gas Sampling Bombs

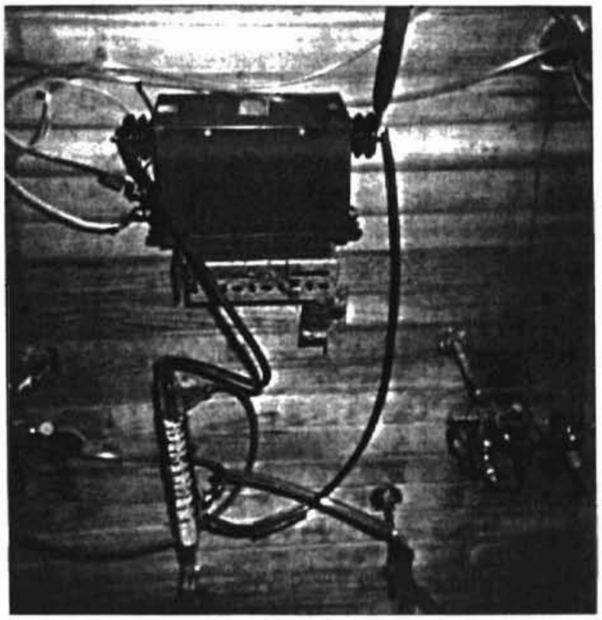


Figure 18: Transformer Hooked Up to the Plasma Reactor

EXPERIMENTAL DESIGN

This section describes and explains the strategy and procedure adopted to systematically determine the effect of varying residence time and humidity on the percent of pollutant left in the effluent.

Concentration in Pollutant Stream

In this research a desired concentration of contaminant in the air stream was achieved through the injection of liquid contaminant into the air stream with the help of a syringe pump. The OSHA's (29 CFR 1910) Hazardous Air Pollutant table in Appendix B lists the acceptable maximum peak for toluene and TCE as 500 ppm and 300 ppm, respectively. Both of these values are above the acceptable ceiling concentration for an eight hour exposure. A target value of 300 ppm was chosen for both chemicals. This concentration was chosen for two reasons: (1) the desire to conduct tests in the vicinity of potential exhaust concentrations of different industries, and (2) higher concentrations caused a problem by forming droplets at the tip of the syringe needle from the syringe pump during injection.

To create a steady stream of 300 ppm in the air stream the required volume for continuous injection of pure contaminant was quantified for both toluene and trichloroethylene. This amount of injected liquid was a function of residence time (i.e volume of air going to plasma), and the volume of syringe. The combination of the syringe pump's speed and the volume of the syringe also effected the volume of injected liquid. This is because at a selected speed the pushing-plate on the syringe pump moved at a constant rate irrespective of the kind of syringe fitted between its plates. The required injection volume of toluene and TCE was calculated to keep a steady concentration of 300 ppm inside the reactor (19.6 ml.) at any time using a 25 microliter Hamilton 710RN Syringe (Supelco Inc., Bellefonte, PA) fitted in the pump. To keep a steady stream of 300 ppm. of these chemicals in the reactor a volume of 0.0216 µl. for TCE and a volume 0.0257 µl. for toluene was injected per selected residence time. Calculations for the volume of contaminant required to produce a steady stream of 300 ppm are given in Appendix C.

Selection of Electrical Parameters

The selection of electrical parameters is an important issue in the design process because the goal is to avoid applying more power than needed, thereby increasing the cost of operating the plasma reactor. Using air as the feed stream at 500 cubic centimeter per minute and 80 per cent humidity, an electric field using varying frequencies and primary voltages was applied to the plasma reactor. The lowest primary voltage selected was 30 volts. At this primary voltage the frequency was changed from 45 hertz to 1200 hertz and the secondary voltage was recorded.

Additional primary voltages selected were 40, 50, 60, and 70 volts, and the same procedure was repeated. In this manner the optimum frequency and power were obtained for this plasma reactor configuration. This topic is discussed further in the results chapter.

Humidity Variation

To measure the effect of humidity on the destructive ability of the plasma reactor three different relative humidities were arbitrarily chosen. These selected relative humidities were 20 percent, 40 percent, and 80 percent. To change the humidity of the reactor feed stream the volume of the air stream going through the water saturator was varied to obtain the desired relative humidity. The following sequence of events was carried out for these test runs:

(1) Air supply is turned on at a desired flow rate. Calculations for flow rates are shown in Appendix C.

(2) The valve leading to the water saturator was manipulated to obtain the desired humidity.

(3) The syringe pump was turned on and set to the desired injection rate.

(4) The system was allowed to run for one hour to purge all the gas from the system. In the meantime the concentration of the influent flow stream was measured using the GC. To measure the concentration of the sample a 5 ml. injection volume was used.

(5) The humidity meter was continuously checked for desired humidity.

(6) After the desired humidity was achieved power was supplied to the reactor and it was tuned to the desired frequency and primary voltage allowing it to form plasma.

(7) Samples were taken for about 65 minutes from both the influent and effluent sampling bombs at five minutes intervals and taken to the adjacent room immediately to be injected into the GC.

(8) Power supply was turned off.

(9) Effluent flow stream concentrations was measured until it reached approximately the same value as the influent. The influent concentration was also measured to provide a standard of comparison.

Residence Time Variation

To measure the effect of residence time on the destruction ability of the plasma reactor three different values of residence time were selected. The plasma reactors residence times used during this project were 3 seconds, 5 seconds, and 10 seconds. To alter the residence time the volume of the air stream going through the reactor was varied to obtain the desired residence time. The following sequence of events was carried out for these test runs:

(1) Air supply was turned on.

(2) The flow module 1 for the air stream was set at the desired flow rate.

(3) The syringe pump was set to the desired injection rate.

(4) The system was allowed to run for one hour to purge all the gas from the system.

(5) In the meantime the concentration of both the influent and effluent flow streams was measured using the GC.

(6) After the desired residence time was achieved power was supplied to the reactor and it was tuned to the desired frequency and primary voltage allowing it to form plasma.

(7) Samples were taken for about 65 minutes from both influent and effluent sampling bombs at five minutes intervals. These samples were analyzed by GC.

(8) Power supply was turned off.

(9) Effluent flow stream concentrations was measured until it reached approximately the same value as the influent. The influent concentration was also measured to provide a standard of comparison.

Mixed Flow Stream of TCE and Toluene

In this step of the research trichloroethylene was equally mixed with toluene. The objective of this experiment was to determine if this mixture showed higher destruction at different frequencies than when these contaminants were individually injected into the air stream. The selection of toluene was based on the reason that toluene being a ring compound might show different behavior than the straight chain trichloroethylene. Equal volumes of both the contaminants were used so that it was easy to monitor the variance in destruction of these chemicals at various frequencies.

CHAPTER IV

RESULTS

SELECTION OF ELECTRICAL PARAMETERS

A series-RLC circuit was used in the apparatus setup for this study. This type of circuit consists of resistance, capacitance, and inductance. In this circuit there are three cases: (1) Inductive reactance is greater than capacitive reactance, (2) Inductive reactance is equal to the capacitive reactance, and (3) Capacitive reactance is greater than inductive reactance (13). The complex impedance Z (Ohms) of an alternating current series-RLC circuit is given by (6)

$$Z = R + iX \qquad (1)$$

where,

Z = Impedance (ohms)

R = Resistance (ohms)

$i = (-1)^{1/2}$

X = Capacitive or inductive reactance

The real part, the resistance, represents a loss of power due to dissipation. The imaginary part, the reactance, indicates the phase difference between the voltage and current. It is either positive or negative depending upon whether the current lags or leads the voltage, respectively.

The capacitive reactance X_C or inductive reactance X_L as given by (6)

$$X_c = 1/\omega C \tag{2}$$

$$X_L = \omega L \tag{3}$$

where,

ω = Angular frequency (rad/s)

C = Capacitance (ohms)

L = Inductance (ohms)

In a circuit containing capacitance only the impedance is given by (6)

$$Z = R - i/\omega C \tag{4}$$

Also, in the circuit containing inductance the impedance is given by (6)

$$Z = R + i\omega L \tag{5}$$

when inductance is equal to the reactance, the impedance is given by (6)

$$Z = R \tag{6}$$

where,

R = Resistance (ohms)

A series-RLC circuit can either be a lagging or leading circuit depending on whether ωL or $1/\omega C$ is larger, respectively. Some equations of series-RLC circuit can be given as follow (13)

$$Z_{RLC} = Z_{RLC} \angle\Phi_{RLC} = R + j\ (X_L - X_C) \tag{7}$$

$$= Z_{RLC} \cos \phi_{RLC} + j\, Z_{RLC} \sin \phi_{RLC} \tag{8}$$

$$Z_{RLC} = \sqrt{\{(R^2 + (X_L - X_C)^2\}} \tag{9}$$

$$\tan \phi = (X_L - X_C)/R \tag{10}$$

Where ϕ is the angle between the Z and R.

For this study the series-RLC circuit was tuned before the setup was used for the experimental destruction of trichloroethylene and toluene. Tuning in this case means correcting the power factor so that the maximum available power is used inside the circuit. In the real world apparent power is paid for but only real power is dissipated, it may be possible to reduce electrical utility charges if the power factor is established as unity. A tuned circuit for this study was a circuit where the power factor was one, meaning the impedance was equal to the resistance of the circuit (13). The impedance of the circuit is due to resistance and the capacitive or inductive reactance of the circuit. The tuning of the RLC circuit of this type is very important because for a given power to be supplied, the current is increased due to the low power factor. Low power factor also causes an increase in copper losses and a decrease in the efficiency of both apparatus and the supply system (14). Therefore, to increase the efficiency of the circuit and to establish the power factor as unity the resonant frequency needed to be determined.

A series-RLC circuit can become resonant in two ways. If the frequency applied is fixed, the elements must be adjusted so that the capacitive reactance cancels the inductive reactance (i.e X_L- X_C=0). If the circuit elements are fixed, then the frequency must be adjusted. Resonant frequency is the frequency of the RLC-series circuit purely resistive in nature. Therefore, frequency can be changed to obtain the resonance frequency where the capacitive reactance is equal to inductive reactance. In short, in a resonant series-RLC circuit (1) the impedance is minimum, (2) impedance equals resistance, (3) current and voltage are in phase, (4) current is maximum, and (5) power dissipation is maximum (13).

The data for the current passing through from the wall socket to the oscillator were obtained by putting an ammeter in series between the wall socket and the oscillator. This current data was multiplied by the voltage of 110 volts to obtain the apparent power consumed by the circuit of the setup. The minimum frequency that could be produced through the oscillator was 45 hertz. The plasma started to form around 500 hertz and diminished around 1000 hertz depending on the primary voltage. Therefore, using different primary voltages of 30, 40, 50, 60, and 70 volts and frequencies between 50 and 1200 hertz the data reported in Tables 6, 7, and 8 were obtained.

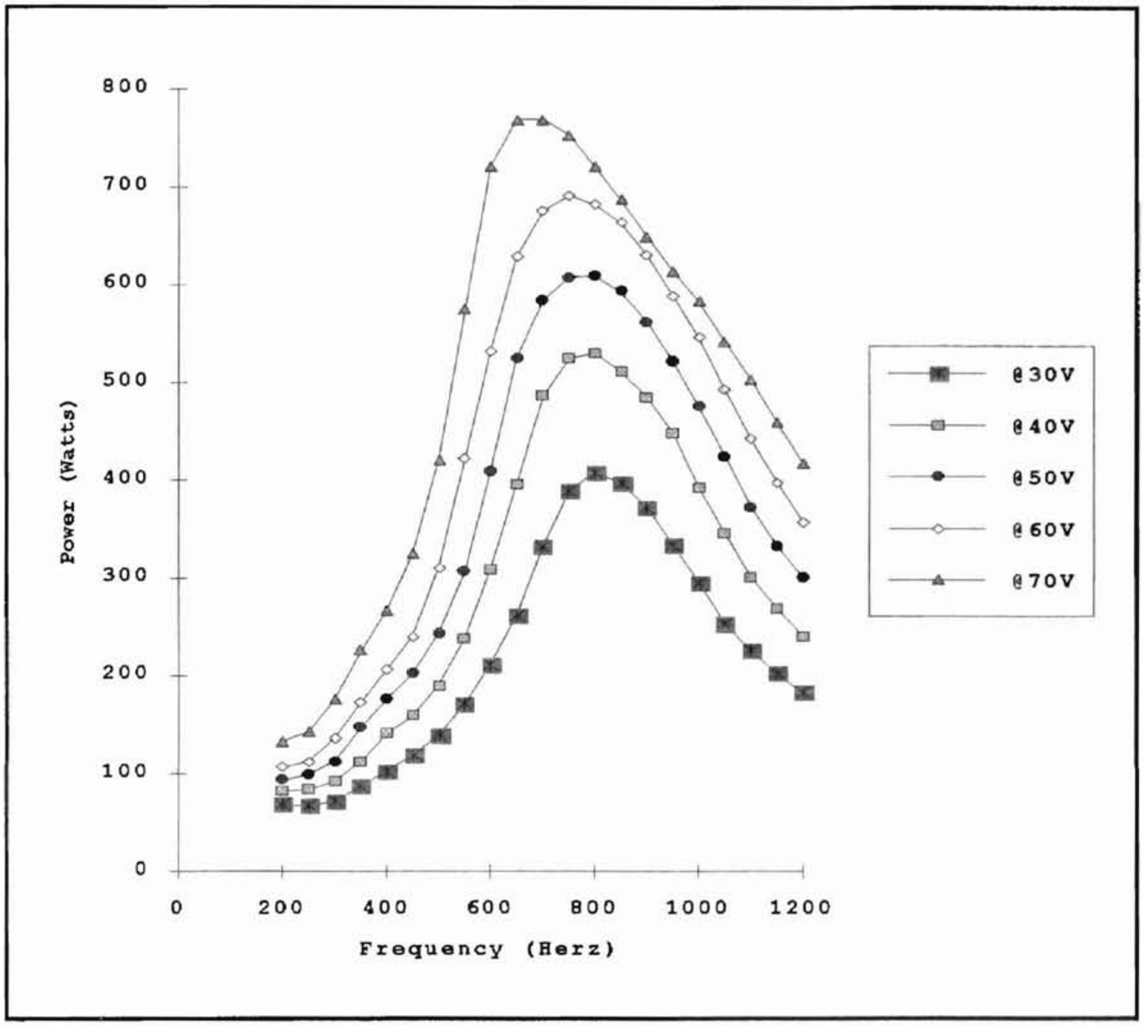
The value of peak power consumed or dissipated i.e the power at resonant frequency or primary voltages is shown in Figure 19. This figure shows peak powers consumed by the circuit at primary voltages of 30, 40, 50, 60, and 70 volts. The bell shaped curves result as the frequency change from left to right on x-axis in Figure 19. In Figure 19 the location of points tracing the shape of the bell curve on either side of the peaks is not exact. These points were obtained by calculation using the following equation

$$P = V * I * \text{Power factor} \tag{11}$$

$$P\ (\text{Watts}) = 110\ \text{Volts} * \text{Current (Amperes)} * 1 \tag{12}$$

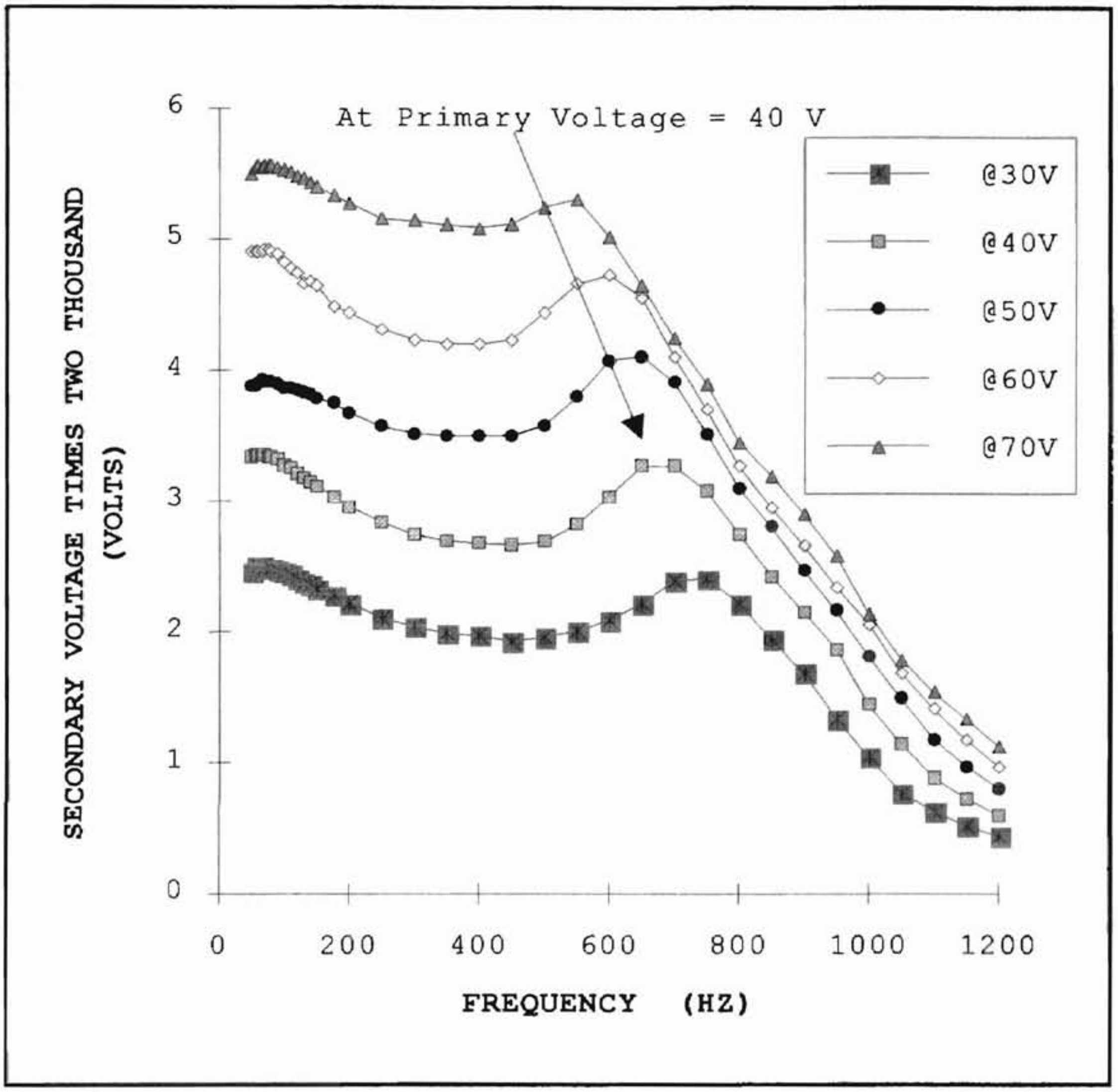
The exact location of the points tracing the shape of curve for different primaries can be calculated analytically by knowing the values of inductance, capacitance, resistance, and current. The location of the peaks of these bell shaped curves is exact because at these locations the power factor is equal to unity. At these peaks the impedance is equal to resistance, indicated by the zero slope of the power curve. Using the original values of the power factor between zero and one for either side of the peaks of the curves in Figure 19 would only change the slope of these five curves. The peaks of the curves which occur only when power factor equals 1 would not change.

This test was conducted to select a primary voltage at the resonant frequency for tuning the plasma reactor. As seen from Figures 19 and 20 the power consumed in the circuit first increases with increasing frequency and reaches a peak. This peak occurs between 650-800 hertz depending on the primary voltage. After this peak the power



Air @ 500 ml/min
80 % humidity
60 F°

Figure 19: Effect of Primary Voltage and Frequency on Power Consumed by Plasma



Air @ 500 ml/min
80 % humidity
60 F°

Figure 20: Effect of Primary Voltage and Frequency on Secondary Voltage

drawn by the system gradually decreases. For a primary voltage of 30 volts the peak is at 800 hertz while the peak for the 70 volts curve was at 650 hertz. This meant that as the primary voltage increased the peak was achieved at a lower frequency. This phenomenon is because of the circuit selectivity. Similar results have been reported by other investigators at Oklahoma State University (12,15). After this peak, at a specific frequency, the power drawn by the system decreased gradually and the plasma cease to form around 1000 hertz. This phenomena of power increasing with the frequency and then decreasing occurs because of "resonance" explained in detail earlier in this section. Transformers basically convert electrical power from one circuit to another circuit at the same frequency (14). It can increase or decrease the voltage with a corresponding decrease or increase in current keeping power constant. This transformation of energy is described by Faraday's Laws of electromagnetic induction through two windings (Primary and Secondary). The primary winding receives energy from an a.c. supply at one voltage; the other circuit called the secondary, delivers energy to the load at a different voltage. The transformer used in this study was a step up transformer and it was rated to step 120 volts to 15,000 volts at the secondary side. Just before the optimum frequency the secondary voltage goes through its maximum as shown in Figure 20. Similar results have been obtained for different plasma reactors (12, 15).

The following sequence of events take place in Figure 19. At a certain voltage, around 200 hertz depending on the primary voltage the current increases so much as to travels through the dielectric (i.e. into the gas in the reactor) and a buzzing sound coming from the reactor can be heard. With further increase in frequency the secondary voltage decreases until the plasma starts to form around 500 hertz (Figure 20). After 500 hertz both secondary voltage and current increase together. Secondary voltage at this point increases because the dielectric starts acting as a capacitor. The current on the other hand increases because of the ionization inside the plasma reactor. Around the point of peak power; between 650-800 hertz, depending on the primary voltage, the capacitance of the circuit reaches the inductance of the transformer. When the difference of ωL or $1/\omega C$ is zero the impedance is equal to resistance in the circuit. At this point the circuit is tuned and resonance occur. Inductance is a property of a coil through which an electromotive force is induced when the flux linked with it is changed. In addition inductance relates the magnetic flux of the circuit to the current flow through the circuit. The magnetic flux is a measure of the electric field of force through a specified area and electromotive force is the algebraic sum of the potential difference in a circuit (6).

The effective opposition offered by an inductance is called inductive reactance shown by eq. 3.

Capacitance is the property of an isolated conductor to store electric energy. The capacitance is defined as the ratio Q/V and is determine by the size and the shape of the conductor. It is constant for an isolated conductor. After the peak power the plasma reactor as a capacitor has reached its maximum capacitance. After this stage the secondary voltage starts decreasing (Figure 20) until plasma dies around 1000 hertz.

From Figure 19 the primary voltage of 40 volts and a frequency of 800 hertz was selected for this system. This particular primary voltage was selected because it yielded satisfactory destruction. Also because there was a sudden jump between the power curves of 30 and 40 volts primary voltages. This peculiar behavior is a property of the dielectric. The dielectric in the circuit was the plasma reactor.

PRELIMINARY TESTS

During calibration tests parafilm was used to close the bottle openings that were used to contain the pollutant mixture (air plus chemical). The feasibility of using parafilm as a lid was investigated and compared with teflon centered plastic lids. Table 11, and 12 in Appendix H show results for calibration data from both methods. Each data point represent one test run. The data from Tables 11 and 12 are plotted in Figures 21 and 22.

An ANOVA (Analysis of Variance) statistical test in Microsoft Excel 4.0 was run for the statistical analysis of the two curves in Figures 21 and 22. ANOVA refers broadly to a collection of experimental situations and statistical procedures for the analysis of quantitative responses from experimental units (16). There are different type of ANOVA tests. The Single-factor ANOVA, or One-way ANOVA was used for the statistical analysis of these plots. One-way ANOVA was used because time was the only factor. The significance level of 0.05 was used. The hypothesis was that the mean of the two data samples is the same. The statistical analysis on Table 11 and 12 of Appendix H are tabulated in Test 1 and 2 of Appendix G. The TCE data (Table 9, Appendix H) was tabulated in Test 1 (Appendix G) and the toluene data was tabulated in Test 2 (Appendix G).

The variance for the plastic cap data (column 1) in Test 1 (Appendix G) was 4.03E-05 and that for parafilm data (column 2) was 3.65E-05. The F-value was 0.01 and F-critical value was 4.49 indicating that the hypothesis that the mean of the two data is the same should be accepted. This also means that the there is no significant statistical difference between the two data sets. The variance for the plastic cap data (column 1) in Test 2 (Appendix G) was 0.001 and that for parafilm data (column 2) was also 0.001. The F-value was 0.008 and F-critical value was 4.494 indicating that the hypothesis that the mean of the two data is the same should be accepted. This also means that the there is no significant statistical difference between the two data sets. Therefore parafilm's performance was same as plastic caps. In this study parafilm was picked because of its ease of use.

Table 13 (Appendix H) tabulates the areas obtained from the GC for the same sample. These data points were recorded by injecting the pollutant gas four times from the same sample and are plotted in Figure 23. The average of the areas in Table 13 was 0.217 with one percent difference with the lowest and the highest data points. This difference was considered acceptable for the purpose of this study. This means that the GC's performance was satisfactory and dependable.

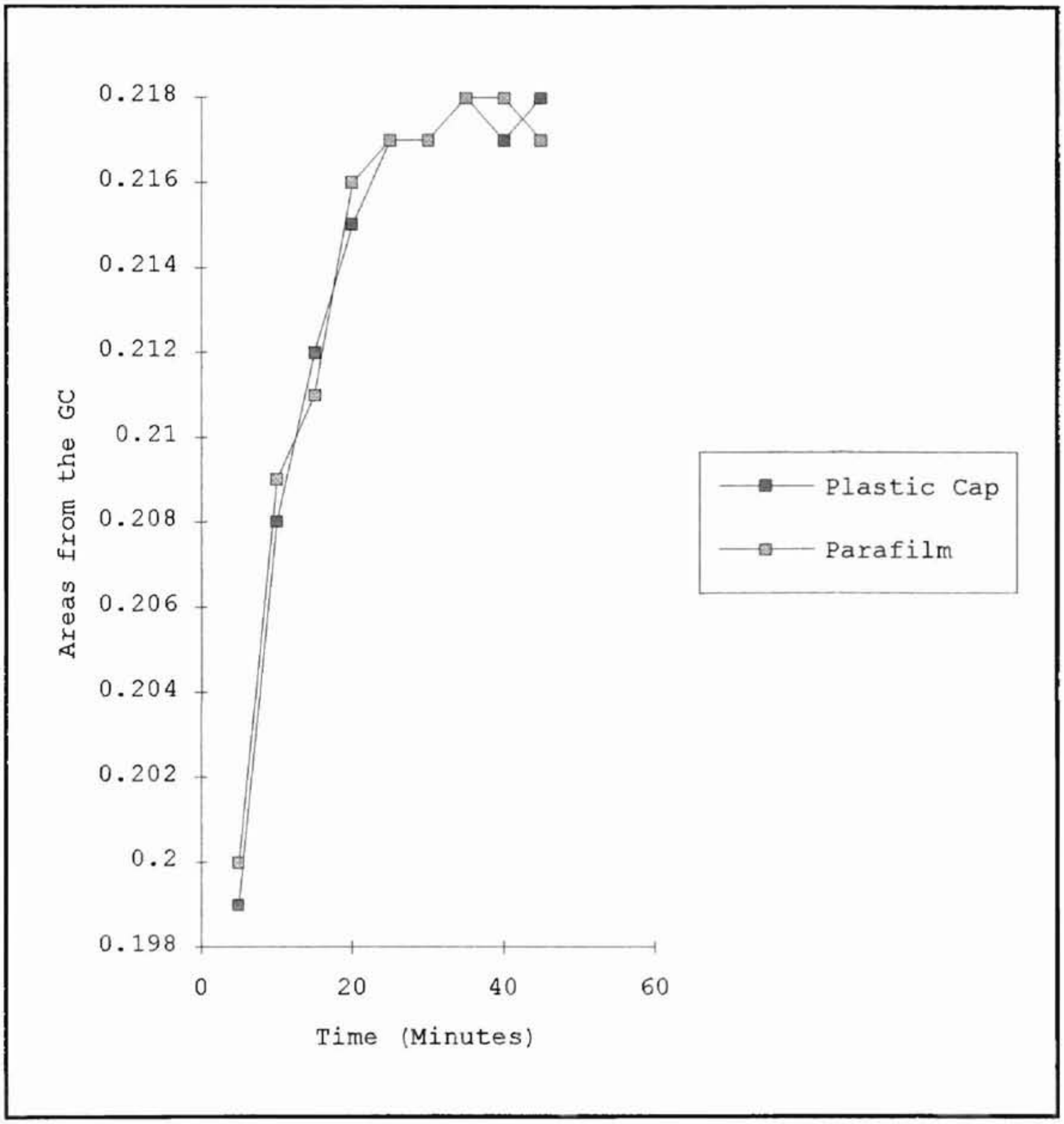


Figure 21: Comparison of Parafilm to Plastic Cap Used as a Lid for the Glass Bottles Holding TCE

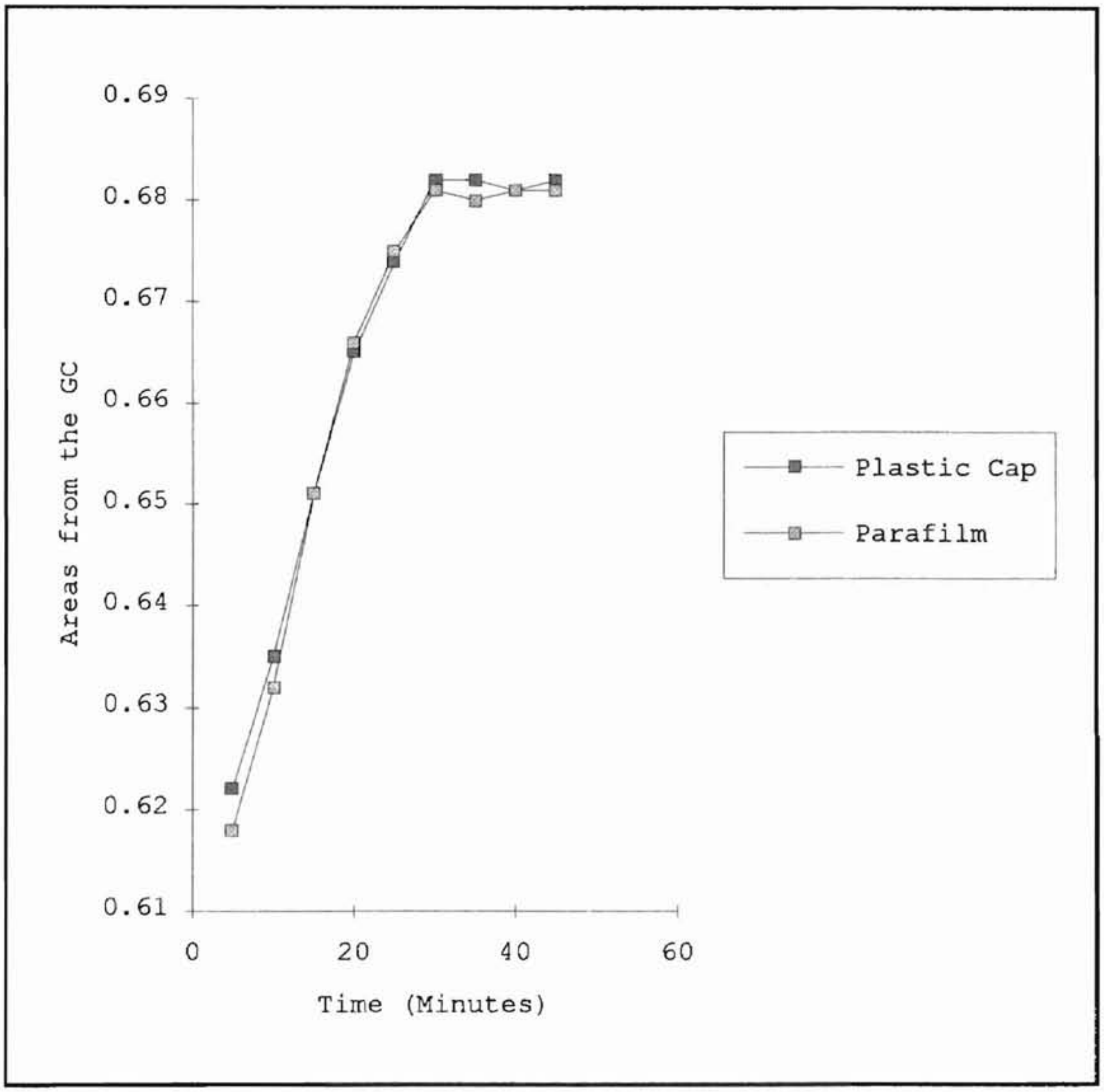


Figure 22: Comparison of Parafilm to Plastic Cap Used as a Lid for the Glass Bottles Holding Toluene

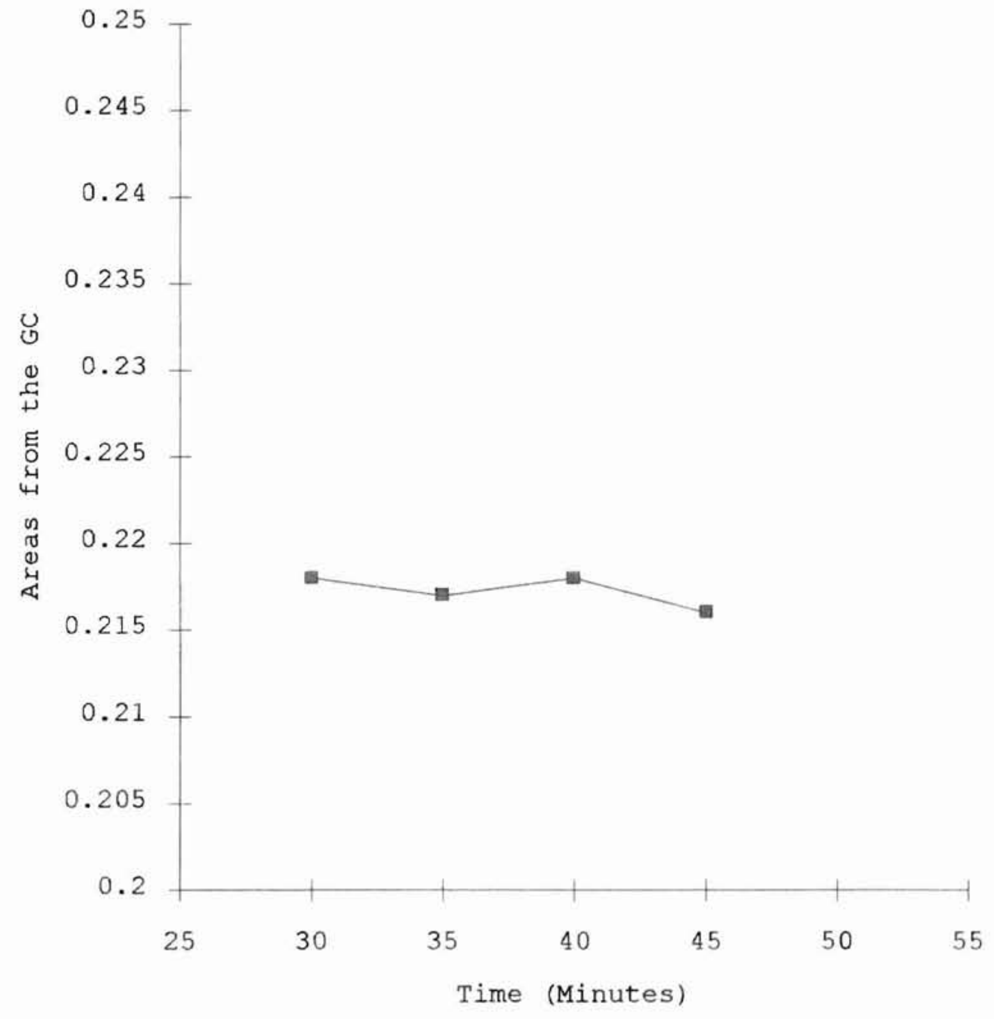


Figure 23: Areas Obtained From the GC for Four Data Points From the Same Sample Bottle

CALIBRATION DATA

The extent of destruction of TCE and toluene in this study was denoted by the difference of influent and effluent concentrations. For a chemical, an effluent concentration of only 5 percent of its influent concentration would translate into 95 percent destruction. To measure the destruction of TCE and toluene three relations needed to be established. First the relation between liquid volume of the chemical and its concentration when injected into a defined air mass was established. Secondly, the relation between the concentration in the air mass (of the standards) and areas plotted by the GC was established. Thirdly, the relation between the areas plotted by the GC and the concentration that these areas represent was established.

The first relation was established by injecting a known volume of the chemical into a known volume of air (mass) where the theoretical concentration (column 1 in Table 2) had already been established mathematically as presented in Appendix C. As seen in Appendix C 0.0216 microliter of TCE is equivalent to 300 ppm in 0.0196 L air mass. The second relation was established with the help of the GC. The pollutant air (air plus chemical) was injected into the GC to establish the relation between theoretical concentration of the pollutant (column 1 of tables 2 and 3) in the mix and the area plotted by the GC (Column 2,3, and 4 of tables 2 and 4). The third relation was that between the areas plotted by the GC (columns 2, 3, and 4 of tables 2 and 4) and the concentrations that these areas indicated (Predicted concentrations in columns 5, 6, and 7 in tables 2 and 4). For this study, this relation is established by an equation of line that was obtained by plotting the theoretical concentrations against the average of the areas obtained from the GC. This equation of line was used to sum up the error introduced by the fact that the GC would give slightly different areas for the same theoretical concentration and evenly distribute it over the range of values when converting the areas from the GC into parts per million of the pollutants. Three calibration curves were constructed for TCE and three for toluene following the process discussed in the analysis section.

Before the tabulation of TCE data in Table 2, five concentrations were chosen. The five concentrations for TCE were 9.79 ppm, 29.37 ppm, 48.96 ppm, 145 ppm, and 331.98 ppm. For every desired concentration a calculated volume of TCE (using the equation shown in Appendix C) was injected into the air present in a large glass bottle as discussed in the analysis section. The volume of air (mass) in the bottles was a known value. Then three 5 ml samples of pollutant air (air plus TCE) from these bottles were taken by a 10 ml gas tight syringe and injected into the GC. This 10 ml gas tight syringe was manufactured by Dynatech Sampling Corporation of Baton Rouge, LA. For the first value of 9.79 ppm in the first column of Table 2 these three injections into the GC taken from the same glass bottle yielded 0.01, 0.0095, and 0.011 in terms of area on the GC plot. It can be noticed that these three numbers for the same concentration and bottle differ in value.

To get the predicted concentration in Table 2 the three areas plotted by the GC (Columns 2,3, and 4) were averaged and plotted against the theoretical values. An equation of the line was obtained from this plot as shown on top of columns 5, 6, and 7 in Table 2. The area values from the GC in columns 2,3, and 4 were put in this equation to get the predicted concentration in columns 5,6, and 7. A column of average values (Column 8) is shown for the three predicted columns. This way the plotted area by the GC can be tied down to a concentration while incorporating the fact that the GC would not give the same area for the same volume of pollutant air using this procedure and equipment.

The last column of Table 2 lists the standard deviations of the predicted concentrations of TCE. The standard deviations for TCE ranged from 0.87 (Minimum) for 145 parts per million to 2.01 (Maximum) for 29.37 parts per million concentration. Table 3 lists the average of the three areas (column 2, 3, and 4 of Table 2) from the GC and the average of the predicted concentrations (column 8 of Table 2). The linear regression data for TCE are tabulated in Appendix D. Figure 24 shows the average of three areas from the GC plotted against the average of the predicted concentrations for TCE. It represents a composite calibration curve for TCE based on the averages of the three independent calibration curves. Also included in this figure is the equation of the line best fit and its r^2 value. Figure 25 shows the theoretical concentrations (column 1 in Table 2) of TCE plotted against the three areas from the GC (column 2, 3, and 4 of Table 2).

A similar method of interpreting calibration results was used for toluene. Table 4 lists the theoretical calculated concentrations, areas under the curve, and predicted concentrations with their averages and standard deviations. Table 5 lists the average of the three areas (column 2, 3, and 4 of Table 4) from the GC and the average of the predicted concentrations (column 8 of Table 4). The linear regression data for toluene is tabulated in Appendix D. The standard deviations ranged from 0.4 (minimum) for the 8.28 parts per million to 7.09 (maximum) for 414.19 parts per million. Figure 26 shows the average of three areas from the GC plotted against the average of the predicted concentrations for toluene. It represents a composite calibration curve for toluene based on the averages of the three independent calibration curves. Also included in this figure is the equation of the line best fit and its r^2 value. Figure 27 shows the theoretical concentrations (column 1 in Table 4) of toluene plotted against the three areas from the GC (column 2, 3, and 4 of Table 4).

A single different calibration data point was checked each day of an experimental run. Each time the concentration value, using the existing calibration curves (Figure 24 and 26), was within 5 percent of the theoretical concentration of the calibration data points. Therefore, a whole new series of calibration data were not repeated and the data in Tables 3 and 5 were relied upon for the duration of this research.

Table 2

Calibration Data for Trichloroethylene

Theoretical Calculated Concentration (PPM)	Areas Under the GC Curve			Predicted Concentration (PPM)			Average Predicted Concentrations (PPM)	Standard Deviation of Predicted Concentrations
	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3		
				Equation of Line $Y = -1.213 + 1400.033 (X)$				
9.792	0.010	0.010	0.011	12.787	12.087	14.187	13.021	1.069
29.370	0.020	0.022	0.022	26.088	29.168	29.868	28.374	2.011
48.960	0.035	0.034	0.035	47.368	45.828	47.788	46.995	1.032
145.000	0.103	0.104	0.105	143.410	143.830	145.090	144.110	0.874
331.980	0.239	0.239	0.238	332.975	333.535	331.295	332.602	1.166

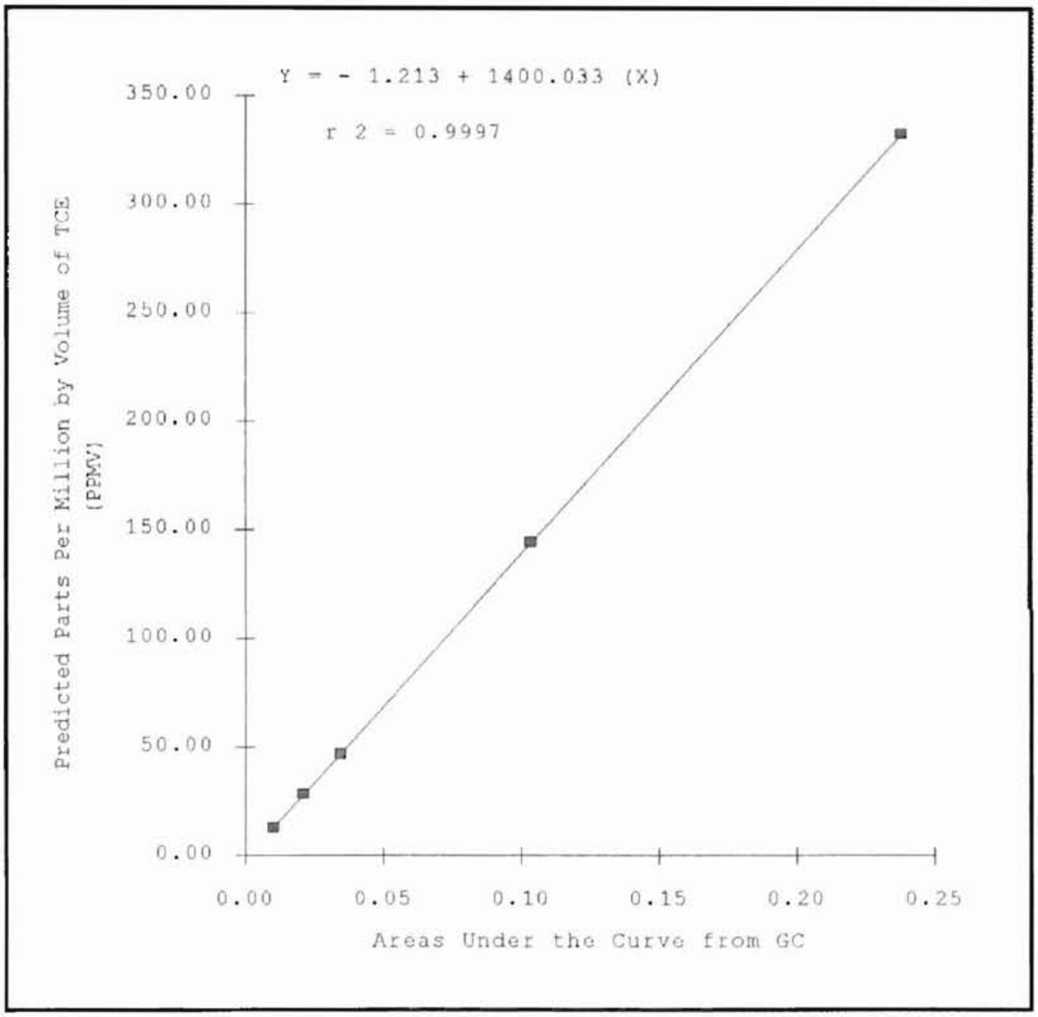


Figure 24: Calibration Curve for Trichloroethylene of Average of Areas from the GC Against Average of Predicted Concentrations

Table 3

Predicted Concentrations of Trichloroethylene

Theoretical Calculated Concentrations (PPM)	Average Areas from GC	Average of Predicted Concentrations (PPM)
9.792	0.010	13.021
29.37	0.021	28.374
48.96	0.034	46.995
145	0.104	144.110
331.98	0.238	332.602

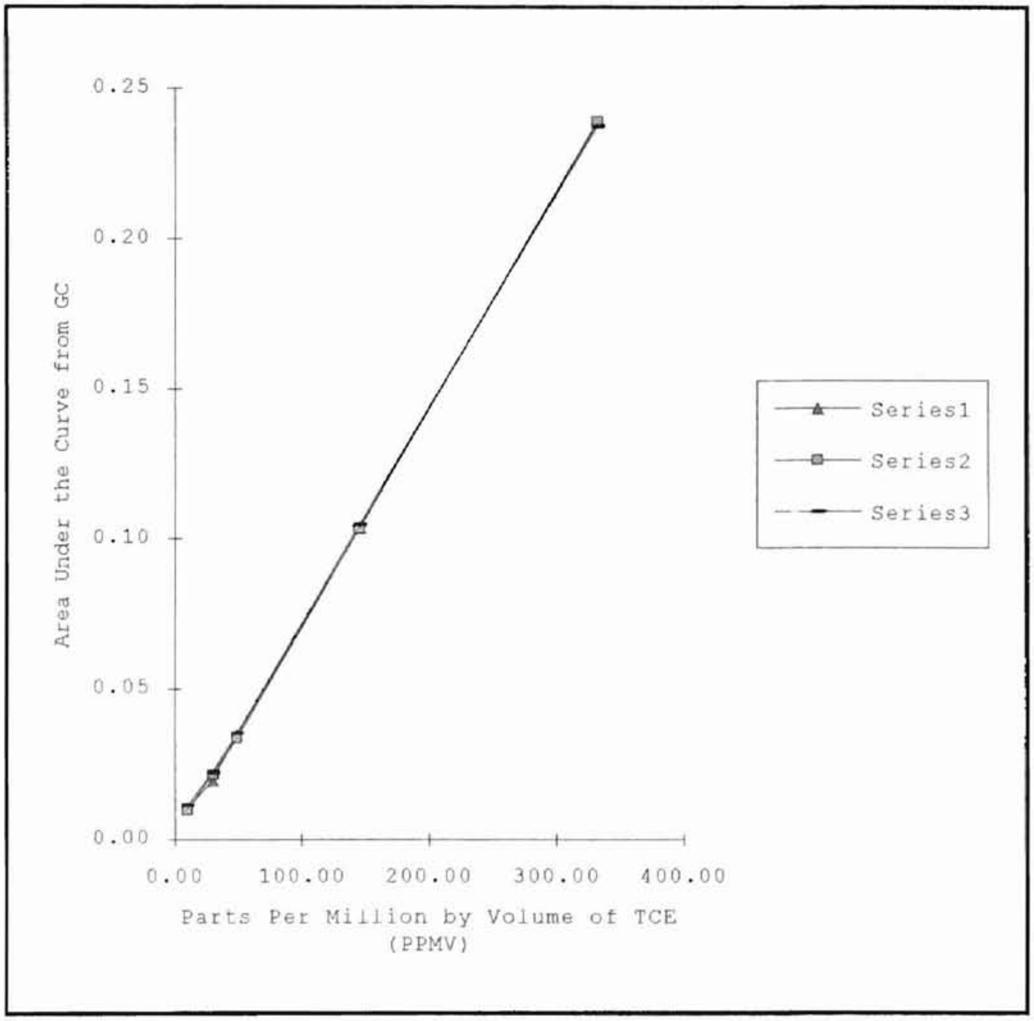


Figure 25: Trichloroethylene Calibration Curve of the Theoretical Values Against the Three Runs of Areas From the GC

Table 4

Calibration Data for Toluene

Theoretical Calculated (PPM)	Area Under the Curve			Predicted Concentrations (PPM)			Average Predicted Conc. (PPM)	Standard Deviation of Predicted Concentrations
	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3		
				Equation of Line Y = 438.874 (X) + 0.32483				
8.28	0.023	0.022	0.021	10.375	10.156	9.585	10.039	0.408
24.85	0.057	0.058	0.053	25.209	25.780	23.585	24.858	1.139
41.41	0.084	0.085	0.081	37.278	37.629	35.918	36.942	0.904
149.95	0.342	0.346	0.371	150.288	151.956	163.323	155.189	7.093
280.84	0.634	0.636	0.635	278.659	279.317	278.922	278.966	0.331
300.00	0.682	0.677	0.682	299.461	297.442	299.681	298.862	1.234
414.19	0.945	0.945	0.942	415.192	414.929	413.876	414.666	0.697

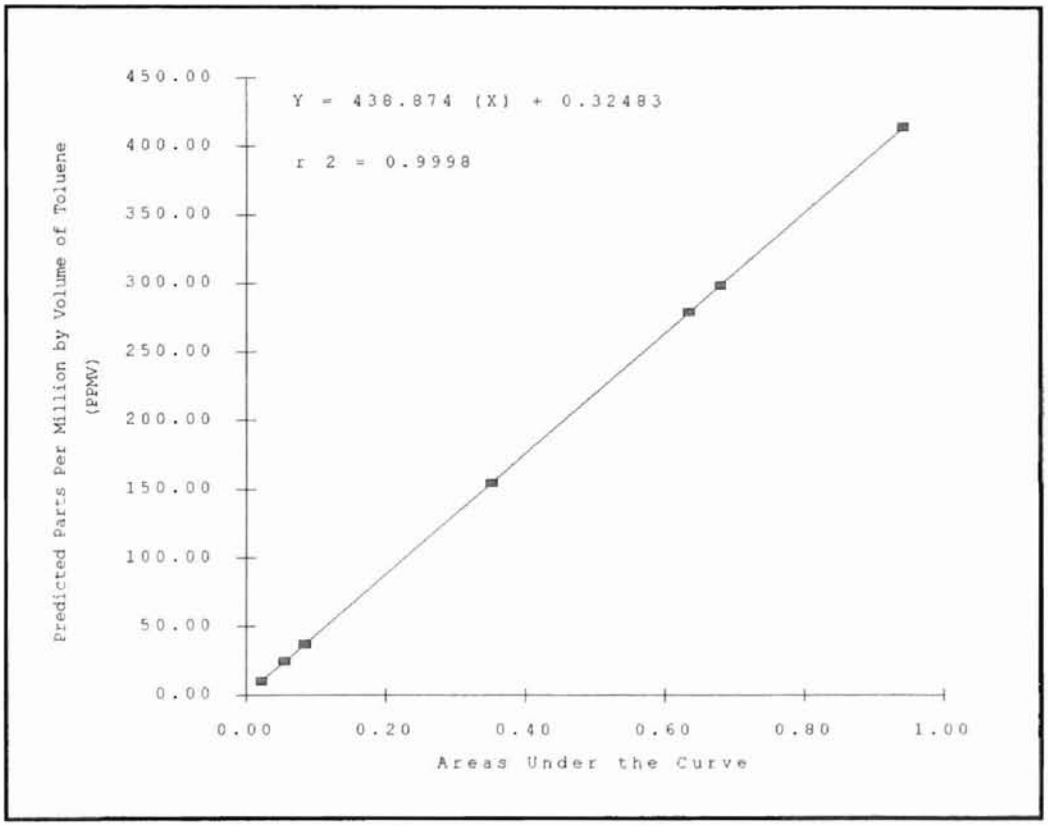


Figure 26: Toluene Calibration Curve of Average of Areas From the GC Against the Average of Predicted Concentrations

Table 5

Predicted Calibrated Concentrations of Toluene

Theoretical Calculated Concentratoins (PPM)	Average Areas from GC	Predicted Concentrations (PPM)
8.28	0.022	10.039
24.85	0.056	24.858
41.41	0.083	36.942
149.95	0.353	155.189
280.84	0.635	278.966
300	0.680	298.862
414.19	0.944	414.666

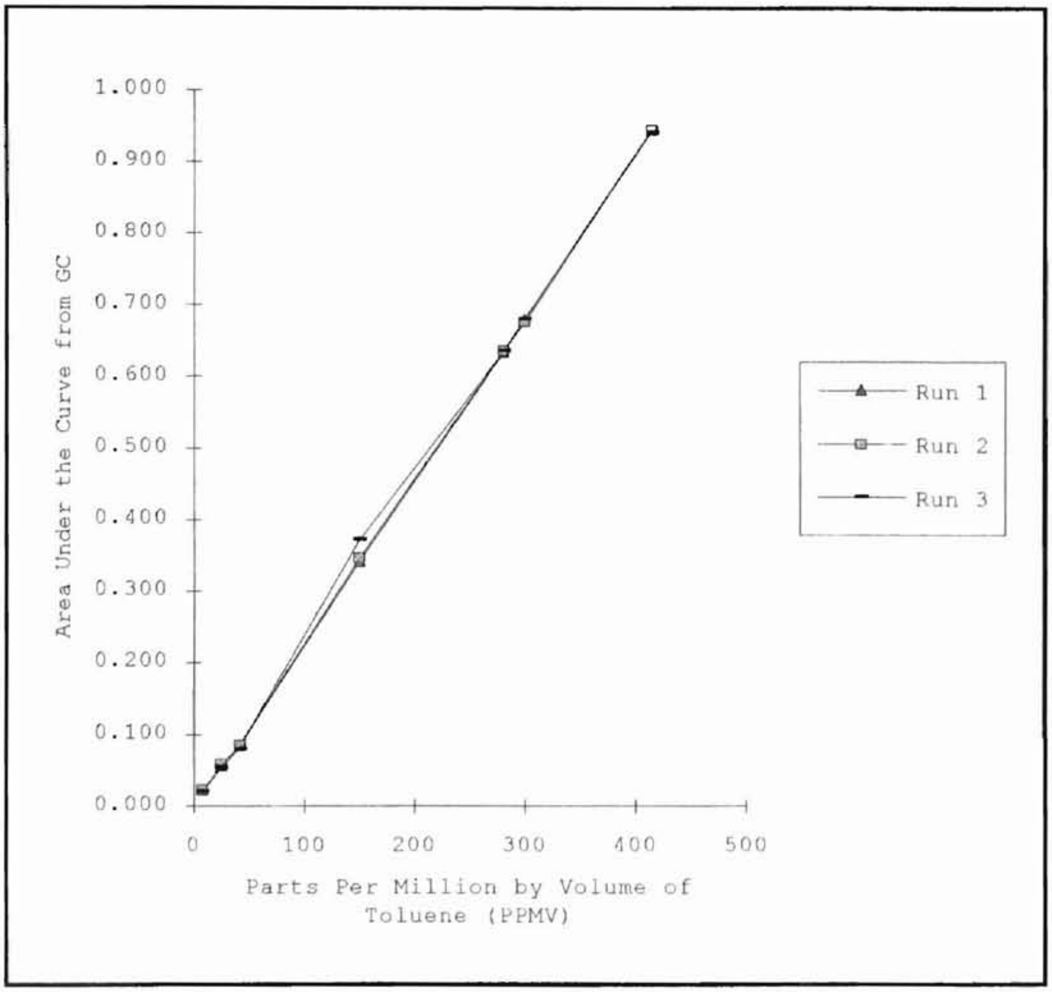


Figure 27: Toluene Calibration Curve of the Theoretical Values Against the Three Runs of Areas From the GC

EFFECT OF RESIDENCE TIME ON DESTRUCTION

To measure the effect of residence time on the destruction ability of the plasma reactor three different values of residence time were chosen. These different residence times were 3 seconds, 5 seconds, and 10 seconds. The maximum destruction can be calculated from Tables 14 and 15 (Appendix H). These tables tabulate the effluent and influent concentrations for a complete run for TCE and toluene, respectively. In this study the destruction was the difference of influent and effluent concentrations. The maximum destruction of trichloroethylene achieved for 3 seconds was 99 percent, for 5 seconds it was 97 percent, and for ten seconds it was 97 percent. For toluene the maximum destruction achieved for 3 seconds was 93 percent, for 5 seconds it was 94 percent, and for ten seconds it was 95 percent. To change the residence time the volume of the air stream going through the reactor was varied to obtain the desired residence time. At three seconds the flow rate was 395 ml/min, for 5 second it was 235 ml/min, and for 10 seconds the flow rate was 118 ml/min (Appendix C). All these tests were run at 20 percent relative humidity to keep the humidity from not being a variable. The temperature during these experiments was 50 F°.

The destruction of the contaminant was plotted in terms of percent remaining in the effluent against time. The plot for the residence times of 3, 5, and 10 seconds for trichloroethylene is shown in Figure 28. The plot for the residence times of 3, 5, and 10 seconds for toluene is shown in Figure 29. The percent remaining in the effluent of the different residence times for both chemicals were plotted together against time in Figure 30.

For each experiment test the equipment was run for one hour to purge all the gas in the system and allow the gas stream to become steady in terms of pollutant concentration and humidity. At the end of one hour several samples were taken. The last two samples, one for effluent and one for influent, are plotted in all the figures. After the second of these two samples were injected into the GC the plasma was turned on and the first sample during the destruction phase of the experiment was taken 5 minutes later. The effluent did not show the maximum destruction achievable after five minutes because of the remaining pollutant in the inside volume (448.6 ml. as calculated in Appendix C) of plumbing after ACPR. It took T = 15-20 minutes for the effluent from the ACPR to totally flush this 448.6 ml. After 20 minutes the effluent concentration reached that of maximum pollutant destruction and remained steady till the plasma was turned off. Only the steady state data was used to calculate the destruction efficiency. After the ACPR was turned off at T = 65 minutes it took the effluent from the ACPR 15-20 minutes to totally flush the inside volume of plumbing (from ACPR to the effluent sampling bulb) before the effluent reached the concentration of influent. During every ninety-five minute test for each residence time several samples were taken from the influent sampling bulb to ensure that a steady stream of 300 ppm of the desired contaminant was being fed to the reactor and the decrease in the effluent concentration occurred because of the destruction in the plasma reactor.

An ANOVA (Analysis of Variance) statistical test in Microsoft Excel 4.0 was run on the three different data sets for 3, 5, and 10 seconds for both TCE and toluene. This data is tabulated in Tests 3 for TCE (test on data contained in Table 14, Appendix H) and Test 4 for toluene (test on data contained in Table 15, Appendix H) as shown in Appendix G. The hypothesis was that during the destruction phase (T = 35 minutes to T = 65 minutes) the means of the different residence times were the same.

For TCE the variance for the 3 second residence time was 4.44, for 5 seconds it was 3.30, and for 10 seconds it was 2.02 as shown in Test 3 (Appendix G). Averages for the same columns were 3.33, 4.44, and 4.60. The F-value was 0.89 and F-critical value was 3.68 indicating that the hypothesis should be accepted and there is no significant statistical difference in the three curves.

For toluene the variance for the 3 seconds residence time was 1.07, 0.71 for 5 seconds, and 5.08 for 10 seconds as shown in Test 4 (Appendix G). The F-value was 1.28 and the F-critical value was 3.81 depicting that the hypothesis should be accepted. This means that there is no significant statistical difference among the three curves.

The ANOVA test was also run on the combined run of all the six residence times of both toluene and TCE (Figure 30) in Test 5 as shown in Appendix G. It was noticed that F-value (1.32) was smaller than F-critical value (2.62) which means that there is no significant statistical difference among the six different curves.

It was observed that in this range of three to ten seconds of residence times the destruction data did not show any considerable difference even when the two compounds were put together. These results signify that the residence time in the vicinity of these values and with this setup would not effect destruction. Therefore operators can run this system at lower residence times increasing the flow rate and thereby decreasing the cost to run the plasma reactor.

Nunez *et al* (9) reported that less destruction occurred when they increased the flow rate from 0.5 L/min to 2.5 L/min for toluene. They used residence time varying between 0.48 seconds to 1.43 seconds. In their study two different concentrations, 50 and 250 ppm, were used. They noticed that the effluent concentration increased from zero to 25 ppm for the influent concentration of 50 ppm. For the 250 ppm the effluent concentration changed from 100 to 250 ppm. Their results are different than this study. This may be because that they used a different type of plasma reactor called packed bed corona reactor, that has been explained on the page 8 of this study. In their plasma reactor continuous sparking occurred which is probably disrupted by the higher flow rate bringing the destruction down.

Hurst (12) reported no significant effect on destruction with increase in flow rates in the plasma reactor for carbon tetrachloride. He used residence times varying between 8 to 70 seconds (for reactor size of 74.78 ml), and concentrations between 19 to 83 ppm. His study was run using the same type of plasma reactor and confirms the results reached in this study.

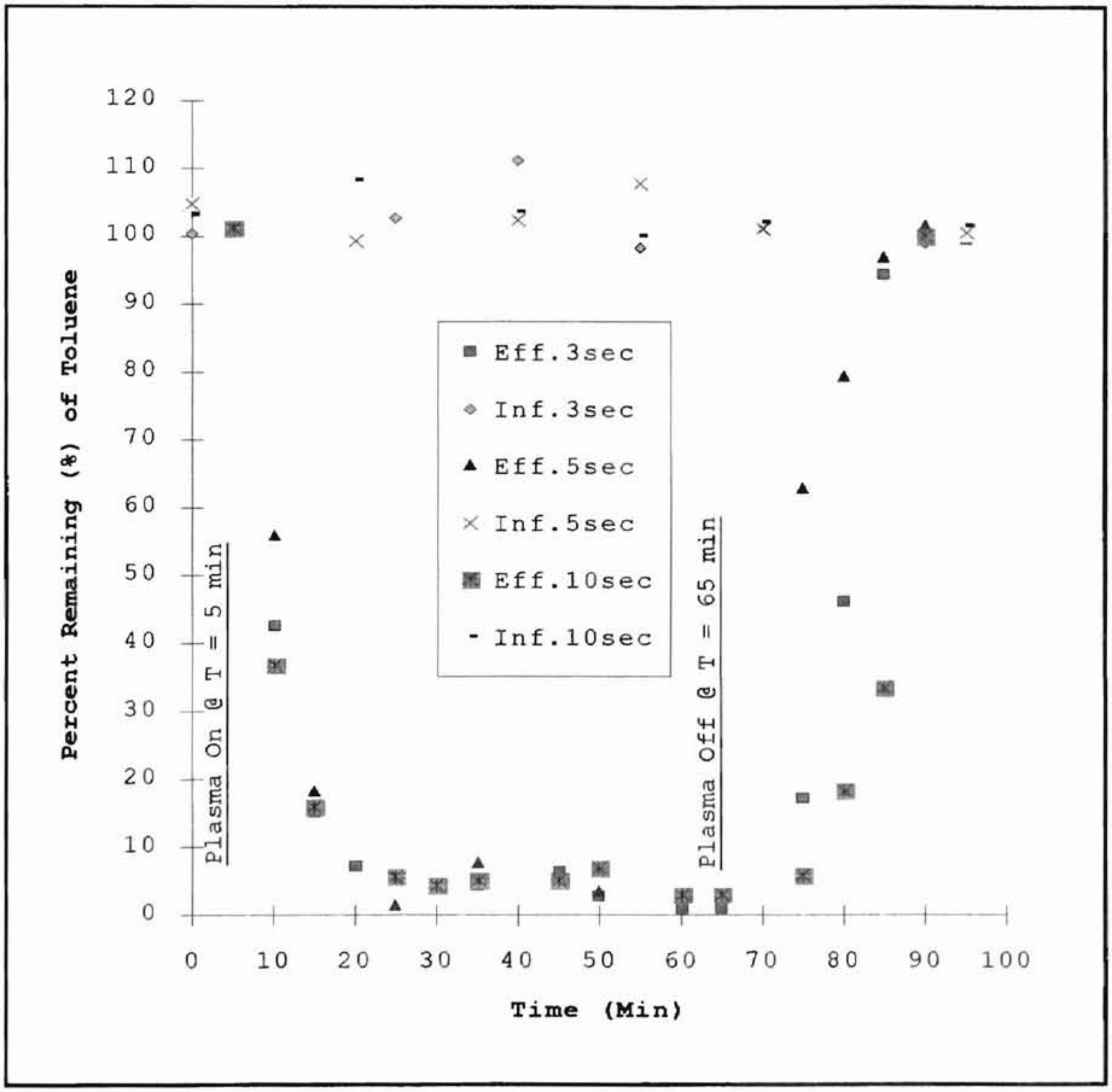


Figure 28: Trichloroethylene Destruction Curve for Residence Time of Three, Five and Ten Seconds

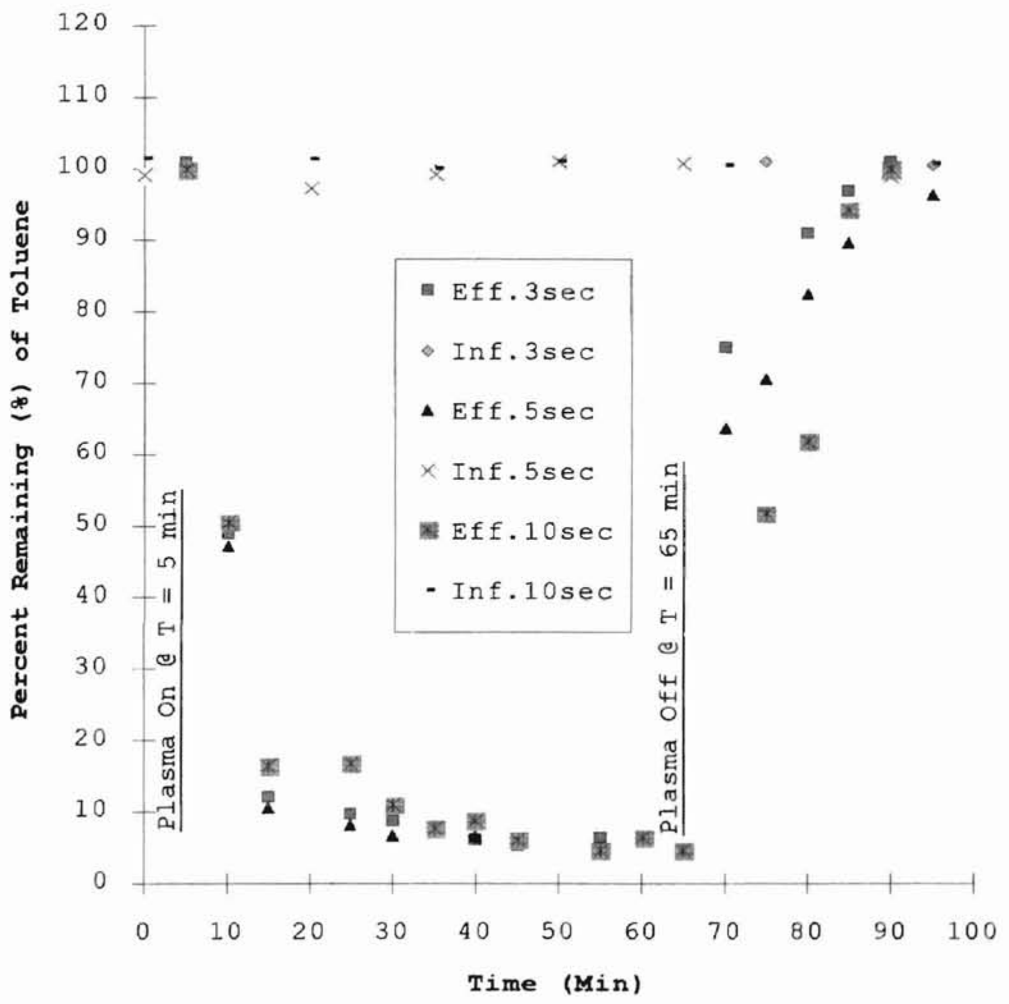


Figure 29: Toluene Destruction Curve for Residence Time of Three, Five, and Ten Seconds

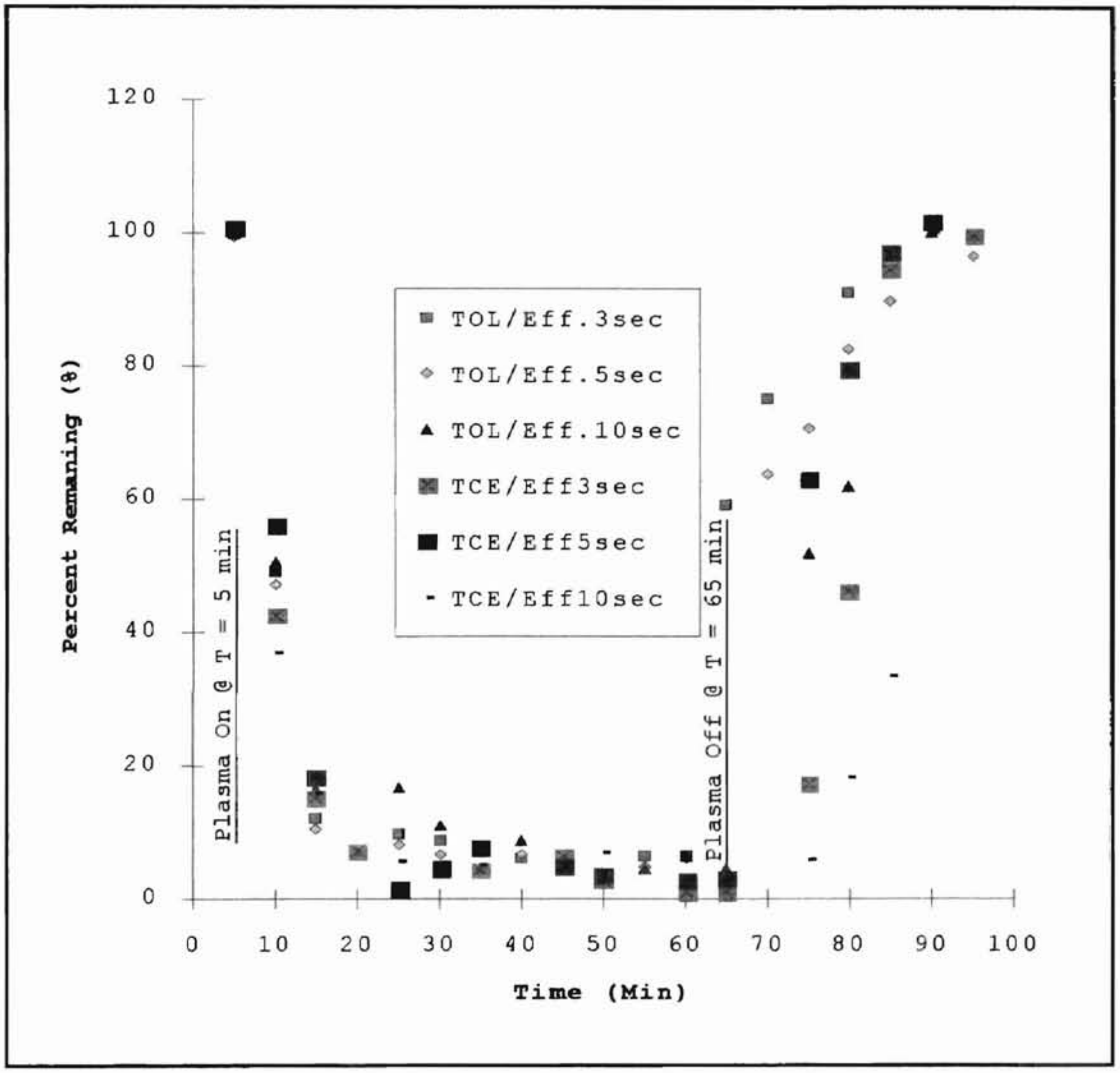


Figure 30: Effect of Residence Time on Destruction of TCE and Toluene

EFFECT OF RELATIVE HUMIDITY ON DESTRUCTION

To measure the effect of relative humidity on the destruction ability of the plasma reactor three different values of humidities were chosen and tested using a 5 second residence time. These different humidities were 20 percent, 40 percent, and 80 percent. For trichloroethylene the maximum destruction at 20 percent relative humidity was 97.1 percent, for 40 percent relative humidity the destruction was 92 percent, and for the 80 percent relative humidity the destruction dropped to 79.2 as shown in Table 16 in the Appendix H. In this study the destruction was the difference of influent and effluent concentrations. The maximum destruction of toluene achieved for 20 percent was 95.25, for 40 percent it was 79.77, and for 80 percent it was 73.73 as shown in Table 17 in Appendix H. It was observed in these tests that humidity inhibited the destruction ability of the plasma reactor. The destruction of the contaminant was plotted in terms of percent remaining in the effluent against time. The TCE data in Table 16 (Appendix H) is plotted in Figures 31. Table 17 that contains the toluene data is plotted in Figure 32. The percent remaining for all three relative humidities for both trichloroethylene and toluene are plotted against time in Figure 33 to allow a better comparison of the effect of relative humidity on the destruction of these two chemicals.

The same equilibrium procedure used for residence time tests was adopted in these tests. The equipment was run for one hour to purge all the gas in the system and allow the system to reach steady state. The last two samples, one for effluent and one for influent, are plotted in all the figures. After the second of these two samples were injected into the GC the plasma was turned on and the first of sample of the destruction phase was taken 5 minutes later. The effluent did not show the maximum destruction achievable after five minutes because of the remaining pollutant in the inside volume of plumbing equipment as explained in the third paragraph of the preceding section. During every ninety-five minute run for each residence time several samples were taken from the influent sampling bulb to ensure that a steady stream of 300 ppm of the contaminant was being fed to the reactor and the decrease in the effluent concentration occurred because of the destruction in the plasma reactor. At T = 65 minutes the plasma was turned off, after the corresponding effluent sample was taken. The effluent concentration increased steadily until it reached the influent concentration.

An ANOVA statistical test was run on the destruction data generated using the three relative humidity percentages. The One-way ANOVA in was used for this analysis. First it was used on the data in Figure 31 that depicts the effect of humidity on the percent trichloroethylene concentration remaining in effluent. The hypothesis tested was that the means of the different relative humidity data during the destruction phase (T = 35 minutes to T = 65 minutes) were the same. The significance level of 0.05 was used. The ANOVA results for the effect of humidity are tabulated in Test 6 (Table 16) and Test 7 (Table 17) in Appendix G for TCE and toluene, respectively. For trichloroethylene the variance for the 20 percent humidity data was 3.44, for 40 percent it was 6.04, and for 80 percent relative humidity it was 0.62. Averages for these three humidities were 4.74, 10.96, and 21.72 for 20, 40, and 80 percent relative humidity, respectively. The F-value was 89.286, and the F-critical value was 3.98 which shows that the hypothesis should be rejected and that there is a significant statistical difference in the three curves.

For the relative humidities of 20, 40, and 80 percent for toluene the variances were 0.66, 1.35, and 0.58 respectively. The F-value was 570.10 and the F-critical value was 4.25 depicting that the hypothesis should be rejected. This means that there is a significant statistical difference among the three different curves.

It was observed that in the range of 20 to 80 percent relative humidity there was a significant statistical difference in the humidity curves of both trichloroethylene and toluene. These statistical results confirm the visual inspection of Figures 32 and 33. Taking into consideration the ultimate destruction obtained by each of these curves and the visual differences between them it can be confirmed that there is a significant difference between these curves and increasing relative humidity decreases the destruction of these chemicals.

If the decision on what comparisons to make is withheld until after the data are examined, statistical comparison may still be made, but the alpha (α) level is altered because such decisions are not taken at random but are based on observed results (17). Newman-Keuls range test is one of several methods that have been introduced to handle such situations (17). Since for this study the decision on what comparisons to make was withheld until after the data were examined it was decided to confirm the results obtained by the ANOVA test by using Newman-Keuls range test on the humidity data of both TCE and toluene. Tests 6 and 7 (Appendix G) contain the test steps and results. According to Newman-Keuls range test shown in Test 6 of Appendix G the three curves of relative humidities for TCE are significantly different from each other. From the Newman-Keuls range test that was applied to the three relative humidities in Test 7 of Appendix G the three curves of toluene are also significantly different from each other. This confirms the earlier results obtained through Single-Factor ANOVA test.

The Newman-Keuls range test was also applied to the combined run of all the six relative humidities of both toluene and TCE (Figure 33) in Test 8 of Appendix G. The results showed that all the six curves are significantly different from each other, except 20 % curve of toluene is not significantly different from 20 % curve of TCE and 40 % curve for toluene is not significantly different from 80 % curve of TCE. This means that the two chemicals act alike at 20 % relative humidity with respect to total destruction. It also means that toluene destruction in ACPR gets relatively more inhibited with increasing relative humidity than TCE.

Hurst (12) reported no significant effect on destruction with changes in relative humidities for carbon tetrachloride. He changed percent relative humidities from 20 to 61, used residence times varying between 8 to 70 seconds (for reactor size of 74.78 ml), and concentrations between 19 to 83 ppm. Kushner *et al* (8) reported that destruction of trichloroethylene in silent discharge plasma decreased with an increase in humidity. Their results confirm the results obtained in this study for trichloroethylene. Their research showed that the ClO radical is an important intermediate which oxidizes TCE. Its consumption by OH radicals is largely responsible for the lower rate of remediation in wet mixtures compared to dry mixtures. The reason of lower destruction with increasing humidities for toluene was unknown in this research.

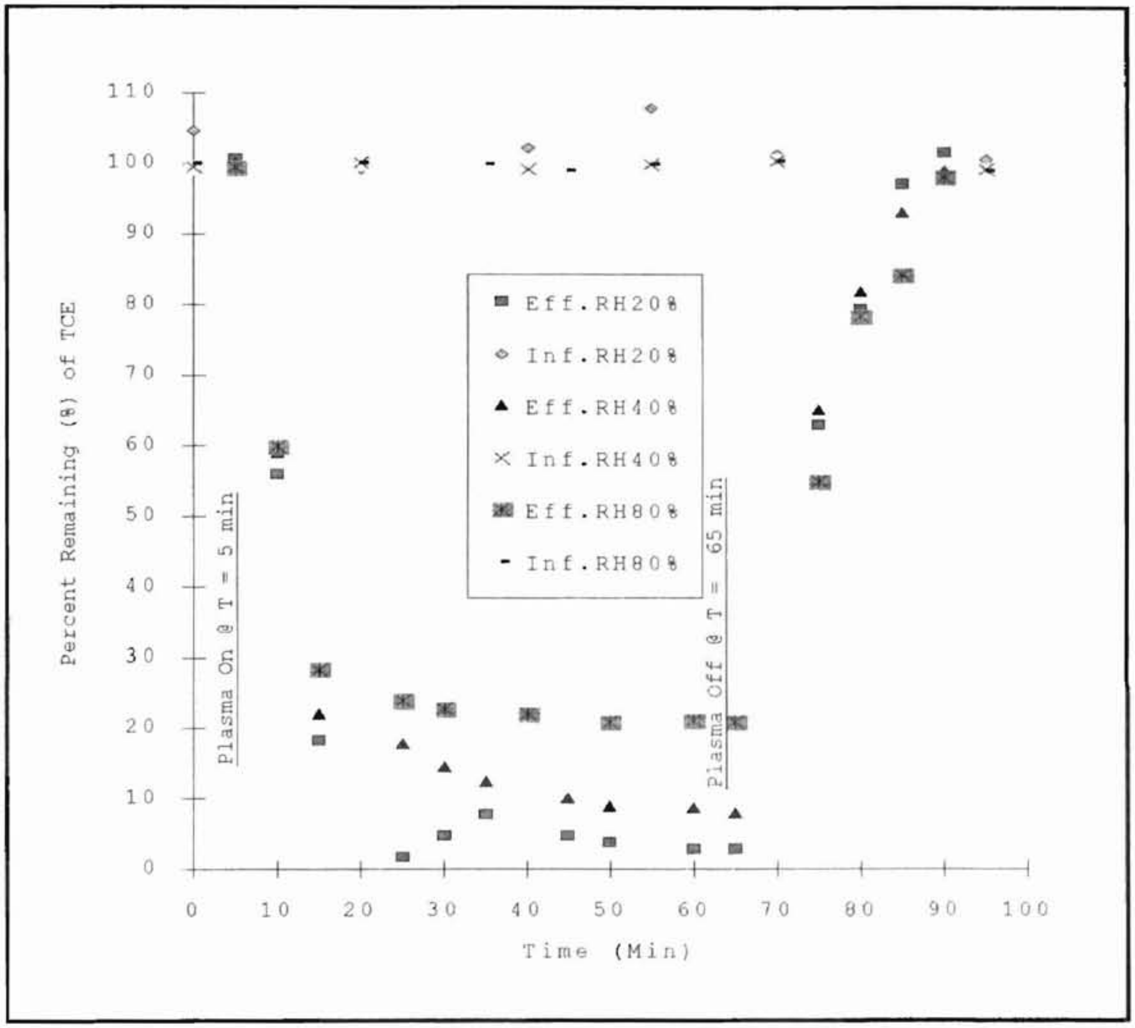


Figure 31: The Effect of Humidity on Destruction of Trichloroethylene

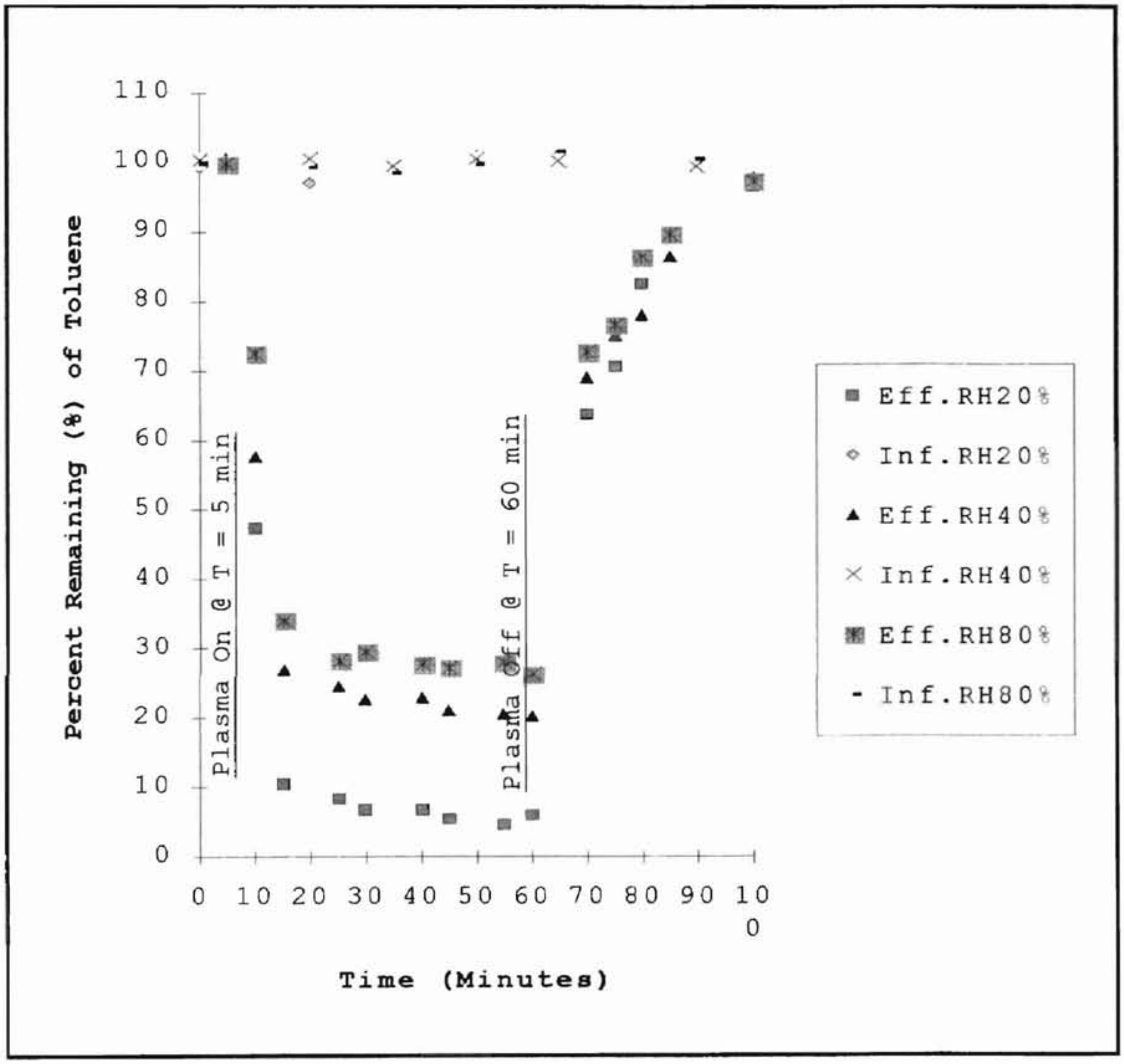


Figure 32: The Effect of Humidity on Destruction of Toluene

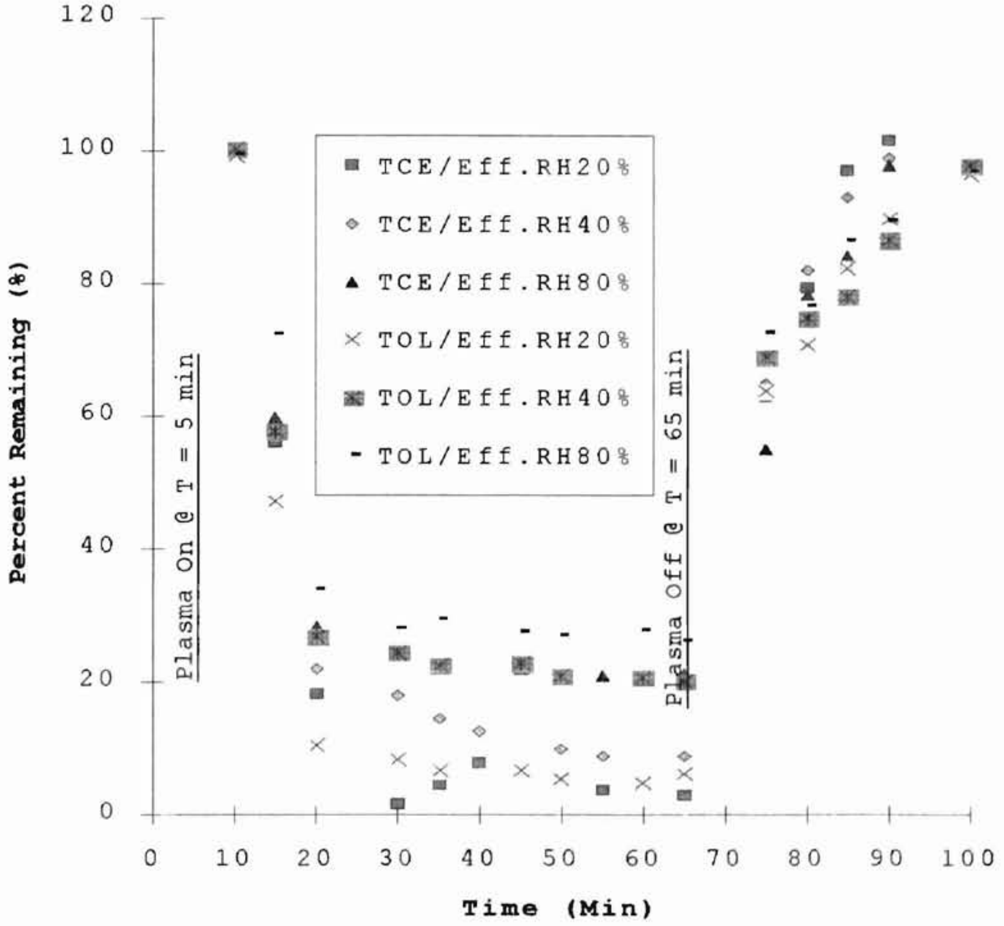


Figure 33: Effect of Humidity on Destruction of TCE and Toluene

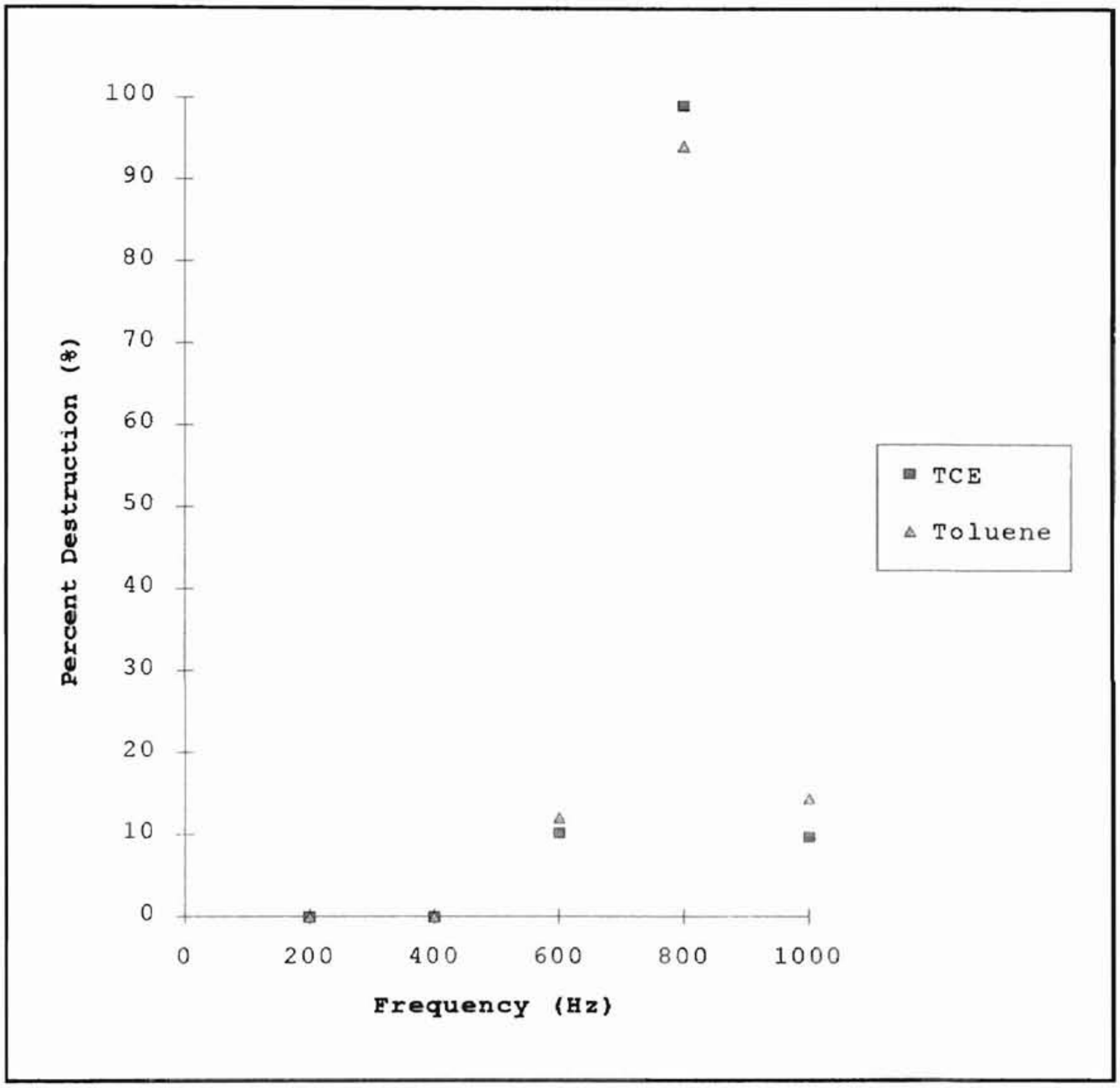
EFFECT OF THE MIXTURE OF TWO POLLUTANT ON DESTRUCTION

The objective of this experiment was to determine the effect of frequency on the destruction of a mixture of two pollutants. In this step of the research trichloroethylene was mixed equally with toluene. Equal concentrations of both contaminants were mixed together to facilitate easy detection of any difference in the behavior of the two chemicals. A residence time of 5 seconds and relative humidity of 20 percent was selected for these tests.

Two different concentrations of the mixture were used in this test. First an equal concentration of 148 ppm of trichloroethylene was mixed with 148 ppm of toluene by mixing in the required amount of these two chemicals. The data are tabulated in Table 18 in Appendix H and plotted in Figure 34. At 200 and 400 hertz the destruction of trichloroethylene was zero. The destruction then increased to 12.45 % at 600 hertz, 98.7 % at 800 hertz, and decreased to 10 % at 1000 hertz. For toluene the destruction was zero at 400 and 600 hertz, it increased to 10.38 % at 600 hertz, 93.4 % for 800 hertz, and decreased to 13.23 % for 1000 hertz. The Single-factor ANOVA results on this test data are shown in Test 9 in Appendix G. The variance for the TCE and toluene data was 1765.29 and 1567, respectively. The F-value was 0.001 and F-critical value was 5.32 indicating that the hypothesis that the mean of the two data are the same should not be rejected. This means that there is no significant statistical difference between the two data sets.

For the second test equal concentration of 200 ppm of the two chemicals were mixed. This data are shown in Table 19 in Appendix H and are plotted in Figure 35. At 200 and 400 hertz the destruction of trichloroethylene was zero, same as for the test at the lower concentration of 148 ppm. The destruction then increased to 10.23 % at 600 hertz, 99.02 % at 800 hertz, and 9.66 % at 1000 hertz. For toluene the destruction was zero at 400 and 600 hertz which increased to 12.04 % at 600 hertz, 94.2 % for 800 hertz, and 14.5 % for 1000 hertz. The ANOVA results on this test data are shown in Test 10 in Appendix G. The variance for the TCE data was 1793.75 and for toluene the variance was 1578.31. The F-value was 0.0002 and F-critical value was 5.317 indicating that the hypothesis that the mean of the two data is the same should not be rejected. This also means that the there is no significant statistical difference in the two data sets.

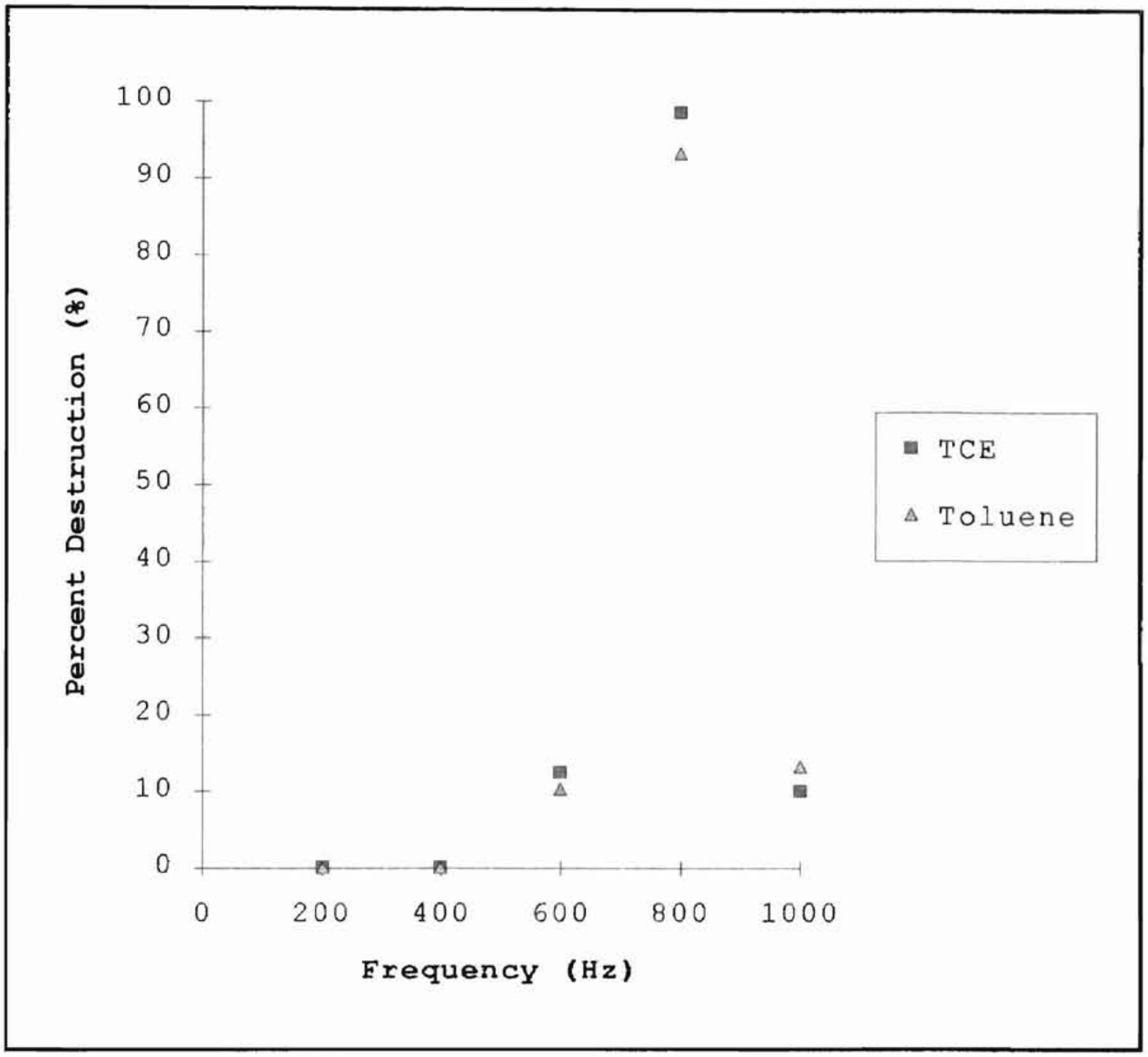
The maximum destruction for TCE and toluene at 5 second residence time tabulated in Table 14 and 15 was 97.07 % and 95.25 %, respectively at 20 % relative humidity. These numbers are very close to the numbers obtained for maximum destruction for both the 148 and 200 ppm mixtures described above. No noticeable variation in the destruction was noticed between these two tests and the 5 second residence time (20 percent humidity) tests conducted earlier in this research for each chemical individually. The absence of any variation indicates that the electrical parameters which were selected for the air phase work the same on these pollutants regardless of the fact that these gases are present in a mixture or individually.



Toluene = 148 PPM

TCE = 148 PPM

Figure 34: Effect of Frequency on the Percent Destruction of Trichloroethylene and Toluene Mix



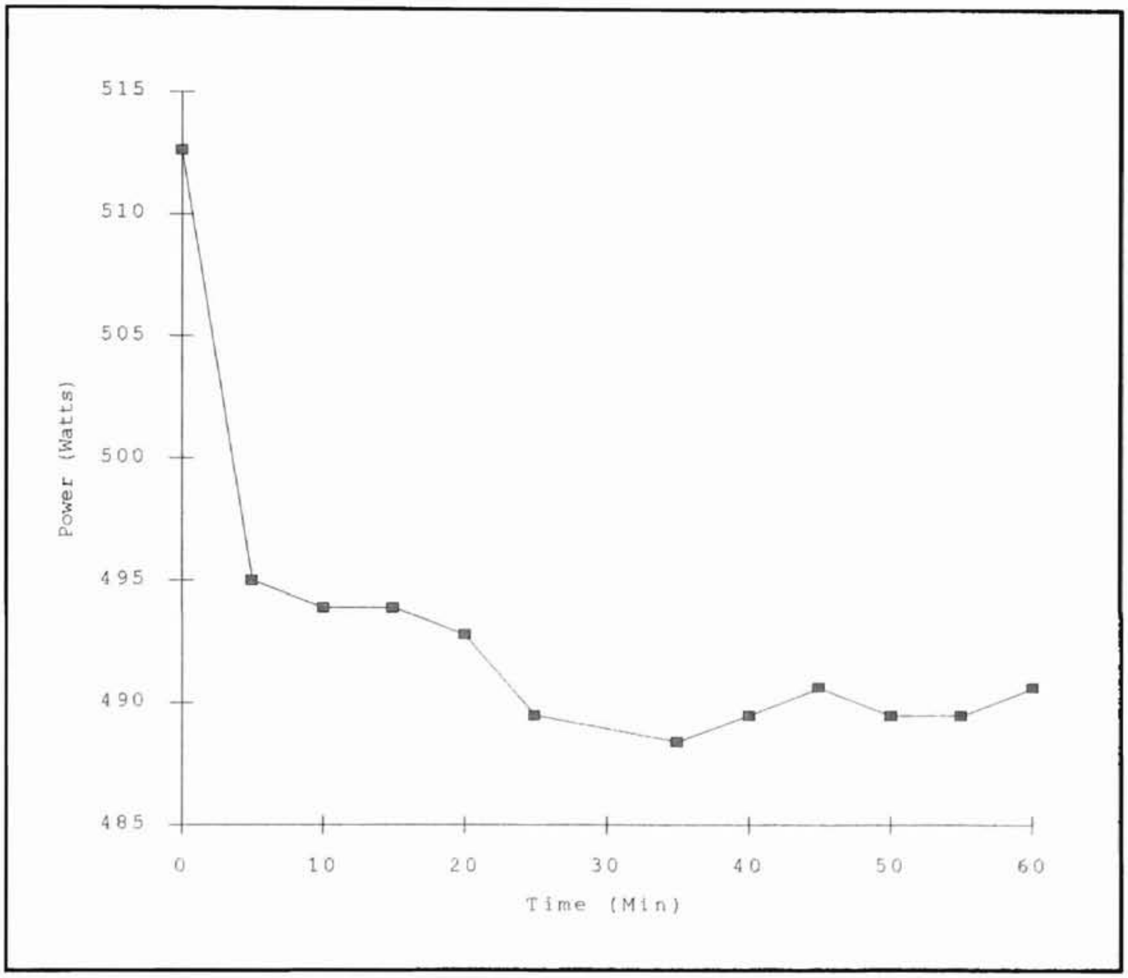
Toluene = 200 PPM

TCE = 200 PPM

Figure 35: Effect of Frequency on the Percent Destruction of Trichloroethylene and Toluene Mix

POWER DISSIPATION OVER A SINGLE RUN

The power did not change significantly over the 65 minute runs as shown in Figure 36. This test was run using trichloroethylene at a residence time of 3 seconds and 20 percent humidities. The data are tabulated in Table 20 in Appendix H. The plasma was started at a primary voltage of 40 and at a frequency of 800 hertz. Immediately after the plasma was turned on the power was 512.6 watts. This value of power was obtained by multiplying the current obtained from the fluke meter that was measuring current flowing to the oscillator (from socket) by the voltage of 110 volts. This value of 512.6 watts decreased to 490.6 watts after 30 minutes and remained constant thereafter. This change of 22 watts was taken into consideration for cost analysis which is based on 490.6 watts. The exact cause of 22 watts drop was unknown in this research. It was not a matter of concern as the equipment was run at least an hour before any tests were performed.



Residence time = 3 seconds
Relative Humidity = 20 %
Temperature = 50 F

Figure 36: Effect of Time on Power Dissipation Over a Trichloroethylene Destruction Test

REPRODUCIBILITY OF RESULTS

Three different duplicates for the trichloroethylene destruction data were taken for the residence time of three seconds. These duplicates were taken to show: (1) At time = 30 minutes the effluent stream reaches a steady state, and (2) The experiments performed using the setup used in this study are reproducible.

Figure 37 shows three influent and three effluent data. The three duplicate runs are tabulated in Table 21 of Appendix H. A Single-factor, or One-way ANOVA statistical test was run on the three duplicates as shown Test 11 in Appendix G. One-way ANOVA was used because the percent remaining of the pollutant was dependent only on the factor of time. The hypothesis was that during destruction phase (T = 35 to T = 90 min) the means of the three duplicate were the same. The variance for first duplicate was 1.28, for second duplicate it was 0.95, and for third duplicate it was 1.38. Averages for the same columns were 2.22, 2.20, and 1.97. The F-value was 0.15 and F-critical value was 3.40 indicating that the hypothesis should be accepted and that there is no significant statistical difference in the three curves of the duplicates. This result demonstrates that the experiments performed using the setup used in this study are reproducible. Also from inspection of the three curves one can see that after thirty-five minutes the destruction remains practically the same indicating steady state.

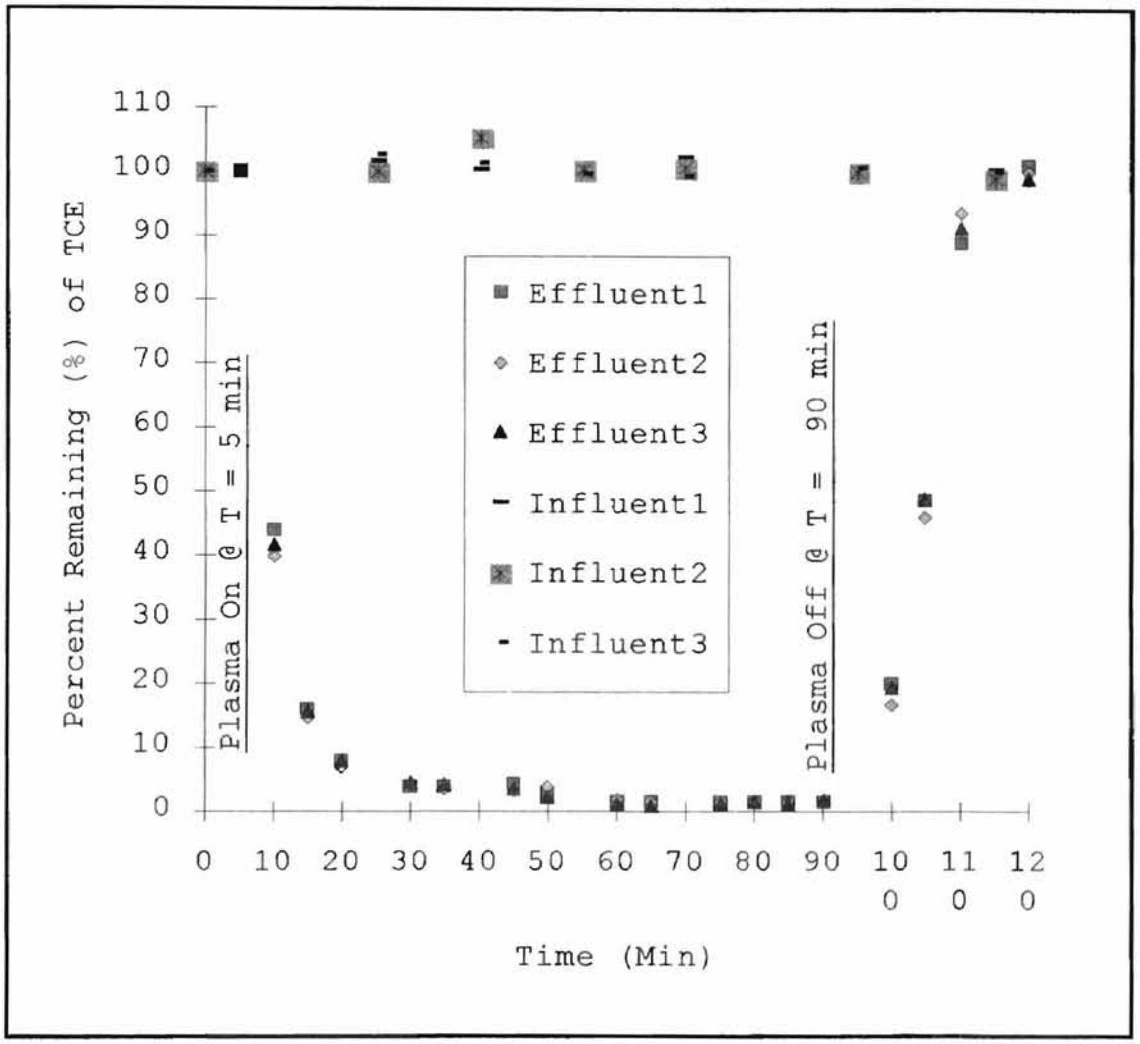


Figure 37: Three Duplicate Curves for Trichloroethylene Destruction Data of Residence Time of Three Seconds

COST ANALYSIS

The cost analysis was based on power used per Kg of trichloroethylene and toluene in the air phase for a concentration of 300 ppm, a residence time of 5 seconds, and a power of 490.6 watts. At this concentration air makes up 99.97 percent of the air phase with trichloroethylene or toluene making up the remaining 0.03 percent by volume. Therefore, the specific gravity of air was used for cost calculations. It was calculated that 0.017 Kg of pollutant in air phase passes through the reactor in one hour as shown in Appendix A. At a cost of 0.08 dollars per kilowatt hour it would cost 2.30 dollars to detoxify one kilogram of pollutant gas. A cost of 0.039 dollars was calculated for running the plasma reactor for one hour. Hurst (10) reported the cost of 0.0081 dollars to run the plasma reactor for one hour. He calculated this cost by using a utility cost of 0.035 dollars per kilowatt hour instead 0.08 dollars per kilowatt hour as used in this study. Also in Hurst's study the volume of the plasma reactor used was 78.74 cubic centimeter which is larger than 19.6 cubic centimeter used in this study. He varied the concentration from 19 to 83 parts per million at a primary voltage of 50 volts.

Kushner et al (7) reported the operating cost to be a little less than a dollar for a Kg of TCE in gas phase. They estimated the cost based on $0.10/kWh. Their cost is less than calculated in this study. They used concentrations varying from 100 to 1000 parts per million. Their lower cost might be because of the square geometry of the Silent Discharge Plasma (SDP) which may be more efficient in establishing a strong electrical field as compared to the cylindrical shape of the alternating current plasma reactor. In their reactor there was no localized arcing because one or both the electrodes in their reactor were covered with dielectric. In the SDP the dielectric surfaces serve the role of the capacitor in series with the plasma saving the power dissipated in the circuit and thereby decreasing the cost.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The specific objective of this research was to prove that the plasma reactor was a feasible method for the destruction trichloroethylene and toluene. The goal of this objective was accomplished by finding and evaluating the effect of design variables on destruction efficiency. The design variables considered were relative humidity and residence time.

CONCLUSIONS

The conclusions arrived at from these research experiments are as follows:

1. The plasma reactor had a small optimum range that enveloped all the peak values for power delivered for different primary voltages.
2. The maximum power consumed elevated with increase in primary voltage.
3. Varying residence time to 3, 5, and 10 seconds did not have any significant effect on the destruction efficiency of TCE and toluene.

4. Humidity had a negative effect on the destruction. The increase in humidity from 20 percent relative humidity to 40 and then 80 percent decreased destruction.
5. The ACPR proved to be an effective method of trichloroethylene destruction under the conditions and equipment used for this research.
6. The maximum destruction achieved for trichloroethylene was 99.03 percent at residence time of 3 seconds and 20 percent relative humidity.
7. The ACPR proved to be an effective method of toluene destruction under the conditions and equipment used for this research
8. The maximum destruction achieved for toluene was 95.43 percent at residence time of 10 seconds and 20 percent humidity, indicating that Alternating Current Plasma reactors used in this study was more successful in altering trichloroethylene (maximum destruction 99.03%).
9. Individual destruction efficiency in the mixture was not significantly different than their individual destruction efficiency in the plasma reactor used in this study.
10. The cost of operating the plasma reactor was calculated to average 2.30 dollars per kilogram of TCE or toluene in air phase. The cost for running the plasma reactor for one hour was 0.039 dollars.

RECOMMENDATIONS

The following recommendations are made:

1. Further research needs to be performed to find the exact nature and sequence of reactions taking place in the ACPR to better control the behavior of pollutants during destruction.
2. The destruction behavior of hazardous air pollutants needs to be investigated with residence time shorter than one second.
3. The destruction behavior under extreme hot and cold temperatures needs to be investigated.
4. Scaling up of the reactor to meet industrial applications should be investigated.

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Appendix A

COST OF REMEDIATION OF TCE AND TOLUENE

COST ESTIMATION

The cost is based on the pollutant mix with air

Effective Volume of the Plasma Reactor = 0.0196 L

Specific gravity of TCE = 1.46 Kg/L

As the mix is more than 99.97 % air (300 Parts/1 Million Parts) the calculations should be based on air.

Assuming, density of air = density of the mix (pollutant + air)

The Density of Air @ 60 F = 0.0763 lb/ft^3 = 0.035 Kg/ft^3

1 ft^3 = 28.317 L

0.035 Kg/ft^3 = 0.00123 Kg/L

For residence time of 5 seconds:

1 hr = 3600 seconds

3600 seconds/5 seconds = 720 times

720 * 0.0196 L * 0.0012 Kg/L = **0.017 Kg of mix/hr**

Cost in Dollars Per Kilogram

For 490.6 Watts/hr @40 Volts Primary (from Table 20)

(490.6 Watt.hr * 1Kg)/0.017 Kg = 28858.82 Watt.hr

= 28.85 KWhr

For .08 dollars/KWhr:

Cost = 28.85 KWhr * 0.08 dollars

= **2.30 dollars/Kg** of toluene or trichloroethylene gas.

Cost in Dollars Per Hour

The cost of running the reactor for 1 hour:

0.4906 KWhr * 0.080 = **0.039 dollars/hr**

Appendix B

Table Z-2

[3] See Table Z-3.
[4] Varies with compound.

TABLE Z-2

Substance	8-hour time weighted average	Acceptable ceiling concentration	Acceptable maximum peak above the acceptable ceiling concentration for an 8-hr shift	
			Concentration	Maximum duration
Benzene[a] (Z37.40–1969)	10 ppm	25 ppm	50 ppm	10 minutes.
Beryllium and beryllium compounds (Z37.29–1970)	2 μg/m^3	5 μg/m^3	25 μg/m^3	30 minutes.
Cadmium fume[b] (Z37.5–1970)	0.1 mg/m^3	0.3 mg/m^3		
Cadmium dust[b] (Z37.5–1970)	0.2 mg/m^3	0.6 mg/m^3.		
Carbon disulfide (Z37.3–1968)	20 ppm	30 ppm	100 ppm	30 minutes.
Carbon tetrachloride (Z37.17–1967)	10 ppm	25 ppm	200 ppm	5 min. in any 4 hrs.
Chromic acid and chromates (Z37.7–1971)		1 mg/10m^3		
Ethylene dibromide (Z37.31–1970)	20 ppm	30 ppm	50 ppm	5 minutes.
Ethylene dichloride (Z37.21–1969)	50 ppm	100 ppm	200 ppm	5 min. in any 3 hrs.
Fluoride as dust (Z37.28–1969)	2.5 mg/m^3			
Formaldehyde; see 1910.1048				
Hydrogen fluoride (Z37.28–1969)	3 ppm			
Hydrogen sulfide (Z37.2–1966)		20 ppm	50 ppm	10 mins. once, only if no other meas. exp. occurs.
Mercury (Z37.8–1971)		1 mg/10m^3		
Methyl chloride (Z37.18–1969)	100 ppm	200 ppm	300 ppm	5 mins. in any 3 hrs.
Methylene chloride (Z37.23–1969)	500 ppm	1,000 ppm	2,000 ppm	5 mins. in any 2 hrs.
Organo (alkyl) mercury (Z37.30–1969)	0.01 mg/m^3	0.04 mg/m^3		
Styrene (Z37.15–1969)	100 ppm	200 ppm	600 ppm	5 mins. in any 3 hrs.
Tetrachloroethylene (Z37.22–1967)	100 ppm	200 ppm	300 ppm	5 mins. in any 3 hrs.
Toluene (Z37.12–1967)	200 ppm	300 ppm	500 ppm	10 minutes.
Trichloroethylene (Z37.19–1967)	100 ppm	200 ppm	300 ppm	5 mins. in any 2 hrs.

[a] This standard applies to the industry segments exempt from the 1 ppm 8-hour TWA and 5 ppm STEL of the benzene standard at 1910.1028.

[b] This standard applies to any operations or sectors for which the Cadmium standard, 1910.1027, is stayed or otherwise not in effect.

APPENDIX C

INJECTION VOLUME DETERMINATION FOR TOLUENE AND TRICHLOROETHYLENE

&

AIR FLOW RATES

TOLUENE

Determine the volume of Toluene to be used for 300 PPM Conc:

T = 77°F = 298K

V = Effective Volume of the ACPR = 19.6 ml = 0.0196L

P = 1 atm.

Density = 0.862 gm/ml (20°C) = 0.8623E-03 gm/µl

n = PV/RT

= 1 atm (0.0196 L)/(0.0821 L x atm/gmole x K)(298K)

= 8.011E-04 g.mol

x mole of toluene =

300 PPM x 8.015E-04 g.mole/1E+06 = 2.405E-07 g mole

Toluene in gms

= 2.405E-07 g mole (92.13/moles of Toluene)

= 2.21×10^{-5} gm

Volume of Toluene = 2.215E-05 gm/0.8623×10^{-3} gm/ml

= 0.0257 µl

This volume of pollutant needs to be injected per residence time.

TRICHLOROETHYLENE

Determine the volume of Trichloroethylene to be used for 300 PPM Conc:

T = 77°F = 298K

V = 19.6 ml = 0.0196 L

P = 1 atm.

Density = 1.46 gm/ml (20°C) = 1.46 E-03 gm/µl

n = PV/RT

= 1 atm (0.0196L)/(0.08206 L.atm/gmole.K)(298K) =

= 8.015E-04 gmol

x mole of trichloroethylene

= 300 ppm x 8.015E-04 g.mol/1 x 10^6

= 2.4045E-07 g.mole

Trichloroethylene in gms

= 2.4045E-07 g.mole * 92.13/moles of trichloroethylene

= 3.159E-05 gm

Volume of Trichloroethylene

= 3.159E-05 gm/0.8623 x 10^{-3} gm/ml

= 0.0216 µl

This volume of pollutant needs to be injected per residence time.

Air Flow Rates:

3 Seconds

(19.6 ml. * 60 seconds)/(3 second * 1 minute)

= 392 ml/min

5 Seconds

(19.6 ml. * 60 seconds)/(5 second * 1 minute)

= 235.2 ml/min

10 Seconds

(19.6 ml. * 60 seconds)/(10 second * 1 minute)

= 117.6 ml/min

Inside Volume of Plumbing:

To calculate the inside volume of plumbing from the reactor to the point of effluent sampling the inside volume of following should be added together:

33 cm. of 2 cm. dia tube (the tube that connected the outlet of ACPR to the 0.635 cm. dia tube)	= 103.6 ml.
300 cm. of 0.635 cm. dia tube	= 95.0 ml.
250 ml. of effluent sampling port	= 250.0 ml.
Total	= 448.6 ml.

APPENDIX D

REGRESSION DATA FOR TRICHLOROETHYLENE AND TOLUENE

Regression Data for Trichloroethylene

```
                    Regression Statistics
               Multiple R                0.9998
               R Square                  0.9997
               Adjusted R Square         0.9996
               Standard Error            0.0020
               Observations                   5

                                Analysis of Variance
                                 Sum of     Mean             Significance
                          df     Squares    Square      F         F
Regression                 1      0.0363    0.0363   8975.30  2.5925E-06
Residual                   3    1.214E-05 4.047E-06
Total                      4      0.0363

                       Standard      t
             Coeff.     Error    Statistic  P-value  Lower 95% Upper 95%
Intercept   0.0002     0.0012     0.1979    0.8528   -0.0037    0.0042
x1          0.0007   7.564E-06   94.7381  7.443E-08   0.0007    0.0007
```

```
              Linear Regression Data for Toluene Caliberation

                         Regression Statistics

                    Multiple R              0.9999
                    R Square                0.9998
                    Adjusted R Square       0.9998
                    Standard Error          0.0053
                    Observations              7

                          Analysis of Variance

                                   Sum of     Mean            Significance
                         df        Squares    Square       F        F
Regression               1         0.7929     0.7929   28446.468 1.3902E-10
Residual                 5         0.0001   2.787E-05
Total                    6         0.7931

                     Standard       t
           Coeff.     Error     Statistic  P-value  Lower 95% Upper 95%
Intercept  -0.0019    0.0031     -0.6228    0.5563   -0.0099    0.0060
   x1       0.0023  1.3504E-05  168.6608  2.93E-12    0.0022    0.0023
```

APPENDIX E

PHYSICAL DATA OF TCE AND TOLUENE

TOLUENE

CHEMICAL FORMULA	C_7H_8	
MOLECULAR MASS	92.13	
CAS CHEMICAL NAME	PHENYLMETHANE	
CAS REGISTRY NO.	108-88-3	
MELTING POINT	-95 C	
BOILING POINT	110.6 C	
DENSITY	0.8669 g/ml	(20 C)
SPECIFIC GRAVITY	0.8623	(20 C)
VAPOR PRESSURE	28.7 mm Hg	(25 C)
FLASH POINT	4.4 C	
IONIZATION ENERGY	8.82 eV	

TRICHLOROETHYLENE

CHEMICAL FORMULA	C_2HCl_3	
MOLECULAR MASS	131.4	
CAS CHEMICAL NAME	TRICHLOROETHENE	
CAS REGISTRY NO.	79-01-6	
MELTING POINT	-84.8 C	
BOILING POINT	86.7 C	
SPECIFIC GRAVITY	1.46	(20 C)
VAPOR PRESSURE	57.8 mm Hg	(20 C)
IONIZATION POTENTIAL	9.47 eV	

APPENDIX F

PRESSURE DATA

MESONET CLIMATOLOGICAL DATA SUMMARY SEPTEMBER 1994 Time Zone: Midnight-Midnight CST
(STIL) STILLWATER Nearest City: 2 W STILLWATER County: PAYNE
Latitude: 36-07-16 Longitude: 97-05-42 Elevation: 892 feet

DAY	TEMPERATURE (°F)				DEG DAYS		HUMIDITY (%)			RAIN	PRESSURE (in)		WIND SPEED (mph)			SOLAR	PCT OF OBS PRESENT				
	MAX	MIN	AVG	DEWPT	HDD	CDD	MAX	MIN	AVG	(in)	STN	MSL	DIR	AVG	MAX	(MJ/m2)	T	RH	P	W	SOL
1	67	63	65.2	62.4	0	0	94	82	88	0.01	29.18	30.14	NNE	7.4	18.6	5.12	100	100	100	100	100
2	76	66	69.3	66.3	0	4	94	69	88	0.06	29.19	30.15	ESE	6.5	15.3	11.33	100	100	100	100	100
3	77	68	72.1	68.7	0	7	93	76	86	0.00	29.13	30.09	SE	8.2	20.3	8.55	100	100	100	100	100
4	91	72	80.1	69.8	0	15	90	39	68	0.00	29.00	29.95	SSE	10.5	28.4	23.62	100	100	100	100	100
5	79	70	73.8	69.3	0	9	93	68	83	0.38	29.08	30.04	SSE	5.7	22.5	9.91	100	100	100	100	100
6	84	60	72.7	65.3	0	8	94	38	76	0.01	29.22	30.18	NE	4.8	16.2	23.49	100	100	100	100	100
7	84	56	70.0	61.5	0	5	95	41	72	0.00	29.16	30.12	ESE	4.5	14.5	21.38	100	100	100	100	100
8	85	62	71.0	65.7	0	6	94	53	80	0.03	29.11	30.07	SSE	4.6	23.9	13.25	100	100	100	100	100
9	81	59	70.1	64.8	0	5	95	57	81	0.01	29.11	30.07	SE	4.1	17.1	16.69	100	100	100	100	100
10	84*	63*	72.0*	63.3*	0*	7*	94*	34*	72*	0.00	29.12*	30.08*	SE *	5.3*	20.3*	21.47*	99	99	99	99	99
11	86	61	72.9	65.3	0	8	93	47	74	0.00	29.15	30.11	SSE	6.0	21.8	21.71	100	100	100	100	100
12	87	65	76.0	67.8	0	11	93	50	72	0.00	29.15	30.11	SSE	6.7	21.1	20.25	100	100	100	100	100
13	88	69	78.3	69.3	0	13	89	49	70	0.00	29.11	30.06	S	8.1	22.1	17.79	100	100	100	100	100
14	89	72	79.4	69.4	0	14	83	48	67	0.00	29.04	30.00	S	9.1	26.0	21.69	100	100	100	100	100
15	81	69	74.5	70.0	0	10	94	64	83	1.33	29.00	29.95	S	5.2	17.4	8.74	100	100	100	100	100
16	82	55	69.6	58.1	0	5	94	29	64	0.00	29.13	30.08	N	6.2	23.8	19.83	100	100	100	100	100
17	82	51	64.9	53.1	0	0	93	25	65	0.00	29.19	30.15	W	4.6	23.4	23.41	100	100	100	100	100
18	80	49	63.6	55.0	1	0	94	37	72	0.00	29.20	30.16	W	3.0	16.1	22.79	100	100	100	100	100
19	82	51	65.9	57.4	0	1	94	37	73	0.00	29.18	30.14	ESE	3.3	16.1	22.59	100	100	100	100	100
20	83	56	69.6	60.0	0	5	94	39	69	0.00	29.10	30.05	SE	4.7	19.0	21.08	100	100	100	100	100
21	83	56	70.9	61.0	0	6	94	42	68	0.73	28.96	29.91	S	8.7	35.9	12.31	100	100	100	100	100
22	65	49	55.8	45.8	9	0	89	30	64	0.06	29.08	30.04	NW	8.9	38.1	18.37	100	100	100	100	100
23	61	44	51.7	43.8	13	0	91	47	68	0.00	28.85	29.80	NNW	7.7	25.0	11.65	100	100	100	100	100
24	66	46	54.2	46.1	11	0	92	40	70	0.00	29.02	29.98	NNW	6.9	23.8	16.10	100	100	100	100	100
25	80	46	62.2	52.7	3	0	93	28	69	0.00	29.03	29.98	NNW	6.2	27.9	18.31	100	100	100	100	100
26	82	51	64.6	53.4	0	0	93	33	63	0.00	28.89	29.84	W	3.4	14.2	21.14	100	100	100	100	100
27	83	49	65.5	55.8	0	0	94	35	69	0.00	28.93	29.88	ESE	4.2	16.7	20.60	100	100	100	100	100
28	89	53	69.7	60.4	0	5	94	30	72	0.00	28.97	29.93	ESE	3.5	15.1	20.45	100	100	100	100	100
29	93	53	74.4	60.9	0	9	95	23	62	0.00	28.95	29.90	S	5.7	22.4	20.70	100	100	100	100	100
30	89	64	75.6	58.1	0	11	67	24	48	0.00	28.91	29.87	S	9.8	30.9	20.48	100	100	100	100	100
	81	58	69.2*	60.7*	<- Monthly Averages ->						29.07*	30.03*	SSE*	6.1*	38.1*	17.83*	99	99	99	99	99

Temperature - Highest: 93*
Lowest: 44*

Degree Days - Total HDD: 38*
Total CDD: 163*

Rainfall: Monthly Total: 2.62 in.
Greatest 24 Hr: 1.33 in.

Humidity - Highest: 95*
Lowest: 23*

Number of Days With:
Tmax ≥ 90: 2*
Tmax ≤ 32: 0*
Tmin ≤ 32: 0*
Tmin ≤ 0: 0*
Rainfall ≥ 0.01 inch: 9
Rainfall ≥ 0.10 inch: 3
Avg Wind Speed ≥ 10 mph: 1*
Max Wind Speed ≥ 30 mph: 3*

* indicates incomplete record

MESONET CLIMATOLOGICAL DATA SUMMARY
(STIL) STILLWATER
Latitude: 36-07-16

OCTOBER 1994
Nearest City: 2 W STILLWATER
Longitude: 97-05-42

Time Zone: Midnight-Midnight CST
County: PAYNE
Elevation: 892 feet

DAY	TEMPERATURE (°F) MAX	MIN	AVG	DEWPT	DEG DAYS HDD	CDD	HUMIDITY (%) MAX	MIN	AVG	RAIN (in)	PRESSURE (in) STN	MSL	WIND SPEED (mph) DIR	AVG	MAX	SOLAR (MJ/m2)	PCT OF OBS PRESENT T	RH	P	W	SOL
1	87	57	73.0	60.8	0	8	92	36	61	0.00	28.85	29.80	S	6.2	21.1	19.51	100	100	100	100	100
2	85	60	72.7	61.5	0	8	88	38	63	0.08	28.76	29.71	ESE	6.4	19.1	16.67	100	100	100	100	100
3	84	65	74.0	66.0	0	9	91	52	72	0.33	28.91	29.86	E	7.6	23.4	15.07	100	100	100	100	100
4	85	64	73.6	65.2	0	9	92	41	71	0.12	29.16	30.12	NE	5.3	18.6	18.73	100	100	100	100	100
5	80	65	71.1	65.0	0	6	93	55	78	0.04	28.99	29.95	SE	6.5	21.9	10.33	100	100	100	100	100
6	84	70	76.2	62.4	0	11	69	40	55	0.00	28.76	29.70	S	14.4	38.7	15.63	100	100	100	100	100
7	75	54	63.1	56.8	2	0	92	52	76	0.47	28.93	29.88	NNW	8.3	22.8	2.60	100	100	100	100	100
8	68	44	57.6	48.5	7	0	92	29	69	0.00	29.15	30.11	NNW	8.8	26.8	18.20	100	100	100	100	100
9	71	39	53.3	42.5	12	0	93	24	67	0.01	29.29	30.25	N	3.1	17.7	20.10	100	100	100	100	100
10	70	37	52.3	42.0	13	0	94	27	68	0.00	29.27	30.23	W	2.9	15.3	19.63	100	100	100	100	100
11	71	35	52.7	41.9	12	0	94	25	65	0.00	29.17	30.13	W	2.8	12.6	19.31	100	100	100	100	100
12	74	37	55.5	48.7	10	0	94	48	75	0.00	29.06	30.02	E	3.0	19.1	18.05	100	100	100	100	100
13	74	48	62.4	55.5	3	0	95	48	75	0.00	29.12	30.08	NE	5.5	18.7	16.53	100	100	100	100	100
14	69	49	59.5	54.3	5	0	95	56	79	0.00	29.07	30.03	SE	5.7	15.3	10.06	100	100	100	100	100
15	62	58	59.8	57.3	5	0	92	83	89	0.21	28.89	29.84	SSE	10.8	25.0	2.07	100	100	100	100	100
16	70	61	66.0	63.7	0	1	94	86	90	0.01	28.95	29.91	SE	10.4	22.6	3.41	100	100	100	100	100
17	71	68	69.1	66.6	0	4	93	83	90	0.03	28.91	29.86	SSE	11.2	25.1	3.49	100	100	100	100	100
18	76	52	66.5	62.5	0	1	94	49	85	0.20	28.90	29.85	SSE	4.4	20.6	9.71	100	100	100	100	100
19	72	48	59.9	57.0	5	0	95	68	88	0.01	29.02	29.97	ENE	3.6	12.0	9.84	100	100	100	100	100
20	76	58	65.8	62.0	0	1	95	58	85	0.00	29.04	29.99	ESE	3.1	9.6	9.96	100	100	100	100	100
21	76	54	66.0	62.1	0	1	95	60	85	0.13	28.86	29.81	N	4.5	21.5	10.54	100	100	100	100	100
22	81	47	61.6	51.7	3	0	95	22	70	0.01	28.94	29.89	N	3.8	17.3	16.42	100	100	100	100	100
23	76	43	59.8	48.0	5	0	94	24	63	0.00	29.11	30.06	ESE	4.6	19.3	16.53	100	100	100	100	100
24	72	51	60.6	48.7	4	0	94	26	61	0.00	29.15	30.11	NNE	7.8	23.7	11.28	100	100	100	100	100
25	60	35	49.0	31.2	16	0	88	20	43	0.00	29.32	30.28	NNE	8.4	22.9	16.60	100	100	100	100	100
26	63	30	45.8	34.1	19	0	94	26	61	0.00	29.31	30.27	SE	2.5	12.1	16.61	100	100	100	100	100
27	68	34	51.7	38.5	13	0	88	28	55	0.00	29.16	30.12	SSE	6.1	21.2	16.04	100	100	100	100	100
28	67	45	55.4	46.9	10	0	78	51	67	0.00	29.01	29.96	SSE	8.8	28.7	9.40	100	100	100	100	100
29	66	50	57.9	51.7	7	0	86	61	75	0.00	29.03	29.99	SSE	4.5	17.1	4.68	100	100	100	100	100
30	68	56	61.0	56.7	4	0	93	64	82	0.02	29.03	29.98	S	3.1	15.5	4.60	100	100	100	100	100
31	59	38	50.7	45.9	14	0	94	51	80	0.38	29.07	30.02	NNW	8.5	41.3	10.12	100	100	100	100	100
	73	50	61.4	53.4	<- Monthly Averages ->						29.04	29.99	SE	6.2	41.3	12.64	100	100	100	100	100

Temperature - Highest: 87
Lowest: 30

Rainfall: Monthly Total: 2.04 in.
Greatest 24 Hr: 0.47 in.

Degree Days - Total HDD: 171
Total CDD: 59

Humidity - Highest: 95
Lowest: 20

Number of Days With:

Tmax ≥ 90:	0	Rainfall ≥ 0.01 inch:	15
Tmax ≤ 32:	0	Rainfall ≥ 0.10 inch:	7
Tmin ≤ 32:	1	Avg Wind Speed ≥ 10 mph:	4
Tmin ≤ 0:	0	Max Wind Speed ≥ 30 mph:	2

* indicates incomplete record

MESONET CLIMATOLOGICAL DATA SUMMARY NOVEMBER 1994 Time Zone: Midnight-Midnight CST
(STIL) STILLWATER Nearest City: 2 W STILLWATER County: PAYNE
Latitude: 36-07-16 Longitude: 97-05-42 Elevation: 892 feet

DAY	TEMPERATURE (°F) MAX	MIN	AVG	DEWPT	DEG DAYS HDD	CDD	HUMIDITY (%) MAX	MIN	AVG	RAIN (in)	PRESSURE (in) STN	MSL	WIND SPEED (mph) DIR	AVG	MAX	SOLAR (MJ/m2)	PCT OF OBS PRESENT T	RH	P	W	SOL
1	70	37	53.5	41.7	12	0	94	25	61	0.00	28.90	29.86	SSE	8.6	27.3	11.87	100	100	100	100	100
2	74	54	64.0	53.6	1	0	74	47	62	0.00	28.70	29.65	S	11.8	31.0	10.45	100	100	100	100	100
3	83	57	70.5	60.8	0	5	84	45	66	0.00	28.82	29.77	SSW	10.9	31.5	12.23	100	100	100	100	100
4	59	44	49.5	47.3	15	0	93	77	90	0.48	28.89	29.84	NNW	6.8	21.9	1.71	100	100	100	100	100
5	54	37	44.5	41.7	20	0	95	64	87	1.02	28.92	29.87	NW	6.9	24.0	4.98	100	100	100	100	100
6	70	33	49.8	41.8	15	0	95	33	72	0.00	29.22	30.18	ESE	3.1	13.1	14.97	100	100	100	100	100
7	72	43	57.3	48.7	8	0	87	45	68	0.00	29.12	30.08	SSE	8.6	26.4	13.11	100	100	100	100	100
8	80	53	66.1	58.9	0	1	88	51	73	0.14	28.90	29.85	SSE	8.6	27.7	10.00	100	100	100	100	100
9	53	41	46.8	42.1	18	0	92	68	79	0.52	29.14	30.10	NNW	10.2	29.4	3.81	100	100	100	100	100
10	57	39	46.9	41.4	18	0	93	55	76	0.00	29.25	30.21	E	6.2	14.8	12.23	100	100	100	100	100
11	60	40	50.3	43.9	15	0	94	51	74	0.00	29.18	30.14	SSE	5.8	17.0	11.51	100	100	100	100	100
12	58	43	50.8	45.2	14	0	89	61	77	0.00	29.07	30.03	SSE	10.3	24.1	8.95	100	100	100	100	100
13	65	57	61.3	57.3	4	0	94	66	83	0.14	28.93	29.88	S	10.2	26.4	1.55	100	100	100	100	100
14	61	48	53.7	49.9	11	0	95	64	83	0.01	29.17	30.13	NNE	6.5	18.6	4.78	100	100	100	100	100
15	58	33	47.1	40.1	18	0	93	42	72	0.00	29.37	30.34	N	8.3	26.5	12.12	100	100	100	100	100
16	61	28	44.7	37.0	20	0	95	35	72	0.01	29.18	30.14	SSE	4.8	18.5	13.84	100	100	100	100	100
17	60	44	53.4	48.9	12	0	90	45	81	0.00	28.85	29.80	S	9.6	26.4	2.39	100	100	100	100	100
18	65	28	47.9	37.5	17	0	94	25	64	0.05	29.14	30.10	ESE	4.8	17.3	12.25	100	100	100	100	100
19	55	51	52.8	50.8	12	0	95	80	91	1.36	29.06	30.02	ESE	10.6	31.2	0.74	100	100	100	100	100
20	60	42	51.9	43.2	13	0	95	27	68	1.45	28.65	29.60	SW	13.9	43.9	7.83	100	100	100	100	100
21	59	38	47.6	38.4	17	0	89	44	63	0.00	29.14	30.09	NNE	8.0	23.0	12.71	100	100	100	100	100
22	42	33	39.6	30.0	25	0	80	42	60	0.00	29.51	30.47	NE	10.1	24.9	2.37	100	100	100	100	100
23	50	27	37.5	30.7	28	0	94	39	72	0.00	29.59	30.56	SSW	2.9	14.0	11.61	100	100	100	100	100
24	54	35	45.6	40.1	19	0	84	63	76	0.00	29.23	30.19	S	8.4	26.2	5.35	100	100	100	100	100
25	51	46	48.3	44.3	17	0	90	73	82	0.00	29.13	30.09	ESE	4.6	13.2	2.77	100	100	100	100	100
26	61	48	52.9	51.2	12	0	95	86	92	0.02	28.81	29.76	SSE	8.3	20.5	2.54	100	100	100	100	100
27	67	35	52.2	40.8	13	0	90	31	58	0.00	28.71	29.65	WNW	12.2	44.0	12.22	100	100	100	100	100
28	59	26	39.0	28.8	26	0	91	18	63	0.00	28.99	29.94	W	4.5	27.5	12.58	100	100	100	100	100
29	51	23	34.9	27.3	30	0	93	33	71	0.00	29.30	30.26	NW	3.4	16.8	12.17	100	100	100	100	100
30	59*	22*	40.6*	27.4*	24*	0*	93*	22*	56*	0.00	29.34	30.30	SW	6.0	29.1	12.10	99	99	100	100	100
	61	39	50.0*	43.0*	<- Monthly Averages ->						29.07	30.03	SSE	7.8	44.0	8.59	99	99	100	100	100

Temperature - Highest: 83*
Lowest: 22*

Rainfall: Monthly Total: 5.19 in.
Greatest 24 Hr: 1.45 in.

Degree Days - Total HDD: 456*
Total CDD: 7*

Humidity - Highest: 95*
Lowest: 18*

Number of Days With:
Tmax ≥ 90: 0* Rainfall ≥ 0.01 inch: 11
Tmax ≤ 32: 0* Rainfall ≥ 0.10 inch: 7
Tmin ≤ 32: 6* Avg Wind Speed ≥ 10 mph: 9
Tmin ≤ 0: 0* Max Wind Speed ≥ 30 mph: 5

* indicates incomplete record

APPENDIX G

STATISTICAL DATA

Table E Upper 5 Percent of Studentized Range q^*

										p^{**}									
n_2	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
1	18.0	26.7	32.8	37.2	40.5	43.1	45.4	47.3	49.1	50.6	51.9	53.2	54.3	55.4	56.3	57.2	58.0	58.8	59.6
2	6.09	8.28	9.80	10.89	11.73	12.43	13.03	13.54	13.99	14.39	14.75	15.08	15.38	15.65	15.91	16.14	16.36	16.57	16.77
3	4.50	5.88	6.83	7.51	8.04	8.47	8.85	9.18	9.46	9.72	9.95	10.16	10.35	10.52	10.69	10.84	10.98	11.12	11.24
4	3.93	5.00	5.76	6.31	6.73	7.06	7.35	7.60	7.83	8.03	8.21	8.37	8.52	8.67	8.80	8.92	9.03	9.14	9.24
5	3.61	4.54	5.18	5.64	5.99	6.28	6.52	6.74	6.93	7.10	7.25	7.39	7.52	7.64	7.75	7.86	7.95	8.04	8.13
6	3.46	4.34	4.90	5.31	5.63	5.89	6.12	6.32	6.49	6.65	6.79	6.92	7.04	7.14	7.24	7.34	7.43	7.51	7.59
7	3.34	4.16	4.68	5.06	5.35	5.59	5.80	5.99	6.15	6.29	6.42	6.54	6.65	6.75	6.84	6.93	7.01	7.08	7.16
8	3.26	4.04	4.53	4.89	5.17	5.40	5.60	5.77	5.92	6.05	6.18	6.29	6.39	6.48	6.57	6.65	6.73	6.80	6.87
9	3.20	3.95	4.42	4.76	5.02	5.24	5.43	5.60	5.74	5.87	5.98	6.09	6.19	6.28	6.36	6.44	6.51	6.58	6.65
10	3.15	3.88	4.33	4.66	4.91	5.12	5.30	5.46	5.60	5.72	5.83	5.93	6.03	6.12	6.20	6.27	6.34	6.41	6.47
11	3.11	3.82	4.26	4.58	4.82	5.03	5.20	5.35	5.49	5.61	5.71	5.81	5.90	5.98	6.06	6.14	6.20	6.27	6.33
12	3.08	3.77	4.20	4.51	4.75	4.95	5.12	5.27	5.40	5.51	5.61	5.71	5.80	5.88	5.95	6.02	6.09	6.15	6.21
13	3.06	3.73	4.15	4.46	4.69	4.88	5.05	5.19	5.32	5.43	5.53	5.63	5.71	5.79	5.86	5.93	6.00	6.06	6.11
14	3.03	3.70	4.11	4.41	4.64	4.83	4.99	5.13	5.25	5.36	5.46	5.56	5.64	5.72	5.79	5.86	5.92	5.98	6.03
15	3.01	3.67	4.08	4.37	4.59	4.78	4.94	5.08	5.20	5.31	5.40	5.49	5.57	5.65	5.72	5.79	5.85	5.91	5.96
16	3.00	3.65	4.05	4.34	4.56	4.74	4.90	5.03	5.15	5.26	5.35	5.44	5.52	5.59	5.66	5.73	5.79	5.84	5.90
17	2.98	3.62	4.02	4.31	4.52	4.70	4.86	4.99	5.11	5.21	5.31	5.39	5.47	5.55	5.61	5.68	5.74	5.79	5.84
18	2.97	3.61	4.00	4.28	4.49	4.67	4.83	4.96	5.07	5.17	5.27	5.35	5.43	5.50	5.57	5.63	5.69	5.74	5.79
19	2.96	3.59	3.98	4.26	4.47	4.64	4.79	4.92	5.04	5.14	5.23	5.32	5.39	5.46	5.53	5.59	5.65	5.70	5.75
20	2.95	3.58	3.96	4.24	4.45	4.62	4.77	4.90	5.01	5.11	5.20	5.28	5.36	5.43	5.50	5.56	5.61	5.66	5.71
24	2.92	3.53	3.90	4.17	4.37	4.54	4.68	4.81	4.92	5.01	5.10	5.18	5.25	5.32	5.38	5.44	5.50	5.55	5.59
30	2.89	3.48	3.84	4.11	4.30	4.46	4.60	4.72	4.83	4.92	5.00	5.08	5.15	5.21	5.27	5.33	5.38	5.43	5.48
40	2.86	3.44	3.79	4.04	4.23	4.39	4.52	4.63	4.74	4.82	4.90	4.98	5.05	5.11	5.17	5.22	5.27	5.32	5.36
60	2.83	3.40	3.74	3.98	4.16	4.31	4.44	4.55	4.65	4.73	4.81	4.88	4.94	5.00	5.06	5.11	5.15	5.20	5.24
120	2.80	3.36	3.69	3.92	4.10	4.24	4.36	4.47	4.56	4.64	4.71	4.78	4.84	4.90	4.95	5.00	5.04	5.09	5.13
∞	2.77	3.32	3.63	3.86	4.03	4.17	4.29	4.39	4.47	4.55	4.62	4.68	4.74	4.80	4.84	4.89	4.93	4.97	5.01

[*] From J. M. May, "Extended and Corrected Tables of the Upper Percentage Points of the Studentized Range," *Biometrika*, vol. 39 (1952), pp. 192–193.

[**] p is the number of quantities (for example, means) whose range is involved. n_2 is the degrees of freedom in the error estimate.

Test 1

Statistics test on

Feasibility of Parafilm as a subtitute of Plastic Cap

(Data Contained in Table 9)

Time (Min)	Areas from the GC	
	Plastic Cap	Parafilm
5	0.199	0.2
10	0.208	0.209
15	0.212	0.211
20	0.215	0.216
25	0.217	0.217
30	0.217	0.217
35	0.218	0.218
40	0.217	0.218
45	0.218	0.217

Anova: Single-Factor

Summary

Groups	Count	Sum	Average	Variance
Column 1	9	1.92	0.21	4.03E-05
Column 2	9	1.92	0.21	3.65E-05

	SS	df	MS	F	P-value	F crit
Between Groups	2.22E-07	1	2.22E-07	0.01	0.94	4.49

Test 2
Statistics test on
Feasibility of Parafilm as a subtitute of Plastic Cap
(Data Contained in Table 10)

Time	Areas from the GC	
(Min)	Plastic Cap	Parafilm
5	0.622	0.618
10	0.635	0.632
15	0.651	0.651
20	0.665	0.666
25	0.674	0.675
30	0.682	0.681
35	0.682	0.68
40	0.681	0.681
45	0.682	0.681

Anova: Single-Factor
Summary

Groups	Count	Sum	Average	Variance
Column 1	9	5.974	0.66	0.001
Column 2	9	5.965	0.66	0.001

	SS	df	MS	F	P-value	F crit
Between Groups	4.5E-06	1	4.5E-06	0.008	0.929	4.494

Test 3
Statistics test on
Effect of Residence Time on Destruction of TCE
(Data Contained in Table 14)

Relative Humidity = 20%
Temperature = 50 F
100% = 300 ppm

Time (Min)	% Parts Per Million in Effluent at Different Residence Times 3 Sec	5 sec	10 sec
5	100.79	100.79	101.30
10	42.51	56.09	36.79
15	15.21	18.33	16.00
20	7.16		
25		1.63	5.67
30	4.42	4.60	4.28
35	4.37	7.77	5.16
40			
45	6.33	4.79	5.12
50	2.79	3.67	6.84
55			
60	1.07	2.88	3.16
65	0.98	2.93	3.07

Anova: Single-Factor for T = 35 Min to T= 65 Min
Alpha = 0.05
Summary

Groups	Count	Sum	Average	Variance
Column 1	6.00	19.95	3.33	4.44
Column 2	6.00	26.65	4.44	3.30
Column 3	6.00	27.63	4.60	2.02

Source of Variation

	SS	df	MS	F	P-value	F crit
Between Groups	5.82	2.00	2.91	0.89	0.43	3.68

Test 4
Statistics test on
Effect of Residence Time on Destruction of Toluene
(Data Contained in Table 15)

Relative Humidity = 20%
Temperature = 50F
100%=300ppm

Time (Min)	% Parts Per Million in Effluent at Different Residence Times 3sec	 5sec	 10sec
5	101.04	99.29	99.87
10	49.13	47.34	50.66
15	12.18	10.49	16.49
20			
25	9.65	8.28	16.68
30	8.62	6.74	10.99
35			7.82
40	6.19	6.63	8.84
45	6.37	5.40	6.04
50			
55	6.35	4.75	4.69
60	6.32	6.06	6.32
65	58.98		4.57

Anova: Single-Factor for T = 35 Min to T = 65 Min
Alpha = 0.05
Summary

Groups	Count	Sum	Average	Variance
Column 1	5	33.85	6.77	1.07
Column 2	5	29.58	5.92	0.71
Column 3	6	44.71	7.45	5.08

Source of Variation

	SS	df	MS	F	P-value	F crit
Between Groups	6.43	2.00	3.22	1.28	0.31	3.81

Test 5
Statistics Test on
Effect of Residence Time on the Destruction of Toluene and TCE
(Data Contained in Table 14 and 15)

Relative Humidity = 20 %
Temperature = 50 F
100% = 300ppm

% Parts Per Million in Effluent
at Different Residence Times

Time		Toluene			TCE	
(Min)	3sec	5sec	10sec	3sec	5sec	10sec
5	101.04	99.29	99.87	100.79	100.79	101.30
10	49.13	47.34	50.66	42.51	56.09	36.79
15	12.18	10.49	16.49	15.21	18.33	16.00
20				7.16		
25	9.65	8.28	16.68		1.63	5.67
30	8.62	6.74	10.99	4.42	4.60	4.28
35			7.82	4.37	7.77	5.16
40	6.19	6.63	8.84			
45	6.37	5.40	6.04	6.33	4.79	5.12
50				2.79	3.67	6.84
55	6.35	4.75	4.69			
60	6.32	6.06	6.32	1.07	2.88	3.16
65	58.98		4.57	0.98	2.93	3.07

Anova: Single-Factor for T = 35 Min to T = 65 Min
Alpha = 0.05
Summary

Groups	Count	Sum	Average	Variance
Column 1	5	84.21	16.84	554.79
Column 2	4	22.84	5.71	0.66
Column 3	6	38.29	6.38	2.87
Column 4	5	15.53	3.11	5.19
Column 5	5	22.05	4.41	4.12
Column 6	5	23.35	4.67	2.49

Source of Variation

	SS	df	MS	F	P-value	F crit
Between Groups	629.34	5.00	125.87	1.32	0.29	2.62

Test 6
Statistics Test on
Effect of Relative Humidity on the Destruction of TCE
(Data Contained in Table 16)

Residence Time = 5 sec
Temperature = 50 F
100% = 300ppm

Time (Min)	% Parts Per Million at Different Effluent Relative Humudities 20%	40%	80%
5	100.79	100.32	99.47
10	56.09	58.93	59.95
15	18.33	22.14	28.47
20			
25	1.63	17.95	23.86
30	4.60	14.47	22.65
35	7.77	12.51	
40			22.09
45	4.79	10.05	
50	3.67	8.98	20.98
55			
60	2.88	8.79	21.16
65	2.93	8.09	20.84

Anova: Single-Factor for T = 35 Min to T = 65 Min
Alpha = 0.05
Summary

Groups	Count	Sum	Average	Variance
Column 1	5	23.72	4.74	3.44
Column 2	5	54.79	10.96	6.04
Column 3	4	86.88	21.72	0.62

Source of Variation

	SS	df	MS	F	P-value	F crit
Between Groups)	646.1629	2	323.081	89.286	1.58E-07	3.982
Within Groups)	39.80357	11	3.619			

Newman-Keuls Method for the TCE Humidities

STEP 1 Mean of Three Humidities

20%	40%	80%
4.744	10.958	21.721

STEP 2 Error Mean Square is 3.619 with 11 degrees of freedom:

STEP 3 $\sqrt{3.619/3}$ = 1.1

STEP 4 From Table E (in Appendix G) the Significant Ranges at 5 % and n2=11 are:

1	2	3
RANGES	3.15	3.88

STEP 5 Multiplying the Std. Error of 1.1 the Least Significant Ranges (LSR) are:

P	2	3
LSR	3.47	4.27

STEP 6

LARGEST VS SMALLEST	21.721	>	4.27
LARGEST VS NEXT SMALLEST	4.744	>	3.47
SECOND LARGEST VERSUS SMALLEST	10.958	>	4.27

From these results the 20%, 40%, and 80 % curves are significantly different from each other.

Test 7
Statistics Test on
Effect of Relative Humidity on the Destruction of Toluene
(Data Contained in Table 17)

Residence Time = 5 sec
Temperature = 50 F
100 % = 300 ppm

Time (Min)	% Parts Per Million Effluent at Different Relative Humudities 20%	40%	80%
5	99.294	100.473	99.740
10	47.338	57.647	72.397
15	10.485	26.926	34.074
20			
25	8.279	24.574	28.279
30	6.738	22.559	29.588
35			
40	6.632	22.853	27.750
45	5.397	21.044	27.132
50			
55	4.750	20.574	27.985
60	6.059	20.235	26.279

Anova: Single-Factor for T = 35 Min to T = 60 Min
Alpha = 0.05
Summary

Groups	Count	Sum	Average	Variance
Column 1	4	22.838	5.710	0.664
Column 2	4	84.706	21.176	1.359
Column 3	4	109.147	27.287	0.580

Source of Variation

	SS	df	MS	F	P-value	F crit
Between Groups)	989.5158	2	494.758	570.107	3.33E-10	4.256
Within Groups)	7.8105	9	0.868			

Newman-Keuls Method for the Toluene Humidities

STEP 1 Mean of the three humidities:

20%	40%	80%
5.71	21.18	27.29

STEP 2 Error Mean Square is 0.868 with 9 degrees of freedom:

STEP 3 $\sqrt{0.868/3} = 0.537$

STEP 4 From Table E (in Appendix G) the significant ranges at 5 % and n2 = 9 are:

1	2	3
RANGES	3.2	3.95

STEP 5 Multiplying the Std. Error of 0.537 the Least Significant Ranges (LSR) are:

P	2	3
LSR	1.72	2.12

STEP 6

LARGEST VS SMALLEST	21.57	>	2.12
LARGEST VS NEXT SMALLEST	6.11	>	1.72
SECOND LARGEST VERSUS SMALLEST	15.46	>	2.12

From these results the 20%, 40%, and 80 % curves are significantly different from each other.

Test 8
Statistics Test on
Effect of Relative Humidity on the Destruction of Toluene and Trichloroethylene
(Data Contained in Table 16 and 17)

Residence Time = 5 sec
Temperature = 50 F
100 % = 300 ppm

% Parts Per Million in Effluent
at Different Residence Times

Time		Toluene			TCE	
(Min)	20%	40%	80%	20%	40%	80%
5	99.29	100.47	99.74	100.79	100.32	99.47
10	47.34	57.65	72.40	56.09	58.93	59.95
15	10.49	26.93	34.07	18.33	22.14	28.47
20						
25	8.28	24.57	28.28	1.63	17.95	23.86
30	6.74	22.56	29.59	4.60	14.47	22.65
35				7.77	12.51	
40	6.63	22.85	27.75			22.09
45	5.40	21.04	27.13	4.79	10.05	
50				3.67	8.98	20.98
55	4.75	20.57	27.99			
60	6.06	20.24	26.28	2.88	8.79	21.16
65				2.93	8.09	20.84

Anova: Single-Factor for T = 35 Min to T = 65 Min
Alpha = 0.05
Summary

Groups	Count	Sum	Average	Variance
Column 1	4	22.84	5.71	0.66
Column 2	4	84.71	21.18	1.36
Column 3	4	109.15	27.29	0.58
Column 4	5	22.05	4.41	4.12
Column 5	5	48.42	9.68	2.99
Column 6	4	85.07	21.27	0.32

Source of Variation

	SS	df	MS	F	P-value	F crit
Between) Groups)	1948.83	5	389.77	209.47	1.48E-16	2.71
Within) Groups)	37.21	20	1.86			

Neumann-Keuls Method for the Toluene and TCE Humidities

STEP 1 Mean of 6 Humidity Curves

B	D	F	A	C	E
20%	40%	80%	20%	40%	80%
5.71	21.18	27.29	4.41	9.68	21.27

STEP 2 Error Mean Square is 1.86 with 20 degrees of freedom:

STEP 3 $\sqrt{1.86/3} = 0.8$

STEP 4 From Table E (in Appendix G) the significant ranges at 5 % and n2 = 20 are:

1	2	3	4	5	6
RANGES	2.95	3.58	3.96	4.24	4.45

STEP 5 Multiplying the Std. Error of 0.8 the Least Significant Ranges (LSR) are:

P	2	3	4	5	6
LSR:	2.36	2.86	3.17	3.39	3.56

STEP 6

LARGEST VS SMALLEST	A-B	1.30	<	3.56
LARGEST VS 2ND SMALLEST	A-C	5.27	>	3.39
LARGEST VS 3RD SMALLEST	A-D	16.77	>	3.17
LARGEST VS 4TH SMALLEST	A-E	16.86	>	2.86
LARGEST VS 5TH SMALLEST	A-F	22.88	>	2.36
2ND LARGEST VS SMALLEST	B-C	3.97	>	3.39
2ND LARGEST VS 2ND SMALLEST	B-D	15.47	>	3.17
2ND LARGEST VS 3RD SMALLEST	B-E	15.56	>	2.86
2ND LARGEST VS 4TH SMALLEST	B-F	21.58	>	2.36
3RD LARGEST VS SMALLEST	C-D	11.50	>	3.17
3RD LARGEST VS 2ND SMALLEST	C-E	11.59	>	2.86
3RD LARGEST VS 3RD SMALLEST	C-F	17.61	>	2.36
4TH LARGEST VS SMALLEST	D-E	0.09	<	2.86
4TH LARGEST VS 2ND SMALLEST	D-F	6.11	>	2.36
5TH LARGEST VS SMALLEST	E-F	6.02	>	2.36

From the above results all six means are significantly diffrent from each other, except 20 % curve of toluene is not significantly different from 20% curve of TCE and 40% curve of toluene is not significantly different from 80% curve of TCE.

Test 9
Statistics Test on
Effect of Frequency on Destruction of Toluene and Trichloroethylene
(Data Contained in Table 18)

Residence Time = 5sec
Temperature = 60 F
100 % = 148 ppm

Frequency (Hz)	% Alteration TCE	Toluene
200	0	0
400	0	0
600	12.45	10.38
800	98.7	93.4
1000	10	13.23

Anova: Single-Factor
Alpha = 0.05
Summary

Groups	Count	Sum	Average	Variance
Column 1	5	121.15	24.23	1765.29
Column 2	5	117.01	23.40	1567.01

Source of Variation

	SS	df	MS	F	P-value	F crit
Between Groups)	1.72	1.00	1.72	0.0010	0.98	5.32

Test 10
Statistics Test on
Effect of Frequency on Destruction of Toluene and Trichloroethylene
(Data Contained in Table 19)

Residence Time = 5sec
Temperature = 60 F
100 % = 200 ppm

Frequency (Hz)	% Destruction TCE	% Destruction Toluene
200	0	0
400	0	0
600	10.23	12.04
800	99.02	94.2
1000	9.66	14.5

Anova: Single-Factor
Alpha = 0.05
Summary

Groups	Count	Sum	Average	Variance
Column 1	5	118.91	23.782	1793.753
Column 2	5	120.74	24.148	1578.306

Source of Variation

	SS	df	MS	F	P-value	F crit
Between Groups)	0.3349	1.0000	0.3349	0.0002	0.9891	5.3176

Test 11
Statistics Test on Reproducibilty of Results for Three Separate Duplicates
(Data Contained in Table 21)

Time	% Parts Per Million					
(Min)	Effluent			Influent		
	I	II	III	I	II	III
0				100.5601	100.0365	99.9394
5	100.0721	99.9312	100.1153			
10	44.0449	40.0365	41.5607			
15	16.1165	14.7387	15.5199			
20	8.0855	6.9952	8.0203			
25				101.7712	100.1117	102.7907
30	3.9756	4.2154	4.5241			
35	3.9874	3.4328	4.3222			
40				100.2171	105.4598	101.3636
45	4.2853	3.2411	3.5143			
50	2.4593	3.7529	2.0833			
55				99.4238	100.4326	99.7544
60	1.5338	1.8631	1.1757			
65	1.5954	1.4623	1.0203			
70				102.4311	100.6046	99.2276
75	1.5429	1.4361	1.2134			
80	1.5344	1.6742	1.4123			
85	1.4991	1.4731	1.1612			
90	1.5186	1.4634	1.8034			

Anova: Single-Factor for T = 35 to T = 90
Alpha = 0.05
Summary

Groups	Count	Sum	Average	Variance
Column 1	9	19.96	2.22	1.28
Column 2	9	19.80	2.20	0.95
Column 3	9	17.71	1.97	1.38

Source of Variation

	SS	df	MS	F	P-value	F crit
Between Groups	0.35	2	0.18	0.15	0.87	3.40

APPENDIX H

COLLECTED DATA

Table 6

Effect of Frequency and Primary Voltage on Power Consumed by the Circuit (Watt)

Relative Humidity = 80 %
Temperature = 67 F

Frequency (Hz)	@30V	@40V	@50V	@60V	@70V
200	68.4276	82.4881	93.7365	106.86	133.106
250	66.5529	83.4255	99.3607	113.421	142.479
300	72.1771	92.7991	113.421	136.855	176.225
350	87.1749	113.421	147.166	173.413	225.905
400	103.11	140.605	176.225	206.22	267.149
450	119.983	159.352	202.471	240.903	325.266
500	139.667	190.285	243.715	311.205	420.877
550	171.538	239.028	307.456	422.752	575.542
600	211.844	309.33	409.629	532.423	721.771
650	261.525	396.505	525.862	628.972	769.577
700	332.765	486.492	584.916	676.778	769.577
750	389.944	524.924	608.35	691.775	753.641
800	408.691	530.549	609.287	682.402	721.771
850	397.443	511.801	593.352	664.592	688.026
900	373.071	485.555	562.419	630.847	649.594
950	334.639	448.998	522.112	589.603	614.911
1000	296.207	393.693	476.181	546.484	583.978
1050	253.089	345.888	424.626	493.054	541.797
1100	225.905	300.894	373.071	442.436	503.365
1150	202.471	269.024	332.765	398.38	459.309
1200	182.786	240.903	300.894	358.073	418.065

Table 7

Effect of Frequency and Primary Voltage on Secondary Voltage (Volts x 2000)

Humidity = 80 %
Temperature = 67 F

Frequency (Herz)	@30V	@40V	@50V	@60V	@70V
50	2.46	3.33	3.88	4.9	5.5
55	2.51	3.35	3.88	4.9	5.55
60	2.51	3.35	3.89	4.9	5.56
65	2.51	3.36	3.93	4.9	5.55
70	2.49	3.35	3.92	4.92	5.56
75	2.49	3.34	3.92	4.93	5.57
80	2.49	3.33	3.91	4.91	5.57
90	2.47	3.32	3.89	4.89	5.54
100	2.46	3.28	3.87	4.83	5.53
110	2.44	3.25	3.87	4.78	5.51
120	2.41	3.21	3.85	4.75	5.48
130	2.38	3.18	3.84	4.67	5.46
140	2.36	3.15	3.81	4.69	5.43
150	2.33	3.12	3.79	4.65	5.41
175	2.28	3.04	3.75	4.49	5.34
200	2.22	2.96	3.68	4.44	5.28
250	2.11	2.84	3.57	4.32	5.16
300	2.04	2.74	3.52	4.24	5.14
350	1.99	2.7	3.5	4.21	5.11
400	1.97	2.68	3.5	4.2	5.09
450	1.93	2.67	3.5	4.24	5.12
500	1.96	2.69	3.58	4.44	5.25
550	2.01	2.82	3.8	4.66	5.31
600	2.09	3.04	4.08	4.73	5.02
650	2.22	3.27	4.11	4.56	4.65
700	2.39	3.27	3.91	4.11	4.25
750	2.41	3.08	3.52	3.7	3.9
800	2.22	2.75	3.1	3.27	3.45
850	1.94	2.43	2.8	2.95	3.2
900	1.68	2.15	2.47	2.66	2.9
950	1.34	1.87	2.16	2.34	2.58
1000	1.04	1.44	1.81	2.06	2.14
1050	0.78	1.14	1.49	1.69	1.79
1100	0.63	0.89	1.18	1.41	1.54
1150	0.52	0.73	0.97	1.17	1.33
1200	0.44	0.6	0.81	0.97	1.13

Table 8

Effect of Primary Voltage and Frequency
on Current (Amperes) Consumed by the Circuit

Relative Humidity = 80 %
Temperature = 67 F

Frequency (Hz)	@30V	@40V	@50V	@60V	@70V
50	1.10903	0.0115	1.62657	2.02911	2.56308
55	1.06795	0.01076	1.48692	1.84838	2.21805
60	1.01045	1.24047	1.37191	1.67586	2.03732
65	0.96116	1.16653	1.3144	1.57728	1.86481
70	0.9283	1.13367	1.22404	1.48692	1.75801
75	0.89544	1.06795	1.19118	1.38834	1.643
80	0.87079	1.04331	1.1501	1.32262	1.55264
90	0.82972	0.9858	1.06795	1.21582	1.42941
100	0.78864	0.93651	1.01866	1.15832	1.35548
110	0.74757	0.88722	0.96937	1.10903	1.29797
120	0.72292	0.84615	0.9283	1.05974	1.24868
130	0.69828	0.8215	0.90365	1.05974	1.20761
140	0.67363	0.79686	0.87079	0.9858	1.17475
150	0.6572	0.77221	0.84615	0.96937	1.15832
175	0.61613	0.73114	0.80507	0.9283	1.14189
200	0.5997	0.72292	0.8215	0.93651	1.16653
250	0.58327	0.73114	0.87079	0.99402	1.24868
300	0.63256	0.81329	0.99402	1.19939	1.54442
350	0.764	0.99402	1.28976	1.51978	1.97982
400	0.90365	1.23225	1.54442	1.8073	2.34128
450	1.05152	1.39655	1.77444	2.11126	2.85061
500	1.22404	1.66765	2.1359	2.72738	3.68854
550	1.50335	2.09483	2.69452	3.70497	5.04401
600	1.85659	2.71095	3.58996	4.66612	6.32555
650	2.29199	3.47495	4.60862	5.51227	6.74452
700	2.91633	4.26359	5.12616	5.93123	6.74452
750	3.41744	4.6004	5.33154	6.06267	6.60486
800	3.58174	4.64969	5.33975	5.98052	6.32555
850	3.48316	4.48539	5.2001	5.82444	6.02981
900	3.26957	4.25537	4.929	5.5287	5.693
950	2.93276	3.93499	4.57576	5.16724	5.38904
1000	2.59594	3.4503	4.17322	4.78935	5.11795
1050	2.21805	3.03134	3.7214	4.32109	4.74827
1100	1.97982	2.63702	3.26957	3.87748	4.41146
1150	1.77444	2.35771	2.91633	3.49138	4.02535
1200	1.60193	2.11126	2.63702	3.13813	3.66389

Table 9

Calibration Data for Trichloroethylene
Theoretical
Values

Time (min)	Areas from the GC
5	0.199
10	0.205
15	0.212
20	0.215
25	0.217
30	0.216
35	0.217
40	0.217
45	0.217

Table 10

Calibration Data for Toluene

Time (min)	Theoretical Value	Areas from the GC
5		0.61
10		0.635
15		0.647
20		0.663
25		0.679
30		0.681
35		0.682
40		0.68
45		0.682

Table 11

Feasibility of Parafilm for Calibration Data of TCE

Time (Min)	Areas from the GC	
	Plastic Cap	Parafilm
5	0.199	0.2
10	0.208	0.209
15	0.212	0.211
20	0.215	0.216
25	0.217	0.217
30	0.217	0.217
35	0.218	0.218
40	0.217	0.218
45	0.218	0.217

Table 12

Feasibility of Parafilm for Calibration Data of Toluene

Time	Areas from the GC	
(Min)	Plastic Cap	Parafilm
5	0.622	0.618
10	0.635	0.632
15	0.651	0.651
20	0.665	0.666
25	0.674	0.675
30	0.682	0.681
35	0.682	0.68
40	0.681	0.681
45	0.682	0.681

Table 13

Feasibility of Parafilm for Calibration Data of TCE*

Time (Min)	Areas from the GC
30	0.218
35	0.217
40	0.218
45	0.216

* From the same bottle with parafilm

Table 14

Effect of Residence Time of Three, Five, and Ten Seconds on Destruction of Trichloroethylene

Relative Humidity = 20 %
Temperature = 50 F
100 % = 300 ppm

Time	% Parts Per Million					
	3 Seconds		5 Seconds		10 Seconds	
(Min)	Effluent	Influent	Effluent	Influent	Effluent	Influent
0		100.42		104.70		103.21
5	100.79		100.79		101.30	
10	42.51		56.09		36.79	
15	15.21		18.33		16.00	
20	7.16			99.30		108.37
25		102.79	1.63		5.67	
30	4.42		4.60		4.28	
35	4.37		7.77		5.16	
40		111.26		102.37		103.77
45	6.33		4.79		5.12	
50	2.79		3.67		6.84	
55		98.47		107.86		100.28
60	1.07		2.88		3.16	
65	0.98		2.93		3.07	
70		100.60		101.30		102.23
75	17.35		63.07		5.95	
80	46.14		79.49		18.19	
85	94.60		97.16		33.53	
90		99.16	101.67		100.28	
95	99.77			100.74		101.77

Table 15

Effect of Residence Time of Three, Five, and Ten Seconds on Destruction of Toluene

Relative Humidity = 20 %
Temperature = 50 F
100 % = 300 ppm

Time	% Parts Per Million					
	3 Seconds		5 Seconds		10 Seconds	
(Min)	Effluent	Influent	Effluent	Influent	Effluent	Influent
0		99.15		99.15		101.35
5	101.04		99.29		99.87	
10	49.13		47.34		50.66	
15	12.18		10.49		16.49	
20		97.22		97.22		101.35
25	9.65		8.28		16.68	
30	8.62		6.74		10.99	
35		99.83		99.30	7.82	100.25
40	6.19		6.63		8.84	
45	6.37		5.40		6.04	
50		101.22		101.22		101.22
55	6.35		4.75		4.69	
60	6.32		6.06		6.32	
65	58.98			101.04	4.57	
70	75.03		63.87			100.79
75		101.12	70.76		51.85	
80	91.07		82.53		62.04	
85	97.04		89.87		94.60	
90	101.12			99.16	100.19	
95		100.64	96.57			101.04

Table 16

Effect of Relative Humidities of 20 , 40 , and 80 Percent on the Destruction of Trichloroethylene

Residence Time = 5 sec
Temperature = 50 F
100 % = 300 ppm

Time	% Parts Per Million					
	3 Seconds		5 Seconds		10 Seconds	
(Min)	Effluent	Influent	Effluent	Influent	Effluent	Influent
0		104.70		99.56		100.11
5	100.79		100.32		99.47	
10	56.09		58.93		59.95	
15	18.33		22.14		28.47	
20		99.30		100.24		100.26
25	1.63		17.95		23.86	
30	4.60		14.47		22.65	
35	7.77		12.51			100.10
40		102.37		99.28	22.09	
45	4.79		10.05			99.12
50	3.67		8.98		20.98	
55		107.86		100.05		100.05
60	2.88		8.79		21.16	
65	2.93		8.09		20.84	
70		101.30		100.53		100.48
75	63.07		65.10		55.04	
80	79.49		82.09		78.49	
85	97.16		93.22		84.30	
90	101.67		99.00		98.05	
95		100.74		99.39		98.98

Table 17

Effect of Relative Humidities of 20 , 40 , and 80 Percent on the Destruction of Toluene

Residence Time = 5 sec
Temperature = 50 F
100 % = 300 ppm

	% Parts Per Million					
Time (Min)	20 Percent		40 Percent		80 Percent	
	Effluent	Influent	Effluent	Influent	Effluent	Influent
0		99.15		100.28		99.86
5	99.29		100.47		99.74	
10	47.34		57.65		72.40	
15	10.49		26.93		34.07	
20		97.22		100.53		99.38
25	8.28		24.57		28.28	
30	6.74		22.56		29.59	
35		99.30		99.60		98.60
40	6.63		22.85		27.75	
45	5.40		21.04		27.13	
50		101.22		100.47		99.74
55	4.75		20.57		27.99	
60	6.06		20.24		26.28	
65		101.04		100.33		101.54
70	63.87		68.98		72.72	
75	70.76		75.03		76.84	
80	82.53		78.10		86.62	
85	89.87		86.63		89.72	
90		99.16		99.47		100.54
100	96.57		98.03		97.29	

Table 18

Effect of Frequency on Percent Destruction of TCE and Toluene Mixture

Residence Time = 5sec
Temperature = 60 F

100 % = 148 ppm

Frequency (Herz)	TCE (%)	Toluene (%)
200	0	0
400	0	0
600	12.45	10.38
800	98.7	93.4
1000	10	13.23

Table 19

Effect of Frequency on Percent Destruction
TCE and Toluene Mixture

Residence Time = 5sec
TCE = 200 ppm
Toluene = 200 ppm

Frequency Herz	TCE %	Toluene %
200	0	0
400	0	0
600	10.23	12.04
800	99.02	94.2
1000	9.66	14.5

Table 20

Power Over a Single Run

Trichloroethylene
Relative Humidity = 20%
Temperature = 45 F
Residence Time = 3 seconds
Primary Voltage = 40 Volts
Frequency = 800 Hertz

Time (Min)	Power (Watts)	Current (Amperes)
0	512.6	4.66
5	495	4.5
10	493.9	4.49
15	493.9	4.49
20	492.8	4.48
25	489.5	4.45
35	488.4	4.44
40	489.5	4.45
45	490.6	4.46
50	489.5	4.45
55	489.5	4.45
60	490.6	4.46

Table 21

Reproducibilty of Results for Three Separate Duplicates
(Trichloroethylene Destruction Data)

Relative Humidity = 20 %
Temperature = 54 F
Residence Time = 3 sec
300 ppm = 100 %

Time (Min)	% Parts Per Million					
	Effluent			Influent		
	I	II	III	I	II	III
0				100.56	100.04	99.94
5	100.07	99.93	100.12			
10	44.04	40.04	41.56			
15	16.12	14.74	15.52			
20	8.09	7.00	8.02			
25				101.77	100.11	102.79
30	3.98	4.22	4.52			
35	3.99	3.43	4.32			
40				100.22	105.46	101.36
45	4.29	3.24	3.51			
50	2.46	3.75	2.08			
55				99.42	100.43	99.75
60	1.53	1.86	1.18			
65	1.60	1.46	1.02			
70				102.43	100.60	99.23
75	1.54	1.44	1.21			
80	1.53	1.67	1.41			
85	1.50	1.47	1.16			
90	1.52	1.46	1.80			
95				99.87	100.12	100.62
100	20.12	16.66	19.39			
105	48.72	45.92	49.04			
110	89.03	93.64	91.13			
115				100.21	99.02	100.14
120	101.12	100.03	99.19			

VITA

Iftikhar Ahmad

Candidate for the Degree of

Master of Science

Thesis: **DESTRUCTION OF TRICHLOROETHYLENE AND TOLUENE IN ALTERNATING CURRENT PLASMA REACTOR**

Major Field: Civil Engineering

Biographical:

Personal Data: Born in Peshawar, Pakistan, April 11, 1966, the son of Bacha Begum and Rehman Gul.

Education: Matriculated from Cadet College Razmak, Pakistan, in 1982; received Higher Secondary School Certificate from Edwardes College, Peshawar, Pakistan in 1985. Attended Cyprus College, Nicosia, Cyprus for the freshman year. Received Bachelor of Science Degree in Civil Engineering from Oklahoma State University in Stillwater, Oklahoma, in 1993; completed requirements for the Master of Science Degree at Oklahoma State University in December, 1996.

Professional Membership: American Society of Civil Engineers.