# ABSTRACT

# A FIELD STUDY COUPLING SOIL FRACTIONATION AND SONIC ENERGY FOR ENHANCING THE *IN SITU* REMOVAL OF VOLATILE ORGANIC COMPOUNDS IN THE VADOSE ZONE

**by**
**Hassan Kaleem**

Remediation of sites contaminated with hazardous wastes could be an expensive endeavor. There is, therefore, the need to explore techniques, which can reduce the remediation time and achieve regulatory specifications, thus reducing the cost involved in a site remediation exercise.

In this work, we investigated the use of sonic energy to enhance the *in situ* removal rate of trichloroethylene and dichloroethylene from a site in Hillsborough Township, New Jersey. The experiments were performed with and without sonic energy and each time the concentration of the trichloroethylene swept out from the site and the flowrate of the effluent gas were measured. The results obtained indicate that when sonic energy is used as an enhancement technique the removal rate of trichloroethylene increases by an average value of about 37.9 % and the concentration of trichloroethylene in the effluent stream increases by an average value of about 20.8 %. These results mean that sonic energy, when used as an enhancement technique, will reduce the remediation time and can help achieve regulatory specifications in a site clean-up exercise after coventional Vapor Extraction methods have reached assymptotic values.

It is recommended that further work be done to find the attenuation coefficients of the sonic field and also to determine the decay rate of the sonic intensity at this site.

# A FIELD STUDY COUPLING SOIL FRACTIONATION AND SONIC ENERGY FOR ENHANCING THE *IN SITU* REMOVAL OF VOLATILE ORGANIC COMPOUNDS IN THE VADOSE ZONE

by
**Hassan Kaleem**

**A Masters Thesis**
**Submitted to the Faculty of**
**New Jersey Institute of Technology**
**in Partial Fulfillment of the Requirements for the Degree of**
**Master of Science in Chemical Engineering**

**Department of Chemical Engineering, Chemistry and Environmental Science**

**January 1999**

# APPROVAL PAGE

# A FIELD STUDY COUPLING SOIL FRACTIONATION AND SONIC ENERGY FOR ENHANCING THE *IN SITU* REMOVAL OF VOLATILE ORGANIC COMPOUNDS IN THE VADOSE ZONE

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To my beloved family

# ACKNOWLEDGMENT

My appreciation to Dr Deran Hanesian and Dr Angelo Perna who not only served as my Thesis advisors but also provided their talent, intuition and extraordinary support throughout the entire project. Thanks to Dr Schuring for his active participation in my committee.

I would also like to thank Tom Boland and my fellow graduate students, Hugo Fernandez, Minhaz Bootwala and Jenny Lin, for all the background work they accomplished prior to our field studies. Finally, thanks to our Undergraduate students Amos Britton, Kristina Ranieri, Marian Nasri, Christopher Rawles, Renee Channer, Neha Shah, Manal Darwish, Janina Alvarez, Daisy Delgado, Chamiros Chamion, Melinda Robinson, Marina Cubias, Guiliana Salinas, Jasjeet Singh and Maria Kostritsyna and the entire Pneumatic Fracturing crew, without whom this work would not exist in its present form.

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# LIST OF SYMBOLS

$a$ = Constant

$A$ = Area for Drying($ft^2$ or $m^2$)

$b$ = Constant

$k$ = Removal Rate Constant ( Hour $^{-1}$, Minute $^{-1}$ or Second $^{-1}$)

$M$ = Mass of Solids (lb or kg)

$R$ = Rate of Drying (lb/$ft^2$-h or kg/$m^2$-h)

$R_c$ = Rate at the First Critical Point in lb/$ft^2$-h or kg/$m^2$-h

$t$ = Drying Time ( Hours, Minutes or Seconds)

$X$ = Free Moisture Content of Soil in Mass of Water per Unit Mass of Dry Soild (lb $H_2O$ per lb Dry Solid or kg $H_2O$ per kg Dry Soild)

$X_c$ = Free Moisture Content at the First Critical Point in Mass of Water per Unit Mass of Dry Soild (lb $H_2O$ per lb Dry Solid or kg $H_2O$ per kg Dry Soild)

$X_o$ = Free Moisture Content of Soil in Mass of Water per Unit Mass of Dry Solid at Time $t = 0$ (lb $H_2O$ per lb Dry Solid or kg $H_2O$ per kg Dry Soild)

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

Soil contamination due to the dumping of hazardous waste is a major problem in the United States where an estimated 33000 to 50000 abandoned hazardous waste sites exist (Bloom, 1986). "The term hazardous wastes means waste or combination of wastes which because of the quantity, concentration, or physical, chemical, or infectious characteristics may;

- Cause, or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible illness; or
- Pose a substantial present or potential hazard to human health or the environment

when improperly treated stored, transported, or disposed of, or otherwise managed", (U.S Environmental Protection Agency, State Decision Makers' Guide for Hazardous Waste Management, U.S EPA OSW SW 412, Washington D.C 1977).

Today, there are sites around the world where unknown quantities of unknown wastes pose a potential environmental as well as a health problem. Table 1.1 gives some statistics of the quantities of hazardous wastes produced in some industrialized regions and Table 1.2 gives sources of hazardous wastes in the United States.

**Table 1.1** Quantities of Hazardous Wastes Produced in Industrialized Regions *.

| Location | Hazardous wastes ($10^6$ tons / yr.) | Total population (millions) |
|---|---|---|
| United states | 40.0 | 220 |
| California | 4.6 | 22 |
| Ohio | 5.0 | 12 |
| Canada | 4.0 | 25 |
| Ontario | 1.5 | 8 |
| West Germany | 3.5 | 62 |
| Bavaria | 0.5 | 11 |
| Netherlands | 1.2 | 13 |

*source: Adapted from Henry J.G., Leachate from Hazardous Waste Landfills, Toronto: University of Toronto, Solid and Hazardous waste Publication No.WM82-02,1982.

**Table 1.2** Hazardous waste sources in the United States*

| Industry | Basis | |
|---|---|---|
| | Dry | Wet |
| Primary Metals | 40% | 29% |
| Inorganic Chemicals | 20% | 12% |
| Organic Chemicals | 20% | 24% |
| Electroplating | 10% | 18% |
| other industries | 10% | 17% |
| Total | 100% | 100% |

*source: U.S EPA, State Decision-Makers' Guide for Hazardous Waste Management, US EPA OSW SW 412, Washington DC, 1977.

The complete EPA treaty on hazardous waste can be found in the May 19, 1980, issue of the Federal Register, vol. 45, No. 98 (Book 2 of 3), pages 33119 to 33137. The following is a listing of the substances considered as hazardous in that document.

- "Spent halogenated solvents used for degreasing, such as trichloroethylene, methylene chloride, and others.
- Spent nonhalogenated solvents such as xylene, acetone, ethyl benzene, ethyl ether, and others.
- Wastewater treatment sludge from electroplating operations.
- Dewatered air pollution control scrubber sludge from coke ovens and blast furnaces.
- Sludge generated during the production of various chromium compounds.
- API separator sludge from petroleum refineries.

Examples of wastes exempted from the hazardous waste lists are domestic sewage; Irrigation return flows; mine tailings; animal manure; fly ash and bottom ash; drilling fluids; and wastes from crude oil and natural gas. Also excluded from this list are radioactive and nuclear wastes, which, because of their special requirements, are controlled separately under the Atomic Energy Act of 1954 and amendments thereto", (U.S Environmental Protection Agency, State Decision Makers' Guide for Hazardous Waste Management, U.S EPA OSW SW 412, Washington D.C 1977).

Chapter 2 discusses some of the approaches to hazardous waste management and the options available for treatment and disposal of hazardous industrial wastes. Some of the existing methods for cleaning up sites contaminated with hazardous wastes are time consuming and expensive. The technology that is presented in this thesis is aimed at reducing the remediation time and achieving the regulatory specifications and thus reducing the cumulative cost involved in a hazardous waste site cleanup exercise. Pneumatic Fracturing and air injection have been successfully used to clean up a site in Highland Park, New Jersey. This site was contaminated with trichoroethylene and the remediation time was reduced from 10 to 2 years, (Fernandez, 1997). This improvement in remediation time justifies further investigation of processes or techniques that will enhance the currently used Pneumatic Fracturing followed by Vapor Extraction method. The research presented in this document discusses an enhancement technique for the conventional Pneumatic Fracturing coupled with sonic energy and Vapor Extraction to decontaminate a soil containing volatile organic compounds in the vadose zone.

## 1.2 Research Objective

The objective of the research presented in this document is to test the benefits of coupling sonic energy enhanced mass transfer with soil fracturing to remove trichloroethylene and dichloroethylene at the Derelco industrial site in Hillsborough, New Jersey. This entire field project is based on earlier laboratory work which showed that, overall, sonic energy enhances the removal of volatile organic contaminants, specifically ethanol, as well as water from a tank simulating the fractured vadose zone, (Fernandez, 1997).

# CHAPTER 2

# BACKGROUND OF THE STUDY

## 2.1 Overview of Current Remediation Technologies

Remediation technologies could be grouped into two major categories.

1. *ex situ* (involving excavation and transportation of the contaminated soil) and
2. *in situ* ( involving treating the contaminated soil where it is found)

### 2.1.1 Excavation and Transportation of Soil

These methods involve *ex situ* treatment of the contaminated soil. The soil is dug up, transported to a remediation facility, treated to remove the volatile organic compounds and returned to its original site. Due to the excavation and transportation of soil involved for treatment *ex situ* methods tend to have a higher cost compared to the *in situ* methods. Some of the *ex situ* methods include;

**2.1.1.1 Thermal Treatment:** This method involves *ex situ* high-temperature (1200°C or more) treatment to dispose of organic wastes. A common example where this technique is used is in incinerators. In this method, the wastes to be incinerated are stored in secured containers. The usual vessels of storage for the waste depends on the type of waste being stored. Solid waste and thick sludge are stored in pits and liquid and semisolid wastes are stored in mixed or heated tanks. Drummed hazardous organics and organic solids and sludge are incinerated together with the drums when necessary. The heat content of the gases produced during the incineration can be utilized by passing the gases through a heat boiler to recover the heat and to use the recovered heat as required.

The gases are also neutralized and desulphurized by removing the sulphur in the form of heavy metal precipitates. Scrubbing and electrostatic precipitation are used to further purify the incinerator exhaust gases. The clean non corrosive gases can then used to turn a turbine in order to generate electricity, (Henry G.J and Heinke, G.W, 1989). A major disadvantage in the use of incinerators is the cost involved in building an industrial scale incinerator.

**2.1.1.2 Secure Landfill:** This method is an *ex situ* treatment technique in which it is intended that a secure landfill holds the organic and inorganic hazardous wastes in as concentrated a form as possible for an indefinite period. If it is necessary, Leachate is removed periodically for treatment and disposal.

**2.1.1.3 Codisposal:** This method is an *ex situ* treatment technique which involves the codisposal of hazardous waste with municipal refuse, it is aimed at using large quantities of refuse to absorb relatively small quantities of hazardous inorganic liquid wastes (and some organics) so that the contaminants can be decontaminated by the refuse and the surrounding soil, (Henry J.G, Heinke G. W, 1989).

**2.1.1.4 Hazardous Waste Treatment Facility:** This method is an *ex situ* treatment technique. In this method, the hazardous substances are transported to a hazardous waste treatment facility. In a hazardous waste treatment facility, organic wastes may be either incinerated or treated to yield a liquid effluent that is non-toxic and a concentrated sludge which is then sent to a secure landfill. Inorganic wastes are treated to make them non-toxic, neutralized, and concentrated to produce a sludge which upon further treatment can be sent to a landfill. Chemical and Physical treatment methods, incineration and landfillng of the residues generated from these methods are the most common types of hazardous waste treatment processes, (Henry J.G, Heinke G. W, 1989). The high cost involved and the high demand for land makes *ex situ* techniques unattractive. Other methods used in conjunction with digging up are chemical treatment of the soil and washing of the soil.

### 2.1.2 *In- Situ* Removal of Contaminants

These methods involve the *in situ* treatment of the contaminated soil. Due to the *in situ* (local ) treatment of soil involved, *in situ* methods tend to have a lower cost compared to the *ex situ* methods. Some of the *in situ* methods include;

**2.1.2.1 Washing:** This technique is a common *in situ* treatment method. Washing is most efficient in permeable soils contaminated with solid and liquid waste. This process involves treating the site with a solution that is able to dissolve the contaminants in the soil. The solvent travels through the pores of the permeable soil, thereby reaching the contaminants and dissolving them. The solvent finally reaches the ground water where it is pumped to the surface through extraction wells, treated and redistributed on the site again. The major advantages of this technology are the ability to remediate the site permanently and the moderate cost involved in implementing the technology. The major disadvantage of this technique is the fact that it can only be utilized in highly permeable soils.

**2.1.2.2 Chemical Treatment:** Most hazardous waste treatment processes include chemical treatment as an essential component. The commonly used chemical treatment processes are oxidation and reduction reactions, pH adjustments and ionic exchange. Ionic exchange involves separating all dissolved inorganics from the waste. Chemical fixation is also a common chemical treatment method for hazardous waste. It involves solidifying the wastes (both organic and inorganic) with cement. This Method tends to stabilize the inorganics into inert silicates or hydroxides. The application of this method to organic wastes is still under development. If the end products of this method are not confirmed to be completely stabilzed, a secure land fill is recommended, (Henry J.G, Heinke G. W, 1989).

**2.1.2.3 Bioremediation:** For low concentrations of toxic substances, biological methods of treatment can be employed. These methods involve using microorganisms to decompose the waste. The process can be carried out using aerobic or anaerobic microorganisms. In general, due to the fact that aerobic processes lead to higher growth of microorganisms they are less sensitive to the toxicity of the waste being decomposed. Typical examples of wastes which can be decomposed by biological processes include; phenols, oils and other refinery wastes, (Henry J.G, Heinke G. W, 1989).

**2.1.2.4 Ultrasonics:** Remediation of subsurface soils using ultrasound is currently under development as an *in situ* technology and has been discussed. Some of the applications of Ultrasound include:

- The enhancement of chemical treatment processes during the decontamination of soils .
- The elimination of microbes using ultrasonic energy. These microbes could decrease the permeability of the soil by clogging the pore spaces of the soil.
- The improvement in the permeability of tightly packed clays. This can be achieved by using the ultrasound to disperse the tightly packed clay formation.

Ultrasound is used as an enhancement technique for other methods of treatment. The ultrasound is used to increase the permeability of the soil so that other remediation agents (such as chemicals and microorganisms) can have easy passage through the soil being remediated. This leads to a faster rate of remediation because there is more contact between the remediation agent and the hazardous waste in the soil, (Fernandez, 1997).

There are other *in situ* techniques being used to treat soil contaminated with hazardous waste. Pneumatic Fracturing followed by Vapor Extraction has proven to be an effective technique. This thesis looks at an enhancement technique for the conventional Pneumatic Fracturing-Vapor Extraction method. It will involve coupling Sonic Energy, Pneumatic Fracturing and Vapor Extraction to remediate a site contaminated with trichloroethylene and dichloroethylene, in Hillsborough Township, New Jersey.

## 2.2 Pneumatic Fracturing

The Hazardous Substance Management Research Center (HSMRC, NJIT) has developed a new method for the remediation of tightly packed soils. This method known as Pneumatic Fracturing is aimed at increasing the permeability of tightly packed soils. The method was tested on a site in Somerville Township, New Jersey, and was proven to be effective in increasing the permeability of the soil, (EPA/540/AR-93/509, July 1993). This study showed that the method of Pneumatic Fracturing increases the permeability of tight soils. This is believed to be achieved by creating more fractures or widening the existing fractures. Another finding from the study was that the removal rate of the major contaminant in the soil (trichloroethylene) was also observed to increase. This result is believed to be a result of the releasing of the organics which were trapped within the formation prior to the Pneumatic Fracturing.

Furthermore, both the observed air flowrates and the removal rate of the organic contaminant were observed to increase significantly. The concentration of the organic contaminant removed was also observed to increase. This is believed to have been caused by the release of some trapped organics which were held within the fractures prior to the Pneumatic Fracturing. Finally, the study found that the nature of the site geology and the presence of built structures (e.g pipe lines) could have a profound impact on the nature of the fracturing, (Accutech Pneumatic Fracturing Extraction and Hot Gas Injection Phase1, Applications Report by EPA/540/AR-93/509, July 1993).

## 2.3 Vapor Extraction

Vapor Extraction is a very effective method during *in situ* site remediation. A major limitation to this technique however, is the permeability of the vadose zone. If the vadose zone is not sufficiently permeable, the organic contaminant will not be swept away with the air stream due to low air flow rates. Currently, there are different ways used to implement Vapor Extraction. One way is to draw the vacuum from the central well and inject air into the neighboring wells or leave the neighboring wells open to the atmosphere. The neighboring wells could also be sealed. Another method is to inject air into the central well and draw the vacuum from the surrounding wells, (Applications Report by EPA/540/AR-93/509, July 1993).

## 2.4 Coupling Pneumatic Fracturing and Vapor Extraction

Vapor Extraction is an efficient approach for organic contaminant removal from soils that are sufficiently permeable and allow for easy passage of air through the pores of the formation. For soils that are not sufficiently permeable, Pneumatic Fracturing can be used to open up the fractures within the soil and thus increase the permeability of the soil. This will then lower the resistance within the fractures in the soil and lead to higher airflow through the soil. Examples of such soils include shale, silts and clays. When Vapor Extraction is then performed on such soils, there is a higher rate of removal of organic contaminant because the higher airflow through the fractures causes more of the organic contaminants to be swept away by the air passing through the pores of the soil. Pneumatic Fracturing usually involves injecting air intermittently (air at about 500 psig < 1 minute) into the soil, (Accutech Pneumatic Fracturing Extraction and Hot Gas Injection Phase1, Applications Report by EPA/540/AR-93/509, July 1993).

### 2.4.1 Theoretical Considerations

When air is injected into a formation it will travel through the path that offers the minimum resistance, which in this case is the fracture. As air passes through the fracture, the moisture in the fracture will evaporate into the air stream. Due to concentration gradients and pressure differences, and depending on the velocity of the air stream, the moisture will be carried along with the air stream. Thus the air flowing through the fracture is drying the ground.

This real situation can be modeled after a tray dryer, in which a continuous stream of air is allowed to pass over a series of wet solids, in trays, thereby causing the moisture in the solids to be swept away by the air stream. Some limitations to applying this model to the actual fracture are summarized below:

1. Some of the air going into the fracture may be dispersed into the formation whereas in the tray dryer all the inlet air comes out.
2. The real fracture will not have a uniform dimension throughout its length and this could lead to variations in the airflow rate in the fracture (some parts of the fracture could be clogged by debris).

**2.4.1.1 Drying of Porous Solids and Capillarity:** Porous substances are made up of a network of pores which are connected to each other in a complicated manner. As a porous substance is being dried, moisture flows through the pores of the material by capillarity to the surface of the material. Figure 2.1 gives the moisture distribution in a porous material as it is being dried, (W.L McCabe, J.C Smith and P. Harriott, 1993).

Figure 2.1 shows that as the distance from the surface of the porous material being dried increases the moisture content of the material also increases and then slightly levels off for large distances from the surface of the material. This graph shows that in a typical Vapor Extraction process, in a porous soil, the surface moisture or organic contaminant will be the first to be swept away. The Figure also shows that the further the moisture or organic contaminant is located from the surface, the less likely it is to be removed by the conventional Vapor Extraction techniques.

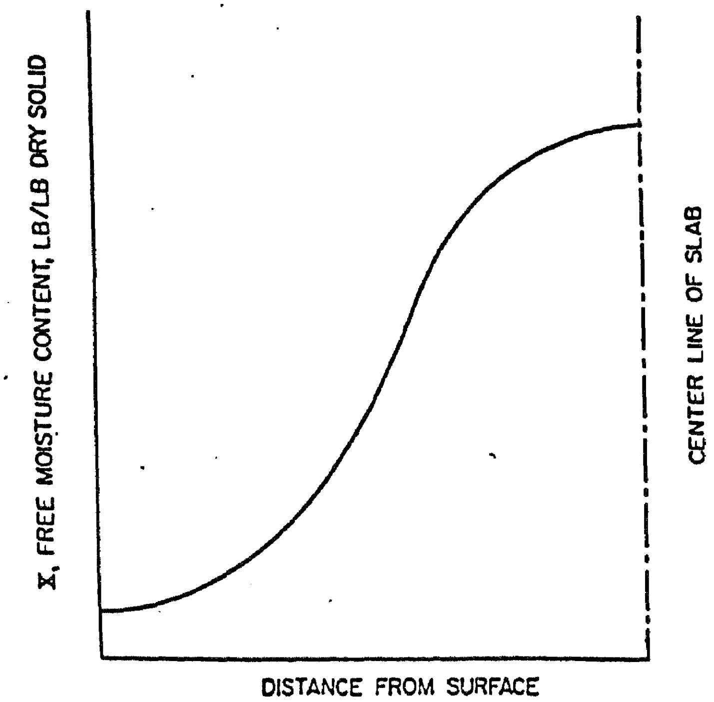


**Figure 2.1** Moisture Distribution in Porous Slab being dried*
*Adapted from (W.L McCabe, J.C Smith and P. Harriott, 1993).

Figure 2.2 shows the drying rate curve for a porous ceramic plate. The rate of drying of porous materials can be divided into three sections, (W.L McCabe, J.C Smith and P. Harriott, 1993). The three sections are shown as section AB, BC and CD in Figure 2.2.

**2.4.1.1.1 Section AB:** This is the initial rate of drying period. During this period the entire surface of the material is covered with moisture. The rate of removal is constant for this period. For this period the following equations are used to find the moisture content present in the soil at any time.

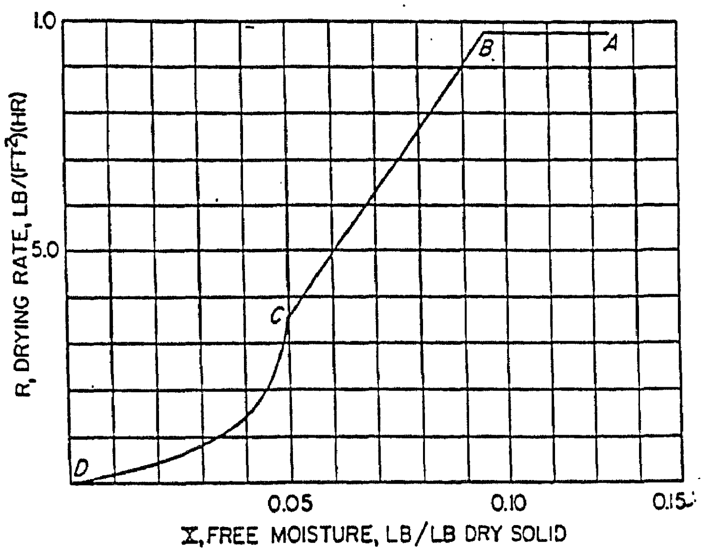


**Figure 2.2** Drying Rate Curve for Porous Ceramic Plate
Adapted from (W.L McCabe, J.C Smith and P. Harriott, 1993).

$$R = -(M/A)(dX/dt) \qquad 2.1$$

For the constant rate period, segment AB, Figure 2.2, the solution of the above equation is given by;

$$X = X_0 - (R\,A/M) * t \qquad 2.2$$

(adapted from W.L McCabe, J.C Smith and P. Harriott, 1993).

Equation 2.2 gives the free moisture content of the soil over time. These equations are used in calculating the moisture content of the soil.

The equations can be generalized to account for volatile organic compounds during the constant rate of removal period. For the purposes of this study the volatile organic contaminant content of the air stream above the organic contaminant in the soil (X) will be measured. The moisture lost from the soil is equal to the moisture gained by the air stream, thus moisture content swept out by the air stream until time t is proportional to $X_0 - X$.

$$X_0 - X = (R\ A/M) * t \tag{2.3}$$

For the falling rate period, segment BC and CD, Figure 2.2, the rate of drying of the porous soil is no longer constant. This falling rate period begins when the surface of the soil starts to dry up. The first part of this falling rate period, segment BC, Figure 2.2, corresponds to the case where the surface is partially covered by moisture and there still some areas of moisture on the surface. The mechanism of evaporation remains unchanged but the rate of removal of the moisture decreases linearly with time. This trend is followed until the surface no longer contains free moisture and the moisture content layer of the soil begins to receed to the interior of the soil. During this period the rate of removal of the moisture from the soil follows a parabolic shape (CD).

For the first falling rate period, segment BC, Figure 2.2, the rate is linear with X for most porous solids. Thus

$$R = aX + b \tag{2.4}$$

In some situations, a straight line representing the falling rate period passes through the origin. For these cases

$$R = aX \tag{2.5}$$

For simplification purposes if Equation 2.5 is assumed, Equation 2.1 can be integrated.

$$X = X_c\, e^{-MAt/a} \tag{2.6}$$

or

$$X = X_c\, e^{-kt} \tag{2.7}$$

Equation 2.7 indicates an exponential decay of the moisture content with time in the falling Rate region. The solution of Equation 2.1 with R = aX + b is given by

$$-Aat/Mb = (\mathrm{Ln}\ R/R_c) * X \tag{2.8}$$

$$a = (R_c - R)/(X_c - X) \tag{2.9}$$

From Equation 2.8 and 2.9

$$Xc\text{-}X = -A[R_c\text{-}R]t/M\ Ln(R/R_c) \qquad 2.10$$

Equation 2.10 has the same form as Equation 2.3 with the constant rate term in Equation 2.3 replaced by the falling rate term.

## 2.5 Overview of Acoustics

### 2.5.1 Acoustic Properties of Soil

Properties of sound in soil depend very much on the nature of the soil. Properties like the speed of sound, amplitude of sound waves and attenuation of sound in soil depend on the porosity of the soil, moisture content of the soil, type of minerals present in the soil and the state of consolidation of the soil. It has been shown that in clay sound waves travel faster and with little change in velocity and also with some attenuation, (Fernandez, 1997).

### 2.5.2 Sonic Drying

Sonic energy increases the drying rate of solids exposed to a sound field but the extent of the improvement varies considerably with the material. Further research has led to the conclusion that sonic drying is most efficient at sound frequencies between 7kHz and 20kHz and sound intensities greater than 145Db, (Fernandez, 1997).

### 2.5.3 Sonic Generators

Fernandez, 1997, investigated the different types of sound generators and gives the main classes of sonic generators as;

1. Electrostatic Generators

2. Electrodynamic Generators

3. Magnetostrictive Generators

4.Piezoelectric Generators

5. Pneumatic Generators (Dynamic Generators and Static Generators)

The principle governing the operation of Electrostatic Generators is that electrostatic forces between the plates of a condenser can change the spacing between the plates .The attraction and repulsion between these plates creates sound vibrations in the air that is near the plates, (Fernandez, 1997).

The principle that governs the operation of Electrodynamic Generators is that an electric current when passed through a coil will generate a magnetic field which causes vibrations in a magnetic plate. These vibrations produce resonance and hence enhance the sound being generated, (Fernandez, 1997).

Magnetostrictive Generators use a voltage applied to a metallic material. The material expands when the voltage is applied to it and contracts to its normal shape when the voltage is removed. Thus, when an alternating voltage is applied to the material a series of vibrations are produced. These vibrations produce an acoustic field, (Fernandez, 1997).

The principle that governs the operation of Piezoelectric Generators is based on the fact that a crystal with piezoelectric properties will build a charge when brought into contact with a voltage. This charged crystal will be attracted to other oppositely charged crystals. When the voltage is reversed the charge on the crystal is also reversed. A series of alternating charges causes the crystal to vibrate. If the vibration of the crystal coincides with its resonance frequency a sound field is generated, (Fernandez, 1997).

Pneumatic Generators produce sound waves using air. Pneumatic Generators can be divided into two subclasses, Static Generators and Dynamic Generators.

Dynamic Generators operate on the principle that when a rotating device is allowed to interrupt a jet of air intermittently, a sound wave is generated. An example of a Dynamic Generator is a Siren, (Fernandez, 1997). A major disadvantage of the siren is its susceptibility to mechanical damage due to its moving parts at high revolutions per second.

The principle governing Static Generators is that a jet of air emerging from a converging nozzle, close to the speed of sound, causes waves to form at the tip of the nozzle. When a resonant cavity is placed in the path of the air jet, a sound wave is produced, (Fernandez, 1997). Whistles are examples of Static Generators. Whistles have a major advantage over sirens in that whistles have no moving parts.

For this research, a whistle will be used as the sonic generator (refer to Chapter 4 for description and specification). This selection is based on previous laboratory work (Fernandez, 1997) and the fact that the whistle is more mechanically resistant compared to the siren.

## 2.6 Coupling Pneumatic Fracturing, Sonic Energy Enhanced Mass Transfer and Vapor Extraction

This method, the subject of this investigation, will be an enhancement of the technique presented in Section 2.4. Previous laboratory studies have revealed that this technique could lead to promising results (Fernandez, 1997). These studies determined that focusing sonic energy into a fracture can lead to an enhancement in the removal rate of liquids that are trapped inside tightly packed soils. Laboratory studies performed on drying of solids in the presence of a sonic field show that several effects are obtained when a sonic intensity of about 160Db is allowed to pass through a fracture, (Fernandez, 1997).

The first effect is the lowering of the net total pressure within the fracture by the compression and dilation of the air within the fracture caused by the sonic energy. These compressions and dilations tend to lower the net total pressure within the fractures because it is known that dilation regions dominate over compression regions. Thus the lower net total pressure causes some of the liquid in the fractures to vaporize and be carried away by the air stream. In addition the lower net total pressure within the fracture causes a pressure gradient to develop which acts as a driving force for liquid to move towards the fractures, (Fernandez, 1997).

Another effect when a sound field of 160 Db is focussed into a fracture is the lowering of the gas – liquid interface film. This is achieved due to the higher turbulence that is built up in the region because of the presence of the sonic field. This decrease in the interface film increases both mass and heat transfer and causes more liquid to be evaporated, (Fernandez, 1997).

Furthermore, moisture that is trapped within the fractures and separated by air bubbles will be released because the sonic energy causes the bubbles to heat and expand. The pressure gradient is in the direction of the fracture and hence, the capillary contents move toward the fracture zone, (Fernandez, 1997).

A last effect that can be obtained when an intense sonic field of 160Db is focussed into a fracture is Cavitaion. This is caused by the intense sound field. It is believed that the effect of Cavitaion may have a positive influence on the removal rate of the contaminant, (Fernandez, 1997).

## 2.7 Trichloroethylene (TCE) and Dichloroethylene (DCE)

### 2.7.1 Dichloroethylene (DCE)

Dichloroethylene ($CHClCHCl$) has two stereo isomeric forms. It is not highly flammable, but, the hot gases containing dichloroethylene can be ignited and continue to burn so long as heat is supplied. It is colorless and boils at a low temperature. It is a slightly toxic liquid with a pleasant odor. Some of its uses are as a solvent for oils, gums, resins, waxes, rubber and cellulose acetate. It is also used in the extraction of dyes, perfumes and organic material. The percentages of the different isomers present determines the physical properties of this mixture. The lethal dose of DCE (based on a 30 minutes test on cats) is 44000 PPM, (Ibert Mellan, 1939).

### 2.7.2 Trichloroethylene (TCE)

Trichloroethylene is a non-flammable and non-explosive organic compound. It is not combustible and has a very low affinity for common metals. Trichloroethylene is considered to be a toxic liquid with a low boiling point. It is also a colorless, mobile, heavy liquid with a smell similar to that of chloroform. Trichloroethylene ($CHClCCl_2$) belongs to a group of compounds known as chlorinated solvents. Members of this group include (Carbon tetrachloride, pentachloroethane, tetrachloroethane, perchloroethylene, dichloroethylene and methyl chloroform). It is the second most toxic member of the group after trichloromethane (Table 2.5). During World War II, it was used extensively in the degreasing of metal parts. Presently, it is widely used as a solvent for gum, crude rubber, dyes, bitumen, fats, waxes and grease. It is miscible with acetone, benzene, toluene, ethyl and methyl acetates and alcohol. Trichloroethylene is also miscible with most organic solvents. Most of the trichloroethylene produced is used for degreasing metal parts (87 %). Major factors that limit its production are air pollution legislation and OSHA restrictions.

Table 2.1 - 2.5 gives some physical properties of Trichloroethylene, (Ibert Mellan, 1939).

**Table 2.1** Specific Gravity of Trichloroethylene at Different Temperatures

| Temperature/°C | Specific Gravity (referred to water at 4°C) |
|---|---|
| 0 | 1.4996 |
| 15 | 1.4762 |
| 30 | 1.4514 |
| 45 | 1.4262 |
| 59.5 | 1.3997 |

source: Industrial Solvents, Ibert Mellan, 1939.

**Table 2.2** Solubility of Water in Trichloroethylene, at Different Temperatures

| Temperature/°C | Solubility/ g. water per 100g. TCE |
|---|---|
| -2 | 0.01 |
| 10 | 0.017 |
| 18 | 0.025 |
| 28 | 0.035 |
| 70 | 0.09 |

source: Industrial Solvents, Ibert Mellan,1939.

**Table 2.3** Viscosity of Trichloroethylene at Different Temperatures

| Temperature/°C | Viscosity/ centipoise |
|---|---|
| -10 | 0.78 |
| 25 | 0.550 |
| 50 | 0.446 |
| 55 | 0.440 |
| 75 | 0.371 |

source: Industrial Solvents, Ibert Mellan,1939.

**Table 2.4** Vapor Pressure of Trichloroethylene at Different Temperatures

| Temperature/°C | Vapor Pressure/mm Hg |
|---|---|
| -10 | 10 |
| 10 | 33 |
| 20 | 60 |
| 30 | 90 |
| 50 | 210 |
| 70 | 450 |
| 80 | 630 |

source: Industrial Solvents, Ibert Mellan,1939.

**Table 2.5** Relative Toxicity*

| | |
|---|---|
| Carbon Tetrachloride ($CCl_4$) | 1.0 |
| Perchloroethylene ($C_2Cl_4$) | 1.6 |
| Dichloroethylene ($C_2H_2Cl_2$) | 1.7 |
| Trichloroethylene ( $C_2HCl_3$ ) | 1.7 |
| Trichloromethane ($CHCl_3$ ) | 2.2 |

source:Industrial Solvents, Ibert Mellan, 1939.* $CCl_4$ arbitrarily taken as1

Other physical properties: (Source: Ibert Mellan, 1939).

| | |
|---|---|
| Molecular weight | 131.40 |
| Melting Point | 73°C |
| Boiling Point | 87.2°C |
| Weight per gallon | 12.20 lb. (20°C) |
| Color | Water-white |
| Threshold limit value | 100 PPM |
| Vapor density | 4.45 (air = 1) |
| Refractive index | 1.4735 (27°C) |
| Surface Tension | 32.0 dynes/cm (25°C) |
| Specific Heat | 0.229 cal./gm (23°C) |
| Solubility in water | 0.1% by wt. ( 25°C) |
| Latent heat of vaporization | 57.3 cal./g. at BP) |
| Coefficient of expansion (per °C) | 0.00115 to 20°C |
| Dielectric constant | 3.42 |
| Lethal dose (in 30 minutes for cats) | 37000 PPM |

# CHAPTER 3

# SITE DESCRIPTION

## 3.1 Background

The actual field studies will be carried out at the Derelco site, at Hillsborough, N.J, contaminated with TCE and DCE. The study will involve sending a sound wave (generated by a whistle) through an air injection well, at points where a fracture connects the air injection well with the extraction well. The whistle has a major advantage because it has no moving parts. The aim of this field study is to test the benefits of coupling Pneumatic Fracturing, Sonic Energy Enhanced Mass Transfer and Vapor Extraction. McLaren/Hart teamed up with our research group at the New Jersey Institute of Technology to perform a field test using sonic energy enhancement coupled with soil fracturing for soil remediation at the Hillsborough site, NJ.

The site had been previously investigated by McLaren/Hart Environmental Engineering. On October 26 1985, a fire at the site destroyed a National Diagnostics Inc. building, located on the site, causing the release of organic contaminants into the site. The major contaminants that were involved are trichloroethylene and dichloroethylene.

The site is located near the Sommerville traffic circle, on route 206 south. It is a flat partly paved site and generally slopes slightly from the Northwest towards the Southwestern direction. The surrounding area is a light industrial area and a tributary of the Royce Brook River runs eastward by the northern border of the site. Also located close to the site, about 100 feet, are a few medium sized building structures, (Boland etal, Ultrasonic Field Demonstration Work Plan, NJIT, 1998).

## 3.2 Site Geology

The geology of the Derelco Site is described by Mclaren/Hart as "underlain by a thin veneer of unconsolidated sediments overlaying shale and siltstone bedrock." The deposits range in thickness from one to three feet. These deposits are believed to derive from the local bedrock and consist primarily of a heterogeneous mixture of silt and clay.

Rock samples by McLaren/Hart in September of 1990 revealed "a reddish brown siltstone with interbedded shale layers" and bedrock of "fair quality" with moderate fracture spacing: 30 centimeters to 1 meter apart. This study by McLaren/Hart also revealed three highly fractured zones within the bedrock. These zones appeared at a depth of 18 feet and at the intervals of 33 to 35 and 64 to 66 feet. Smaller fractures were also encounted at 29 feet, 40 feet, 55 feet, and 75 feet. Fractures are oriented both vertically and horizontally. Horizontal fractures occurred along bedding planes that dip five to ten degrees to the west. The vertical fractures are planar and parallel to the strike of the formation which, run Northwest to Southwest, (Boland etal, Ultrasonic Field Demonstration Work Plan, NJIT, 1998).

## 3.3 Site Hydrology

Previous investigations of the Derelco Site by McLaren/Hart Environmental Engineering, revealed that the ground water circulation at the site occurred at a depth of about thirty feet below the ground level and the circulation is limited to the fractures located in this region. The studies also showed that the ground water circulated towards the Northeastern direction, (Boland etal, Ultrasonic Field Demonstration Work Plan, NJIT, 1998).

## 3.4 Well Layout

The locations of the wells within the site are depicted in Figure 3.1. Measured data for the wells at the Derelco site, Hillsborough Township, N.J, prior to the field studies, are given in Table 3.1 and Table 3.2.

**Table 3.1** Measured Data, Derelco Site Hillsborough Township, New Jersey

| Well Number | X(ft) | Y(ft) | Depth(ft) | Conc. of TCE (PPMv) | Bore-hole size (inch) | Well Depth (ft) |
|---|---|---|---|---|---|---|
| 1 | 53.3 | 25.6 | 26.80 | 1.8 | | 85.00 |
| 2 | 47.9 | 19.7 | 7.00 | 30.0 | | 19.10 |
| 3 | 58.1 | 20.0 | 6.90 | 13.2 | | 17.55 |
| 4 | 36.5 | 19.2 | 7.90 | 59.5 | 4.0 | 21.65 |
| 5 | 30.5 | 31.1 | 8.42 | 13.0 | | 21.22 |
| 6 | 23.9 | 30.1 | 8.49 | 6.8 | | 24.27 |
| 7 | 24.7 | 22.3 | 8.32 | 7.6 | 4.0 | 22.16 |
| 8 fw | 29.5 | 21.0 | 8.30 | 11.5 | 3.5 | 20.50 |
| 9 | 10.6 | 26.5 | 9.04 | 14.3 | | 22.90 |
| 10 | 19.9 | 23.6 | 8.90 | 3.6 | | 22.02 |
| 11 | 23.9 | 16.3 | 8.40 | 7.5 | 4.0 | 22.04 |
| 12 | 28.2 | 15.3 | 8.32 | 7.9 | | 15.10 |
| 13 | 33.2 | 14.2 | 8.32 | 13.8 | 4.0 | 22.08 |
| 14 | 27.9 | 10.4 | 7.90 | 8.7 | | 24.86 |
| 15 | 25.9 | 0.0 | 7.60 | 8.5 | | 20.76 |

Source: (Boland etal, Ultrasonic Field Demonstration Work Plan, NJIT,1998).

**Table 3.2** Well Water Sample Analysis, Derelco Site Hillsborough Township, NJ.

| Well Number | TCE, PPMv | DCE, PPMv |
|---|---|---|
| 1 | | |
| 2 | | |
| 3 | | |
| 4 | 23.14 | 4.66 |
| 5 | 19.98 | 2.32 |
| 6 | | |
| 7 | 0.02 | 0.01 |
| 8 | 4.60 | 2.90 |
| 9 | 1.11 | 0.70 |
| 10 | 0.02 | 0.011 |
| 11 | 0.0 | 0.52 |
| 12 | 0.29 | 0.17 |
| 13 | 2.14 | 1.38 |
| 14 | 0.59 | 0.61 |
| 15 | | |

Source: (Boland etal, Ultrasonic Field Demonstration Work Plan, NJIT, 1998).

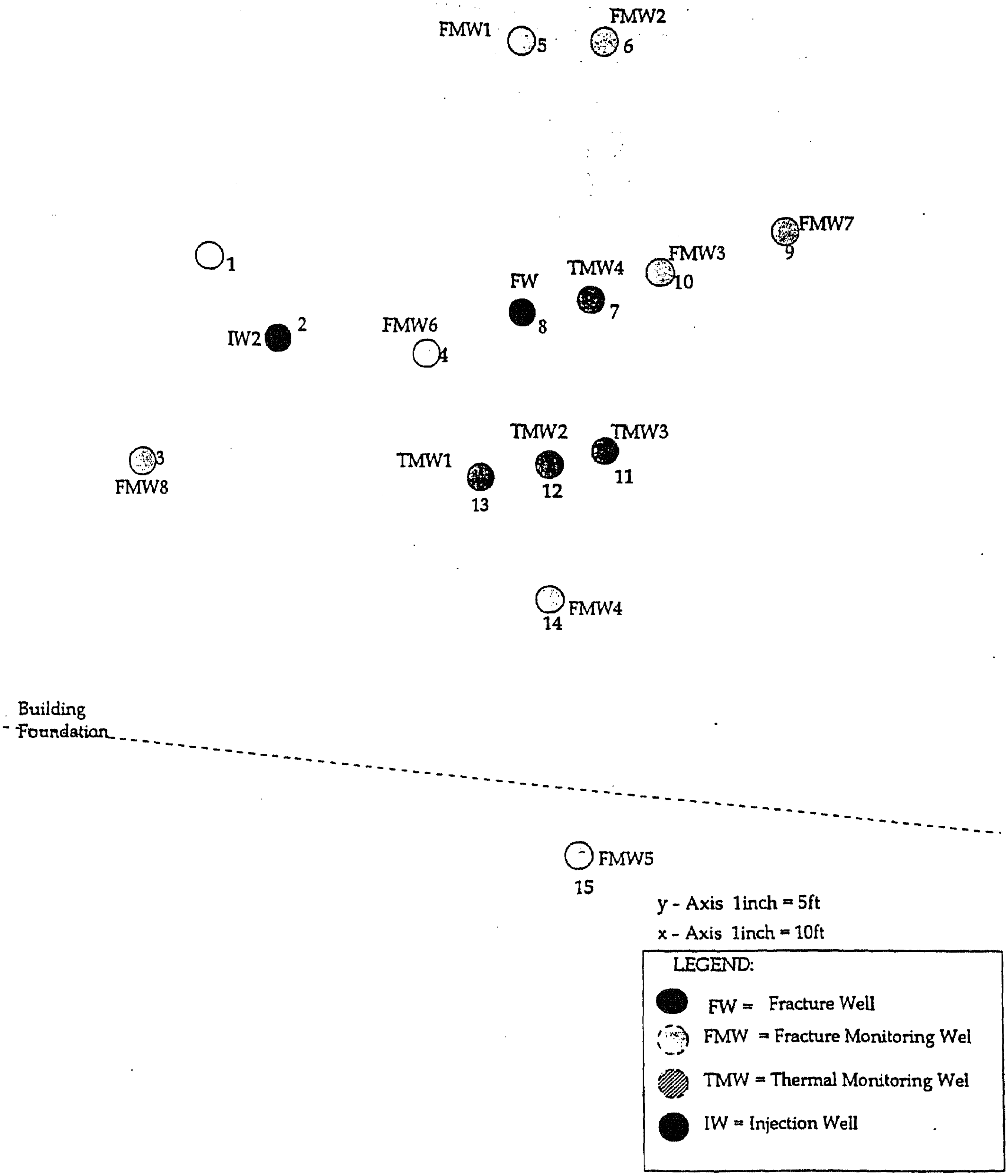


**Figure 3.1** Location of Wells at the Derelco Site, Hillsborough Township, New Jersey Source: (Boland etal, Ultrasonic Field Demonstration Work Plan, NJIT, 1998)

# CHAPTER 4

# UTILITIES AND EQUIPMENT SPECIFICATION

The utilities and equipment specification for the ultrasonic field test are divided into two main categories.

- The injection system utilities and equipment specification
- The extraction system utilities and equipment specification

## 4.1 Injection System - Equipment Specification

The major components of the injection system are shown in Figures C.2, C.3, C.4a and C.4b (Appendix C). Other parts of the injection system are described below:

### 4.1.1 Compressor

The compressor serves the purpose of providing the compressed air needed for the sonic experiments. The compressor used for the experiments was a rented, medium sized, Smith brand, 100 cubic feet per minute compressor capable of providing the desired flowrates (20- 40 SCFM). During operation, the compressor runs at 120- 160 °F range and 95-115 Psi range. There are gauges to monitor the operating Temperature, Pressure, Battery Charge and Fuel Level. There is easy accessibility to the parts of the compressor and adjustments can be made to the compressor during varied process conditions. During cold morning operation the choke is used and the compressor is allowed to warm up for about twenty minutes until the steady operating temperature (160 °F) is attained. During warm up, the discharge valve is closed and during operation it is opened towards the outward direction to an angle of 45°. By means of bleed valves, located underneath the compressor, all condensation can be bled out of the compressor at specific intervals of time. A valve which can be regulated to attain the desired outlet airflow rate controls the discharge of the compressor.

### 4.1.2 Flow Manifold

The flow manifold arrangement, for the sonic field-test, is shown in Figure C.1. The flow manifold is mounted on a rectangular board made from wood. The board is supported vertically by four stands that stand out at an angle of 30° from the surface of the board.

The flow manifold consists of four, 3/4 inch ID flowmeters (2.4 - 24.0) SCFM. Each flowmeter is equipped with a 1/2 inch Sch. 40 Bronze Globe valve at the inlet and a 1/2 inch Sch. 40-IPS Forged-Brass Ball valve at the outlet. By means of these valves, air can be made to travel through the desired flowmeters. Each flowmeter is also equipped with a 1/8 inch ID, 0-100 PSIG, pressure gauge at its outlet. The pressure gauges indicate the pressure drop through the injection system and the pressure drop through the whistles and their feed lines. All four flow meters are connected on a single line, at the inlet, by means of four 1 inch Sch.40 Steel Tees, seven nipples and three tubing unions (1 inch Sch. 40). This single inlet line to the four flowmeters is connected to a compressor. There is also a 0-100PSIG pressure gauge placed on this line. By means of 25 feet of 1/2 inch OD hoses, the outlet of each flowmeter is connected to the well-head assembly (Figure C.2).

### 4.1.3 Well-head Assembly for Ultrasonic Field Test

The Well-head assembly, for the Ultrasonic Field Test is shown in Figure C.2. The well-head assembly together with the flow manifold arrangement will be the parts of the Ultrasonic Bore-hole Test Assembly above ground level. The rest of the assembly will be submerged into the fracture well (Number 4).

The well-head assembly consists of a 1.5 inch Sch. 40 Tee made of steel. To the lower end of this Tee are connected three steel pipes (3 feet 1 1/4inch Sch 40) in series by means of a 1 1/4inch Sch. 40 Galvanized nipple 1 inch long.To the upper end of the Tee a pipe adapter is connected which makes it possible to draw in air (from two of the four flowmeters) through a Twin self-extracting Nylon air Hose (25 feet of 1/2 inch OD plastic Hose). To the third end of the Tee, a 1 inch Sch. 40, 45 degree lateral steel Tee is connected by means of a bushing nipple. This 45 degree lateral Tee makes it possible to draw in two extra lines of air (from the two other flowmeters) by means of 25 feet of 1/2 inch OD plastic Hose.

### 4.1.4 Extension Pipes and Fittings

The extension pipes and fittings are shown in Figure C.3. The extension pipes are 3 feet, 1 1/4inch Sch. 40 made of steel. Within this extension pipe, two lines made of 1/2 inch OD Teflon tubing run from the well head assembly and extend all the way down to the end of the extension pipe where the ultrasonic device (Whistles) is located. The 1/2 inch OD Teflon tubings are connected to the air feed tubes of the two whistles. This makes it possible to send air from the well-head assembly through the extension pipes and fittings and then through the whistles. It is similarly possible to bypass the whistles by sending the air through the 45 degree lateral Tee.

### 4.1.5 Ultrasonic Transducer (Whistle)

Two unidirectional whistles are the main parts of the ultrasonic system. They were purchased from Applied Ultrasonics, Bethel, Connecticut. Each of the whistles is about 3 inches long and are protected by two aluminum plates (Figure C.4b). These aluminum plates protect the whistle from scraping along the wall of the bore-hole.

The whistles all face a single direction to focus and maximize sonic energy into the fractures. Each of the two whistles is equipped with a 1/2 inch air feed tube. Figure C.4a is a schematic of the ultrasonic device showing the two whistles and the aluminium plates. Figure C.4b is a detailed schematic showing the two whistles and the aluminium plates . Table C.1 shows the Bill of materials needed for the entire injection assembly.

### 4.1.6 Packers

The sonic system will be coupled with two, four foot packers to isolate and prevent air leakage from the sonic zone. These packers will be placed before and after the sonic generators in the bore-hole to isolate the treatment zone. Figure C.4 depicts the relative positions of the packers and the sonic system. The packers have an external tubing through which an external nitrogen or air source can be used to inflate them as required.

## 4.2 Extraction System - Equipment Specification

### 4.2.1 Packers

The extraction unit is basically made up of a packer arrangement (separated by a perforated pipe fitting). This packer arrangement is coupled to three steel Sch. 40 pipes each 4 feet long and 1 1/4 inch in nominal diameter and in series (Figure C.5 and C.6).

### 4.2.2 Photoionization Detector and Field-GC

The analytical system used for this field study can be divided into two parts. A portable GC was used to determine the type of organic contaminant present in the site and a Photoionization Detector was used for measuring the concentrations over time of the contaminants. The GC was used during the initial stages of the study to find out which were the major contaminants present in the site.

**4.2.2.1 Photoionization Detector:** The Photoionization Detector (PID) was used to measure the concentration of the contaminant over time. The PID was a Thermo Brand which can be run in battery or in direct current mode. For the purposes of this field study the PID was run on battery mode. This required overnight charging of the battery after each day's run. For the purposes of this field study the PID was calibrated using a standard sample of TCE and it was connected to the extraction line. The PID is equipped with an internal vacuum pump and during operation it continuously draws in a sample from the extraction line, through an inlet port located at its front end, into an analyzing chamber and gives the instantaneous concentrations of the contaminant in parts per million by volume, PPMv. It is capable of displaying up to two analyses every second.

The exhaust gases are continuously emitted via an exhaust port located at the rear end of the PID, to the atmosphere.

**4.2.2.2 Field – GC:** The GC used for this field study is a Scentograph Plus II, designed by Sentex Systems Inc.. It is a portable gas chromatrograph which is capable of performing the following functions;

- Calibrating a known Sample
- Analysing Samples
- Collecting and Injecting samples into the analyzing chamber
- Separating Compounds
- Detecting Compounds
- Identifying and Integrating Peaks.
- Displaying and storing data of concentrations, retention times and operating conditions.
- Continuos Operation
- Automatic recalibration

The Scentograph Plus II could operate in one of the following two modes.

1. Calibration Mode
2. Sample Analysis Mode

Calibration Mode:

During the calibration mode, a sample of known concentration is introduced into the analyzing chamber of the GC. A retention time is associated with each sample. An area is then associated with each sample depending on its concentration. The data obtained from the calibration run are then stored in the GC and the graph of the calibration run is displayed on the screen. This graph serves as the basis for calculating the concentrations of all samples to be analyzed until another calibration run is performed.

Sample Analysis Mode:

When the Scentograph is operating in sample analysis mode, the sample to be analyzed is introduced through the sample analysis ports, which are located behind the GC. The concentration of the sample is calculated by comparing the area under the graph displayed to the area under the graph of the calibration run, at the same retention time. Compounds that are detected and which do not match any retention time obtained during calibration are listed as “unknown”. The Scentograph gives very accurate results due to the fact that calibration can be performed as frequently as desired, (Scentograph “plus II” Operating Manual, 1993).

For the purpose of this field study, the calibration gas used is a standard mixture of TCE (12 PPM), cis-DCE (12 PPM) and trans-DCE ( 15 PPM).

### 4.2.3 Flow Manifold

The flow manifold for the extraction system is an electronic flowmeter. The electronic flow meter is connected to the extraction line, after the PID. It is capable of displaying instantaneous flowrates in SCFM, electronically. Also connected to the extraction line is a piezometer tube. The piezometer tube is connected after the electronic flow meter. Based on the area of the pipe to which the piezometer is connected and the reading on the piezometer, the flow rate through the extraction line can be determined. With this installation in place, the accuracy of the electronic flow meter was confirmed.

# CHAPTER 5

# EXPERIMENTAL APPROACH AND RESULTS

The field study that was performed at the Derelco Site encumbers the following;

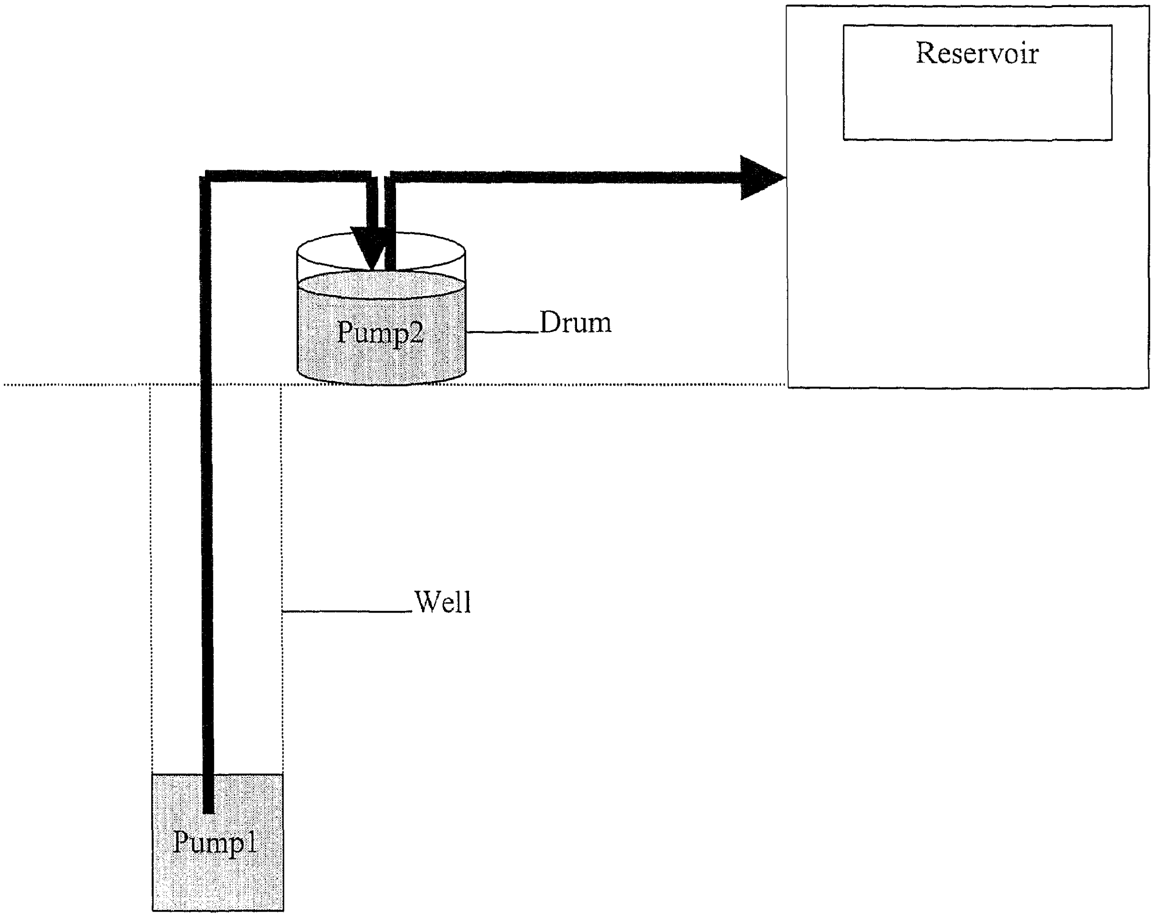
1. Site Dewatering
2. Permeability Studies
3. Experimental studies

## 5.1 Site Dewatering

The first activity carried out on the Site was dewatering. The purpose of dewatering was to get the water level below the fracture zone, about 13 feet below ground surface (BGS). This is necessary to keep the fracture zone free of water and to allow free passage of injected air into the fractures.

### 5.1.1 Method

The dewatering process at the Derelco Site is an ongoing process. The process involves first pumping water from the wells into a drum and from the drum into a larger reservoir (Figure 5.1). The water is then treated and discharged. Pump 1 (Figure 5.1) is a positive displacement pump. Pump 2 (Figure 5.1) is operated with a float level control system. Pump 2 stops when the float is in the horizontal position and starts when the float is above the horizontal position. Depending on the water level in the drum, the float will be either above the horizontal position (drum more than a third filled with water) or below the horizontal position (drum almost empty).



**5.1** Site Dewatering System

Pump 1 pumps water out of the wells into the drum and pump 2 pumps from the drum into the reservoir. With this system in place, the water level in the wells is about 13 feet BGS. When there is the need for aggressive pumping, the pumps can be switched from automatic operation to manual operation. Thus with this system in place the ground water can be kept at the desired level, which is greater than 13 feet BGS.

At the beginning of a pumping cycle the water level in the borehole rapidly rises as soon as pump 1 is switched off. It usually takes about 5 minutes to rise five feet. However, when aggressive pumping has gone on for about 60 minutes, the water level tends to rise slowly, 2 feet every 15 to 30 minutes. Pump 2 automatically starts when there is enough water in the drum to keep the float, controlling pump 2, above the horizontal inclination. Pump 1 can either be manually turned on to pump water out of the well or can be set to pump water out of the well at specified intervals of time. All the water recovered from the wells is pumped to an on-site water treatment facility from which the water is recirculated into the local drainage system. Some typical values of the water level 8 minutes after a pumping cycle are given below.

**Table 5.1** Water Level in Selected Wells after a Pumping Cycle

| Well Number | Water level, feet BGS |
|---|---|
| 1 | 23.8 |
| 2 | 12.8 |
| 3 | 10.7 |
| 4 | 17.5 |
| 5 | 14.5 |
| 6 | 13.4 |
| 7 | 10.4 |
| 8 | 14.6 |
| 9 | 12.8 |
| 10 | 13.2 |

**Table 5.1** Water Level in Selected Wells after a Pumping Cycle
(Continued)

| Well Number | Water level, feet BGS |
|---|---|
| 11 | 10.6 |
| 12 | Not accessible |
| 13 | 13.0 |
| 14 | 13.2 |
| 15 | 12.0 |

The data obtained from the Site dewatering experiments suggest that a period of about one hour of aggressive dewatering is required prior to the start of the experimental runs.

## 5.2 Field Permeability Studies

The aim of the permeability study was to find out if the resistance in the existing fractures was still low enough to permit easy passage of air. Low permeability will suggest that the soil fracturing process will have to be repeated at the Derelco Site. The permeability study was also designed to find out if the resistance in the piping and tubing were low enough to attain the desired air flowrates. The desired flowrate through the fractures, for the purposes of this study, is 10 – 20 SCFM. The field permeability study was carried out on both wells number 8 and number 7. The method involved connecting the extraction system to each of the wells in turn (Figure 5.2). Air was then sucked out of the wells at different levels of vacuum and the flowrate was measured for each different level of vacuum. First, the vacuum pump was set to maximum vacuum level and then gradually decreased for well 8 (Table 5.2). The flowrate was measured for each point until the minimum vacuum level was reached. The procedure was repeated for well 7 by increasing the vacuum and the flowrates were checked until the maximum vacuum level was attained (Table 5.3).

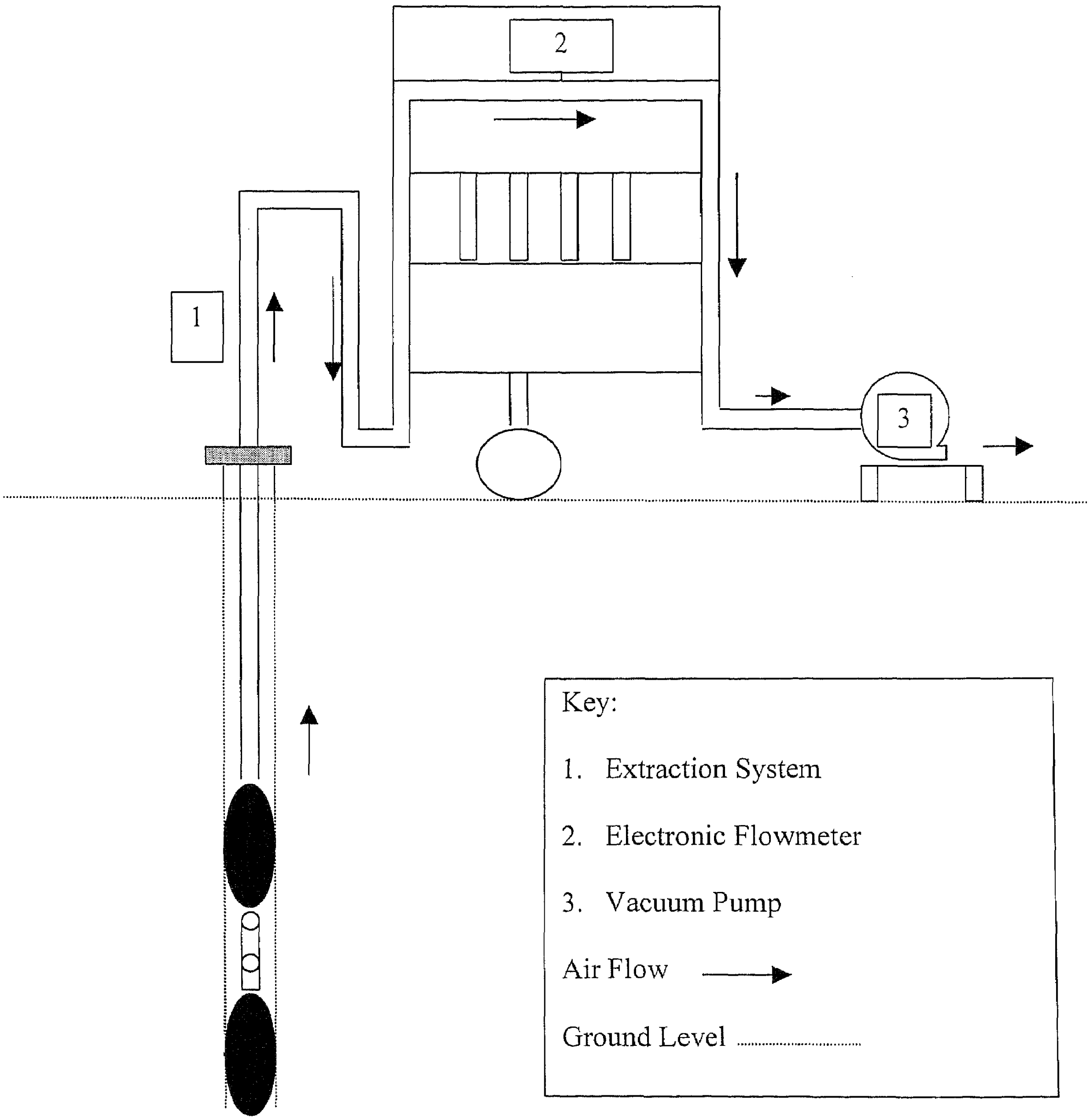


**Figure 5.2** Field Permeability Studies

The field permeability data are shown in Tables 5.2 and 5.3.

**Table 5.2** Field Permeability Studies

| Flowrate/SCFM-Air | Vacuum/ Inches of water | Well Number |
|---|---|---|
| 15.50 | 54.5 | 8 |
| 13.75 | 50.0 | 8 |
| 12.50 | 45.0 | 8 |
| 11.25 | 40.0 | 8 |
| 9.50 | 35.0 | 8 |
| 8.25 | 30.0 | 8 |
| 5.50 | 25.0 | 8 |
| 1.75 | 20.0 | 8 |

**Table 5.3** Field Permeability Studies

| Flowrate/SCFM-Air | Vacuum/inches of water | Well number |
|---|---|---|
| 1.75 | 20 | 7 |
| 5.75 | 25 | 7 |
| 7.75 | 30 | 7 |
| 9.00 | 35 | 7 |
| 10.25 | 40 | 7 |
| 11.50 | 45 | 7 |
| 13.00 | 50 | 7 |
| 14.00 | 55 | 7 |
| 14.25 | 56 | 7 |

The results obtained show that the maximum flowrate attainable, using the existing system is 15.50 SCFM. The major factor limiting the flow was the resistance within the copper lines. In order to reach the desired flowrates (10 – 20 SCFM) the flow manifold was redesigned to include an electronic flow meter and a 1 ½ inch copper piping fitting. The ¾ inch copper piping was by-passed and this new design increased the flow-rates almost 3 fold. The maximum flow rate was about 50 SCFM, reached at the maximum vacuum of 55 inches of water.

The permeability study showed that the fractures were still open and that the resistance within them was low enough to allow for the desired amount of air (10 –20 SCFM) to pass through the formation.

### 5.3 Preliminary Field Experimental Studies

Prior to the experimental study, a preliminary study was conducted. The aim of this study was to get familiarized with the operation of the equipment and also to have an idea of the major contaminants present at the site. The first part of this study involved drawing samples of air from the intended extraction well (using the vacuum pump) and analyzing the concentrations of the contaminants with both the GC and a PID. Two runs were conducted with a time lapse of about 11 minutes between the two runs. The vacuum pump was left running for the period between the two runs. The results obtained from the GC were checked with a PID to verify the reliability of the data obtained. The results are summarized in Table 5.4.

**Table 5.4** Preliminary Field Study

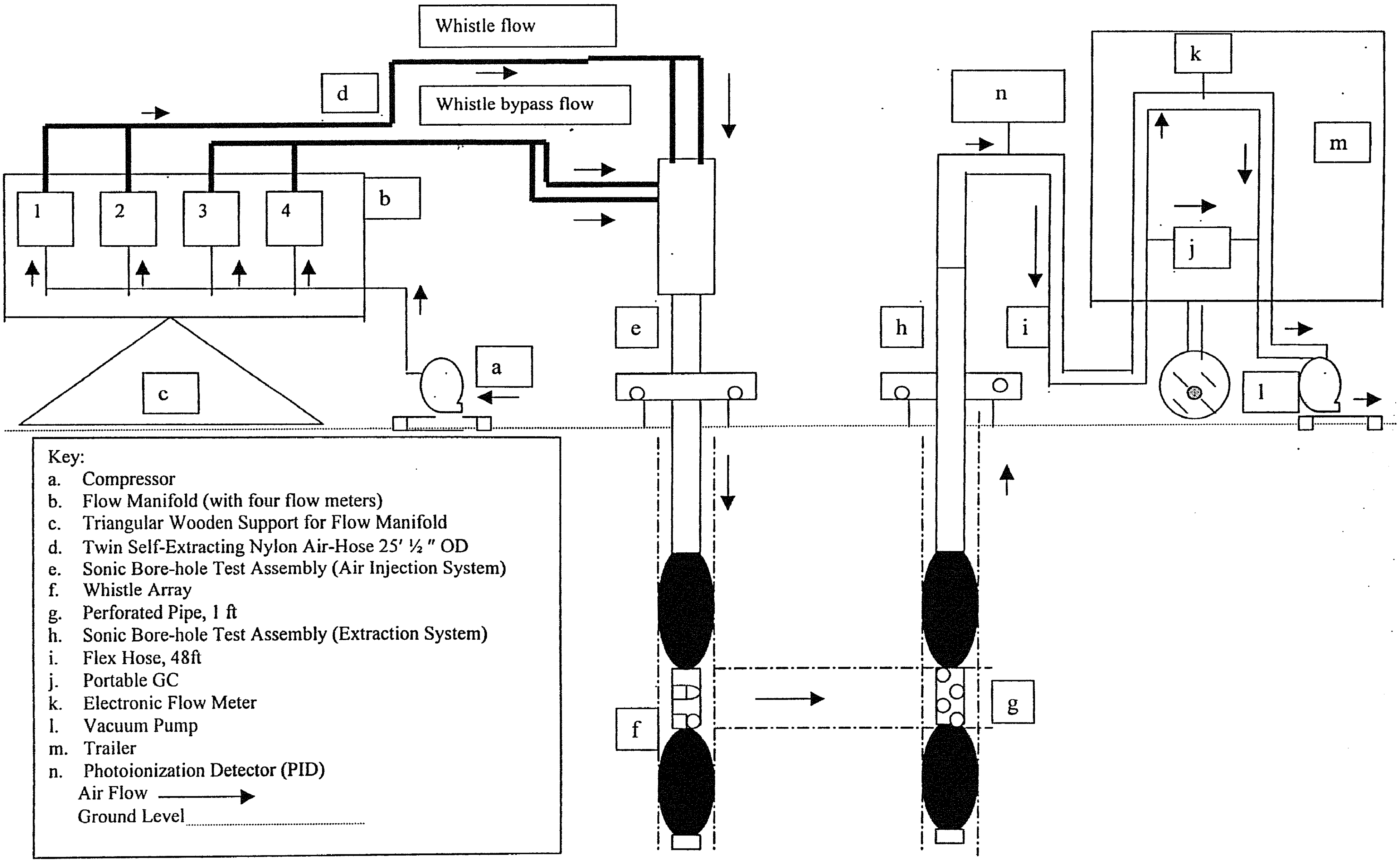
| Contaminant | Concentration, PPMv | Concentration, PPMv |
|---|---|---|
| | GC | PID |
| TCE | 5.58 | 6.6 |
| DCE | 0 | 0 |

For each case, the detector was placed at the exhaust of the vacuum pump and the sample was taken at the same time that the GC started to sample. Other results obtained from the first part of the preliminary study are summarized in Table A.34 and Table A.35 (Appendix A).

The first part of the preliminary field study led to the following conclusion:

1. Table A.34 shows that the pressure drop through the whistles and the feed lines increases substantially with flowrate.
2. The major contaminant present appears to be TCE (Table A.35).
3. There may be traces of DCE and other unknowns (Table A.35).

The second part of the preliminary field study involved performing the first sonic experiments. For this purpose two preliminary experiments were performed. The process flow diagram for the preliminary experiments is shown in Figure 5.3.



Key:
a. Compressor
b. Flow Manifold (with four flow meters)
c. Triangular Wooden Support for Flow Manifold
d. Twin Self-Extracting Nylon Air-Hose 25′ ½ ″ OD
e. Sonic Bore-hole Test Assembly (Air Injection System)
f. Whistle Array
g. Perforated Pipe, 1 ft
h. Sonic Bore-hole Test Assembly (Extraction System)
i. Flex Hose, 48ft
j. Portable GC
k. Electronic Flow Meter
l. Vacuum Pump
m. Trailer
n. Photoionization Detector (PID)
Air Flow ⟶
Ground Level ..........

**Figure 5.3** Field Layout

### 5.3.1 First Preliminary Run (Saturday, September 26, 1998)

The first preliminary run was carried out on September 26, 1998. The run started around 10.00 AM. The weather conditions for this day were mild with a cool morning and perfectly dry conditions. There were no strong winds on this day.

**5.3.1.1 Experimental Procedure for Preliminary Experiment 1:** The experimental procedure involved the following;

Well number 4 was used as the injection well and well number 8 was used as the extraction well. This arrangement was chosen because at a distance of about 9 feet down well number 8 there was a constriction which prevented the whistle array from going lower into the well. Also the well video tapes showed that well number 4 and well number 8 had very good fractures. All the other wells were sealed with rubber caps which tightened by a bolt and expanded against the inside wall of the borehole pipe. The distance between the centers of the two wells is 7 feet and 8 inches. The injection system was lowered into well number 4 so that the center of the two whistles was at 13.3 feet BGS. The extraction system was lowered into well number 8 so that the center of the perforated pipe was at 14.9 feet BGS. The equipment was laid out as shown in Figure 5.3. The packers were then inflated with an external source of Nitrogen until there was a tight seal in each of the two wells. The compressor was turned on for about five minutes to allow all the water vapor to evaporate. The vacuum pump was then turned on and the compressed air from the compressor was then connected to the flow manifold. The flow meters were then adjusted so that no flow went through flowmeters 1 and 2 (whistles shut) and 5 SCFM was allowed to go through each of the flowmeters 3 and 4 (total flow = 10 SCFM, whistle by pass open).

The PID was then used to measure the concentrations of the gases going through the extraction line, as a function of time. The PID was used to measure concentrations for a total of 3772 seconds (about one hour). After this period the flow was switched from the by pass to the whistles. This was done in order to find the impact of the sonic energy on the amount of organic removed. The flow was switched so that no flow went through flow meters 3 and 4(by pass shut) and then flowmeters 1 and 2 were each turned on to 5 SCFM (total flow = 10 SCFM, whistles open). The PID was then allowed to take samples for a total duration of 2090 seconds (35 minutes).

The flow was then switched back to flowmeters 3 and 4 so that no flow went through 1 and 2 (whistles shut). A flow of 5 SCFM was allowed to go through each of the flow meters 3 and 4 (by pass open). The PID was again used to sample for 1055 seconds (18 minutes). This entire cycle completed the first preliminary experiment. The total duration of this experiment was about 1 hour and 55minutes.

### 5.3.2 Second Preliminary Run (Saturday, September 26, 1998)

The second preliminary run was carried out on September 26, 1998. The run started around 1.30 PM. The weather conditions for this day were mild with a warm afternoon and perfectly dry conditions. There were no strong winds on this day.

**5.3.2.1 Experimental Procedure for Preliminary Experiment 2:** The procedure for preliminary Experiment 2 was as follows;

The flow meters were adjusted so that no flow went through flowmeters 1 and 2 (whistles shut) and 5 SCFM was allowed to go through each of the flowmeters 3 and 4 (total flow = 10 SCFM, whistle by pass open). The PID was then used to measure the concentrations of the gases going through the extraction line, as a function of time. The PID was used to measure the concentration of TCE for a total of 3085 seconds (about 52 minutes). After this period the flow was switched from the by pass to the whistle. This was done in order to find the impact of the sonic energy on the amount of organic removed. The flow was switched so that no flow went through flow meters 3 and 4 (whistle by pass shut) and then flow meters 1 and 2 were each turned on to 5 SCFM (total flow = 10SCFM, whistles open). The PID was then used to measure concentrations for a total duration of 2930 seconds (about 49 minutes). This entire cycle completed the second preliminary experiment. The entire experiment was for a duration of about 1 hour and 40 minutes.

### 5.3.3 Results of the Preliminary Studies

The results obtained for the preliminary field sonic experimental studies are presented in Figure 5.4 – Figure 5.7 and the measured data are shown in Tables A.1 - A.7.

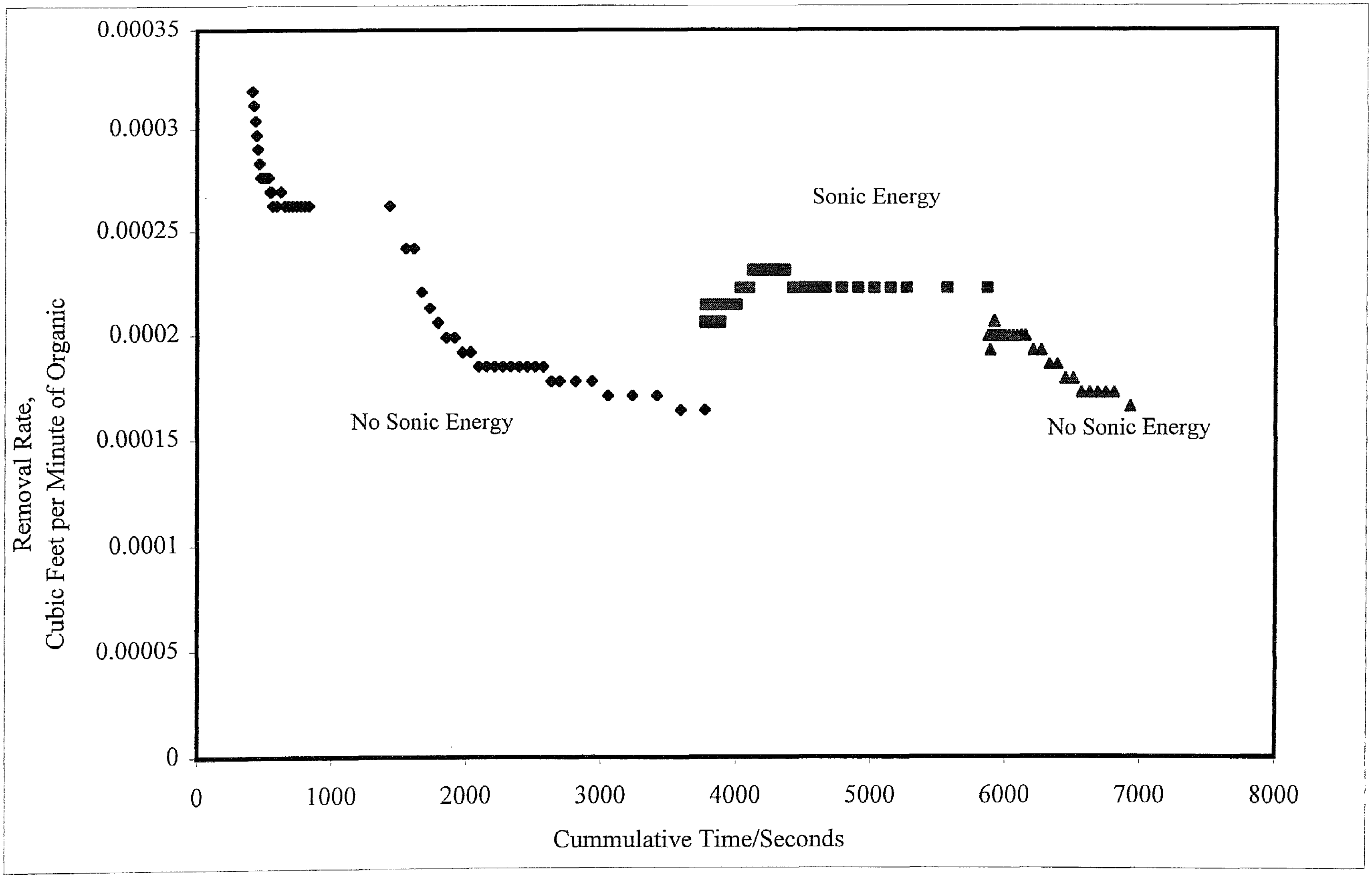


**Figure 5.4** Removal Rate of Organic (First Preliminary Study)

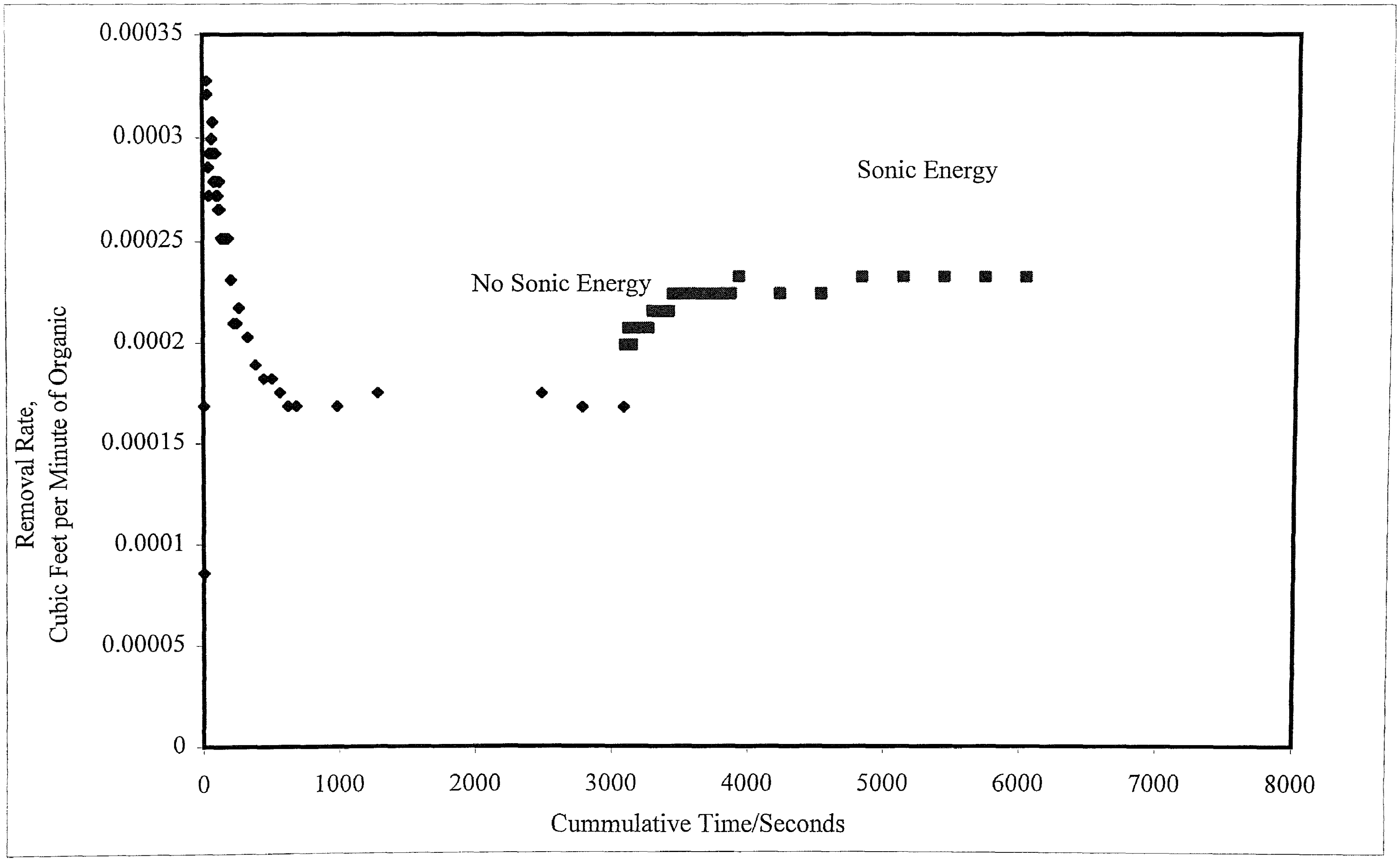


**Figure 5.5** Removal Rate of Organic (Second Preliminary Study)

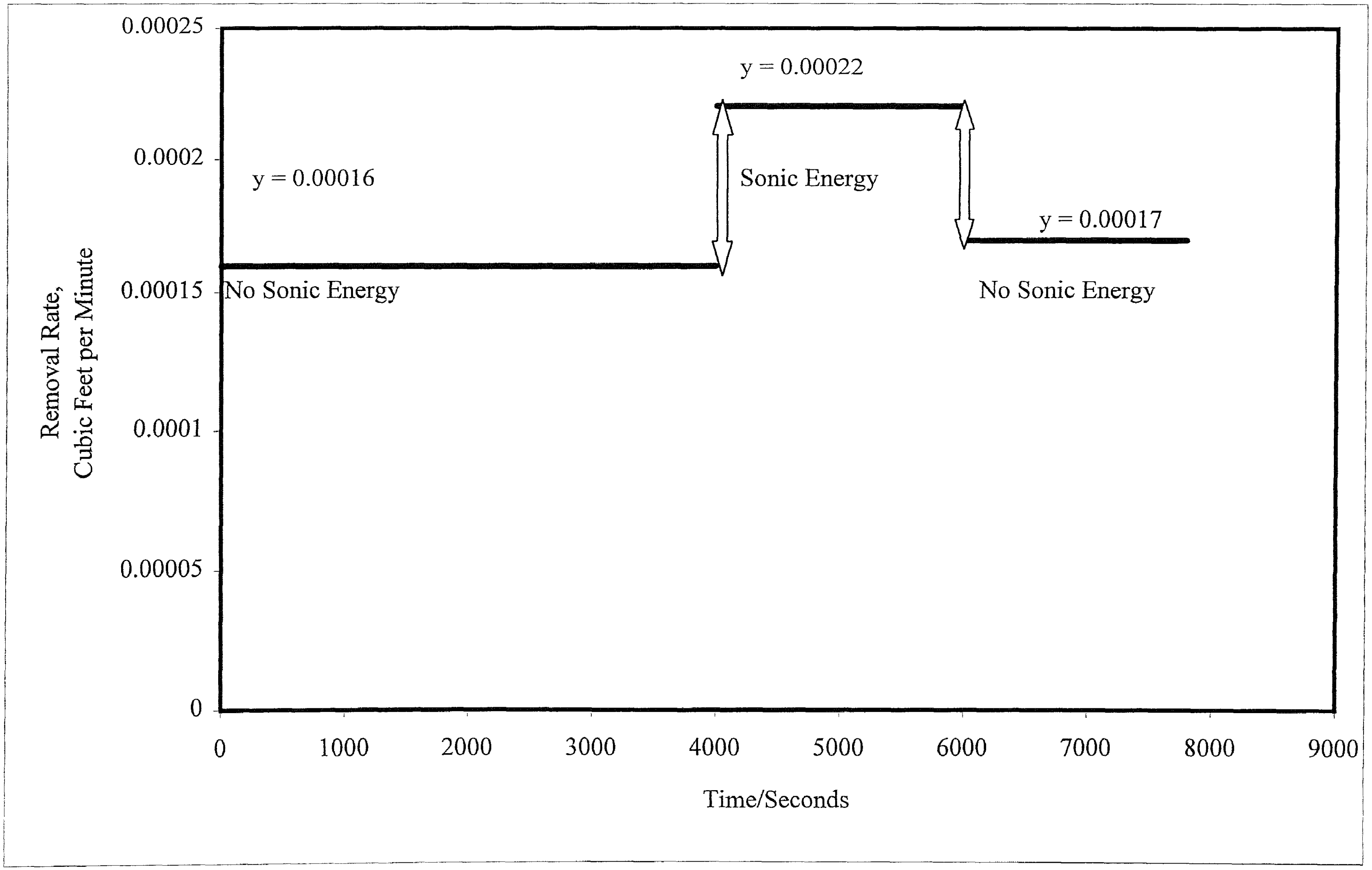


**Figure 5.6** Average Rate of Removal of Organic at Assymptotic Value (First Preliminary Study)

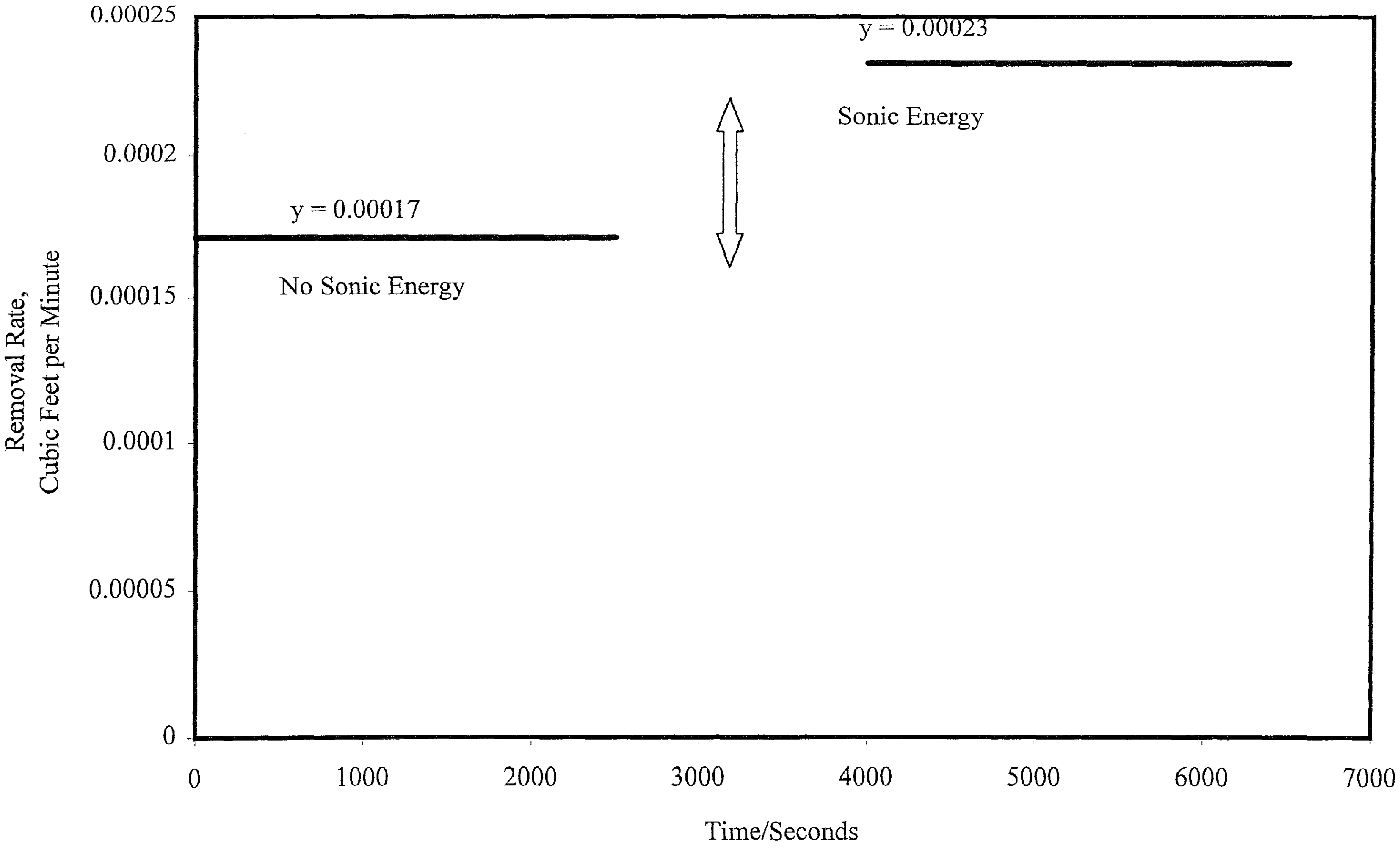


**Figure 5.7** Average Rate of Removal of Organic at Assymptotic Value (Second Preliminary Study)

### 5.3.4 Discussion of the Results Obtained from the Preliminary Field Study

In Figure 5.4, initially the experiments are performed using air alone. During this period the rate of removal of the organic contaminant decreases from a peak value of about 0.00025 cubic feet per minute until it stabilizes at a constant rate of removal of about 0.00017 cubic feet per minute. The rate of removal remains at this constant value for about 20 minutes. When the Sonic energy is turned on, the sonic energy causes the rate of removal to increase from the original constant value of 0.00017 cubic feet per minute to a higher constant rate of removal of about 0.00023 cubic feet per minute. The rate of removal remains at this higher constant value for about 30 minutes. When the operating conditions are turned back to air, the rate of removal again drops from about 0.00023 cubic feet per minute to an average value of about 0.00017 cubic feet per minute and stays at this value until the end of the first preliminary study.

Figure 5.5 Shows the results obtained for the second preliminary study. Initially, the experiments are performed using air alone. During this period the rate of removal of the organic contaminant decreases from a peak value of about 0.0003 cubic feet per minute until it stabilizes at a constant rate of removal of about 0.00017 cubic feet per minute. The rate of removal remains at this constant value for about 40 minutes. When the sonic energy is turned on, the sonic energy causes the rate of removal to increase from the original constant value of 0.00017 cubic feet per minute to a higher constant rate of removal of about 0.00023 cubic feet per minute. The rate of removal remains at this higher constant value for about 43 minutes, end of the second preliminary study. Figure 5.6 and Figure 5.7 give the average values of the constant rate periods over the total duration of the experiments. The percentage improvement, calculated from Figure 5.6 is about 37.5% for the first part and 29.4% for the second part. The percentage improvement, calculated from Figure 5.7 is about 35%.

The preliminary field study shows that sonic energy can lead to a significant improvement in both the rate of removal and the amount of organic contaminant removed. The results of the preliminary studies also show that the existing experimental system, experimental approach and the site under investigation were well suited to perform the sonic field experiments.

## 5.4 Detailed Field Experimental Studies

The experimental study involved four runs. The dates of the experimental runs were :

Experimental Run 1 : Sunday September 27, 1998.
Experimental Run 2 : Saturday November 7, 1998.
Experimental Run 3 : Saturday November 14, 1998.
Experimental Run 4 : Sunday November 15, 1998.
Additional Field Experiment: Sunday November 8, 1998.

The experiments were carried out each time switching between the use of sonic energy and without the use of sonic energy. A summary of the experiments is given below.

Experimental Run 1 : Sonic energy – no sonic energy –Sonic energy - no sonic energy
Experimental Run 2 : Sonic energy- no sonic energy-Sonic energy- no sonic energy
Experimental Run 3 : no sonic energy-Sonic energy- no sonic energy-Sonic energy
Experimental Run 4 : Sonic energy- no sonic energy-Sonic energy- no sonic energy

Additional Field Experiment: no sonic energy-Sonic energy- no sonic energy-Sonic energy- no sonic energy

### 5.4.1 Setup of Experimental Apparatus

The entire setup for the sonic field study is shown in Figure 5.3.

### 5.4.2 Experimental Runs

Each of the experimental runs is described in detail in the following sections. The results obtained are also presented here and the discussion of the results, for each of the runs, is given in Chapter 6.

**5.4.2.1 Experimental Run 1, Sunday September 27, 1998:** The first experimental run was carried out on September 27, 1998. The run started around 9.15 AM. It was a nice day with some sunshine and dry conditions. There were no strong winds on this day.

**5.4.2.1.1 Experimental Procedure:** The flow was switched so that no flow went through flow meters 3 and 4 (whistle by pass shut) and then flow meters 1 and 2 were each turned on to 5 SCFM (total flow = 10SCFM, whistles open). The PID was then used to measure the concentration of TCE for a total duration of 2130 seconds (about 36 minutes). The flow meters were then adjusted so that no flow went through flowmeters 1 and 2 (whistles shut) and 5 SCFM was allowed to go through each of the flowmeters 3 and 4 (total flow = 10 SCFM, whistle by pass open). The PID was then used to measure the concentrations of the gases going through the extraction line, as a function of time. The PID was used to sample for a total of 2975 seconds (about 50 minutes).

After this period the flow was switched from the by pass to the whistle. This was done in order to find the impact of the sonic energy on the amount of organic removed. The flow was switched so that no flow went through flow meters 3 and 4 (whistle by pass shut) and then flow meters 1 and 2 were each turned on to 5 SCFM (total flow = 10 SCFM, whistles open). The PID was then used to measure the concentration of TCE for a total duration of 2905 seconds (48 minutes). The flow was again switched back to flowmeters 3 and 4 so that no flow went through 1 and 2 (whistles shut). A flow of 5 SCFM was allowed to go through each of the flow meters 3 and 4 (whistle by pass open). The PID was again used to measure the concentration of TCE for 1840 seconds (about 30 minutes). This entire cycle completed the first experimental run. The total duration of this experiment was about 2 hours and 45 minutes.

**5.4.2.1.2 Results of Experimental Run 1, Sunday September 27, 1998:** The results obtained for the first experimental run are presented in Figure 5.8 – Figure 5.13 and Tables A.8 –A.12.

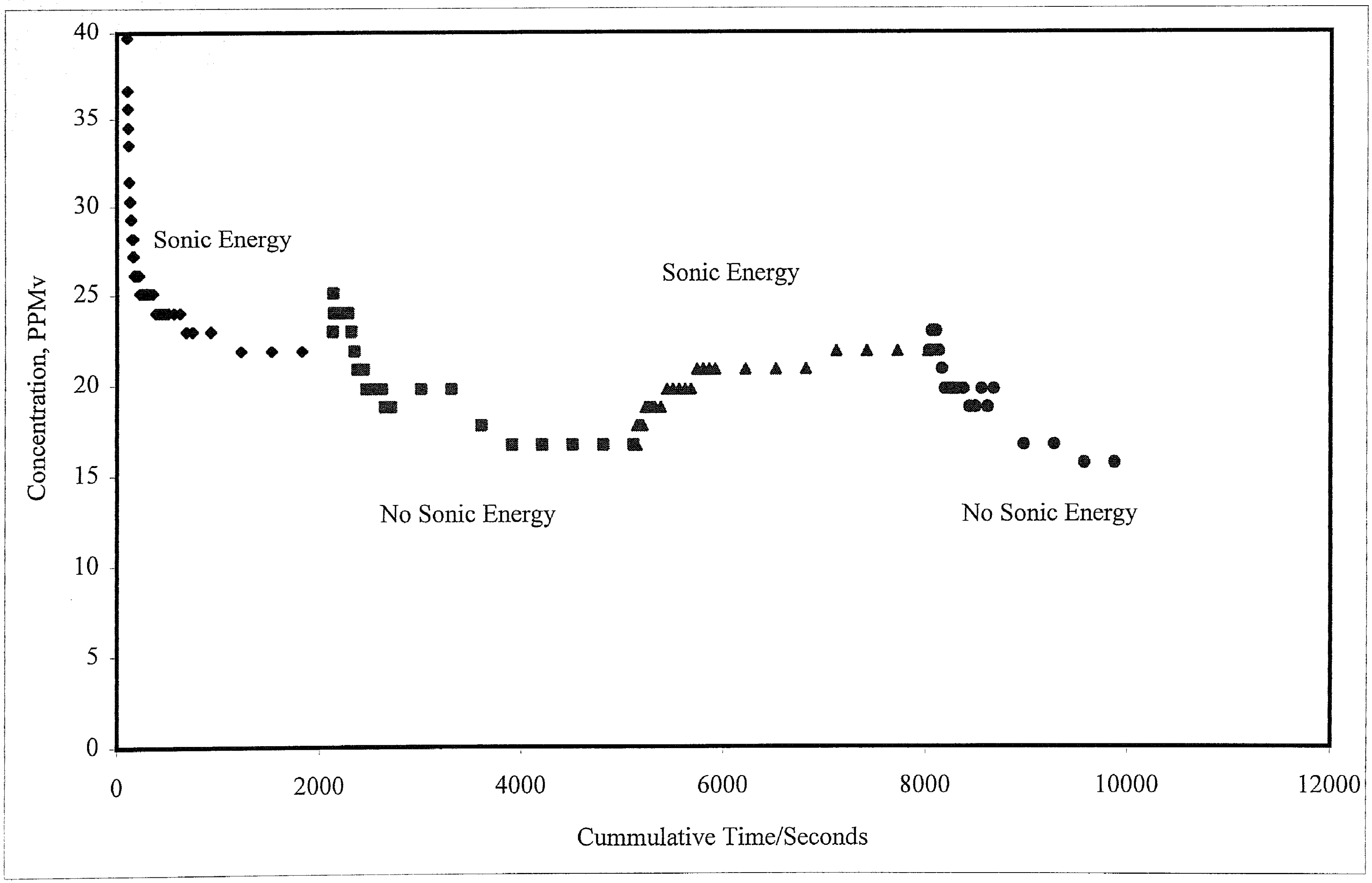


**Figure 5.8** Concentration of Trichloroethylene in Effluent Stream (Experiment 1)

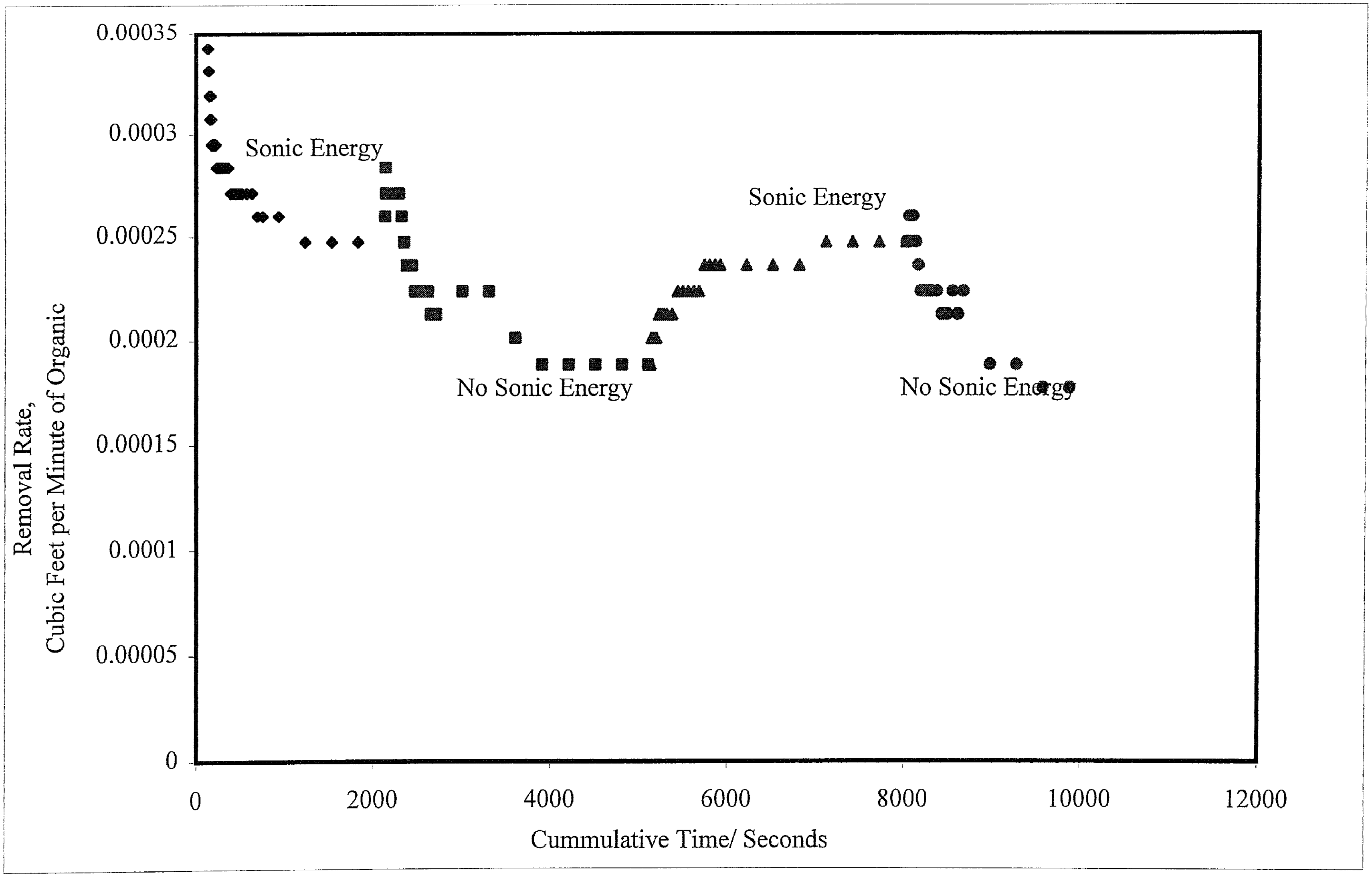


**Figure 5.9** Removal Rate of Organic (Experiment 1)

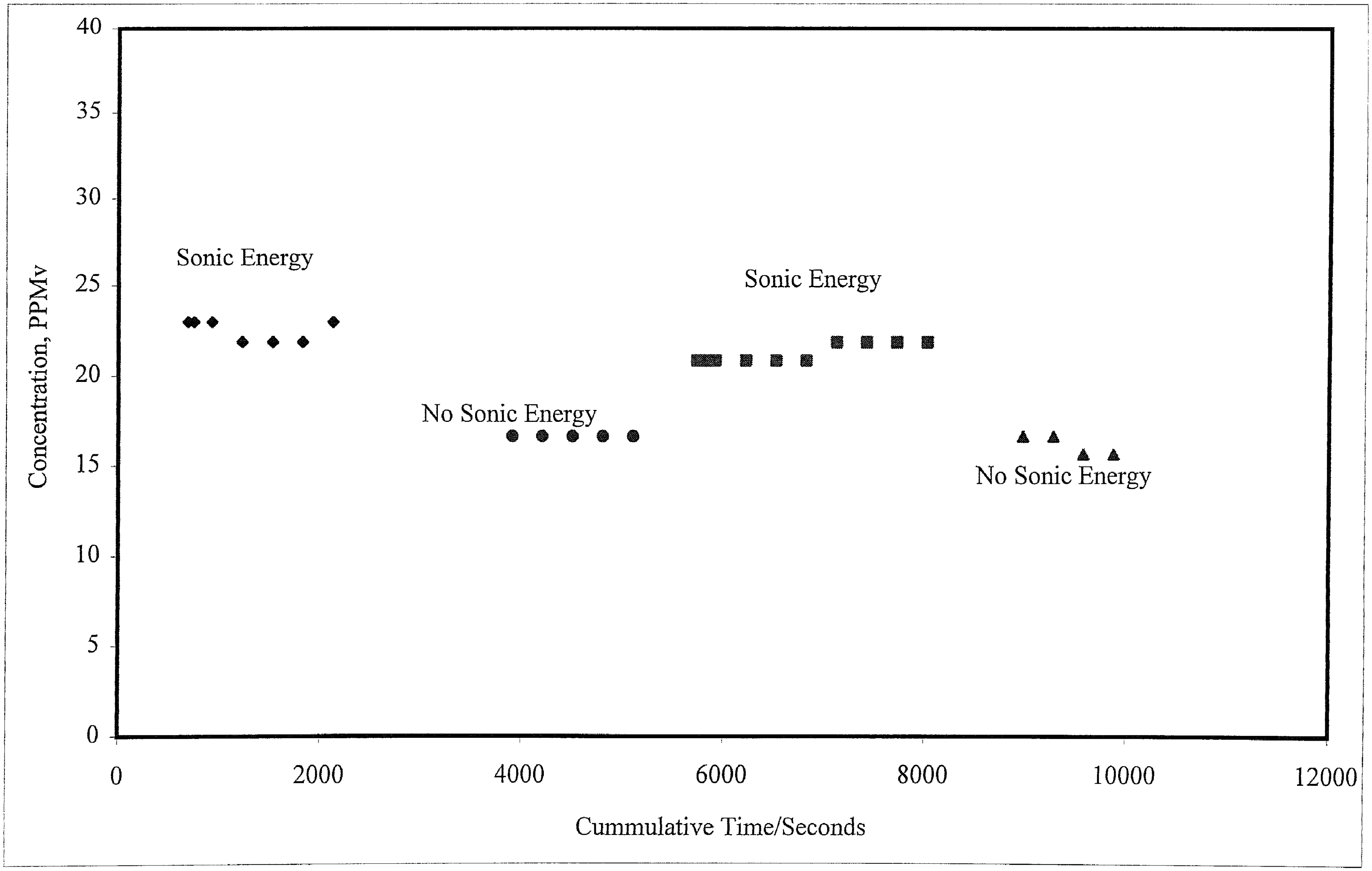


**Figure 5.10** Assymptotic Values of Concentration of Trichloroethylene in Effluent Stream (Experiment 1)

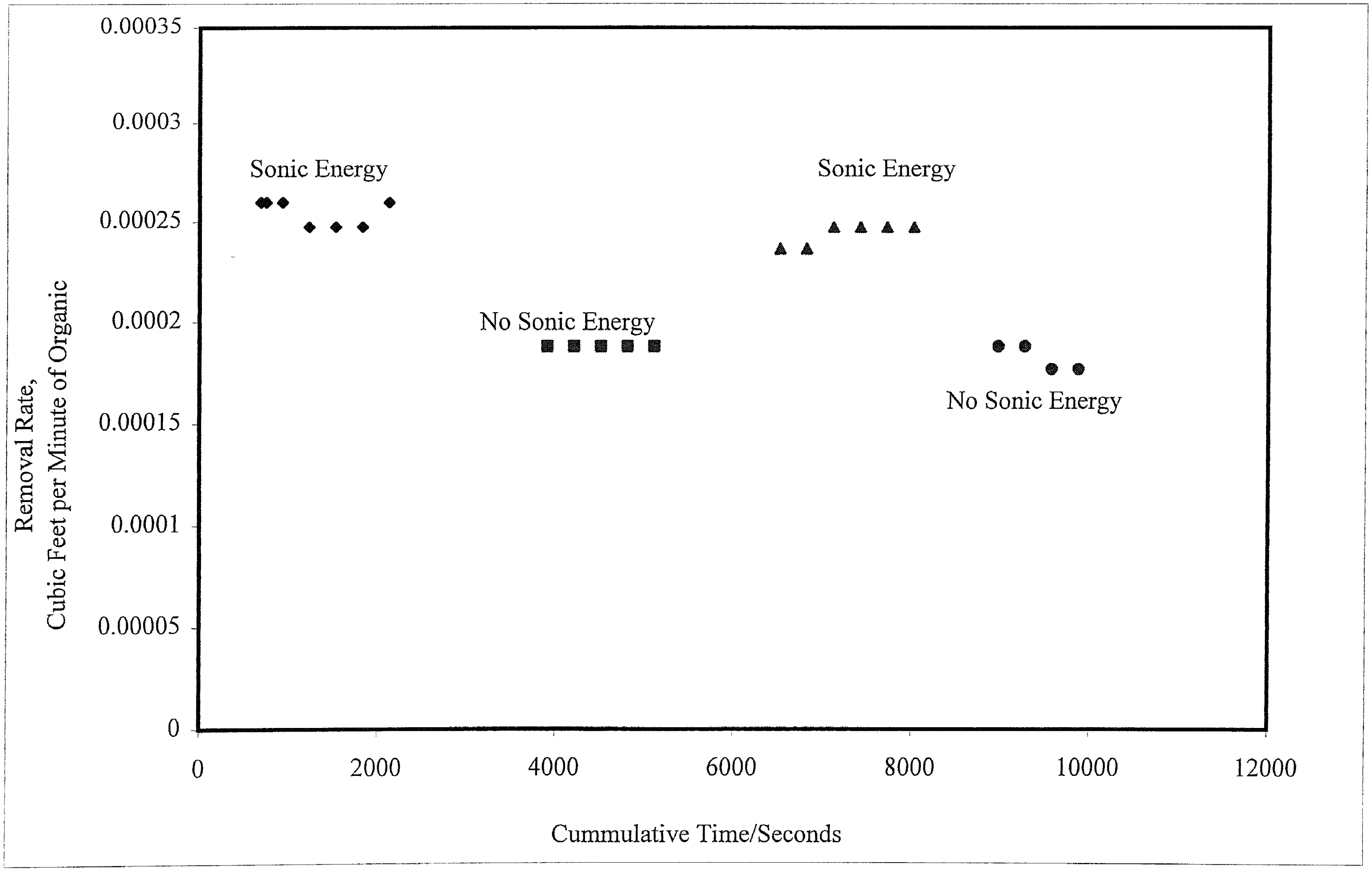


**Figure 5.11** Assymptotic Values of Removal Rate of Organic (Experiment 1)

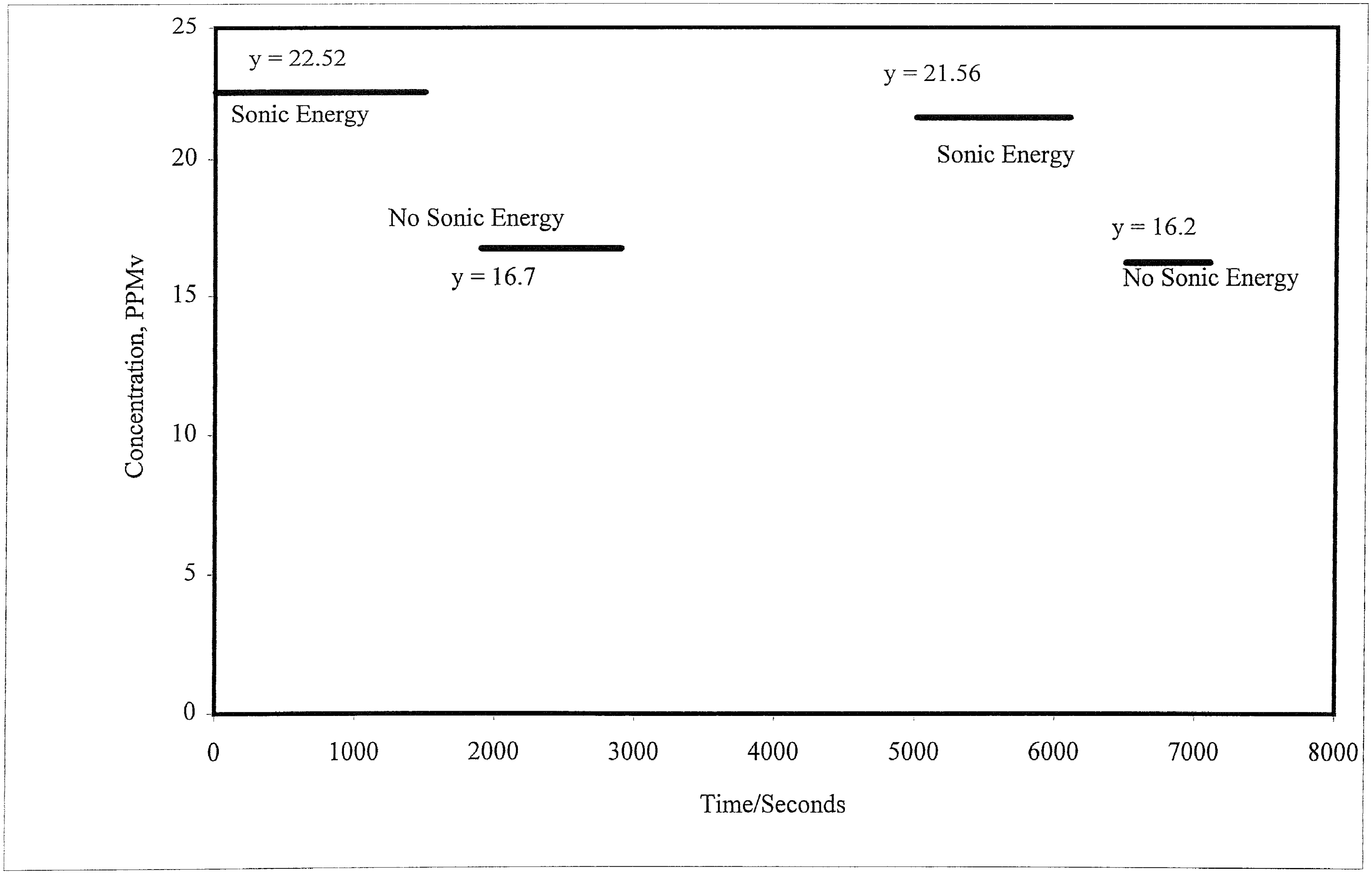


**Figure 5.12** Average Value of Concentration of Trichloroethylene in Effluent Stream at Assymptotic Value (Experiment 1)

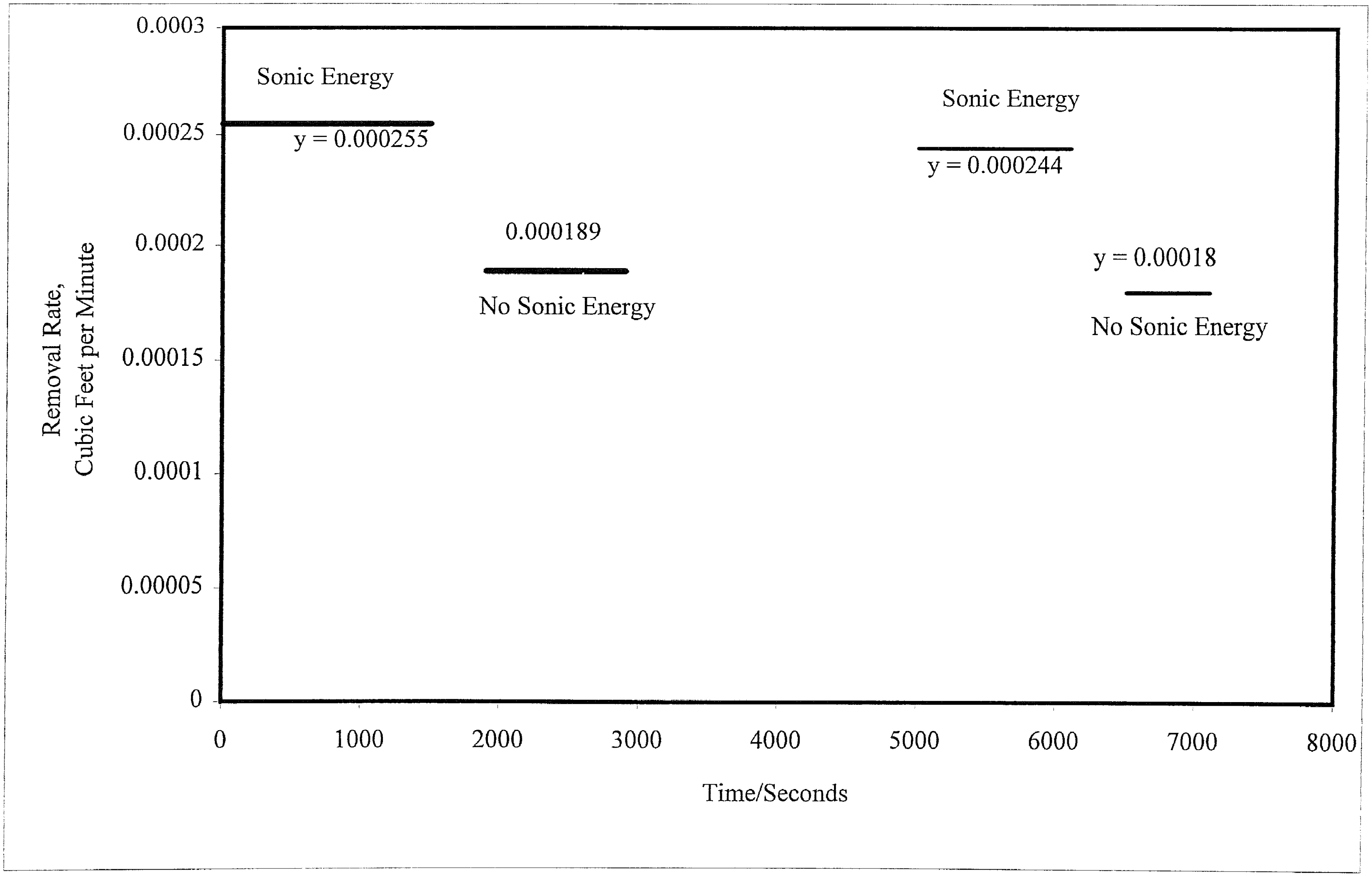


**Figure 5.13** Average Rate of Removal of Organic at Assymptotic Value (Experiment 1)

**5.4.2.2 Experimental Run 2, Saturday November 7, 1998:** The Second experimental run was carried out on November 7, 1998. The run started around 12.44 PM. It was a sunny day with some gentle wind and dry conditions.

**5.4.2.2.1 Experimental Procedure:** The procedure for Experimental Run 2 was as follows;

The flow was switched so that no flow went through flow meters 3 and 4 (whistle by pass shut) and then flow meters 1 and 2 were each turned on to 5 SCFM (total flow = 10 SCFM, whistles open). The PID was then used to measure the concentration for a total duration of 3355 seconds (about 60 minutes). The flow meters were then adjusted so that no flow went through flowmeters 1 and 2 (whistles shut) and 5 SCFM was allowed to go through each of the flowmeters 3 and 4 (total flow = 10 SCFM, whistle by pass open). The PID was then used to measure the concentrations of the gases going through the extraction line, as a function of time. The PID was used to sample for a total of 3630 seconds (about 60 minutes).

After this period the flow was switched from the by pass to the whistle. This was done in order to find the impact of the sonic energy on the amount of organic removed. The flow was switched so that no flow went through flow meters 3 and 4 (whistle by pass shut) and then flow meters 1 and 2 were each turned on to 5 SCFM (total flow = 10 SCFM, whistles open). The PID was then used to take samples for a total duration of 3000 seconds (50 minutes).The flow was again switched back to flowmeters 3 and 4 so that no flow went through 1 and 2 (whistles shut). A flow of 5 SCFM was allowed to go through each of the flow meters 3 and 4 (whistle by pass open). The PID was again used to measure the concentration of TCE for 2460 seconds (about 41 minutes). This entire cycle completed the second experimental run. The total duration of this experiment was about 3 hours and 30 minutes.

**5.4.2.2.2 Results of Experimental Run 2, Saturday November 7, 1998:** The results obtained for the second experimental run are presented in Figure 5.14 – Figure 5.19 and Tables A.13 – A.17.

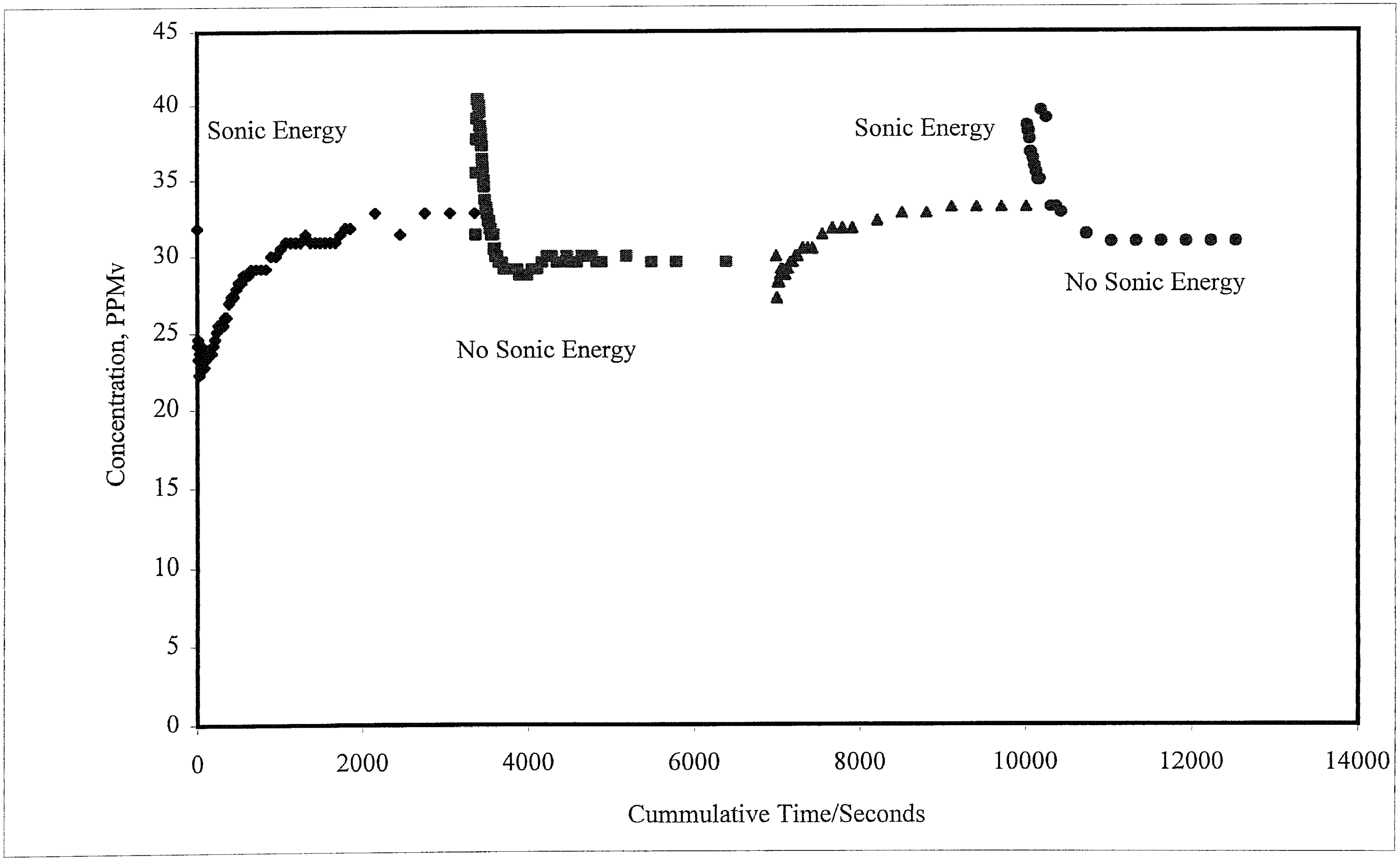


**Figure 5.14** Concentration of Trichloroethylene in Effluent Stream (Experiment 2)

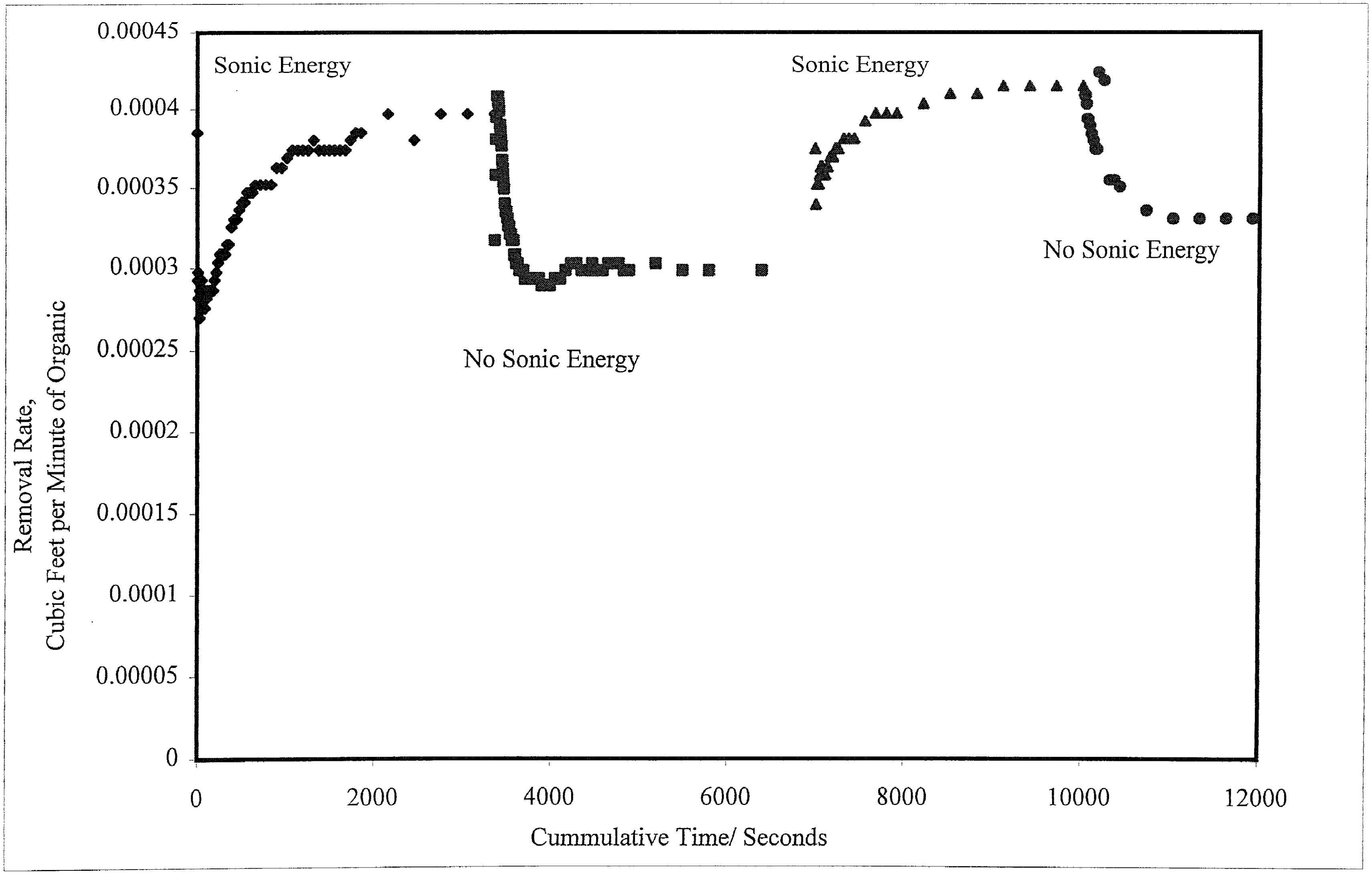


**Figure 5.15** Removal Rate of Organic (Experiment 2)

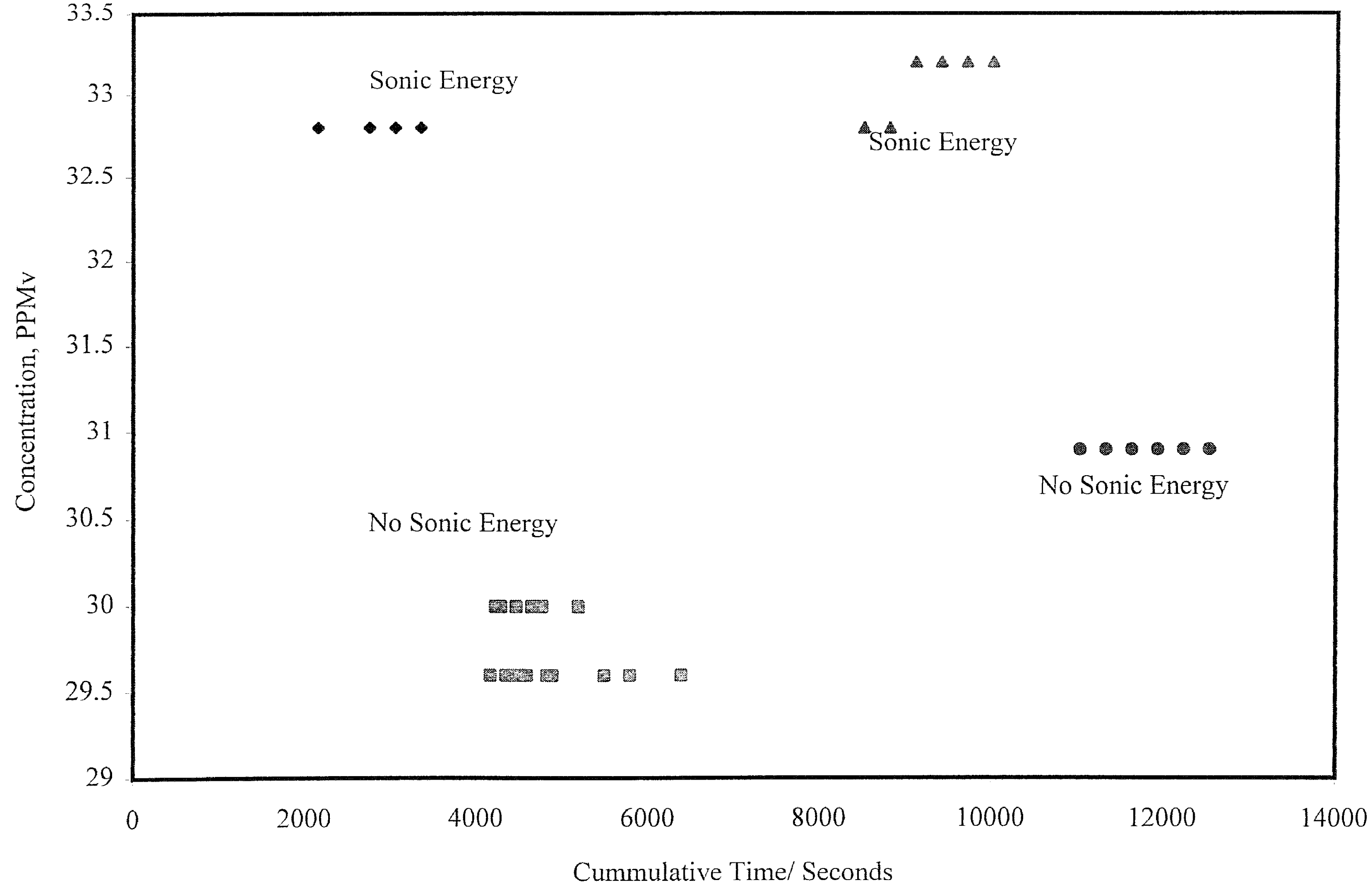


**Figure 5.16** Assymptotic Values of Concentration of Trichloroethylene in Effluent Stream (Experiment 2)

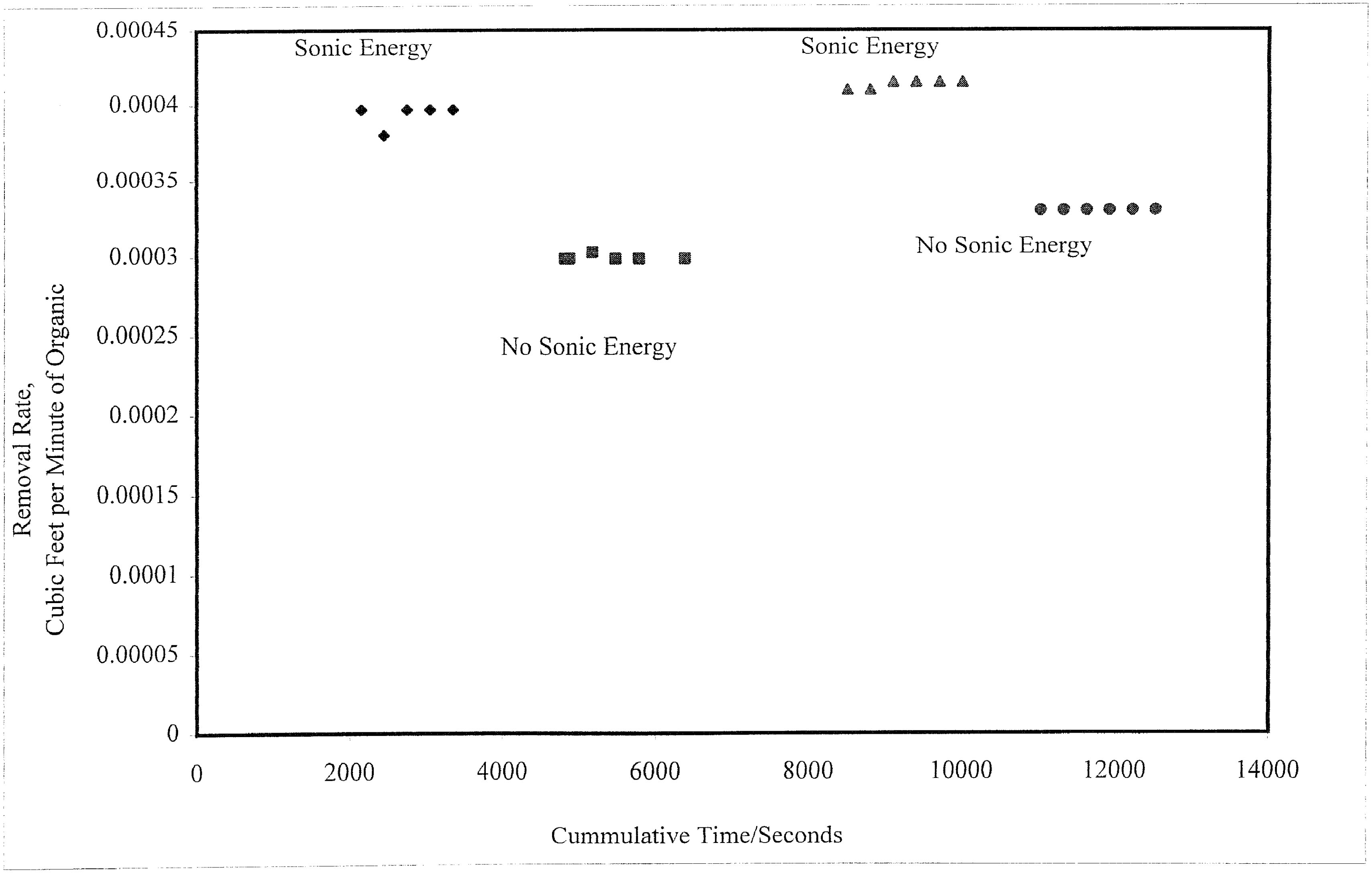


**Figure 5.17** Assymptotic Values of Removal Rate of Organic (Experiment 2)

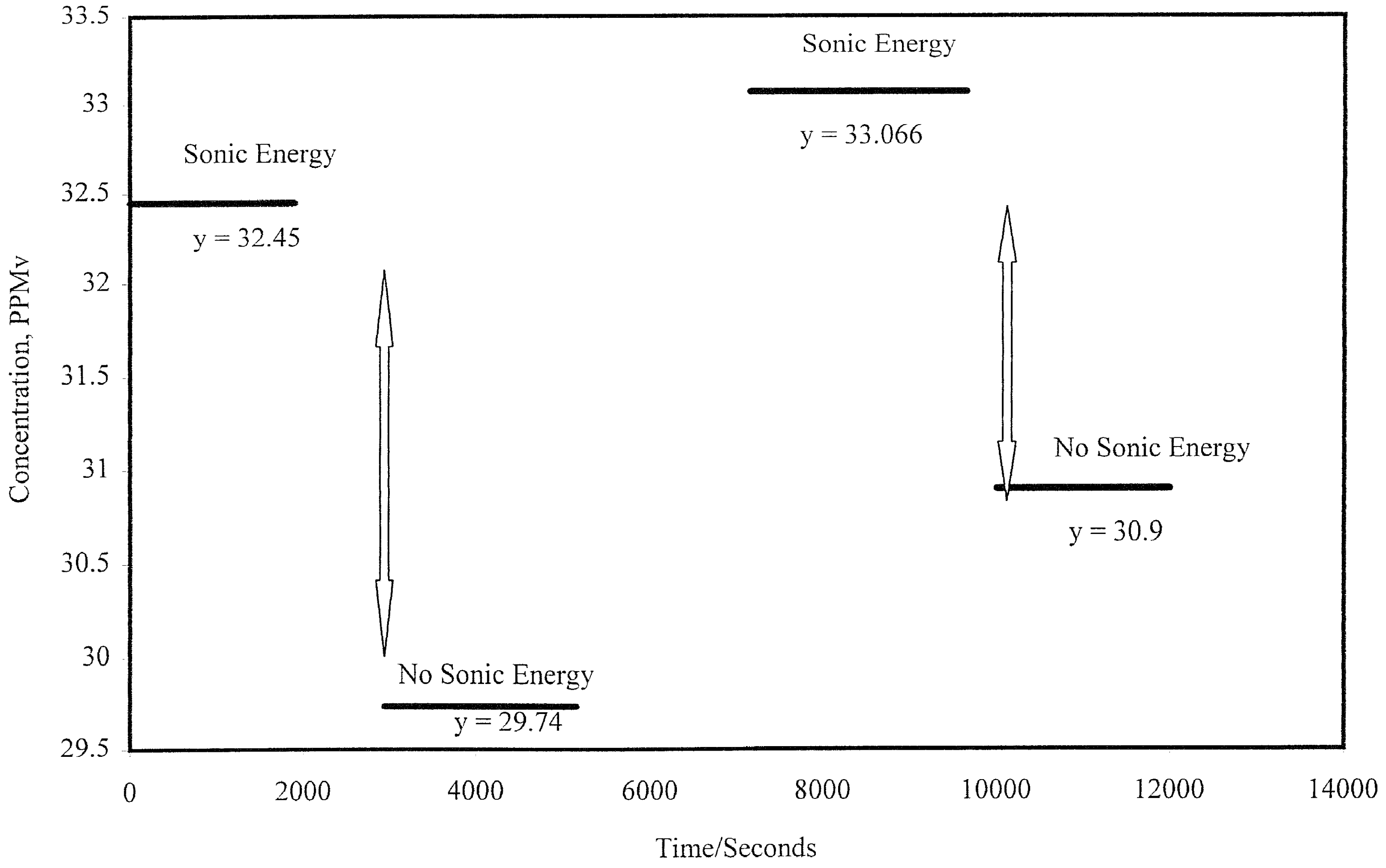


**Figure 5.18** Average Value of Concentration of Trichloroethylene in Effluent Stream at Assymptotic Value (Experiment 2)

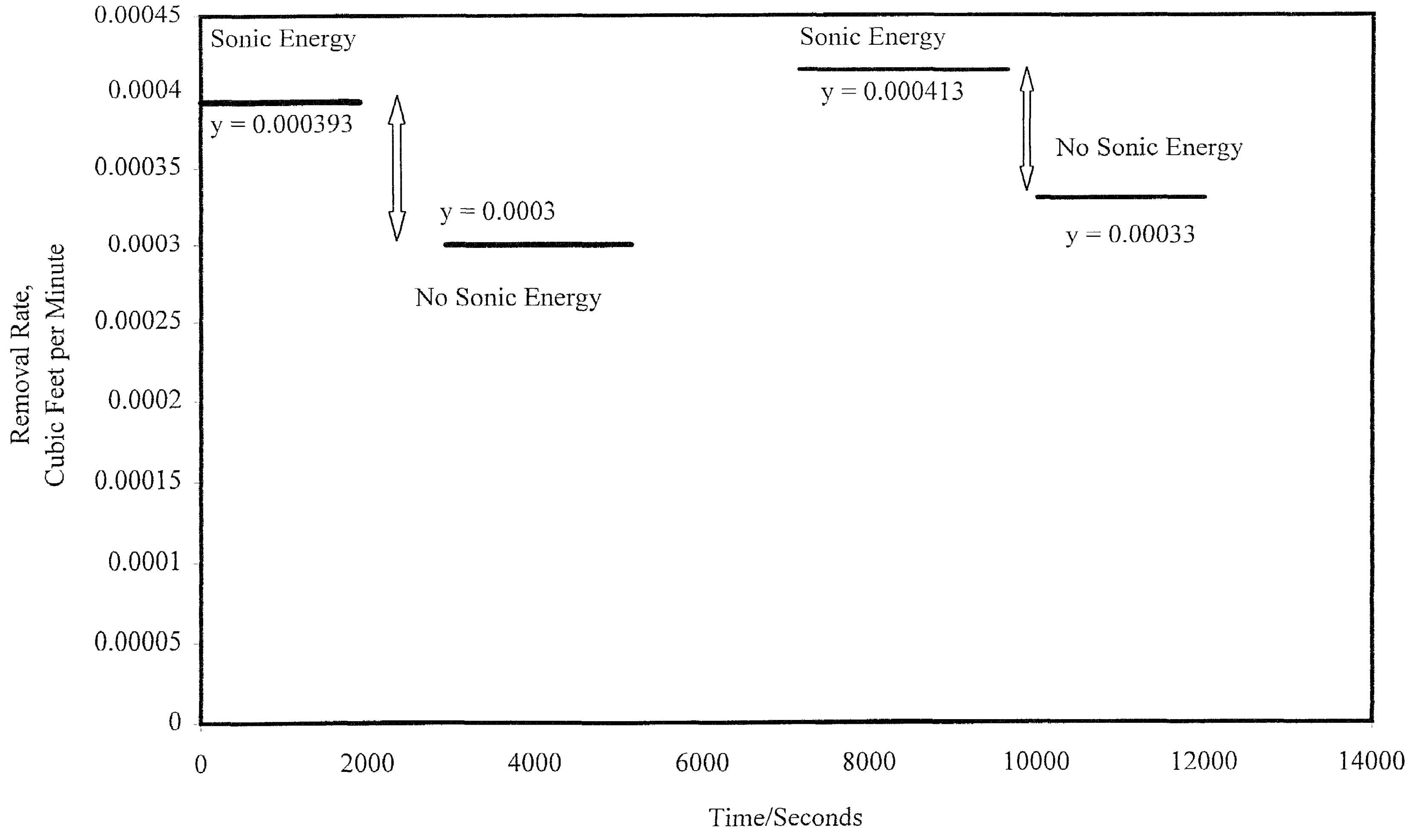


**Figure 5.19** Average Rate of Removal of Organic at Assymptotic Value (Experiment 2)

**5.4.2.3 Experimental Run 3, Saturday November 14, 1998:** The third experimental run was carried out on November 14, 1998. The run started around 10.25 AM. It was a cool, sunny day with dry conditions and there were no strong winds on this day.

**5.4.2.3.1 Experimental Procedure:** The procedure for Experimental Run 3 was as follows;

The flow rate of air was switched so that no flow went through flowmeters 1 and 2 (whistles shut) and then flowmeters 3 and 4 were each turned on to 5 SCFM (total flow = 10SCFM, whistle by pass open). The PID was then used to measure the concentration of TCE for a total duration of 3000 seconds (about 50 minutes). The flow meters were then adjusted so that no flow went through flowmeters 3 and 4 (whistles open) and 5 SCFM was allowed to go through each of the flowmeters 1 and 2 (total flow = 10 SCFM, whistle by pass shut). The PID was then used to measure the concentrations of the gases going through the extraction line, as a function of time. The PID was used to measure the concentration of TCE for a total duration of 3000 seconds (about 50 minutes).

After this period the flow was switched from the whistle to the by pass. This was done in order to find the impact of the sonic energy on the amount of organic removed. The flow was switched so that no flow went through flow meters 1 and 2 (whistles shut) and then flow meters 3 and 4 were each turned on to 5 SCFM (total flow = 10 SCFM, whistle by pass open). The PID was then used to take samples for a total duration of 2580 seconds (43 minutes). The flow was again switched back to flowmeters 1 and 2 so that no flow went through 3 and 4 (whistles open). A flow of 5 SCFM was allowed to go through each of the flow meters 1 and 2 (whistles open). The PID was again allowed to sample for 3600 seconds (about 60 minutes). This entire cycle completed the third experimental run. The total duration of this experiment was about 3 hours and 23 minutes.

**5.4.2.3.2 Results of Experimental Run 3, Saturday November 14, 1998:** The results obtained for the third experimental run are presented in Figure 5.20 – Figure 5.25 and Tables A.19 – A.22.

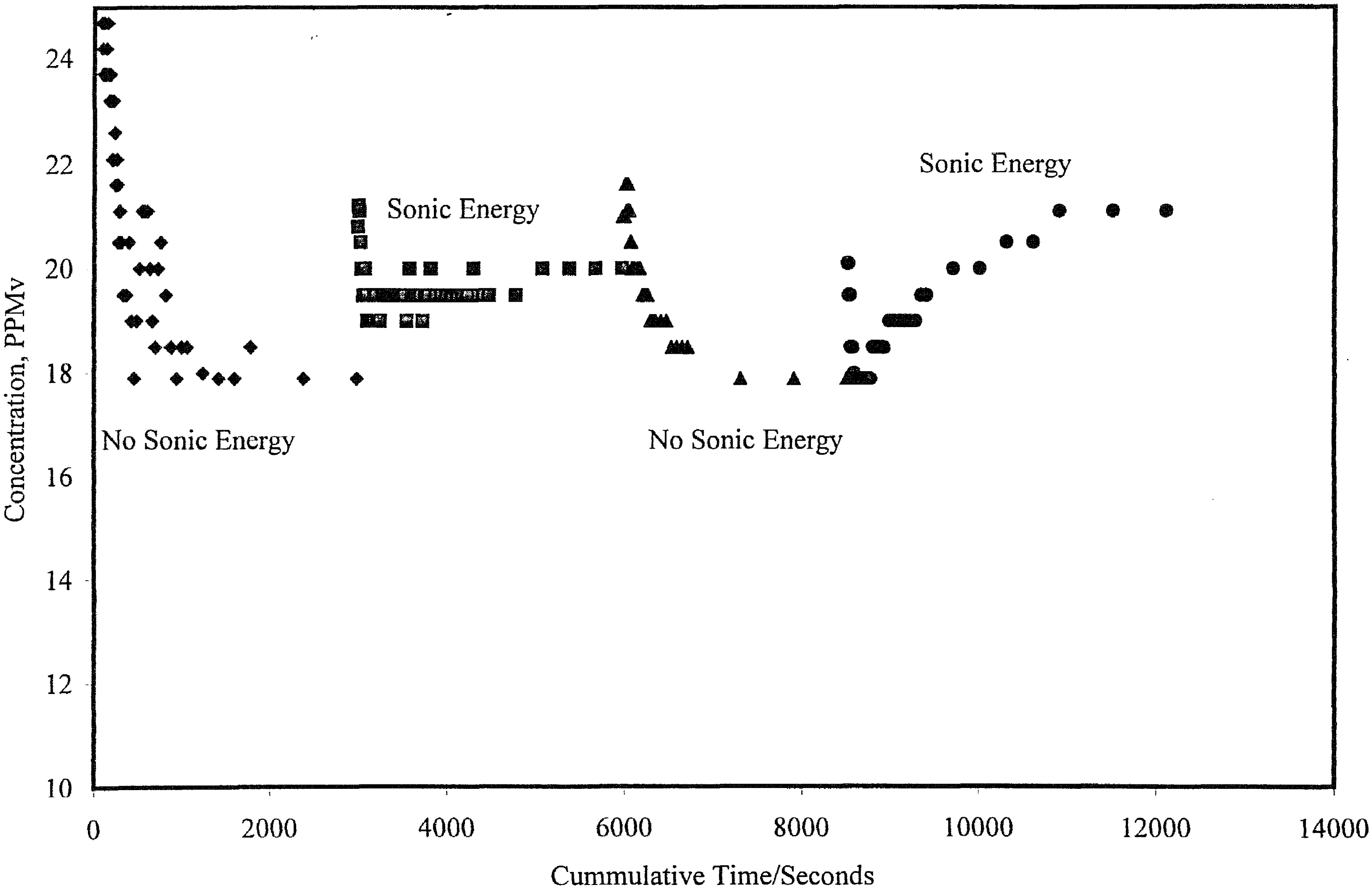


**Figure 5.20** Concentration of Trichloroethylene in Effluent Stream (Experiment 3)

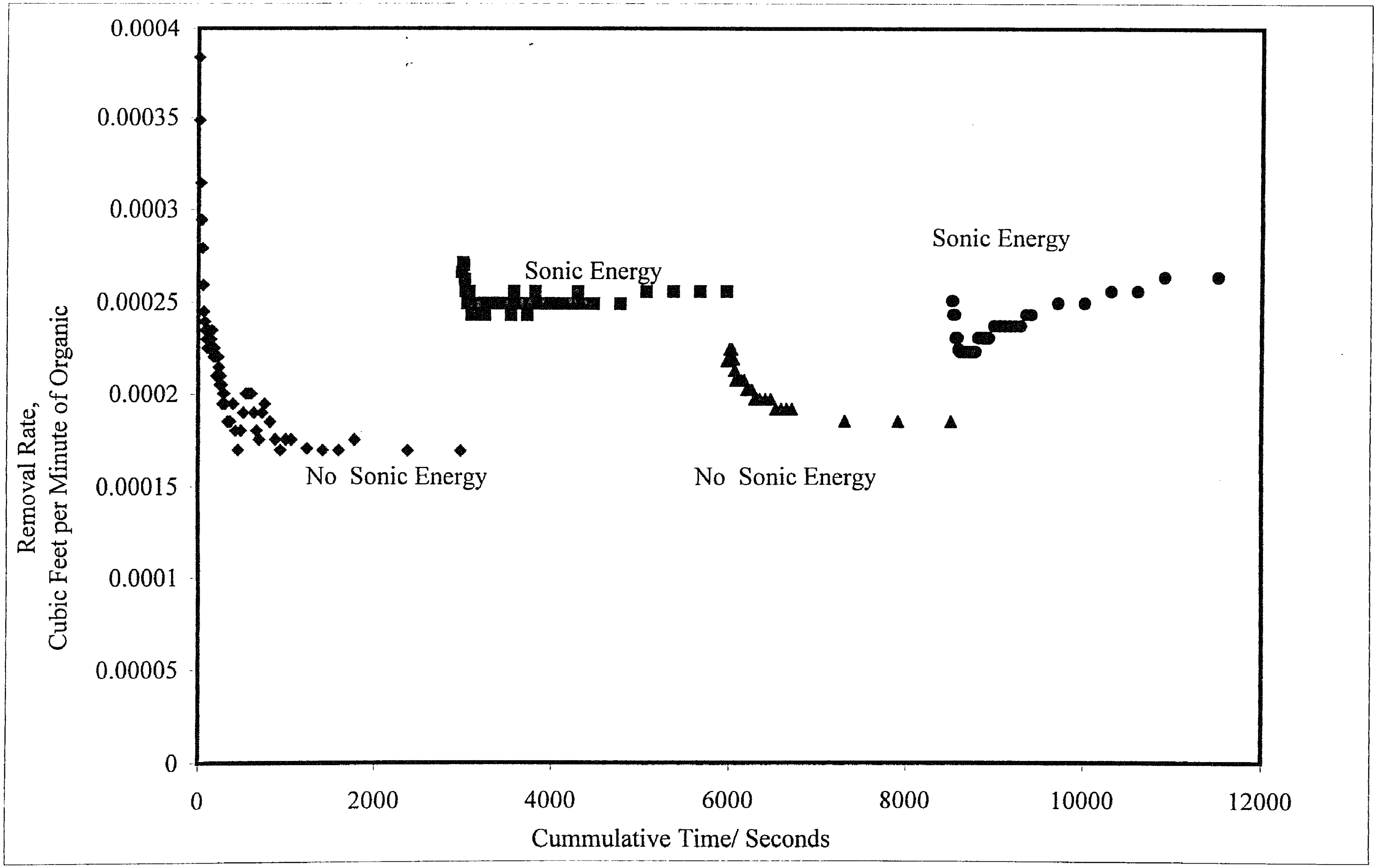


**Figure 5.21** Removal Rate of Organic (Experiment 3)

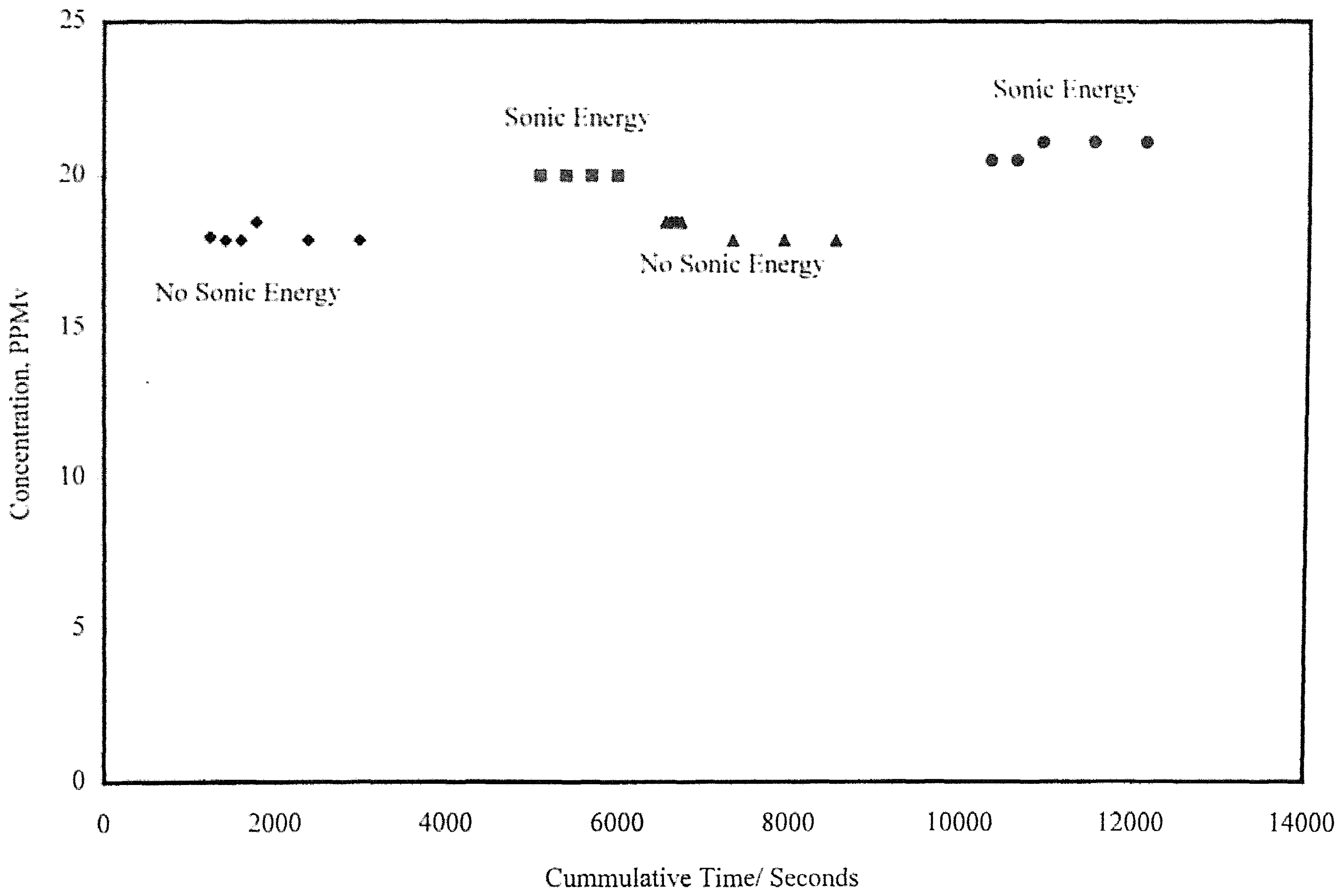


**Figure 5.22** Assymptotic Values of Concentration of Trichloroethylene in Effluent Stream (Experiment 3)

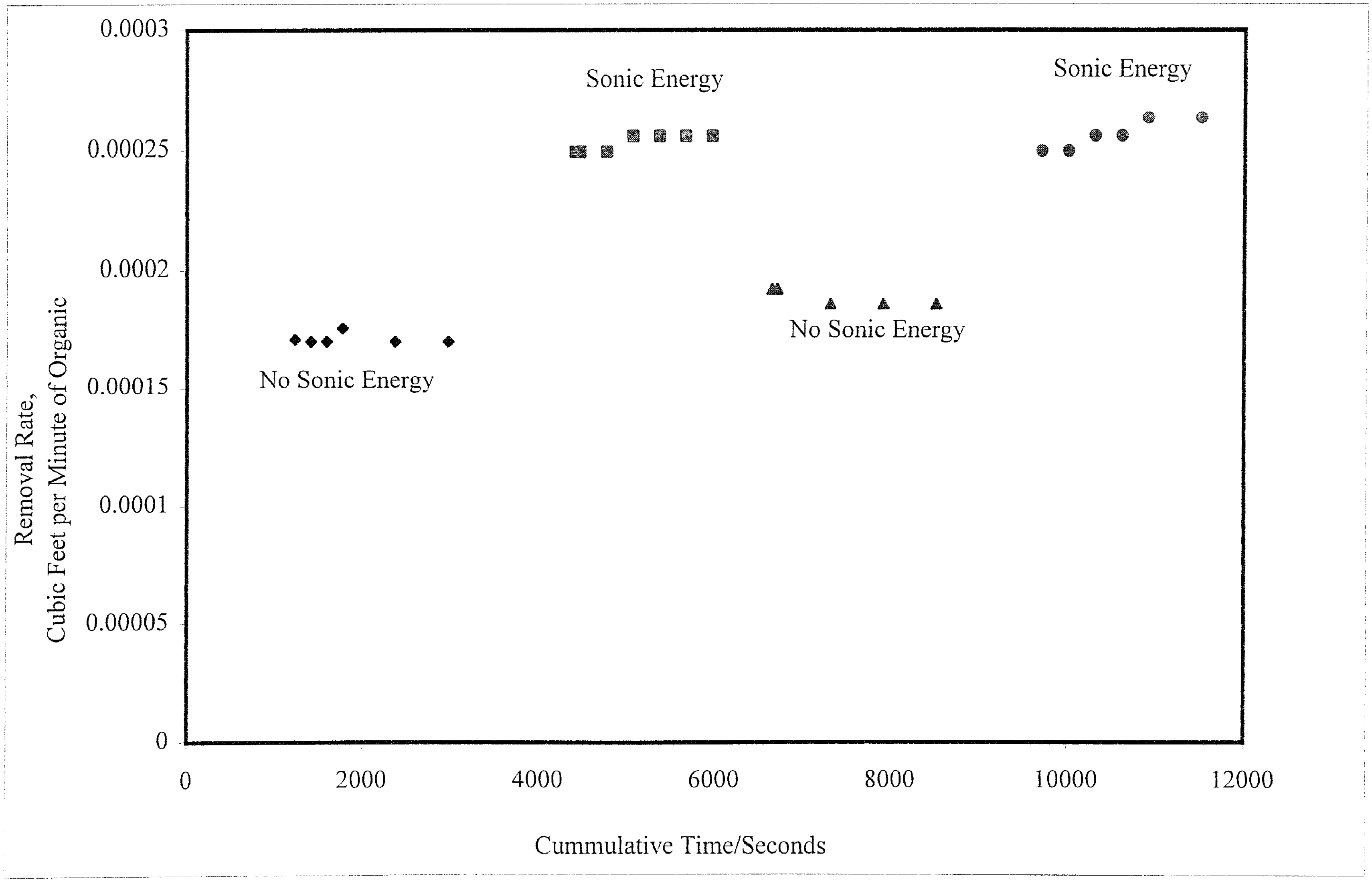


**Figure 5.23** Assymptotic Values of Removal Rate of Organic (Experiment 3)

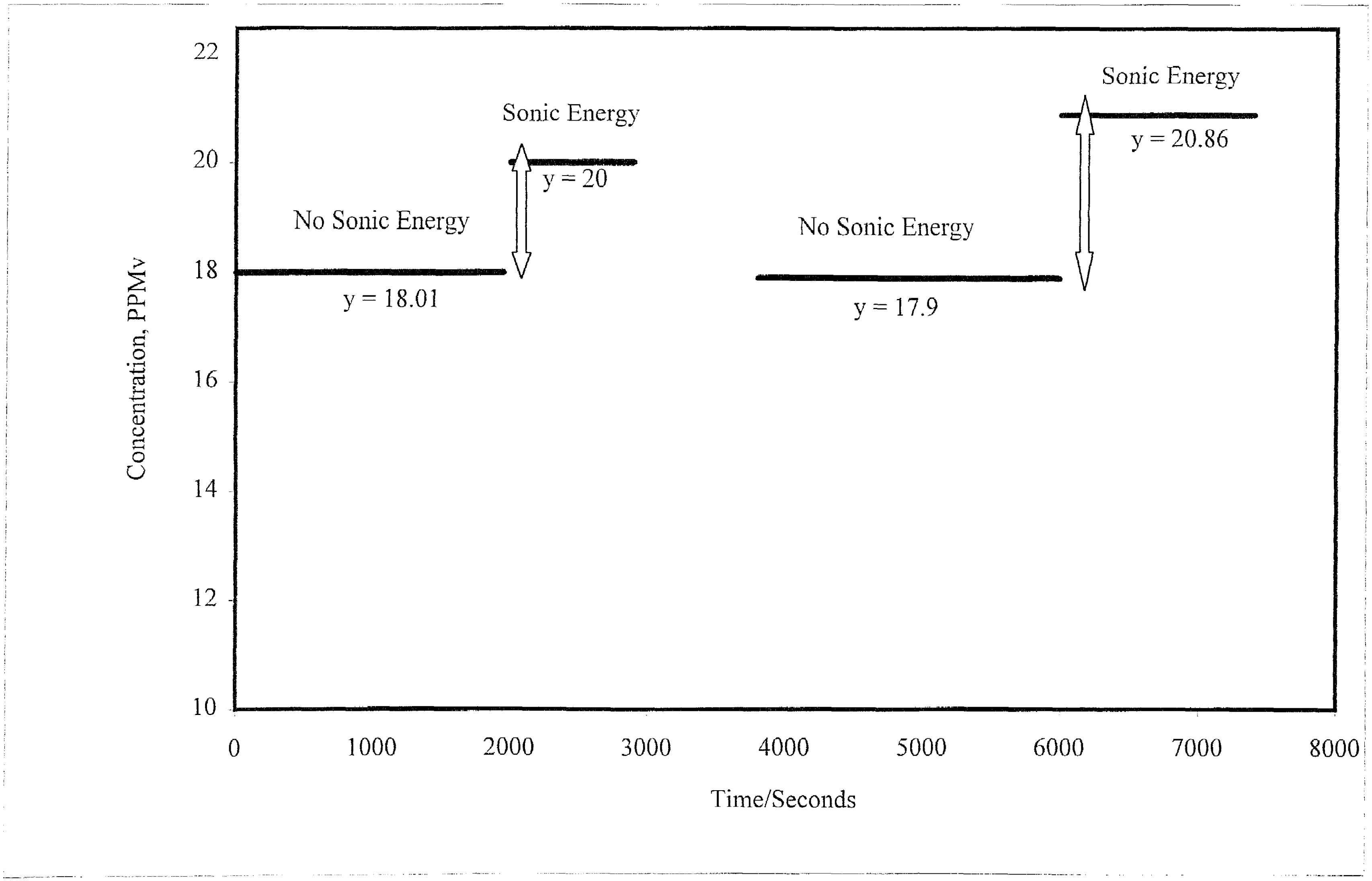


**Figure 5.24** Average Value of Concentration of Trichloroethylene in Effluent Stream at Assymptotic Value (Experiment 3)

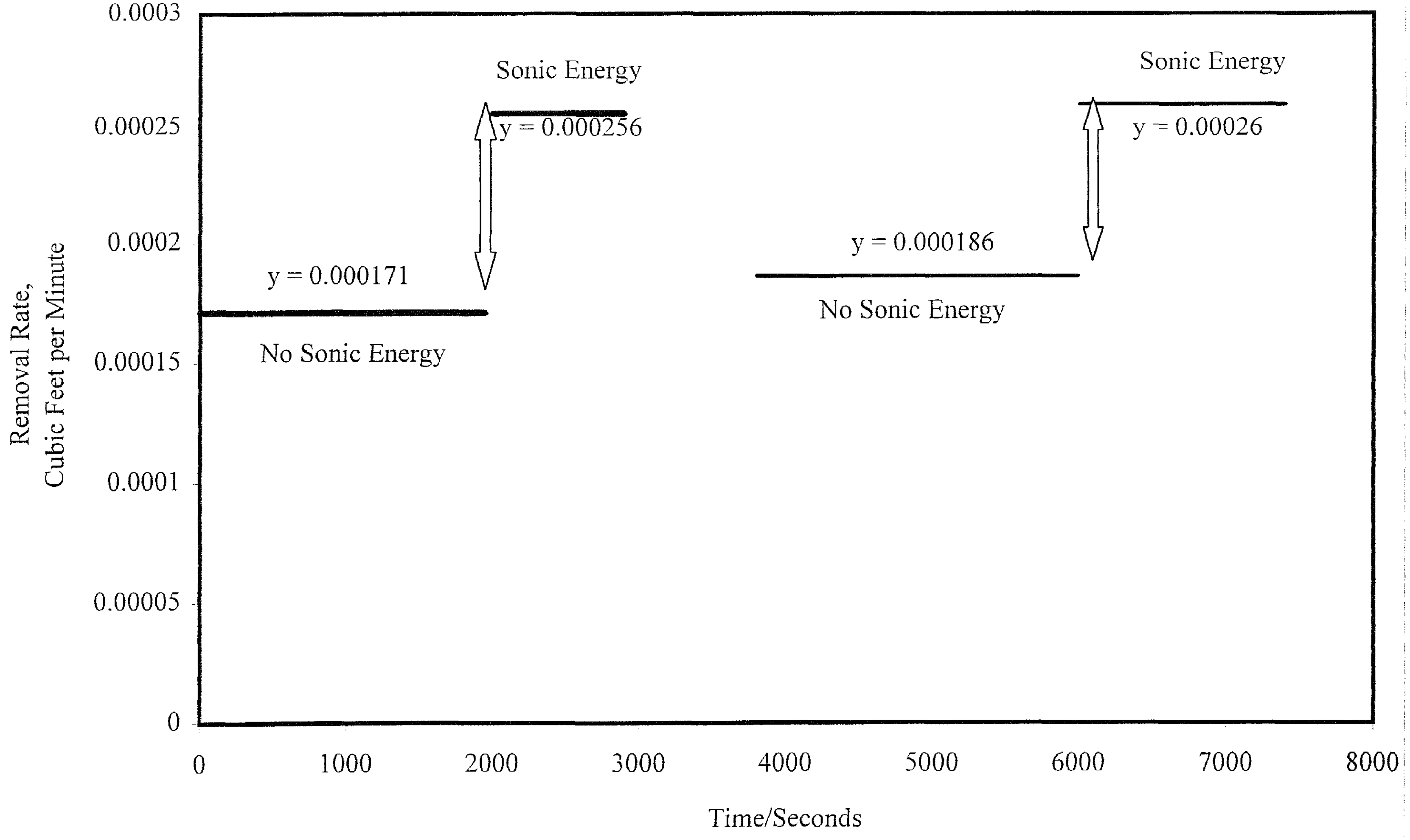


**Figure 5.25** Average Rate of Removal of Organic at Assymptotic Value (Experiment 3)

**5.4.2.4 Experimental Run 4, Sunday November 15, 1998:** The fourth experimental run was carried out on November 15, 1998. The run started around 12.15 PM . It was a cold day with some sunshine and conditions were generally dry. There were some strong winds on this day.

**5.4.2.4.1 Experimental Procedure:** The flow was switched so that no flow went through flow meters 3 and 4 (whistle by pass shut) and then flow meters 1 and 2 were each turned on to 5 SCFM (total flow = 10 SCFM, whistles open). The PID was then used to take samples for a total duration of 1945 seconds (about 32 minutes). The flow meters were then adjusted so that no flow went through flowmeters 1 and 2 (whistles shut) and 5 SCFM was allowed to go through each of the flowmeters 3 and 4 (total flow = 10 SCFM, whistle by pass open). The PID was then used to measure the concentrations of the gases going through the extraction line, as a function of time. The PID was used to sample for a total of 1895 seconds (about 32 minutes).

After this period the flow was switched from the by pass to the whistle. This was done in order to find the impact of the sonic energy on the amount of organic removed. The flow was switched so that no flow went through flow meters 3 and 4 (whistle by pass shut) and then flow meters 1 and 2 were each turned on to 5 SCFM (total flow = 10 SCFM, whistles open). The PID was then used to measure conentrations for a total duration of 2030 seconds (34 minutes).The flow was again switched back to flowmeters 3 and 4 so that no flow went through 1 and 2 (whistles shut). A flow of 5 SCFM was allowed to go through each of the flow meters 3 and 4 (whistle by pass open). The PID was again allowed to sample for 2260 seconds (about 38 minutes). This entire cycle completed the fourth experimental run. The total duration of this experiment was about 2 hours and 15 minutes.

**5.4.2.4.2 Results of Experimental Run 4, Sunday November 15, 1998:** The results obtained for the fourth experimental run are presented in Figure 5.26 – Figure 5.31 and Tables A.23 – A.27.

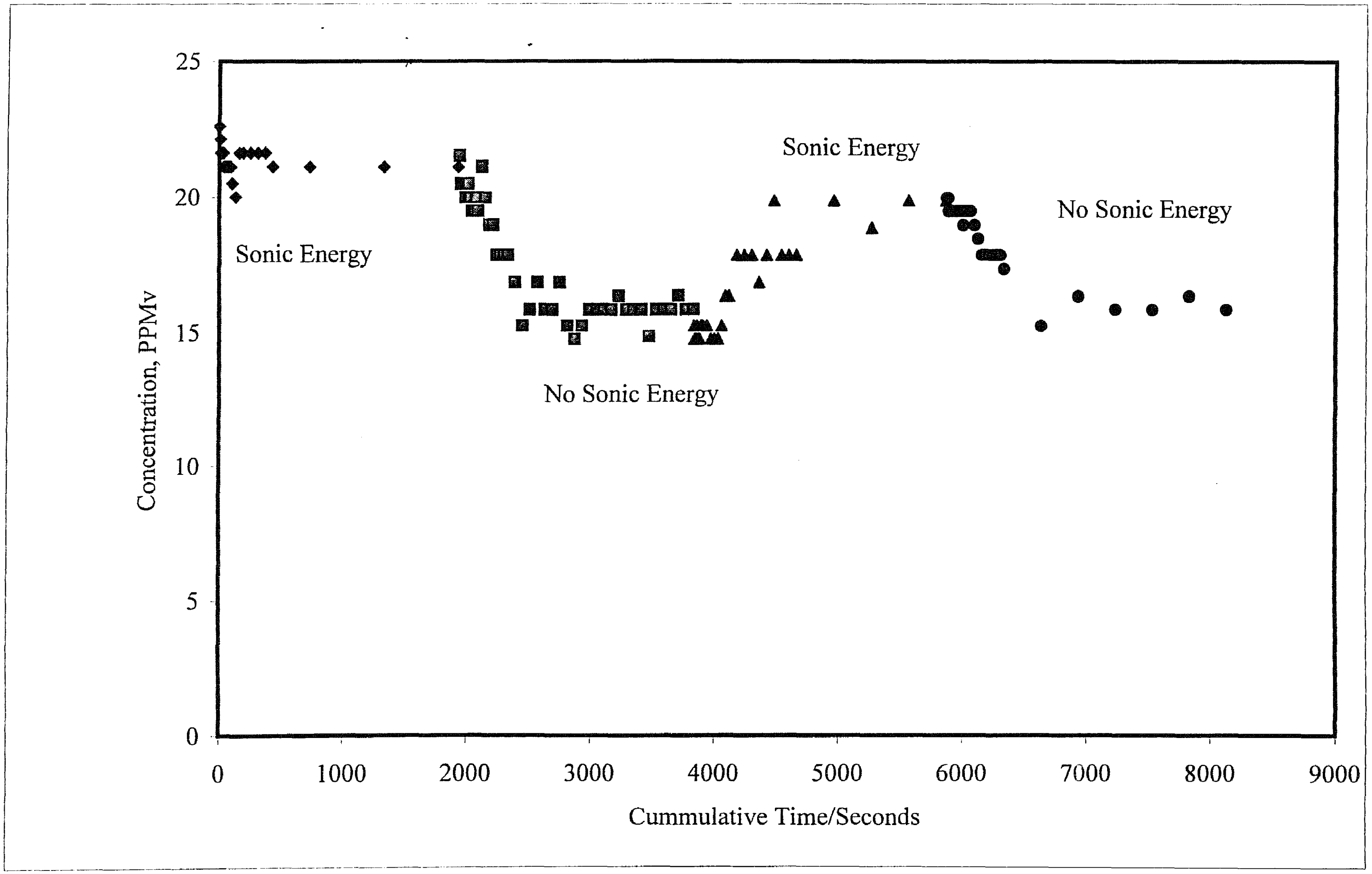


**Figure 5.26** Concentration of Trichloroethylene in Effluent Stream (Experiment 4)

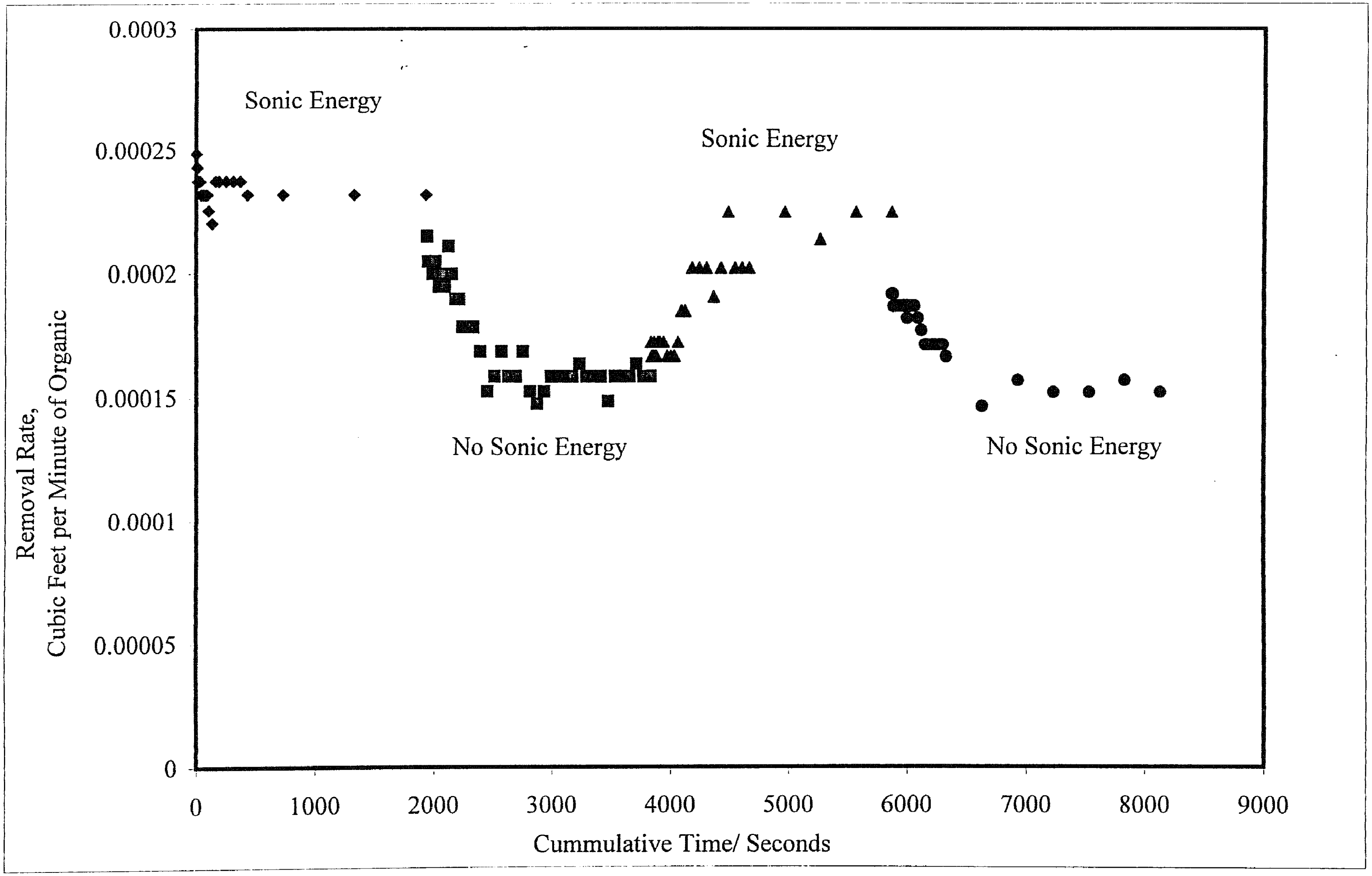


**Figure 5.27** Removal Rate of Organic (Experiment 4)

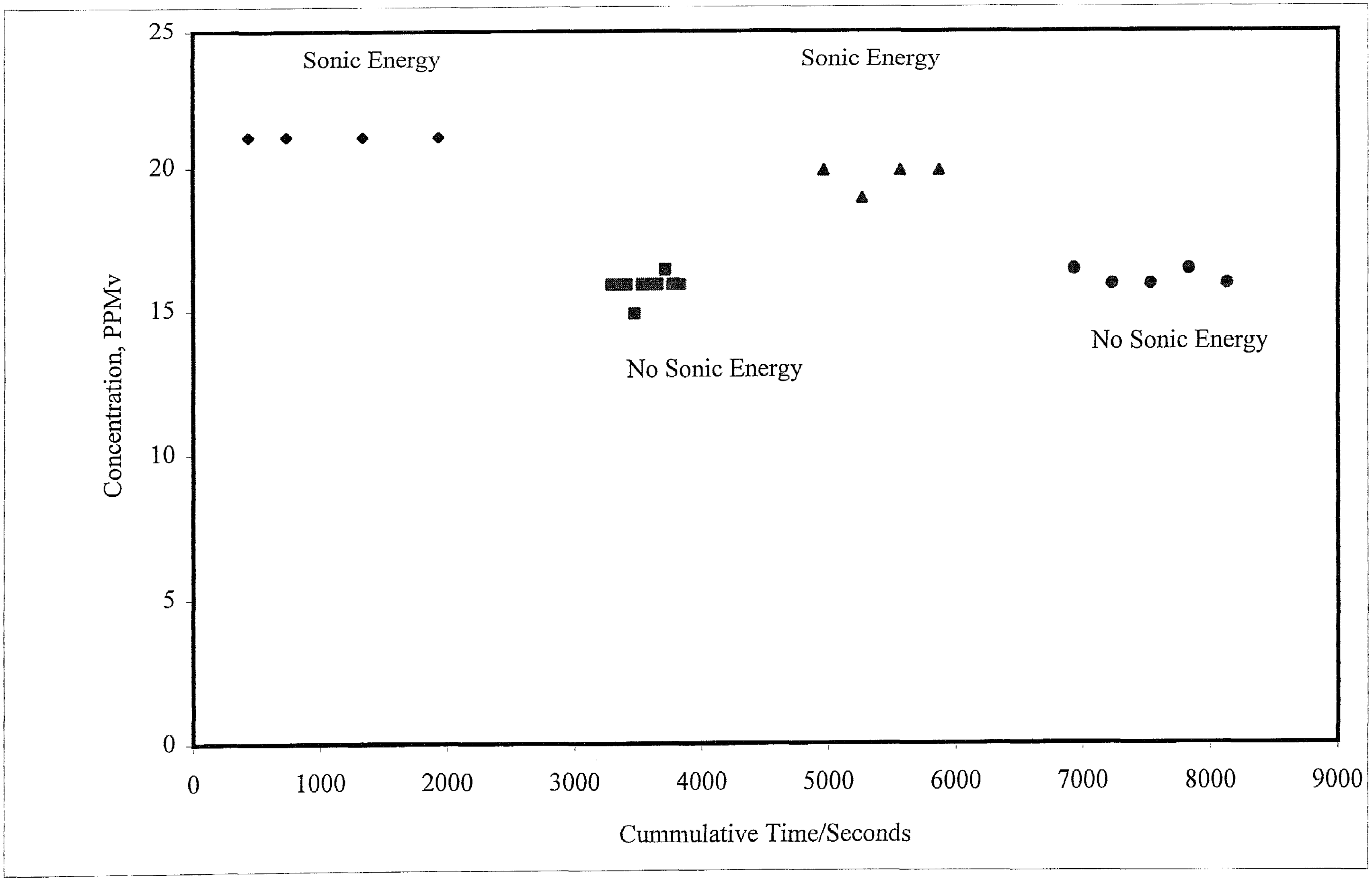


**Figure 5.28** Assymptotic Values of Concentration of Trichloroethylene in Effluent Stream (Experiment 4)

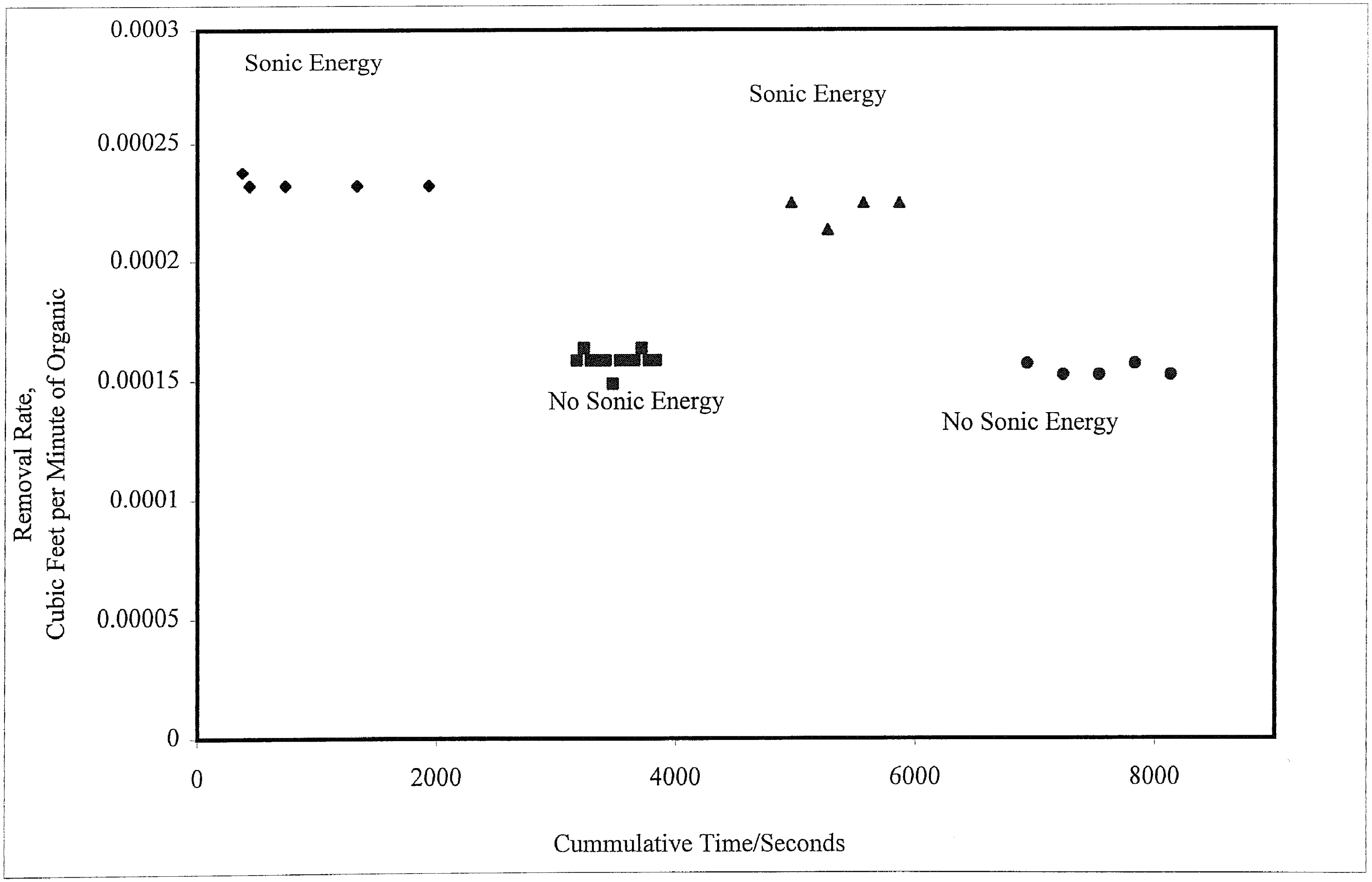


**Figure 5.29** Assymptotic Values of Removal Rate of Organic (Experiment 4)

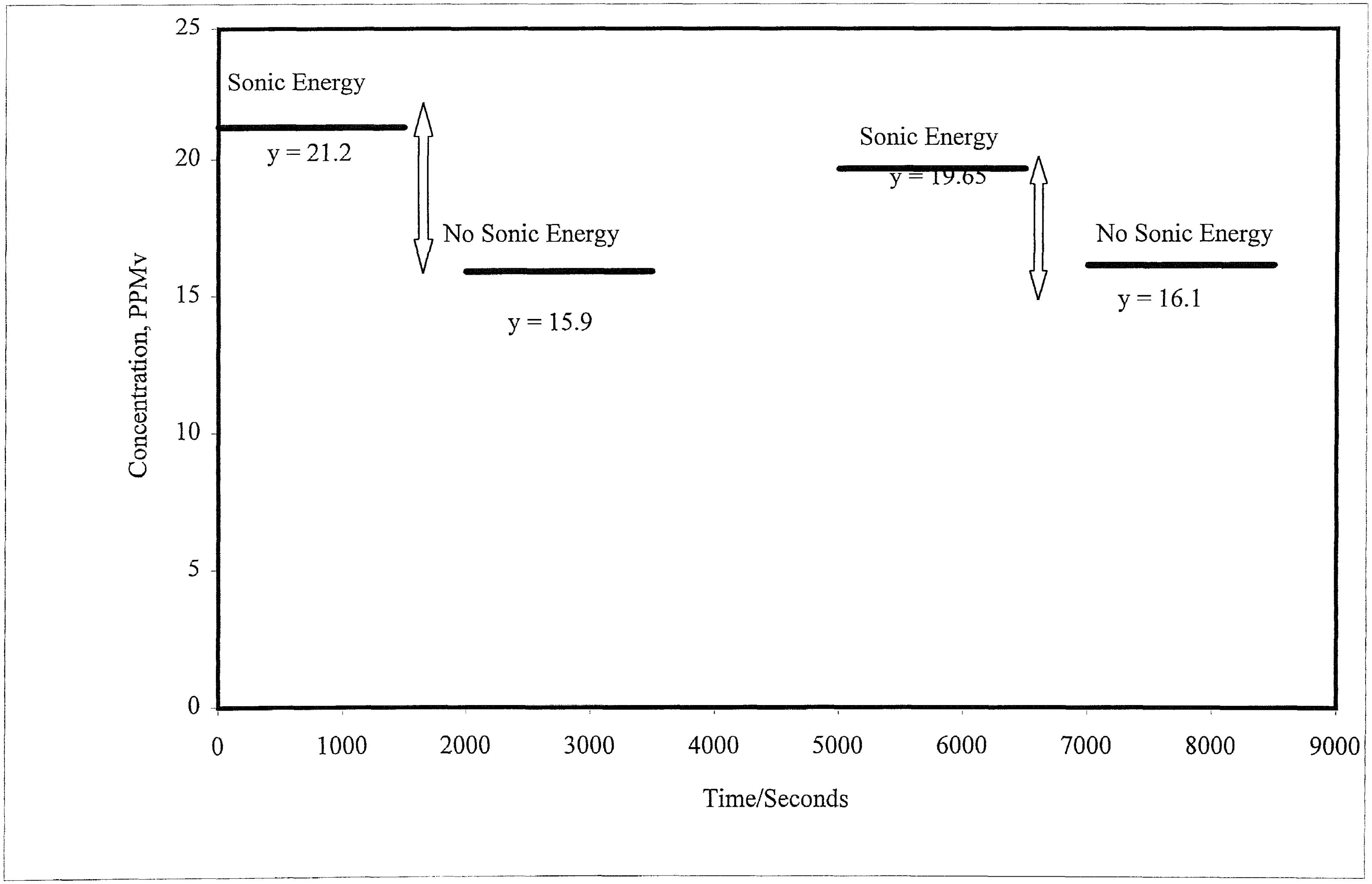


**Figure 5.30** Average Value of Concentration of Trichloroethylene in Effluent Stream at Assymptotic Value (Experiment 4)

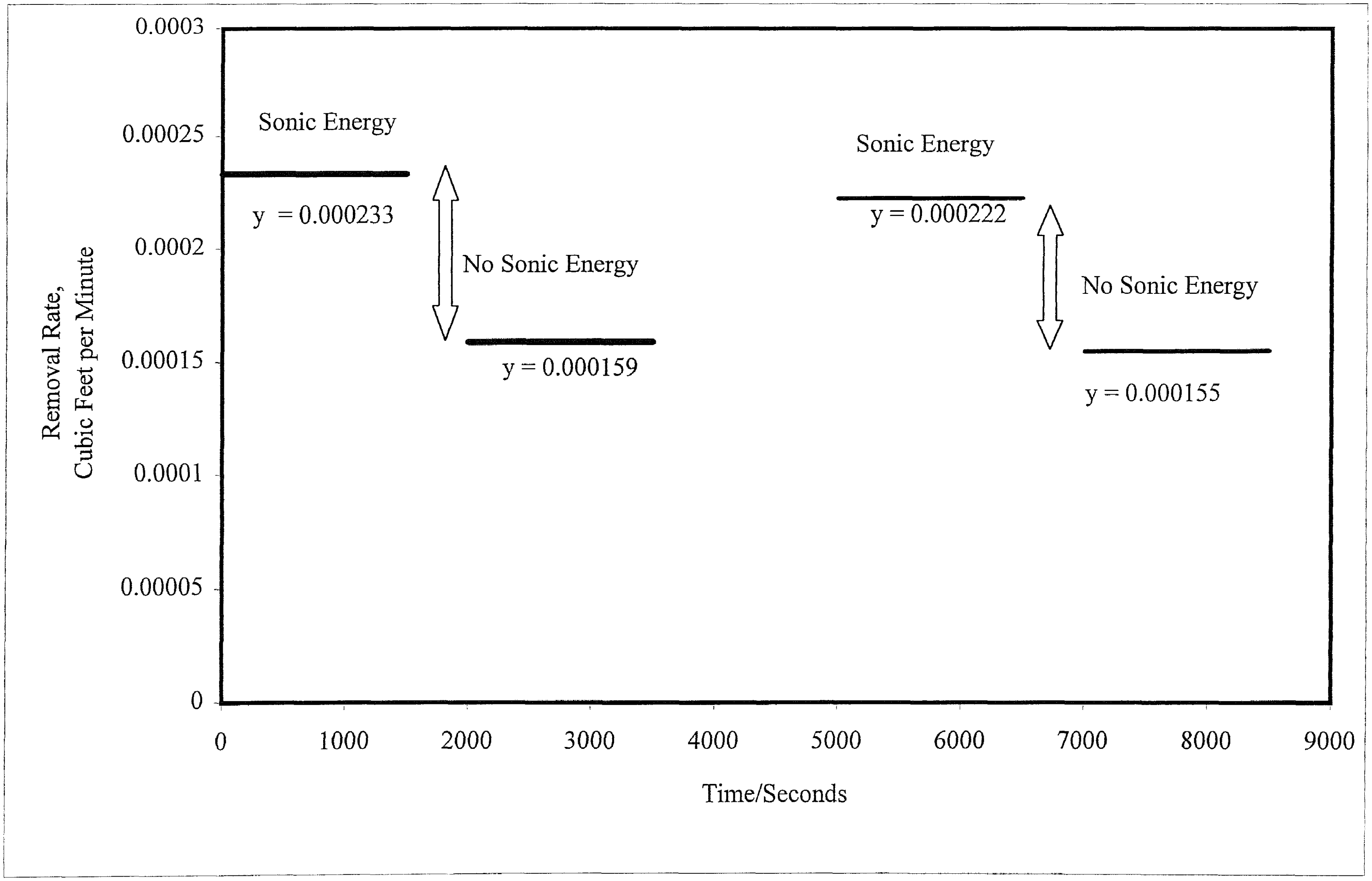


**Figure 5.31** Average Rate of Removal of Organic at Assymptotic Value (Experiment 4)

**5.4.2.5 Additional Experiment, Saturday November 8, 1998:** The additional experiment was carried out on November 8, 1998. The run started around 10.00 AM. It was a cold day with some light showers. There were some strong winds on this day.

**5.4.2.5.1 Experimental Procedure:** The additional experiment was performed to find the influence of some of the operating parameters on the amount and rate of removal of the organic contaminant. The particular operating parameter investigated was the vacuum drawn from the extraction well.

The flow was switched so that no flow went through flow meters 1 and 2 (whistles shut) and then flow meters 3 and 4 were each turned on to 5 SCFM (total flow = 10 SCFM, whistle by pass open). The vacuum pump was then adjusted to a reading of 27 inches of water vacuum. The PID was then used to measure the concentration of TCE for a total duration of 2380 seconds (about 40 minutes).

The flow meters were then adjusted so that no flow went through flowmeters 3 and 4 (whistles open) and 5 SCFM was allowed to go through each of the flowmeters 1 and 2 (total flow = 10 SCFM, whistle by pass shut).

The vacuum pump was then adjusted to a lower reading of 20 inches of water vacuum. This adjustment was made in order to determine the influence of operating at different levels of vacuum on the sonic experiments. The objective was to determine by how much the vacuum could be reduced when sonic energy was used. The PID was then used to measure the concentrations of the gases going through the extraction line, as a function of time. The PID was used to measure the concentration of TCE for a total of 3030 seconds (about 50 minutes).

After this period the flow was switched from the whistle to the by pass. In order to determine the influence of operating at different levels of vacuum, the vacuum pump was again adjusted to a higher reading of 27 inches of water vacuum. The flow was then switched so that no flow went through flow meters 1 and 2 (whistles shut) and then flow meters 3 and 4 were each turned on to 5 SCFM (total flow = 10 SCFM, whistle by pass open). The PID was then used to measure the concentration of TCE for a total duration of 2140 seconds (40 minutes).

The flow was again switched back to flowmeters 1 and 2 so that no flow went through 3 and 4 (whistles open). The vacuum pump reading was again set to 20 inches of water vacuum. A flow of 5 SCFM was allowed to go through each of the flow meters 1 and 2 (whistles open). The PID was again allowed measure the concentration of TCE for 2160 seconds (about 36 minutes).

After this period, the whistles were shut and the by pass was opened. The vacuum pump was then adjusted to a lower reading of 20 inches of water vacuum. The PID was then allowed to sample for another 30 minutes. This entire cycle completed the additional experimental run. The total duration of this additional experiment was about 3 hours and 15 minutes.

**5.4.2.5.2 Results of the Additional Experiment, Sunday November 8, 1998:** The results obtained for the additional experimental run are presented in Figure 5.32 – Figure 5.37 and Tables A.28 – A.33.

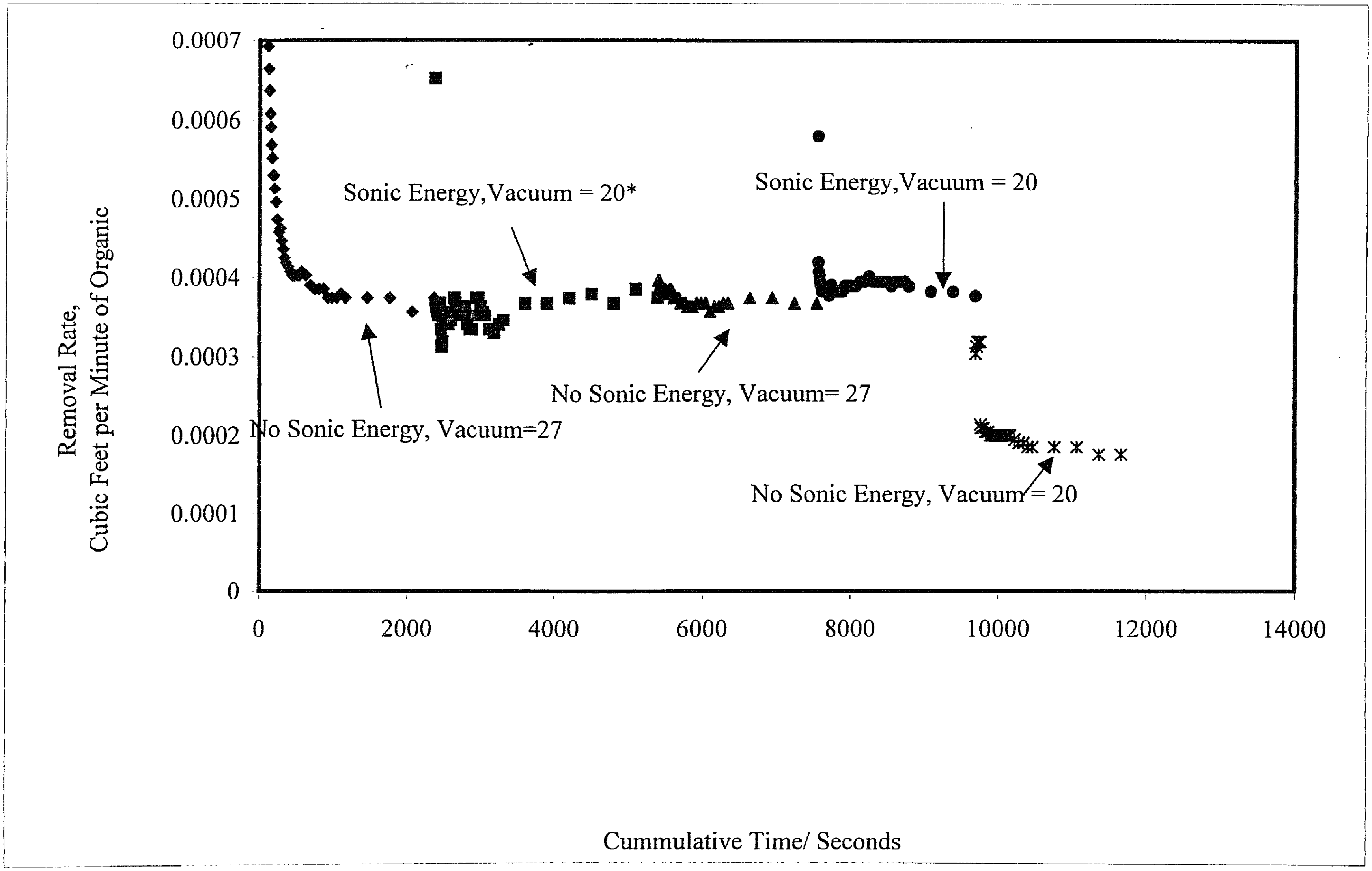


**Figure 5.33** Removal Rate of Organic (Additional Experiment, *Inches of Water Vacuum )

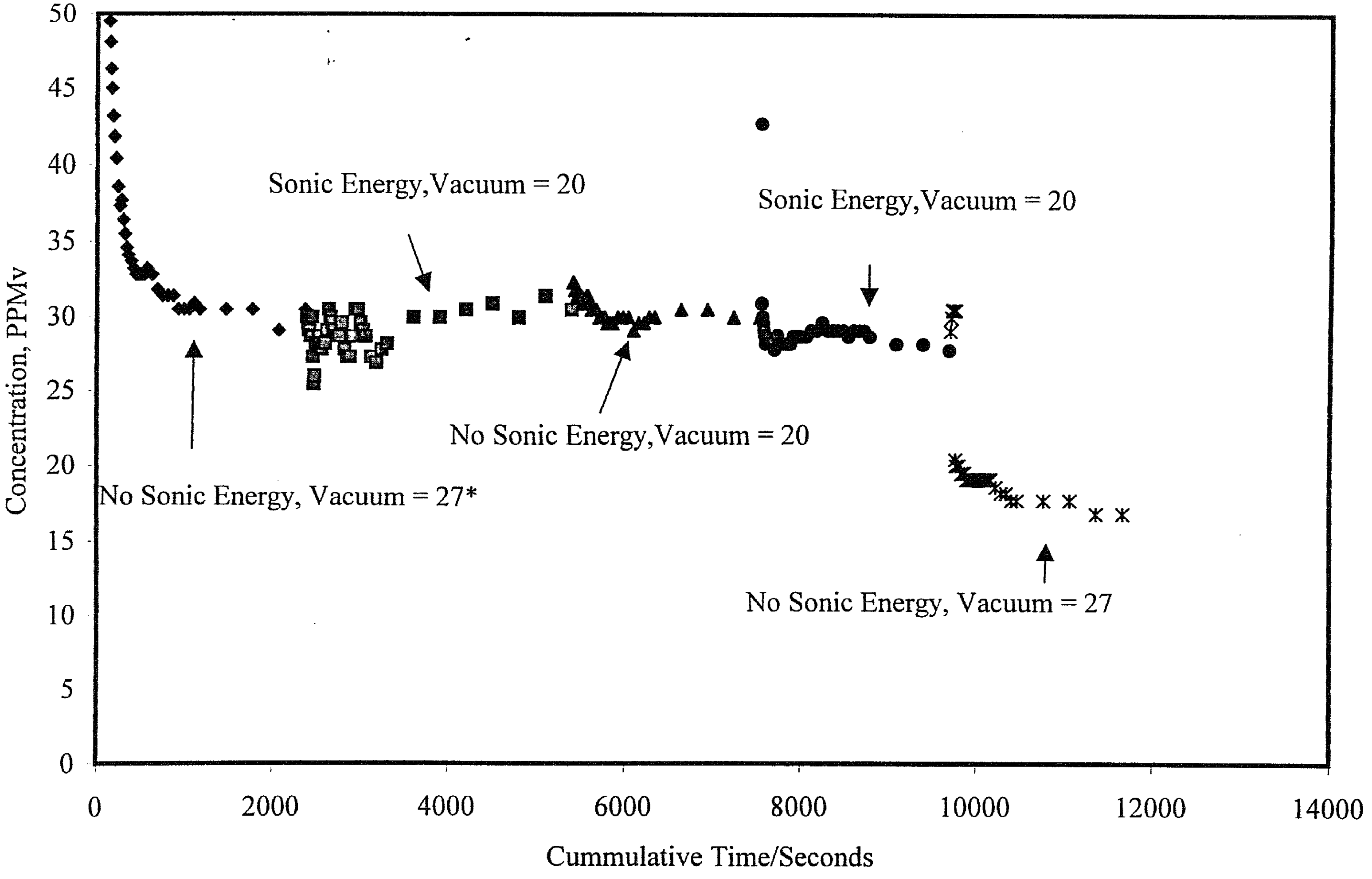


**Figure 5.32** Concentration of Trichloroethylene in Effluent Stream (Additional Experiment, *Inches of Water Vacuum)

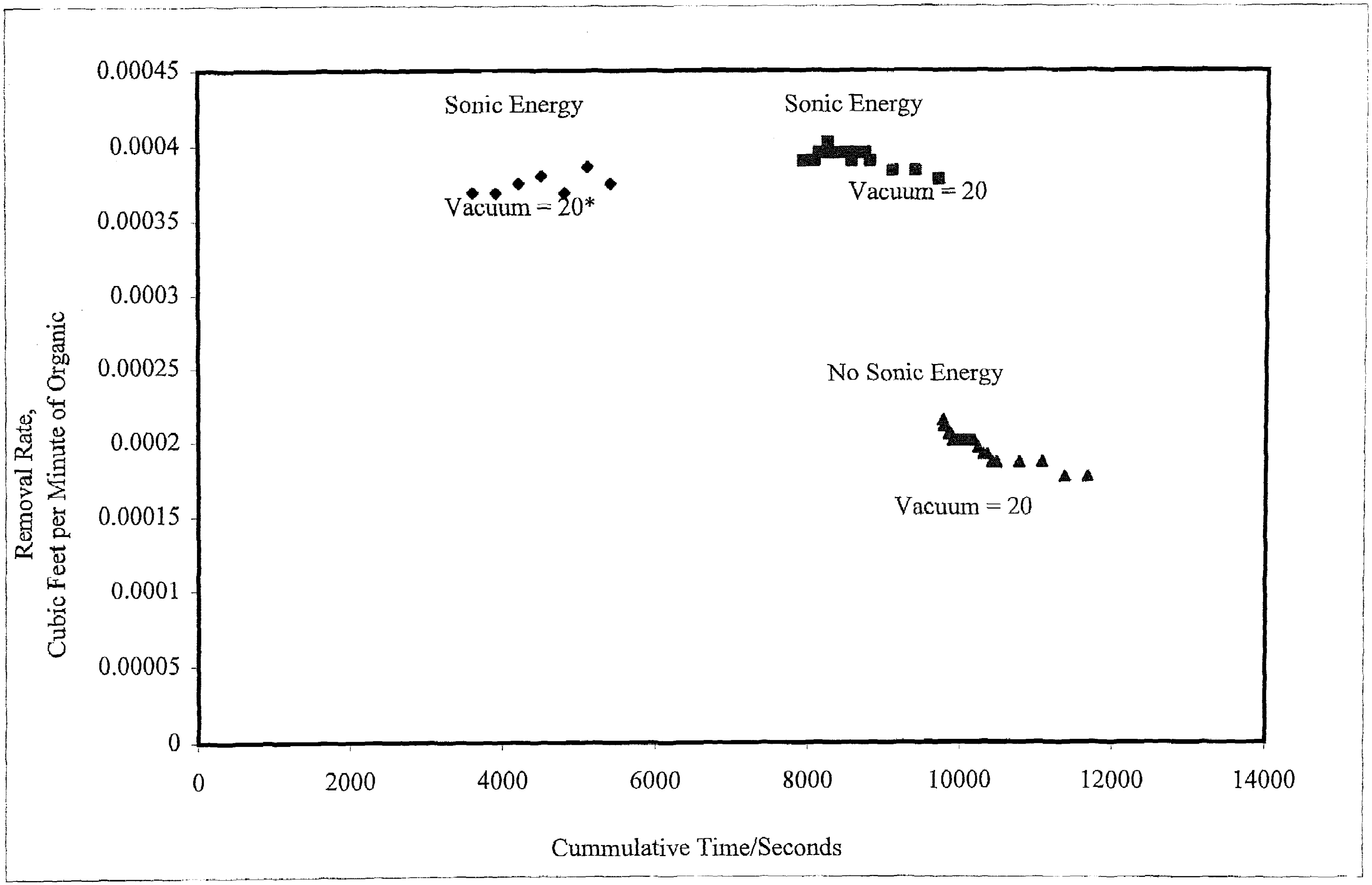


**Figure 5.34** Assymptotic Values of Removal Rate of Organic (Additional Experiment, *Inches of Water Vacuum)

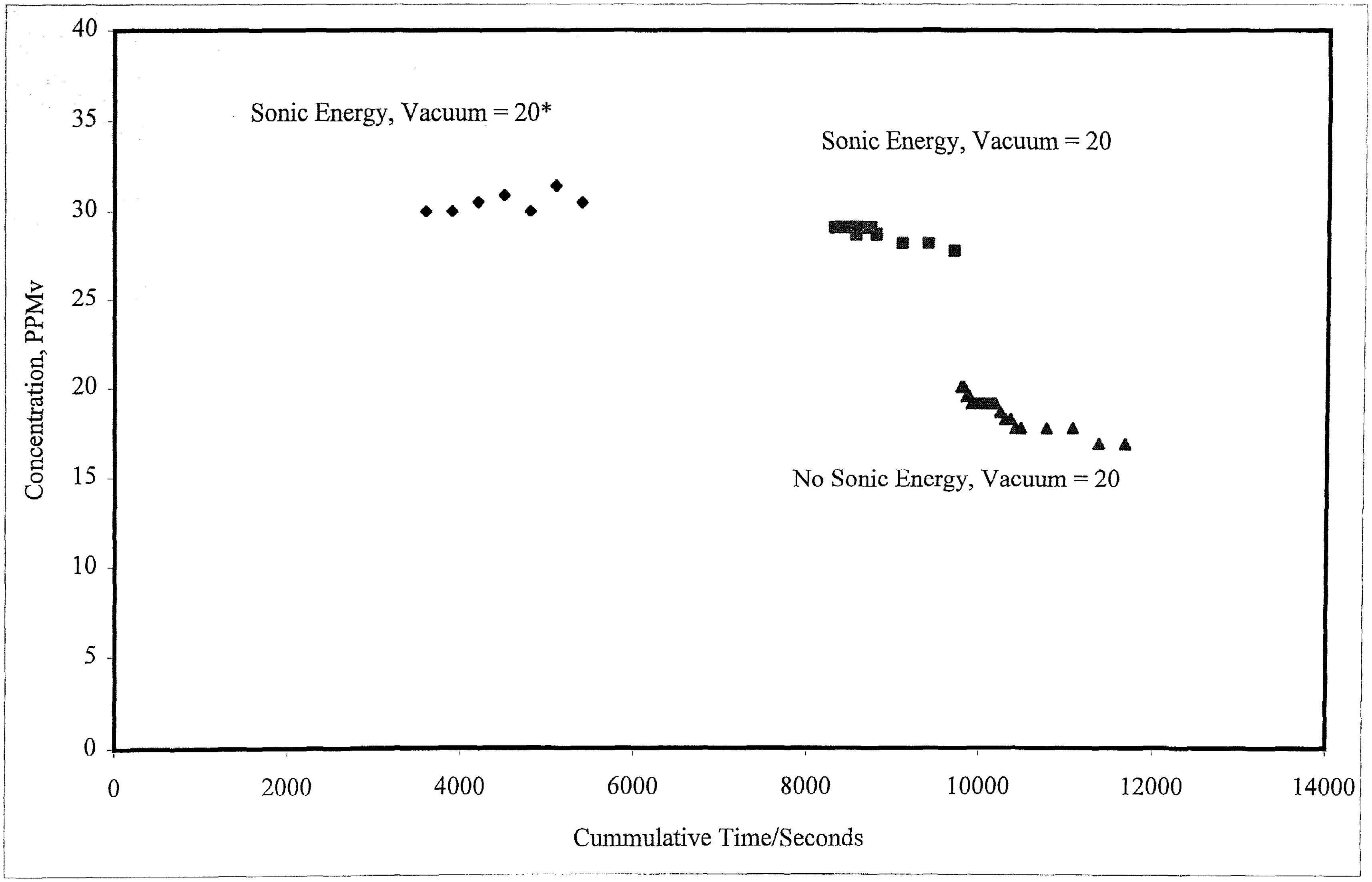


**Figure 5.35** Assymptotic Concentration of Trichloroethylene in Effluent Stream (Additional Experiment, *Inches of Water Vacuum)

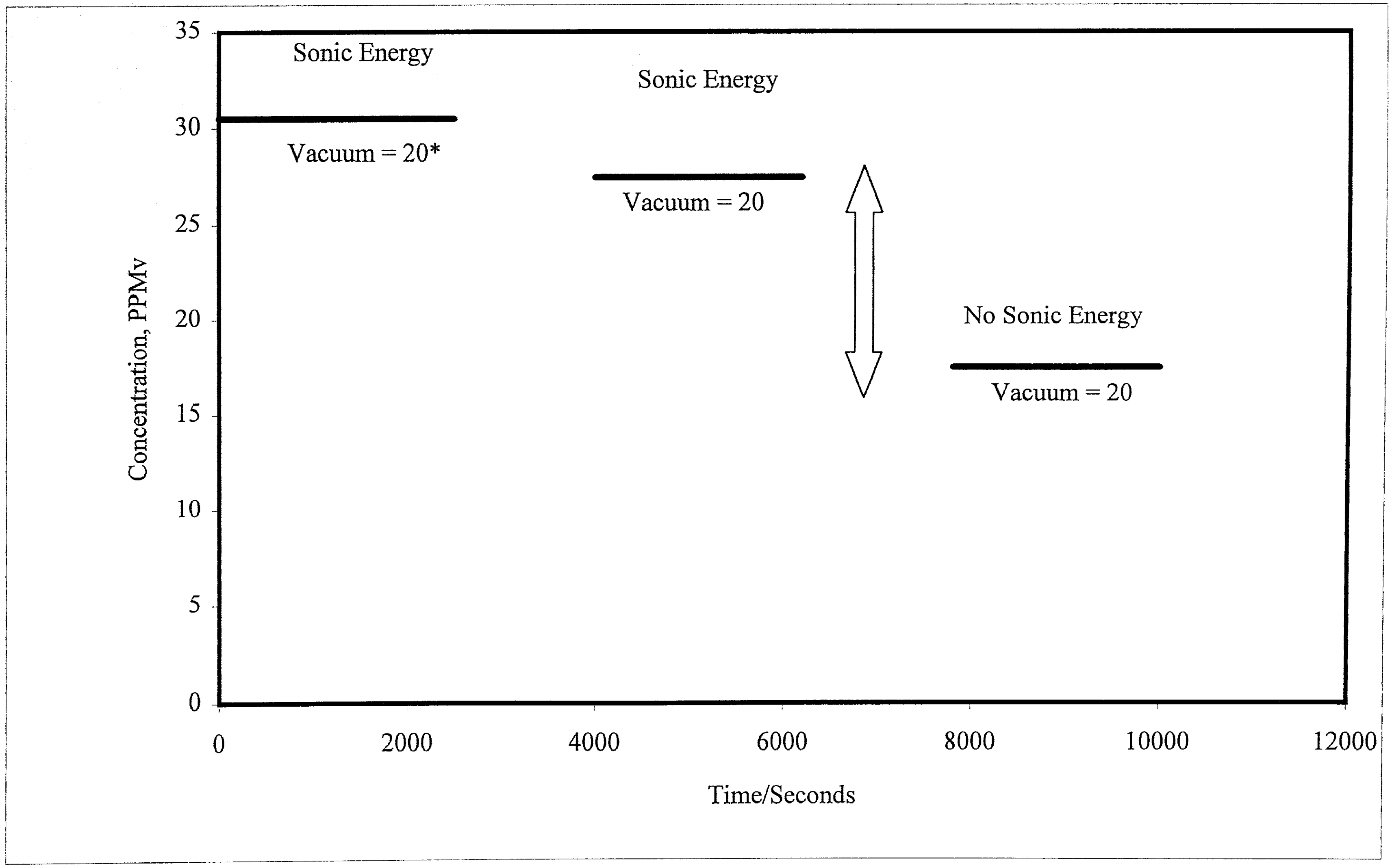


**Figure 5.36** Average Concentration of Trichloroethylene in Effluent Stream at Assymptotic Value (Additional Experiment, *Inches of Water Vacuum)

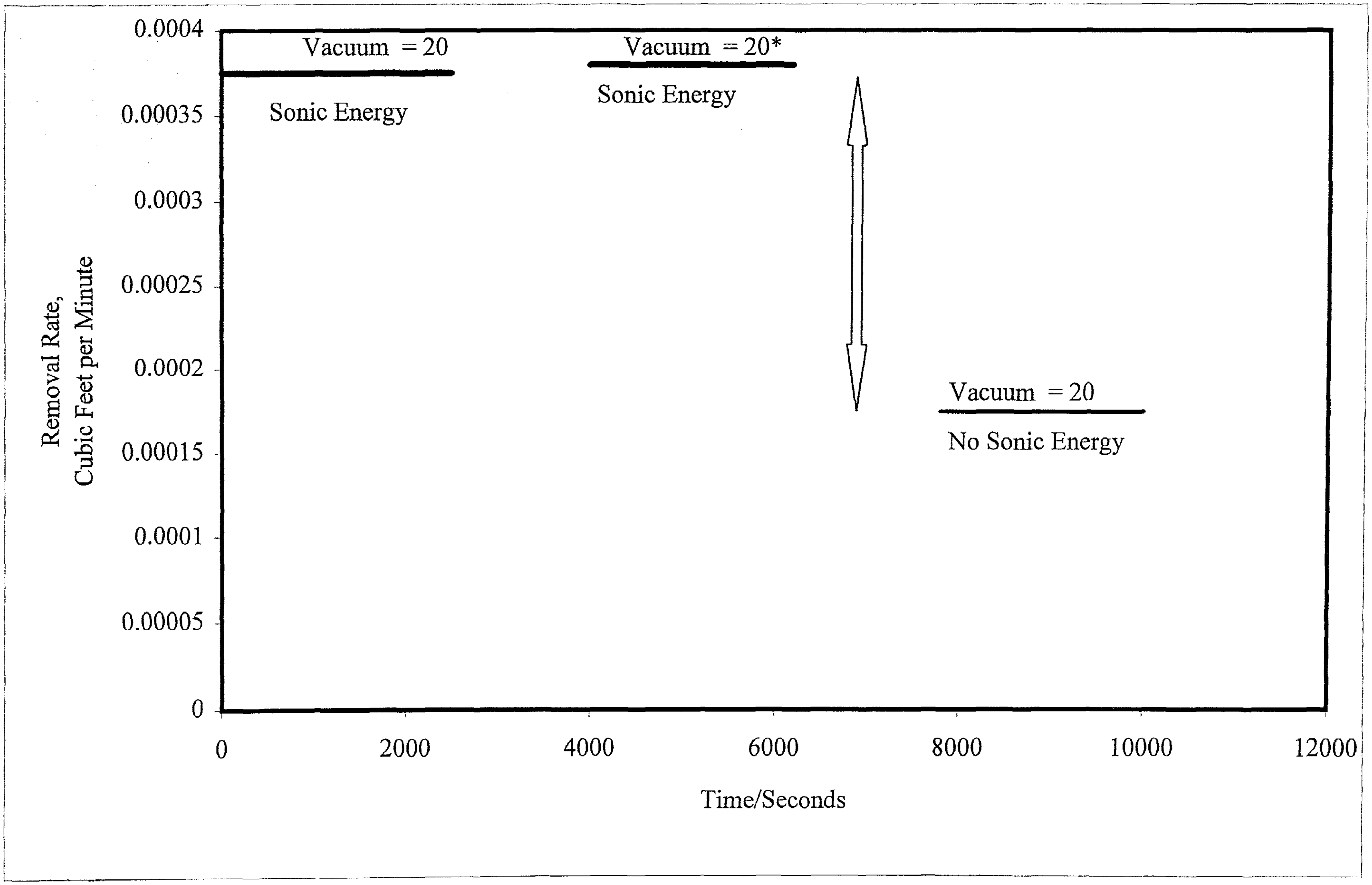


**Figure 5.37** Average Rate of Removal of Organic at Assymptotic Value (Additional Experiment, *Inches of Water Vacuum )

# CHAPTER 6

# DISCUSSION OF EXPERIMENTAL RESULTS

## 6.1 Experimental Run 1 (Sunday, September 27, 1998)

The results of experimental run one are presented in Figure 5.8 to Figure 5.13.In Figure 5.8, initially the experiments are performed using sonic energy (whistles turned on). At the start of the experiment, the concentration of trichloroethylene in the effluent stream decreases rapidly from a value of about 40 PPMv until it stabilizes at a constant value of about 22 PPMv. This initial decline in the concentration can be explained by the fact that initially only the contaminants on the surface of the fractures are being removed. The amount of these surface contaminants removed is directly proportional to their concentration on the surface. Thus the concentration of the contaminant on the surface is the limiting condition that controls the amount of contaminant removed. As the concentration of the contaminant on the surface decreases the concentration of trichloroethylene in the effluent stream also decreases. This trend is followed until the contaminants on the surface of the fractures are depleted.

After this period, Figure 5.8, the concentration of trichloroethylene in the effluent stream stays at this constant value of about 22 PPMv. This observation can be explained by the fact that during this period the contaminants trapped within the fractures are being removed. As these contaminants are being removed from a tight formation, the limiting condition for the concentration of trichloroethylene in the effluent stream during this period is the penetration ability of the sonic energy into the fractures. Since the amplitude and frequency and the intensity of the sound at the source from the sonic device remain constant during the experiment the penetration ability of the sonic energy into the formation also remains constant and hence the concentration of the effluent stream is constant for this period.

When the method of operation is switched from sound to air, with no sound, Figure 5.8, the concentration of trichloroethylene in the effluent stream drops to a lower constant value of about 16.5 PPMv. This observation can be explained by the fact that during this period the contaminants that are being removed are still those that are trapped within the formation. As the air carries less energy and produces less vibrations within the fractures, compared to the sound, the ability of the air to penetrate the tight geological formation is considerably decreased. This explains the observed drop in concentration of trichloroethylene in the effluent stream (from about 22 PPMv with sound to about 16.5 PPMv with air).

The observed initial increase in the concentration of trichloroethylene in the effluent stream when the air is first turned on can be explained by the fact that the air may be sweeping out some contaminants that were left loose by the vibrations of the sonic energy. This explanation is justified by the fact that the duration of this increase lasts for only about 5 to 10 seconds compared to the total duration of the experimental run (about 11000 seconds). The subsequent increase in the concentration of trichloroethylene in the effluent stream (to about 22 PPMv) when the sound is again switched on and the drop in the concentration of trichloroethylene in the effluent stream (to about 16.5 PPMv) when the sound is again switched off (Figure 5.8) follow the same explanation as given above.

Figure 5.9 is obtained from Figure 5.8 by converting the concentrations of TCE in the effluent stream to removal rates (Appendix B). In Figure 5.9, initially the experiments are performed using sonic energy (whistles turned on). At the start of the experiment, the removal rate of trichloroethylene, which is the product of the air flow rate and concentration of TCE, decreases rapidly from a value of about 0.0004 cubic feet per minute until it stabilizes at a constant value of about 0.000255 cubic feet per minute. When the mode of operation is switched from sound to no sound the effluent flowrate remains unchanged but the removal rate of TCE drops from 0.000255 cubic feet per minute to 0.000189 cubic feet per minute. When the sound is again turned on and then switched off, the effluent flowrate still remains the same but the removal rate of the TCE increases and then decreases respectively (Table 6.1). The trend follows the same explanation as given for Figure 5.8. The results indicate that the sonic energy is effective in removing the TCE from the soil.

**Table 6.1** Average Concentration of TCE and Removal Rates at Assymptotic Values.

| Experiment | Mode of Operation | Concentration of TCE at the Assymptotic Value, PPMv | Effluent Flowrate, scfm | Removal Rate of TCE at Assymptotic Value, Cubic Feet Per Minute |
|---|---|---|---|---|
| 1 | sound | 22.0 | 11.3 | 0.000255 |
| 1 | no sound | 16.5 | 11.3 | 0.000189 |
| 1 | sound | 22.0 | 11.3 | 0.000240 |
| 1 | no sound | 16.5 | 11.3 | 0.000180 |
| 2 | sound | 33.0 | 12.1 | 0.000393 |

**Table 6.1** Average Concentration of TCE and Removal Rates at Assymptotic Values. (Continued)

| Experiment | Mode of Operation | Concentration of TCE at the Assymptotic Value, PPMv | Effluent Flowrate, scfm | Removal Rate of TCE at Assymptotic Value, Cubic Feet Per Minute |
|---|---|---|---|---|
| 2 | no sound | 30.0 | 10.1 | 0.000300 |
| 2 | sound | 33.0 | 12.5 | 0.000413 |
| 2 | no sound | 30.0 | 10.7 | 0.000330 |
| 3 | nosound | 18.0 | 9.5 | 0.000121 |
| 3 | sound | 20.0 | 12.8 | 0.000256 |
| 3 | no sound | 18.0 | 10.4 | 0.000186 |
| 3 | sound | 20.0 | 12.5 | 0.000260 |
| 4 | sound | 21.0 | 11.0 | 0.000233 |
| 4 | no sound | 16.0 | 10.0 | 0.000159 |
| 4 | sound | 19.9 | 11.3 | 0.000222 |
| 4 | no sound | 16.0 | 9.6 | 0.000155 |

Figure 5.10 shows the assymptotic values for Figure 5.8 and Figure 5.11 shows the corresponding constant rate plot for Figure 5.9. These are the periods during which the penetration ability of the method employed limit both the amount and rate of removal of the organic contaminant. From Figure 5.10 and 5.11, it is evident that both the amount and the removal rate of the organic are increased when sonic energy is focused into the fractures. The percentage increase when sonic energy is focussed into the fractures is calculated by taking the averages of the assymptotic values of Figure 5.10 and 5.11. This

is shown in Figure 5. 12 (average concentration of trichloroethylene in the effluent stream at assymptotic value, from Figure 5.10) and Figure 5.13 (average rate of removal of organic at assymptotic value, from Figure 5.11). The percentage improvement in concentrations for the first sound-air pair, as calculated from Figure 5.12 is 34.8% and from the second-air pair is 33.08%. Also, the percentage improvement in removal rate for the first sound-air pair, as calculated from Figure 5.13 is 34.92% and from the second-air pair is 33.33%.

These results show that there is a remarkable improvement when sonic energy is used as an enhancement technique to remove volatile organic compounds.

## 6.2 Experimental Run 2 (Saturday, November 7, 1998)

The results of experimental run 2 are presented in Figure 5.14 to Figure 5.19. In Figure 5.14, initially the experiments are performed using sonic energy (whistles turned on). At the start of the experiment, the concentration of trichloroethylene in the effluent stream builds up from a low value of about 23 PPMv to a high value of about 33 PPMv. This observation can be explained by the fact that at the time that this run was started there was not a considerable amount of organic contaminant left on the surface of the fractures. This is a result of the fact that the vacuum pump had been left running prior to the experiment, while the experimental conditions were being prepared, setting the compressor and checking the water levels. The initial build up period also justifies the fact that the sonic energy needs a finite time to penetrate the fractures and manifest its effect. This time is measured as about 30 minutes, from Figure 5.14. After this period,

Figure 5.14, the concentration of trichloroethylene in the effluent stream stays at a constant value of about 33 PPMv (Table 6.1).

When the method of operation is switched from sound to no sound, Figure 5.14, the concentration of trichloroethylene in the effluent stream drops to a lower constant value of about 30 PPMv. The subsequent increase in the concentration of trichloroethylene in the effluent stream (to about 33PPMv) when the sound is again switched on and the drop in the concentration of trichloroethylene in the effluent stream (to about 30 PPMv) when the sound is switched off (Table 6.1) follow the same explanation as given for Figure 5.8. Table 6.1 shows that these changes in concentration are not as large as in experiment 1 because the effluent flow rate also changed. Had the flow rate stayed constant at 12.1 SCFM the concentration would have been lower than 30 PPMv.

Figure 5.15 is similar to Figure 5.14 with the concentrations converted to removal rates (refer to Appendix B for sample calculation). Figure 5.15 unlike Figure 5.14 takes into account the variation of the effluent flowrate. In Figure 5.15, initially the experiments are performed using sonic energy (whistles turned on). At the start of the experiment, the removal rate of trichloroethylene builds up from a low value of about 0.00027 cubic feet per minute to a high value of about 0.000393 cubic feet per minute (Table 6.1). After this period, Figure 5.15, the removal rate of trichloroethylene stays at a constant value of about 0.000393 cubic feet per minute.

When the method of operation is switched from sound to no sound the removal rate of trichloroethylene drops to a lower constant value of about 0.0003 cubic feet per minute but the effluent flowrate also drops from 12.1 scfm to 10.1 scfm (Table 6.1). This drop in effluent flowrate means that the drop in the rate of removal would be higher if the effluent flowrates were maintained at the same value. There is no single explanation for the observed drop in the effluent flowrate. A possible explanation however is the possibility of the air being lost within the formation and hence resulting in an unsteady state balance.

The subsequent increase in the removal rate of trichloroethylene (to about 0.000413 cubic feet per minute) when the sound is again switched on and the drop in the removal rate of trichloroethylene (to about 0.00033 cubic feet per minute) when the sound is again switched off (Table 6.1) follow the same explanation as given for Figure 5.8.

Figure 5.16 shows the assymptotic values for Figure 5.14 and Figure 5.17 shows the corresponding constant rate plot for Figure 5.15. These are the periods during which the penetration ability of the method employed limits both the amount and rate of removal of the organic contaminant. From Figure 5.16 and 5.17, it is evident that both the amount and the removal rate of the organic are increased when sonic energy is focused into the fractures.

The percentage increase when sonic energy is focussed into the fractures is calculated by taking the averages of the assymptotic values of Figure 5.16 and 5.17. This is shown in Figure 5. 18 (average concentration of trichloroethylene in the effluent stream at assymptotic value, from Figure 5.16) and Figure 5.19 (average rate of removal of organic at assymptotic value, from Figure 5.17). The percentage improvement in concentration for the first sound-air pair, as calculated from Figure 5.18 is 9.1% and from the second-air pair is 7%. Also, the percentage improvement in removal rate for the first sound-air pair, as calculated from Figure 5.19 is 31% and from the second-air pair is 25%. The change in the removal rate is more consistent with Experiment 1 because the effluent flow rate changed between the runs (Table 6.1). These results, like the results from experiment 1, show that there is a remarkable improvement when sonic energy is used as an enhancement technique to remove volatile organic compounds.

### 6.3 Experimental Run 3 (Saturday, November 14, 1998)

The results of experimental run 3 are presented in Figure 5.20 to Figure 5.25. The procedure for this experiment was reversed, compared to Experiment 1 and 2. In this experiment the first run was performed using no sound. In Figure 5.20, initially the experiments are performed using no sound (whistles shut). At the start of the experiment the concentration of trichloroethylene in the effluent stream decreases rapidly from a value of about 30 PPMv until it stabilizes at a constant value of about 18 PPMv. The drop in the concentration of trichloroethylene in the effluent stream (from 30PPMv to 18 PPMv ) took about 15 minutes. This initial decline observed was very similar to the decline observed in Figure 5.8. Thus the method of operation does not affect the initial period. The concentration of the organic removed then stayed at this value of 18 PPMv until the whistles were turned on. When the whistles were turned on, there was an observed sharp increase in the concentration of trichloroethylene in the effluent stream, from 18 PPMv to 20 PPMv and an increase in the effluent flowrate from 9.5 scfm to 12.8 scfm (Table 6.1). Thus, the increase in the concentration was underestimated due to the dilution effect of the increased air flowrate. The concentration of trichloroethylene in the effluent stream stayed constant at 20 PPMv for about 20 minutes.

When the method of operation was switched from sound to air, Figure 5.20, the concentration of trichloroethylene in the effluent stream drops to a lower constant value of about 18 PPMv. The effluent flowrate also dropped to 10.4 scfm. This drop in effluent flowrate indicates that the drop in concentration was underestimated.

Figure 5.21 is similar to Figure 5.20 but with the concentrations of TCE in Figure 5.20 converted to removal rates (Appendix B). Figure 5.21 also takes into account the variation in the effluent flowrates. In Figure 5.21, initially the experiments are performed using air (whistles shut). At the start of the experiment the removal rate of trichloroethylene decreases rapidly from a value of about 0.0004 cubic feet per minute until it stabilizes at a constant value of about 0.000171 cubic feet per minute. The drop in the removal rate of trichloroethylene (from 0.0004cubic feet per minute to 0.000171 cubic feet per minute) took about 15 minutes. This initial decline observed was very similar to the decline observed in Figure 5.9. The rate of removal of the organic then stayed at this value of 0.000171 cubic feet per minute until the whistles were turned on.

When the whistles were turned on, there was an observed sharp increase in the removal rate of trichloroethylene, from 0.000171 cubic feet per minute to 0.000256 cubic feet per minute. The removal rate of trichloroethylene stayed constant at this value for about 20 minutes.

When the method of operation was switched from sound to air, Figure 5.21, the removal rate of trichloroethylene drops to a lower constant value of about 0.000186 cubic feet per minute (Table 6.1). The trends displayed follow the same explanation as given for Figure 5.8. Figure 5.21 unlike Figure 5.20 takes into account the variation of the effluent flowrates.

Figure 5.22 shows the assymptotic values for Figure 5.20 and Figure 5.23 shows the corresponding constant rate plot for Figure 5.21. These are the periods during which the penetration ability of the method employed limits both the amount and rate of removal of the organic contaminant. From Figure 5.22 and 5.23, it is evident that both the amount and the removal rate of the organic are increased when sonic energy is focused into the fractures. The percentage increase when sonic energy is focussed into the fractures is calculated by taking the averages of the assymptotic values of Figure 5.22 and 5.23. This is shown in Figure 5.24 (average concentration of trichloroethylene in the effluent stream at assymptotic value, from Figure 5.22) and Figure 5.25 (average rate of removal of organic at assymptotic value, from Figure 5.23). The percentage improvement for the first air-sound pair, as calculated from Figure 5.24 is 11% and from the air-sound pair is 16.2%. Also, the percentage improvement in removal rate for the first air-sound pair, as calculated from Figure 5.25 is 49.7% and from the second-air pair is 39.7%. These results, like the results of experiment 1 and 2, show that there is a remarkable improvement when sonic energy is used as an enhancement technique to remove volatile organic compounds.

### 6.4 Experimental Run 4 (Sunday, November 15, 1998)

The results of experimental run 4 are presented in Figure 5.26 to Figure 5.31.In Figure 5.26, initially the experiments are performed using sonic energy (whistles turned on). At the start of the experiment, the concentration of trichloroethylene in the effluent stream decreases slightly from a value of about 23 PPMv until it stabilizes at a constant value of about 21 PPMv . After this period, Figure 5.26, the concentration of trichloroethylene in the effluent stream stays at this constant value of about 21 PPMv.

When the method of operation is switched from sound to air, Figure 5.26, the concentration of trichloroethylene in the effluent stream drops to a lower constant value of about 16 PPMv (Table 6.1). The effluent flowrate is also observed to drop slightly from 11 scfm to 10 scfm. This drop in effleunt flowrate caused the drop in the concentration to be underestimated. It took about 15 minutes for the concentration to drop from 21 PPMv to about 16 PPMv.

The subsequent increase in the concentration of trichloroethylene in the effluent stream (to about 19.9 PPMv) when the sound is again switched on and the drop in the concentration of trichloroethylene in the effluent stream (to about 16 PPMv) when the sound is again switched off (Figure 5.26) follow the same explanation as given for Figure 5.8. For this last sound and no sound pair, the effluent flow rate was again observed to drop from 19.9 scfm to 16 scfm, when the mode of operation was switched from sound to no sound ( Table 6.1).

Figure 5.27 is similar to Figure 5.26 but with the concentrations of Figure 5.26 converted to removal rates in Figure 5.27. Thus, Figure 5.27 takes into account the variation in effluent flowrates observed, in Table 6.1, whereas Figure 5.26 does not. In Figure 5.27, initially the experiments are performed using sonic energy (whistles turned on). At the start of the experiment, the removal rate of trichloroethylene decreases slightly from a value of about 0.00025 cubic feet per minute until it stabilizes at a constant value of about 0.000233 cubic feet per minute.

After this period, Figure 5.27, the removal rate of trichloroethylene stays at this constant value of about 0.000233 cubic feet per minute (Table 6.1).

When the method of operation is switched from sound to air, Figure 5.27, the removal rate of trichloroethylene drops to a lower constant value of about 0.000159 cubic feet per minute. It took about 15 minutes for the removal rate to drop from 0.000233 cubic feet per minute to about 0.000159 cubic feet per minute.

The subsequent increase in the removal rate of trichloroethylene (to about 0.000222 cubic feet per minute) when the sound is again switched on and the drop in the removal rate of trichloroethylene (to about 0.000155 cubic feet per minute) when the sound is again switched off (Figure 5.27) follow the same explanation as for Figure 5.8.

Figure 5.28 shows the assymptotic values for Figure 5.26 and Figure 5.29 shows the corresponding constant rate plot for Figure 5.27. These are the periods during which the penetration ability of the method employed limits both the amount and rate of removal of the organic contaminant. From Figure 5.28 and 5.29, it is evident that both the amount and the removal rate of the organic are increased when sonic energy is focused into the fractures.

The percentage increase when sonic energy is focussed into the fractures is calculated by taking the averages of the assymptotic values of Figure 5.28 and 5.29. This is shown in Figure 5. 30 (average concentration of trichloroethylene in the effluent stream at assymptotic value, from Figure 5.28) and Figure 5.31 (average rate of removal of organic at assymptotic value, from Figure 5.29).

The percentage improvement in concentration for the first sound-air pair, as calculated from Figure 5.30 is 33.3% and from the second-air pair is 22%. Also, the percentage improvement in removal rate for the first sound-air pair, as calculated from Figure 5.31 is 46.5% and from the second-air pair is 43.22%. These results, like the results from experiment 1,2 and 3, confirm that there is a remarkable improvement when sonic energy is used as an enhancement technique to remove volatile organic compounds.

Table 6.2 gives the average of the percentage improvements for each of the experimental runs and the average over the entire field study.

**Table 6.2** Average Percentage Improvement for Each of the Experimental Runs

| Experiment* | Percent Improvement Concentration/PPMv | Percent Improvement Cubic Feet per Minute |
|---|---|---|
| 1a | 34.8 | 34.9 |
| 1b | 33.0 | 33.3 |
| 2a | 9.1 | 31.0 |
| 2b | 7.0 | 25.1 |
| 3a | 11.0 | 49.7 |
| 3b | 16.5 | 39.7 |
| 4a | 33.3 | 46.5 |
| 4b | 22.0 | 43.2 |
| | **Average = 20.8375%** | **Average = 37.925 %** |
| | **Standard Deviation = 11.60** | **Standard Deviation = 8.33** |
| | **95% Confidence Interval** 11.14-30.55 | **95% Confidence Interval** 30.96-44.89 |

*a = First pair (of no sound and Sound), b= second pair ( of no sound and Sound)

The probability is 0.95 that the interval 11.138 to 30.5495 will contain the true mean percentage improvement of the concentration of TCE in the effluent stream and the probability is 0.95 that the interval 30.96 to 44.89 will contain the true mean percentage improvement of the removal rate of TCE.

### 6.5 Additional Experiment (Saturday November 8, 1998)

In Figure 5.32, with no sonic energy, initially concentration of trichloroethylene dropped from a value of 50 PPMv to a value of about 30 PPMv. This observation can be explained by the fact that the contaminants on the surface of the fractures were being removed. After this period the removal rate of trichloroethylene in effluent stream remains at this constant value of 30 PPMv for about 30 minutes. During this entire period the vacuum pump reading was set to 27 inches of water vacuum.

When the sonic energy was turned on, for a considerably lower vacuum of 20 inches of water vacuum, the concentration of trichloroethylene in effluent stream remains fairly constant. This can be explained by the fact that due to the vibrations occurring within the fractures when sonic energy is focussed into them both the concentration and the removal rate of organic is increased and one could afford to set the vacuum pump to a lower reading of 20 inches of water vacuum and still have the same amount of organic removed, as in air at a higher vacuum reading of 27 inches of water vacuum. The procedure was then repeated for another air –sonic energy pair. The results obtained are as explained above (Figure 5.32). Finally, a last run was performed using no sound and setting the vacuum pump to 20 inches of water vacuum (same vacuum pump reading as in the sonic energy experiments). This led to a rapid decline in the removal rate of trichloroethylene in effluent stream (Figure 5.32). This proved that the sonic energy enhanced the removal rate of trichloroethylene in effluent stream.

Figure 5.33 is similar to Figure 5.32 , with all concentrations converted to removal rates (Refer to appendix B for sample calculation). Figure 5.34 shows the assymptotic values for Figure 5.32. Only the runs with a vacuum of 20 inches of water vacuum are shown. This was done in order to facilitate a comparison of the effect of the sonic energy at a given vacuum. Figure 5.35 is the corresponding at assymptotic value for Figure 5.33. Figure 5.36 represents the average concentration of Trichloroethylene in the effluent stream, at assymptotic value. It is corresponds to the average value of Figure 5.34. Finally, Figure 5.37 represents the average removal rate of trichloroethylene, at assymptotic value. It is corresponds to the average value of Figure 5.35. Thus, this test showed that for about the same removal rate a vacuum of 20 inches of water is needed with sonic energy compared to 27 inches of water with no sonic energy. Furthermore, a comparison of sonic energy and no sonic energy at 20 inches of water vacuum showed a marked decline in the removal rate when sonic energy was not used.

# CHAPTER 7

# CONCLUSIONS AND RECOMMENDATIONS

The conclusions of the study are;

1. The field study, like the previous laboratory studies, show that sonic energy significantly improves the rate of removal and the amount of the organics removed.
2. In every experiment the rate of removal increased when sonic energy is focussed into the fractures
3. The average percent increase achieved (over the entire field study) on the concentration of the organic in the effluent stream, when sonic energy is focussed into the fractures is 20.8%
4. The average percent increase achieved (over the entire field study) on the rate of removal of organic contaminant is 37.9%.
5. These values are very significant and shows that sonic energy can be used to reduce the time requirements of a site remediation exercise.
6. Also the results of the additional study shows that for the same removal rate less vacuum and therefore, less vacuum pump energy will be consumed using sound, compared to using air alone. This is seen in the vacuum requirements needed to achieve the same removal rate. Thus in situations where the cost of energy is critical using sonic energy could lead to multiple gains.
7. The probability is 0.95 that the interval 11.14 to 30.54 percent will contain the true mean percentage improvement of the concentration of TCE in the effluent stream.
8. The probability is 0.95 that the interval 30.95 to 44.89 percent will contain the true mean percentage improvement of the removal rate of trichloroethylene.

**Recommendations:**

1. It is recommended that more tests should be made to investigate other parameters that may greatly affect the outcome of the results. A key factor in this category is the attenuation of the sonic field within the formation. Tests should also be run to find the attenuation coefficients in different types of soils and also to establish the radius of influence of the whistle.
2. It is also recommended that the optimum power levels at which the whistle should operate be established.
3. Also the effect of other parameters such as the orientation and location of the fractures can be studied. Eventually all these parameters can be built into a mathematical model to predict the expected amount of enhancement and the effective range of sonic field. These factors will enhance the design of future field decontamination studies.

## APPENDIX A FIELD DATA

Preliminary Experiment1( Saturday ,26 September, 1998)

Morning Session

**No Sound– sound –No Sound**

**Table A.1** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 90-115 | 95-115 | 0 | |
| 2 | 90-115 | 95-115 | 0 | |
| 3 | 0 | 95-115 | 5 | |
| 4 | 0 | 95-115 | 5 | |

Electronic flowmeter reading: 9.9 scfm (Air1)

**Table A.2** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 30-40 | 95-115 | 5 | |
| 2 | 25-30 | 95-115 | 5 | |
| 3 | 95-115 | 95-115 | 0 | |
| 4 | 95-115 | 95-115 | 0 | |

Electronic flowmeter reading: 11.9 scfm (Sound)

**Table A.3** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 90-115 | 95-115 | 0 | |
| 2 | 90-115 | 95-115 | 0 | |
| 3 | 0 | 95-115 | 5 | |
| 4 | 0 | 95-115 | 5 | |

Electronic flowmeter reading: 9.6 scfm (Air2

**Table A.4** Field Data for Preliminary Experiment 1

| Time/sec | Conc. of TCE/PPMv | ft^3(organic)/min (flowrate) | Experiment Type, Air flow |
|---|---|---|---|
| 0 | 340 | 0.003366 | No Sound, 9.9 SCFM |
| 4 | 115 | 0.0011385 | |
| 6 | 110 | 0.001089 | |
| 8 | 110 | 0.001089 | |
| 10 | 105 | 0.0010395 | |
| 12 | 97 | 0.0009603 | |
| 17 | 98.7 | 0.00097713 | |
| 22 | 98 | 0.0009702 | |
| 27 | 91.6 | 0.00090684 | |
| 32 | 94.5 | 0.00093555 | |
| 37 | 88.1 | 0.00087219 | |
| 42 | 85 | 0.0008415 | |
| 47 | 89.5 | 0.00088605 | |
| 52 | 83.1 | 0.00082269 | |
| 57 | 86.1 | 0.00085239 | |
| 62 | 81 | 0.0008019 | |
| 67 | 80.3 | 0.00079497 | |
| 72 | 79.6 | 0.00078804 | |
| 77 | 76.8 | 0.00076032 | |
| 82 | 77.5 | 0.00076725 | |
| 87 | 73.9 | 0.00073161 | |
| 92 | 76.1 | 0.00075339 | |
| 102 | 70.8 | 0.00070092 | |
| 112 | 70.4 | 0.00069696 | |
| 132 | 70.4 | 0.00069696 | |
| 142 | 66.9 | 0.00066231 | |
| 152 | 60.5 | 0.00059895 | |
| 162 | 58.4 | 0.00057816 | |
| 172 | 54.1 | 0.00053559 | |
| 182 | 52 | 0.0005148 | |
| 192 | 49.2 | 0.00048708 | |
| 202 | 47.7 | 0.00047223 | |
| 212 | 47 | 0.0004653 | |
| 222 | 45.6 | 0.00045144 | |
| 232 | 44.9 | 0.00044451 | |
| 242 | 43.5 | 0.00043065 | |
| 252 | 41.2 | 0.00040788 | |
| 262 | 43.5 | 0.00043065 | |
| 272 | 44.9 | 0.00044451 | |
| 282 | 47.7 | 0.00047223 | |
| 292 | 49.4 | 0.00048906 | |

**Table A.4** Field Data for Preliminary Experiment 1
(Continued)

| Time/sec | Conc. of TCE/PPMv | ft^3(organic)/min (flowrate) | Experiment Type, Air flow |
|---|---|---|---|
| 302 | 47.7 | 0.00047223 | |
| 312 | 47 | 0.0004653 | |
| 322 | 45.6 | 0.00045144 | |
| 332 | 44.2 | 0.00043758 | |
| 342 | 42.3 | 0.00041877 | |
| 352 | 39.9 | 0.00039501 | |
| 362 | 37.8 | 0.00037422 | |
| 372 | 35.7 | 0.00035343 | |
| 412 | 32.2 | 0.00031878 | |
| 422 | 31.5 | 0.00031185 | |
| 432 | 30.7 | 0.00030393 | |
| 442 | 30 | 0.000297 | |
| 452 | 29.3 | 0.00029007 | |
| 462 | 28.6 | 0.00028314 | |
| 472 | 27.9 | 0.00027621 | |
| 482 | 27.9 | 0.00027621 | |
| 492 | 27.9 | 0.00027621 | |
| 502 | 27.9 | 0.00027621 | |
| 512 | 27.9 | 0.00027621 | |
| 522 | 27.9 | 0.00027621 | |
| 532 | 27.9 | 0.00027621 | |
| 542 | 27.2 | 0.00026928 | |
| 552 | 27.2 | 0.00026928 | |
| 562 | 26.5 | 0.00026235 | |
| 592 | 26.5 | 0.00026235 | |
| 622 | 27.2 | 0.00026928 | |
| 652 | 26.5 | 0.00026235 | |
| 682 | 26.5 | 0.00026235 | |
| 712 | 26.5 | 0.00026235 | |
| 742 | 26.5 | 0.00026235 | |
| 772 | 26.5 | 0.00026235 | |
| 802 | 26.5 | 0.00026235 | |
| 832 | 26.5 | 0.00026235 | |
| 1432 | 26.5 | 0.00026235 | |
| 1552 | 24.4 | 0.00024156 | |
| 1612 | 24.4 | 0.00024156 | |
| 1672 | 22.3 | 0.00022077 | |
| 1732 | 21.5 | 0.00021285 | |
| 1792 | 20.8 | 0.00020592 | |
| 1852 | 20.1 | 0.00019899 | |

**Table A.4** Field Data for Preliminary Experiment 1
(Continued)

| Time/sec | Conc. of TCE/PPMv | ft^3(organic)/min (flowrate) | Experiment Type, Air flow |
|---|---|---|---|
| 1912 | 20.1 | 0.00019899 | |
| 1972 | 19.4 | 0.00019206 | |
| 2032 | 19.4 | 0.00019206 | |
| 2092 | 18.7 | 0.00018513 | |
| 2152 | 18.7 | 0.00018513 | |
| 2212 | 18.7 | 0.00018513 | |
| 2272 | 18.7 | 0.00018513 | |
| 2332 | 18.7 | 0.00018513 | |
| 2392 | 18.7 | 0.00018513 | |
| 2452 | 18.7 | 0.00018513 | |
| 2512 | 18.7 | 0.00018513 | |
| 2572 | 18.7 | 0.00018513 | |
| 2632 | 18 | 0.0001782 | |
| 2692 | 18 | 0.0001782 | |
| 2812 | 18 | 0.0001782 | |
| 2932 | 18 | 0.0001782 | |
| 3052 | 17.3 | 0.00017127 | |
| 3232 | 17.3 | 0.00017127 | |
| 3412 | 17.3 | 0.00017127 | |
| 3592 | 16.6 | 0.00016434 | |
| 3772 | 16.6 | 0.00016434 | |
| 3774 | 17.3 | 0.00020587 | **Sound,11.9 SCFM** |
| 3776 | 17.3 | 0.00020587 | |
| 3778 | 18 | 0.0002142 | |
| 3780 | 17.3 | 0.00020587 | |
| 3782 | 17.3 | 0.00020587 | |
| 3784 | 18 | 0.0002142 | |
| 3786 | 18 | 0.0002142 | |
| 3788 | 18 | 0.0002142 | |
| 3790 | 18 | 0.0002142 | |
| 3792 | 17.3 | 0.00020587 | |
| 3794 | 17.3 | 0.00020587 | |
| 3799 | 17.3 | 0.00020587 | |
| 3804 | 17.3 | 0.00020587 | |
| 3809 | 18 | 0.0002142 | |
| 3814 | 17.3 | 0.00020587 | |
| 3819 | 17.3 | 0.00020587 | |
| 3824 | 18 | 0.0002142 | |
| 3829 | 17.3 | 0.00020587 | |

**Table A.4** Field Data for Preliminary Experiment 1
(Continued)

| Time/sec | Conc. of TCE/PPMv | ft^3(organic)/mi (flowrate) | Experiment Type, Air flow |
|---|---|---|---|
| 3834 | 17.3 | 0.00020587 | |
| 3839 | 18 | 0.0002142 | |
| 3844 | 17.3 | 0.00020587 | |
| 3854 | 18 | 0.0002142 | |
| 3864 | 17.3 | 0.00020587 | |
| 3874 | 18 | 0.0002142 | |
| 3884 | 17.3 | 0.00020587 | |
| 3894 | 18 | 0.0002142 | |
| 3904 | 18 | 0.0002142 | |
| 3914 | 18 | 0.0002142 | |
| 3944 | 18 | 0.0002142 | |
| 3974 | 18 | 0.0002142 | |
| 4004 | 18 | 0.0002142 | |
| 4034 | 18.7 | 0.00022253 | |
| 4064 | 18.7 | 0.00022253 | |
| 4094 | 18.7 | 0.00022253 | |
| 4124 | 19.4 | 0.00023086 | |
| 4154 | 19.4 | 0.00023086 | |
| 4184 | 19.4 | 0.00023086 | |
| 4214 | 19.4 | 0.00023086 | |
| 4244 | 19.4 | 0.00023086 | |
| 4274 | 19.4 | 0.00023086 | |
| 4304 | 19.4 | 0.00023086 | |
| 4364 | 19.4 | 0.00023086 | |
| 4424 | 18.7 | 0.00022253 | |
| 4484 | 18.7 | 0.00022253 | |
| 4544 | 18.7 | 0.00022253 | |
| 4604 | 18.7 | 0.00022253 | |
| 4664 | 18.7 | 0.00022253 | |
| 4784 | 18.7 | 0.00022253 | |
| 4904 | 18.7 | 0.00022253 | |
| 5024 | 18.7 | 0.00022253 | |
| 5144 | 18.7 | 0.00022253 | |
| 5264 | 18.7 | 0.00022253 | |
| 5564 | 18.7 | 0.00022253 | |
| 5864 | 18.7 | 0.00022253 | |
| 5869 | 20.8 | 0.00019968 | **No Sound, 9.6 SCFM** |
| 5874 | 20.8 | 0.00019968 | |
| 5879 | 20.8 | 0.00019968 | |
| 5884 | 20.1 | 0.00019296 | |

**Table A.4** Field Data for Preliminary Experiment 1
(Continued)

| Time/sec | Conc. of TCE/PPMv | ft^3(organic)/min (flowrate) | Experiment Type, Air flow |
|---|---|---|---|
| 5889 | 20.8 | 0.00019968 | |
| 5894 | 20.8 | 0.00019968 | |
| 5899 | 20.8 | 0.00019968 | |
| 5904 | 20.8 | 0.00019968 | |
| 5909 | 20.8 | 0.00019968 | |
| 5914 | 21.5 | 0.0002064 | |
| 5919 | 21.5 | 0.0002064 | |
| 5924 | 20.8 | 0.00019968 | |
| 5929 | 20.8 | 0.00019968 | |
| 5934 | 20.8 | 0.00019968 | |
| 5939 | 20.8 | 0.00019968 | |
| 5944 | 20.8 | 0.00019968 | |
| 5954 | 20.8 | 0.00019968 | |
| 5964 | 20.8 | 0.00019968 | |
| 5974 | 20.8 | 0.00019968 | |
| 5984 | 20.8 | 0.00019968 | |
| 5994 | 20.8 | 0.00019968 | |
| 6024 | 20.8 | 0.00019968 | |
| 6054 | 20.8 | 0.00019968 | |
| 6084 | 20.8 | 0.00019968 | |
| 6114 | 20.8 | 0.00019968 | |
| 6144 | 20.8 | 0.00019968 | |
| 6204 | 20.1 | 0.00019296 | |
| 6264 | 20.1 | 0.00019296 | |
| 6324 | 19.4 | 0.00018624 | |
| 6384 | 19.4 | 0.00018624 | |
| 6444 | 18.7 | 0.00017952 | |
| 6504 | 18.7 | 0.00017952 | |
| 6564 | 18 | 0.0001728 | |
| 6624 | 18 | 0.0001728 | |
| 6684 | 18 | 0.0001728 | |
| 6744 | 18 | 0.0001728 | |
| 6804 | 18 | 0.0001728 | |
| 6924 | 17.3 | 0.00016608 | End |

## Preliminary Experiment 2( Saturday ,26 September, 1998)

Afternoon Session:

**Air – Sound**

**Table A.5** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 90-115 | 95-115 | 0 | |
| 2 | 90-115 | 95-115 | 0 | |
| 3 | 0 | 95-115 | 5 | |
| 4 | 0 | 95-115 | 5 | |

Electronic flowmeter reading: 9.75 scfm(Air),

**Table A.6** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 30-40 | 95-115 | 5 | |
| 2 | 25-30 | 95-115 | 5 | |
| 3 | 95-115 | 95-115 | 0 | |
| 4 | 95-115 | 95-115 | 0 | |

Electronic flowmeter reading: 12 scfm(Sound)

**Table A.7** Field Data for Preliminary Experiment 2

| Time/sec | Conc. of TCE/PPMv | ft^3(organic)/min (flowrate) | Experiment type, Air flow |
|---|---|---|---|
| 2 | 8.8 | 0.0000858 | **No Sound, 9.75 SCFM** |
| 4 | 8.8 | 0.0000858 | |
| 6 | 17.3 | 0.000168675 | |
| 8 | 60.5 | 0.000589875 | |
| 10 | 73.9 | 0.000720525 | |
| 12 | 73.2 | 0.0007137 | |
| 14 | 65.5 | 0.000638625 | |
| 16 | 57.9 | 0.000564525 | |
| 18 | 48.4 | 0.0004719 | |
| 20 | 43.5 | 0.000424125 | |
| 25 | 38.5 | 0.000375375 | |

**Table A.7** Field Data for Preliminary Experiment 2
(Continued)

| Time/sec | Conc. of TCE/PPMv | ft^3(organic)/min (flowrate) | Experiment type, Air flow |
|---|---|---|---|
| 30 | 33.6 | 0.0003276 | |
| 35 | 32.9 | 0.000320775 | |
| 40 | 29.3 | 0.000285675 | |
| 45 | 27.9 | 0.000272025 | |
| 50 | 30 | 0.0002925 | |
| 55 | 30 | 0.0002925 | |
| 60 | 30 | 0.0002925 | |
| 65 | 30.7 | 0.000299325 | |
| 70 | 30 | 0.0002925 | |
| 75 | 31.5 | 0.000307125 | |
| 80 | 28.6 | 0.00027885 | |
| 85 | 30 | 0.0002925 | |
| 90 | 28.6 | 0.00027885 | |
| 95 | 30 | 0.0002925 | |
| 100 | 27.9 | 0.000272025 | |
| 105 | 27.9 | 0.000272025 | |
| 110 | 27.9 | 0.000272025 | |
| 115 | 27.2 | 0.0002652 | |
| 120 | 28.6 | 0.00027885 | |
| 125 | 27.2 | 0.0002652 | |
| 135 | 25.8 | 0.00025155 | |
| 145 | 25.8 | 0.00025155 | |
| 155 | 25.8 | 0.00025155 | |
| 165 | 25.8 | 0.00025155 | |
| 185 | 25.8 | 0.00025155 | |
| 205 | 23.7 | 0.000231075 | |
| 225 | 21.5 | 0.000209625 | |
| 245 | 21.5 | 0.000209625 | |
| 265 | 22.3 | 0.000217425 | |
| 325 | 20.8 | 0.0002028 | |
| 385 | 19.4 | 0.00018915 | |
| 445 | 18.7 | 0.000182325 | |
| 505 | 18.7 | 0.000182325 | |
| 565 | 18 | 0.0001755 | |
| 625 | 17.3 | 0.000168675 | |
| 685 | 17.3 | 0.000168675 | |
| 985 | 17.3 | 0.000168675 | |
| 1285 | 18 | 0.0001755 | |

**Table A.7** Field Data for Preliminary Experiment 2
(Continued)

| Time/sec | Conc. of TCE/PPMv | ft^3(organic)/min (flowrate) | Experiment type, Air flow |
|---|---|---|---|
| 2485 | 18 | 0.0001755 | |
| 2785 | 17.3 | 0.000168675 | |
| 3085 | 17.3 | 0.000168675 | |
| 3095 | 16.6 | 0.0001992 | Sound, 12 SCFM |
| 3105 | 16.6 | 0.0001992 | |
| 3115 | 17.3 | 0.0002076 | |
| 3125 | 17.3 | 0.0002076 | |
| 3135 | 17.3 | 0.0002076 | |
| 3145 | 16.6 | 0.0001992 | |
| 3155 | 17.3 | 0.0002076 | |
| 3165 | 17.3 | 0.0002076 | |
| 3175 | 17.3 | 0.0002076 | |
| 3185 | 17.3 | 0.0002076 | |
| 3195 | 17.3 | 0.0002076 | |
| 3205 | 17.3 | 0.0002076 | |
| 3235 | 17.3 | 0.0002076 | |
| 3265 | 17.3 | 0.0002076 | |
| 3295 | 18 | 0.000216 | |
| 3325 | 18 | 0.000216 | |
| 3355 | 18 | 0.000216 | |
| 3385 | 18 | 0.000216 | |
| 3415 | 18 | 0.000216 | |
| 3445 | 18.7 | 0.0002244 | |
| 3475 | 18.7 | 0.0002244 | |
| 3505 | 18.7 | 0.0002244 | |
| 3535 | 18.7 | 0.0002244 | |
| 3565 | 18.7 | 0.0002244 | |
| 3625 | 18.7 | 0.0002244 | |
| 3685 | 18.7 | 0.0002244 | |
| 3745 | 18.7 | 0.0002244 | |
| 3805 | 18.7 | 0.0002244 | |
| 3865 | 18.7 | 0.0002244 | |
| 3925 | 19.4 | 0.0002328 | |
| 4225 | 18.7 | 0.0002244 | |
| 4525 | 18.7 | 0.0002244 | |
| 4825 | 19.4 | 0.0002328 | |
| 5125 | 19.4 | 0.0002328 | |
| 5425 | 19.4 | 0.0002328 | |
| 5725 | 19.4 | 0.0002328 | |
| 6025 | 19.4 | 0.0002328 | END |

## Experimental Studies

Experimental Run 1 : Sunday September 27, 1998.

**Sound- No Sound- Sound- No Sound**

**Table A.8** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 30-40 | 95-115 | 5 | |
| 2 | 25-30 | 95-115 | 5 | |
| 3 | 95-115 | 95-115 | 0 | |
| 4 | 95-115 | 95-115 | 0 | |

Electronic flowmeter reading: 11.3 scfm(Sound)

**Table A.9** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 90-115 | 95-115 | 0 | |
| 2 | 90-115 | 95-115 | 0 | |
| 3 | 0 | 95-115 | 5 | |
| 4 | 0 | 95-115 | 5 | |

Electronic flowmeter reading: 11.3 scfm(Air)

**Table A.10** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 30-40 | 95-115 | 5 | |
| 2 | 25-30 | 95-115 | 5 | |
| 3 | 95-115 | 95-115 | 0 | |
| 4 | 95-115 | 95-115 | 0 | |

Electronic flowmeter reading: 11.3 scfm (Sound)

**Table A.11** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 90-115 | 95-115 | 0 | |
| 2 | 90-115 | 95-115 | 0 | |
| 3 | 0 | 95-115 | 5 | |
| 4 | 0 | 95-115 | 5 | |

Electronic flowmeter reading: 11.3 scfm (Air)

**Table A.12** Field Data for Experimental Run1

| Time/sec | Conc. of TCE/PPMv | Ft^3 organic/min (flowrate) | Experiment type, Air flow |
|---|---|---|---|
| 0 | 284 | 0.003209 | Sound, 11.3 SCFM |
| 10 | 388 | 0.004384 | |
| 15 | 446 | 0.00504 | |
| 20 | 484 | 0.005469 | |
| 25 | 499 | 0.005639 | |
| 30 | 489 | 0.005526 | |
| 35 | 443 | 0.005006 | |
| 40 | 420 | 0.004746 | |
| 45 | 377 | 0.00426 | |
| 50 | 233 | 0.002633 | |
| 55 | 151 | 0.001706 | |
| 60 | 119 | 0.001345 | |
| 65 | 91 | 0.001028 | |
| 70 | 74.3 | 0.00084 | |
| 75 | 64.9 | 0.000733 | |
| 80 | 56.5 | 0.000638 | |
| 85 | 52.3 | 0.000591 | |
| 90 | 46 | 0.00052 | |
| 95 | 41.9 | 0.000473 | |
| 100 | 39.7 | 0.000449 | |
| 105 | 36.6 | 0.000414 | |
| 110 | 35.6 | 0.000402 | |
| 115 | 34.5 | 0.00039 | |
| 120 | 33.5 | 0.000379 | |
| 125 | 31.4 | 0.000355 | |
| 130 | 30.3 | 0.000342 | |
| 135 | 30.3 | 0.000342 | |
| 140 | 29.3 | 0.000331 | |
| 145 | 29.3 | 0.000331 | |
| 150 | 28.2 | 0.000319 | |
| 155 | 28.2 | 0.000319 | |
| 160 | 27.2 | 0.000307 | |
| 165 | 28.2 | 0.000319 | |
| 170 | 27.2 | 0.000307 | |
| 175 | 26.1 | 0.000295 | |
| 180 | 26.1 | 0.000295 | |
| 185 | 26.1 | 0.000295 | |
| 190 | 26.1 | 0.000295 | |
| 200 | 26.1 | 0.000295 | |
| 210 | 26.1 | 0.000295 | |
| 220 | 26.1 | 0.000295 | |

**Table A.12** Field Data for Experimental Run1
(Continued)

| Time/sec | Conc. of TCE/PPMv | Ft^3 organic/min (flowrate) | Experiment type, Air flow |
|---:|---:|---:|---:|
| 230 | 25.1 | 0.000284 | |
| 240 | 25.1 | 0.000284 | |
| 250 | 25.1 | 0.000284 | |
| 260 | 25.1 | 0.000284 | |
| 270 | 25.1 | 0.000284 | |
| 280 | 25.1 | 0.000284 | |
| 290 | 25.1 | 0.000284 | |
| 300 | 25.1 | 0.000284 | |
| 330 | 25.1 | 0.000284 | |
| 360 | 25.1 | 0.000284 | |
| 390 | 24 | 0.000271 | |
| 420 | 24 | 0.000271 | |
| 450 | 24 | 0.000271 | |
| 480 | 24 | 0.000271 | |
| 510 | 24 | 0.000271 | |
| 570 | 24 | 0.000271 | |
| 630 | 24 | 0.000271 | |
| 690 | 23 | 0.00026 | |
| 750 | 23 | 0.00026 | |
| 930 | 23 | 0.00026 | |
| 1230 | 21.9 | 0.000247 | |
| 1530 | 21.9 | 0.000247 | |
| 1830 | 21.9 | 0.000247 | |
| 2130 | 23 | 0.00026 | |
| 2135 | 23 | 0.00026 | **No Sound,** |
| 2140 | 25.1 | 0.000284 | **11.3 SCFM** |
| 2145 | 24 | 0.000271 | |
| 2150 | 24 | 0.000271 | |
| 2155 | 24 | 0.000271 | |
| 2160 | 24 | 0.000271 | |
| 2165 | 24 | 0.000271 | |
| 2170 | 24 | 0.000271 | |
| 2175 | 24 | 0.000271 | |
| 2180 | 24 | 0.000271 | |
| 2185 | 24 | 0.000271 | |
| 2190 | 24 | 0.000271 | |
| 2195 | 24 | 0.000271 | |
| 2200 | 24 | 0.000271 | |
| 2230 | 24 | 0.000271 | |

**Table A.12** Field Data for Experimental Run1
(Continued)

| Time/sec | Conc. of TCE/PPMv | Ft^3 organic/min (flowrate) | Experiment type, Air flow |
|---|---|---|---|
| 2260 | 24 | 0.000271 | |
| 2290 | 24 | 0.000271 | |
| 2320 | 23 | 0.00026 | |
| 2350 | 21.9 | 0.000247 | |
| 2380 | 20.9 | 0.000236 | |
| 2410 | 20.9 | 0.000236 | |
| 2440 | 20.9 | 0.000236 | |
| 2470 | 19.8 | 0.000224 | |
| 2500 | 19.8 | 0.000224 | |
| 2530 | 19.8 | 0.000224 | |
| 2560 | 19.8 | 0.000224 | |
| 2590 | 19.8 | 0.000224 | |
| 2620 | 19.8 | 0.000224 | |
| 2650 | 18.8 | 0.000212 | |
| 2680 | 18.8 | 0.000212 | |
| 2710 | 18.8 | 0.000212 | |
| 3010 | 19.8 | 0.000224 | |
| 3310 | 19.8 | 0.000224 | |
| 3610 | 17.8 | 0.000201 | |
| 3910 | 16.7 | 0.000189 | |
| 4210 | 16.7 | 0.000189 | |
| 4510 | 16.7 | 0.000189 | |
| 4810 | 16.7 | 0.000189 | |
| 5110 | 16.7 | 0.000189 | |
| 5115 | 16.7 | 0.000189 | **Sound,** |
| 5120 | 16.7 | 0.000189 | **11.3 SCFM** |
| 5125 | 16.7 | 0.000189 | |
| 5130 | 16.7 | 0.000189 | |
| 5135 | 16.7 | 0.000189 | |
| 5140 | 16.7 | 0.000189 | |
| 5145 | 17.8 | 0.000201 | |
| 5150 | 17.8 | 0.000201 | |
| 5155 | 17.8 | 0.000201 | |
| 5160 | 17.8 | 0.000201 | |
| 5165 | 17.8 | 0.000201 | |
| 5170 | 17.8 | 0.000201 | |
| 5180 | 17.8 | 0.000201 | |
| 5190 | 17.8 | 0.000201 | |
| 5200 | 17.8 | 0.000201 | |

**Table A.12** Field Data for Experimental Run1
(Continued)

| Time/sec | Conc. of TCE/PPMv | Ft^3 organic/min (flowrate) | Experiment type, Air flow |
|---|---|---|---|
| 5230 | 18.8 | 0.000212 | |
| 5260 | 18.8 | 0.000212 | |
| 5290 | 18.8 | 0.000212 | |
| 5320 | 18.8 | 0.000212 | |
| 5380 | 18.8 | 0.000212 | |
| 5440 | 19.8 | 0.000224 | |
| 5500 | 19.8 | 0.000224 | |
| 5560 | 19.8 | 0.000224 | |
| 5620 | 19.8 | 0.000224 | |
| 5680 | 19.8 | 0.000224 | |
| 5740 | 20.9 | 0.000236 | |
| 5800 | 20.9 | 0.000236 | |
| 5860 | 20.9 | 0.000236 | |
| 5920 | 20.9 | 0.000236 | |
| 6220 | 20.9 | 0.000236 | |
| 6520 | 20.9 | 0.000236 | |
| 6820 | 20.9 | 0.000236 | |
| 7120 | 21.9 | 0.000247 | |
| 7420 | 21.9 | 0.000247 | |
| 7720 | 21.9 | 0.000247 | |
| 8020 | 21.9 | 0.000247 | |
| 8030 | 21.9 | 0.000247 | **No Sound,** |
| 8040 | 21.9 | 0.000247 | **11.3 SCFM** |
| 8050 | 21.9 | 0.000247 | |
| 8060 | 23 | 0.00026 | |
| 8070 | 23 | 0.00026 | |
| 8080 | 23 | 0.00026 | |
| 8090 | 23 | 0.00026 | |
| 8100 | 23 | 0.00026 | |
| 8110 | 21.9 | 0.000247 | |
| 8120 | 21.9 | 0.000247 | |
| 8130 | 21.9 | 0.000247 | |
| 8160 | 20.9 | 0.000236 | |
| 8190 | 19.8 | 0.000224 | |
| 8220 | 19.8 | 0.000224 | |
| 8250 | 19.8 | 0.000224 | |
| 8280 | 19.8 | 0.000224 | |
| 8310 | 19.8 | 0.000224 | |
| 8370 | 19.8 | 0.000224 | |

**Table A.12** Field Data for Experimental Run1
(Continued)

| **Time/sec** | **Conc. of TCE/PPMv** | **Ft^3 organic/min (flowrate)** | **Experiment type, Air flow** |
|---|---|---|---|
| 8430 | 18.8 | 0.000212 | |
| 8490 | 18.8 | 0.000212 | |
| 8550 | 19.8 | 0.000224 | |
| 8610 | 18.8 | 0.000212 | |
| 8670 | 19.8 | 0.000224 | |
| 8970 | 16.7 | 0.000189 | |
| 9270 | 16.7 | 0.000189 | |
| 9570 | 15.7 | 0.000177 | |
| 9870 | 15.7 | 0.000177 | **End** |

Experimental Run 2 : Saturday November 7, 1998.

**Sound- No Sound- Sound- No Sound**

**Table A.13** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 30-40 | 95-115 | 5 | |
| 2 | 25-30 | 95-115 | 5 | |
| 3 | 95-115 | 95-115 | 0 | |
| 4 | 95-115 | 95-115 | 0 | |

Electronic flowmeter reading: 12.1 scfm (Sound)

**Table A.14** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 90-115 | 95-115 | 0 | |
| 2 | 90-115 | 95-115 | 0 | |
| 3 | 0 | 95-115 | 5 | |
| 4 | 0 | 95-115 | 5 | |

Electronic flowmeter reading: 10.1 scfm(Air)

**Table A.15** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 30-40 | 95-115 | 5 | |
| 2 | 25-30 | 95-115 | 5 | |
| 3 | 95-115 | 95-115 | 0 | |
| 4 | 95-115 | 95-115 | 0 | |

Electronic flowmeter reading: 12.5 scfm (Sound)

**Table A.16** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 90-115 | 95-115 | 0 | |
| 2 | 90-115 | 95-115 | 0 | |
| 3 | 0 | 95-115 | 5 | |
| 4 | 0 | 95-115 | 5 | |

Electronic flowmeter reading: 10.7scfm (Air)

**Table A.17** Field Data for Experimental Run 2

| CummulativeTime/sec | Conc. of TCE (PPMV) | Ft^3 organic/min (flowrate) | Experiment type, Air flow |
|---|---|---|---|
| 0 | 31.8 | 0.00038478 | **Sound1,** |
| 5 | 24.2 | 0.00029282 | **12.1scfm** |
| 10 | 24.6 | 0.00029766 | |
| 15 | 23.3 | 0.00028193 | |
| 20 | 24.2 | 0.00029282 | |
| 25 | 22.3 | 0.00026983 | |
| 30 | 23.7 | 0.00028677 | |
| 35 | 23.3 | 0.00028193 | |
| 40 | 23.7 | 0.00028677 | |
| 45 | 22.8 | 0.00027588 | |
| 50 | 24.2 | 0.00029282 | |
| 55 | 23.3 | 0.00028193 | |
| 60 | 23.7 | 0.00028677 | |
| 65 | 23.3 | 0.00028193 | |
| 70 | 23.7 | 0.00028677 | |
| 75 | 23.3 | 0.00028193 | |
| 80 | 23.7 | 0.00028677 | |
| 85 | 22.8 | 0.00027588 | |
| 95 | 23.3 | 0.00028193 | |

**Table A.17** Field Data for Experimental Run 2
(Continued)

| CummulativeTime/sec | Conc. of TCE/PPMv | Ft^3 organic/min (flowrate) | Experiment type, Air flow |
|---:|---:|---:|---|
| 105 | 23.3 | 0.00028193 | |
| 115 | 23.7 | 0.00028677 | |
| 125 | 23.7 | 0.00028677 | |
| 135 | 23.7 | 0.00028677 | |
| 145 | 23.7 | 0.00028677 | |
| 155 | 23.7 | 0.00028677 | |
| 165 | 23.7 | 0.00028677 | |
| 175 | 23.7 | 0.00028677 | |
| 195 | 24.2 | 0.00029282 | |
| 215 | 24.6 | 0.00029766 | |
| 235 | 25.1 | 0.00030371 | |
| 255 | 25.5 | 0.00030855 | |
| 275 | 25.5 | 0.00030855 | |
| 295 | 25.5 | 0.00030855 | |
| 315 | 25.5 | 0.00030855 | |
| 335 | 26 | 0.0003146 | |
| 355 | 26 | 0.0003146 | |
| 385 | 26.9 | 0.00032549 | |
| 415 | 27.3 | 0.00033033 | |
| 445 | 27.3 | 0.00033033 | |
| 475 | 27.8 | 0.00033638 | |
| 505 | 28.2 | 0.00034122 | |
| 535 | 28.2 | 0.00034122 | |
| 565 | 28.7 | 0.00034727 | |
| 595 | 28.7 | 0.00034727 | |
| 625 | 28.7 | 0.00034727 | |
| 655 | 29.1 | 0.00035211 | |
| 715 | 29.1 | 0.00035211 | |
| 775 | 29.1 | 0.00035211 | |
| 835 | 29.1 | 0.00035211 | |
| 895 | 30 | 0.000363 | |
| 955 | 30 | 0.000363 | |
| 1015 | 30.5 | 0.00036905 | |
| 1075 | 30.9 | 0.00037389 | |
| 1135 | 30.9 | 0.00037389 | |
| 1195 | 30.9 | 0.00037389 | |
| 1255 | 30.9 | 0.00037389 | |
| 1315 | 31.4 | 0.00037994 | |
| 1375 | 30.9 | 0.00037389 | |

**Table A.17** Field Data for Experimental Run 2
(Continued)

| CummulativeTime/sec | Conc. of TCE/PPMv | Ft^3 organic/min (flowrate) | Experiment type, Air flow |
|---|---|---|---|
| 1435 | 30.9 | 0.00037389 | |
| 1495 | 30.9 | 0.00037389 | |
| 1555 | 30.9 | 0.00037389 | |
| 1615 | 30.9 | 0.00037389 | |
| 1675 | 30.9 | 0.00037389 | |
| 1735 | 31.4 | 0.00037994 | |
| 2155 | 32.8 | 0.00039688 | |
| 2455 | 31.4 | 0.00037994 | |
| 2755 | 32.8 | 0.00039688 | |
| 3055 | 32.8 | 0.00039688 | |
| 3360 | 32.8 | 0.00039688 | **No Sound,** |
| 3365 | 31.4 | 0.00031714 | **10.1scfm** |
| 3370 | 35.5 | 0.00035855 | |
| 3375 | 37.7 | 0.00038077 | |
| 3380 | 39.1 | 0.00039491 | |
| 3385 | 40.4 | 0.00040804 | |
| 3390 | 40.4 | 0.00040804 | |
| 3395 | 40.4 | 0.00040804 | |
| 3400 | 40 | 0.000404 | |
| 3405 | 40 | 0.000404 | |
| 3410 | 39.5 | 0.00039895 | |
| 3415 | 38.6 | 0.00038986 | |
| 3420 | 38.6 | 0.00038986 | |
| 3425 | 38.2 | 0.00038582 | |
| 3430 | 37.7 | 0.00038077 | |
| 3435 | 37.3 | 0.00037673 | |
| 3440 | 37.3 | 0.00037673 | |
| 3445 | 36.4 | 0.00036764 | |
| 3450 | 35.9 | 0.00036259 | |
| 3455 | 35.5 | 0.00035855 | |
| 3460 | 35 | 0.0003535 | |
| 3465 | 34.6 | 0.00034946 | |
| 3475 | 33.7 | 0.00034037 | |
| 3485 | 33.2 | 0.00033532 | |
| 3495 | 33.2 | 0.00033532 | |
| 3505 | 32.8 | 0.00033128 | |
| 3515 | 32.3 | 0.00032623 | |
| 3525 | 32.3 | 0.00032623 | |
| 3535 | 31.8 | 0.00032118 | |

**Table A.17** Field Data for Experimental Run 2
(Continued)

| CummulativeTime/sec | Conc. of TCE/PPMv | Ft^3 organic/min (flowrate) | Experiment type, Air flow |
|---|---|---|---|
| 3545 | 31.8 | 0.00032118 | |
| 3555 | 31.4 | 0.00031714 | |
| 3565 | 31.4 | 0.00031714 | |
| 3575 | 31.4 | 0.00031714 | |
| 3585 | 30.5 | 0.00030805 | |
| 3595 | 30.5 | 0.00030805 | |
| 3605 | 30 | 0.000303 | |
| 3615 | 30 | 0.000303 | |
| 3625 | 30 | 0.000303 | |
| 3645 | 29.6 | 0.00029896 | |
| 3665 | 29.6 | 0.00029896 | |
| 3685 | 29.6 | 0.00029896 | |
| 3705 | 29.1 | 0.00029391 | |
| 3725 | 29.1 | 0.00029391 | |
| 3745 | 29.1 | 0.00029391 | |
| 3765 | 29.1 | 0.00029391 | |
| 3785 | 29.1 | 0.00029391 | |
| 3805 | 29.1 | 0.00029391 | |
| 3835 | 29.1 | 0.00029391 | |
| 3865 | 29.1 | 0.00029391 | |
| 3895 | 28.7 | 0.00028987 | |
| 3925 | 28.7 | 0.00028987 | |
| 3955 | 28.7 | 0.00028987 | |
| 3985 | 28.7 | 0.00028987 | |
| 4045 | 29.1 | 0.00029391 | |
| 4105 | 29.1 | 0.00029391 | |
| 4165 | 29.6 | 0.00029896 | |
| 4225 | 30 | 0.000303 | |
| 4285 | 30 | 0.000303 | |
| 4345 | 29.6 | 0.00029896 | |
| 4405 | 29.6 | 0.00029896 | |
| 4465 | 30 | 0.000303 | |
| 4525 | 29.6 | 0.00029896 | |
| 4585 | 29.6 | 0.00029896 | |
| 4645 | 30 | 0.000303 | |
| 4705 | 30 | 0.000303 | |
| 4765 | 30 | 0.000303 | |
| 4825 | 29.6 | 0.00029896 | |

**Table A.17** Field Data for Experimental Run 2
(Continued)

| CummulativeTime/sec | Conc. of TCE/PPMv | Ft^3 organic/min (flowrate) | Experiment type, Air flow |
|---|---|---|---|
| 4885 | 29.6 | 0.00029896 | |
| 5185 | 30 | 0.000303 | |
| 5485 | 29.6 | 0.00029896 | |
| 5785 | 29.6 | 0.00029896 | |
| 6385 | 29.6 | 0.00029896 | |
| 6985 | 30 | 0.000375 | **sound2,** |
| 6995 | 27.2 | 0.00034 | **12.5scfm** |
| 7005 | 28.2 | 0.0003525 | |
| 7015 | 28.2 | 0.0003525 | |
| 7025 | 28.2 | 0.0003525 | |
| 7035 | 28.7 | 0.00035875 | |
| 7045 | 29.1 | 0.00036375 | |
| 7055 | 29.1 | 0.00036375 | |
| 7065 | 29.1 | 0.00036375 | |
| 7095 | 28.7 | 0.00035875 | |
| 7125 | 29.1 | 0.00036375 | |
| 7155 | 29.6 | 0.00037 | |
| 7185 | 29.6 | 0.00037 | |
| 7215 | 30 | 0.000375 | |
| 7245 | 30 | 0.000375 | |
| 7305 | 30.5 | 0.00038125 | |
| 7365 | 30.5 | 0.00038125 | |
| 7425 | 30.5 | 0.00038125 | |
| 7545 | 31.4 | 0.0003925 | |
| 7665 | 31.8 | 0.0003975 | |
| 7785 | 31.8 | 0.0003975 | |
| 7905 | 31.8 | 0.0003975 | |
| 8205 | 32.3 | 0.00040375 | |
| 8505 | 32.8 | 0.00041 | |
| 8805 | 32.8 | 0.00041 | |
| 9105 | 33.2 | 0.000415 | |
| 9405 | 33.2 | 0.000415 | |
| 9705 | 33.2 | 0.000415 | |
| 10005 | 33.2 | 0.000415 | |
| 10015 | 38.6 | 0.00041302 | **No Sound,** |
| 10025 | 38.2 | 0.00040874 | **10.7scfm** |
| 10035 | 38.2 | 0.00040874 | |
| 10045 | 37.7 | 0.00040339 | |
| 10055 | 36.8 | 0.00039376 | |

**Table A.17** Field Data for Experimental Run 2
(Continued)

| **CummulativeTime/sec** | **Conc. of TCE/PPMv** | **Ft^3 organic/min (flowrate)** | **Experiment type, Air flow** |
|---|---|---|---|
| 10065 | 36.8 | 0.00039376 | |
| 10085 | 36.4 | 0.00038948 | |
| 10105 | 35.9 | 0.00038413 | |
| 10125 | 35.5 | 0.00037985 | |
| 10145 | 35 | 0.0003745 | |
| 10165 | 35 | 0.0003745 | |
| 10185 | 39.6 | 0.00042372 | |
| 10245 | 39.1 | 0.00041837 | |
| 10305 | 33.2 | 0.00035524 | |
| 10365 | 33.2 | 0.00035524 | |
| 10425 | 32.8 | 0.00035096 | |
| 10725 | 31.4 | 0.00033598 | |
| 11025 | 30.9 | 0.00033063 | |
| 11325 | 30.9 | 0.00033063 | |
| 11625 | 30.9 | 0.00033063 | |
| 11925 | 30.9 | 0.00033063 | |
| 12225 | 30.9 | 0.00033063 | |
| 12525 | 30.9 | 0.00033063 | **End** |

Experimental Run 3 : Saturday November 14, 1998.

**Air-Sound-Air-Sound**

**Table A.18** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 90-115 | 95-115 | 0 | |
| 2 | 90-115 | 95-115 | 0 | |
| 3 | 0 | 95-115 | 5 | |
| 4 | 0 | 95-115 | 5 | |

Electronic flowmeter reading: 9.5 scfm(Air1)

**Table A.19** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 30-40 | 95-115 | 5 | |
| 2 | 25-30 | 95-115 | 5 | |
| 3 | 95-115 | 95-115 | 0 | |
| 4 | 95-115 | 95-115 | 0 | |

Electronic flowmeter reading: 12.8 scfm (Sound)

**Table A.20**Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 90-115 | 95-115 | 0 | |
| 2 | 90-115 | 95-115 | 0 | |
| 3 | 0 | 95-115 | 5 | |
| 4 | 0 | 95-115 | 5 | |

Electronic flowmeter reading: 10.4 scfm(Air)

**Table A.21** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 30-40 | 95-115 | 5 | |
| 2 | 25-30 | 95-115 | 5 | |
| 3 | 95-115 | 95-115 | 0 | |
| 4 | 95-115 | 95-115 | 0 | |

Electronic flowmeter reading: 12.5 scfm (Sound)

**Table A.22** Field Data for Experimental Run 3

| time/sec | Conc. of TCE/PPMv | ft^3 organic/min (flowrate) | Type of experiment, flowrate |
|---|---|---|---|
| 0 | 59.1 | 0.000561 | No Sound1, 9.5 scfm |
| 5 | 48.2 | 0.000458 | |
| 10 | 40.4 | 0.000384 | |
| 15 | 36.7 | 0.000349 | |
| 25 | 33.1 | 0.000314 | |
| 35 | 31 | 0.000295 | |
| 45 | 29.4 | 0.000279 | |
| 55 | 27.3 | 0.000259 | |
| 65 | 25.8 | 0.000245 | |
| 75 | 25.2 | 0.000239 | |
| 85 | 24.7 | 0.000235 | |

**Table A.22** Field Data for Experimental Run 3
(Continued)

| time/sec | Conc. of TCE/PPMv | ft^3 organic/min (flowrate) | Type of experiment, flowrate |
|---|---|---|---|
| 95 | 24.2 | 0.00023 | |
| 105 | 23.7 | 0.000225 | |
| 115 | 24.7 | 0.000235 | |
| 125 | 23.7 | 0.000225 | |
| 135 | 23.7 | 0.000225 | |
| 145 | 24.2 | 0.00023 | |
| 155 | 24.7 | 0.000235 | |
| 165 | 23.7 | 0.000225 | |
| 175 | 23.2 | 0.00022 | |
| 185 | 23.7 | 0.000225 | |
| 195 | 23.2 | 0.00022 | |
| 205 | 22.1 | 0.00021 | |
| 215 | 22.1 | 0.00021 | |
| 225 | 23.2 | 0.00022 | |
| 235 | 22.6 | 0.000215 | |
| 245 | 21.6 | 0.000205 | |
| 255 | 22.1 | 0.00021 | |
| 265 | 21.6 | 0.000205 | |
| 275 | 20.5 | 0.000195 | |
| 285 | 21.1 | 0.0002 | |
| 295 | 21.1 | 0.0002 | |
| 305 | 20.5 | 0.000195 | |
| 335 | 19.5 | 0.000185 | |
| 365 | 19.5 | 0.000185 | |
| 395 | 20.5 | 0.000195 | |
| 425 | 19 | 0.000181 | |
| 455 | 17.9 | 0.00017 | |
| 485 | 19 | 0.000181 | |
| 515 | 20 | 0.00019 | |
| 545 | 21.1 | 0.0002 | |
| 575 | 21.1 | 0.0002 | |
| 605 | 21.1 | 0.0002 | |
| 635 | 20 | 0.00019 | |
| 665 | 19 | 0.000181 | |
| 695 | 18.5 | 0.000176 | |
| 725 | 20 | 0.00019 | |
| 755 | 20.5 | 0.000195 | |
| 815 | 19.5 | 0.000185 | |
| 875 | 18.5 | 0.000176 | |

**Table A.22** Field Data for Experimental Run 3
(Continued)

| time/sec | Conc. of TCE/PPMv | ft^3 organic/min (flowrate) | Type of experiment, flowrate |
|---|---|---|---|
| 935 | 17.9 | 0.00017 | |
| 995 | 18.5 | 0.000176 | |
| 1055 | 18.5 | 0.000176 | |
| 1235 | 18 | 0.000171 | |
| 1415 | 17.9 | 0.00017 | |
| 1595 | 17.9 | 0.00017 | |
| 1775 | 18.5 | 0.000176 | |
| 2375 | 17.9 | 0.00017 | |
| 2975 | 17.9 | 0.00017 | |
| 2985 | 20.8 | 0.000266 | Sound1, 12.8scfm |
| 2995 | 21.2 | 0.000271 | |
| 3005 | 21.1 | 0.00027 | |
| 3015 | 20.5 | 0.000262 | |
| 3025 | 20 | 0.000256 | |
| 3035 | 20 | 0.000256 | |
| 3045 | 19.5 | 0.00025 | |
| 3055 | 20 | 0.000256 | |
| 3065 | 20 | 0.000256 | |
| 3075 | 19.5 | 0.00025 | |
| 3085 | 19.5 | 0.00025 | |
| 3095 | 19 | 0.000243 | |
| 3105 | 19 | 0.000243 | |
| 3115 | 19 | 0.000243 | |
| 3125 | 19 | 0.000243 | |
| 3135 | 19 | 0.000243 | |
| 3145 | 19 | 0.000243 | |
| 3155 | 19 | 0.000243 | |
| 3165 | 19 | 0.000243 | |
| 3175 | 19.5 | 0.00025 | |
| 3185 | 19.5 | 0.00025 | |
| 3195 | 19.5 | 0.00025 | |
| 3210 | 19 | 0.000243 | |
| 3240 | 19 | 0.000243 | |
| 3270 | 19.5 | 0.00025 | |
| 3300 | 19.5 | 0.00025 | |
| 3330 | 19.5 | 0.00025 | |
| 3360 | 19.5 | 0.00025 | |
| 3390 | 19.5 | 0.00025 | |
| 3420 | 19.5 | 0.00025 | |
| 3450 | 19.5 | 0.00025 | |

**Table A.22** Field Data for Experimental Run 3
(Continued)

| time/sec | Conc. of TCE/PPMv | ft^3 organic/min (flowrate) | Type of experiment, flowrate |
|---|---|---|---|
| 3480 | 19.5 | 0.00025 | |
| 3510 | 19.5 | 0.00025 | |
| 3540 | 19 | 0.000243 | |
| 3570 | 20 | 0.000256 | |
| 3600 | 19.5 | 0.00025 | |
| 3630 | 19.5 | 0.00025 | |
| 3660 | 19.5 | 0.00025 | |
| 3690 | 19.5 | 0.00025 | |
| 3720 | 19 | 0.000243 | |
| 3750 | 19.5 | 0.00025 | |
| 3780 | 19.5 | 0.00025 | |
| 3810 | 20 | 0.000256 | |
| 3870 | 19.5 | 0.00025 | |
| 3930 | 19.5 | 0.00025 | |
| 3990 | 19.5 | 0.00025 | |
| 4050 | 19.5 | 0.00025 | |
| 4110 | 19.5 | 0.00025 | |
| 4170 | 19.5 | 0.00025 | |
| 4230 | 19.5 | 0.00025 | |
| 4290 | 20 | 0.000256 | |
| 4350 | 19.5 | 0.00025 | |
| 4410 | 19.5 | 0.00025 | |
| 4470 | 19.5 | 0.00025 | |
| 4770 | 19.5 | 0.00025 | |
| 5070 | 20 | 0.000256 | |
| 5370 | 20 | 0.000256 | |
| 5670 | 20 | 0.000256 | |
| 5970 | 20 | 0.000256 | |
| 5975 | 21 | 0.000218 | **No Sound 2, 10.4scfm** |
| 5980 | 21 | 0.000218 | |
| 5985 | 21 | 0.000218 | |
| 5990 | 21 | 0.000218 | |
| 5995 | 21 | 0.000218 | |
| 6000 | 21 | 0.000218 | |
| 6005 | 21.6 | 0.000225 | |
| 6010 | 21.6 | 0.000225 | |
| 6015 | 21.6 | 0.000225 | |
| 6020 | 21.1 | 0.000219 | |
| 6025 | 21.1 | 0.000219 | |

Table A.22 Field Data for Experimental Run 3
(Continued)

| time/sec | Conc. of TCE/PPMv | ft^3 organic/min (flowrate) | Type of experiment, flowrate |
|---|---|---|---|
| 6030 | 21.1 | 0.000219 | |
| 6035 | 21.6 | 0.000225 | |
| 6040 | 21.1 | 0.000219 | |
| 6045 | 21.1 | 0.000219 | |
| 6050 | 21.1 | 0.000219 | |
| 6055 | 21.1 | 0.000219 | |
| 6060 | 20.5 | 0.000213 | |
| 6065 | 20.5 | 0.000213 | |
| 6070 | 20.5 | 0.000213 | |
| 6075 | 20 | 0.000208 | |
| 6080 | 20 | 0.000208 | |
| 6110 | 20 | 0.000208 | |
| 6140 | 20 | 0.000208 | |
| 6170 | 20 | 0.000208 | |
| 6200 | 19.5 | 0.000203 | |
| 6230 | 19.5 | 0.000203 | |
| 6260 | 19.5 | 0.000203 | |
| 6290 | 19 | 0.000198 | |
| 6320 | 19 | 0.000198 | |
| 6350 | 19 | 0.000198 | |
| 6410 | 19 | 0.000198 | |
| 6470 | 19 | 0.000198 | |
| 6530 | 18.5 | 0.000192 | |
| 6590 | 18.5 | 0.000192 | |
| 6650 | 18.5 | 0.000192 | |
| 6710 | 18.5 | 0.000192 | |
| 7310 | 17.9 | 0.000186 | |
| 7910 | 17.9 | 0.000186 | |
| 8510 | 17.9 | 0.000186 | |
| 8515 | 20.1 | 0.000251 | Sound2,12.5scfm |
| 8520 | 20.1 | 0.000251 | |
| 8525 | 20.1 | 0.000251 | |
| 8530 | 19.5 | 0.000244 | |
| 8535 | 19.5 | 0.000244 | |
| 8540 | 19.5 | 0.000244 | |
| 8550 | 19.5 | 0.000244 | |
| 8560 | 18.5 | 0.000231 | |
| 8570 | 18.5 | 0.000231 | |
| 8580 | 18.5 | 0.000231 | |

**Table A.22** Field Data for Experimental Run 3
(Continued)

| time/sec | Conc. of TCE/PPMv | ft^3 organic/min (flowrate) | Type of experiment, flowrate |
|---|---|---|---|
| 8590 | 18 | 0.000225 | |
| 8600 | 18 | 0.000225 | |
| 8610 | 17.9 | 0.000224 | |
| 8620 | 17.9 | 0.000224 | |
| 8630 | 17.9 | 0.000224 | |
| 8660 | 17.9 | 0.000224 | |
| 8690 | 17.9 | 0.000224 | |
| 8720 | 17.9 | 0.000224 | |
| 8750 | 17.9 | 0.000224 | |
| 8780 | 17.9 | 0.000224 | |
| 8810 | 18.5 | 0.000231 | |
| 8840 | 18.5 | 0.000231 | |
| 8870 | 18.5 | 0.000231 | |
| 8900 | 18.5 | 0.000231 | |
| 8930 | 18.5 | 0.000231 | |
| 8990 | 19 | 0.000238 | |
| 9050 | 19 | 0.000238 | |
| 9110 | 19 | 0.000238 | |
| 9170 | 19 | 0.000238 | |
| 9230 | 19 | 0.000238 | |
| 9290 | 19 | 0.000238 | |
| 9350 | 19.5 | 0.000244 | |
| 9410 | 19.5 | 0.000244 | |
| 9710 | 20 | 0.00025 | |
| 10010 | 20 | 0.00025 | |
| 10310 | 20.5 | 0.000256 | |
| 10610 | 20.5 | 0.000256 | |
| 10910 | 21.1 | 0.000264 | |
| 11510 | 21.1 | 0.000264 | |
| 12110 | 21.1 | 0.000264 | **End** |

Experimental Run 4 : Sunday November 15, 1998.

**Sound-Air-Sound-Air**

**Table A.23** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 30-40 | 95-115 | 5 | |
| 2 | 25-30 | 95-115 | 5 | |
| 3 | 95-115 | 95-115 | 0 | |
| 4 | 95-115 | 95-115 | 0 | |

Electronic flowmeter reading: 11.0 scfm (Sound)

**Table A.24** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 90-115 | 95-115 | 0 | |
| 2 | 90-115 | 95-115 | 0 | |
| 3 | 0 | 95-115 | 5 | |
| 4 | 0 | 95-115 | 5 | |

Electronic flowmeter reading: 10.0 scfm(Air)

**Table A.25** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 30-40 | 95-115 | 5 | |
| 2 | 25-30 | 95-115 | 5 | |
| 3 | 95-115 | 95-115 | 0 | |
| 4 | 95-115 | 95-115 | 0 | |

Electronic flowmeter reading: 11.3 scfm (Sound)

**Table A.26** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 90-115 | 95-115 | 0 | |
| 2 | 90-115 | 95-115 | 0 | |
| 3 | 0 | 95-115 | 5 | |
| 4 | 0 | 95-115 | 5 | |

Electronic flowmeter reading: 9.6 scfm (Air2)

Table A.27 Field Data for Experimental Run 4

| time/sec | Conc. of TCE/PPMv | ft^3 organic/min (flowrate) | Experiment Type, flowrate |
|---|---|---|---|
| 0 | 22.6 | 0.000249 | **Sound1,11.0scfm,** |
| 5 | 22.6 | 0.000249 | |
| 10 | 22.1 | 0.000243 | |
| 15 | 21.6 | 0.000238 | |
| 20 | 21.6 | 0.000238 | |
| 25 | 21.6 | 0.000238 | |
| 30 | 21.6 | 0.000238 | |
| 35 | 21.6 | 0.000238 | |
| 40 | 21.1 | 0.000232 | |
| 45 | 21.1 | 0.000232 | |
| 55 | 21.1 | 0.000232 | |
| 65 | 21.1 | 0.000232 | |
| 75 | 21.1 | 0.000232 | |
| 85 | 21.1 | 0.000232 | |
| 95 | 21.1 | 0.000232 | |
| 105 | 20.5 | 0.000226 | |
| 135 | 20 | 0.00022 | |
| 165 | 21.6 | 0.000238 | |
| 195 | 21.6 | 0.000238 | |
| 255 | 21.6 | 0.000238 | |
| 315 | 21.6 | 0.000238 | |
| 375 | 21.6 | 0.000238 | |
| 435 | 21.1 | 0.000232 | |
| 735 | 21.1 | 0.000232 | |
| 1335 | 21.1 | 0.000232 | |
| 1935 | 21.1 | 0.000232 | |
| 1945 | 21.5 | 0.000215 | **No Sound1,10scfm** |
| 1955 | 20.5 | 0.000205 | |
| 1965 | 20.5 | 0.000205 | |
| 1975 | 20.5 | 0.000205 | |
| 1985 | 20.5 | 0.000205 | |
| 1995 | 20 | 0.0002 | |
| 2005 | 20.5 | 0.000205 | |
| 2015 | 20.5 | 0.000205 | |
| 2025 | 20 | 0.0002 | |
| 2035 | 20 | 0.0002 | |
| 2045 | 19.5 | 0.000195 | |
| 2055 | 19.5 | 0.000195 | |
| 2065 | 19.5 | 0.000195 | |
| 2075 | 20 | 0.0002 | |

**Table A.27** Field Data for Experimental Run 4
(Continued)

| time/sec | Conc. of TCE/PPMv | ft^3 organic/min (flowrate) | Experiment Type, flowrate |
|---|---|---|---|
| 2085 | 20 | 0.0002 | |
| 2095 | 19.5 | 0.000195 | |
| 2125 | 21.1 | 0.000211 | |
| 2155 | 20 | 0.0002 | |
| 2185 | 19 | 0.00019 | |
| 2215 | 19 | 0.00019 | |
| 2245 | 17.9 | 0.000179 | |
| 2275 | 17.9 | 0.000179 | |
| 2305 | 17.9 | 0.000179 | |
| 2335 | 17.9 | 0.000179 | |
| 2395 | 16.9 | 0.000169 | |
| 2455 | 15.3 | 0.000153 | |
| 2515 | 15.9 | 0.000159 | |
| 2575 | 16.9 | 0.000169 | |
| 2635 | 15.9 | 0.000159 | |
| 2695 | 15.9 | 0.000159 | |
| 2755 | 16.9 | 0.000169 | |
| 2815 | 15.3 | 0.000153 | |
| 2875 | 14.8 | 0.000148 | |
| 2935 | 15.3 | 0.000153 | |
| 2995 | 15.9 | 0.000159 | |
| 3055 | 15.9 | 0.000159 | |
| 3115 | 15.9 | 0.000159 | |
| 3175 | 15.9 | 0.000159 | |
| 3235 | 16.4 | 0.000164 | |
| 3295 | 15.9 | 0.000159 | |
| 3355 | 15.9 | 0.000159 | |
| 3415 | 15.9 | 0.000159 | |
| 3475 | 14.9 | 0.000149 | |
| 3535 | 15.9 | 0.000159 | |
| 3595 | 15.9 | 0.000159 | |
| 3655 | 15.9 | 0.000159 | |
| 3715 | 16.4 | 0.000164 | |
| 3775 | 15.9 | 0.000159 | |
| 3835 | 15.9 | 0.000159 | |
| 3840 | 15.3 | 0.000173 | **Sound2,11.3 scfm** |
| 3845 | 14.8 | 0.000167 | |
| 3850 | 14.8 | 0.000167 | |
| 3855 | 14.8 | 0.000167 | |
| 3860 | 14.8 | 0.000167 | |

**Table A.27** Field Data for Experimental Run 4
(Continued)

| time/sec | Conc. of TCE/PPMv | ft^3 organic/min (flowrate) | Experiment Type, flowrate |
|---|---|---|---|
| 3865 | 15.3 | 0.000173 | |
| 3870 | 14.8 | 0.000167 | |
| 3875 | 14.8 | 0.000167 | |
| 3880 | 14.8 | 0.000167 | |
| 3885 | 14.8 | 0.000167 | |
| 3895 | 15.3 | 0.000173 | |
| 3905 | 15.3 | 0.000173 | |
| 3915 | 15.3 | 0.000173 | |
| 3945 | 15.3 | 0.000173 | |
| 3975 | 14.8 | 0.000167 | |
| 4005 | 14.8 | 0.000167 | |
| 4035 | 14.8 | 0.000167 | |
| 4065 | 15.3 | 0.000173 | |
| 4095 | 16.4 | 0.000185 | |
| 4125 | 16.4 | 0.000185 | |
| 4185 | 17.9 | 0.000202 | |
| 4245 | 17.9 | 0.000202 | |
| 4305 | 17.9 | 0.000202 | |
| 4365 | 16.9 | 0.000191 | |
| 4425 | 17.9 | 0.000202 | |
| 4485 | 19.9 | 0.000225 | |
| 4545 | 17.9 | 0.000202 | |
| 4605 | 17.9 | 0.000202 | |
| 4665 | 17.9 | 0.000202 | |
| 4965 | 19.9 | 0.000225 | |
| 5265 | 18.9 | 0.000214 | |
| 5565 | 19.9 | 0.000225 | |
| 5865 | 19.9 | 0.000225 | |
| 5870 | 20 | 0.000192 | **No Sound 2, 9.6 scfm** |
| 5875 | 20 | 0.000192 | |
| 5880 | 20 | 0.000192 | |
| 5885 | 19.5 | 0.000187 | |
| 5890 | 19.5 | 0.000187 | |
| 5895 | 19.5 | 0.000187 | |
| 5900 | 19.5 | 0.000187 | |
| 5905 | 19.5 | 0.000187 | |
| 5910 | 19.5 | 0.000187 | |
| 5915 | 19.5 | 0.000187 | |
| 5920 | 19.5 | 0.000187 | |

**Table A.27** Field Data for Experimental Run 4
(Continued)

| time/sec | Conc. of TCE/PPMv | ft^3 organic/min (flowrate) | Experiment Type, flowrate |
|---|---|---|---|
| 5930 | 19.5 | 0.000187 | |
| 5940 | 19.5 | 0.000187 | |
| 5950 | 19.5 | 0.000187 | |
| 5960 | 19.5 | 0.000187 | |
| 5970 | 19.5 | 0.000187 | |
| 5980 | 19.5 | 0.000187 | |
| 5990 | 19.5 | 0.000187 | |
| 6000 | 19 | 0.000182 | |
| 6010 | 19.5 | 0.000187 | |
| 6020 | 19.5 | 0.000187 | |
| 6030 | 19.5 | 0.000187 | |
| 6060 | 19.5 | 0.000187 | |
| 6090 | 19 | 0.000182 | |
| 6120 | 18.5 | 0.000178 | |
| 6150 | 17.9 | 0.000172 | |
| 6180 | 17.9 | 0.000172 | |
| 6210 | 17.9 | 0.000172 | |
| 6240 | 17.9 | 0.000172 | |
| 6270 | 17.9 | 0.000172 | |
| 6300 | 17.9 | 0.000172 | |
| 6330 | 17.4 | 0.000167 | |
| 6630 | 15.3 | 0.000147 | |
| 6930 | 16.4 | 0.000157 | |
| 7230 | 15.9 | 0.000153 | |
| 7530 | 15.9 | 0.000153 | |
| 7830 | 16.4 | 0.000157 | |
| 8130 | 15.9 | 0.000153 | End |

Additional Experiment : Sunday November 8, 1998.

**Air-Sound-Air-Sound-Air**

**Table A.28** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 90-115 | 95-115 | 0 | |
| 2 | 90-115 | 95-115 | 0 | |
| 3 | 0 | 95-115 | 5 | |
| 4 | 0 | 95-115 | 5 | |

Electronic flowmeter reading: 12.3 scfm(Air)
Vacuum Pump Reading: 27 inches of water vacuum

**Table A.29** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 30-40 | 95-115 | 5 | |
| 2 | 25-30 | 95-115 | 5 | |
| 3 | 95-115 | 95-115 | 0 | |
| 4 | 95-115 | 95-115 | 0 | |

Electronic flowmeter reading: 12.3scfm (Sound)
Vacuum Pump Reading: 20 inches of water vacuum

**Table A.30** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 90-115 | 95-115 | 0 | |
| 2 | 90-115 | 95-115 | 0 | |
| 3 | 0 | 95-115 | 5 | |
| 4 | 0 | 95-115 | 5 | |

Electronic flowmeter reading: 12.3scfm(Air)
Vacuum Pump Reading: 27 inches of water vacuum

**Table A.31** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 30-40 | 95-115 | 5 | |
| 2 | 25-30 | 95-115 | 5 | |
| 3 | 95-115 | 95-115 | 0 | |
| 4 | 95-115 | 95-115 | 0 | |

Electronic flowmeter reading: 13.6 scfm (Sound)
Vacuum Pump Reading: 20 inches of water vacuum

**Table A.32** Flow Manifold Data

| Flow meter | Outlet pressure/psi | Inlet pressure/psi | Reading/SCFM | |
|---|---|---|---|---|
| 1 | 90-115 | 95-115 | 0 | |
| 2 | 90-115 | 95-115 | 0 | |
| 3 | 0 | 95-115 | 5 | |
| 4 | 0 | 95-115 | 5 | |

Electronic flowmeter reading: 10.5 scfm(Air)
Vacuum Pump Reading: 20 inches of water vacuum

**Table A. 33** Field Data for Additional Experiment

| **Cummulative time/seconds** | **Conc. of TCE PPMv** | **ft^3 organic/min (flowrate)** | **Type of Experiment, Flowrate** |
|---|---|---|---|
| 0 | 140 | 0.001722 | **No Sound1, 12.3scfm** |
| 10 | 277 | 0.003407 | |
| 20 | 121 | 0.001488 | |
| 30 | 88.9 | 0.001093 | |
| 40 | 80.3 | 0.000988 | |
| 50 | 79.4 | 0.000977 | |
| 60 | 73.9 | 0.000909 | |
| 70 | 67.7 | 0.000833 | |
| 80 | 64.4 | 0.000792 | |
| 90 | 60.8 | 0.000748 | |
| 100 | 58.5 | 0.00072 | |
| 110 | 56.3 | 0.000692 | |
| 120 | 54 | 0.000664 | |
| 130 | 51.8 | 0.000637 | |
| 140 | 49.5 | 0.000609 | |
| 150 | 48.1 | 0.000592 | |
| 160 | 46.3 | 0.000569 | |
| 170 | 45 | 0.000554 | |
| 180 | 43.2 | 0.000531 | |
| 190 | 43.2 | 0.000531 | |
| 200 | 41.8 | 0.000514 | |
| 220 | 40.4 | 0.000497 | |
| 240 | 38.6 | 0.000475 | |

**Table A. 33** Field Data for Additional Experiment
(Continued)

| Cummulative time/seconds | Conc. of TCE/ PPMv | ft^3 organic/min (flowrate) | Type of Experiment, Flowrate |
|---|---|---|---|
| 260 | 37.3 | 0.000459 | |
| 280 | 37.7 | 0.000464 | |
| 300 | 36.4 | 0.000448 | |
| 320 | 35.5 | 0.000437 | |
| 340 | 34.6 | 0.000426 | |
| 360 | 34.1 | 0.000419 | |
| 390 | 33.7 | 0.000415 | |
| 420 | 33.2 | 0.000408 | |
| 450 | 32.8 | 0.000403 | |
| 480 | 32.8 | 0.000403 | |
| 510 | 32.8 | 0.000403 | |
| 540 | 32.8 | 0.000403 | |
| 570 | 33.2 | 0.000408 | |
| 630 | 32.8 | 0.000403 | |
| 690 | 31.8 | 0.000391 | |
| 750 | 31.4 | 0.000386 | |
| 810 | 31.4 | 0.000386 | |
| 870 | 31.4 | 0.000386 | |
| 930 | 30.5 | 0.000375 | |
| 990 | 30.5 | 0.000375 | |
| 1050 | 30.5 | 0.000375 | |
| 1110 | 30.9 | 0.00038 | |
| 1170 | 30.5 | 0.000375 | |
| 1470 | 30.5 | 0.000375 | |
| 1770 | 30.5 | 0.000375 | |
| 2070 | 29.1 | 0.000358 | |
| 2370 | 30.5 | 0.000375 | |
| 2380 | 53 | 0.000652 | **sound1,12.3 scfm** |
| 2390 | 30 | 0.000369 | |
| 2400 | 29.6 | 0.000364 | |
| 2410 | 29.1 | 0.000358 | |
| 2420 | 29.1 | 0.000358 | |
| 2430 | 28.7 | 0.000353 | |
| 2440 | 28.7 | 0.000353 | |
| 2450 | 30 | 0.000369 | |
| 2460 | 27.3 | 0.000336 | |
| 2470 | 25.5 | 0.000314 | |
| 2480 | 26 | 0.00032 | |
| 2490 | 28.2 | 0.000347 | |

**Table A. 33** Field Data for Additional Experiment
(Continued)

| Cummulative time/seconds | Conc. of TCE PPMv | ft^3 organic/min (flowrate) | Type of Experiment, Flowrate |
|---|---|---|---|
| 2500 | 28.2 | 0.000347 | |
| 2510 | 28.2 | 0.000347 | |
| 2520 | 28.2 | 0.000347 | |
| 2530 | 28.7 | 0.000353 | |
| 2540 | 28.2 | 0.000347 | |
| 2560 | 27.8 | 0.000342 | |
| 2580 | 28.2 | 0.000347 | |
| 2600 | 28.2 | 0.000347 | |
| 2620 | 29.1 | 0.000358 | |
| 2640 | 30.5 | 0.000375 | |
| 2660 | 30 | 0.000369 | |
| 2680 | 29.6 | 0.000364 | |
| 2700 | 29.1 | 0.000358 | |
| 2730 | 28.7 | 0.000353 | |
| 2760 | 28.7 | 0.000353 | |
| 2790 | 29.6 | 0.000364 | |
| 2820 | 27.8 | 0.000342 | |
| 2850 | 27.3 | 0.000336 | |
| 2880 | 27.3 | 0.000336 | |
| 2910 | 28.7 | 0.000353 | |
| 2940 | 30.5 | 0.000375 | |
| 2970 | 30.5 | 0.000375 | |
| 3000 | 29.6 | 0.000364 | |
| 3030 | 29.1 | 0.000358 | |
| 3060 | 28.7 | 0.000353 | |
| 3120 | 27.3 | 0.000336 | |
| 3180 | 26.9 | 0.000331 | |
| 3240 | 27.8 | 0.000342 | |
| 3300 | 28.2 | 0.000347 | |
| 3600 | 30 | 0.000369 | |
| 3900 | 30 | 0.000369 | |
| 4200 | 30.5 | 0.000375 | |
| 4500 | 30.9 | 0.00038 | |
| 4800 | 30 | 0.000369 | |
| 5100 | 31.4 | 0.000386 | |
| 5400 | 30.5 | 0.000375 | |
| 5410 | 32.3 | 0.000397 | **No Sound 2,12.3 scfm** |
| 5420 | 32.3 | 0.000397 | |
| 5430 | 31.8 | 0.000391 | |

**Table A. 33** Field Data for Additional Experiment
(Continued)

| Cummulative time/seconds | Conc. of TCE/PPMv | ft^3 organic/ min (flowrate) | Type of Experiment, Flowrate |
|---|---|---|---|
| 5440 | 31.8 | 0.000391 | |
| 5450 | 31.8 | 0.000391 | |
| 5460 | 31.4 | 0.000386 | |
| 5470 | 31.4 | 0.000386 | |
| 5480 | 31.4 | 0.000386 | |
| 5490 | 31.4 | 0.000386 | |
| 5500 | 31.4 | 0.000386 | |
| 5510 | 31.4 | 0.000386 | |
| 5520 | 30.9 | 0.00038 | |
| 5530 | 30.9 | 0.00038 | |
| 5540 | 30.9 | 0.00038 | |
| 5550 | 30.9 | 0.00038 | |
| 5560 | 31.4 | 0.000386 | |
| 5580 | 31.4 | 0.000386 | |
| 5600 | 30.9 | 0.00038 | |
| 5620 | 30.5 | 0.000375 | |
| 5640 | 30.5 | 0.000375 | |
| 5660 | 30.5 | 0.000375 | |
| 5680 | 30.5 | 0.000375 | |
| 5710 | 30 | 0.000369 | |
| 5740 | 30 | 0.000369 | |
| 5770 | 30 | 0.000369 | |
| 5800 | 29.6 | 0.000364 | |
| 5830 | 29.6 | 0.000364 | |
| 5860 | 29.6 | 0.000364 | |
| 5920 | 30 | 0.000369 | |
| 5980 | 30 | 0.000369 | |
| 6040 | 30 | 0.000369 | |
| 6100 | 29.1 | 0.000358 | |
| 6160 | 29.6 | 0.000364 | |
| 6220 | 29.6 | 0.000364 | |
| 6280 | 30 | 0.000369 | |
| 6340 | 30 | 0.000369 | |
| 6640 | 30.5 | 0.000375 | |
| 6940 | 30.5 | 0.000375 | |
| 7240 | 30 | 0.000369 | |
| 7540 | 30 | 0.000369 | |
| 7550 | 42.7 | 0.000581 | **sound2, 13.6 scfm** |
| 7560 | 30.9 | 0.00042 | |

**Table A. 33** Field Data for Additional Experiment
(Continued)

| Cummulative time/seconds | Conc. of TCE/PPMv | ft^3 organic /min (flowrate) | Type of Experiment, Flowrate |
|---|---|---|---|
| 7570 | 30 | 0.000408 | |
| 7580 | 29.6 | 0.000403 | |
| 7590 | 29.1 | 0.000396 | |
| 7600 | 28.7 | 0.00039 | |
| 7610 | 28.2 | 0.000384 | |
| 7620 | 28.7 | 0.00039 | |
| 7630 | 28.2 | 0.000384 | |
| 7640 | 28.2 | 0.000384 | |
| 7650 | 28.2 | 0.000384 | |
| 7680 | 28.2 | 0.000384 | |
| 7710 | 27.8 | 0.000378 | |
| 7740 | 28.8 | 0.000392 | |
| 7770 | 28.2 | 0.000384 | |
| 7800 | 28.2 | 0.000384 | |
| 7830 | 28.2 | 0.000384 | |
| 7860 | 28.2 | 0.000384 | |
| 7890 | 28.2 | 0.000384 | |
| 7920 | 28.7 | 0.00039 | |
| 7950 | 28.7 | 0.00039 | |
| 7980 | 28.7 | 0.00039 | |
| 8010 | 28.7 | 0.00039 | |
| 8070 | 28.7 | 0.00039 | |
| 8130 | 29.1 | 0.000396 | |
| 8190 | 29.1 | 0.000396 | |
| 8250 | 29.6 | 0.000403 | |
| 8310 | 29.1 | 0.000396 | |
| 8370 | 29.1 | 0.000396 | |
| 8430 | 29.1 | 0.000396 | |
| 8490 | 29.1 | 0.000396 | |
| 8550 | 28.7 | 0.00039 | |
| 8610 | 29.1 | 0.000396 | |
| 8670 | 29.1 | 0.000396 | |
| 8730 | 29.1 | 0.000396 | |
| 8790 | 28.7 | 0.00039 | |
| 9090 | 28.2 | 0.000384 | |
| 9390 | 28.2 | 0.000384 | |
| 9690 | 27.8 | 0.000378 | |
| 9700 | 29.1 | 0.000306 | **No Sound 3, 10.5 scfm** |
| 9710 | 30 | 0.000315 | |

**Table A. 33** Field Data for Additional Experiment
(Continued)

| Cummulative time/seconds | Conc. of TCE/PPMv | ft^3 organic/min (flowrate) | Type of Experiment, Flowrate |
|---|---|---|---|
| 9720 | 30.5 | 0.00032 | |
| 9730 | 30.5 | 0.00032 | |
| 9740 | 30.5 | 0.00032 | |
| 9750 | 30.5 | 0.00032 | |
| 9760 | 30.5 | 0.00032 | |
| 9770 | 20.5 | 0.000215 | |
| 9780 | 20.1 | 0.000211 | |
| 9810 | 20.1 | 0.000211 | |
| 9840 | 19.6 | 0.000206 | |
| 9870 | 19.6 | 0.000206 | |
| 9900 | 19.2 | 0.000202 | |
| 9930 | 19.2 | 0.000202 | |
| 9960 | 19.2 | 0.000202 | |
| 9990 | 19.2 | 0.000202 | |
| 10020 | 19.2 | 0.000202 | |
| 10050 | 19.2 | 0.000202 | |
| 10080 | 19.2 | 0.000202 | |
| 10110 | 19.2 | 0.000202 | |
| 10140 | 19.2 | 0.000202 | |
| 10170 | 19.2 | 0.000202 | |
| 10230 | 18.7 | 0.000196 | |
| 10290 | 18.3 | 0.000192 | |
| 10350 | 18.3 | 0.000192 | |
| 10410 | 17.8 | 0.000187 | |
| 10470 | 17.8 | 0.000187 | |
| 10770 | 17.8 | 0.000187 | |
| 11070 | 17.8 | 0.000187 | |
| 11370 | 16.9 | 0.000177 | |
| 11670 | 16.9 | 0.000177 | **End** |

Table A.34 gives a summary of some of the results obtained from the first part of the field preliminary studies. It shows the pressure through the sonic device at a flow rate of 5 SCFM and 11 SCFM. Only one whistle is used for this study.

**Table A.34** One Whistle Study

| Flowrate/SCFM | Pressure/psi |
|---|---|
| 5 | 32-40 |
| 11 | 105 |
| | |

Table A.35 gives a summary of the rest of the results obtained from the first part of the field preliminary studies. It shows the removal rates of some of the samples that were analyzed by the GC (for 3 runs). For each sample a brief description of the run and the contaminants detected are shown. The last two rows of Table A.35 (run 3) also show a comparison of the GC results and the PID results, for a point chosen randomly during the preliminary study.

**Table A.35** GC Data Obtained for a Particular Day

| Contaminant | Run | Description of run | GC/PPMv | |
|---|---|---|---|---|
| DCE | 1 | Vacuum pump running | 12 PPMv | |
| TCE | 1 | Vacuum pump running | 700 PPMv | |
| DCE | 2 | Vacuum Pump stopped | 2 PPMv | |
| TCE | 2 | Vacuum Pump Stopped | 417 PPMv | |
| | | | PID/PPMv | GC/PPMv |
| TCE | 3 | point during experiments | 250 | 211.8 |
| DCE | 3 | point during experiments | 0 | 0 |

# APPENDIX B

# CALCULATIONS

### Removal Rate of Organic:

Calculation of removal rate of organic: (based on first data point in Experimental Run 1)

Removal Rate of Organic (cubic feet of organic/ minute) =
(cubic feet of organic/cubic feet air)* (cubic feet air/minute)

Sample Calculation:
284 PPMV = 284 (cubic feet of organic/ 10^6 *cubic feet air)

Removal Rate of Organic = 284 (cubic feet of organic/ 10^6 *cubic feet air)
*11.3 (cubic feet air / minute)
= 0.003209 cubic feet of organic/ minute

### Statistics:

**Table B.1** Statistical Treatment of the Average Percent Improvement

| **Concentration** | **Removal Rate** | **Concentration** | **Removal Rate** |
|---|---|---|---|
| Percent Improvement/ PPMv | Percent Improvement / Cubic Feet Per Minute | Percent Improvement$^2$ /PPMV$^2$ | Percent Improvement$^2$ Cubic Feet Per Minute$^2$ |
| 34.8 | 34.9 | 1211.04 | 1218.01 |
| 33 | 33.3 | 1089 | 1108.89 |
| 9.1 | 31 | 82.81 | 961 |
| 7 | 25.1 | 49 | 630.01 |
| 11 | 49.7 | 121 | 2470.09 |
| 16.5 | 39.7 | 272.25 | 1576.09 |
| 33.3 | 46.5 | 1108.89 | 2162.25 |
| 22 | 43.2 | 484 | 1866.24 |
| **Sum = 166.7** | **Sum = 303.4** | **Sum = 4417.99** | **Sum = 11992.58** |
| **Sum$^2$ = 27788.89** | **Sum$^2$ = 92051.56** | | |

Standard Deviation for the Percent Improvement (based on Concentration/PPMv):

Standard Deviation = $[(8\ (4417.99) - 27788.89)/(8*7)]^{0.5} = 11.6$

Standard Deviation for the Percent Improvement (based on Cubic Feet per Minute):

Standard Deviation = $[(8\ (11992.58) - 92051.56)/(8*7)]^{0.5} = 8.333$

### t-test and Confidence interval calculations:

For small samples ($n < 30$), the 95% confidence interval for the true mean of the population is given by:

$X - t_{0.025}*$ standard deviation/$(n)^{0.5}$ < **Mean** < $X + t_{0.025}*$ standard deviation/$(n)^{0.5}$ ------equation 6.1, ( Freund, 1970).

Where:
X = Sample Mean.
n = Sample Size.
Mean = true population mean.
$t_{0.025}$ = t distribution factor for 95% confidence interval
$t_{0.025} = 2.365$ (for n = 8), (Freund, 1970).
Standard deviation = Sample standard deviation.

From equation 6.1, the confidence interval for the true population mean is calculated as follows:

<u>95% Confidence interval for the mean Percent Improvement</u>

<u>( based on Concentration/PPMV):</u>

$$20.8375-2.365*11.6/ 8^{0.5} < \text{Mean} < 20.8375+2.365*11.6/ 8^{0.5}$$

$$11.138 < \text{Mean} < 30.5495$$

The probability is 0.95 that the interval 11.138 to 30.5495 will contain the true mean percentage improvement.

## 95% Confidence interval for the mean Percent Improvement

## ( based on Cubic Feet per Minute)

$$37.925 - 2.365*8.333/8^{0.5} < \text{Mean} < 37.925+2.365*8.333/8^{0.5}$$

$$30.95688 < \text{Mean} < 44.89312$$

The probability is 0.95 that the interval 30.95688 to 44.89312 will contain the true mean percentage improvement.

# APPENDIX C

## PARTS DESCRIPTION AND COSTS

**Table C.1** Assembly Parts for Ultrasonic Field Apparatus

| Part Number | Description | Catalog No. McMaster | Quantity | Price/ unit | Total Price |
|---|---|---|---|---|---|
| 1 | ½" × 1/8" Sch. 40 Hex Bushing Galv. | 4638K636 | 4 | $0.46 | $1.84 |
| 2 | 1/8" ID Pressure Gages | 3847K2 | 4 | $7.21 | $28.84 |
| 3 | 1 3/8" Nipple ¾" Sch. 40 Galv. | 4549K591 | 8 | $0.64 | $5.12 |
| 4 | ½"×3/4" Sch.40 Bushing Galv. | 4638K455 | 8 | $1.57 | $12.56 |
| 5 | ¾" ID Flowmeter (2.4-24.0) SCFM | 4111K33 | 4 | $314.65 | $1258.60 |
| 6 | ½" Sch.40 Bronze Globe Valve | 4695K53 | 4 | $21.90 | $87.60 |
| 7 | ½" Sch. 40 Union Galv. | 4638K733 | 4 | $3.34 | $13.36 |
| 8 | ¾" Nipple ½" Sch. 40 Galv. | 4549K593 | 4 | $0.72 | $2.88 |
| 9 | 1"×1/2" Sch.40 Hex Bushing Galv. | 4638K663 | 6 | $1.19 | $7.14 |
| 10 | 1" Sch. 40 Plug Galv. | 4638K516 | 1 | $0.69 | $0.69 |
| 11 | Twin Self-Extracting Nylon Air-Hose 25', ½"OD | 5612K33 | 2 | $85.42 | $170.84 |
| 12 | ½" Sch.40 Elbow 90° Galv. | 4638K133 | 4 | $0.85 | $3.40 |
| 13 | 2" Nipple 1" Sch.40 Galv. | 4549K611 | 4 | $0.93 | $3.72 |
| 14 | ½" Sch.40 Tee Galv. | 4638K123 | 4 | $1.10 | $4.40 |
| 15 | 1" Sch.40 Union Galv. | 4638K735 | 3 | $5.02 | $15.06 |
| 16 | 1" Sch.40 Tee Galv. | 4638K125 | 4 | $2.86 | $11.44 |
| 17 | 2.5" Nipple 1" Sch.40 Galv. | 4549K613 | 4 | $1.19 | $4.76 |

**Table C.1** Assembly Parts for Ultrasonic Field Apparatus (Continued)

| Part Number | Description | Catalog No. McMaster | Quantity | Price/unit | Total Price |
|---|---|---|---|---|---|
| 18 | ½" IPS Forged-Brass Ball valves | 45085K33 | 4 | $7.23 | $28.92 |
| 19 | ½" Sch.40 Female Plug Hose Connector | 6534K76 | 8 | $3.91 | $31.28 |
| 20 | ½" Sch.40 male Hose Connection | 6534K83 | 8 | $10.33 | $82.64 |
| 22 | ½"OD × ½"ID Tubing-to-Pipe Adapter | 5182K268 | 2 | $16.63 | $33.26 |
| 23 | 1" Sch.40 Tee Steel | 4443K666 | 1 | $14.83 | $14.83 |
| 24 | 1.5" Sch.40 Galv. | 4549K661 | 1 | $3.10 | $3.10 |
| 25 | 1 ' ¼" sch 40 union | | | | |
| 26 | 1/2" OD Tubing Union | 5182K345 | 4 | $12.66 | $50.64 |
| 27 | Pipe adapter | 4638K466 | 1 | | |
| 28 | 1" Sch.40 Laterals 45° Tee Steel | 4429K364 | 1 | $18.62 | $18.62 |
| 29 | 1"× 11/4" Sch.40 Bushing Galv. | 4638K459 | 2 | $2.61 | $5.22 |
| 31 | 1' 1" perforated pipe | 4638K737 | 2 | $8.80 | $17.60 |
| 32 | 3' 11/4" Sch.40 Pipe | 4549K664 | 6 | | |
| 33 | 1/2" OD Teflon Tubing | 52355K15 | 100 | $1.17 | $117.00 |
| 35 | 4' Packer 1" Sch.40 | | | | |
| 36 | Ultrasonic Whistle Array | | | | |
| 37 | 1' Packer 1" Sch.40 | | | | |
| Total | Total | | | | $ |

**McMaster – Supply Co., 473 Ridge Rd., Dayton, NJ 08810-0317. Catalog 101.**

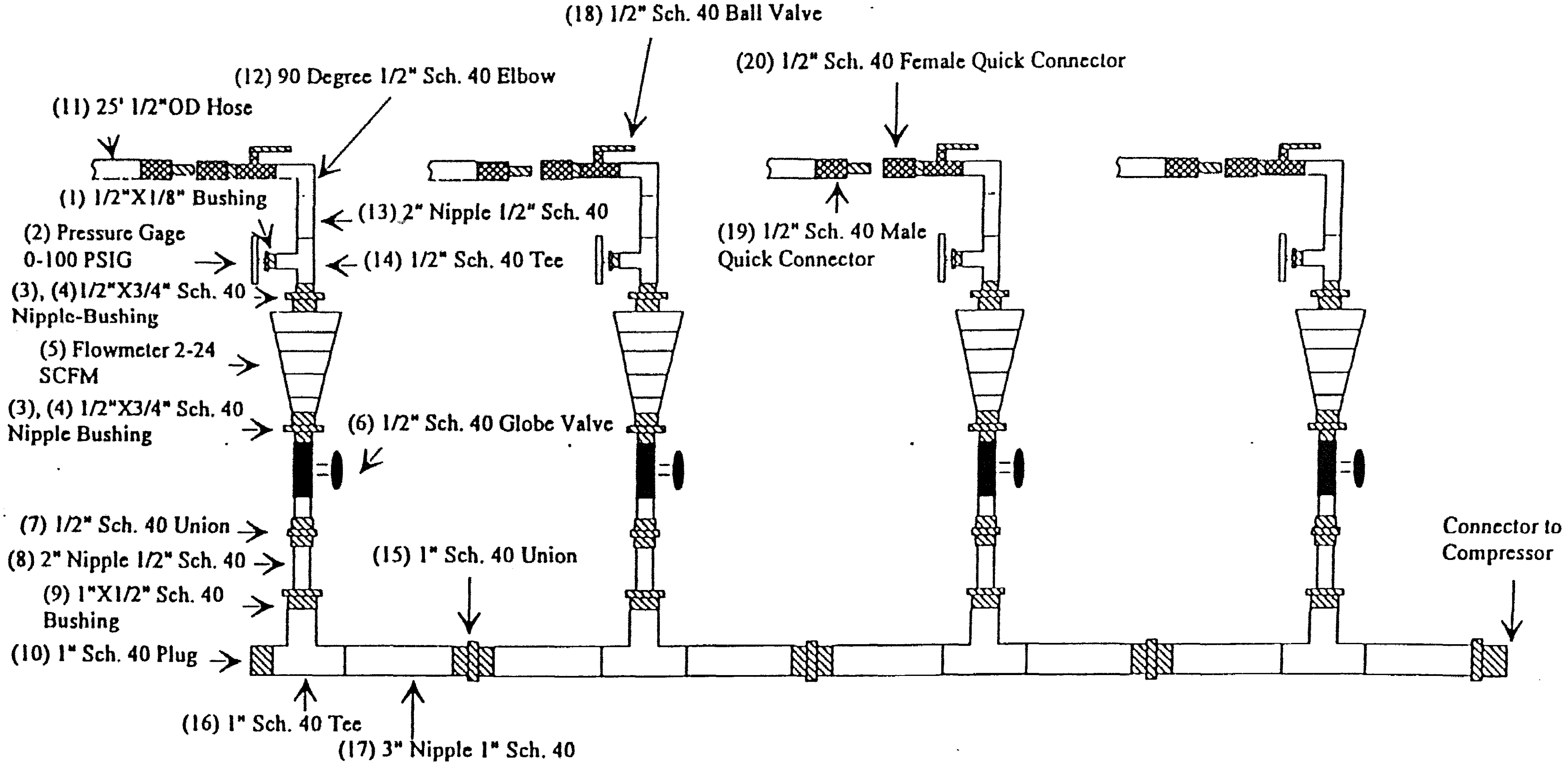


**Figure C.1** Flow Manifold for the Ultrasonic Experiment (Fernandez, 1997)

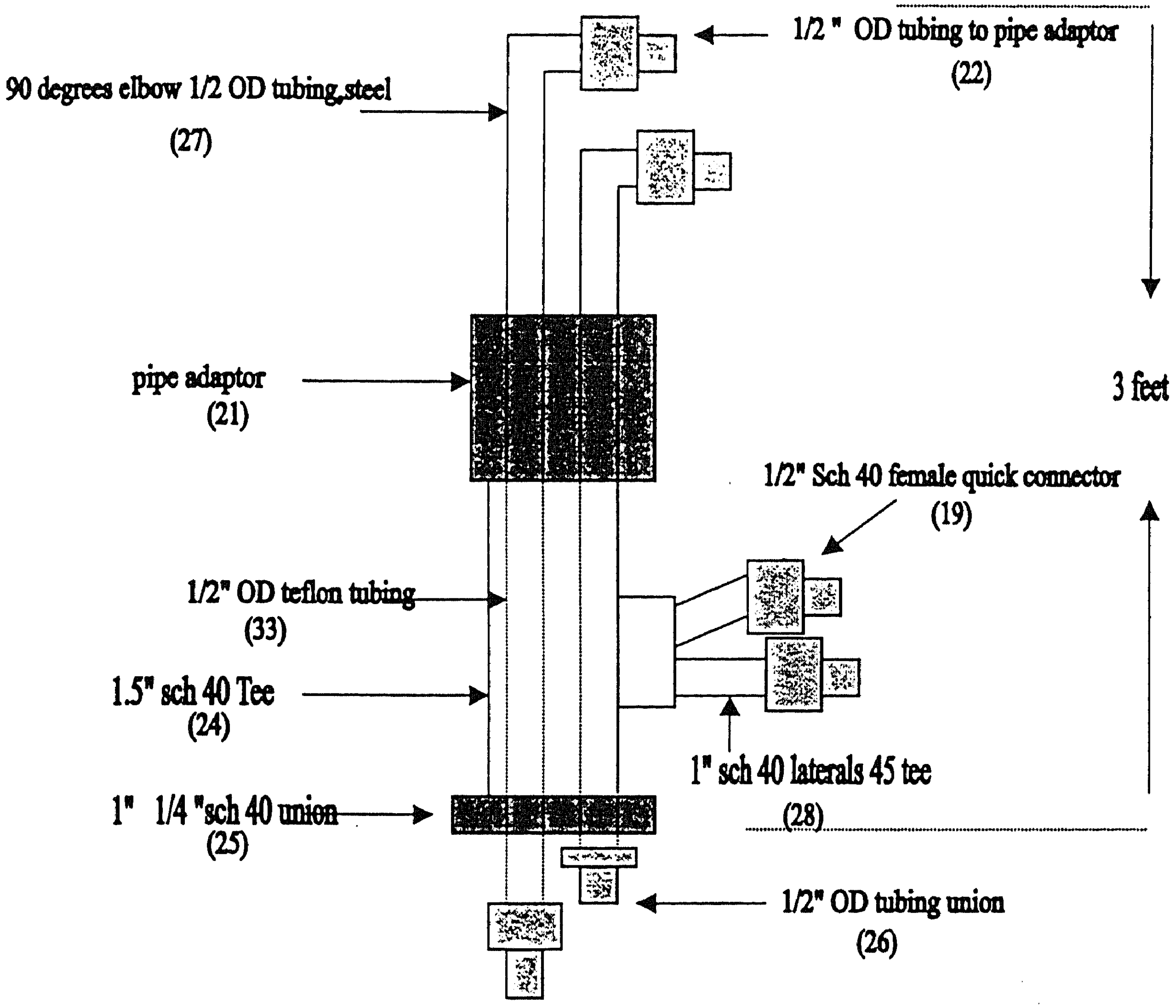


**Figure C.2** Well-Head Assembly for Ultrasonic Field Test

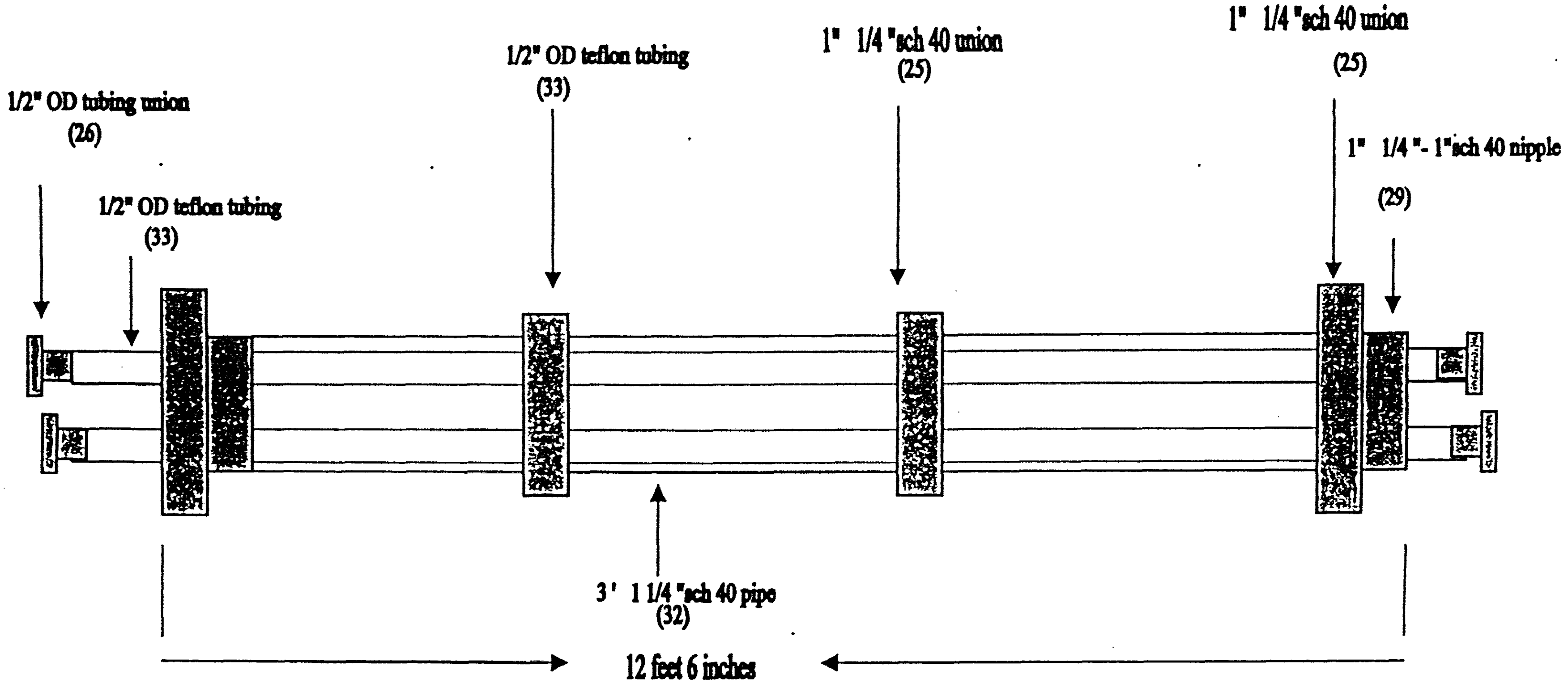


**Figure C.3** Bore-Hole Extension Pipe and Fittings

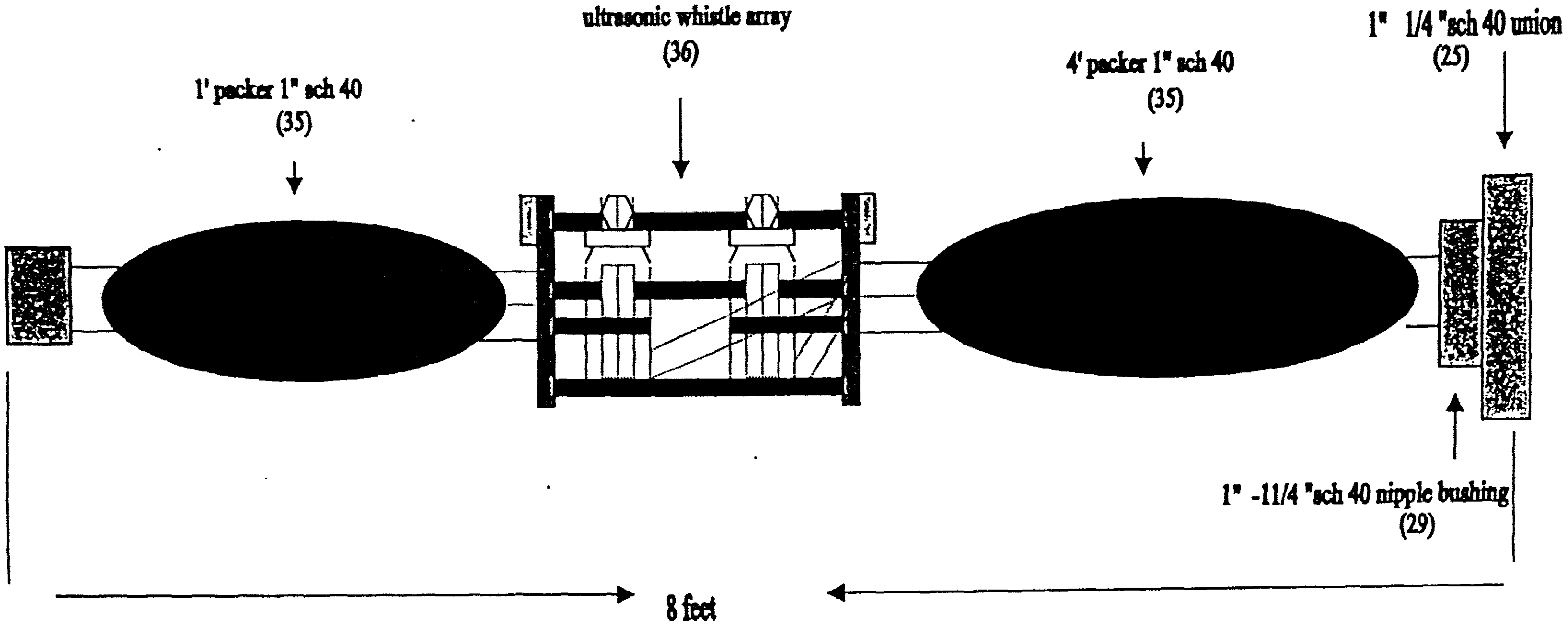


Figure C.4a Ultrasonic Transducer (Whistle)

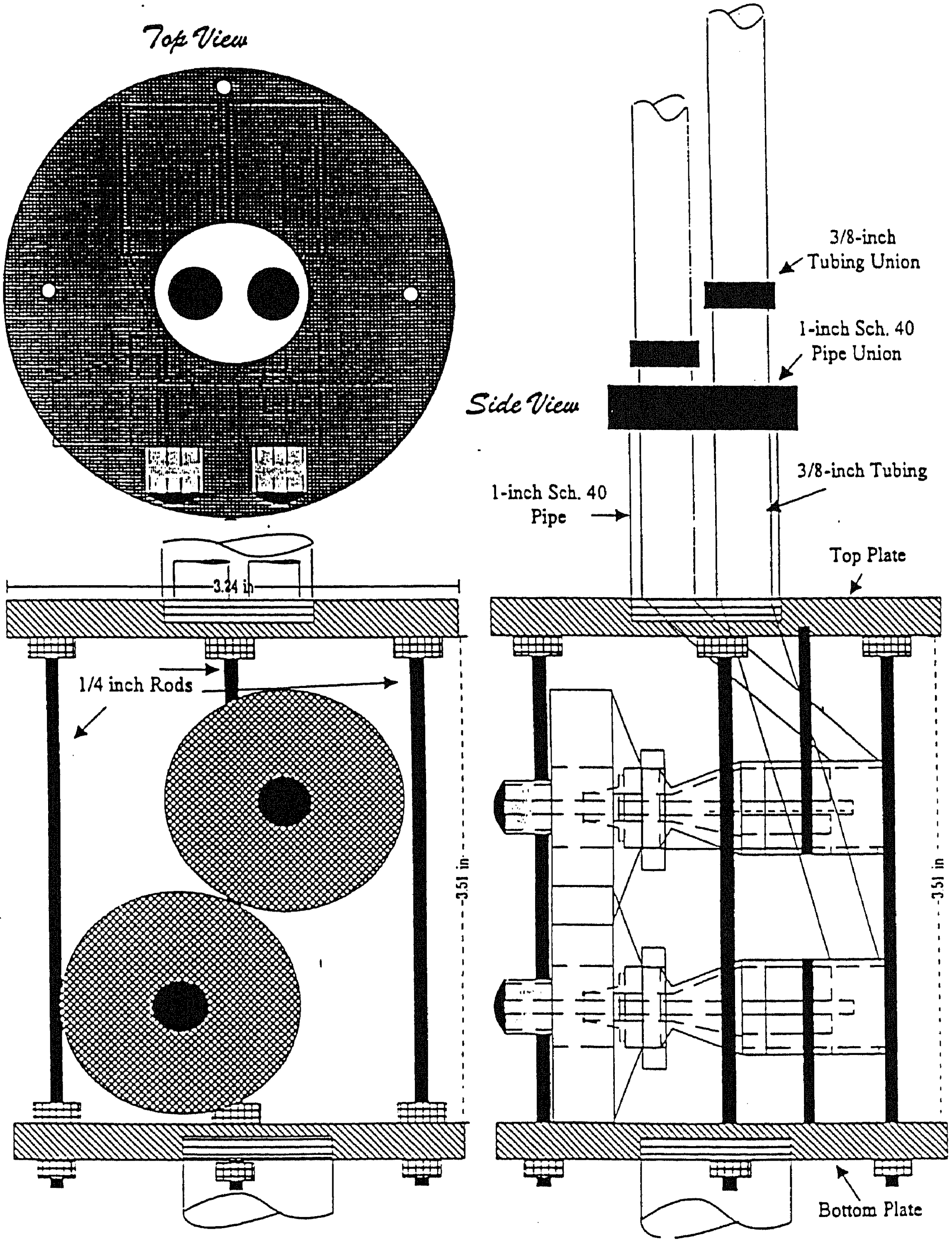


**Figure C. 4b** Detail Schematic of Whistle (Fernandez,1997)

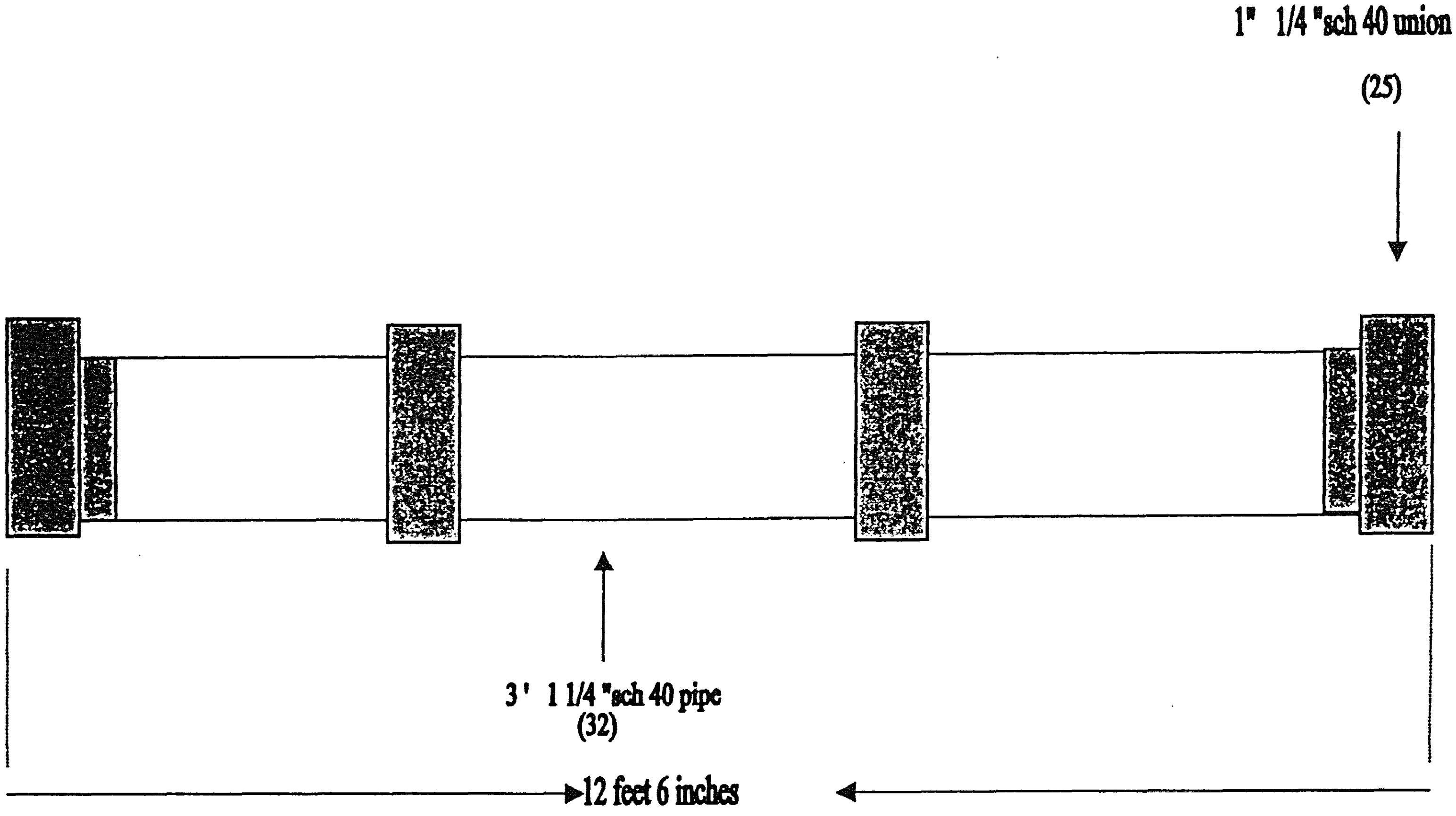


**Figure C.5** Bore-Hole Extension Pipe (Extraction System)

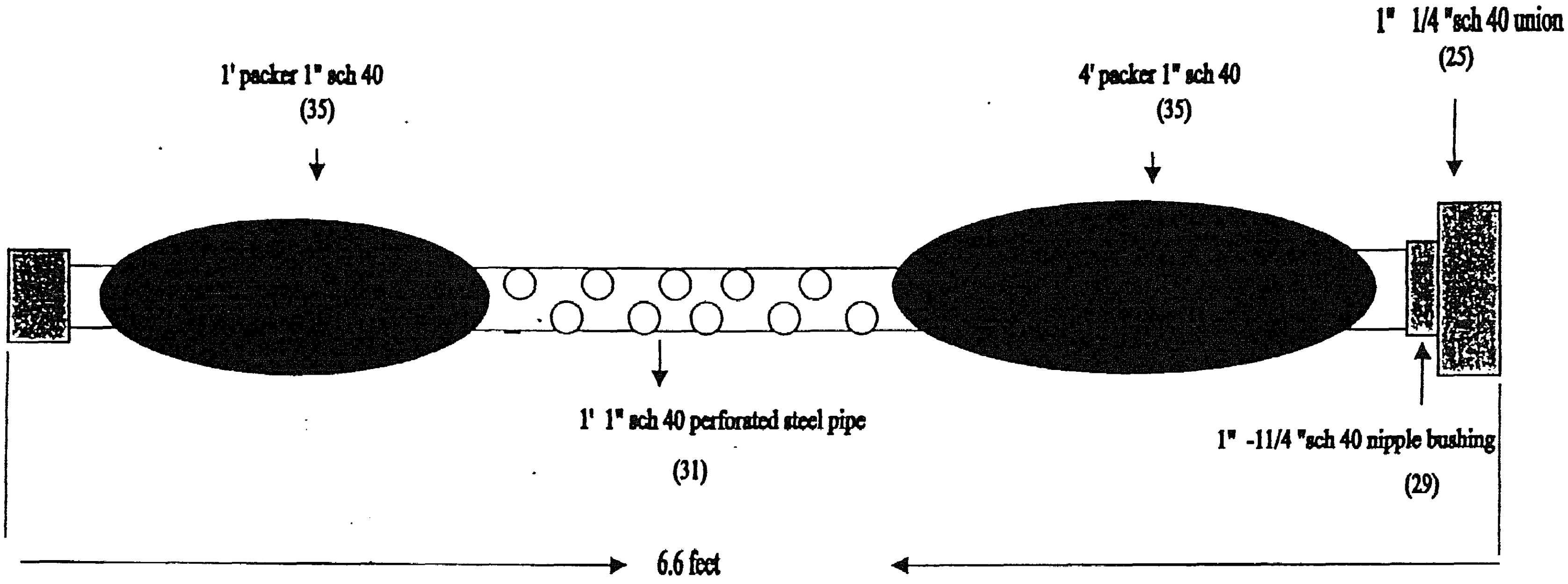


Figure C.6 Packers (Extraction System)

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