To the Graduate Council:

I am submitting herewith a thesis written by Timothy Lyle Alexander entitled "The Development of a Simplified Compliance Tool for Monitoring Destruction and Removal Efficiency in Combustion Systems." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental Engineering.

Wayne T. Davis, Major Professor

We have read this thesis and
recommend its acceptance:

Accepted for the Council:

Vice Provost and
Dean of the Graduate School

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Master's degree at the University of Tennessee, Knoxville, I agree that the Library shall make it available to borrowers under the rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgement of the source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his absence, by the Head of Interlibrary Services when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.

Signature Timothy L. Alexander
Date November 27, 1989

THE DEVELOPMENT OF A SIMPLIFIED COMPLIANCE TOOL FOR MONITORING DESTRUCTION AND REMOVAL EFFICIENCY IN COMBUSTION SYSTEMS

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Timothy L. Alexander
December 1989

ACKNOWLEDGEMENTS

During the course of my graduate program, a number of professors have offered me special guidance and advice. I am grateful to Dr. Wayne T. Davis, who served as my major professor, and to Dr. Gregory Reed and Dr. Terry Miller who also served on my graduate committee.

I wish to thank my wife, Cindy, and my sons, Daniel and Caleb, for their persistent love, support, and encouragement throughout this endeavor. Also, I wish to acknowledge Mr. Arijit Pakrasi and Mr. Nianjun Zhou for their invaluable assistance in my research efforts. I am grateful to Mr. James Myers for assisting me in formatting the text and producing the computer graphics for this thesis.

I am supremely indebted to Jesus Christ who gave me the strength to persevere. He carried me through the worst of times and multiplied my joys in the best of times.

ABSTRACT

This study presents the development of a low-cost compliance tool by which short-term combustion efficiency can be monitored. The more traditional methods of hazardous and solid waste management, such as landfilling and surface impoundment, are being replaced by on-site treatment technologies. Among the best long-term options is some type of thermal treatment for waste management. As the use of thermal treatment increases, the need for effective destruction and removal efficiency (DRE) monitoring also increases.

The compliance tool described in this study serves as a low-cost option for monitoring the efficiency of a combustion system. Normally, the demonstration of acceptable emissions is accomplished through a series of trial burns at the start-up of a facility. However, as time progresses the destruction and removal efficiency may decrease to unacceptable levels for a variety of reasons including age, changes in operating conditions, and possible faulty maintenance. This simple monitoring device allows for periodic checks by which this type of situation can be identified and rectified, well in advance of serious deterioration in destruction efficiency.

This compliance tool assists in improving public security and acceptance. While most scientists and engineers consider incineration to be a favorable option for waste disposal, much of the general public does not. The public's perception of combustion systems, waste emissions, and potentially hazardous secondary chemical reactions has been understandably negative. This tool provides visible evidence to the general public that efforts are being made to monitor and control emissions.

This study demonstrates the simplicity and adaptability of this tool. The compliance tool incorporates the devices which are needed for routine monitoring, and they are arranged for convenient use in a single stack port. This tool can be stack-specific or applied to multiple exhaust systems, and it serves as a valuable indicator of minor mechanical perturbations which must be corrected before the major ones develop.

TABLE OF CONTENTS

CHAPTER PAGE

1. INTRODUCTION AND SUMMARY 1

2. DESTRUCTION AND REMOVAL EFFICIENCY IN INCINERATION SYSTEMS 5
   - A. Compliance Standards for Destruction and Removal Efficiency 5
   - B. Geometric Characteristics Influencing DRE 6
   - C. Residence Time and Temperature Relationships in Combustion Systems 7
   - D. Waste Mixing and Excess Air 9

3. THE USE OF SF_6 AS A SURROGATE AND TRACER FOR MONITORING DRE 10
   - A. Introduction 10
   - B. SF_6 as a Surrogate and Tracer in Recent Investigations 10
   - C. Performance Characteristics of a Chemical Surrogate 13

4. A SIMPLIFIED COMPLIANCE TOOL FOR EVALUATING DRE 20
   - A. Objectives 20
   - B. A Simplified Compliance Device for Monitoring DRE 20
   - C. Development of Methodology to Calculate DRE 24
   - D. SF_6 Injection Rate and Inlet Concentration 31
   - E. SF_6 Outlet Concentration 32
   - F. Calculation of DRE and Residence Time 33

5. EXPERIMENTAL PROCEDURE 34
   - A. Introduction 34
   - B. Calibration Curve 34
   - C. Velocity Traverse 36
   - D. Collection of Representative Samples 38
   - E. Test for Reliability of Analytical Procedure 42

TABLE OF CONTENTS (Continued)

CHAPTER PAGE

6. RESULTS AND ASSESSMENTS 45
   A. Introduction 45
   B. Demonstration of the Compliance Tool on a Combustion System 45
   C. Characteristics of the Simplified Compliance Tool 50

7. CONCLUSIONS 55

LIST OF REFERENCES 57

APPENDICES 63
   APPENDIX A. Sample Calculations 64
   APPENDIX B. Velocity Traverse Data 69
   APPENDIX C. Sampling Data 72

VITA 86

LIST OF FIGURES

FIGURE PAGE

3.1. Thermal Stability Profiles for Sulfur Hexafluoride Mixture Constituents as Evaluated Under Oxidative Conditions. 15

3.2. Thermal Stability Profiles for Sulfur Hexafluoride Mixture Constituents as Evaluated Under Pyrolytic Conditions. 16

3.3. Plot of Penetration (1-DRE) Measurements for Three Candidate Tracers in a Circulating Bed Combustor. 17

3.4. Relative Sensitivity of Tracer Gases to Electron-Capture Detection by Gas Chromatography Techniques. 18

4.1. Sampling Device. 22

4.2. Isokinetic Sampling Configuration. 23

4.3. Photograph of the Sampling Device Components Which Are Inserted into the Stack Port. 25

4.4. Photograph of the Sampling Device Components External to the Stack Port. 26

4.5. Photograph of the Gas Chromatograph Used in the Flue Gas Sample Analyses. 27

5.1. Steam Plant Boiler System and Sampling Ports Configuration. 35

5.2. Gas Chromatograph Calibration Curve. 37

5.3. SF_6 Injection Points Around Boiler. 40

5.4. Plot of the Zero Efficiency (± 2 Standard Errors) for Ports 2,4, and 6. 44

6.1. Destruction and Removal Efficiency of SF_6 in the Boiler System for Representative Sample Runs. 46

6.2. Range and Average Destruction and Removal Efficiency of SF_6 for Each Sampling Day. 47

6.3. SF_6 Destruction and Removal Efficiency as a Function of Residence Time for Sampling Day 1. 47

6.4. SF_6 Destruction and Removal Efficiency as a Function of Residence Time for Sampling Day 2. 48

LIST OF FIGURES (Continued)

FIGURE PAGE

6.5. SF_6 Destruction and Removal Efficiency as a Function of Residence Time for Sampling Day 3. 48

6.6. SF_6 Destruction and Removal Efficiency as a Function of Residence Time for Sampling Day 4. 49

6.7. SF_6 Destruction and Removal Efficiency as a Function of Residence Time for Sampling Day 5. 49

6.8. Average Destruction and Removal Efficiency for Each SF_6 Injection Point in the Boiler System. 51

CHAPTER 1

INTRODUCTION AND SUMMARY

Environmental concern regarding improper and inefficient waste disposal methods has resulted in the promulgation of federal and state regulations which mandate waste clean up and control. Many of these statutes focus on the growing problem of hazardous waste generation and disposal. The basic impact of these regulations has been the revision of waste management practice and administrative controls, including the need to carefully monitor waste effluents and their potentially harmful effect on the environment. The more traditional and low-cost methods of waste management, such as direct landfilling and surface impoundment, are being replaced by on-site treatment technologies. Among the best long-term waste management options is some type of thermal treatment (1). In the incineration process, thermal decomposition of the waste constituents occurs by means of thermal oxidation, and the total waste volume is substantially reduced. Incineration can be valuable in the context of reducing the large quantities of domestic and municipal refuse generated each year, and it is especially important in the management of hazardous wastes. Among the best candidates for incineration are wastes with a significant hazardous organic content, but in reality any waste with even trace quantities of organic components can by regarded as appropriate for incineration. The need for carefully controlled incineration as a waste management option is made evident against the backdrop of the massive quantities of domestic and hazardous waste generated in the United States each year. However, one of the primary barriers to the increased use of incinerators in this country is public opposition. A great deal of public opposition

has arisen concerning the siting and permitting of new incineration systems. The most rigorous public opposition has been aimed at restricting the permitting and construction of off-site facilities, including ocean incinerators, mobile incinerators, and thermal treatment units designed to destroy polychlorinated biphenyls (PCBs).

EPA conducted an evaluation to assess the general public's perception of the potential benefits of incineration versus the potential detriments; the primary concerns expressed by citizens included the following:

1. Hazardous materials spills in storage, treatment, and handling;
2. Environmental and health impacts of land-based and ocean facilities;
3. Poor site selection processes;
4. Distrust of incinerator owners and operators;
5. Inability of government agencies to enforce compliance.

This EPA study revealed that public opposition to incineration would most likely decline if regulatory officials would more effectively address the issues surrounding these public concerns, especially regarding safety and compliance enforcement (2). The use of simplified compliance monitoring devices to verify destruction and removal efficiency (DRE) is one means by which incinerator owners and operators can assist in improving public awareness and acceptance.

A properly designed incineration system is capable of achieving a high destruction and removal efficiency for a broad range of waste streams. Incinerators are currently used for many different industrial and commercial applications. Incineration is currently the most widely favored method for disposing of hazardous waste, and the kind of incineration system used is determined by the waste type (3). Some of the more common incinerator designs

include single-chamber liquid injection units, rotary kilns, multiple hearth furnaces, fluidized bed systems, and ocean vessel incinerators (4). Ocean incineration is currently receiving a great deal of attention from both opponents and proponents. Advocates argue that ocean incineration is well suited for handling certain environmentally toxic and persistent wastes (5). Agencies such as the National Wildlife Federation (NWF) oppose wide-scale ocean dumping, but the NWF admits that a potential value does exist for ocean incineration as a supplement to land-based incineration (6). A number of industries are using boilers for thermal destruction because of their ability to recover heat generated by the incinerated wastes.

Current EPA regulations require that incineration facilities demonstrate near-100 percent destruction and removal efficiencies for the principle organic hazardous constituents (POHC) present in the waste stream. This demonstration is normally accomplished through a series of trial burns and compliance tests at the start-up of these facilities. The concept of a simplified compliance tool for evaluating DRE should be attractive to industries and government facilities which use combustion as a part of their normal operations, because thermal destruction is very important in many pollution control efforts. Over a period of years and with continued use, the efficiency of a thermal treatment facility can significantly decrease. Many operators are unaware of the level of potential degradation in their incineration systems until the occurrence of severe system difficulties, which can result in substantial regulatory fines. Historically, however, the cost and complexity of periodic compliance testing has been prohibitive. A major issue and research need in thermal treatment technology is the development of simplified quality control procedures and low-cost compliance tools by which short-term incineration efficiency can be monitored (7). The compliance tool

subsequently described meets these criteria and is, therefore, proposed as a viable option for routine DRE evaluations.

The objectives of this research effort were to develop a low-cost compliance tool for monitoring DRE and to demonstrate its application as a tool for quality control. After its development, the tool was demonstrated at a stoker boiler located at the University of Tennessee Steam Plant. This simple monitoring device allows for periodic checks by which substantial deterioration in DRE can be identified and corrected well in advance of any serious regulatory violation. Also, this compliance tool serves to improve public security and acceptance by demonstrating visible evidence that efforts are being made on a local level to monitor and control emissions and maintain a safe ecological environment.

The compliance tool is a stack sampling extraction system which utilizes SF_6 as a surrogate gas to determine conservative DRE. The tool can be easily transported from one site to another, or it can be installed permanently at a single site to allow periodic measurement of the DRE.

Chapters 2 and 3 of this research paper contain the related literature review. Specifically, Chapter 2 discusses destruction and removal efficiency in combustion systems, and Chapter 3 discusses the use of SF_6 as a chemical surrogate and tracer for monitoring DRE. Chapter 4 describes the physical configuration and operating principles of the proposed compliance tool. Chapter 5 describes the experimental procedure conducted at the University of Tennessee Steam Plant, and Chapter 6 covers the results of the testing. Chapter 7 discusses the value of this monitoring device in real-time performance assurance.

CHAPTER 2

DESTRUCTION AND REMOVAL EFFICIENCY IN INCINERATION SYSTEMS

A. Compliance Standards for Destruction and Removal Efficiency

The term destruction and removal efficiency (DRE) describes the level of waste destruction which occurs in an incineration facility. EPA has applied the concept of destruction and removal efficiency to the elimination of principle organic hazardous constituents (POHC) in a waste stream. Performance standards listed in the Code of Federal Regulations (40 CFR 264.343) require an incineration facility to attain a 99.99 percent destruction and removal efficiency for each POHC in the waste feed. The final DRE is determined from the combination of thermal destruction in the incineration system and the removal of residual pollutants in the offgas by the air pollution control devices. DRE is calculated on a mass basis as indicated below:

$$DRE = [(W_{in} - W_{out})/W_{in}] \quad (2\text{-}1)$$

where: DRE = fraction of total destruction and removal efficiency,

W_{in} = mass feed rate of the principle organic hazardous constituent in the incinerated waste stream,

W_{out} = mass emission rate of the principle organic hazardous constituent at the point of atmospheric discharge.

The destruction and removal efficiency for thermal treatment systems is dependent upon several factors which include incinerator geometry, furnace temperature, residence time, fuel-waste mixing, and excess air. The geometric

characteristics of incinerators or boiler furnaces vary widely. Temperature, time, and excess air are measured quantities which are often basically consistent among similar thermal systems. Mixing is not a measured quantity, but efficient mixing is normally achieved through experience and overdesign (8).

B. Geometric Characteristics Influencing DRE

The type of thermal treatment system and its corresponding furnace geometry is chosen according to the nature of the waste to be incinerated. The physical, chemical, and thermodynamic properties of the waste feed determine the characteristics of the combustion chamber and its operating conditions. In order to achieve a high DRE, the combustion chamber or furnace should be designed for maximum residence times, and burners should be carefully located for maximum utilization of combustion space. Depending upon the application, burners may be set for radial, tangential, or axial firing. Also, proper fuel atomization is imperative if a high DRE is to be obtained in liquid combustors. Certain types of nozzles have been produced which inject mists with average droplet diameters as small as one micrometer; this contrasts with some oil burners which produce droplet sizes in the range of ten to fifty micrometers. The atomization from very fine-mist nozzles benefits mixing which, in turn, helps to improve final DRE.

An example of a relatively efficient combustion system is a rotary kiln incinerator. The cylindrical-shaped rotary kiln incinerator typically provides high DREs because of its chamber geometry and waste mixing capacity. The combustion chamber in this type of incinerator is elongated and is mounted on a slight incline. The elongated chamber allows for increased residence time, and the rotation of the shell provides for waste transportation and mixing

enhancement. Also, the versatility of a rotary kiln incinerator is demonstrated in its ability to accept wastes in the solid, gaseous, or liquid phase (2).

C. Residence Time and Temperature Relationships in Combustion Systems

Time and temperature are related to destruction and removal efficiency by solving the first order Arrhenius equation and using the definition of DRE given above in equation 2-1.

$$dm/dt = -km \tag{2-2}$$

$$k = A \exp(-E/RT) \tag{2-3}$$

$$\int_{W_{IN}}^{W_{OUT}} dm / m = -k \int_{0}^{t} dt \tag{2-4}$$

$$\ln m \Big|_{W_{IN}}^{W_{OUT}} = -kt \tag{2-5}$$

$$\ln W_{OUT} - \ln W_{IN} = -kt \tag{2-6}$$

$$\ln (W_{OUT} / W_{IN}) = -A \exp(-E/RT)t \tag{2-7}$$

Rearranging equation 2-1 gives:

$$DRE = (W_{IN} / W_{IN}) - (W_{OUT} / W_{IN}) \tag{2-8}$$

$$DRE = 1 - (W_{OUT} / W_{IN}) \tag{2-9}$$

$$W_{OUT} / W_{IN} = 1 - DRE \tag{2-10}$$

Substituting equation 2-10 into equation 2-7 gives:

$$\ln (1 - DRE) = -At(-E/RT) = -kt \tag{2-11}$$

where: m = the mass of the constituent,

k = the first order kinetic rate constant,

E = the activation energy,

R = the universal gas constant,

A = the Arrhenius constant,

t = residence time,

T = absolute temperature.

Using this relationship, time versus temperature plots can be generated for a particular POHC at a given DRE, and the required residence time for a given temperature can then be estimated from the resulting graphs. Hall, Kemner, and Staley evaluated options for incinerating certain hazardous wastes in high temperature industrial units. They offered the following definition for residence time within a control volume:

$$t_r = [\,294.4\ V / Q\,(Te - Tm)]\ \ln(Te/Tm) \qquad (2\text{-}12)$$

where: t_r = residence time,

V = volume of the investigated region,

Q = volumetric flow rate at the system outlet,

Te = control volume exit temperature,

Tm = maximum temperature within the control volume.

This relationship assumes that the temperature of the gas varies linearly with distance between maximum and minimum temperature points within the control volume (9). When using this equation for experimental applications, the maximum temperature (Tm) may be extrapolated from temperature measurements at different locations within the control volume. The volumetric flow rate at the outlet can be calculated by multiplying the inlet air flow rate value by an air expansion correction factor. Also, studies have indicated that residence time effects may be completely dominated by temperature effects. Thermal destruction evaluations using benzene showed the absence of residence time effects for temperatures above 1400°F; this points to the fact that thermal

destruction may occur primarily within the flame (10). Experiments conducted by Kramlich, Seeker, and Heap established a similar relationship for thermal destruction within the flame. They injected a mixture of POHCs and chloroform tracer gas directly into a flame, and the resulting DREs were greater than 99.995 percent (11). These studies indicate that residence time within the flame, rather than merely residence time within the combustion chamber, may be the significant issue in determining the level of DRE obtained for a particular facility (12).

D. Waste Mixing and Excess Air

Other important factors in the consideration of DRE are the mixing which occurs between the waste and fuel and the excess air needed to enhance the mixing process. A good fuel-waste mix is essential if a high destruction efficiency is to be achieved and if products of incomplete combustion (PICs) are to be kept to a minimum. However, no incineration system can consistently accomplish the intimate mix of fuel, waste, and air needed for perfect combustion. Therefore, incineration systems are typically operated with combustion conditions greater than the stoichiometric quantity of air. Excess air is combined with the fuel and waste components in the combustion chamber to insure sufficient oxygen contact. Poor mixing conditions result in a need for more excess air, which can cause reduced chamber temperatures and heat loss through the offgas. If the excess air is decreased and the oxygen supply becomes insufficient to produce complete combustion, undesirable residual components, such as carbon monoxide and unburned hydrocarbons, can remain in the combustion products (13).

CHAPTER 3

THE USE OF SF_6 AS A SURROGATE AND TRACER FOR MONITORING DRE

A. Introduction

For many years, engineers and scientists have sought a chemical surrogate which can be used to evaluate the destruction and removal efficiency in hazardous waste incineration systems. A technically defensible approach for monitoring DRE in boilers and incinerators is to evaluate the destruction of a conservative surrogate material in the waste stream versus the destruction of any volatile organic hazardous constituent also present in the waste stream (14). The preponderance of recent studies has pointed toward the use of SF_6 as the most viable option for a dependable chemical surrogate and tracer gas (15).

B. SF_6 as a Surrogate and Tracer in Recent Investigations

Sulfur hexafluoride was discovered in 1886 by Henri Moissan during his research efforts to isolate free fluorine. Moissan concluded that fluorine could be more easily isolated from its compound with a nonmetal than with a metal. On June 26, 1886 he burned a crystal of silicon in a series of test gases, the silicon caught fire, and free fluorine resulted. Sulfur which was burned in the gas formed residual SF_6. Further information on the characteristics of SF_6 was gathered by Henri Moissan and Paul Lebeau in 1900 during their research on sulfuryl fluoride (SO_2F_2) and its related compounds. They described SF_6 as a tasteless, colorless, and incombustible gas, with an inertness resembling nitrogen. They also noted that the gas was unaffected at high temperatures (16).

Since the efforts of Moissan and Lebeau, the various applications of SF_6 in historical research have collectively pointed toward its multifaceted value as a tracer and surrogate. The following examples from recent investigations illustrate this fact.

Khoury et al. used a simplified monitoring device to investigate the reentrainment of building exhaust into the fresh air inlet of a heat recovery system. SF_6 was injected into the exhaust line and was monitored in the various compartments of the heat recovery unit. Sampling probes placed in the gas stream were used to collect samples in gas bags. From the resulting SF_6 concentrations present in the sampling bags and the known volumetric flow rates for the system, the percent of reentrainment to the heat recovery unit was calculated (17).

Hanna and Paine used SF_6 as a tracer in tall stack emissions to develop diffusion relationships in the convective boundary layer. They found that during convective conditions with light winds, very buoyant SF_6 tracer plumes often rose near the top of the atmospheric mixing layer. Because SF_6 allowed for dependable tracer analyses, the maximum predicted and actual observed test results agreed within 15 percent (18). Hanna, Weil, and Paine used SF_6 emissions data from the Kincaid Power Plant in Illinois and the Bull Run Power Plant in Tennessee to evaluate the performance of certain plume dispersion models (19).

Stokes, Kennedy, and Hardcastle reported on the viability of SF_6 as a real-time tracer gas in mine ventilation studies (20). In similar experiments, SF_6 derived air flow patterns were used to evaluate mine ventilation and to estimate the amount of methane released from the coal mined at various locations (21).

In gas chromatography research, SF_6 was used in the development of a very sophisticated method to detect extremely small concentrations (i.e., parts per trillion) of halocarbons in gaseous samples. The procedure involved complex gas chromatograph electron-capture detection to analyze stratospheric air samples and industrial emission samples. The analytical capability of this method was demonstrated in the repeated successful detection of ppb amounts of certain compounds in a matrix of SF_6 tracer gas (22).

SF_6 has been used extensively in the analysis of electrical phenomena and high voltage insulation. Koenig and Lautenschlaeger used SF_6 as a base gas to which different gaseous mixtures were added in order to evaluate corona stabilization properties (23). Ijumba, Chalmers, and Farish reported on the effects of adding small quantities of Freon 113 to the SF_6 which was used to evaluate direct current corona discharge in a point-plane gap (24). Similar investigations involved the use of SF_6 as a charged carrier gas for electron energy distribution and transport analysis (25), for alternating current impulse flashover voltage evaluations (26,27), and for the generation of thermochemical data for gas phase compounds relating to SF_6 dielectric breakdown (28).

Groenskei used SF_6 to evaluate vertical diffusion from automobile exhaust. The tracer experiments were used to show that the vertical diffusion of exhaust gases was greater from cars traveling at higher speeds than from cars traveling at lower speeds (29).

SF_6 has been used extensively in the evaluation of indoor air quality. As one example, it was used as a tracer gas in radon studies conducted in homes in Maine to measure air exchange rates of indoor air (30).

C. Performance Characteristics of a Chemical Surrogate

In order for a substance to serve as a valid chemical surrogate or tracer in DRE evaluations, the following characteristics must be exhibited by the surrogate:

1. It must be relatively nontoxic.
2. It must have a thermal stability greater than any of the hazardous components in the waste stream.
3. The surrogate material must not be a component in the hazardous waste.
4. The surrogate must be capable of detection at extreme low concentrations for quasi-real-time monitoring.
5. A direct relationship must exist between surrogate destruction and the thermal destruction of the hazardous waste constituents.

Numerous research efforts regarding SF_6 have indicated that below 1000 parts per million (ppm) the gas is nontoxic. Cytotoxicity studies reported by the American Conference of Governmental Industrial Hygienists indicate that SF_6 produces no toxic effects for concentrations below the 1000 ppm threshold limit value (31). As a surrogate, the concentrations of SF_6 typically used at the injection inlet of an incineration system are well below 1000 ppm (e.g., 0.1 ppm), therefore SF_6 can be considered nontoxic for DRE evaluations or other types of related tracer analyses.

Laboratory evaluations have been reported by Taylor and Chadbourne on the thermal stability of SF_6 as a function of exposure temperature, waste feed composition, and reaction atmosphere. Their analyses indicate that regardless of the oxygen concentration present in the test mixture, SF_6 has a far greater

thermal stability than any of the hazardous organic constituents tested. Thermal stability profiles for the SF_6 mixture constituents, as evaluated under oxidative and pyrolytic conditions, are presented in Figures 3.1 and 3.2 (32). England, Teuscher, and Quon also evaluated the thermal stability of SF_6 as a surrogate compound for measuring the destruction of POHCs. Their test program consisted of burning SF_6 concurrently with POHCs for three different temperature conditions and three different residence times. Results indicated that the overall thermal stability of SF_6 was greater than that for the hazardous organics tested, and the DRE for each of the POHCs was greater than 99.99 percent, which is the required destruction limit imposed by EPA regulations (12). Experimental evaluations reported by England et al. compared the DRE for SF_6 and two other candidate tracers, Freon 113 and tetrachloromethane. Figure 3.3 is a plot of the penetration (i.e., 1 - DRE) for each of the three candidate tracers. As shown on the plot, SF_6 exhibited the greatest penetration (33).

Among the major gases which have been studied for the purpose of surrogate testing are sulfur hexafluoride (SF_6), dibromodifluoromethane (Freon 12B2), trichlorofluoromethane (Freon 11), bromotrifluoromethane (Freon 13B1), 1,1,2-trichlorotrifluoroethane (Freon 113), octafluorocyclobutane (Freon C-318), dichlorodifluoromethane (Freon 12), 1,2-dichlorotetrafluoroethane (Freon 114), and chlorodifluoromethane (Freon 22). All of these gases are colorless, tasteless, noncorrosive, nonflammable, and chemically inert. Each of these tracer gases can be analyzed with a high degree of sensitivity, but SF_6 possesses the highest response to electron capture by ECD-gas chromatography. Figure 3.4 is a log-scale plot showing the minimum detectable concentration of certain candidate

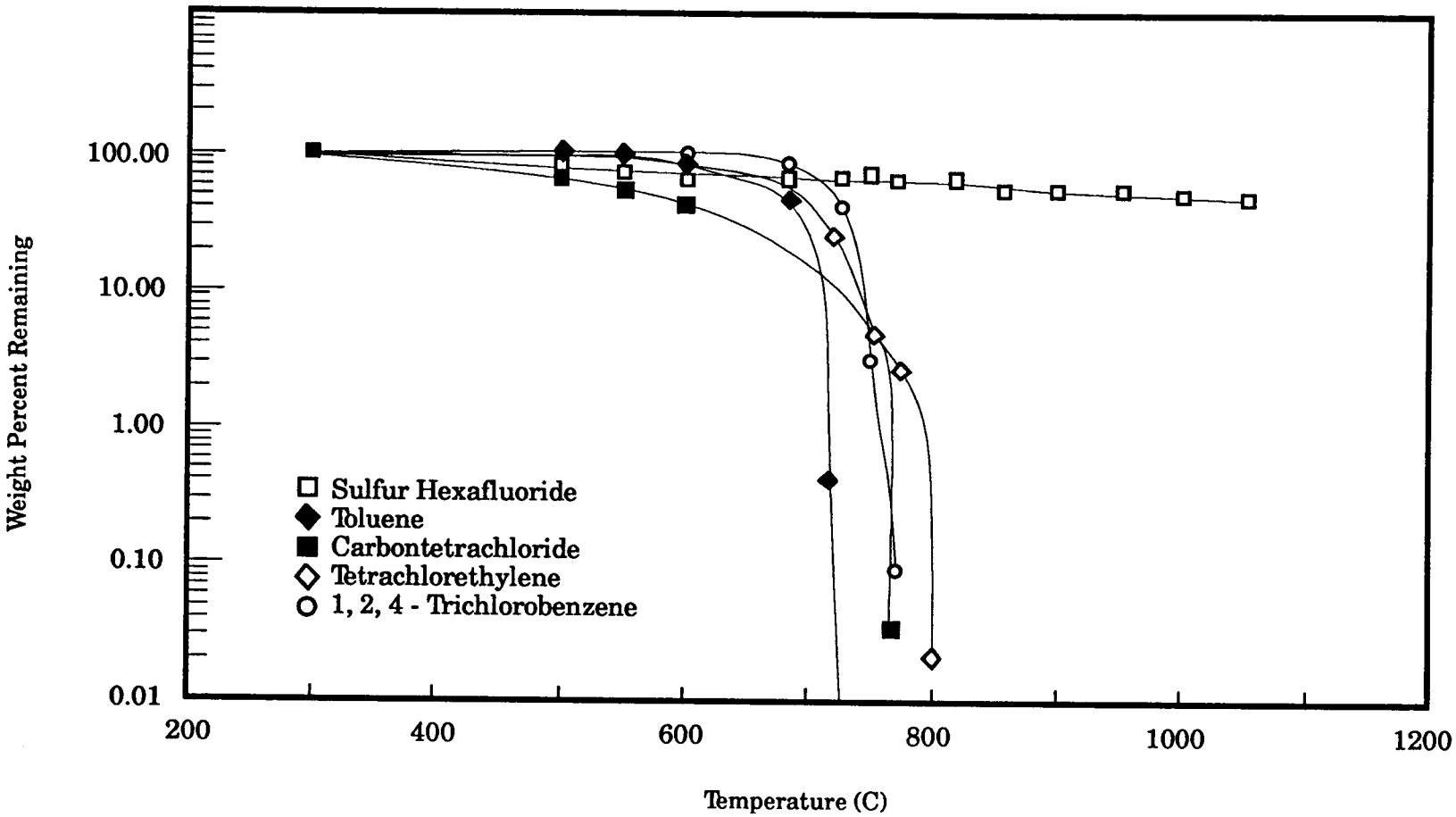


Figure 3.1 **Thermal Stability Profiles for Sulfur Hexafluoride Mixture Constituents as Evaluated Under Oxidative Conditions.**

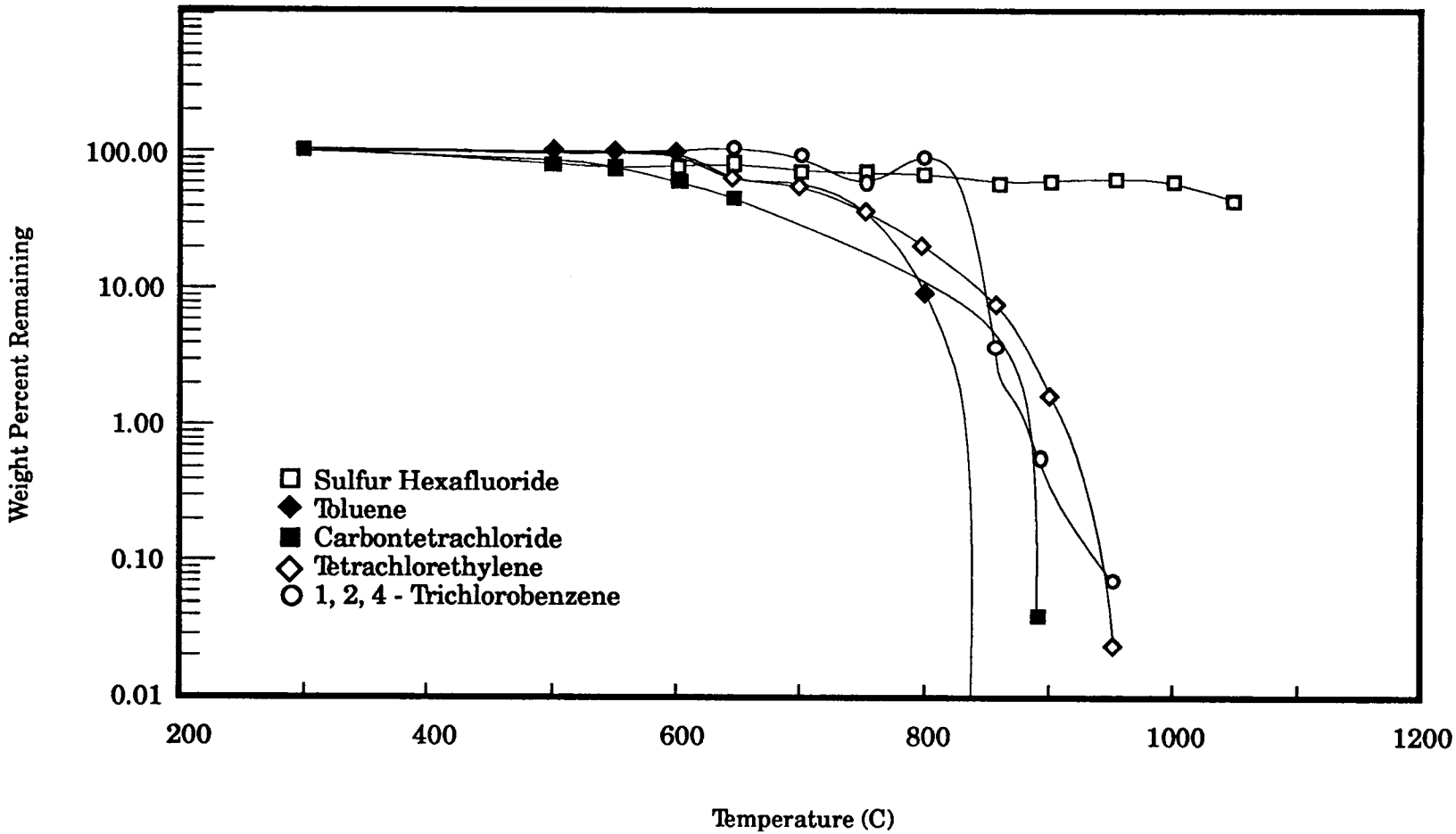


Figure 3.2 Thermal Stability Profiles for Sulfur Hexafluoride Mixture Constituents as Evaluated Under Pyrolytic Conditions.

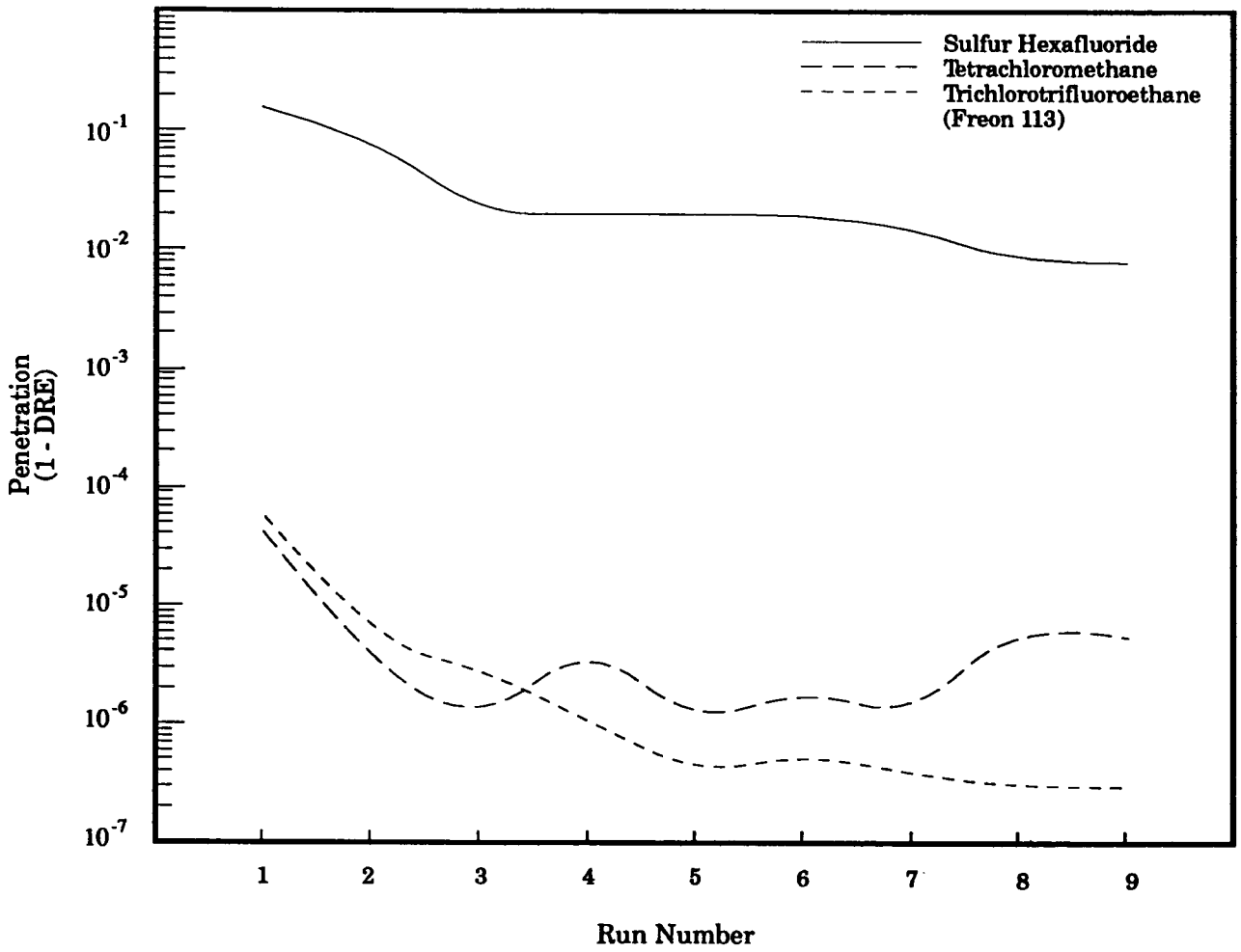


Figure 3.3. Plot of Penetration(1-DRE)Measurements for Three Candidate Tracers in a Circulating Bed Combuster.

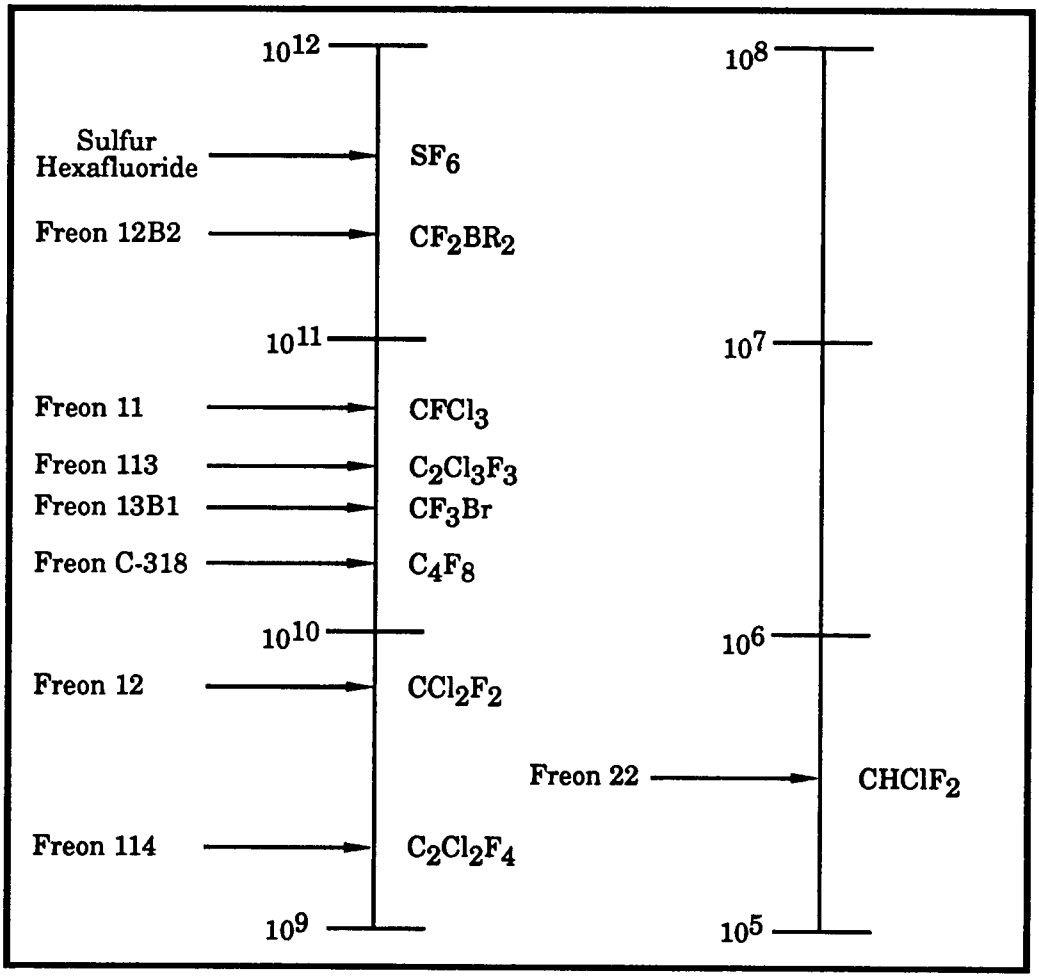


Figure 3.4. Relative Sensitivity of Tracer Gases to Electron - Capture Detection by Gas Chromatography Techniques.

tracer gases. Sulfur hexafluoride has the highest sensitivity to gas chromatograph analyses and can be detected on the order of 10^{-12} parts SF_6 to one part air (15).

Taylor and Chadbourne demonstrated a relationship between the thermal stability of SF_6 and the thermal stability of certain hazardous constituents for a variety of oxygen concentrations at high temperatures (see Figures 3.1 and 3.2). SF_6 proved to be the most stable component in the waste stream. Their further investigations revealed that SF_6 had a 99.99 percent destruction temperature greater than 1050°C. Various field studies have confirmed the conservative nature of SF_6 by demonstrating that a 99.9 percent destruction of SF_6 results in greater than 99.999 percent destruction of any known hazardous constituent (32). Therefore, the correlation between waste destruction and SF_6 thermal stability at high temperatures indicates the potential value of SF_6 as a continuous-monitoring surrogate for analyzing boiler or incinerator performance.

Sulfur hexafluoride possesses the characteristics which are considered to be the most desirable for a chemical surrogate and tracer. SF_6 is nontoxic, chemically inert, colorless, tasteless, nonradioactive, and easily obtainable. It has a greater thermal stability than any volatile organic hazardous constituent, a conservative relationship exists between SF_6 and waste component destruction, and it is amenable to gas chromatograph sample analysis at extremely low concentrations.

CHAPTER 4

A SIMPLIFIED COMPLIANCE TOOL FOR EVALUATING DRE

A. Objectives

The objectives of this research project were to develop a low-cost compliance device for monitoring DRE and to demonstrate, through experimental procedure, its application as a tool for quality control. This compliance tool is a stack sampling extraction system which uses sulfur hexafluoride as a chemical surrogate and tracer gas to determine conservative DRE. This tool is designed to be inserted into a standard four-inch stack sampling port and is used to extract bag samples of flue gas containing small concentrations of SF_6. The gas extractions must be collected at a location far enough downstream of the combustion chamber to assure that no further thermal destruction is occurring. The SF_6 concentrations in the gas samples are analyzed with a gas chromatograph. The DRE is determined by comparing the measured SF_6 outlet concentrations to the theoretical concentrations, based on a mass balance, which would have resulted without the occurrence of thermal destruction.

B. A Simplified Compliance Device for Monitoring DRE

The components of this compliance tool are a specially designed sampling device, a sampling pump, a digital thermometer, magnehelic pressure gauges, Tedlar sampling bags, sampling hoses, and a semi-portable gas chromatograph. Each of these components can be used at the sampling site. However, the gas chromatograph may be kept in the laboratory for convenience.

The sampling device (Figure 4.1) is constructed on a nine-inch by one-inch steel circular plate, and five different sampling components extend through drilled holes in the steel plate and are held in place by pressure nuts. First, the primary sampling probe, made from 1/2-inch stainless steel tubing, passes through the steel plate and extends 42 inches beyond the inside of the mounting flange. A 1/2-inch diameter sampling nozzle is mounted on the end, and this probe serves as the major pathway through which the gas samples are drawn. Second, a Stausscheibe (Type S) pitot tube is mounted beside the sampling probe and arranged so that the nozzle configuration for an EPA-approved isokinetic sampling system is essentially duplicated (Figure 4.2). The pitot tube is used to measure the velocity pressure of the gas stream. Third, a thermocouple is attached to the pitot tube assembly and extends 42 inches beyond the mounting flange. The thermocouple is used to measure the stack temperature. Fourth is a 1/2-inch diameter return gas port. This return port is connected to the primary sampling probe assembly by means of a 1/2-inch, U-shaped, stainless steel connecting pipe. The purpose of the return gas port is to exhaust the unextracted flue gas back into the stack. Fifth, a static pressure port is constructed from 1/4-inch stainless steel tubing and extends 14 inches beyond the inside of the mounting flange. The static pressure value is used in the calculation of the velocity pressure.

The five components of the sampling device are arranged so that they can all be inserted into a 4-inch diameter standard EPA sampling port. The sampling device is secured onto the sampling port by means of a nine-inch by one-inch aluminum annulus flange, which has standard four-inch internal threads.

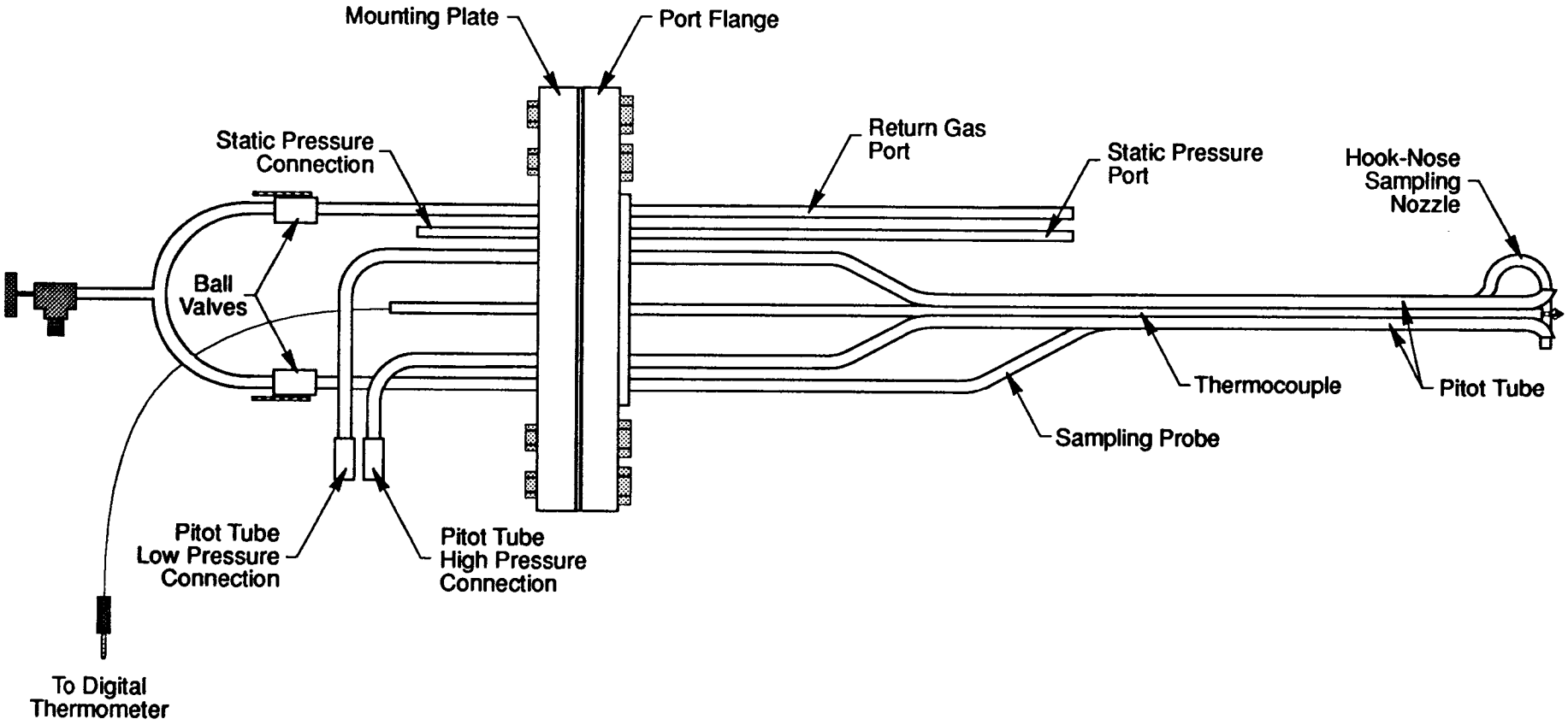


Figure 4.1. Sampling Device.

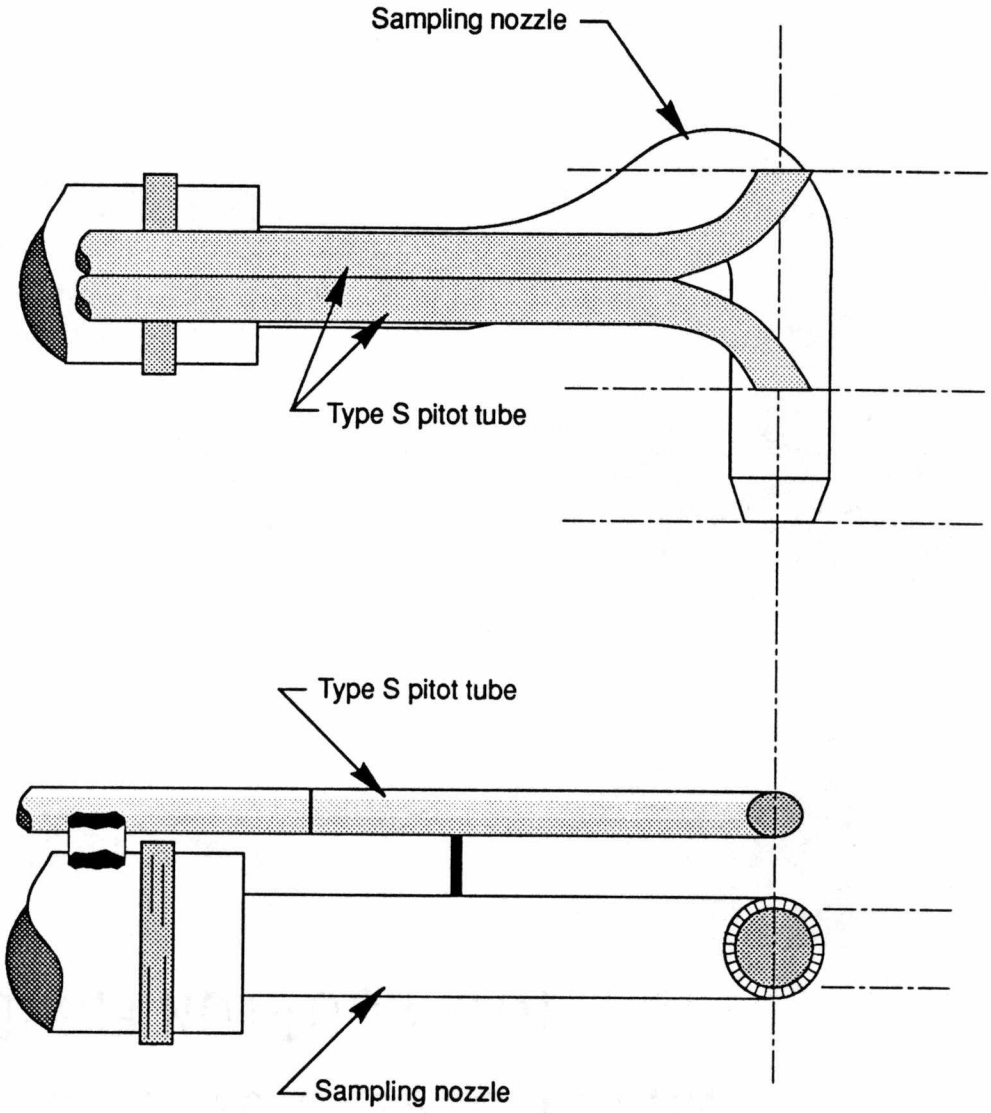


Figure 4.2. Isokinetic Sampling Configuration.

The aluminum flange is screwed onto the sampling port, the sampling device is inserted into the port, and the steel flange and the aluminum flange are bolted together by eight 3/8-inch hex bolts.

The sampling device installed in the stack port is aligned so that the sampling nozzle is exactly parallel to the direction of the gas flow. The tip of the hook-shaped nozzle should face directly into the gas stream.

Once the sampling device is secured in the sampling port, the various hoses and gauges are attached, the sampling pump is connected, and the gas samples are extracted. A sufficient number of bag samples should be taken for each run in order to assure an integrated gas mixture. If the gas chromatograph is a portable or semi-portable type, evaluation of the gas samples can take place on site, thereby making quasi-real-time sampling analysis possible. Figures 4.3 and 4.4 are photographs showing the different sections and components of the sampling device. Figure 4.5 shows the gas chromatograph used in the flue gas sample analyses.

C. Development of Methodology to Calculate DRE

The analytical procedure for the determination of the DRE involved several simplifying assumptions which established relationships between the initial calibration values and subsequent measurements for velocity pressure, flue gas temperature, flue gas molecular weight, and barometric pressure. The analyses also involved the calculation of the flow rate through the boiler system, the calculation of the SF_6 residence time in the boiler, the derivation of a moisture correction factor, and the GC analysis of the SF_6 concentration in the gas sampling bags.

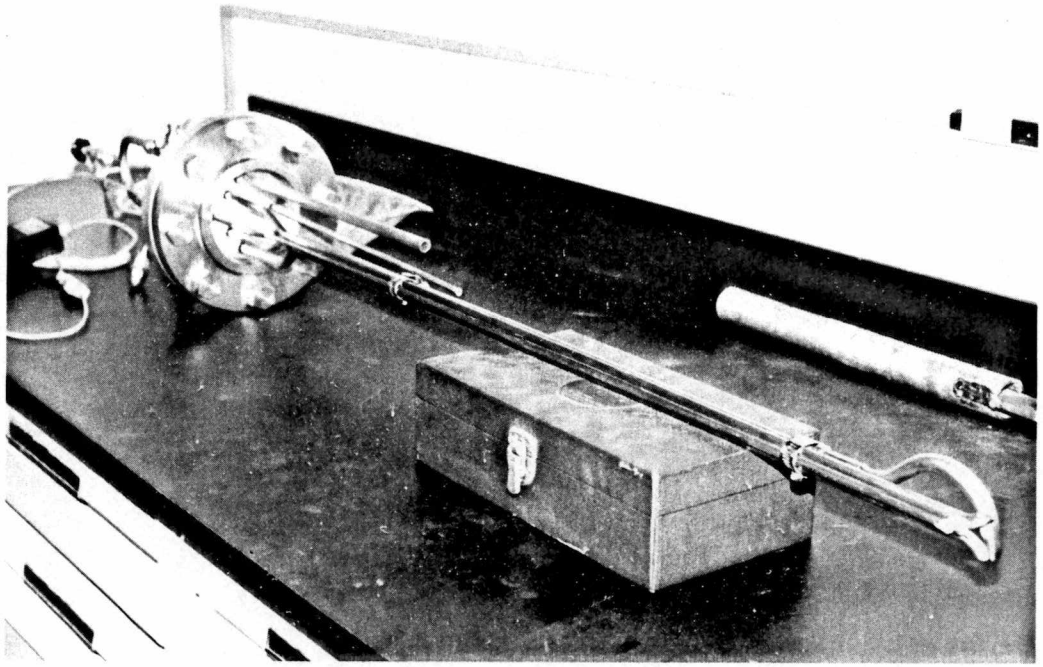


Figure 4.3. Photograph of the Sampling Device Components Which Are Inserted into the Stack Port.

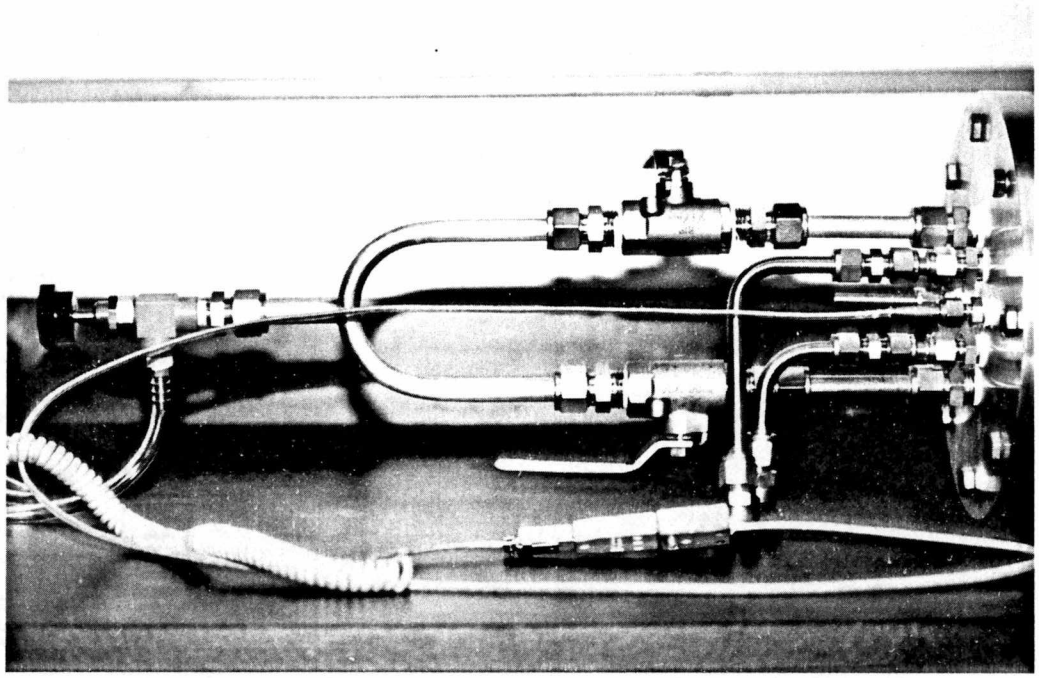


Figure 4.4. Photograph of the Sampling Device Components External to the Stack Port.

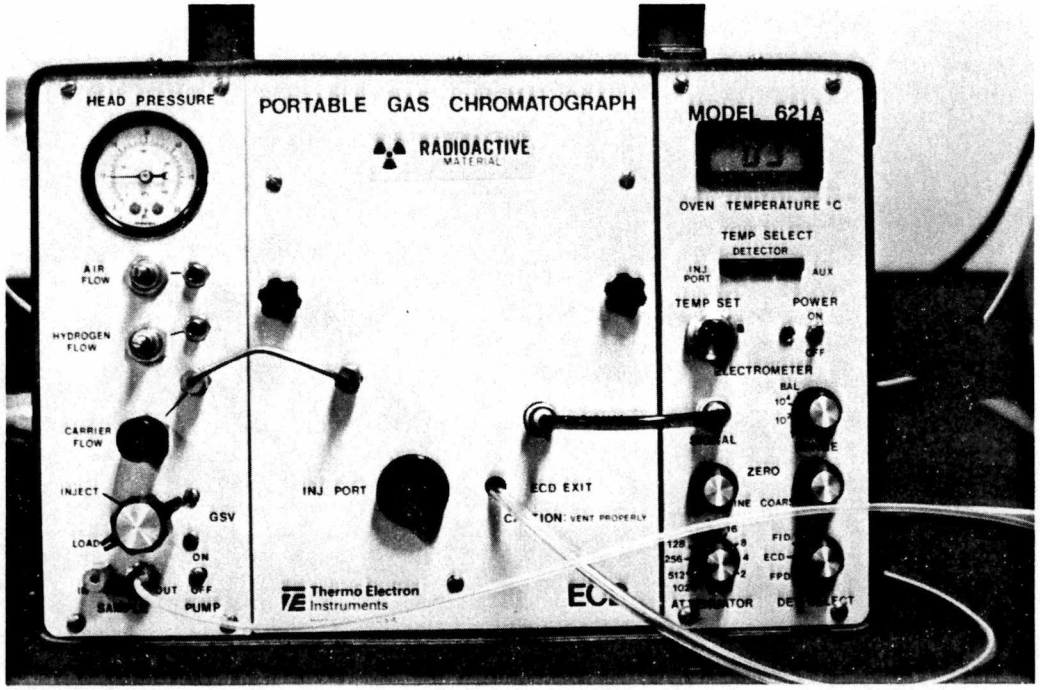


Figure 4.5. Photograph of the Gas Chromatograph Used in the Flue Gas Sample Analyses.

One of the simplifying assumptions was that the stack flow rate could be measured at anytime (t) by relating the velocity pressure at the compliance tool's pitot tube to the average velocity pressure in the duct (ΔP). The average velocity pressure in the duct may occur at a location which is different from the ΔP measured by the stationary pitot tube. Therefore, a relationship was needed between the average calibration velocity pressure (ΔP_c), obtained from the velocity traverse, and subsequent stationary pitot tube velocity pressure measurements (ΔP_t) taken at a single point. By establishing this relationship of proportionality, only one initial velocity traverse would have to be performed in order to use this compliance tool. Also, by assuming a proportional relationship between the initial and subsequent ΔP values, a relationship was derived between the calibration flow rate (Q_C) and the flow rate at any future sampling time (Q_t). The derivation of these relationships and the simplifying assumptions involved are discussed below.

The basic flow rate equation (4-1) and the EPA-defined pitot tube velocity equation (4-2) are:

$$Q = A\,V \tag{4-1}$$

$$V = Kp\,Cp\,(\Delta P\,T / P\,MW)^{1/2} \tag{4-2}$$

The velocity at anytime 1 at point i is:

$$V_{1i} = Kp\,Cp\,(\Delta P_{1i}\,T_{1i} / P_{1i}\,MW_{1i})^{1/2} \tag{4-3}$$

The velocity at anytime 2 at point i is:

$$V_{2i} = Kp\,Cp\,(\Delta P_{2i}\,T_{2i} / P_{2i}\,MW_{2i})^{1/2} \tag{4-4}$$

The average velocity in a duct in which N velocity measurements have been made is:

$$V_{AVG} = \sum_{i=1}^{N} V_i \qquad (4\text{-}5)$$

Therefore, the average velocity in the duct at time 1 is:

$$V_1 = Kp\ Cp \sum_{i=1}^{N} (\Delta P_{1i}\ T_{1i} / P_{1i}\ MW_{1i})^{1/2} \qquad (4\text{-}6)$$

At time 2, the average velocity in the duct is:

$$V_2 = Kp\ Cp \sum_{i=1}^{N} (\Delta P_{2i}\ T_{2i} / P_{2i}\ MW_{2i})^{1/2} \qquad (4\text{-}7)$$

Based on the fact that the flow in the duct is turbulent, the velocity profiles for time 1 and 2 have the same shape. Therefore, at any point in space $V_{2i} = k\ V_{1i}$, where k is a constant that is independent of location. Since the relative profile of the velocity is constant, the velocity at any location (i) can be related to the average velocity as follows:

$$V_{1i} = k_i\ V_1 \qquad (4\text{-}8)$$

and

$$V_{2i} = k_i\ V_2 \qquad (4\text{-}9)$$

where k_i depends on the location i but is constant in time and, therefore, is a constant for any given location. Combining equations 4-8 and 4-9 gives:

$$V_2 = V_1\ (V_{2i} / V_{1i}) \qquad (4\text{-}10)$$

Equation 4-10 states that the average velocity at time 2 can be determined by knowing the average velocity at time 1 and the single point measurements of the velocity at location i at times 1 and 2. If the full traverse of the duct is known at some initial time, one can, at a later time, take a single point velocity

measurement and determine the overall average velocity. From this average velocity value the flow rate can be derived, because the flow rate is the product of the average velocity and the cross-sectional area (A) of the duct.

Substituting equations 4-3 and 4-4 into equation 4-10 gives:

$$V_2 = V_1 \frac{Kp\,Cp\,(\Delta P_{2i}\,T_{2i}\,/\,P_{2i}\,MW_{2i})^{1/2}}{Kp\,Cp\,(\Delta P_{1i}\,T_{1i}\,/\,P_{1i}\,MW_{1i})^{1/2}} \qquad (4\text{-}11)$$

On the basis that P_{1i}, T_{1i}, MW_{1i}, P_{2i}, T_{2i}, and MW_{2i} are constant for all points i at times 1 and 2, then:

$$P_{1i} = P_1 \qquad (4\text{-}12)$$

$$T_{1i} = T_1 \qquad (4\text{-}13)$$

$$MW_{1i} = MW_1 \qquad (4\text{-}14)$$

$$P_{2i} = P_2 \qquad (4\text{-}15)$$

$$T_{2i} = T_2 \qquad (4\text{-}16)$$

$$MW_{2i} = MW_2 \qquad (4\text{-}17)$$

Equation 4-11 simplifies to:

$$V_2 = V_1\,[(\Delta P_{2i}\,T_2\,P_1\,MW_1)/(\Delta P_{1i}\,T_1\,P_2\,MW_2)]^{1/2} \qquad (4\text{-}18)$$

Defining time 1 as time C, at which a calibration (C) velocity traverse was made, and the velocity at time 2 as a measurement at some later time (t), then:

$$V_t = V_C\,[(\Delta P_{ti}\,T_t\,P_C\,MW_C)/(\Delta P_{Ci}\,T_C\,P_t\,MW_t)]^{1/2} \qquad (4\text{-}19)$$

The flow rate then becomes:

$$Q_t = Q_C [(\Delta P_{ti}\, T_t\, P_C\, MW_C)/(\Delta P_{Ci}\, T_C\, P_t\, MW_t)]^{1/2} \quad (4\text{-}20)$$

In most cases where combustion flue gases are measured, the molecular weight remains constant with time such that:

$$MW_t = MW_C \quad (4\text{-}21)$$

and the overall flow rate equation can be simplified to:

$$Q_t = Q_C [(\Delta P_{ti}\, T_t\, P_C)/(\Delta P_{Ci}\, T_C\, P_t)]^{1/2} \quad (4\text{-}22)$$

In this study the process was a combustion process, therefore equation 4-22 was used to relate flow rates, with the assumption that the molecular weight remained constant. For evaluations at the same facility, for turbulent flow and under similar operating conditions, the assumptions made in deriving equation 4-22 were reasonable. Using this relationship, the flow rates were determined for each run on each sampling day. In order to eliminate problems associated with the temperature differences between the boiler chamber and the sampling duct, the flow rates were converted to standard liters per minute (SLPM).

D. SF_6 Injection Rate and Inlet Concentration

The SF_6 was injected through a Dwyer rotameter, which controlled the flow of SF_6 into the boiler system. The rotameter was calibrated in the laboratory with pure SF_6. The calibration procedure was repeated several times to ensure an accurate measurement. The results indicated that sulfur hexafluoride was being injected at a rate of 0.111 liters per minute when the rotameter was indicating a 0.1 liters per minute flow rate.

The SF_6 inlet concentration, reported in ppb, was then determined by dividing the volume of the tracer gas by the total volume of the flue gas passing through the system and multiplying by 10^9. The inlet concentration of SF_6 was reported as $SF_{6(IN)}$.

E. SF_6 Outlet Concentration

The SF_6 outlet concentration, also expressed in ppb, was determined by gas chromatograph analysis of the sampling bag contents. Because of the moisture content of the flue gas, a correction factor was applied to the GC readings to determine the actual SF_6 concentration in the sampling bags. The principles used in deriving the correction factor are discussed below:

1. The moisture content of the flue gas was determined from the measured dry bulb temperature, the measured wet bulb temperature, and the psychrometric chart. From the psychrometric chart at the measured temperatures, the volume fraction of water vapor in the flue gas which entered the sampling bag was determined.

2. As the flue gas cooled to the ambient air temperature at the time of analysis, moisture condensed in the bag, thus decreasing the total volume and increasing the SF_6 concentration. Consequently, the GC values were higher than actual.

3. To adjust for the moisture in the bag which did not condense out at the ambient air temperature, the value for the water vapor fraction at ambient conditions was subtracted from the respective value at flue gas temperature. This gave the actual volume fraction of condensed water vapor in the gas bags.
4. The actual value of the SF_6 outlet concentration in the stack became:

$$SF_{6(OUT)} = C_{GC}(1\text{-}Bw) \tag{4-25}$$

where: C_{GC} = GC concentration value,

Bw = volume fraction of water vapor condensed in the sampling bag,

$SF_{6(OUT)}$ = actual SF_6 concentration in the stack.

F. Calculation of DRE and Residence Time

The destruction and removal efficiency (DRE) for each run was determined by the equation:

$$DRE = [SF_{6(IN)} - SF_{6(OUT)} / SF_{6(IN)}] \tag{4-26}$$

The residence time of SF_6 in the boiler chamber for each run was calculated using the definition offered by Hall, Kemner, and Staley, described earlier in equation 2-12.

CHAPTER 5

EXPERIMENTAL PROCEDURE

A. Introduction

This research effort was conducted at the University of Tennessee Steam Plant and was funded in part by the University of Tennessee Waste Management Research and Education Institute. The stoker coal-fired boilers at the steam plant represent an appropriate example of a thermal facility and the stack sampling ports are easily accessed, making this facility a logical experimental site. Figure 5.1 shows a simplified flow schematic of the Steam Plant boiler unit 1, the forced-air fans, and the sampling ports.

B. Calibration Curve

The first phase in this research project was to develop a calibration curve against which the subsequent gas samples could be measured. Calibration standards of 1 ppb, 10 ppb, and 100 ppb SF_6 in nitrogen were purchased from a gas supply company. The 10 ppb and 100 ppb calibration standards were diluted with appropriate quantities of 99.98 percent pure nitrogen to provide a broader range of concentrations for plotting the calibration curve. The carrier gas used was a mixture of 95 percent argon and 5 percent methane. Samples of the calibration gases were injected into the GC gas sampling valve (GSV) inlet by means of disposable 10 cc syringes; self-sealing septums prevented any gas

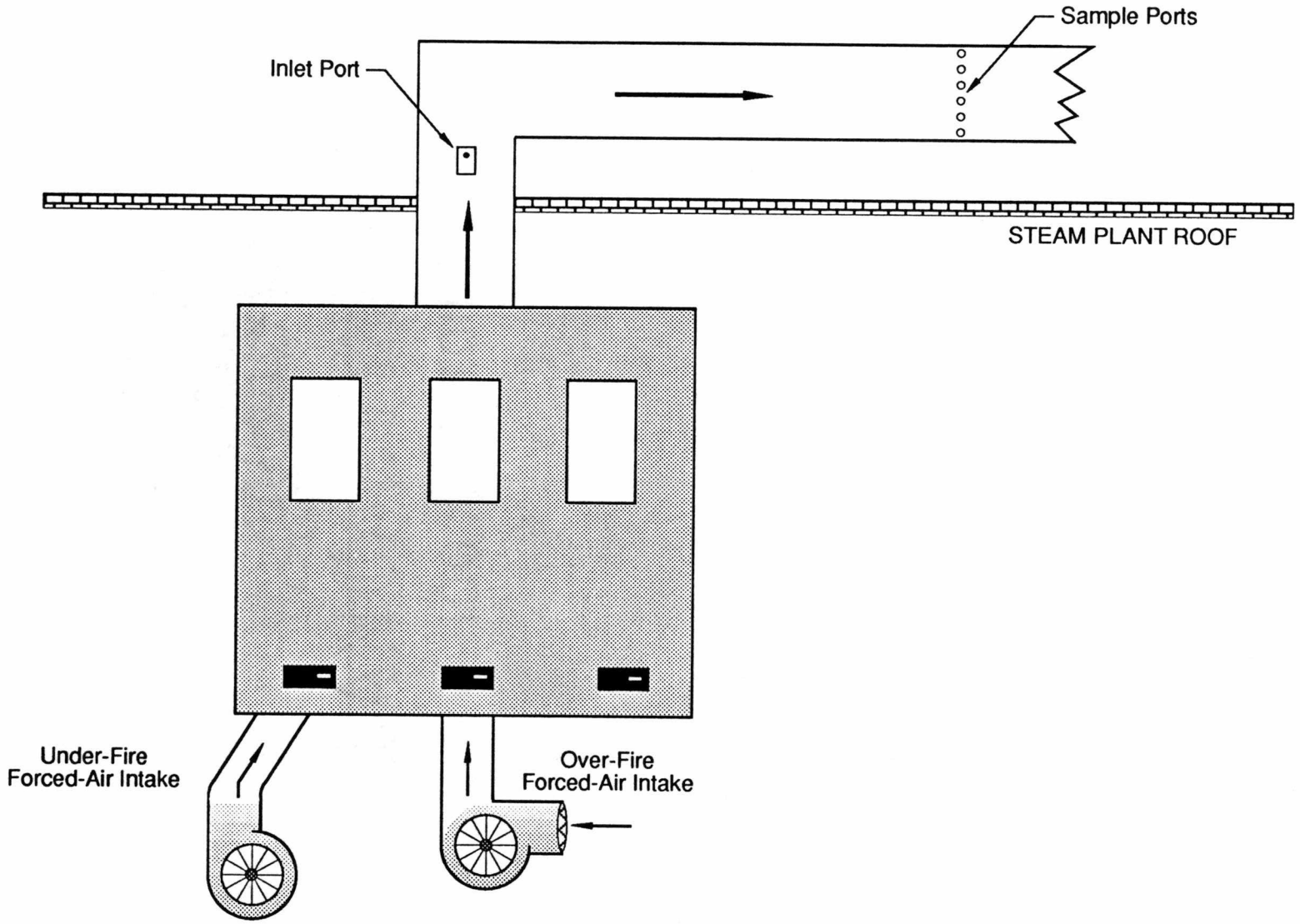


Figure 5.1. Steam Plant Boiler System and Sampling Ports Configuration.

leakage during injection. Before injection, each syringe was flushed several times to minimize any difficulties associated with the absorption of SF_6 in the syringe or plunger. Only one syringe was flushed and used for each concentration of the calibration gas in order to avoid dilution errors. Even though the GSV sample loop was limited to only a 1 ml volume, the injection of a 10 cc gas sample volume served to flush the loop and insure that the integrity of the calibration standard was maintained as it passed into the GC column for analysis. The final calibration curve was developed by measuring the SF_6 peaks on the recorder chart and plotting those heights (in inches) as a function of the known SF_6 concentrations (in ppb). This calibration curve is shown in Figure 5.2. In order to demonstrate the reproducibility and accuracy of this curve, subsequent injections and SF_6 peak measurements were made for the corresponding known concentrations during the course of the project. The results were the same within 2 percent; the errors involved were most likely associated with minor fluctuations in GC settings (e.g., head pressure, carrier gas flow, and oven temperature).

C. Velocity Traverse

The second phase of this project involved performing an EPA Method 1 velocity traverse in order to characterize the typical flow in the exhaust duct. Boiler number 1 was used exclusively for this research project because of the availability of the exhaust gas sampling ports downstream. The six sampling ports for this boiler are located on the rectangular duct (4 ft. x 5 ft.) which runs just above the roof of the steam plant. These ports are arranged vertically, one above the other (see Figure 5.1). For each of the six ports, traverse points were located at 6, 18, 30, 42, and 54 inches inside the duct wall. From the velocity

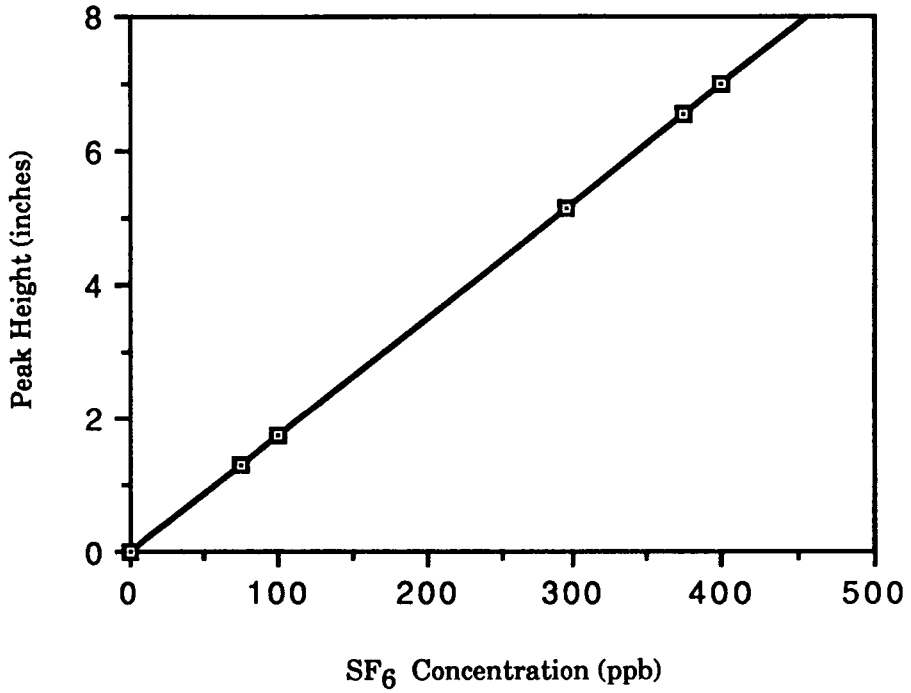


Figure 5.2. Gas Chromatograph Calibration Curve.

pressure readings obtained at each traverse point, a complete analysis of the flow profile was made. The full velocity traverse data and the procedure for calibrating the average velocity pressure in the duct are shown in Appendix B.

D. Collection of Representative Samples

The third phase of this project involved collecting gas samples over a period of weeks at the steam plant. The days on which sample runs could be made at the plant were dictated by which boiler was in operation. A total of sixty-eight successful sample runs were collected and analyzed on five different sampling days over a one month period so that the integrity, simplicity, and capacity for replication could be demonstrated for this compliance tool. This phase of the project required five steps.

The first step in the gas sample extraction procedure was to insert the sampling device into the duct and secure it to the sampling port. On days one and two the sampling device was removed at the conclusion of the gas extraction procedure, but from sampling day three through five the device remained installed in the port for convenience.

The second step was to connect the appropriate hoses and sampling devices. A 3/8-inch sampling hose was attached to the probe gas line, which led into the inlet of a Cole-Parmer Model DOA-P104-AA sampling pump. A Tedlar gas bag was connected to the sampling pump outlet. A 3/8-inch hose was also connected to each of the pitot tube low pressure and high pressure lines. The pitot tube lines led to the corresponding high and low connectors on a magnehelic gauge. A 1/4-inch sampling hose was attached to the static pressure port and connected to the low pressure connector on another magnehelic gauge. The

thermocouple line was plugged into a Kane-May digital thermometer, which measured the flue gas temperature in °F.

The third step was to measure the flame temperature in the boiler. The flame temperature in the chamber was obtained by using a portable pyrometer. The pyrometer was unavailable for use on the last two sampling days, therefore an extrapolated boiler temperature was used in the calculations for these days. Additional temperature measurements were taken at various points in the boiler with a temperature probe and digital thermometer. The different values obtained were used in the extrapolation of an average temperature in the boiler.

The fourth step in collecting the samples involved releasing a continuous flow of pure SF_6 into the boiler at nine different locations (Figure 5.3). The location used for most of the sample runs was the forced air fan, which feeds under-fire air to the boiler coal grate. The flow rate was controlled by a Dwyer rotameter. The SF_6 injection rate for all of the sample runs was maintained at 0.1 standard liters per minute. The pure SF_6 was allowed to flow through the boiler system for several minutes to assure a thorough gas mixture before sampling began.

The fifth step was to collect the actual gas samples in the Tedlar gas bags. A total of 68 samples were successfully collected for analysis during this research effort. On the first sampling day nineteen runs were completed, and the samples were taken approximately five minutes apart. On day two, eleven runs were completed at an average extraction interval of four minutes, but one gas bag leaked, leaving ten samples for analysis. Ten samples were collected on day three, and the gas extractions averaged two minutes apart. On day four, eleven runs were made; each run was approximately two minutes apart. Twenty runs were made on sampling day five, however two of the bags developed a leak,

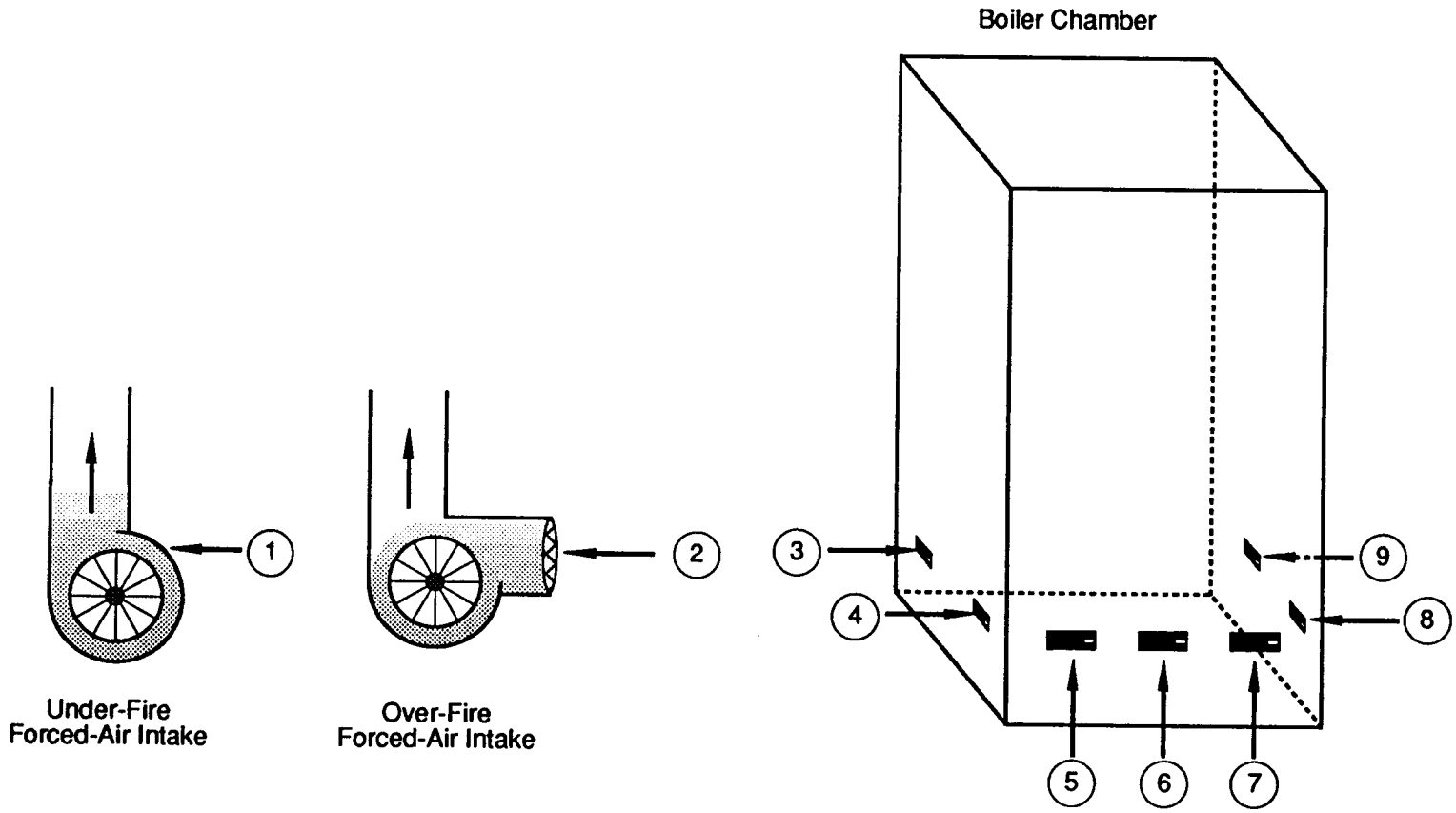


Figure 5.3. SF_6 Injection Points Around Boiler.

leaving eighteen samples for analysis. Each run interval for this day averaged five minutes.

In order to test for possible excessive absorption of SF_6 by the Tedlar sampling bags, the first gas bag from sampling day 1 was kept intact throughout the research period. Repeated gas chromatograph analyses revealed that there was no detectable SF_6 absorption by the Tedlar material. The GC peak readings indicated an essentially consistent sulfur hexafluoride concentration in the bag from one analysis to the next, indicating the integrity of the sampling bags for this type of effort.

After the runs were completed for each sampling day, the gas samples were carried to the laboratory for analysis. The analytical procedure involved extracting syringe samples from a gas bag, and after several flushes, injecting it into the gas chromatograph. The SF_6 present in the flue gas registered as a distinctive peak on the recorder chart. The actual concentration of SF_6 was determined by measuring the peak height, correcting for moisture condensation in the sampling beg, and comparing that measurement to the calibration chart developed earlier. Several minutes were allowed between syringe sample injections so that the carrier gas could flush out any residual SF_6 in the GC column. After the gas in each gas bag had been analyzed, the results were recorded and compared. The specific results of the analysis for each of the sixty-eight runs are discussed in the following chapter.

E. Test for Reliability of Analytical Procedure

The accuracy of the sampling device and the analytical procedure used in determining the final DRE values were evaluated by injecting a known quantity of SF_6 into an inlet port, located downstream of the boiler chamber, where the gas temperature was well below the temperature required to thermally destruct SF_6. Thirteen bag samples were extracted at three sampling ports (i.e., ports 2, 4, and 6) and were analyzed to determine the SF_6 concentration of the flue gas mixture. Assuming that no thermal destruction of SF_6 occurred, the concentrations of SF_6 injected would equal the SF_6 outlet concentrations, yielding a destruction efficiency of 0%.

A 90° turn in the duct (see Figure 5.1), upstream of the sampling ports, and rapid variations in flows from the fan produced random turbulence and erratic gas flows, especially near the walls of the duct (e.g., sampling port 6) where the gas velocity was already low. The measured outlet concentrations for the samples taken at port 6 were greater than the calculated inlet concentration values, resulting in a calculated efficiency of -15.3%.

The flow rates at ports 2 and 4 were much more consistent and characteristic of the overall flow in the duct. Since all of the 68 DRE samples were extracted at port 3, the mean and variability of the efficiency derived from ports 2 and 4 were applied to the DRE values obtained from port 3.

For ports 2 and 4 combined and for the 68 DRE samples taken at port 3, the mean efficiency for the zero percent efficiency test was 8.07%, with a standard error of 0.9%. The data for the zero percent efficiency test are contained in Appendix C. Figure 5.4 shows the means ± 2 standard errors for these tests at sampling ports 2, 4, and 6.

The zero efficiency tests were conducted on a day in which the boiler had just been placed on line and only at partial load. As a result, the tests were not ideal. The low velocities in the duct resulted in errors in the calculated inlet concentrations. The efficiency for port 6 was -15%, and the efficiency for ports 2 and 4 was 8%. Additional tests are recommended and should be conducted under more normal conditions.

Calculations were conducted to determine the effect of the above errors on the ability to calculate the DRE. These calculations assume no SF_6 destruction and the extremes of -15% and 8% for the prediction of DRE. The effect of these errors on other values of DRE are shown in Appendix C. At a DRE of 50%, the calculated DRE would be 41% to 53.7%, depending on which port was used for sampling. At a DRE value of 95%, the calculated DRE would be 94.1% to 95.4%. While a higher flow rate would have been desirable, allowing for a better estimate of the zero error, the effect on the DRE was less than 1% for DREs greater than 95%.

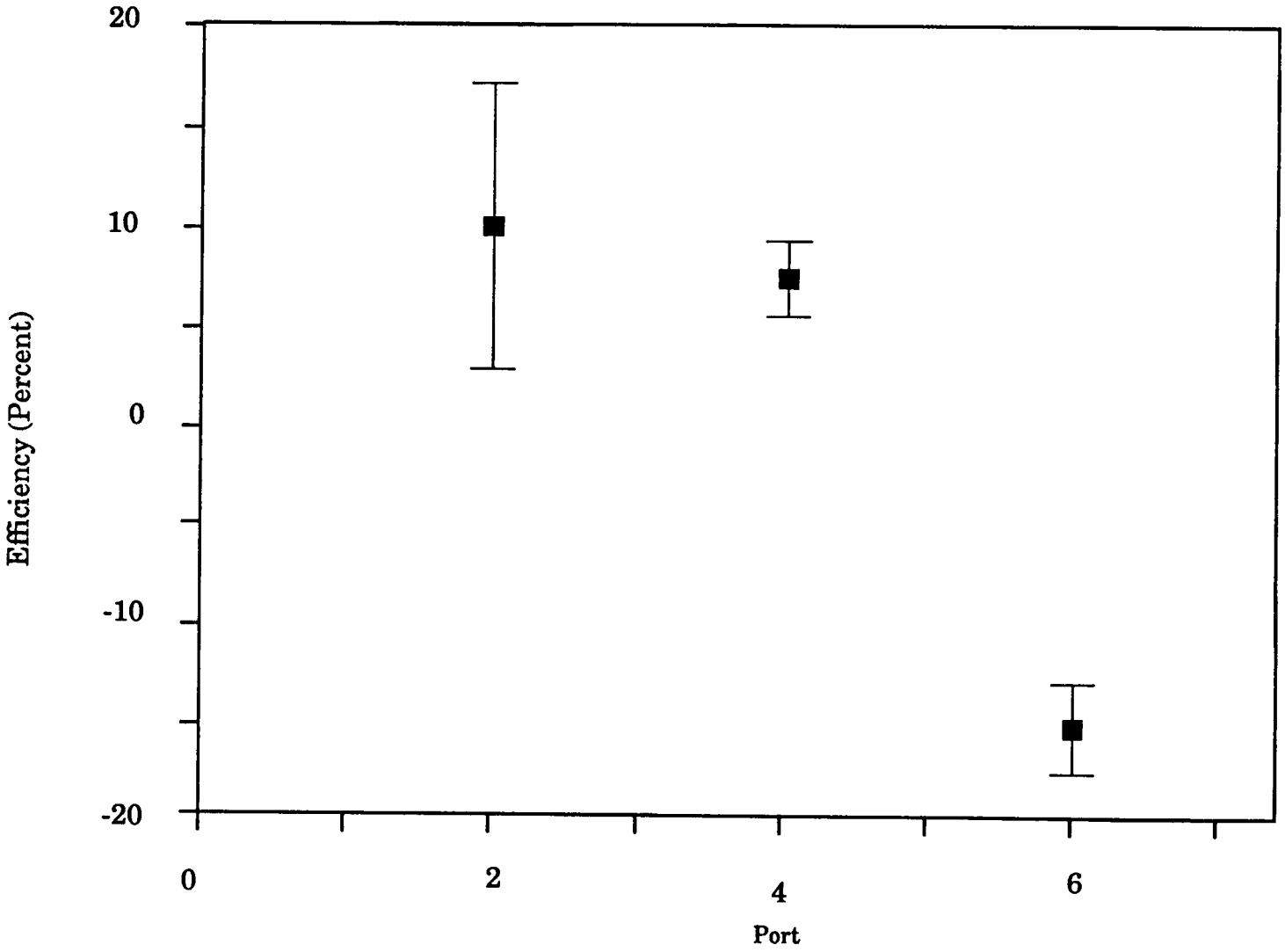


Figure 5.4. Plot of the Zero Efficiency (± 2 Standard Errors) for Ports 2, 4, and 6.

CHAPTER 6

RESULTS AND ASSESSMENTS

A. Introduction

Based on the experimental procedure discussed in the preceding chapter, DRE testing was conducted at the University of Tennessee Steam Plant. The utility and adaptability of the proposed simplified compliance tool was demonstrated by injecting a controlled quantity of SF_6 into one of nine boiler inlets, collecting multiple bag samples from each inlet, and analyzing the flue gas for SF_6 destruction and removal efficiency.

B. Demonstration of the Compliance Tool on a Combustion System

The analytical results of the DRE testing are shown on the following graphs. Figure 6.1 shows the destruction and removal efficiencies for each of the sixty-eight analyzed samples extracted during the entire testing period. The level of DRE ranged from a low of 94.5 % to a high of 97.9 %. The increased DRE for sample 20 through sample 68 was due to a decrease in the flow rate through the boiler system, which allowed a slight increase in residence time effects. Figure 6.2 indicates the range and average DRE for each sampling day. The highest average DRE (i.e., 97.1 %) occurred on sampling day 4 due to a decreased flow rate and high flame temperatures.

Figures 6.3 - 6.7 show sulfur hexafluoride DRE as a function of the residence time in the boiler system for each sampling day. The residence time for each run was calculated using the relationship described in equation 2-12. The data presented in these graphs indicate that DRE is not merely a function of

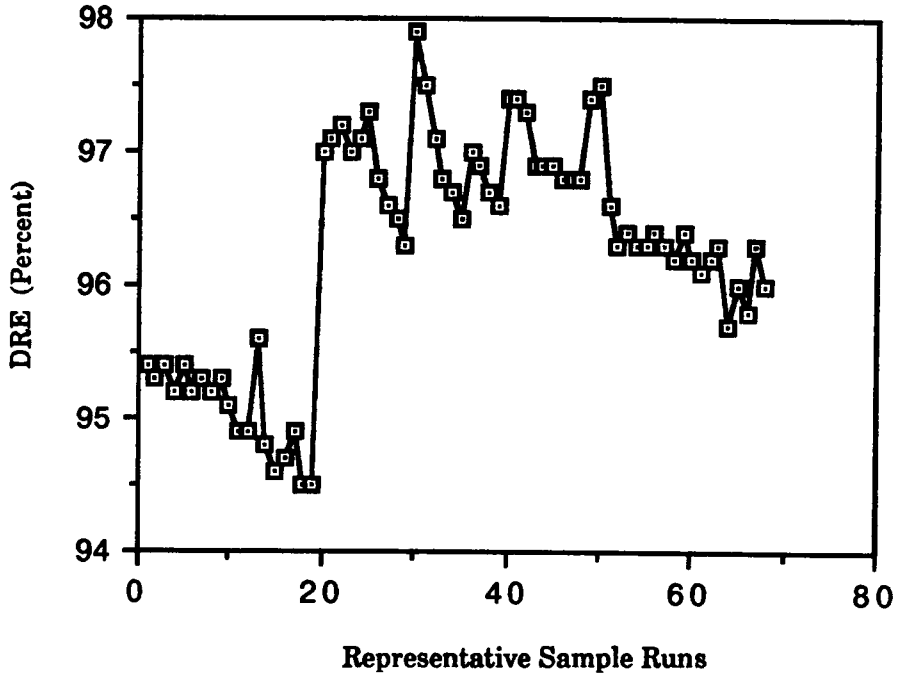


Figure 6.1. Destruction and Removal Efficiency of SF_6 in the Boiler System for Representative Sample Runs.

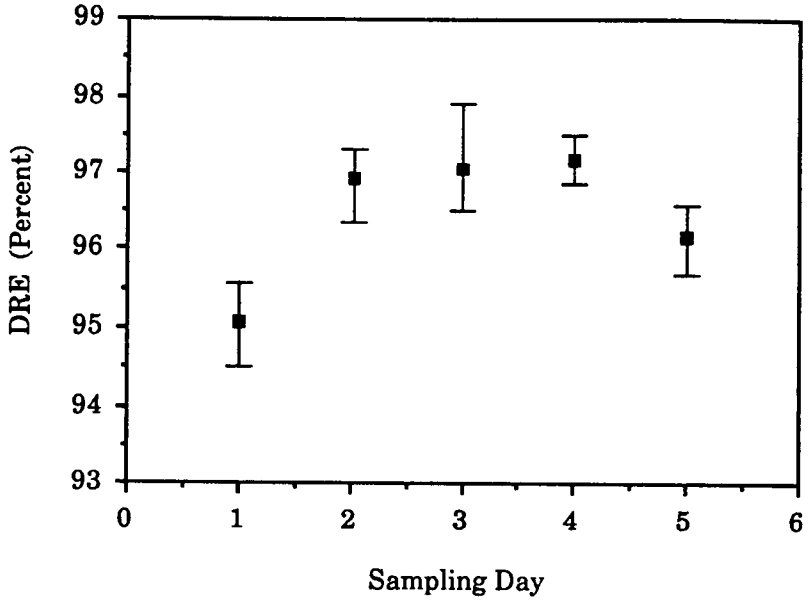


Figure 6.2. **Range and Average Destruction and Removal Efficiency of SF_6 for Each Sampling Day.**

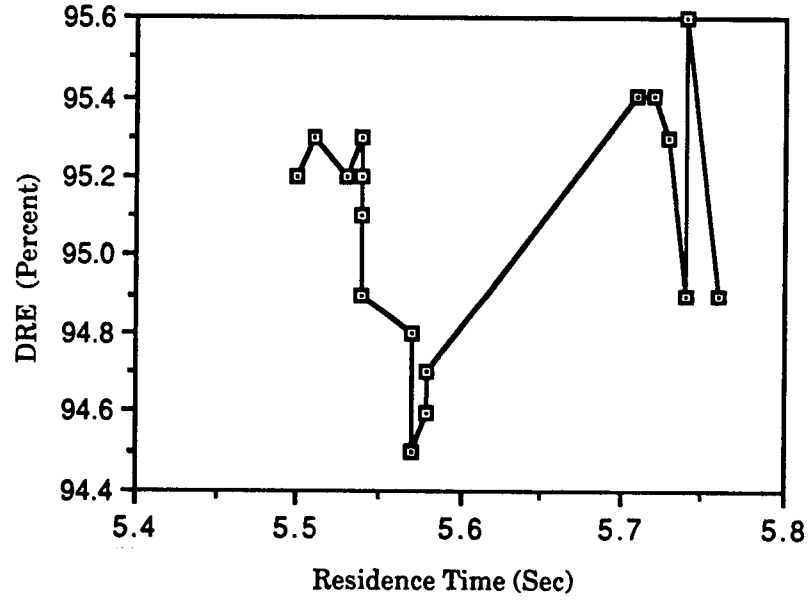


Figure 6.3. **SF_6 Destruction and Removal Efficiency as a Function of Residence Time for Sampling Day 1.**

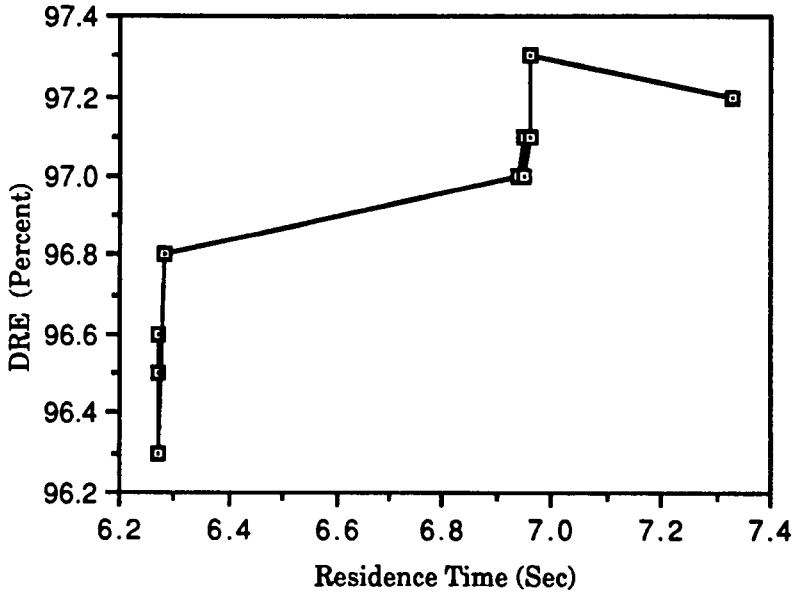


Figure 6.4. **SF_6 Destruction and Removal Efficiency as a Function of Residence Time for Sampling Day 2.**

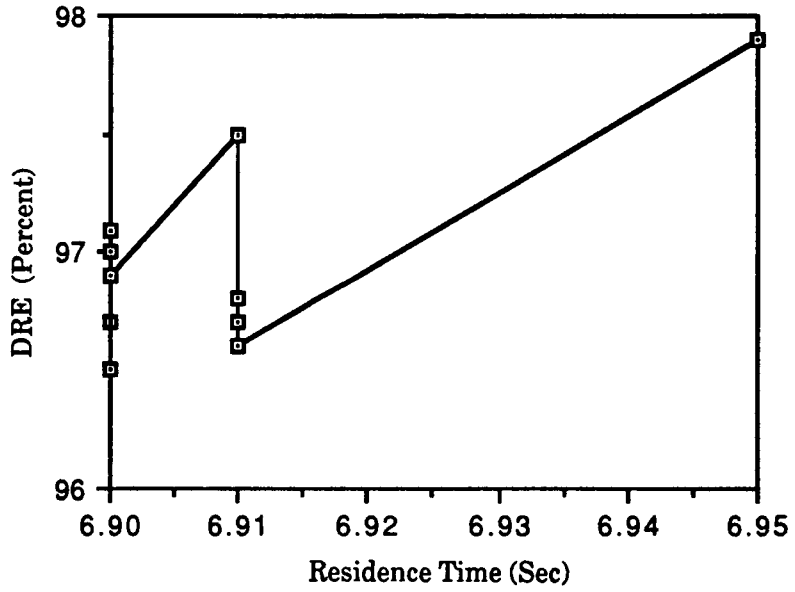


Figure 6.5. **SF_6 Destruction and Removal Efficiency as a Function of Residence Time for Sampling Day 3.**

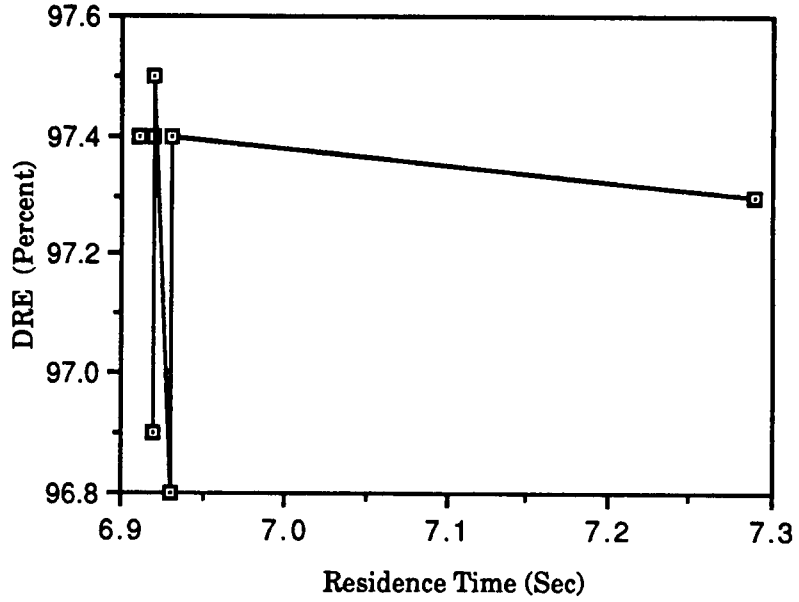


Figure 6.6. SF_6 Destruction and Removal Efficiency as a Function of Residence Time for Sampling Day 4.

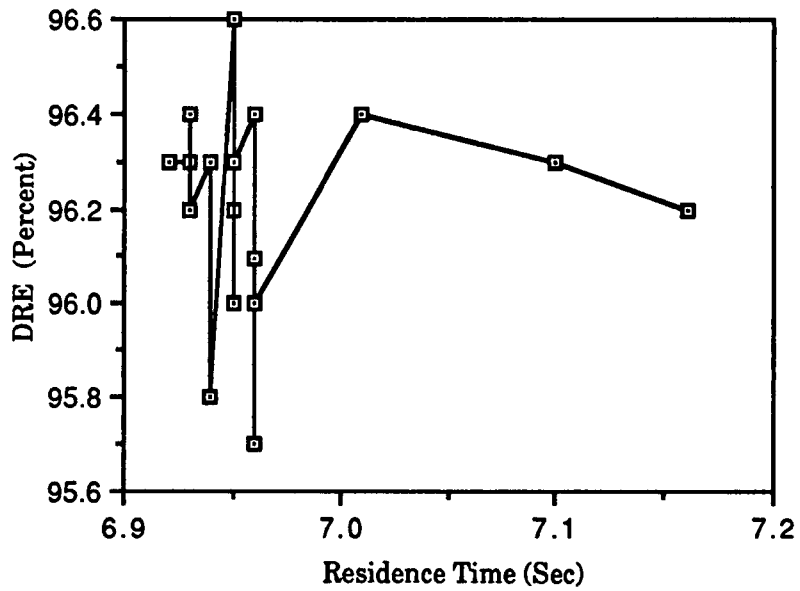


Figure 6.7. SF_6 Destruction and Removal Efficiency as a Function of Residence Time for Sampling Day 5.

residence time in the boiler system. The DREs might have been expected to increase solely as a function of residence time in the combustion chamber, but instead the DREs varied. These fluctuations in DRE, in spite of the occurrence of increased residence times in the boiler system, seem to support the concept presented by Lee and Morgan (10) that residence time within the flame is the key factor in overall DRE.

Figure 6.8 shows the relationship between the average DRE values for each of the nine SF_6 injection points located around the boiler. The highest average DRE for a single injection point occurred at inlet location 1, which was the under-fire, forced-air fan inlet (see Figure 5.3). The SF_6 injected at this point experienced the most direct route through the boiler flames, which offers additional support to the concept of increased flame-mode DRE.

C. Characteristics of the Simplified Compliance Tool

An effective compliance tool for monitoring DRE on a routine basis must meet certain criteria. The tool must be inexpensive as compared to traditional testing methods, relatively simple and timely to use, capable of producing multiple sample runs at any designated time, and readily adaptable to any incineration facility.

At the start-up of an incineration facility, EPA requires the demonstration of 99.99 percent destruction and removal efficiency, and if certain F-listed wastes are to be incinerated the requirement is 99.9999 percent DRE (34). This demonstration is normally accomplished by performing a series of tests using EPA compliance methods. However, the cost of using these methods on a routine basis to verify continued high DRE is not practical. Also, the costs for consultants with the capabilities and equipment to perform EPA sampling methods can be

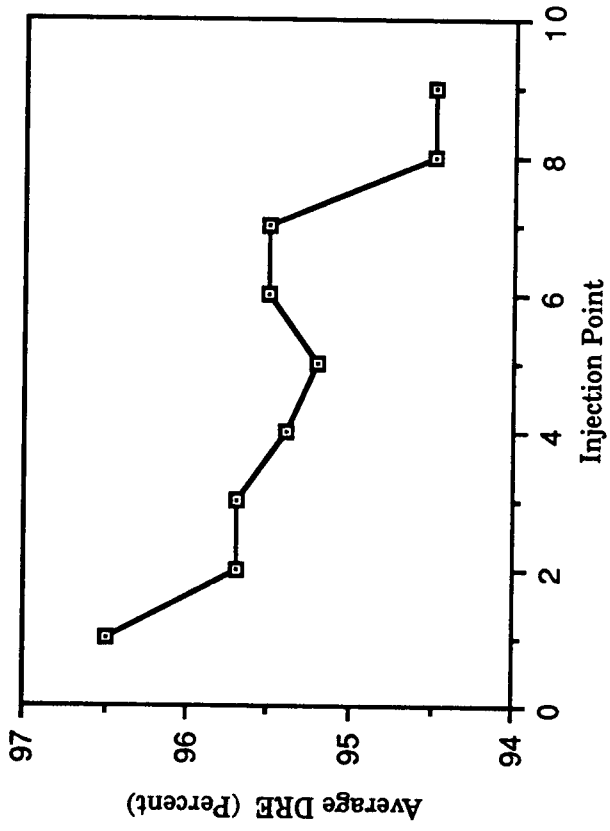


Figure 6.8. Average Destruction and Remocal Efficiency for Each SF_6 Injection Point in the Boiler System.

excessive. The option of using the proposed simplified compliance tool requires an initial investment of only a fraction of the typical consultant's fee. Once the sampling apparatus has been constructed and the various components purchased, no further major investments are required; small purchases would have to be made periodically for additional analytical supplies and calibration gases.

A routinely functional compliance tool should also be relatively simple to operate and time efficient. Traditional methods for compliance testing are typically very complex and can require several days for extensive analytical procedures prior to and after testing (35). This compliance tool minimizes the majority of the analytical complexities through the incorporation of a conservative surrogate waste in the gas stream, yet it maintains a viable approach to DRE evaluations. The preliminary laboratory procedure involves the generation of a gas chromatograph (GC) calibration curve. Once this calibration curve has been completed, sampling may be performed, followed by gas sample analyses. An entire sample run, including multiple samples, can easily be accomplished in one day.

A third important and attractive feature of this compliance tool is its capability of producing multiple sample runs at short-term intervals during the time the facility is in operation. Many of the other compliance test methods require large sampling devices and heavy, bulky gas pumps and gas monitoring equipment. Also, the time needed to perform calibration procedures and set up the equipment makes short-term, repetitive testing difficult, if not impossible. For example, the EPA Method 6, which is used to determine sulfur dioxide emissions from stationary sources, requires a stainless steel or borosilicate glass probe, bubblers and impingers, an ice bath, a sampling pump, a surge tank, and a dry

gas meter as its basic components (36). While the Method 6 sampling train is essential for proper environmental assessment, it can hardly be considered as an option for simplified compliance testing. Conversely, the sampling method prescribed for the simplified compliance tool requires only a short time to set up the surrogate sampling gas, install the probe apparatus, and begin gas extractions. In some cases, the sampling device could be left in the stack port indefinitely; set-up time would be reduced even further. With this type of rapid sampling capability, DRE monitoring can take place at virtually any short-term interval dictated by the facility's operational needs.

Finally, a simplified compliance tool must be readily adaptable to any incineration system, and the compliance tool developed in this research effort also meets this requirement. First of all, the sampling apparatus for this compliance tool is constructed so that it can fit easily into a standard EPA four-inch stack port. All stacks which exhaust contaminated gas streams contain these sampling ports through which EPA criteria pollutant testing is performed. The fact that these ports are common to most large stacks allows this tool to be widely adaptable. Also, this compliance tool can be adapted to serve a single stack or multiple stacks. Large industrial and government facilities will often have several incinerator or boiler units in operation, which are exhausted through several stacks. In this case, the sampling apparatus can be designed to serve all of the stacks at different times, or one sampling device can be constructed for each exhaust system and remain unique to a given stack. If a very small stack (e.g. six-inch diameter) is used in a particular offgas system, a miniature version of the sampling apparatus can be constructed and used just as the larger type for routine DRE evaluations.

The economy, relative operating simplicity, expediency, and adaptability of this compliance tool make it a viable option for routine DRE monitoring in

combustion systems. This tool can be stack-specific or applied to multiple exhaust systems, and it can serve as a valuable indicator of minor mechanical perturbations which must be corrected before the major ones develop.

CHAPTER 7

CONCLUSIONS

The central aim of this research effort was to demonstrate the simplicity and adaptability of the proposed compliance tool. This tool incorporates the devices needed for routine, simplified compliance monitoring, and each of the sampling devices (i.e., probe, pitot tube, thermocouple, static pressure port, and return gas port) are physically arranged for convenient use in a single stack port. The effectiveness of this tool is based upon the capacity of sulfur hexafluoride to serve as a viable chemical surrogate and tracer gas for monitoring DRE in incineration systems. Recent investigations have shown that SF_6 is valuable as a surrogate and tracer because of its thermal stability, high sensitivity to electron-capture detection, nontoxicity below 1000 ppm, nonradioactivity, and basic chemical inertness. By injecting small quantities of pure SF_6 into the inlet of an incineration system, extracting flue gas at the outlet using this proposed compliance tool, and analyzing the extracted gas samples for remaining SF_6, owners and operators of combustion facilities can be alerted to significant changes in overall DRE.

One of the chief advantages of this compliance tool is its adaptability to specific facilities. Besides scaling the physical size of the device to meet site needs, a thorough correlation of SF_6 versus site-specific POHCs is recommended. This correlation could easily be done during an initial EPA-required trial test burn. Different incineration facilities contain different types and levels of POHCs in the waste stream. By developing thermal relationships between SF_6 and any

hazardous constituents of concern, a safety factor can be established when using SF_6 as a surrogate for monitoring that particular facility.

This compliance tool can be used effectively as an option for quasi-real-time performance monitoring if analyses of the gas samples are done at the gas extraction site. The only major requirement for this type of analysis is the availability of a portable or semi-portable gas chromatograph. Additional refinements of this compliance tool would include improved techniques for real-time gas chromatograph analyses of the extracted gas samples and further correlation of SF_6 versus specific POHC thermal stability.

LIST OF REFERENCES

1. Corey, Richard C., "Incineration," Air Pollution, Edited by Arthur C. Stern, Vol. 4, Academic Press, New York, 1977.

2. Oppelt, E. Timothy, "Incineration of Hazardous Waste," Journal of the Air Pollution Control Association, Vol.37, No. 5, 558, May 1987.

3. Phifer, Russel W., and William R. McTigue, Handbook of Hazardous Waste Management for Small Quantity Generators, Lewis Publishers, Chelsea, Michigan, 1988.

4. Brunner, Calvin R., Hazardous Air Emissions from Incineration, Chapman and Hall Publishers, New York, 1985.

5. Velde, George V., and Edward F. Glod, "Ocean-Based Incineration of Chemical Waste: Background, Technology and Performance of the Vulcanus Systems," Marine Technology Society Journal, Vol. 20, No. 1, 29, March, 1986.

6. Kamlet, Kenneth S., "The Case for Ocean Incineration of Hazardous Wastes," Marine Technology Society Journal, Vol. 20, No. 1, 42, March 1986.

7. Zeeuw, Martin A., and Saul M. Lemkowitz, Environmentally Acceptable Incineration of Chlorinated Chemical Waste, Delft University Press, Delft, the Netherlands, 1987.

8. Berger, Mark L., "Sulfur Hexafluoride as a Surrogate Waste for Verification of Destruction Removal Efficiency," Masters Thesis, University of Florida, Gainesville, 1985.

9. Hall, F.D., W.F. Kemner, and L. Staley, "Evaluation of Feasibility of Incinerating Hazardous Wastes in High Temperature Industrial Processes," Proceedings of the Eighth Annual Research Symposium on Incineration of Hazardous Waste, EPA-600/9-83-003.

10. Lee, K.C., N. Morgan, J.L. Hansen, and G.M. Whipple, "Revised Model for the Prediction of the Time-Temperature Requirements for Thermal Destruction of Dilute Organic Vapors and Its Usage for Predicting Compound Destructibility," Presented at the 75th Annual Meeting of the Air Pollution Control Association, New Orleans, Louisiana, June 1982.

11. Kramlich, J.C., M.P. Heap, and W.R. Seeker, "Flame-Mode Destruction of Hazardous Waste Components," Presented at the Twentieth International Symposium on Combustion, Michigan, Ann Arbor, Michigan.

12. England, Walter G., Lynn H. Teuscher, and Steven L. Quon, "The Correlation of SF_6 Destruction with Principle Organic Hydrocarbon Destruction in Incineration Processes," Presented at the 80th Annual Meeting of the Air Pollution Control Association, New York, New York, June 1987.

13. Flagan, Robert C., and John H. Seinfeld, Fundamentals of Air Pollution Engineering, Prentice Hall, Englewood Cliffs, New Jersey, 1988.

14. Dellinger, Barry, and Douglas L. Hall, "Surrogate Compounds for Monitoring the Effectiveness of Incineration Systems," Journal of the Air Pollution Control Association, Vol. 36, No. 2, 1986.

15. Deuble, J.L., "Atmospheric Tracer Gas Technology, Techniques and Applications," Technical Bulletin 79-5, Systems, Science and Software, La Jolla, California, 1979.

16. Partington, J.R., A History of Chemistry, Vol. 4, Macmillian and Company Ltd, St. Martin's Press, New York, 1964.

17. Khoury, G.A., S.N. Chang, D.A. Lessley, A.A. Abdelghani, and A.C. Anderson, "An Investigation of Reentrainment of Chemical Fume Hood Exhaust Air in a Heat Recovery Unit," Journal of the American Industrial Hygiene Association, Vol. 49, No.2, 1988.

18. Hanna, Steven R., and Robert J. Paine, "Convective Scaling Applied to Diffusion of Buoyant Plumes from Tall Stacks," Atmospheric Environment, Vol.21, No. 10, 1987.

19. Hanna, Steven R., Jeffery C. Weil, and Robert J. Paine, "Testing of a New Plume Dispersion Model with the Kincaid and Bull Run Data," Proceedings of the 80th Annual Meeting of the Air Pollution Control Association, Vol.5, 87/73.4, 1987.

20. Stokes, A.W., D.J. Kennedy, and S.G. Hardcastle, "A Real-Time Tracer Gas Analyzer -- An Investigational Tool for Mine Ventilation Studies," Mining Science and Technology, Vol. 5. No. 2, 1987.

21. Chiasson, L.A., and A.W. Stokes, "Determination of the Methane Make on 9 East Longwall Face Using Sulfur Hexafluoride Derived Air Flows," Energy Research Abstracts, Vol. 12, No. 15, Abstract No. 30000, 1987.

22. Noy, T., P. Fabian, R. Borchers, F. Janssen, C. Cramers, and J. Rijks, "Trace Analysis of Halogenated Hydrocarbons in Gaseous Samples by On-Line Enrichment in an Adsorption Trap, On-Column Cold-Trapping and Capillary Gas Chromatography, Journal of Chromatography, Vol. 393, No. 3, 1987.

23. Koenig, D., H. Lautenschlaeger, "The Influence of Gaseous Admixtures to Sulfur Hexafluoride on the Corona Stabilized Regime at AC and at Positive Impulse Voltage," Proceedings of the International Symposium on Gaseous Dielectrics, 1987.

24. Ijumba, N.M., I.D. Chalmers, and O. Farish, "Nonuniform Field Corona and Breakdown Characteristics of Sulfur Hexafluoride/Freon Mixtures," Proceedings of the International Symposium on Gaseous Dielectrics, 1987.

25. Ko, S.T., K.H. Schoenbach, V.K. Lakdawala, and H. Chen, "Analysis of the Cathode Fall of Glow Discharges in a Helium/Sulfur Hexafluoride Gas Mixture," Proceedings of the International Symposium on Gaseous Dielectrics, 1987.

26. Sudhakar, C.E., and K.D. Srivastava, "Influence of 60 Hz A.C. Charging of Spacers on Subsequent Impulse Flashover in Compressed Sulfur Hexafluoride," Proceedings of the International Symposium on Gaseous Dielectrics, 1987.

27. Rajan, J. Sundara, K.S. Arunachala Sastry, and C.S. Lakshminarasimha, "Surface Flashover of Polyester, Polypropylene, and Teflon Films in Low Pressure Sulfur Hexafluoride and Nitrogen Media," Proceedings of the International Symposium on Gaseous Dielectrics, 1987.

28. Herron, John T., "Thermochemical Data on Gas Phase Compounds of Sulfur, Fluorine, Oxygen, and Hydrogen Related to Pyrolysis and Oxidation of Sulfur Hexafluoride,"Journal of Physical and Chemical Reference Data, Vol. 16, No. 1, 1987.

29. Groenskei, K.E., "The Influence of Car Speed on Dispersion of Exhaust Gases," Atmospheric Environment, Vol. 22, No. 2, 1988.

30. Hess, C.T., M.A. Vietti, and D.T. Mage, "Radon from Drinking Water -- Evaluation of Water-Borne Transfer into House Air," Environmental Geochemistry and Health, Vol. 9, 1987.

31. American Conference of Governmental Industrial Hygienists, Documentation of the Threshold Limit Values, Fourth Edition, Cincinnati, Ohio, 1982.

32. Taylor, Philip H., and John F. Chadbourne, "Sulfur Hexafluoride as a Surrogate for Monitoring Hazardous Waste Incinerator Performance," Journal of the Air Pollution Control Association, Vol. 37, No. 6, 1987.

33. England, Walter G., Thomas J. Rappolt, Lynn H. Teuscher, Steven L. Kerrin, and Robert E. Mournighan, "Measurement of Hazardous Waste Incineration Destruction and Removal Efficiencies Using Sulfur Hexafluoride as a Chemical Surrogate," Presented at the 79th Annual Meeting of the Air Pollution Control Association, Minneapolis, Minnesota, June, 1986.

34. 40 CFR 264, Code of Federal Regulations, Title 40, Part 264.343, "Incinerator Performance Standards," Office of Federal Register, Washington, D.C.

35. James, R.M., H.K. Dillon, and M.C. Miller, "Survey Methods for the Determination of Principle Organic Hazardous Constituents (POHCs) I. Methods for Laboratory Analysis," Presented at the Eighth Annual Research Symposium, Land Disposal, Incineration and Treatment of Hazardous Wastes, Fort Mitchell, Kentucky, March, 1982.

36. 40 CFR 60, Code of Federal Regulations, Title 40, Part 60, Appendix A, "Reference Methods," Office of Federal Register, Washington, D.C.

APPENDICES

APPENDIX A

SAMPLE CALCULATIONS

The constants used in the DRE calculations are as follows:

ΔP_C = 0.11
T_C = 472°F = 932°R
P_C = 30.08 inches Hg
Kp = 85.486 feet/second
Cp = 0.84
MW_C = 29.577 lb/lb mole
A = 20 ft^2

The derivation of the value for Q_C is shown below:

$$Q_C = A\,[Kp\ Cp\ (\Delta P_C\ T_C / P_C\ MW_C)^{1/2}$$

$$Q_C = (20\ ft^2)[[85.486][0.84][(0.11)(932)/(30.08)(29.577)]^{1/2}]$$

$$Q_C = 487.5\ ft^3/sec$$

$$Q_C = 29{,}251\ ft^3/min\ \ (ACFM)$$

The calculations used in determining the DRE of the SF_6 and the SF_6 residence time in the boiler are shown below. The input values for these sample calculations are taken from Sampling Day 5, Run 1.

$Q_t = Q_C (\Delta P_t\ T_t\ P_C / \Delta P_{Ci}\ T_C\ P_t)^{1/2}$

$Q_t = (29{,}251\ ACFM)[(0.05)(915)(30.08)/(0.14)(932)(29.88)]^{1/2}$

$Q_t = 17{,}379\ ACFM = 492{,}160\ ALPM$

Converting to standard conditions:

$Q_t = 17{,}379\ (460 + 32 / 460 + 455)(29.88 / 29.92)$

$Q_t = 9{,}332\ SCFM = 264{,}290\ SLPM = 4{,}405\ SLPS$

The SF_6 injection concentration (ppb) was derived as follows:

$Q_{ROTAMETER}\ (SF_6) = 0.111$ liters/min (calibrated)

Converting to standard conditions:

$Q_{SF6} = 0.111$ l/min $(460 + 32 / 460 + 85)(29.88 / 29.92)$

$Q_{SF6} = 0.1$ SLPM

$SF_{6(IN)}$ (in ppb) = (Volume of Tracer Gas / Total Volume of Gas Mixture)(10^9)

$SF_{6(IN)} = [0.1 / (0.1 + 264{,}290)]\ (10^9)$

$SF_{6(IN)} = 378.4$ ppb

The moisture correction factor was determined as follows:

Dry bulb temperature = 455°F
Wet bulb temperature = 131°F

From the psychrometric chart, at these temperatures, the pounds of water per pound of dry air is 0.04. Converting to volume fraction:

Volume = (0.04/18) / [(0.04/18) + (1/28.96)]

Volume = 0.06 = 6.0 %

The concentration of SF_6 injected, on a dry basis, is:

$SF_{6(IN)}$ = 378.4 / (1-0.06)

$SF_{6(IN)}$ = 402.6 ppb

The volume fraction of water at 80°F (i.e., the ambient air temperature at the time of GC analysis) is 0.032 (3.2 %). Therefore, the actual percent of condensed water vapor in the gas bags is:

9.2 % - 3.2 % = 6.0 %

The SF_6 outlet concentration is:

C_{GC} (1 - 0.06) = C_{ACTUAL}

14.7 ppb (0.94) = 13.8 ppb

The DRE in the boiler system is determined as follows:

$$DRE = [SF_{6(IN)} - SF_{6(OUT)} / SF_{6(IN)}] (100)$$

$$DRE = [(402.6) - (13.8) / (402.6)] (100)$$

$$DRE = 96.6\ \%$$

The SF6 residence time in the boiler system was calculated using the following relationship:

$$t_r = [294.4\ V / Q\ (Te - Tm)]\ \ln(Te/Tm)$$

where:
- V = boiler volume = 190,310.4 liters
- Q = flow rate at exit = 8,203 liters/sec
- Te = exit temperature = 508.2°K
- Tm = maximum temperature in control volume = 1,700°K

$$t_r = [294.4\ (190,310.4) / (8,203)(508.2 - 1,700)]\ \ln(508.2/1,700)$$

$$t_r = 6.92\ sec$$

APPENDIX B

VELOCITY TRAVERSE DATA

	Distance Into Stack (inches)	ΔP (in. H_2O)
Port 1:	6	0.050
	18	0.110
	30	0.090
	42	0.110
	54	- 0.100
Port 2:	6	0.095
	18	0.120
	30	0.140
	42	0.095
	54	0.090
Port 3:	6	0.120
	18	0.125
	30	0.120
	42	0.135
	54	0.130
Port 4:	6	0.170
	18	0.130
	30	0.140
	42	0.135
	54	0.140
Port 5:	6	0.120
	18	0.140
	30	0.125
	42	0.135
	54	0.145

	Distance Into Stack (inches)	ΔP (in. H_2O)
Port 6:	6	0.165
	18	0.170
	30	0.170
	42	0.150
	54	0.130

The calibration velocity pressure (ΔP_C) is found using the following equation:

Average ΔP = [Sum of the $(\Delta P)^{1/2}$ at each point/Total number of points]^2

Using this equation, the calibration velocity pressure is:

Average $\Delta P = (9.971/30)^2 = 0.11$.

APPENDIX C

SAMPLING DATA

DATA SET FOR SAMPLING DAY 1: FLOW RATE CALCULATIONS

RUN	ΔP_t(in.H_2O)	P_s(in. H_2O)	T_t(°R)	Q_t(ACFM)	Q_t(SLPS)
1	0.075	0.50	911	21,220	5,411
2	0.080	0.50	911	21,916	5,588
3	0.075	0.50	911	21,220	5,411
4	0.080	0.50	911	21,916	5,588
5	0.075	0.50	912	21,232	5,408
6	0.080	0.50	912	21,928	5,585
7	0.075	0.50	912	21,232	5,408
8	0.081	0.51	911	22,052	5,617
9	0.075	0.50	910	21,208	5,414
10	0.080	0.50	910	21,904	5,592
11	0.080	0.50	910	21,904	5,592
12	0.075	0.50	907	21,173	5,423
13	0.075	0.50	908	21,185	5,420
14	0.080	0.50	905	21,844	5,607
15	0.080	0.50	904	21,831	5,610
16	0.080	0.50	904	21,831	5,610
17	0.075	0.50	904	21,138	5,432
18	0.080	0.50	905	21,844	5,607
19	0.080	0.50	906	21,856	5,604

Constants:

O_2 Content = 8.5 %

T_w = 132°F

Tm = 2,563°F = 1,679°K

P_b = 29.97 inches Hg

P_t = 29.93 inches Hg

Boiler Volume, V = 190,310.4 liters

DATA SET FOR SAMPLING DAY 1: DRE AND RESIDENCE TIME

RUN	$SF_{6(IN)}$ (ppb)	$SF_{6(OUT)}$ (ppb)	Q_t(l/sec)	Te(°K)	DRE (%)	t_r(sec)
1	327.7	14.9	10,016	506.0	95.4	5.72
2	317.3	15.0	10,344	506.0	95.3	5.54
3	327.7	15.2	10,016	506.0	95.4	5.72
4	317.3	15.2	10,344	506.0	95.2	5.54
5	327.9	15.0	10,022	506.5	95.4	5.71
6	317.5	15.3	10,350	506.5	95.2	5.53
7	327.9	15.5	10,022	506.5	95.3	5.51
8	315.7	15.0	10,409	506.0	95.2	5.50
9	327.5	15.4	10,010	505.4	95.3	5.73
10	317.1	15.5	10,339	505.4	95.1	5.54
11	317.1	16.2	10,339	505.4	94.9	5.54
12	326.9	16.7	9,994	503.8	94.9	5.74
13	327.1	14.3	9,999	504.3	95.6	5.74
14	316.2	16.4	10,310	502.6	94.8	5.57
15	316.1	17.1	10,304	502.1	94.6	5.58
16	316.1	16.8	10,304	502.1	94.7	5.58
17	326.4	16.6	9,977	502.1	94.9	5.76
18	316.2	17.4	10,310	502.6	94.5	5.57
19	316.4	17.3	10,316	503.2	94.5	5.57

DATA SET FOR SAMPLING DAY 2: FLOW RATE CALCULATIONS

RUN	ΔP_t(in. H_2O)	P_s(in. H_2O)	T_t(°R)	Q_t(ACFM)	Q_t(SLPS)
1	0.050	0.75	917	17,374	4,406
2	0.050	0.75	916	17,365	4,408
3	0.045	0.75	916	16,474	4,182
4	0.050	0.75	916	17,365	4,408
5	0.050	0.75	915	17,355	4,411
6	0.050	0.75	915	17,355	4,411
7	0.060	0.75	926	19,126	4,803
8	0.060	0.75	928	19,146	4,798
9	0.060	0.75	928	19,146	4,798
10	0.060	0.75	928	19,146	4,798

Constants:

O_2 Content = 8.5 %

T_w = 132°F

Tm = 2,580°F = 1,689°K

P_b = 30.02 inches Hg

P_t = 29.96 inches Hg

Boiler Volume, V = 190,310.4 liters

DATA SET FOR SAMPLING DAY 2: DRE AND RESIDENCE TIME

RUN	$SF_{6(IN)}$ (ppb)	$SF_{6(OUT)}$ (ppb)	Q_t(l/sec)	Te(°K)	DRE (%)	t_r(sec)
1	402.4	11.9	8,201	509.3	97.0	6.94
2	402.2	11.8	8,196	508.8	97.1	6.95
3	424.0	11.7	7,776	508.8	97.2	7.33
4	402.2	11.9	8,196	508.8	97.0	6.95
5	402.0	11.8	8,192	508.2	97.1	6.96
6	402.0	11.0	8,192	508.2	97.3	6.96
7	369.2	11.8	9,027	514.3	96.8	6.28
8	369.5	12.7	9,037	515.4	96.6	6.27
9	369.5	12.9	9,037	515.4	96.5	6.27
10	369.5	13.8	9,037	515.4	96.3	6.27

DATA SET FOR SAMPLING DAY 3: FLOW RATE CALCULATIONS

RUN	ΔP_t(in.H_2O)	P_s(in. H_2O)	T_t(°R)	Q_t(ACFM)	Q_t(SLPS)
1	0.050	0.75	910	17,319	4,420
2	0.050	0.75	916	17,376	4,405
3	0.050	0.75	917	17,386	4,403
4	0.050	0.75	916	17,376	4,405
5	0.050	0.75	917	17,386	4,403
6	0.050	0.75	917	17,386	4,403
7	0.050	0.75	917	17,386	4,403
8	0.050	0.75	917	17,386	4,403
9	0.050	0.75	916	17,376	4,405
10	0.050	0.75	916	17,376	4,405

Constants:

O_2 Content = 8.5 %

T_w = 133°F

Tm = 2,605°F = 1,703°K

P_b = 29.98 inches Hg

P_t = 29.92 inches Hg

Boiler Volume, V = 190,310.4 liters

DATA SET FOR SAMPLING DAY 3: DRE AND RESIDENCE TIME

RUN	$SF_{6(IN)}$ (ppb)	$SF_{6(OUT)}$ (ppb)	Q_t(l/sec)	Te(°K)	DRE (%)	t_r(sec)
1	401.1	8.6	8,175	505.4	97.9	6.95
2	402.5	9.9	8,202	508.8	97.5	6.91
3	402.7	11.7	8,206	509.3	97.1	6.90
4	402.5	12.9	8,202	508.8	96.8	6.91
5	402.7	13.2	8,206	509.3	96.7	6.90
6	402.7	14.0	8,206	509.3	96.5	6.90
7	402.7	12.1	8,206	509.3	97.0	6.90
8	402.7	12.4	8,206	509.3	96.9	6.90
9	402.5	13.2	8,202	508.8	96.7	6.91
10	402.5	13.8	8,202	508.8	96.6	6.91

DATA SET FOR SAMPLING DAY 4: FLOW RATE CALCULATIONS

RUN	ΔP_t(in.H_2O)	P_s(in. H_2O)	T_t(°R)	Q_t(ACFM)	Q_t(SLPS)
1	0.050	0.75	915	17,379	4,405
2	0.050	0.75	916	17,388	4,402
3	0.045	0.75	916	16,496	4,176
4	0.050	0.75	915	17,379	4,405
5	0.050	0.75	915	17,379	4,405
6	0.050	0.75	915	17,379	4,405
7	0.050	0.75	914	17,369	4,407
8	0.050	0.75	914	17,369	4,407
9	0.050	0.75	913	17,360	4,410
10	0.050	0.75	914	17,369	4,407
11	0.050	0.75	915	17,379	4,405

Constants:

O_2 Content = 8.0 %

T_w = 137°F

Tm = 2,600°F = 1,700°K

P_b = 29.94 inches Hg

P_t = 29.88 inches Hg

Boiler Volume, V = 190,310.4 liters

DATA SET FOR SAMPLING DAY 4: DRE AND RESIDENCE TIME

RUN	$SF_{6(IN)}$ (ppb)	$SF_{6(OUT)}$ (ppb)	Q_t(l/sec)	Te(°K)	DRE (%)	t_r(sec)
1	402.5	10.4	8,203	508.2	97.4	6.92
2	402.8	10.6	8,207	508.8	97.4	6.91
3	424.6	11.6	7,786	508.8	97.3	7.29
4	402.5	12.5	8,203	508.2	96.9	6.92
5	402.5	12.6	8,203	508.2	96.9	6.92
6	402.5	12.5	8,203	508.2	96.9	6.92
7	402.3	12.8	8,198	507.6	96.8	6.93
8	402.3	12.9	8,198	507.6	96.8	6.93
9	402.1	13.0	8,194	507.1	96.8	6.93
10	402.3	10.6	8,198	507.6	97.4	6.93
11	402.5	10.0	8,203	508.2	97.5	6.92

DATA SET FOR SAMPLING DAY 5: FLOW RATE CALCULATIONS

RUN	ΔP_t(in.H_2O)	P_s(in. H_2O)	T_t(°R)	Q_t(ACFM)	Q_t(SLPS)
1	0.050	0.75	915	17,379	4,405
2	0.050	0.75	914	17,369	4,407
3	0.050	0.75	913	17,360	4,410
4	0.050	0.75	912	17,350	4,412
5	0.050	0.70	915	17,379	4,405
6	0.049	0.75	912	17,176	4,368
7	0.050	0.75	912	17,350	4,412
8	0.050	0.70	913	17,360	4,410
9	0.050	0.70	910	17,331	4,417
10	0.047	0.75	912	16,821	4,278
11	0.050	0.75	910	17,331	4,417
12	0.050	0.75	911	17,340	4,414
13	0.048	0.75	910	16,981	4,328
14	0.050	0.75	910	17,331	4,417
15	0.050	0.75	911	17,340	4,414
16	0.050	0.75	912	17,350	4,412
17	0.050	0.75	911	17,340	4,414
18	0.050	0.75	910	17,331	4,417

Constants:

O_2 Content = 8.0 %

T_w = 131°F

Tm = 2,600°F = 1,700°K

P_b = 29.94 inches Hg

P_t = 29.88 inches Hg

Boiler Volume, V = 190.310.4 liters

DATA SET FOR SAMPLING DAY 5: DRE AND RESIDENCE TIME

RUN	$SF_{6(IN)}$ (ppb)	$SF_{6(OUT)}$ (ppb)	Q_t(l/sec)	Te(°K)	DRE (%)	t_r(sec)
1	401.7	13.8	8,185	506.0	96.6	6.95
2	402.3	14.9	8,198	507.6	96.3	6.93
3	402.1	14.6	8,194	507.1	96.4	6.93
4	401.9	14.8	8,189	506.5	96.3	6.94
5	402.5	14.9	8,203	508.2	96.3	6.92
6	405.9	14.6	8,107	506.5	96.4	7.01
7	401.9	14.9	8,189	506.5	96.3	6.94
8	402.1	15.3	8,194	507.1	96.2	6.93
9	401.4	14.4	8,180	505.4	96.4	6.96
10	414.5	15.6	7,940	506.5	96.2	7.16
11	401.4	15.6	8,180	505.4	96.1	6.96
12	401.7	15.3	8,185	506.0	96.2	6.95
13	409.7	15.3	8,015	505.4	96.3	7.10
14	401.4	17.1	8,180	505.4	95.7	6.96
15	401.7	16.1	8,185	506.0	96.0	6.95
16	401.9	16.9	8,189	506.5	95.8	6.94
17	401.7	14.9	8,185	506.0	96.3	6.95
18	401.4	16.1	8,180	505.4	96.0	6.96

DATA SET FOR ZERO PERCENT EFFICIENCY TEST

PORT	SAMPLE	ΔP_t (in.H_2O)	P_s (in. H_2O)	T_t (°R)
2	1	0.060	0.78	936
2	2	0.070	0.75	940
4	1	0.080	0.80	933
4	2	0.080	0.75	931
4	3	0.080	0.70	930
4	4	0.085	0.70	929
4	5	0.075	0.70	929
4	6	0.080	0.70	931
4	7	0.085	0.70	931
4	8	0.085	0.70	931
6	1	0.140	0.75	929
6	2	0.150	0.80	929
6	3	0.140	0.80	934

DATA SET FOR ZERO PERCENT EFFICIENCY TEST

PORT	SAMPLE	Q_t(SLPM)	$SF_{6(IN)}$ (ppb)	$SF_{6(OUT)}$ (ppb)	EFFICIENCY (%)
2	1	310,209	336.5	290.8	13.6
2	2	334,350	312.2	292.5	6.3
4	1	332,160	314.2	283.9	9.6
4	2	332,517	313.9	284.1	9.5
4	3	332,695	313.8	287.3	8.4
4	4	343,119	304.2	287.3	5.6
4	5	332,304	323.9	287.3	11.3
4	6	332,517	313.9	290.8	7.4
4	7	342,750	304.5	290.8	4.5
4	8	342,750	304.5	290.8	4.5
6	1	411,911	253.4	287.3	-13.4
6	2	426,369	244.8	287.3	-17.4
6	3	410,807	254.1	292.5	-15.1

DATA SET FOR ZERO PERCENT EFFICIENCY TEST

PORT	MEAN EFFICIENCY	STANDARD DEVIATION	STANDARD ERROR
2	9.95%	5.162%	3.65%
4	7.60%	2.541%	0.90%
6	-15.3%	1.996%	1.15%

QUALITATIVE ESTIMATE OF EFFECT OF ZERO EFFICIENCY VALUES ON DRE

EFFICIENCY (PERCENT)	EFFICIENCY (PORT 2 AND 4)	EFFICIENCY (PORT 6)
50	53.7	41.0
90	90.7	88.2
95	95.4	94.1
99	99.1	98.8

VITA

Timothy Lyle Alexander was born in Memphis, Tennessee on August 4, 1958. He attended elementary schools in that city and was graduated from Harding Academy in May 1976. The following August he entered Freed-Hardeman College in Henderson, Tennessee, and in December 1979 he graduated with a Bachelor of Arts degree. In January 1982 he entered the University of North Carolina at Asheville. He was graduated in May 1984 with a Bachelor of Science degree in Atmospheric Science.

After working several years with the National Climatic Data Center and the Air Force Environmental Technical Applications Center, he moved to Knoxville, Tennessee and entered The Graduate School of the University of Tennessee. He received the Master of Science degree with a major in Environmental Engineering in December 1989.

The author is a member of the Air and Waste Management Association. Mr. Alexander is employed by Science Applications International Corporation and works as a Meteorologist and Air Quality Engineer.