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EVALUATION OF INNOVATIVE VOLATILE ORGANIC COMPOUND AND HAZARDOUS AIR POLLUTANT CONTROL TECHNOLOGIES FOR U.S. AIR FORCE PAINT SPRAY BOOTHS

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13. ABSTRACT *(Maximum 200 words)*

In this report, carbon paper adsorption/catalytic incineration (CPACI) and fluidized-bed catalytic incineration (FBCI) were evaluated as control technologies to destroy volatile organic compound (VOC) emissions from paint spray booths. Simultaneous testing of pilot-scale units was performed to evaluate the technical performance of both technologies. Results showed that each technology maintained greater than 99 percent Destruction and Removal Efficiencies (DREs). Particulate emissions from both pilot-scale units were less than 0.08 grains/dry standard cubic foot. Emissions of the criteria pollutants—SO_x, NO_x, and CO—were also below general regulatory standards for incinerators. Economic evaluations were based on a compilation of manufacturer-supplied data and energy consumption data gathered during the pilot-scale testing. CPACI and FBCI technologies are less expensive than standard VOC control technologies when net present costs (NPCs) for a 15-year equipment life are compared.

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EXECUTIVE SUMMARY

A. OBJECTIVE

The objective of this project was to identify and evaluate innovative emission control technologies that can cost-effectively lower or eliminate volatile organic compound (VOC) and hazardous air pollutant (HAP) emissions from a typical United States Air Force (USAF) paint spray booth.

B. BACKGROUND

Significant quantities of volatile organic compounds (VCCs) and hazardous air pollutants (HAPs) are released into the atmosphere during USAF maintenance operations. Painting operations conducted in paint spray booths are major sources of these pollutants. Solvent-based epoxy primers and solvent-based polyurethane coatings are typically used by the Air Force for painting aircraft and associated equipment. Solvents used in these paints include methyl ethyl ketone (MEK), toluene, lacquer thinner, and other solvents involved in painting and component cleaning.

USAF maintenance facilities have been identified as VOC and HAP emissions sources, and as such are regulated by the Clean Air Act (CAA) and related state and local regulations. Because many USAF bases are located in areas that have not yet attained pollution control goals established by the CAA, local air pollution control agencies are requesting that the USAF decrease its VOC and HAP emissions. In response to these regulations, the U.S. Air Force Engineering Services Center (AFESC), in cooperation with the Air and Energy Engineering Research Laboratory (AEERL) of the U.S. Environmental Protection Agency (EPA), initiated technology evaluation programs to minimize VOC and HAP emissions through the application of source control reductions and system modifications to existing paint spray booth operations.

C. SCOPE

Technical and economic evaluations, in conjunction with a vendor survey, were performed for 11 innovative emission control technologies. Based upon the results of these tasks, two technologies were selected for field-testing: carbon paper adsorption/catalytic incineration (CPACI), and fluidized-bed catalytic incineration (FBCI). In these evaluations, CPACI and FBCI were compared with standard VOC emission control technologies, such as regenerative thermal incineration (RTI).

During the field-testing, one CPACI pilot-scale unit and one FBCI pilot-scale unit were tested simultaneously, at the "Big Bertha" paint spray booth in Building 655 at McClellan Air Force Base (AFB), California.

D. METHODOLOGY

Field tests of the pilot-scale CPACI and FBCI units were conducted by using Bay Area Air Quality Management District (BAAQMD) and EPA-approved source test methods. BAAQMD

Method ST-7, and EPA Methods 2, 3A, 4, 5, 10, and 25A were used. Organics in the exhaust gases were characterized using National Institute for Occupational Safety and Health (NIOSH) Method 1300. Economic evaluations were based on manufacturer-supplied data used in conjunction with estimates provided in the EPA's EAB Cost Control Manual. This manual and the Naval Facilities Engineering Command's Economic Analysis Handbook were referenced to develop the net present cost (NPC) and treatment costs for each technology evaluated.

E. TEST DESCRIPTION

Tests of the pilot-scale units were accomplished over a 10-day period, during which the technologies were operated under a variety of conditions. The control technologies' operating temperatures and the flow rate of exhaust gas to be treated were controlled to meet desired operating parameters. Operating conditions generally fell into one of three categories: low flow rate and high temperature, high flow rate and low temperature and high flow rate and high temperature. During the tests, the paint spray booth was operated normally.

F. RESULTS

Information gathered in the vendor survey indicates that certain innovative VOC control technologies could be applied to paint spray booths. Regenerative thermal oxidation (RTO), RTI, membrane vapor separation/condensation, carbon adsorption/incineration, CPACI and FBCI technologies might be applied successfully to USAF paint spray booths. Field tests of CPACI and FBCI have demonstrated that each unit can achieve VOC destruction and removal efficiencies (DREs) of 99 percent during normal operating conditions.

An economic evaluation performed for a CPACI device sized to treat 60,000 scfm for 15 years resulted in an NPC of $2,570,000.

An economic evaluation performed for an FBCI device sized to treat 60,000 scfm for 15 years resulted in an NPC of $2,369,000.

G. CONCLUSIONS

CPACI, FBCI, and RTO technologies appear feasible, based on manufacturers' literature and reported uses in the automobile and aircraft manufacturing industries. The DRE of 99 percent achieved in field tests of the CPACI and FBCI pilot-scale units indicates that these systems can effectively control VOC emissions from USAF paint spray booths. This DRE is equivalent to or better than the DREs achievable with standard technologies. RTO has not been tested on USAF paint booths as yet, but its performance is expected to be acceptable.

The economic evaluations of the CPACI and FBCI technologies showed that the technologies compare favorably to standard treatment technologies such as thermal incineration. NPCs and treatment costs for both CPACI and FBCI are lower than those associated with standard VOC emission control technologies. Implementation of flow reduction techniques can further decrease the costs of VOC emission control technologies. For example, a 90-percent flow reduction could lower capital costs of a catalytic incinerator treating 50,000 dscfm of paint booth exhaust from $425,000 to $150,000.

H. RECOMMENDATIONS

Either CPACI or FBCI can be used effectively and economically to control VOC emissions from USAF paint spray booths. Other technologies, such as RTO, may be applicable, but they should first be field-tested at the pilot-scale level in paint spray booths to determine their viability.

Flow reduction technologies need to be incorporated into existing paint spray booths if possible. Reduction of paint spray booth exhaust by as much as 90 percent may be possible with these technologies. Such a flow reduction is beneficial because it can substantially decrease both treatment and capital costs.

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PREFACE

This report was prepared by Acurex Corporation, Mountain View, California, under Environmental Protection Agency (EPA) Contract No. 68-02-4285, funded by the Air Force Engineering and Services Center, Engineering and Services Laboratory (AFESC/RDVS), Tyndall Air Force Base, Florida 32403-6001.

This report summarizes work done between August 1988 and August 1990, under the direction of Dr. Dean Wolbach, Acurex Corporation. The EPA work assignment officer was Charles H. Darvin, Air and Energy Engineering Research Laboratory, Research Triangle Park, North Carolina. Mr. Surendra B. Joshi and Dr. Joseph D. Wander were the Air Force project officers for this contract.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for public release.

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LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

AEERL	Air and Energy Engineering Research Laboratory (EPA)
AFB	Air Force base
AFESC	Air Force Engineering and Services Center
APCD	air pollution control device
BAAQMD	Bay Area Air Quality Management District
Btu	British thermal unit
Btu/hr	British thermal units per hour
C	capital cost
CAA	Clean Air Act
CCR	carbon and catalyst replacement cost
CEM	continuous emission monitoring
cfm	cubic feet per minute
CO	carbon monoxide
CO_2	carbon dioxide
CPACI	carbon paper adsorption/catalytic incineration
CPR	carbon paper regeneration
CR	catalyst replacement
CrO	chromium oxide
°F	degrees Fahrenheit
DHHS	Department of Health and Human Services
DOD	United States Department of Defense
DRE	destruction and removal efficiency
dscf	dry standard cubic foot/feet
dscfm	dry standard cubic feet per minute
EAB	Economic Analysis Branch (EPA)
EPA	United States Environmental Protection Agency
ESD	Environmental Systems Division (Acurex)
FBCI	fluidized-bed catalytic incineration
FR	filter replacement
ft	foot, feet
ft^3	cubic foot, cubic feet
gal	gallon
GC/FID	gas chromatography/flame ionization detector
g	gram
gr	grain

gr/dscf	grains per dry standard cubic foot
>	greater than
HAP	hazardous air pollutant
hr	hour
HTE	high transfer efficiency
I	installation cost
in	inch, inches
in Hg	inches of mercury
$K	thousands of dollars
kW	kilowatt
kWh	kilowatt-hour
L	liter
lb	pound
LEL	lower explosive limit
<	less than
MEK	methyl ethyl ketone (2-butanone)
mg	milligram
MIBK	methyl isobutyl ketone (4-methyl-2-pentanone)
μg	micrograms
μg/L	micrograms per liter
min	minute
MMBtu	millions of British thermal units
MMBtu/lb	millions of British thermal units per pound
N_2	nitrogen
NDIR	nondispersive infrared
NFPA	National Fire Prevention Association
NIOSH	National Institute for Occupational Safety and Health
No.	number
NO_x	oxides of nitrogen
NPC	net present cost
NR	not required
O&M	operation and maintenance
OSHA	Occupational Safety and Health Administration
O_2	oxygen
OVA	organic vapor analyzer
PG&E	Pacific Gas and Electric
ppb	parts per billion

ppm	parts per million
ppmv	parts per million volume
PVDR	Power/VOCs Destroyed Ratio
Q	flow rate to be treated (scfm)
QA/QC	quality assurance/quality control
RCA	regenerable carbon adsorption (with catalytic incineration)
RCRA	Resource Conservation and Recovery Act
RFQ	Request for Quotation
RPD	relative percent difference
RTI	recuperative thermal incineration
RTO	regenerative thermal oxidation
scfm	standard cubic feet per minute
SMUD	Sacramento Municipal Utilities District
T	total cost
Temp.	temperature
TUHC	total unburned hydrocarbon
U	annual utility cost
U.S.	United States
USAF	United States Air Force
UV	ultraviolet
VOC	volatile organic compound
WA	work assignment
WG	wage grade
yr	year

METRIC CONVERSION TABLE.

U.S. Customary	SI	SI Symbol	To Convert from English to SI, Multiply By
Area			
Square inch	Square meter	m^2	0.0006452
Square foot	Square meter	m^2	0.09290
Length			
Inch	Meter	m	0.0254
Foot	Meter	m	0.3048
Volume			
Cubic inch	Cubic meter	m^3	0.000016387
Cubic foot	Cubic meter	m^3	0.02832
Mass			
Pound mass	Kilogram	kg	0.4536
Grain	Gram	g	0.0648
Work, Energy, Heat			
Btu	Joule	J	1055
Btu	Kilowatt-hour	kWh	0.000293
Kilowatt-hour	Kilojoule	kJ	3600
Power, Heat Rate			
Horsepower	Watt	W	745.7
Btu/hour	Watt	W	0.2931
Temperature			
Fahrenheit	Celsius	°C	(5/9) (°F-32)
Flow Rate			
Cubic foot/minute	Cubic meter/second	m^3/s	0.0004719

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SECTION I
INTRODUCTION

A. OBJECTIVE

The United States Department of Defense (DOD) and the United States Environmental Protection Agency (EPA) are engaged in a joint program to address environmental problems within the DOD. Under this program, the Air Force Engineering and Services Center (AFESC) and the EPA's Air and Energy Engineering Research Laboratory (AEERL) have conducted research and engineering development on technologies for minimizing emissions of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) from military sources. A study of innovative VOC and HAP control technologies that might destroy or reduce VOC and HAP emissions from typical United States Air Force (USAF) base paint spray booths was completed by Acurex's Environmental Systems Division (ESD) under EPA Contract 68-02-4285, Work Assignments (WAs) 1/010, 1/025, 2/034, and 2/042. This project represents a joint effort between AFESC and AEERL under a letter of agreement between EPA and USAF. The study was designed to identify and evaluate technically and economically viable innovative emission control concepts that lower or eliminate VOC and HAP emissions. Although USAF paint spray booths were the particular focus of this study, the results will be applicable to commercial booths.

This study focused on the control of the emissions from those paint spray booths in which solvent-based epoxy primers and polyurethane topcoats are normally used. The primary VOCs are methyl ethyl ketone (MEK), ethyl acetate, methoxyacetone, 4-methyl-2-pentanone (MIBK), toluene, butyl acetate, ethylbenzene, xylenes, 2-ethoxyethyl acetate, and 2-methoxyethoxy-ethanol.

B. BACKGROUND

The USAF uses a number of organic solvents and coatings for aircraft and aircraft-related equipment maintenance. This maintenance includes such operations as metal cleaning, painting, and paint removal. These operations release large quantities of VOCs and HAPs into the atmosphere. Consequently, USAF maintenance facilities have been identified as VOC and HAP emissions sources, and are therefore regulated by the Clean Air Act (CAA) and related state and local regulations. Because many USAF bases reside in areas that have not yet attained pollution control goals set by the CAA, local air pollution control agencies are requesting that the USAF decrease its VOC and HAP emissions.

In response to these regulations, AFESC has initiated technology evaluation and engineering development programs that will lead to the minimization of VOC and HAP emissions from these sources. Because of the benefits of this study to commercial industry, EPA enthusiastically supported the study.

EPA and USAF have cooperated in a series of research projects to evaluate VOC and HAP emissions from USAF paint spray booths. Acurex completed two major projects as a result of this cooperation.

The first project was a study to determine the nature of VOC and HAP emissions from three USAF paint spray booths. The final report for the project, submitted by Acurex to EPA and USAF in January 1988, discussed the nature of the VOC and HAP emissions from the three booths. It was concluded that the booths had VOC emissions ranging from 12.5 g/hr to 7.6 kg/hr (Reference 1). Particulate emissions were low, ranging from 1.7 to 16 mg/m^3. Recommendations were provided of actions that could be taken to reduce the VOC emissions, and it was concluded that the installation of a return air booth accompanied by a VOC control device is the most cost-effective method of reducing VOC emissions from paint spray booth facilities. Other recommendations included the adaptation of more-efficient coating application methods and the use of coatings having lower VOC content.

The second major project Acurex completed was a VOC emission reduction study at Hill Air Force Base, Utah. In the technical report, Acurex characterized the solvent emissions profile of a paint spray booth and recommended viable emission control technologies (Reference 2). Acurex also determined that high concentrations of hazardous compounds, such as volatile organics, metals, and diisocyanates, were present at the 4-foot level in the vicinity of the painter. High concentrations were also found near the booth exhaust outlet.

C. SCOPE

Although control technologies are available that can capture or destroy VOCs, their present capital and operating costs have made their application to paint spray booths typically prohibitive. The identified technologies of this study claimed to impact the cost of operation, making them applicable for spray booth operation. The purpose of the study was to develop technical and economic data on innovative emission control concepts that could decrease or eliminate VOC and HAP emissions from USAF paint spray booths. Through a literature study and pilot-scale testing, the required information was obtained. The results of the study will provide USAF facilities with VOC and HAP control options that will assist USAF in meeting future challenges to reduce air emissions. These results will also assist USAF and EPA in implementing strategies for the minimization of VOC and HAP emissions from military installations and from commercial industrial facilities as well.

During the literature study conducted in Phase 1 of the study, information was obtained on the following innovative VOC control technologies:

- Fluidized-bed catalytic incineration
- Regenerative thermal oxidation
- Carbon paper adsorption/catalytic incineration
- Regenerative incineration

- Fluidized-bed adsorption/regeneration
- Carbon adsorption/incineration
- Membrane vapor separation/condensation
- Supercritical fluid oxidation
- UV/ozone destruction
- Molten salt combustion process
- Infrared incineration

In addition, source modifications of equipment and processes were reviewed. Equipment modifications reviewed included the mobile zone, air recirculation, and a split-flow concept. Process modifications included high transfer efficiency (HTE) spray systems.

The information obtained provides data on the performance and operating costs of the technologies, including data on destruction and removal efficiencies (DREs), advantages, disadvantages, and operating conditions. However, the information from the study is insufficient to predict the performance of a given VOC control system applied to emissions from paint spray booths. Such data can be obtained only through operational or laboratory tests. The information was used, however, to select the technologies evaluated in the pilot-scale testing.

The information gathered during this pilot-scale study is organized into a format that will assist USAF and EPA in assessing the VOC and HAP control capabilities of the technologies evaluated. Specifically, this final report is divided into the following sections:

- Section I: Introduction
- Section II: Review of Technologies
- Section III: Test Facility Description
- Section IV: Test Program Description
- Section V: Pilot-Scale Test Results and Discussion: Technology Performance Evaluation
- Section VI: Full-Scale System Technical Evaluation and Cost Projection
- Section VII: CPACI Full-Scale System Technical Evaluation and Cost Projection
- Section VIII: FBCI Full-Scale System Technical Evaluation and Cost Projection
- Section IX: Specification Criteria for System Selection and System Procurement
- Section X: Conclusions and Recommendations

Sections I and II present the background information required to give the reader an immediate overview of the topic. Sections III through V detail the pilot-scale testing program and results. Section VI discusses the full-scale technical and economic projection considerations. Sections VII and VIII discuss the full-scale technical and cost projections for the technologies tested. Sections IX and X present the specification criteria for system selection and procurement, and our conclusions and recommendations, respectively.

SECTION II
REVIEW OF TECHNOLOGIES

The control of VOC and HAP emissions from dilute, large-volume sources such as paint spray booths has long been a challenging problem. Most USAF paint spray booths are operated intermittently, making economical control of emissions from their exhausts difficult. Conventional technologies, such as carbon adsorption/solvent recovery, are technically feasible. However, they are not cost-effective in handling the high air volumes and low solvent concentrations from paint booths, since the capital costs of VOC control systems have a direct, but not always linear, relationship to airflow rate from the emission source. Normally, a higher flow rate requires larger equipment to handle the increased air volume. Operating costs have a similar relationship to airflow rates. The intention of this study is to evaluate technologies that address not only the technical aspects of controlling VOC and HAP emissions, but also the costs of controlling these pollutants.

An innovative VOC and HAP emissions control technology for this project is defined as any VOC and HAP control system that has not been demonstrated on USAF paint spray booths, and that will have a substantial likelihood of achieving greater or equivalent VOC and HAP emissions reductions at lower cost than existing systems. A technology is considered innovative if it combines two or more separate technologies, or if it incorporates new designs that allow it to achieve greater VOC and HAP removal or destruction, as well as higher energy efficiencies than conventional treatment technologies. To identify candidate control technologies that met the above criteria, a literature study was conducted, from which 11 candidate technologies were identified. These technologies are summarized in Table 1. This section covers details of the study and the reasons behind the selection of particular technologies.

A. TECHNOLOGY STUDY

The technology study was the starting point in the identification and evaluation of the innovative VOC and HAP emissions control technologies best suited for use in paint spray booths. The study's primary goal was the selection of two or three technologies for pilot-scale field testing. The study identified innovative and emerging technologies, problems specific to particular control systems, and technical information needed to define their compliance with the selection criteria for this program. The major critical elements of the study were:

- Ability to obtain reliable background information and data from manufacturers
- Willingness of manufacturers to provide information when required

The study was broken down into several stages. It began with the study of the current VOC and HAP emissions problems at the different USAF paint spray booth operations. The following minimum conditions and criteria for selecting the pilot-scale system were formulated:

TABLE 1. INNOVATIVE VOC AND HAP EMISSION CONTROL TECHNOLOGIES, MANUFACTURERS, AND TYPES OF WASTES HANDLED.

Innovative VOC Control Technology	Key Innovation	Applicable Waste Type
Fluidized-bed catalytic incineration	• Fluidized-bed design • Non-precious metal catalyst (manganese dioxide or chromium oxide)	• Hydrocarbons • Oxygenated solvents
Regenerative thermal oxidation	• Consolidation of the oxidizer's chamber and heat exchanger • 98 percent heat recovery	• Hydrocarbons • Oxygenated solvents • Very dilute chlorinated hydrocarbons
Carbon paper adsorption/catalytic incineration	• Combination of three technologies (activated carbon fiber adsorption, thermal regeneration, and catalytic incineration)	• Hydrocarbons • Oxygenated solvents
Regenerative incineration	• Combination of thermal oxidation (incineration) with internal energy recovery	• Hydrocarbons • Chlorinated hydrocarbons
Fluidized-bed adsorption/ regeneration	• Fluidized-bed design • Use of unique polymer adsorbent	• Hydrocarbons • Chlorinated hydrocarbons
Carbon adsorption/ incineration	• Combination of three technologies (adsorption with granular activated carbon, thermal regeneration with hot gases, and controlled oxidation)	• Hydrocarbons and chlorinated hydrocarbons • Oxygenated solvents
Membrane vapor separation/ condensation	• Technology using polymer membrane to separate air stream contaminants	• Hydrocarbons • Oxygenated solvents • Chlorinated hydrocarbons
Supercritical fluid oxidation	• Technology utilizing high pressure to convert organic wastes into superheated steam, innocuous gases, and salts	• Hydrocarbons • Chlorinated hydrocarbons • Oxygenated solvents
UV/ozone destruction	• Technology for destroying or detoxifying hazardous chemicals in solutions or in air streams, using a combination of ozonation and UV irradiation	• Hydrocarbons • Chlorinated hydrocarbons
Molten salt incineration	• Technology that destroys combustible hazardous waste materials using molten salt reactors	• Hydrocarbons • Chlorinated hydrocarbons
Infrared incineration	• Technology designed to decompose hazardous wastes, using infrared heating elements	• Hydrocarbons • Chlorinated hydrocarbons

- The technology had to be innovative and capable of achieving a DRE of more than 98 percent
- The system had to be capable of controlling or destroying VOCs such as methyl ethyl ketone (MEK), isopropyl alcohol, toluene, lacquer thinner, and other solvents involved in painting and component cleaning operations
- The pilot-scale unit had to be available for loan or lease to the project
- The system had to be able to handle flow rates ranging up to 3000 scfm and VOC concentrations up to 2500 ppm
- The pilot-scale unit had to be available for testing at a predetermined USAF base

After establishing the minimum conditions and criteria, the technologies presented in Table 1 were reviewed. Conventional low-pressure, HTE spray gun technologies and paint spray booth airflow rate reduction systems were also identified as viable control technologies. However, these represented process modifications rather than air pollution control systems, and are therefore not included in Table 1.

Types of test methods and procedures, as well as costs of acquiring, installing, and testing each pilot-scale technology, were also developed. Based on the information gathered in the technology study, three control technologies were selected for pilot-scale field testing. The innovative technologies chosen were carbon paper adsorption/catalytic incineration (CPACI), fluidized-bed catalytic incineration (FBCI), and regenerative thermal oxidation (RTO).

Study results indicate that several innovative VOC and HAP emissions control technologies have been developed and are commercially available. Other systems exist as emerging technologies in developmental stages. Carbon adsorption systems have been widely used to remove organic vapors from exhaust gases, and these systems can also be used to recover solvents from exhaust gases. Incineration, on the other hand, has been developed over a number of years as a means of disposing of various types of wastes, including waste gases. From an environmental standpoint, both technologies are suitable for removing, concentrating, or disposing of certain VOCs and HAPs in waste gases. Many of the surveyed technologies are innovative in that they creatively combine aspects of both carbon adsorption and incineration.

Table 2 presents the various technologies, including their advantages and disadvantages. Table 3 presents the factors used in evaluating the technologies. Table 3 also includes overall evaluations of the three technologies selected for pilot-scale field testing and of the following technologies:

- Regenerative incineration
- Fluidized-bed adsorption/regeneration
- Carbon adsorption/incineration
- Membrane vapor separation/condensation

TABLE 2. VOC AND HAP EMISSION CONTROL TECHNOLOGIES—PAINT SPRAY BOOTH APPLICATIONS.

Control Technology	Benefits	Limitations
EMISSIONS CONTROL:		
Fluidized-bed catalytic *incineration (base metal)*	● High VOC DRE ● *Base metal catalyst is resistant to poisoning* ● Base metal lowers oxidation temperature ● Fluidized-bed design lowers power consumption ● Self-sustaining: low fuel consumption if VOC concentration is high enough	● Needs additional air pollution control devices for treatment of halogenated solvents
Regenerative thermal oxidation	● High heat recovery efficiency ● Proven VOC destruction capability ● Compact design ● Low maintenance requirements	● Needs additional air pollution control devices for treatment of halogenated solvents
Carbon paper adsorption/ catalytic incineration	● High VOC DRE ● Low operating costs ● Installation quick and inexpensive ● Long carbon and catalyst life	● Needs additional air pollution control devices for treatment of halogenated solvents
Regenerative incineration	● High VOC DRE ● Self-sustaining: low fuel consumption if VOC concentration is high enough ● Excellent for multiple sources ● High turndown ratio ● Employs indestructible media	● System is large ● Needs additional air pollution control devices for treatment of halogenated solvents
Fluidized-bed adsorption/ regeneration	● Low energy consumption ● Purity of recovered solvent is high ● Moisture content does not affect purity of recovered solvent	
Carbon adsorption/ incineration	● Can handle fluctuations in VOC loadings ● Low energy costs	● Needs additional air pollution control devices for treatment of halogenated solvents ● System is large ● System is expensive

(continued)

TABLE 2. VOC AND HAP EMISSION CONTROL TECHNOLOGIES—PAINT SPRAY BOOTH APPLICATIONS (CONCLUDED).

Control Technology	Benefits	Limitations
Membrane vapor separation/condensation	• Compact design • Attractive for recovery of valuable solvents	• High capital and O&M costs • Not field-tested
Supercritical fluid oxidation	• Closed-loop system • Heat energy recovered	• Not cost-effective
UV/ozone destruction	• High VOC DRE	• May not be cost-effective • Excess ozone emissions may occur • Needs additional air pollution control devices for treatment of halogenated solvents
Molten salt incineration	• High VOC DRE • Excellent heat transfer to VOCs • Salt bath may be recycled • Acid gases are not generated	• Corrosion problems • High O&M costs
Infrared incineration	• High VOC DRE • Flexible design; adjustable operating parameters	• Not cost-effective • Needs additional air pollution control devices for treatment of halogenated solvents
TECHNOLOGY MODIFICATION:		
Mobile zone unit	• Reduces exhaust gas volume • Minimizes capital costs of emission control equipment • May reduce operating costs of emission control	• Does not destroy or remove VOCs • Requires extensive ductwork modification • Not field-tested
High transfer efficiency spray system	• Reduces overspray by increasing painting efficiency • Minimizes VOC and particulate emissions • Can be retrofitted to existing air spray guns	• Not compatible with some paints • May require operator training
Recirculation	• Reduces exhaust gas volume • Minimizes capital costs of emission control equipment • May reduce operating costs of emission control	• Does not destroy or remove VOCs • Requires extensive ductwork modification

TABLE 3. SUMMARY OF INNOVATIVE VOC CONTROL TECHNOLOGY EVALUATION FACTORS.

	Innovative VOC Emissions Control Technology						
Evaluation Factors	**Fluidized-Bed Catalytic Incineration**	**Regenerative Thermal Oxidation**	**Carbon Paper Adsorption Catalytic Incineration**	**Regenerative Incineration**	**Fluidized-Bed Adsorption**	**Carbon Adsorption/ Incineration**	**Membrane Vapor Separation/ Condensation**
Applicability/ability to collect or destroy identified VOCs	Excellent	Excellent	Excellent	Excellent	Good	Excellent	Good
System overall VOC emission control efficiency (%)	95 to 98	90 to 98	90 to 95	90 to 95	90 to 92[a]	95 to 99	90 to 95[a]
— Design operating temperature (°F)	550 to 650	1,800	700	1,400	NA	1,450 to 1,650	Room temperature
— Residence time at operating temperature (s)	0.25	1.00	0.25	0.50	NA	1.00	NA
Full-scale system price (3,000 scfm)							
— Capital cost ($)	98,000	145,000	150 000	335,000	260,000	350,000	1,500,000
— Installation cost ($)	49,000	55,000	100,000	75,000	110,000	90,000	500,000
— Total cost ($)	147,000	200,000	250,000	410,000	370,000	440,000	2,000,000
— Annual operating cost ($)	12,000	10,000	6,000	6,000	27,000	4,000	300,000[b]
Environmental and energy considerations	● Solvent destruction technology ● Energy efficient	● Solvent destruction technology	● Solvent destruction technology ● Energy efficient	● Solvent destruction technology	● Solvent recovery technology ● Energy efficient	● Solvent destruction technology ● Energy efficient	● Meets regulatory requirements ● Solvent recovery technology
Flow rate range (scfm)	500 to 75,000	3,000 to 200,000	350 to 105,000	1,000 to 500,000	3,000 to 13,000	1,000 to 50,000	20 to 50
Concentration range (ppmv)	1 to 1,500	1 to 1,500	5 to 500	1 to 2,500	1 to 2,700	1 to 500	5 to 2,000

[a] Solvent collection efficiency
[b] Includes membrane replacement
NA — Not available

(continued)

TABLE 3. SUMMARY OF INNOVATIVE VOC CONTROL TECHNOLOGY EVALUATION FACTORS (CONCLUDED).

Evaluation Factors	Innovative VOC Emissions Control Technology						
	Fluidized-Bed Catalytic Incineration	Regenerative Thermal Oxidation	Carbon Paper Adsorption Catalytic Incineration	Regenerative Incineration	Fluidized-Bed Adsorption	Carbon Adsorption/ Incineration	Membrane Vapor Separation/ Condensation
Developmental status	More than 10 years in operation; over 50 units installed	Over 5 years in operation; 35 units installed in Scandinavia, at least 1 in U.S.	10 years in operation; 30 units installed worldwide	15 years in operation in several countries	2 units now operational in Sweden	1 year in operation	Not field-tested
Operation and maintenance (O&M) requirements	Electric power, compressed air, natural gas	Electric power	Electric power, air, activated carbon fiber and catalyst	Electric power, natural gas	Electric power, air or hot nitrogen	Natural gas, electric power, air, activated carbon	Electric power, chilled water, holding tank
Material of construction	Manganese dioxide catalyst, 304 stainless steel	Silica gravel, 316 stainless steel	Activated carbon fiber, carbon steel	Carbon steel with refractory lining and insulation	NA	Carbon steel, activated carbon	NA
Flexible design capabilities	Wide range of operational, design and installation flexibility	Wide range of operational, design and installation flexibility	Wide range of operational, design and installation flexibility	Modular design	Modular design	Process handles instantaneous fluctuations in influent composition	Modular design
Important safety features	Flame safeguard system with purge timer, pilot timer, and UV electronic flame detector	Excellent safety features	Important safety controls to shut off system	Temperature control, fire protection, computerized control	Shut-off system	Flame detector safeguards with automatic shut-off valves and alarms	Safety switches, pressure and temperature sensors

NA — Not available

Two of the selected technologies, CPACI and FBCI, were field-tested and are detailed in Section B, Subsections 1 and 2, respectively. RTO, unfortunately, could not be field-tested as no pilot-scale units were available from manufacturers during the scheduled testing period.

Of the 11 technologies, six have been operational for a number of years and have been utilized in treating VOC and HAP emissions from paint spray booths. The membrane vapor separation/condensation process has not been field-tested. The four remaining emerging technologies were not evaluated for pilot-scale testing or full-scale unit capacity; they are:

- Supercritical fluid oxidation
- UV/ozone destruction
- Molten salt incineration
- Infrared incineration

The evaluations focus on the competitive aspects of the commercial VOC and HAP emission control technologies. However, choosing among the technologies involves consideration of many factors, some of which are either strictly technical or strictly economic. Choices may be made depending on federal, state, and local regulatory programs currently in place, and those programs planned for the future. The principal considerations for evaluating each technology, and for selecting the three technologies for pilot-scale testing, were:

- Overall destruction and removal efficiency (DRE)
- Reliability
- Overall heat recovery efficiency
- Environmental media most affected
- Cost

B. DESCRIPTION OF TECHNOLOGIES SELECTED FOR FIELD-TESTING

1. Carbon Paper Adsorption/Catalytic Incineration (CPACI)

CPACI is a hybrid system that combines carbon adsorption and catalytic incineration. Essentially, the contaminated air stream is cleaned by carbon adsorption. Catalytic incineration is used to destroy the VOCs desorbed from the carbon adsorption system. The manner in which the technologies are combined decreases the volume of contaminated air that must be incinerated (Reference 3).

Full-scale CPACI units are available in sizes that treat waste gas flow rates ranging from 350 to 105,000 scfm. Primary equipment associated with CPACI technology includes a rotating carbon paper adsorber, a catalyst bed, and a natural gas burner. Heat exchangers are integral to this technology's energy-saving design, as described below. Fans, burners, valves, control panels, safety devices and other appurtenances found on incinerators are common to CPACI units.

Figure 1 is a schematic of a CPACI unit. Air emissions from the paint spray booth are passed through a particulate filter, then through a granular activated carbon filter. Next, the

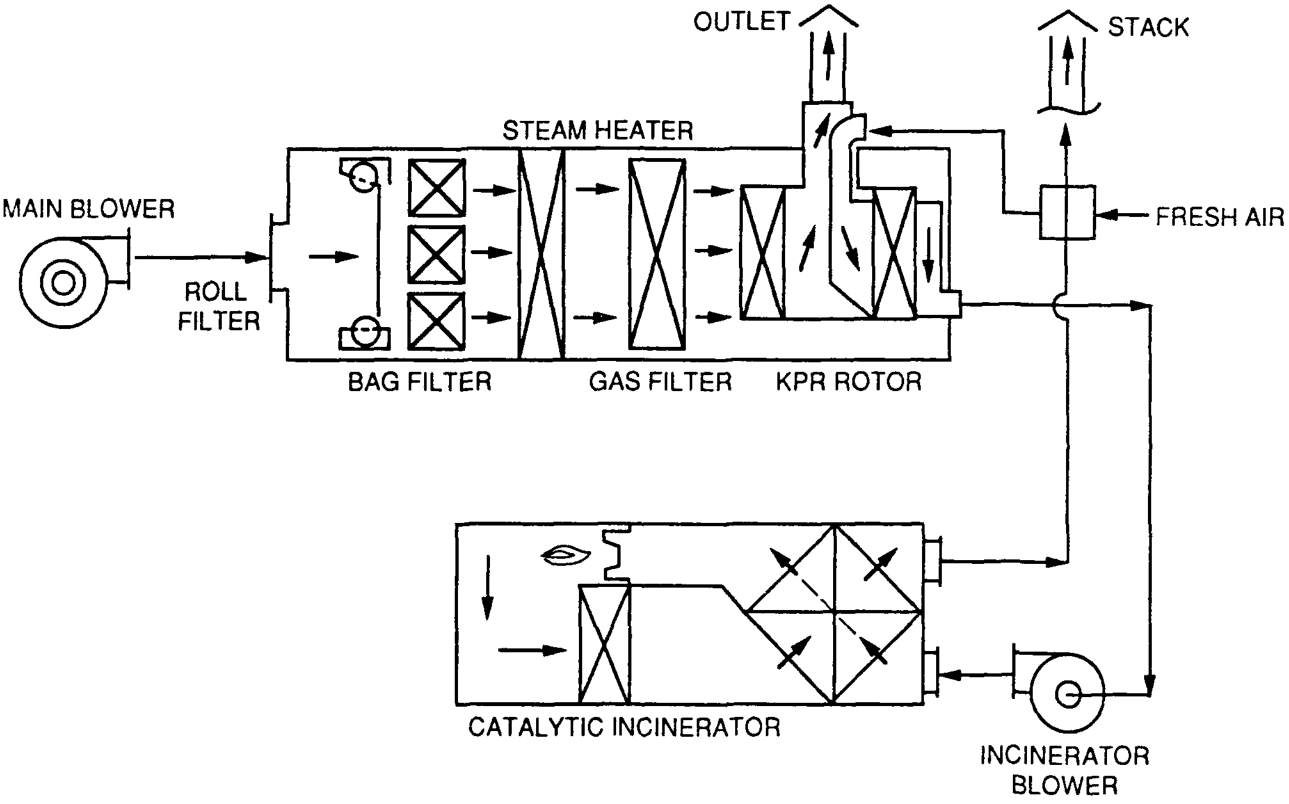


Figure 1. **Process Flow Diagram for Carbon Paper Adsorption/Catalytic Incineration (Adapted from Diagram Supplied by Met-Pro Corporation)**

air flows through a carbon paper filter that is fashioned into a cylindrical, continuously turning rotor. The honeycombed structure of this filter allows for a high VOC removal efficiency. Paint spray booth emissions pass through one end of the cylinder. However, air passes through only about seven-eighths of the area at the end of the carbon paper rotor (Figure 2) before exhausting to the atmosphere. The remaining one-eighth of filter area is used in the incineration loop of the CPACI technology.

Since the carbon paper filter is always rotating, a portion of the filter always adsorbs VOCs from the contaminated air. In addition, a part of the carbon paper rotor is always moving into a counter-current stream of hot desorption air (Figure 3). This air represents a separate stream entering the CPACI at a flow rate of about one-fifteenth that of the air emissions coming from the paint spray booth. This desorption air stream preheats in a heat exchanger, desorbs the VOCs from the carbon paper rotor, and carries them to a catalytic incinerator. The VOCs are destroyed by the catalytic incinerator and the desorption air is then exhausted to the atmosphere.

CPACI was evaluated as a VOC control technology by field-testing a pilot-scale unit supplied by Met-Pro Corporation. The pilot-scale CPACI consists mainly of a carbon paper adsorber, a ceramic catalyst bed, a heat exchanger, and electric heaters; the heaters are used instead of a natural gas burner in the unit's catalytic incinerator.

2. Fluidized-Bed Catalytic Incineration (FBCI)

FBCI is a technology designed to destroy VOCs. This technology combines catalytic incineration and thermal oxidation to accomplish VOC destruction.

Full-scale units consist primarily of a fluidized catalyst bed and a burner with a combustion chamber. Supporting appurtenances include forced-draft fans, valves, fuel lines, control panels, and safety devices. FBCI is considered innovative due to the fluidization of the catalyst bed. Proprietary catalysts are reportedly used to enhance the combustion process. FBCI devices are available in a range of sizes that handle waste gas flow rates from 500 to 75,000 scfm.

FBCI units operate in a manner analogous to single-chamber thermal incineration devices. VOC-laden waste gas is brought into the incinerator by a forced-draft fan. The gas is preheated by a heat exchanger and put in direct contact with a natural gas burner. This provides 20 to 50 percent of the total destruction of VOCs. The heated gas then flows through a baffled distribution grate and into a bed of fluidized spheres. These spheres consist of a proprietary metal oxide coated on proprietary solid pellets. The exhaust from the catalyst bed is vented to the atmosphere. Full-scale units incorporate a heat exchanger into the design to recoup heat from the exhaust gas before the gas is vented. Operating temperatures can range from 550 to 1250°F, but are generally maintained between 550 and 700°F. Figure 4 is a schematic of the pilot-scale unit (Reference 4).

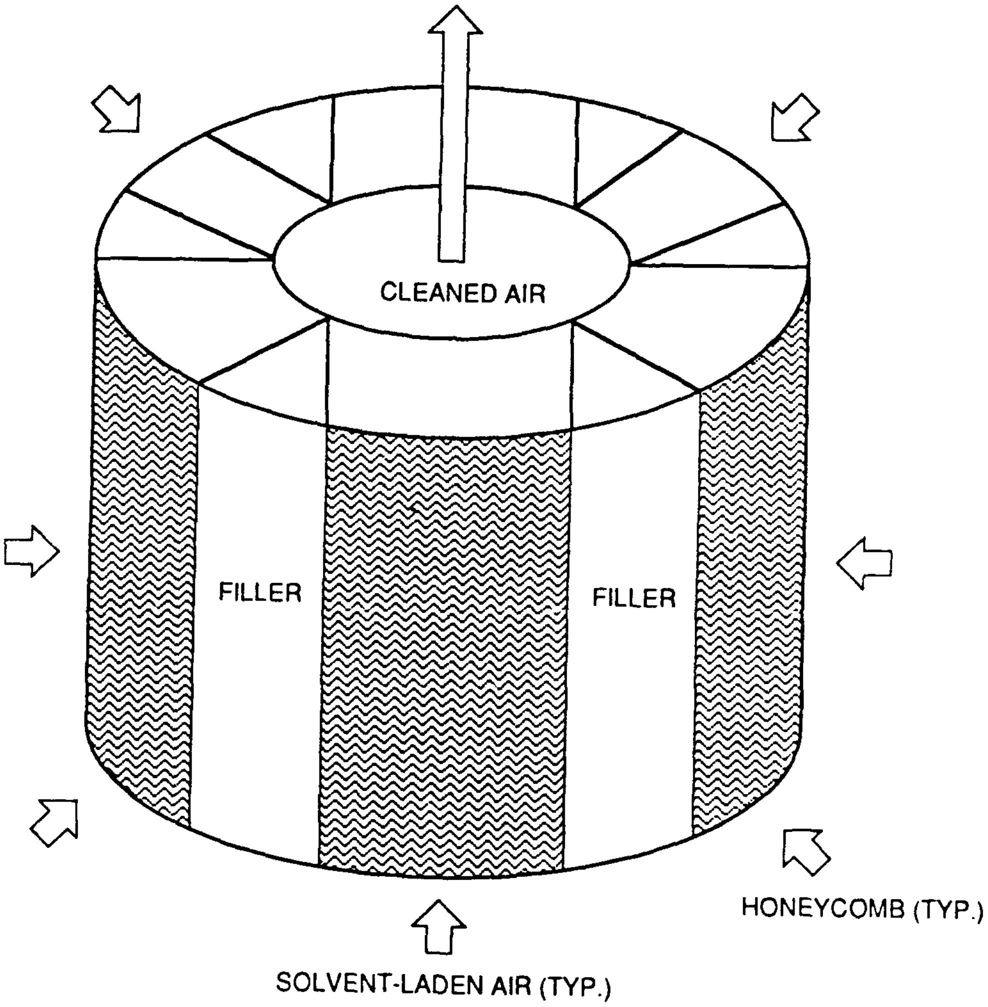


Figure 2. **KPR Cylinder Type Rotor Adsorbing (Adapted from Diagram Supplied by Met-Pro Corporation)**

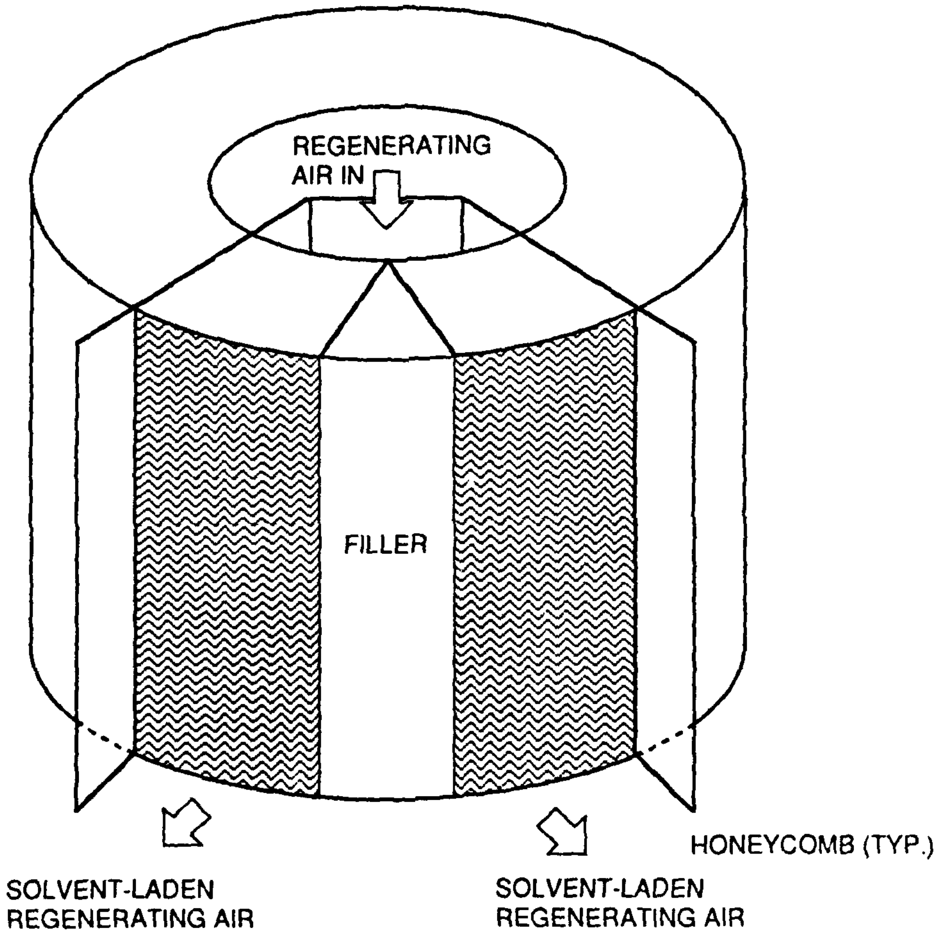


Figure 3. KPR Cylinder Type Rotor Desorbing (Adapted from Diagram Supplied by Met-Pro Corporation)

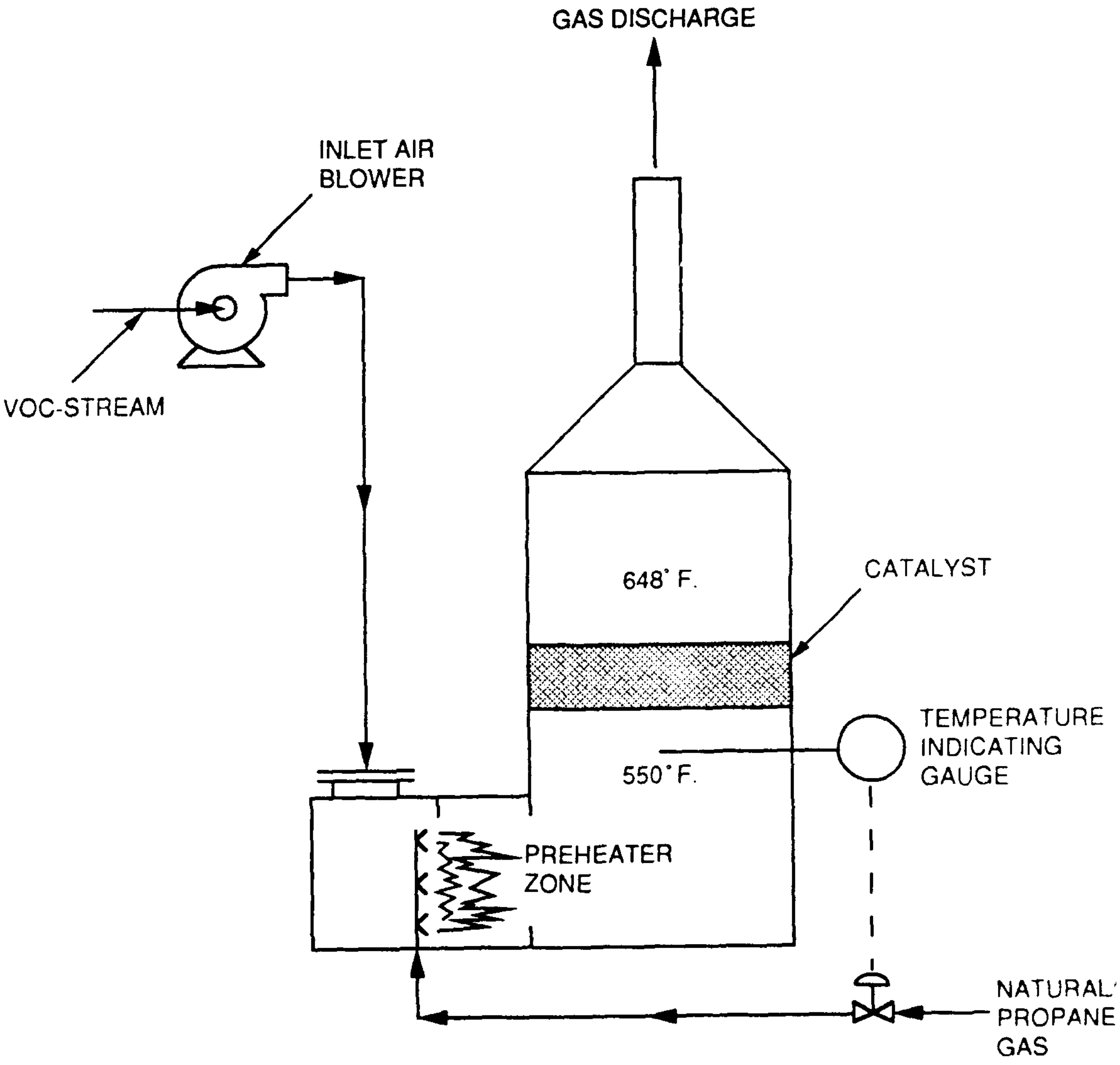


Figure 4. Process Flow Diagram for Fluidized-Bed Catalytic Incineration (Adapted from Diagram Supplied by ARI Technologies, Inc.)

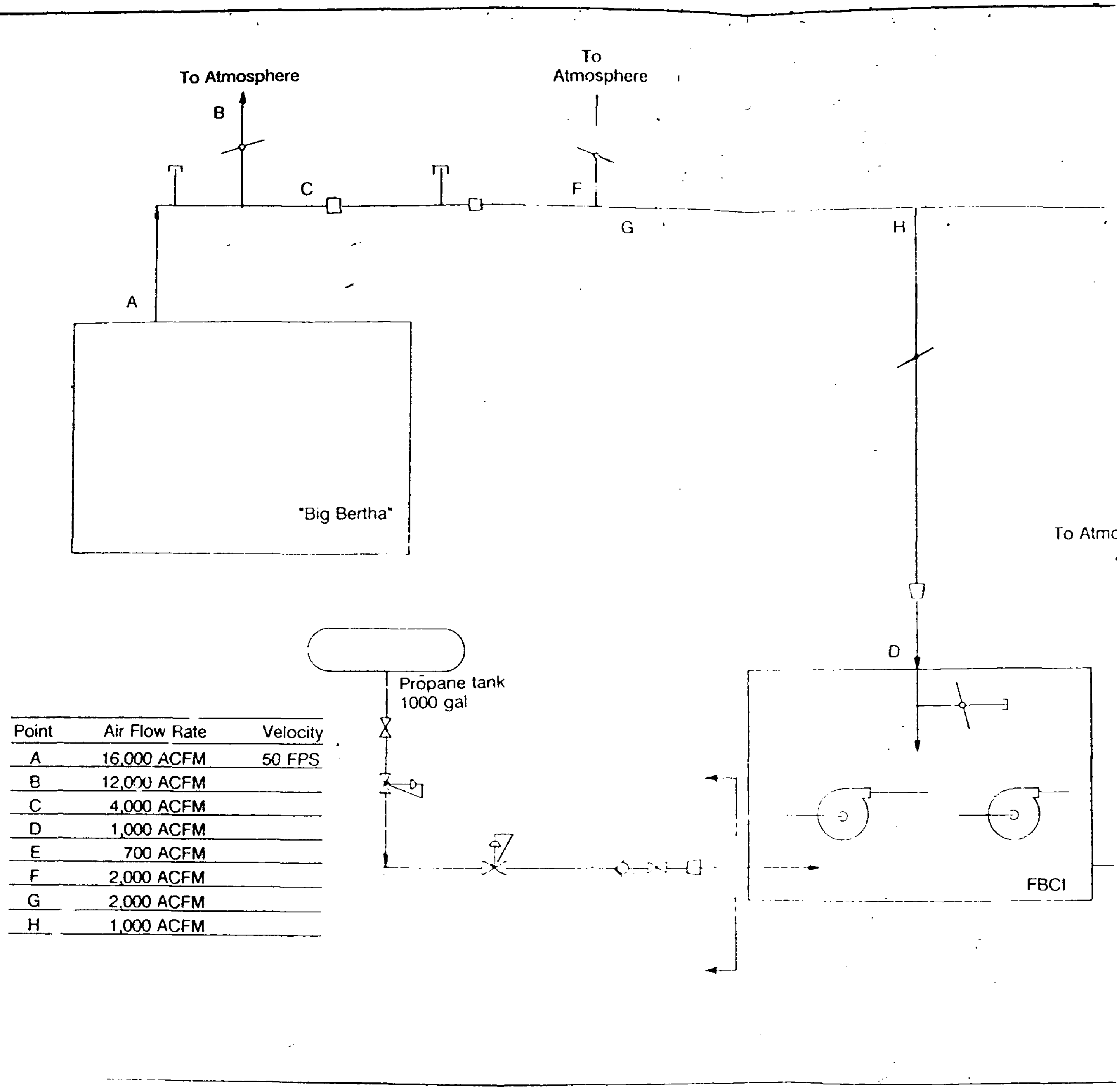
FBCI was evaluated as a VOC control technology through the field-testing of a pilot-scale unit supplied by ARI Technologies, Inc. The unit consisted of three main components: a catalyst bed, a burner with combustion chamber, and a forced-draft fan. It did not have a heat exchanger. The pilot-scale FBCI was sized for 500 scfm and could operate at flow rates of as low as 250 scfm or as high as 800 scfm.

SECTION III
TEST FACILITY DESCRIPTION

The test site for the pilot-scale tests was a paint spray booth (called "Big Bertha") in Building 655 at McClellan Air Force Base, California. This horizontal-flow, dry-wall booth measures approximately 50 feet long x 22 feet wide x 15 feet high. Air enters the booth through dry filters at the front and exhausts through dry filters at the rear. The front filters remove ambient dust to prevent the soiling of freshly painted pieces. The rear filters remove overspray particulate matter from the booth's ventilation air. Two fans draw a total of 32,000 cfm of air through the booth. The facility is normally used to paint large semitrailer-size equipment and other moderate-size equipment such as communication shelters.

Site preparation required the design and installation of operating pads and ductwork to direct a fraction of the booth exhaust to the FBCI and CPACI pilot-scale units. This effort included specification, acquisition, and installation of accessory equipment; electrical design and installation; and preparation of system layout drawings. The process flow diagram and "as-builts" are shown in Figures 5 through 7. Approximately 4000 cfm of the exhaust was drawn through a 20-inch-diameter galvanized iron duct. The ductwork was designed to allow simultaneous testing of the two systems.

Each test unit was skid-mounted and set on 2-inch-thick asphalt. A 1000-gallon propane tank supplied propane gas to the FBCI; the FBCI used propane gas because the nearest natural gas line at McClellan Air Force Base is at the opposite side of Building 655. Both pilot-scale units required electric power.



Point	Air Flow Rate	Velocity
A	16,000 ACFM	50 FPS
B	12,000 ACFM	
C	4,000 ACFM	
D	1,000 ACFM	
E	700 ACFM	
F	2,000 ACFM	
G	2,000 ACFM	
H	1,000 ACFM	

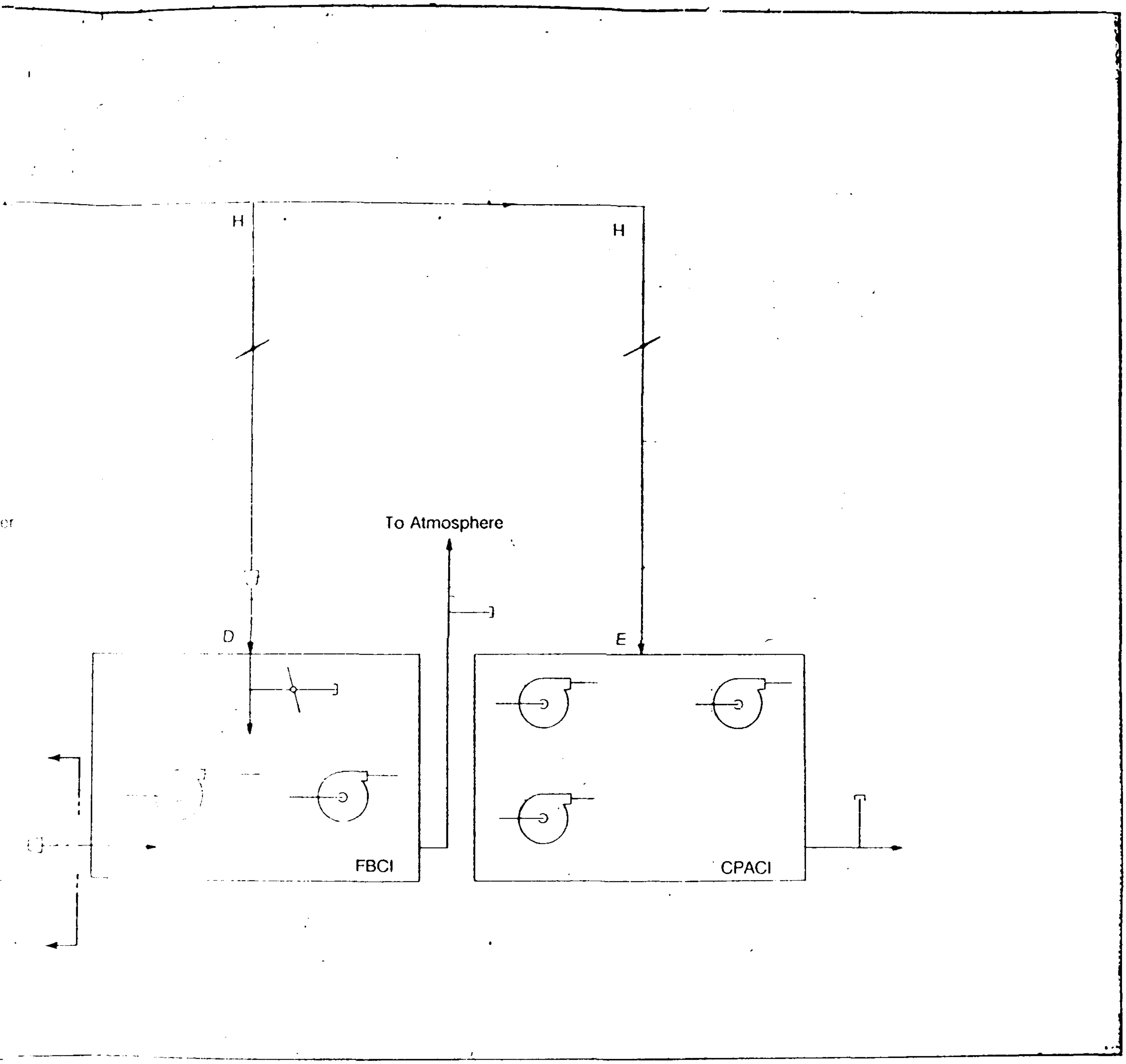


Figure 5. CPACI/FBCI Process Flow Diagram

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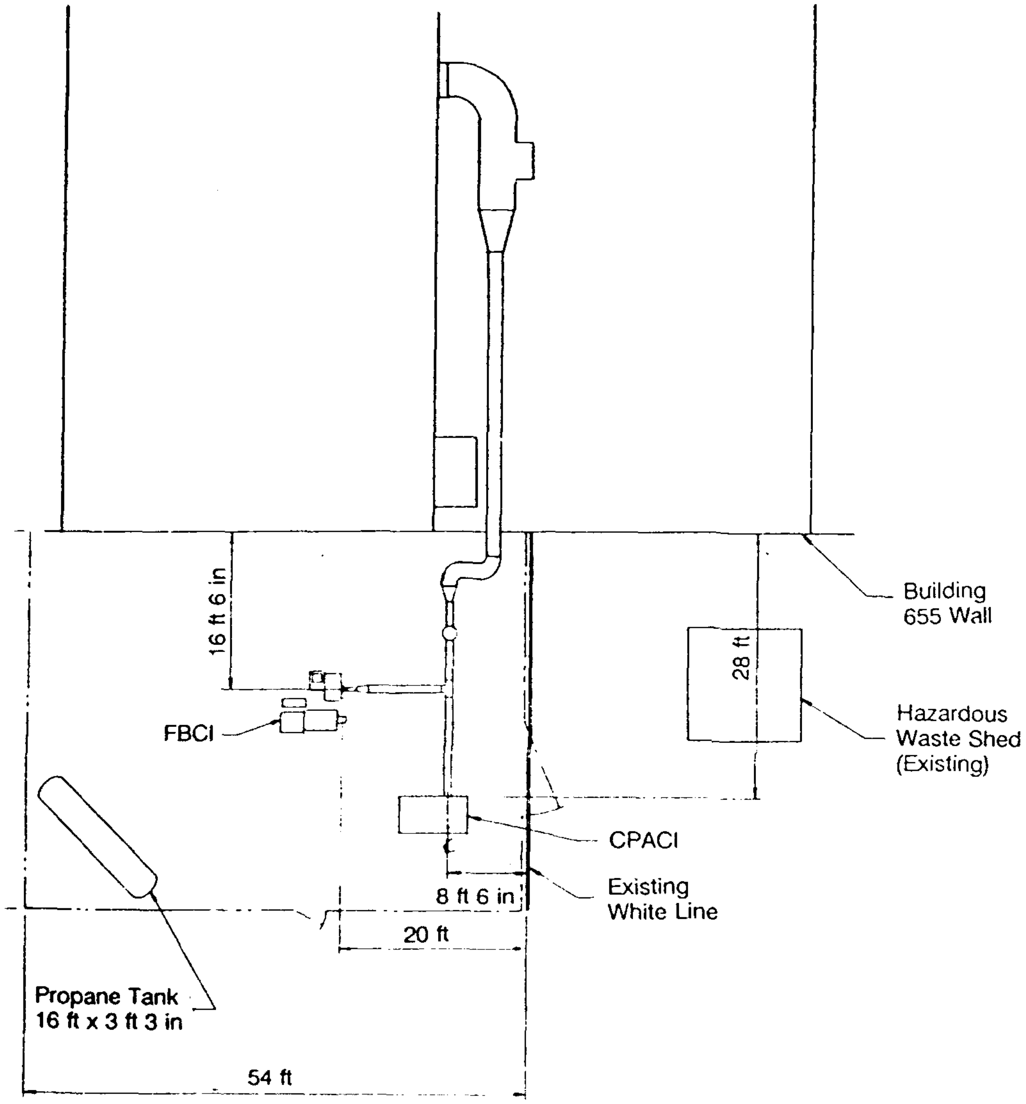

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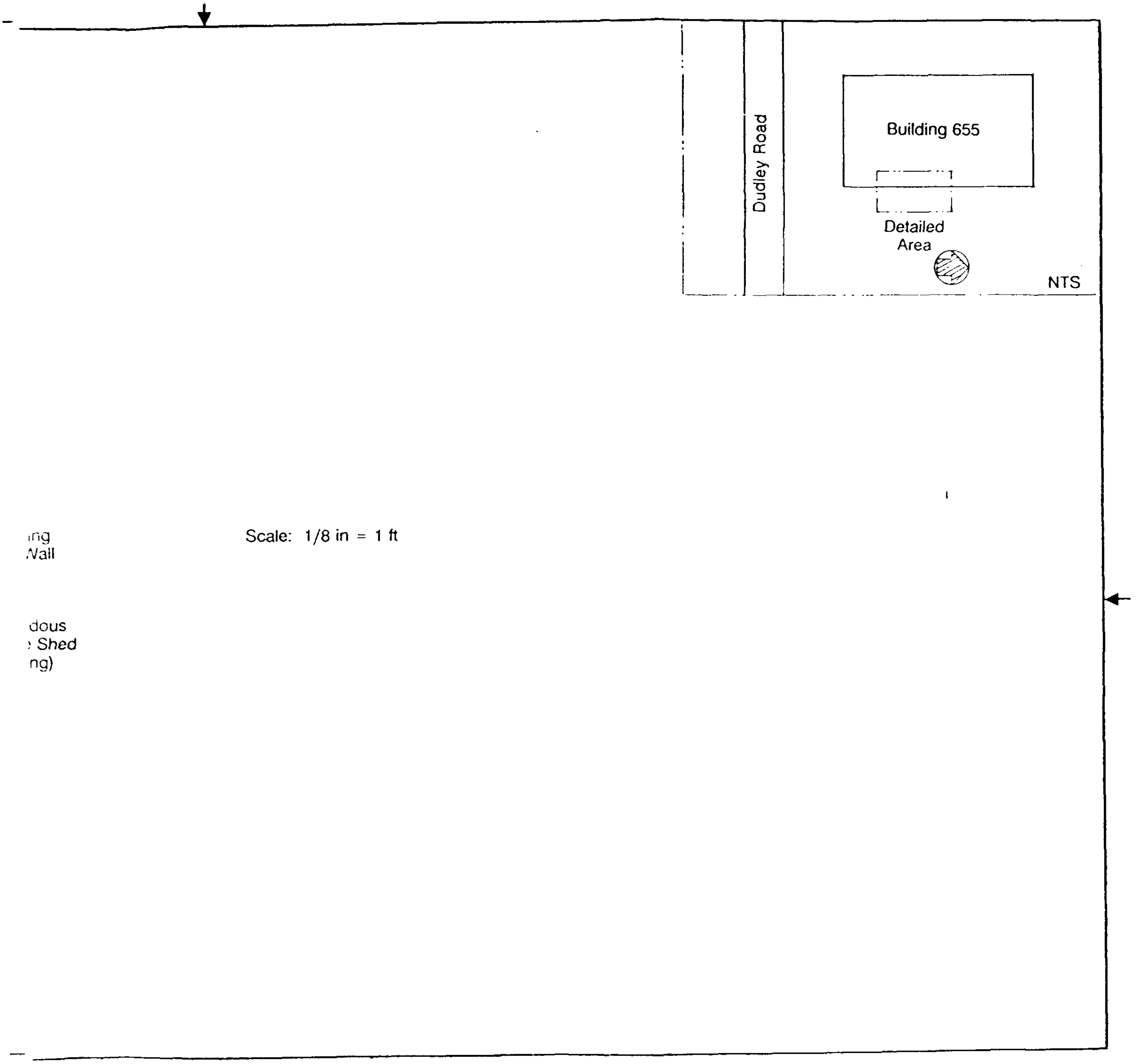

Figure 6. **Equipment Arrangement Plan View**

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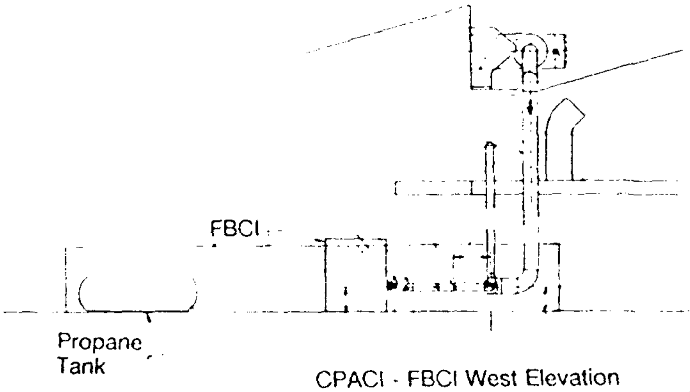
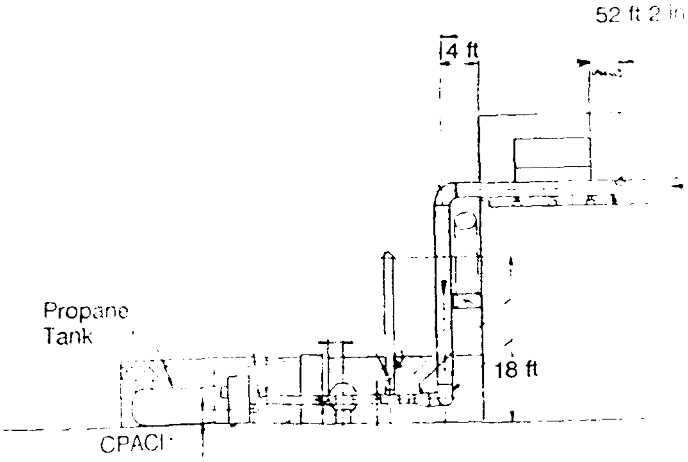


CPACI - FBCI West Elevation

B



CPACI - FBCI North Elevation

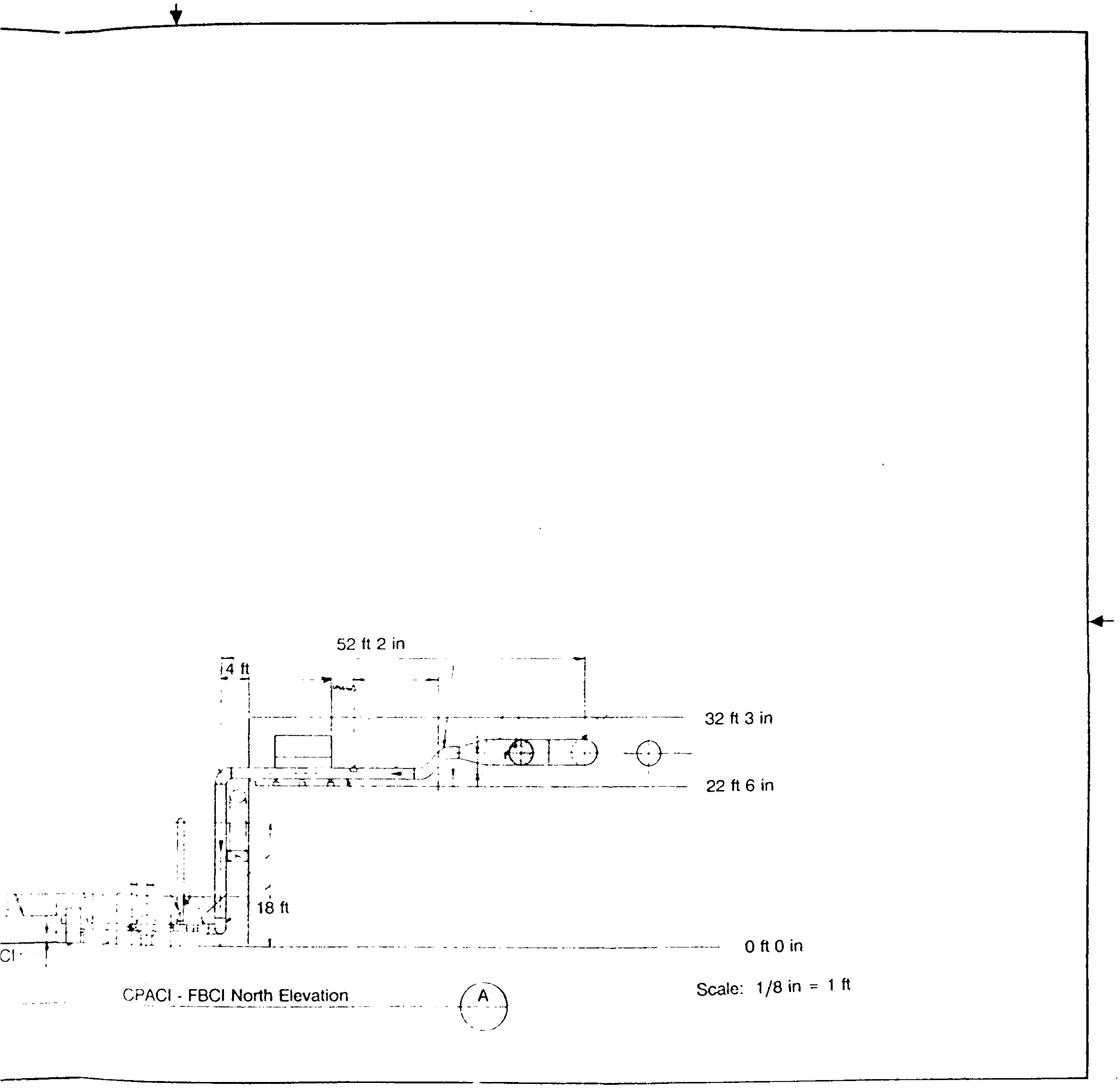


Figure 7. General Arrangement Elevation Views

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SECTION IV

TEST PROGRAM DESCRIPTION

This section discusses the test program, including the test matrix, system operation, painting schedule and test methods.

A. TEST MATRIX

The technical objective was to evaluate the two control technologies by determining their efficiencies in controlling VOC emissions. This was accomplished by measuring inlet and outlet VOC concentrations and the airflow rates of each unit. Measurements of gas and electrical usage were used to estimate energy consumption.

A summary of the tests performed, the data collected, and the numbers of samples taken during the entire sampling effort are presented in Table 4. This table lists the site numbers and locations, the type of sample taken, and the total number of sampling events. The methods used to monitor each of these parameters are summarized in Table 5. Figure 8 shows the configuration of the sampling sites.

There were six sampling sites, as described below. Exhaust from the paint spray booth was sampled at Sites 1 and 1A, prior to reaching the control devices. FBCI exhaust sampling was performed at Site 4. CPACI exhaust sampling was conducted at two sites, 5 and 6. Site 5 was the carbon paper exhaust and Site 6 was the incinerator exhaust. Flow rates for the inlet streams to the control devices were tested at Sites 7 and 8 for the CPACI and the FBCI, respectively. Electric power consumption data for the CPACI and FBCI were measured at Site 2. Propane gas input data for the FBCI were taken at Site 3.

Paint spray booth emissions were sampled and analyzed for four parameters. These parameters were particulate matter concentration, organic speciation, total unburned hydrocarbon (TUHC), and volume flow rate. EPA Method 5 (Reference 5) and EPA Method 2 (Reference 6) were used to measure particulate matter concentration and volume flow rate, respectively. These sampling methods were performed at Site 1A. Organic speciation and TUHC concentration of the paint spray booth exhaust were measured at Site 1. TUHC measurements were made by using BAAQMD Method ST-7 (Reference 7). Organic speciation of the paint spray booth exhaust was determined by NIOSH Method 1300 (Reference 8). Concentrations of CO_2, CO, O_2 and NO_x in the paint spray booth exhaust were assumed to be the same as ambient air levels, since the painting operation will not significantly alter the concentrations of these parameters.

CPACI exhaust measurements were made of particulate matter concentration, organic speciation, TUHC, volume flow rate, CO, CO_2, O_2, and NO_x. These measurements were made at the CPACI exhaust points, Sites 5 and 6. CO, CO_2, O_2, and NO_x emission levels were checked at Site 5, the carbon paper exhaust, to verify that these parameters were indeed at

TABLE 4. SAMPLING MATRIX FOR CONTROL TECHNOLOGIES.

Site No.	Site Location	Number of Sampling Events						
		Volume Flow	Organic Speciation	Total Unburned Hydrocarbons	Particulate and Moisture	Moisture	Electricity Consumption	CO, CO_2, O_2, NO_x
1	Paint booth exhast (organic sampling)	NA	23	Continuous	NA	NA	NA	NA
1A	Paint booth exhaust (particulate sampling)	14	NA	NA	12	NA	NA	NA
2	Electrical power input	NA	NA	NA	NA	NA	Continuous	NA
3	Propane gas input	NA	NA	NA	NA	NA	Continuous	NA
4	FBCI[a] incinerator exhaust	3	20	Continuous	18	1	NA	Continuous
5	CPACI main exhaust	20	22	Continuous	NA	4	NA	Continuous
6	CPACI incinerator exhaust	14	22	Continuous	12	5	NA	Continuous
7	CPACI inlet[b]	46	NA	NA	NA	NA	NA	NA
8	FBCI inlet[b]	40	NA	NA	NA	NA	NA	NA

[a] Volume flow data are generated during the particulate and moisture test (EPA Method 5)
[b] Organic speciation data and total unburned hydrocarbon data for Site 1 is the same for Sites 7 and 8
NA-Not applicable

TABLE 5. SAMPLING METHODS.

Parameter	Method
Volume flow	EPA Method 2
Organic Speciation	NIOSH Method 1300
Inlet total unburned hydrocarbons	BAAQMD ST-7
Incinerator exhaust total unburned hydrocarbons	EPA Method 25A
Particulate and moisture	EPA Method 5
Moisture	EPA Method 4
Electricity consumed	Standard electrical meter
Propane consumed	Dry gas meter

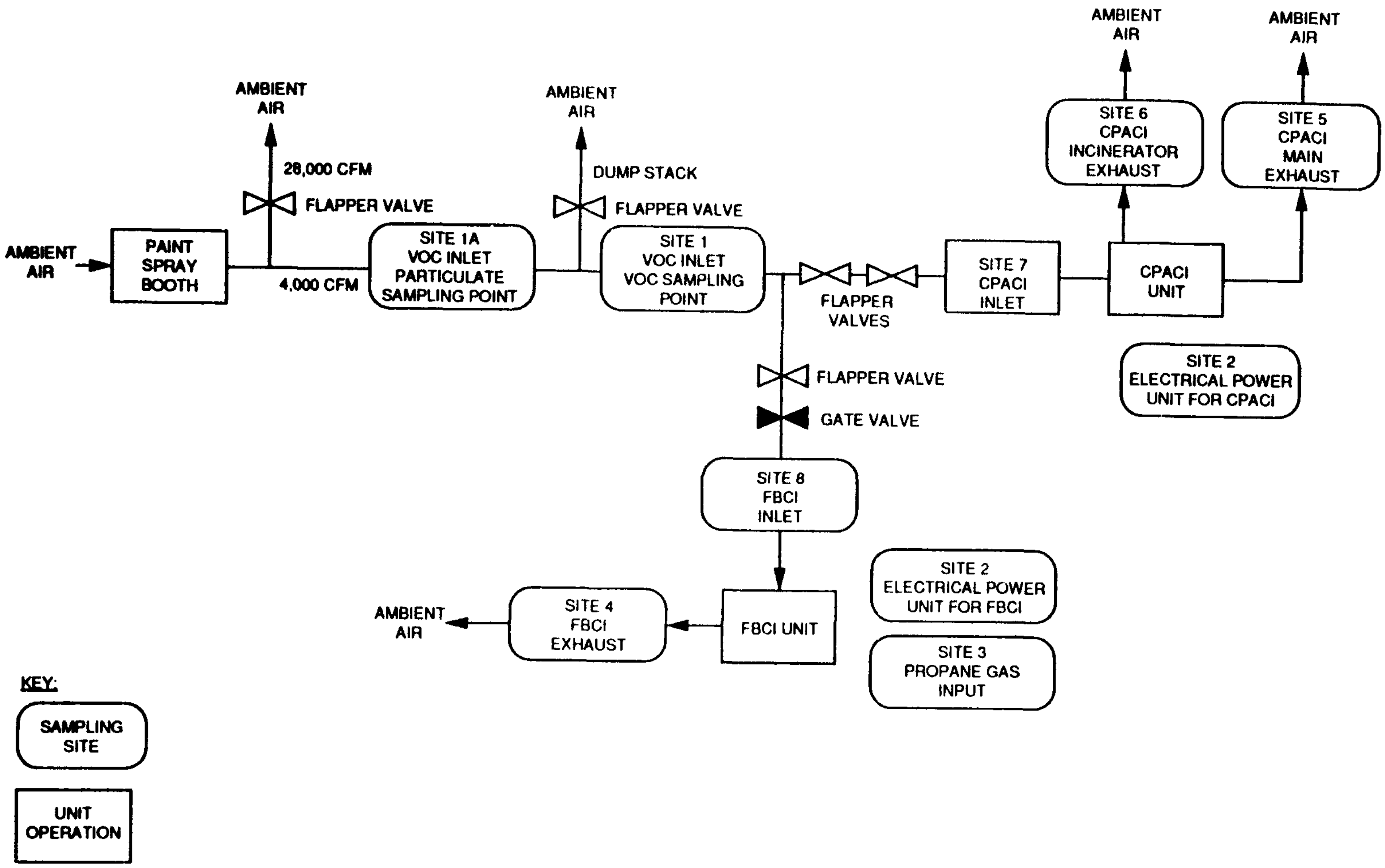

Figure 8. Configuration of Sampling Sites

ambient levels, as was expected. These parameters were recorded on a regular basis at Site 6, the CPACI incinerator exhaust. EPA Methods 3A, 7E, and 10 (References 9, 10, and 11) were used for monitoring CO_2, O_2, NO_x, and CO. TUHC concentrations at both Sites 5 and 6 were measured according to EPA Method 25A specifications (Reference 12). An EPA Method 5 sampling train was used to measure particulate matter concentration at Site 6. Because exhaust from the CPACI carbon paper was not expected to contain any particulate matter (the air is filtered three times before it is vented to the atmosphere), particulate sampling was not done at Site 5. Organic speciations and volume flow rates were determined at both Sites 5 and 6. The test methods used were NIOSH Method 1300 and EPA Method 2.

FBCI exhaust was evaluated for the same parameters as was the CPACI exhaust, and the same sampling methods were used.

The VOC control devices were tested under numerous operating conditions. One objective of the test program was to evaluate the technologies during operating conditions that would promote best-case destruction efficiency, optimum destruction efficiency/operational costs and worst-case operational costs. The high temperature/low flow rate condition was used to demonstrate the best-case destruction efficiency for VOCs. The optimum temperature/optimum flow rate condition was tested as the most efficient operating condition. The high temperature/high flow rate condition demonstrated the worst-case operational cost.

The temperatures and flow rates for the three operating conditions were finalized onsite with input from the vendors, EPA project officer, USAF project officer, and the field test crew chief. Under the direction of these individuals, tests were also run at other operating conditions such as low temperature/high flow rate. These conditions were selected to further characterize each technology's VOC control capability when operating conditions are outside manufacturers' specifications. The operating parameters for each condition varied for the two different VOC control devices due to the design differences of these devices. Table 6 summarizes the desired operating conditions for both control devices.

The actual operating parameters obtained during the test program are summarized in Table 7. This table lists the dates and times that the tests were performed, whether the tests were for organic speciation or particulates and moisture, and the actual flow rates and temperatures obtained in both the CPACI and FBCI units during the test.

B. SYSTEM OPERATION

The temperatures and flow rates were set according to the test matrix agreed upon by the EPA and Air Force project officers, the vendors, and the test crew chief. The FBCI unit was run by an Acurex field crew member after a day of training by the ARI Technologies, Inc., representative. The CPACI unit was run by a pilot engineer from the Met-Pro Corporation.

The flow rates to both the CPACI unit and the FBCI unit were set manually. The VOC inlet stream was split into two 10-inch ducts, each feeding a control device. The duct feeding the

TABLE 6. DESIRED OPERATING CONDITIONS.

Device	Operating Condition	Temperature (°F)	Flow Rate (dscfm)
FBCI	High temperature/low flow rate	>750	<450
FBCI	Optimum temperature/optimum flow rate	650-750	450-550
FBCI	High temperature/high flow rate	>750	>550
CPACI	High temperature/low flow rate	>650	<450
CPACI	Optimum temperature/optimum flow rate	550-650	450-600
CPACI	High temperature/high flow rate	>650	>600

TABLE 7. CHRONOLOGICAL TEST SUMMARY.

Date	Time	Test Type	Run Number	CPACI Flow Rate[a] (dscfm)	CPACI Temperature[a] (°F)	FBCI Flow Rate[a] (dscfm)	FBCI Temperature[a] (°F)
5/10/89	0930-1030	M5	Test-1	300/340	650/640	500/466	700/698
5/10/89	0930-1010	NIOSH	Test-2	300/340	650/640	500/466	700/698
5/10/89	1300-1340	NIOSH	Test-3	500/507	650/665	400/348	950/950
5/10/89	1830-1930	M5	Test-2	500/503	650/625	400/446	950/950
5/10/89	1830-1910	NIOSH	Test-4	500/503	650/625	400/446	950/950
5/11/89	1030-1130	M5	Test-3	400/435	750/600-730	400/402	1250/1000
5/11/89	1035-1115	NIOSH	Test-5	400/435	750/660-730	400/402	1250/1000
5/11/89	1250-1330	NIOSH	Test-6	500/525	650/655-670	500/495	950/950
5/11/89	1655-1755	M5	Test-4	500/517	750/750	500/494	700/700
5/11/89	1700-1740	NIOSH	Test-7	500/517	750/750	500/494	700/700
5/12/89	0915-1015	M5	Test-5	500/529	650/650	500/535	1250/965-1027
5/12/89	0920-1000	NIOSH	Test-8	500/529	650/650	500/535	1250/965-1027
5/12/89	1235-1315	NIOSH	Test-9	600/535	650/660-675	600/691	950/809-805
5/15/89	1035-1135	M5	Test-6	600/626	650/650	Down	Down
5/15/89	1025-1050 1205-1215	NIOSH	Test-10	600/626	650/650	Down	Down
5/15/89	1250-1330	NIOSH	Test-11	700/700	750/750	Down	Down
5/15/89	1700-1800	M5	Test-7	600/601	750/750	Down	Down
5/15/89	1700-1740	NIOSH	Test-12	600/601	750/750	Down	Down
5/16/89	1035-1135	M5	Test-8	400/441	650/650	600/524	1250/1002
5/16/89	1035-1115	NIOSH	Test-13	400/441	650/650	600/524	1250/1002
5/16/89	1235-1315	NIOSH	Test-14	400/405	650/650	600/524	1250/1002
5/17/89	0910-1010	M5	Test-10	700/675	650/650	600/584	700/700
5/17/89	0915-0955	NIOSH	Test-16	700/675	750/650	600/584	700/700
5/17/89	1215-1255	NIOSH	Test-17	700/668	650/650	600/580	700/700
5/17/89	1815-1915	M5	Test-11	600/587	750/750	600/611	775/775

(continued)

[a] Temperatures and flow rates are to be read as: Desired/Actual

[b] Temperature was set initially at 500°F for 25 minutes, then ramped to 700°F for the remainder of the test

TABLE 7. CHRONOLOGICAL TEST SUMMARY (CONCLUDED).

Date	Time	Test Type	Run Number	CPACI Flow Rate[a] (dscfm)	CPACI Temperature[a] (°F)	FBCI Flow Rate[a] (dscfm)	FBCI Temperature[a] (°F)
5/17/89	1815-1855	NIOSH	Test-18	600/587	750/750	600/611	775/775
5/18/89	1035-1135	M5	Test-12	500/517	750/750	300/339	700/706-725
5/18/89	1040-1120	NIOSH	Test-19	500/517	750/750	300/339	700/706-725
5/18/89	1220-1320	M5	Test-13	400/393	750/750	300/297	550/550-557
5/18/89	1825-1905	NIOSH	Test-20	300/279	650/650	600/565	550/550
5/18/89	1840-1940	M5	Test-14	300/279	650/650	600/565	550/550
5/18/89	2115-2215	M5	Test-15	300/303	750/750	600/620	550/550
5/18/89	2120-2200	NIOSH	Test-21	300/303	750/750	600/620	550/550
5/19/89	1230-1330	M5	Test-16	700/715	750/750	300/328	500/550-707[b]
5/19/89	1230-1310	NIOSH	Test-22	700/715	750/750	300/328	500/550-707[b]
5/19/89	1345-1445	M5	Test-17	700/695	650/650	400/396	550/550
5/19/89	1345-1425	NIOSH	Test-23	700/695	650/650	400/369	550/550
5/19/89	1700-1740	NIOSH	Test-24	DID NOT TEST CPACI		600/570	600/595-510
5/19/89	1645-1745	M5	Test-18	DID NOT TEST CPACI		600/570	600/595-510

[a] Temperatures and flow rates are to be read as: Desired/Actual

[b] Temperature was set initially at 500°F for 25 minutes, then ramped to 700°F for the remainder of the test

FBCI unit had a gate valve, which consisted of a steel plate that cut the duct cross-sectionally and could be moved up or down to increase or decrease the flow. The CPACI had a flapper valve for adjusting the flow rates. Flow rates were set by performing a velocity traverse using EPA Method 2 to determine the velocity of the gas stream in the duct. The valves were then adjusted to increase or decrease the flow accordingly, and another velocity traverse was performed. This procedure was repeated until the flow rates to both units were set at the desired levels. Flow rate in each 10-inch duct was monitored and recorded from two to five times during each sampling event.

The temperature on the FBCI unit was regulated through a digital controller. After the set point on the controller was entered by the operator, the system required 30 to 60 minutes to attain its desired temperature.

The temperature control on the CPACI was set manually. Toggle switches controlled three heating elements, rated at 1 kW, 3 kW, and 4 kW respectively, that controlled the temperature of the catalyst. The operator manually monitored the temperature of the catalyst with a thermometer and turned on or shut off the elements accordingly. The operator also set the carbon paper rotor speed based on the system flow rate.

C. PAINTING SCHEDULE

The painting and sampling schedules were coordinated by the Acurex field crew members. A member of the field crew was in close contact with the painters so the crew could be alerted when painting was imminent. Before starting, the painters shut the main doors to the paint spray booth so the flow rates to the control devices could be set by the method described in Section B. This process took no more than 20 minutes, at which time the painting session could begin. The times of the painting sessions and the types of paints being used were recorded in the field notebook. Table 8 summarizes the color of paint used, the military specification, and the date that the paint was used.

D. TEST METHOD DESCRIPTIONS

The sampling methods used during the test program are summarized in Table 5. The EPA methods are described in detail in References 5, 6, and 9 through 12. BAAQMD Method ST-7 is detailed in Reference 7. The NIOSH method used is detailed in Reference 8. Volume flow data were taken using EPA Method 2. In this method, the average gas velocity in the stack is determined from the gas density and from measurement of the average velocity head with a standard or Type S pitot tube. The temperature and static pressure are determined in each duct or stack and the barometric pressure is recorded. Two perpendicular traverses of five points each were made through the duct to record pressure changes. An inclined manometer or a magnehelic gauge was used to measure these pressure changes. All of the information obtained

TABLE 8. PAINTING LOG.

Date	Color	Military Specification
5/10/89	Field Drab	MIL-C-46168D
5/10/89	Green 383 Camouflage	MIL-C-46168D
5/11/89	Wash Primer	GS-10F-51047
5/11/89	Deft Primer	MIL-85582A
5/11/89	Olive Drab	MIL-C-46168C
5/12/89	Green 383 Camouflage	MIL-C-46168D
5/15/89	Wash Primer	GS-10F-51047
5/15/89	Crown Metro Primer	MIL-P-85582A
5/16/89	Gray	unknown
5/16/89	Wash Primer	GS-10F-51047
5/16/89	Deft Primer	MIL-85582A
5/17/89	Deft Primer	MIL-85582A
5/17/89	383 Forest Green	MIL-C-46168D
5/17/89	Field Drab	MIL-C-46168D
5/18/89	Deft Primer	MIL-C-85582A
5/18/89	383 Forest Green	MIL-C-46168D
5/19/89	Field Drab	MIL-C-46168D
5/19/89	383 Forest Green	MIL-C-46168D
5/19/89	White	MIL-HS-8386

was then entered into a computer spreadsheet that utilized the calculations outlined in EPA Method 2. The spreadsheet was used to calculate the average flow rate in the duct.

Organic speciation data were obtained by following NIOSH Method 1300 sample collection procedures. This method involves drawing a known volume of gas through a charcoal adsorbent contained in a glass tube (charcoal tube). The charcoal is then desorbed with a solvent appropriate for the class of compounds under study, and the extract is analyzed by gas chromatography/flame ionization detection (GC/FID). Two charcoal tubes were connected in series to ensure complete sample capture in case breakthrough occurred in the upstream tube. NIOSH Method 1300 specifies the use of a 100-mg/50-mg charcoal tube (100 mg of charcoal in the front section and 50 mg of charcoal in the back section). However, two sizes of charcoal tubes were used during this test. At the VOC emission control inlet (Site 1) a larger, 400-mg/200-mg, tube was used. At the FBCI exhaust, CPACI carbon paper exhaust, and the CPACI incinerator exhaust, 100-mg/50-mg charcoal tubes were used. Sample volumes of 8 liters each were pulled from the incinerator exhaust streams and 40-liter samples were pulled from the VOC inlet stream.

EPA Method 5 was used to measure particulate mass and moisture in the stack gas. This is an isokinetic sampling method that entails a multipoint duct traverse to collect a known volume of sample gas. The gas sample is pulled through a preweighed filter that collects the particulate matter. The gas is then pulled through a series of four impingers to collect any moisture in the gas stream. The gas volume is accurately measured by a dry gas meter. The front half of the sampling train, which contains the preweighed filter, is heated to avoid condensation on the filter. The back half of the train contains the impingers in an ice bath to promote condensation of any liquid in the gas stream. These impingers may either be empty or contain liquid or silica gel. All of the impingers are tared before they are used and weighed after the sampling event. The increase in weight, attributed to moisture collection, can then be used to calculate the moisture content of the gas stream. The filter is desiccated and reweighed to determine the particulates collected. Figure 9 is a schematic of a Method 5 sampling train.

In this test series, the first two impingers each contained 100 mL of distilled water. The third impinger was dry and the fourth impinger contained silica gel. A gas sample volume of approximately 60 cubic feet was collected during each of these tests. Two perpendicular, 30-minute traverses were performed across the cross section of the VOC emission control inlet ducting (Site 1A). Two 30-minute traverses on one axis were performed at the FBCI exhaust stack because only one sampling port existed on the stack. A single-point sample was pulled at the CPACI incinerator exhaust stack due to the configuration of the stack. This stack diameter was only 4 inches, which made multipoint sampling impractical.

Moisture content was measured at the FBCI exhaust, CPACI carbon paper exhaust, and the CPACI incinerator exhaust, when Method 5 data were not obtained. EPA Method 4 was used

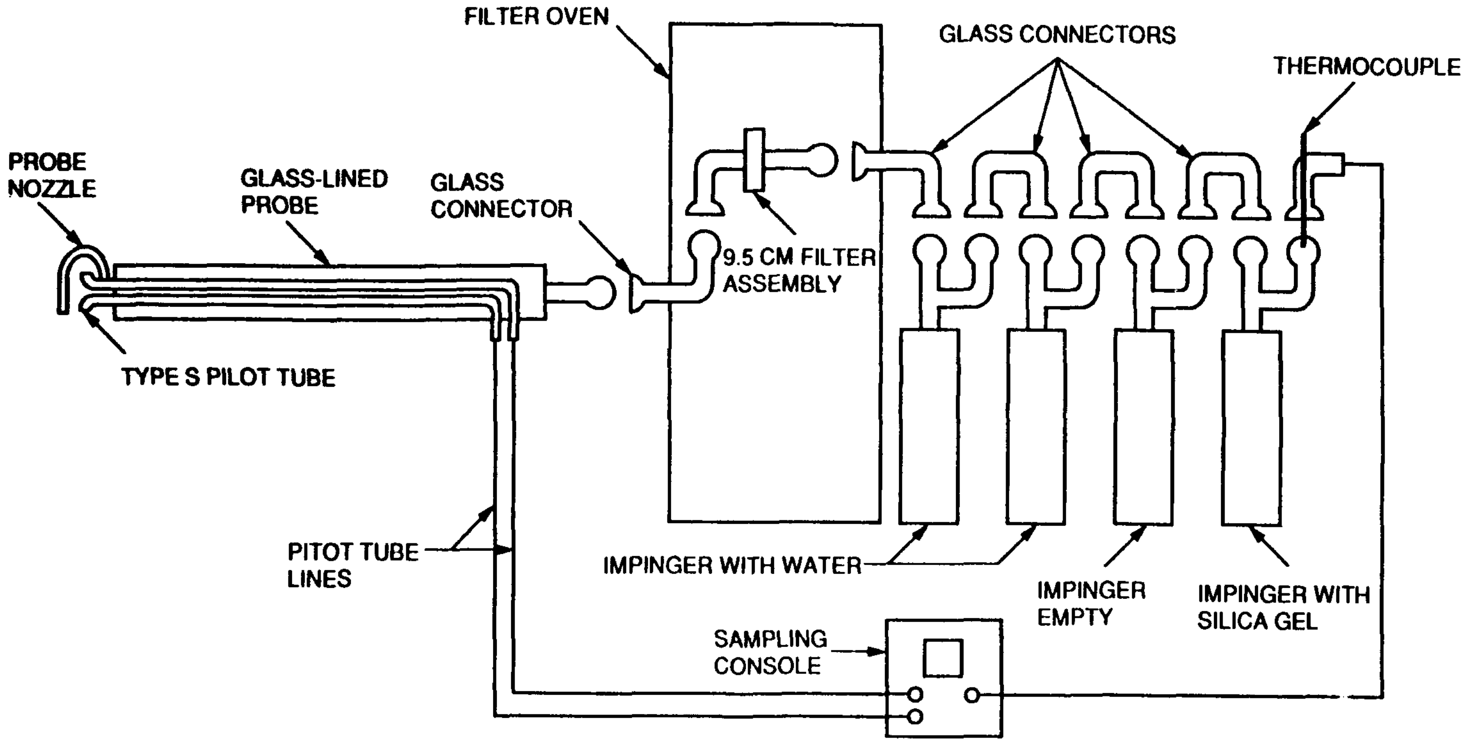

Figure 9. Schematic of EPA Method 5 Sampling System

to obtain this information. This method requires single-point sampling using one empty impinger and one silica gel impinger.

Electricity consumption was measured using a standard watt-hour meter. Propane consumption was measured with a standard dry gas meter. These data were recorded in the field notebook.

Inlet hydrocarbons were analyzed continuously using BAAQMD Method ST-7. The continuous emissions monitor used was a Beckman 400. This unit consists of a tube furnace, which oxidizes organic carbon to CO_2 in the gas stream being analyzed, and uses a nondispersive infrared (NDIR) analyzer, which measures the carbon as CO_2.

Continuous emission monitoring (CEM) was performed on the FBCI exhaust and the CPACI incinerator exhaust. Hydrocarbon concentrations were monitored continuously at the exhaust outlets during testing by EPA Method 25A. This method draws a sample through a heated line to a flame ionization detector. The detector is intermittently zeroed and spanned with zero air and a methane standard, respectively. Two units were used to monitor total unburned hydrocarbons at the FBCI exhaust and the CPACI incinerator exhaust. These units were a Rattfisch and a Horiba F1A-23A.

One set of instruments was alternately used to performed O_2, CO, CO_2, and NO_x testing. Oxygen concentrations were monitored with the Teledyne Analytical 326A monitor, which uses an electrochemical fuel cell. Carbon monoxide levels were measured with a Horiba PIR-2000 NDIR detector. Carbon dioxide levels were monitored with an ANRAD AR500, which also uses an NDIR detector. Nitrogen oxides were measured with a Thermo Electron Corp 10AR monitor, which uses chemiluminescence as its principle of operation. These monitoring instruments were shared between the two incinerator exhaust streams.

SECTION V

PILOT-SCALE TEST RESULTS AND DISCUSSION: TECHNOLOGY PERFORMANCE EVALUATION

To evaluate each technology, it was necessary to calculate DREs and pollutant emission rates for each test. Power consumption by each unit during each testing period was also determined. Results of these tests were then grouped according to the three test conditions described in the work plan and in the preceding section. These conditions are high temperature/low flow rate, optimum temperature/optimum flow rate, and high temperature/ high flow rate. Subsection A contains the results of the paint spray booth emissions testing. Sections B and C present the results for the VOC control devices. Discussions of the test results are also presented in each section.

A. DESCRIPTION OF EXHAUST FROM PAINT SPRAY BOOTH

The VOC-contaminated air stream from the paint spray booth was sampled to establish particulate concentration and hydrocarbon levels. NIOSH sampling was also performed to speciate the VOCs present. Table 9 summarizes the particulate results. Particulate concentrations were low, the maximum value being 0.0044 gr/dscf. The average particulate concentration was 0.002 gr/dscf. Table 10 identifies the VOCs present at detectable levels. The most frequently seen compound was MEK (2-butanone). Continuous emissions monitoring results for inlet hydrocarbon levels are presented in Appendix C (Table C-1). The concentration of hydrocarbons varied, as is expected for the batch nature of the spray painting that generates the air emissions. Observed concentrations of hydrocarbon, as organic carbon, occurred over the range of 30 to 752 ppmv, the average being 132 ppmv.

Hydrocarbon levels correlate with the type of work being performed in the paint spray booth. When wash primer was being sprayed, hydrocarbon levels generally ranged from 30 to 45 ppmv. Higher levels were detected when top coats were being sprayed. The highest hydrocarbon levels were measured when MEK was sprayed directly into the paint booth exhaust stream. This was an attempt to artificially load the units with air high in solvent concentrations.

B. CPACI

VOC emissions from Paint Booth 665 were vented to the CPACI unit. Flow into the unit was monitored and adjusted as necessary. The CPACI was tested at both emission points—the main exhaust (carbon paper) and the incinerator exhaust. Table 11 summarizes the test results for the CPACI.

1. Method 5 Results

EPA Method 5 test results for the CPACI are presented in Table 12. Particulate concentration (gr/dscf) and particulate mass emission rate (lb/hr) were both very low for all tests performed. The highest concentration found was 0.0057 gr/dscf. The maximum mass

TABLE 9. PAINT SPRAY BOOTH EXHAUST PARTICULATE RESULTS.

Date	Run Number	Particulate Emissions gr/dscf	Particulate Emissions lb/hr
5/10/89	M5-01	0.0018	0.02
5/10/89	M5-02	0.0006	0.01
5/10/89	M5-03	0.0018	0.02
5/11/89	M5-04	0.0011	0.01
5/12/89	M5-05	0.0015	0.02
5/15/89	M5-06	0.0038	0.04
5/15/89	M5-07	0.0044	0.05
5/16/89	M5-08	0.0040	0.05
5/16/89	M5-09	0.0020	0.03
5/17/89	M5-10	0.0009	0.01
5/17/89	M5-11	0.0002	0.003
5/17/89	M5-12	0.0015	0.02

TABLE 10. VOCs DETECTED.

Organic Chemicals Present At Detectable Quantities	Paint Spray Booth Exhaust	CPACI Carbon Paper Exhaust	CPACI Incinerator Exhaust	FBCI Exhaust
2-Butanone[a]	X	X	X	
Methoxyacetone	X		X	
4-Methyl-2-pentanone	X			
Toluene	X		X	X
Butyl acetate	X		X	
Ethylbenzene	X		X	
p-Xylene	X			
o-Xylene	X			
2-Ethoxyethyl acetate	X			
2-Methoxyethoxyethanol	X			

[a] MEK (2-butanone) was the most frequently observed organic compound

TABLE 11. CPACI RESULTS SUMMARY.

Run No.[a]	Temperature (°F)	Inlet Flow Rate (dscfm)	Incinerator Exhaust (dscfm)	Main Exhaust (dscfm)	Unit DRE (%)	Organic Emissions (lb VOC/hr)	Particulate Emissions (lb/hr)	Power Usage (Btu/hr)	Power/VOCs Destroyed Ratio (MMBtu/lb VOC destroyed)
Test-2	640	340	35	340	NA	NA	0.0001	NA	NA
Test-3	665	507	40	507	99.4	0.00098	NA	28,300	0.17
Test-4	625	503	40	503	99.6	0.0012	0.0001	43,900	0.15
Test-5	660-730	435	39	435	99.6	0.00041	0.0006	31,600	0.28
Test-6	665-670	525	38	525	>99.6	0.00040	NA	31,900	0.35
Test-7	750	517	40	517	>98.8	0.00045	0.0016	NA	NA
Test-8	650	529	40	529	>99.5	0.00085	0.0025	8,500	0.050
Test-9	660-675	535	42	535	>96.9	0.0013	NA	34,200	0.83
Test-10	650	626	42	626	98.8	0.0075	0.0001	NA	NA
Test-11	750	700	28	700	>98.6	0.0020	NA	23,800	0.33
Test-12	750	601	41	601	>99.6	0.00055	0.0011	40,700	0.31
Test-13	650	441	39	441	>99.1	0.00043	0.0008	37,600	0.20
Test-14	650	405	38	405	98.1	0.00066	NA	37,600	0.21
Test-16	650	675	43	675	>99.5	0.00072	0.0004	51,200	0.90
Test-17	650	668	43	668	>99.7	0.00072	NA	34,200	0.44
Test-18	750	587	33	587	>99.8	0.00052	0.0003	39,800	0.80
Test-19	750	517	41	517	>99.1	0.00045	0.0003	37,600	0.79
Test-20	650	279	32	279	>98.9	0.00028	NA	34,800	0.37
Test-21	750	303	27	303	>99.7	0.00023	NA	27,000	0.27
Test-22	750	715	44	715	>99.8	0.00041	NA	49,000	0.034
Test-23	650	695	41	695	NA	NA	NA	43,600	NA

[a] Test-1 was a background test

[b] Test-15 was aborted

NA—Not available

TABLE 12. CPACI: PARTICULATE RESULTS.

Date	Run Number	Flow Rate (dscfm)	Temperature (°F)	Particulate Emissions	
				gr/dscf	lb/hr
5/10/89	M5-01	340	640	0.0002	0.0001
5/10/89	M5-02	503	625	0.0001	0.0001
5/10/89	M5-03	435	660-730	0.0017	0.0006
5/11/89	M5-04	517	750	0.0047	0.0016
5/12/89	M5-05	529	650	0.0057	0.0025
5/15/89	M5-06	626	650	0.0003	0.0001
5/15/89	M5-07	601	750	0.0037	0.0011
5/16/89	M5-08	441	650	0.0027	0.0008
5/17/89	M5-10	675	650	0.0014	0.0004
5/17/89	M5-11	587	750	0.0010	0.0003
5/18/89	M5-12	517	750	0.0011	0.0003

emission rate was 0.0025 lb/hr. Both occurred during a test in which the operating temperature was 650°F and the influent flow rate was 529 dscfm. Minimum particulate concentration and mass emission rates were 0.0001 gr/dscf and 0.0001 lb/hr, respectively. These occurred when the operating temperature was 625°F and the influent flow rate was 503 dscfm. The average particulate concentration was 0.0020 gr/dscf. The average particulate mass emission rate was 0.0007 lb/hr. These averages include results gathered from sampling the CPACI over a wide range of operating conditions.

2. NIOSH Method 1300 Test Results

NIOSH tests were performed at the carbon paper exhaust and at the incinerator exhaust. Results of the analyses of charcoal tubes collected at these points were used to speciate the organic compounds in the exhaust of the CPACI; they were not used to quantify individual VOC emission levels.

Samples collected at the carbon paper adsorber exhaust point consistently contained VOC levels below the sensitivity of the analytical technique (0.1 to 10 ppb). Only 2 of 23 tests run showed any measurable VOCs. Tests 10 and 23 showed MEK. NIOSH charcoal tubes collected at the CPACI incinerator exhaust had measurable quantities of VOCs in 16 of the 23 tests performed. The organic compound found most frequently and at the highest concentrations was MEK. Other compounds found are listed in Table 10. Laboratory analytical reports and tables of VOC concentrations are available upon request from EPA or Acurex.

3. Continuous Emissions Monitoring Results

EPA Method 25A was used to measure the total unburned hydrocarbon (TUHC) from both emission points of the CPACI (Table 13). TUHC measurements from the carbon paper adsorber were usually below the detectable limit (0.5 ppmv). On 15 May 1989, during NIOSH test Number 10 (NIOSH-10), the TUHC level was 6.7 ppmv. TUHC measurements made at the CPACI incinerator exhaust were below 10 ppm for over 65 percent of the tests. Maximum values seen were 53 and 47.2 ppmv. The minimum values found were 1.9 ppmv and a measurement that was below the detectable limit.

4. Destruction and Removal Efficiencies (DREs)

The results of the NIOSH 1300 tests and the CEM measurements were used to calculate DREs for the CPACI. DREs were calculated for both CPACI emission points and for the unit as a whole. Table 11 displays the DREs for the whole CPACI. Thirteen of the 19 DREs calculated were greater than 99 percent. Five of the remaining calculated DREs were greater than 98 percent. Most of the DREs (including the lowest one, >96.9 percent) are the largest volumes allowed by the calculation (i.e., the hydrocarbon emission levels were below detectable levels). This procedure enables only a minimum value of the DRE to be calculated. Thus, these values are preceded by the "greater than" (>) sign.

TABLE 13. CPACI: TUHC RESULTS.

Date	Run Number	Actual Flow Rate (dscfm)	Actual Temperature (°F)	TUHC Carbon Bed (ppmv)	TUHC Incinerator (ppmv)
5/10/89	Test-2	340	640	NA	0.5
5/10/89	Test-3	507	665	NA	27.9
5/10/89	Test-4	503	625	NA	33.1
5/11/89	Test-5	435	660-730	0.6	5.2
5/11/89	Test-6	525	665-670	0.5	7.6
5/11/89	Test-7	517	750	0.5	6.9
5/12/89	Test-8	529	650	0.5	17.3
5/12/89	Test-9	535	660-675	0.5	29.6
5/15/89	Test-10	626	650	6.7	47.2
5/15/89	Test-11	700	750	0.5	53.0
5/15/89	Test-12	601	750	0.5	7.7
5/16/89	Test-13	441	650	0.5	6.7
5/16/89	Test-14	405	650	1.4	4.4
5/17/89	Test-16	675	650	0.5	11.7
5/17/89	Test-17	668	650	0.5	11.8
5/17/89	Test-18	587	750	0.5	7.6
5/18/89	Test-19	517	750	0.5	2.3
5/18/89	Test-20	279	650	0.5	3.9
5/19/89	Test-21	303	750	NA	4.2
5/19/89	Test-22	715	750	0.5	1.9
5/19/89	Test-23	695	650	NA[a]	NA[a]

[a] Unit overheated

NA—Not available. Data were not collected.

Removal efficiencies for the CPACI carbon paper rotor are presented in Appendix B; Table C-2 shows that the paper rotor achieved removal efficiencies of >99 percent for all tests performed except one. That exception had a removal efficiency of 98.5 percent.

DREs for the CPACI incinerator are also presented in Table C-2. Only two values were lower than 99 percent. The DRE for the testing event NIOSH-9 was 97.4 percent. DRE during the testing event NIOSH-11 was 98.8 percent.

5. Power Usage Results

Power consumption by the CPACI is summarized in Table 11. Consumption rates that were calculated for each test are reported in Btu/hr to standardize the data. The rates ranged from a low of 8,500 Btu/hr to a high of 51,200 Btu/hr. The low occurred during a test in which the unit was operating at a temperature of 650°F and an influent flow rate of 529 dscfm (Test-8, Table 11). The highest rate occurred when the system was operating at a temperature of 650°F and 675 dscfm.

Power consumption of the CPACI was also evaluated on a daily basis. Table 14 presents these data. Daily power usage numbers average the many conditions under which the CPACI was operating each day. The maximum daily power consumption, 79,800 Btu/hr, occurred on 19 May 1989.

6. Discussion

Particulate concentration from the CPACI averaged 0.002 gr/dscf. This concentration is below the RCRA limit of 0.08 gr/dscf (Reference 13). Examination of the particulate data in Table 12 reveals no correlation between the flow rate and particulate concentration or between temperature and particulate concentration. The CPACI design does not contribute to particulate emissions. The solvent-laden air is prefiltered to remove any particulate matter. Exhaust from the carbon paper rotor was, therefore, not expected to have any particulate matter and was not subjected to Method 5 sampling. The CPACI incinerator exhaust was also not expected to have a significant concentration of particulate matter. Air flow rate to the incinerator is very low, between 30 and 70 dscfm. This air is ambient air and presumably low in particulate concentration. These factors contribute to the very low particulate concentration and emission rates from the CPACI incinerator exhaust gas and the entire CPACI.

NIOSH test results were combined with the CEM hydrocarbon data to determine the mass emission rate of VOCs for the CPACI. Organic emissions for each test are listed in Table 11. The largest emission rate was 0.0075 lb/hr of VOCs. This happened during highest solvent loading to the unit, 0.641 lb/hr VOCs. The CPACI was operating at 650°F and 626 dscfm. These operating parameters are at the upper end of the pilot-scale unit's temperature and flow rate ranges of 625°F and 700 dscfm. Exhaust from the carbon paper adsorber contained most of the solvent loading in this case, 0.005 lb/hr. This test, NIOSH-10,

TABLE 14. DAILY POWER USAGE TOTALS.

Date	CPACI Unit				FBCI Unit		
	Time (hr)	Power Used (kW-hr)	Rate of Usage (kW)	Rate of Usage (Btu/hr)	Time (hr)	Propane Used (ft^3)	Rate of Usage (Btu/hr)
5/08/89	Unit	--------------Shut Down-------------			7.05	1460	473,000
5/09/89	7.42	80.00	10.78	36,800	8.00	1310	374,000
5/10/89	9.92	101.00	10.18	34,800	13.10	2500	436,000
5/11/89	9.00	101.50	11.28	38,500	10.90	2240	469,000
5/12/89	5.50	84.25	15.32	52,300	5.78	1660	656,000
5/15/89	3.30	23.00	6.97	23,800	13.50	2750	465,000
5/16/89	13.75	150.50	10.95	37,400	12.50	2580	471,000
5/17/89	13.50	166.50	12.33	42,100	13.50	2640	446,000
5/18/89	11.95	112.00	9.37	32,000	7.75	1300	383,000
5/19/89	8.02	187.50	23.38	79,800	9.36	1220	298,000

was the only test in which a noticeable hydrocarbon concentration was found in the carbon paper adsorber exhaust. During this test period, MEK was sprayed directly into the exhaust ducts of the paint spray booth. There was a resultant hydrocarbon spike of 69 ppmv in the carbon paper exhaust. The implication is that the carbon paper rotor may be saturated by a high VOC concentration in a volume of air moving through the system in a plug flow fashion. Overall, the CPACI had very low organic emission rates, as seen in Table 11.

The main reason for the low VOC emission rates appears to be the consistent 98 to 99 percent DREs that the CPACI achieved. Review of the data in Table 11 shows that 98 percent and 99 percent DREs were consistently obtained by the CPACI under a variety of operating conditions. No significant correlations could be made between DREs, operating temperatures and flow rates. Even during periods of heavier solvent loading and high flow rates, DREs were greater than 98 percent.

Power usage for the CPACI appears to be low. This is expected since only 30 to 70 dscfm of air needs to be heated. The air that is heated contains concentrated VOCs, which can add energy to the system when combusted. There are also no correlations between influent flow rate and power usage. Since the energy being used is heating the desorption air and not the whole influent gas, this is expected. The data in Table 11 reveal a relationship between Btu/hr and desorption airflow rate. (The incinerator exhaust flow rate is the same flow rate as the desorption air flow rate.) When the desorption airflow rate was between 30 and 45 dscfm, the power consumption was usually greater than 30,000 Btu/hr. During tests in which the desorption airflow rate was less than 30 dscfm, the power consumption was less than 30,000 Btu/hr.

Temperature comparisons with power usage do not show a general trend of increasing power consumption with increasing operating temperature. This is probably a result of not having enough data points to evaluate the relationship adequately. The CPACI was operated mainly at three temperatures—625, 650 and 750°F.

Power consumption information was combined with data regarding the mass of VOCs destroyed to calculate a ratio of power consumed per pound of VOCs destroyed (MMBtu/lb VOCs destroyed). These ratios are shown for each test in Table 11. Table 15 shows the Power/VOCs Destroyed Ratio (PVDR) values by test condition, solvent loading and power usage. PVDRs are relevant for comparison purposes when solvent waste stream loading is similar. Within these constraints, the loading into the CPACI was similar, on the average, for two operating conditions. These conditions, Test Condition 1 and Test Condition 2, correspond to high temperature/low flow rate and optimum temperature/optimum flow rate (manufacturer-suggested) parameters. Respective PVDRs for these two conditions are 0.38 and 0.29 MMBtu/lb VOCs destroyed. Since the CPACI was operating at a lower temperature during Test

TABLE 15. CPACI: POWER/VOCs DESTROYED RATIOS.

Date	Test Run No.	Condition No.[a]	Inlet (lb VOC/hr)	Outlet (lb VOC/hr)	VOCs Destroyed (lb VOC/hr)	Fuel Usage Rate (Btu/hr)	Power/VOCs Destroyed Ratio (MMBtu/lb VOC Destroyed)
5/10/89	Test-3	2	0.16	0.00098	0.16	28,200	0.17
5/10/89	Test-4	2	0.29	0.0012	0.29	43,900	0.15
5/11/89	Test-5	1	0.11	0.00041	0.11	31,600	0.28
5/11/89	Test-6	2	0.094	0.00040	0.094	31,900	0.34
5/12/89	Test-8	2	0.17	0.00085	0.17	8,540	0.049
5/12/89	Test-9	2	0.042	0.0013	0.041	34,200	0.84
5/15/89	Test-11	3	0.073	0.0020	0.071	23,800	0.34
5/15/89	Test-12	3	0.13	0.00055	0.13	40,700	0.31
5/16/89	Test-13	2	0.18	0.00043	0.18	37,600	0.21
5/16/89	Test-14	1	0.18	0.00066	0.18	37,600	0.21
5/17/89	Test-16	3	0.057	0.00072	0.056	51,200	0.91
5/17/89	Test-17	3	0.077	0.00072	0.076	34,200	0.45
5/17/89	Test-18	3	0.050	0.00052	0.049	39,800	0.81
5/18/89	M5-13	1	0.048	0.00045	0.048	37,600	0.79
5/18/89	Test-20	1	0.094	0.00028	0.094	35,000	0.37
5/18/89	Test-21	1	0.10	0.00023	0.10	27,000	0.27
5/19/89	Test-22	3	1.5	0.00041	1.5	49,000	0.034
5/19/89	Test-23	3	0.39	NA	NA	43,600	NA

[a] Test Conditions:
1. High temperature/low flow rate (>650°F, <450 dscfm)
2. Optimum temperature/optimum flow rate (550 to 650°F, 450 to 600 dscfm)
3. High temperature/high flow rate (>650°F, >600 dscfm)

NA—Not available

Condition 2, it is expected that less power was being used. Operating the CPACI under optimal conditions used less power to destroy the same amount of VOCs compared with operating the system at higher temperatures. However, the DRE (Tables 16 and 17) is the same under both conditions (>99 percent).

Tables 16 through 18 average the test results for the sampling events that happened during three specific test conditions, Test Condition 1, Test Condition 2, and Test Condition 3. Comparison of the three tables elicits the following observations. Fuel usage was lowest for tests run at optimal temperature and flow rate conditions. Particulate mass emission rates are 0.001 lb/hr or less for each condition. Organic mass emission rates, although low, increased from Test Condition 1 to Test Condition 3. This is expected since Test Condition 1 reflects a best destruction situation, lower solvent loading and high temperature. Test Condition 3 characterizes a worst-performance condition, high loading of the carbon paper adsorber. Despite the different operating conditions, DREs for all test conditions were greater than 99 percent.

The carbon paper adsorber/catalytic incinerator, at the pilot scale, does not have any significant pollutant emissions and can consistently achieve DREs in the 98 to 99 percent range. Operating temperatures and desorption flow rates do affect power consumption. Power consumption in general is low for this treatment technology. Concentration of the solvent wastes into a smaller air stream reduces the power needed for satisfactory destruction.

C. FBCI

VOC emissions from the booth were vented to the FBCI unit. Monitoring was performed at the VOC inlet and at the FBCI exhaust. Flow rates were monitored at each of these points. FBCI test results are summarized in Table 19.

1. Method 5 Results

EPA Method 5 test results for the FBCI are summarized in Table 20. In general, particulate concentration (gr/dscf), and particulate mass emission rate (lb/hr) were found to be below RCRA specifications (0.08 gr/dscf). Test M5-05 (NIOSH-8) had the maximum particulate emission rate of 0.23 lb/hr, corresponding to a concentration of 0.035 gr/dscf. For this test, FBCI flow rates were 535 dscfm and temperatures ranged from 965 to 1027°F. The minimum particulate mass loading (0.01 lb/hr) and concentration (0.015 gr/dscf) occurred during Test M5-12, in which the system was operating at a flow rate of 339 dscfm and a temperature range of 706 to 725°F.

2. NIOSH Method 1300 Test Results

NIOSH Method 1300 tests were performed at the FBCI exhaust for all runs, with the exception of Test M5-13. Results of the analyses of charcoal tubes collected at this point were used to speciate the organic compounds in the exhaust stream. Table 10 lists the organic compounds found in the flue gas. The average detection limit for the 400-mg/200-mg charcoal tubes was 0.65 ppb; the average detection limit for the 100-mg/50-mg charcoal tubes was

TABLE 16. TEST AVERAGES: CPACI TEST CONDITION 1[a].

Date/ Time	Run Number	Flow Rate (dscfm)	Temp. (°F)	Rate of Usage (Btu/hr)	DRE (%)	Particulate Emissions (lb/hr)
5/11/89 1030-1130	Test-5 (M5-3)	435	695	31,600	99.6	0.0006
5/16/89 1235-1315	Test-14	405	650	37,600	98.1	NA
5/18/89 1220-1320	M5-13	393	750	37,600	98.7	NA
5/18/89 1825-1940	Test-20 (M5-14)	279	650	34,800	>98.9	NA
5/18/89 2115-2215	Test-21 (M5-15)	303	750	27,000	>99.7	0.0003
Average:		363	699	33,700	>99.0	0.00045

[a] High temperature/low flow rate (>650°F, <450 dscfm)

NA—Not available. Particulate samples not collected.

TABLE 17. TEST AVERAGES: CPACI TEST CONDITION 2[a].

Date/ Time	Run Number	Flow Rate (dscfm)	Temp. (°F)	Rate of Usage (Btu/hr)	DRE (%)	Particulate Emissions (lb/hr)
5/10/89 1300-1340	Test-3	507	665	28,200	99.4[b]	NA
5/10/89 1830-1930	Test-4 (M5-2)	503	625	43,900	99.6[b]	0.0001
5/11/89 1250-1330	Test-6	525	663	31,900	>99.6	NA
5/12/89 0915-1015	Test-8 (M5-5)	529	650	8,540	>99.5	0.0025
5/12/89 1235-1315	Test-9	535	668	34,200	>96.9	NA
5/16/89 1035-1135	Test-13 (M5-8)	441	650	37,600	>99.1	0.0008
Average:		507	654	30,700	>99.0	0.001

[a] Optimum temperature/optimum flow rate (550 to 650°F, 450 to 600 dscfm)

[b] Number reflects CPACI incinerator DRE only; the CPACI carbon paper exhaust was not monitored

NA—Not available. Particulate samples not collected.

TABLE 18. TEST AVERAGES: CPACI TEST CONDITION 3[a].

Date/ Time	Run Number	Flow Rate (dscfm)	Temp. (°F)	Rate of Usage (Btu/hr)	DRE (%)	Particulate Emissions (lb/hr)
5/15/89 1230-1330	Test-11	700	750	23,800	>98.6	NA
5/15/89 1700-1800	Test-12 (M5-7)	601	750	40,700	>99.6	0.001
5/17/89 0910-1010	Test-16 (M5-10)	675	650	51,200	>99.5	0.0004
5/17/89 1215-1255	Test-17	668	650	34,200	>99.7	NA
5/17/89 1815-1915	Test-18 (M5-11)	587[b]	750	39,800	>99.8	0.0003
5/19/89 1230-1330	Test-22 (M5-16)	715	750	49,000	>99.8	NA
Average:		658	717	39,800	>99.5	0.0006

[a] High temperature/high flow rate (>650°F, >600 dscfm)

[b] Flow rate fluctuations occurred during the test, which brought the average down to below 600 dscfm. The data point was included since the flow rate is close to 600 dscfm and within the Standard Deviation of ±19 for that test.

NA—Not available

TABLE 19. FBCI RESULTS SUMMARY.

Run No.[*]	Inlet Temperature (°F)	Outlet Flow Rate (dscfm)	Unit Flow Rate (dscfm)	Organic DRE (%)	Organic Emissions (lb VOC/hr)	Particulate Emissions (lb/hr)	CO (ppmv)	NO_x (ppmv)
Test-2	698	466	720	99.0	0.0013	0.01	43	10.7
Test-3	950	348	543	>99.8	0.00024	NA	58	19.3
Test-4	950	446	543	>99.9	0.00024	0.03	56	10.7
Test-5	1000	402	553	>99.8	0.00025	0.07	45	NA
Test-6	950	495	679	>99.7	0.00025	NA	NA	NA
Test-7	700	494	679	>99.2	0.00029	0.10	16	NA
Test-8	965-1027	535	773	>99.8	0.00035	0.23	21	NA
Test-9	809-805	691	948	>99.2	0.00042	NA	40	NA
Test-13	1002	524	684	99.2	0.00053	0.12	19	20.0
Test-14	1002	524	684	>99.3	0.00038	NA	NA	NA
Test-16	700	584	794	>99.7	0.00036	0.14	75	12.3
Test-17	700	580	794	>99.9	0.00037	NA	NA	NA
Test-18	775	611	794	99.2	0.0022	0.20	99	11.3
Test-19	706-725	339	438	>99.3	0.00019	0.01	37	11.8
M5-13	550-557	279	423	98.7	0.00043	0.02	68	9.9
Test-20	550	565	726	97.7	0.0011	0.11	68	10.1
M5-14	550	565	726	99.4	0.0011	0.11	68	10.1
Test-21	550	620	771	99.7	0.00056	0.12	90	9.0
Test-22	550-707	328	638	>99.7	0.00029	0.04	59	11.6
Test-23	550	369	639	99.6	0.0033	0.04	110	8.4
Test-24	595-510	570	723	99.8	0.00081	0.05	88.6	7.0

[*] Test-1 was a background test. The FBCI was not operational during Tests-10, -11, and -12. Test-15 was not used due to sporadic painting.

NA—Not available

TABLE 20. FBCI: PARTICULATE RESULTS.

Date	Run Number	Flow Rate (dscfm)	Temperature (°F)	Particulate Emissions	
				gr/dscf	lb/hr
5/10/89	M5-01	466	698	0.0021	0.01
5/10/89	M5-02	446	950	0.0073	0.03
5/10/89	M5-03	402	1000	0.014	0.07
5/11/89	M5-04	494	700	0.017	0.10
5/12/89	M5-05	535	965-1027	0.035	0.23
5/16/89	M5-08	524	1002	0.021	0.12
5/17/89	M5-10	584	700	0.021	0.14
5/17/89	M5-11	661	775	0.029	0.20
5/18/89	M5-12	339	706-725	0.0015	0.01
5/18/89	M5-13	297	550-557	0.0042	0.02
5/18/89	M5-14	565	550	0.018	0.11
5/18/89	M5-15	620	550	0.018	0.12
5/19/89	M5-16	328	550-707	0.0078	0.04
5/19/89	M5-17	369	550	0.0075	0.04
5/19/89	M5-18	570	595-510	0.0084	0.05

1.7 ppb. NIOSH Method 1300 results revealed only one instance in which concentrations at the FBCI exhaust were above the method detection limits. During Test-23, toluene was detected at a concentration of 2.0 ppb.

3. Continuous Emissions Monitoring Results

Continuous emissions monitoring of the FBCI unit was performed at the exhaust. EPA Method 25A was used to monitor TUHC at the FBCI exhaust. The exhaust gases CO, CO_2, O_2 and NO_x were also continuously monitored. Results are summarized in Table 21.

Continuous monitoring of the exhaust gases CO and NO_x demonstrated concentrations that were consistently below general RCRA regulatory specifications for incinerators (Reference 13). NO_x values ranged from 7.0 to 20.0 ppmv, with an average of 11.6 ppmv. CO concentrations ranged from 16 to 110 ppmv, with an average value of 59 ppmv; the maximum occurred during Test-23, when MEK was sprayed directly into the inlet stream. Monitoring of CO_2 and O_2 showed averages of 1.4 and 20.0 percent respectively.

4. Destruction and Removal Efficiencies (DREs)

DREs were calculated for the FBCI for a total of 21 tests. NIOSH 1300 data were used to find the percent composition of the organic constituents in the influent waste stream. Calculated DREs are summarized in Table 19. DREs for the FBCI were consistently greater than 99 percent. The only exceptions occurred during Test-21 and Test M5-13, for which the respective DREs were 97.7 percent and 98.7 percent.

5. Power Usage Results

The propane gas usage for the FBCI was monitored continuously with a dry gas meter. Readings were taken periodically during each test. The daily power usage for the FBCI unit is summarized in Table 14. Results of the fuel usage, by test condition, are shown in Table 22.

A maximum average daily rate of power usage of 656,000 Btu/hr occurred on 12 May 1989. Two tests were run on this date, at flow rates of 691 dscfm and 535 dscfm, respectively. Minimum average daily power usage, 298,000 Btu/hr, occurred on 19 May 1989. Three tests were run on this date, at flow rates of 328 dscfm, 369 dscfm and 570 dscfm, respectively.

For individual tests, the maximum power usage rates occurred during Test-7 and Test-9 and were each greater than 540,000 Btu/hr. Operating conditions were 494 dscfm and 700°F for Test-7, and 691 dscfm and 807°F for Test-9. Minimum power usage, 37,000 Btu/hr, occurred during Test-2, for which operating conditions were 466 dscfm and 698°F.

6. Discussion

M5 results show that there is a clear correlation between flow rate and particulate loading. Figure 10 shows that flow rates above 500 dscfm do result in greater particulate emissions. Six tests were performed in which flow rate conditions were greater than 500 dscfm. These tests resulted in an average particulate loading of 0.14 lb/hr. In eight tests for which the

TABLE 21. FBCI: CONTINUOUS EMISSIONS MONITORING RESULTS SUMMARY.

				Emissions				
Date	Run Number	Actual Flow Rate (dscfm)	Actual Temperature (°F)	CO (ppmv)	CO_2 (%)	O_2 (%)	NO_x (ppmv)	TUHC (ppmv)
5/10/89	Test-2	466	698	43	2.2	20.2	10.7	2.1
5/10/89	Test-3	348	950	58	0.6	19.8	19.3	0.5
5/10/89	Test-4	446	950	56	0.9	20.1	10.7	0.5
5/11/89	Test-5	402	1000	45	0.3	19.0	NA	0.5
5/11/89	Test-6	495	950	NA	NA	NA	NA	0.5
5/11/89	Test-7	494	700	16	1.5	20.5	NA	0.5
5/12/89	Test-8	535	965-1027	21	0.7	18.5	NA	0.5
5/12/89	Test-9	691	809-805	40	1.1	20.4	NA	0.5
5/16/89	Test-13	524	1002	19	2.3	20.1	20.0	0.7
5/16/89	Test-14	524	1002	NA	NA	NA	NA	0.5
5/17/89	Test-16	584	700	75	1.8	20.1	12.3	0.5
5/17/89	Test-17	580	700	NA	NA	NA	NA	0.5
5/17/89	Test-18	661	775	99	2.0	19.4	11.3	3.1
5/18/89	Test-5-13	297	550-557	68	1.2	20.1	9.9	1.2
5/18/89	Test-19	339	706-725	37	1.7	19.4	11.8	0.5
5/18/89	Test-20	565	550	68	1.1	20.7	10.1	1.6
5/18/89	Test-21	620	550	90	1.3	20.7	9.0	0.7
5/19/89	Test-22	328	550-707	59	1.7	20.7	11.6	0.5
5/19/89	Test-23	369	550	110	1.5	20.7	8.7	5.8
5/19/89	Test-24	570	595-510	89	1.3	20.1	7.0	1.3

NA—Not available

TABLE 22. FBCI: POWER/VOCs DESTROYED RATIOS.

Date	Test Run No.	Condition No.[a]	Inlet (lb VOC/hr)	Outlet (lb VOC/hr)	VOCs Destroyed (lb VOC/hr)	Fuel Usage Rate (Btu/hr)	Power/VOCs Destroyed Ratio (MMBtu/lb VOC Destroyed)
5/10/89	Test-2	2	0.13	0.00130	0.13	370,000	3.0
5/10/89	Test-3	1	0.11	0.00024	0.11	434,000	3.9
5/10/89	Test-4	1	0.26	0.00024	0.26	490,000	1.9
5/11/89	Test-5	1	0.10	0.00025	0.10	525,000	5.1
5/11/89	Test-7	2	0.89	0.00029	0.088	548,000	6.2
5/12/89	Test-9	3	0.055	0.00042	0.054	548,000	10
5/17/89	Test-18	3	0.28	0.00220	0.27	498,000	1.8

[a] Test Conditions:
1. High temperature/low flow rate (>750°F, <450 dscfm)
2. Optimum temperature/optimum flow rate (650 to 750°F, 450 to 550 dscfm)
3. High temperature/high flow rate (>750°F, >550 dscfm)

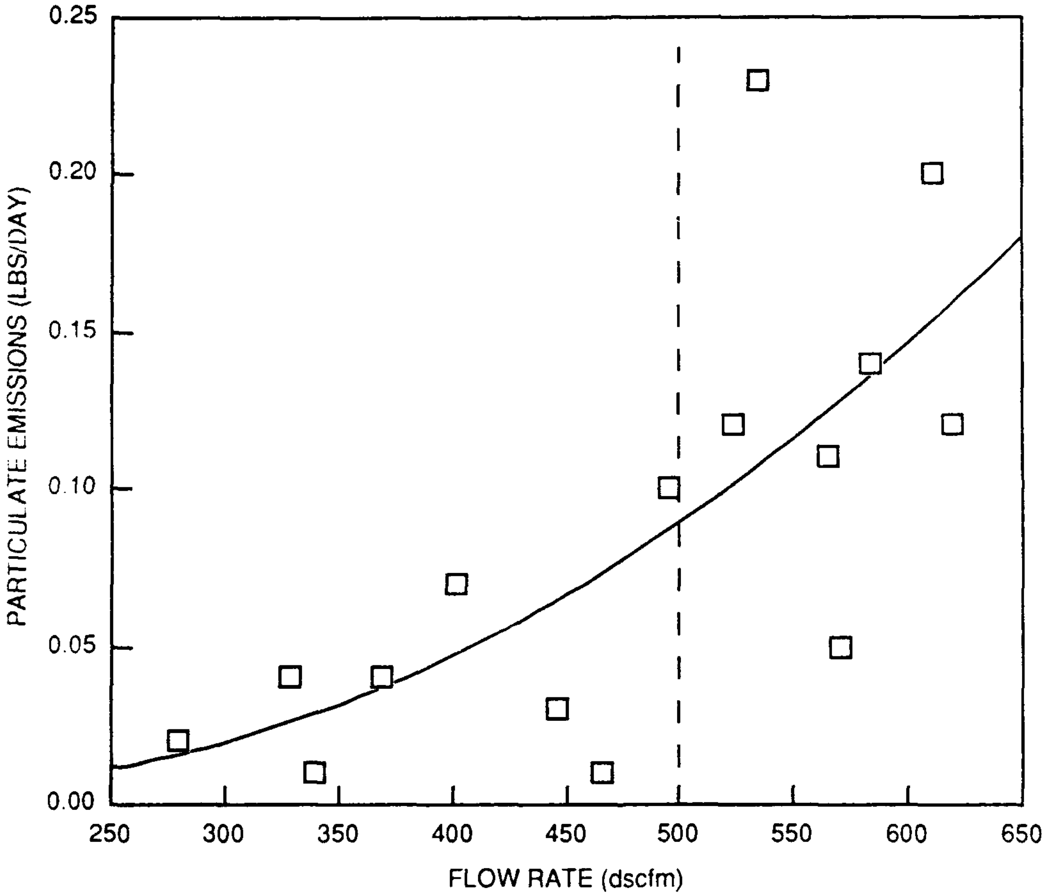

Figure 10. Flow Rate Versus Particulate Emissions

flow rate was less than 500 dscfm, the average emission rate was 0.04 lb/hr. Operating at high flow rates, especially above those established by the manufacturer of an FBCI, can result in the entraining of catalyst by the flue gas. Visual inspections of the M5 filters collected at these conditions confirms this. These filters had a thick, grey powder on them. The powder is suspected to be catalyst, but analytical testing of the filters was not performed to confirm this.

NIOSH Method 1300 test results were combined with the continuous emissions monitoring hydrocarbon data to determine the mass emission rate of VOCs for the FBCI. The main purpose for collecting data by NIOSH sampling methods was to determine the speciation of the organics present in the gas streams. This information was then used to calculate the pounds of VOCs emitted. In general, NIOSH test results for the FBCI exhaust were consistently below method detection limits.

The FBCI unit showed greater than 99 percent DRE for 19 of the 21 tests performed. One of the best DREs occurred during Test-23, when the maximum inlet concentration of VOCs was introduced. During this test, MEK was sprayed directly into the inlet stream for 15 minutes. Hydrocarbon levels of as high as 4000 ppmv were recorded during the test period, resulting in an overall average of 752 ppmv. These high inlet concentrations were accompanied by detectable TUHC emissions at the FBCI exhaust, from which the DRE was calculated to be 99.6 percent. Low VOC levels at the inlet allow detection limits at the FBCI exhaust to affect DRE calculations. This is the case for Test-20 and Test M5-13, for which DREs below 99 percent were calculated.

The dependence of power usage on temperature and flow rate for individual tests was evaluated. Review of Table 22 shows no consistent correlations are apparent. When power usage is examined for the specific test conditions, some trends are noticed (see Tables 23 through 25). A minimum value of 459,000 Btu/hr occurred when the system was running under optimum conditions (Table 24). Higher consumptions were observed when conditions of greater temperature and higher flow rates were introduced. Test Condition 1 (high temperature/low flow rate) resulted in an average of 483,000 Btu/hr (Table 23). A maximum rate of 523,000 Btu/hr occurred for Test Condition 3 (high temperature/high flow rate) (Table 25). These data suggest that overall power usage is more directly affected by flow rate than by temperature.

A similar correlation can be found in the results of daily power usage seen in Table 10. The maximum rate of usage (occurring on 12 May 1989) corresponds to the highest average flow rate for tests performed on a single day. The minimum rate of usage (on 19 May 1989) coincided with the minimum average flow rate.

Values for the PVDRs for the FBCI are listed in Table 22. There is an apparent trend of increasing ratio with increasing temperatures or flow rates, as expected, but there are not enough data points to support a conclusion. Under optimum operating conditions (Test Condition 2) the FBCI had a PVDR of 4.58 MMBtu/lb VOCs destroyed.

TABLE 23. TEST AVERAGES: FBCI TEST CONDITION 1[a].

Date/ Time	Run Number	Rate of Usage (Btu/hr)	CO (ppmv)	NO_x (ppmv)	Particulate Emissions (lb/hr)	DRE (%)
5/10/89 1300-1340	Test-3	434,000	58	19.3	--	>99.8
5/10/89 1830-1930	Test-4 (M5-2)	490,000	56	10.7	0.03	>99.9
5/11/89 1030-1130	Test-5 (M5-3)	525,000	45	--	0.07	>99.8
Average:		483,000	53	15.0	0.05	>99.8

[a] High temperature/low flow rate (>750°F, <450 dscfm)

TABLE 24. TEST AVERAGES: FBCI TEST CONDITION 2[a].

Date/ Time	Run Number	Rate of Usage (Btu/hr)	CO (ppmv)	NO_x (ppmv)	Particulate Emissions (lb/hr)	DRE (%)
5/10/89 0930-1030	Test-2 (M5-1)	370,000	43	10.7	0.01	>99.0
5/11/89 1655-1755	Test-7 (M5-4)	548,000	16	--	0.10	>99.2
Average:		459,000	29.5	--	0.055	>99.1

[a] Optimum temperature/optimum flow rate (650 to 750°F, 450 to 550 dscfm)

TABLE 25. TEST AVERAGES: FBCI TEST CONDITION 3[a].

Date/ Time	Run Number	Rate of Usage (Btu/hr)	CO (ppmv)	NO_x (ppmv)	Particulate Emissions (lb/hr)	DRE (%)
5/12/89 1235-1315	Test-9	548,000	40	NA	NA	>99.2
5/17/89 1815-1915	Test-18 (M5-11)	498,000	99	11.3	0.20	99.2
Average:		523,000	70	NA	0.20	>99.2

[a] High temperature/high flow rate (>750°F, 550 dscfm)
NA—Not available

The FBCI achieved DREs of 99 percent or greater under a variety of operating conditions, extending beyond those established by the manufacturer. While operating at flow rates above manufacturer-suggested ranges, the FBCI showed higher particulate loadings. Organics that are less readily combusted, such as toluene, may break through during periods of extreme loading. Emissions of criteria pollutants were not significant, except that CO levels may peak above 100 ppmv during periods of high loadings. As expected, power consumption by the FBCI was high, always greater than 0.3 MMBtu/hr. Power consumption increased when the unit was operated at a higher flow rate or higher temperature.

SECTION VI

FULL-SCALE SYSTEM TECHNICAL EVALUATION AND COST PROJECTION

The projection of operational and utility requirements for full-scale air pollution control systems of the type evaluated in this project requires both pilot-scale field data and manufacturers' data. This is because full-scale systems have additional equipment (for example, heat exchangers for energy conservation) that pilot-scale units do not have. Operational, utility, modification, and space requirement data collected during site preparations and pilot-scale testing were combined with manufacturer information to technically and economically evaluate full-scale systems.

A. FULL-SCALE SYSTEM TECHNICAL EVALUATION

Evaluating full-scale units with pilot-scale field data can yield misleading results if not properly performed. Full-scale VOC emission control devices treat larger waste gas flow rates than do pilot-scale units. The scaleup of pilot-scale data depends mainly on the increased flow rates. The impact of these increased flow rates on the pilot-scale data is important. Several questions must be addressed when scaling up pilot-scale data. Will the increased flow rates significantly alter the pilot-scale evaluation? What pilot-scale results can be directly applied to the technologies at the full-scale? Which parameters scale linearly and which do not? Mass emissions rates, catalyst, carbon and filter quantities, and power consumption scale up linearly (this assumes that the pilot-scale units have heat exchange capacities similar to those of the full-scale systems). Operation and maintenance needs will not scale linearly. Increasing the flow rates will have either direct or indirect impacts on the control technology. Direct impacts are those parameters, such as fan sizes, that might be directly affected by increased waste gas flow rates. Indirect impacts are those arising from the operation and maintenance of full-scale treatment systems. For example, heat exchangers are common appurtenances on full-scale systems, but are installed only infrequently in pilot-scale units. Maintaining a pilot-scale unit does not involve the maintenance of a heat exchanger, whereas servicing a full-scale unit does.

1. Direct Impacts

The increased waste gas flow rates treated by the full-scale technologies should not affect the DREs observed at pilot scale. VOC, NO_x and CO concentrations in the full-scale unit exhaust will not vary significantly from those observed at pilot scale. Particulate concentrations in the exhaust from full-scale units will not be different from those observed at pilot scale. VOC speciation should not be different when scaling up from a pilot-scale test to a full-scale application. Hourly emission rates of the contaminants mentioned above will be higher than the rates observed in the exhaust of the pilot-scale units, because the increased exhaust gas flow rates carry a larger mass of contaminant than the pilot-scale unit exhaust gas over equivalent periods of time.

Power consumption for a full-scale unit will increase as a result of scaling up data from a pilot-scale unit. Increasing the flow rate to be treated requires more power to heat a larger volume of air to the desired operating temperature. More power is also needed to drive larger fans that move the higher influent and effluent gas volumes through the full-scale system. Treating a larger flow rate of waste gas demands bigger and heavier hardware to accomplish the task. Therefore, full-scale units are naturally larger and heavier than pilot-scale systems.

2. Indirect Impacts

The larger size of full-scale units will impact operations, maintenance, and waste generation. Full-scale units are larger because they treat waste gas at higher flow rates than do pilot-scale units. Applying pilot-scale data concerning operating procedures, waste generation, maintenance and appurtenances to full-scale technologies requires informed judgment. Full-scale units require more maintenance than do pilot-scale units, but probably less time to operate. Current control technologies can provide complete automation requiring minimal operator labor. Full-scale units will generate larger volumes of secondary pollutants or waste. Quantities of waste carbon, catalyst or filters will be larger because greater quantities are used.

The increased size and weight of a full-scale unit, as compared to a pilot-scale system, must also be considered in the scaling process. Large units may not be as conveniently located as pilot-scale units can be. The operating schedule of the paint booth—intermittent versus continuous—should not impact full-scale control technologies any differently than it did the pilot-scale units.

B. FULL-SCALE SYSTEM COST PROJECTIONS

Cost projections for the CPACI and FBCI control technologies are based on manufacturers' data, and information from both the EPA's EAB Cost Control Manual, 3rd Edition (Reference 14) and the Naval Facilities Engineering Command Economic Analysis Handbook (Reference 15). The terms that describe the various costs and expenditures are listed and defined below.

- Capital cost: cost of design, equipment, and materials
- Installation cost: cost to install technology (does not include site modification)
- Installed cost: sum of capital cost and installation cost
- Operation and maintenance (O&M) cost: cost of operating and maintaining technology (includes labor, maintenance parts and tools, but does not include replacement catalyst, carbon, and filters)
- Utility costs: costs of natural gas and electricity

The costs of air pollution control systems are dominated by the flow rate of waste gas to be treated. Linear and even exponential cost increases arise from increasing flow rates. (Reference 14). Figure 11, a graph of thermal incinerator equipment costs versus waste gas flow rate, demonstrates this relationship (Reference 14). Capital costs for the CPACI and FBCI technologies were evaluated with respect to increasing waste gas flow rates to be treated. Cost

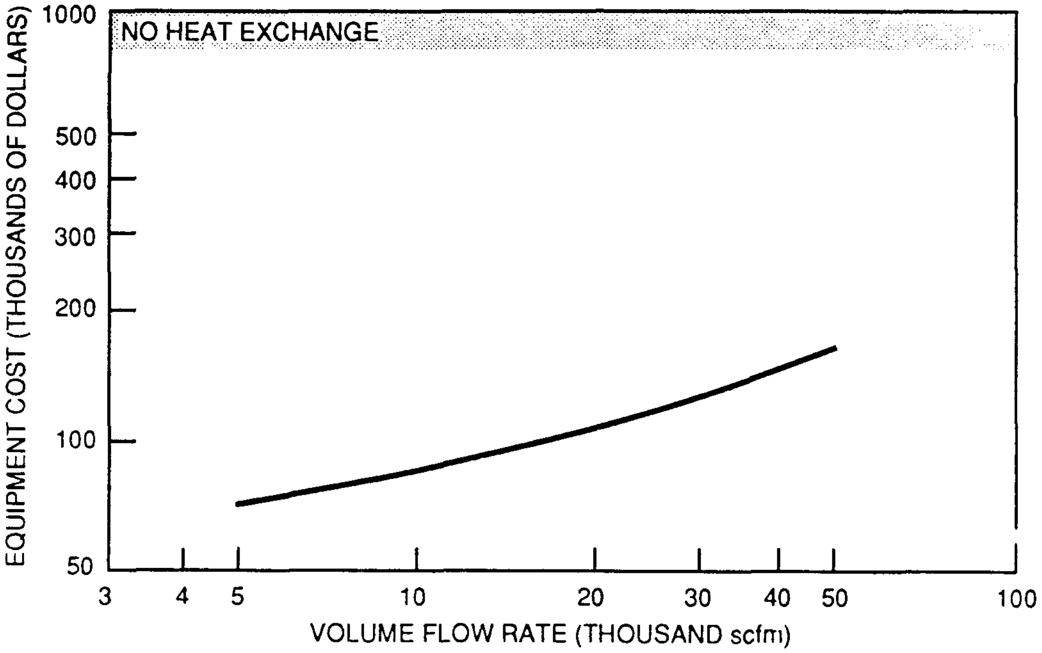

Figure 11. Thermal Incinerator Equipment Cost Estimate

information was obtained from manufacturers and then graphed in a manner analogous to that of Figure 11; these graphs are presented in Sections VII and VIII. Mathematical equations describing these graphs, also included in Sections VII and VIII, can be used as cost equations. These equations are relevant to "off-the-shelf" models. Generally, air pollution control devices that treat waste gas at flow rates greater than 100,000 scfm must be custom-designed, so the cost equations may not be relevant.

Manufacturer-supplied data were also used for utility costs, catalyst and filter replacement costs and installation costs. When manufacturers' data were not available, costs were estimated using the information and equations provided in Reference 14. These cost estimates were not generated from pilot-scale data, since field test data are unsatisfactory for scaling up these costs to a full-scale unit. Full-scale plants may have different appurtenances, such as heat exchangers and full control panels. Utility costs are therefore difficult to evaluate for full-scale technologies based on pilot-scale studies. A similar constraint exists for annual O&M costs for emission control systems. Furthermore, utilities, disposal, and O&M and costs will vary from region to region. Because pilot-scale units were tested in Central California, costs from this geographical area were selected. Utility costs chosen are $4.521/MMBtu and $0.0785/kW-hr. These rates are from Pacific Gas and Electric and the Sacramento Municipal Utilities District, respectively. O&M estimates (from Reference 14) are given in terms of estimation factors based on labor hours. O&M cost estimation factors are given below:

Operating labor: 0.5 hr/shift
Supervisory labor: 15 percent of operating labor
Maintenance labor: 0.5 hr/shift at 110 percent of operating labor rate
Maintenance materials: 100 percent of maintenance labor

The wage grade (WG) level chosen to determine annual O&M costs was WG Level 3. The typical labor rate for a WG Level 3 employee in the San Francisco Bay Area is $9/hr, or $17/hr when loaded with 90 percent general administration and overhead.

C. TECHNICAL AND COST COMPARISON

Sections VII and VIII each provide a technical and economic comparison of conventional VOC control technologies to the field-tested technologies. Section VII compares CPACI to recuperative thermal incineration and to regenerative carbon adsorption with catalytic incineration. Section VIII compares FBCI technology to the same conventional systems. Economic comparisons are based on net present costs (NPCs) and treatment costs. Technical comparisons summarize the advantages and disadvantages of each technology.

Economic comparisons are made by evaluating the NPCs and the treatment costs ($/lb VOCs destroyed) of each technology. NPC is the current cost in constant dollars of the treatment option for its equipment life. NPCs for each treatment option are calculated using a 10-percent discount rate that accounts for inflation. Capital recovery factors and tax items are not addressed, and the equipment life of each technology is assumed to be 15 years. These assumptions are made based on guidance from References 14 and 15. Cash-flow diagrams prepared for each option follow the format displayed in Figure 12. In this figure, arrows pointing downward represent costs. The cash-flow diagram is a graphic representation of the expected expenditures over the equipment life of the technology. Information from the diagram is then translated into an equation that provides the NPC. This equation is given below:

$$\begin{aligned} NPC = \$C + \$I &+ CCR(P/F,10\%,\underline{n}) + U(P/A,10\%,\underline{n}) + FR(P/A,10\%,\underline{n}) \\ &+ O\&M(P/A,10\%,\underline{n}) \end{aligned} \tag{1}$$

where:

$\$C$ = capital cost
$\$I$ = installation cost
CCR = carbon and catalyst replacement cost
U = annual utility cost
O&M = annual operation and maintenance cost
$(P/F,10\%,\underline{n})$ = discount factor for present cost from future cost for 10 percent discount rate over an $\underline{n}$-year period
$(P/A,10\%,\underline{n})$ = discount factor for present cost from future annual cost for 10 percent discount rate over an $\underline{n}$-year period

D. FLOW-REDUCTION TECHNOLOGIES AND THEIR IMPACT

Flow-reduction technologies can be combined with CPACI, FBCI or other VOC control systems. Decreasing the flow rate of exhaust gas from paint spray booths is technically and economically beneficial (Reference 1). Lower exhaust gas flow rates generally require smaller VOC emission control devices, which have correspondingly lower costs. Two principal techniques of reducing waste gas flow rate are recirculation and split flow. Both of these techniques can lower the flow rates of paint booth exhaust by as much as 90 percent. Mobile zone control is an unproven flow reduction method that claims an 80-percent reduction.

Recirculation is a flow-reduction technology that can reduce the exhaust gas flow rate and increase the solvent concentration in the exhaust gas. This technology does not destroy VOCs and HAPs; however, its application to a paint spray booth can decrease the required size of such VOC emission control technologies as CPACI and FBCI. Recirculation involves recycling a portion of the exhaust gas back into the paint spray booth. Modifications to the booth ductwork, safety features, and product quality considerations must be taken into account when implementing recirculation systems.

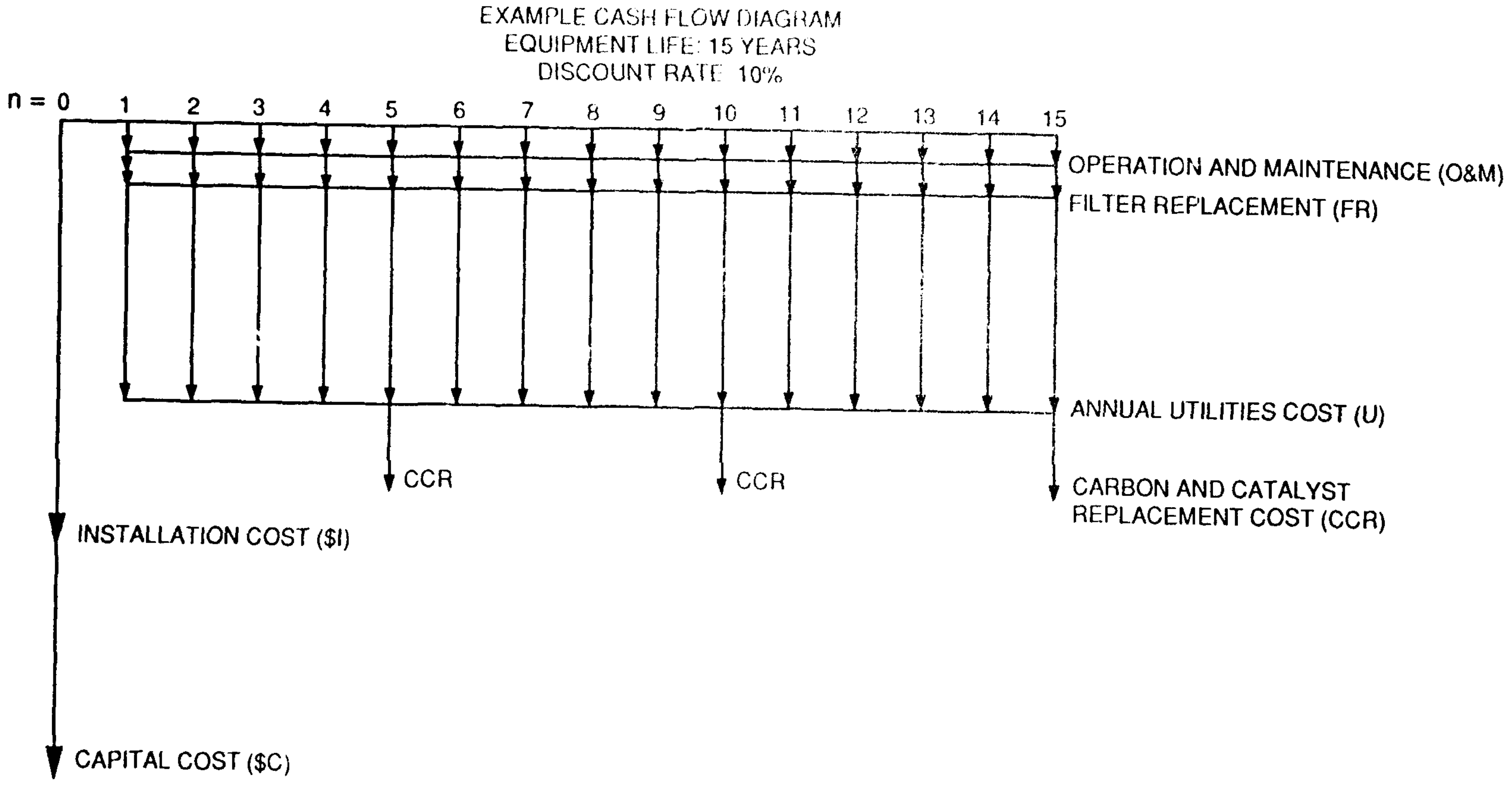

Figure 12. Sample Cash-Flow Diagram

Split-flow technique is a flow-reduction technology that has not been field-tested as yet, but shows promise. This technology will vent a selected portion of the paint spray booth exhaust and recycle the remainder back to the booth. The design is intended to vent the most hazardous portion of the exhaust air. Research has shown that the distribution of VOCs within paint spray booths is structured (Reference 2).

The economic benefits of applying flow-reduction technologies to a paint spray booth are demonstrated in the following example. In this example, a hypothetical paint spray booth exhausts 50,000 scfm of gas that must be treated to remove VOCs and HAPs. If a catalytic incinerator is selected as the emissions control device, the capital cost for a properly sized system is $425,000, as shown in Figure 13. When a flow-reduction technology is applied, reducing the exhaust flow rate by 90 percent, to 5,000 scfm, the capital cost for the catalytic incinerator is $150,000. This represents a substantial savings. Equally attractive savings will be seen in energy costs, O&M costs, and installation costs. Final decisions regarding the use of flow-reduction technologies should consider the modification costs. These are generally low, and offset by the savings in emission control equipment costs. Other advantages gained from using flow-reduction technologies are decreased space and weight requirements for VOC emissions control equipment.

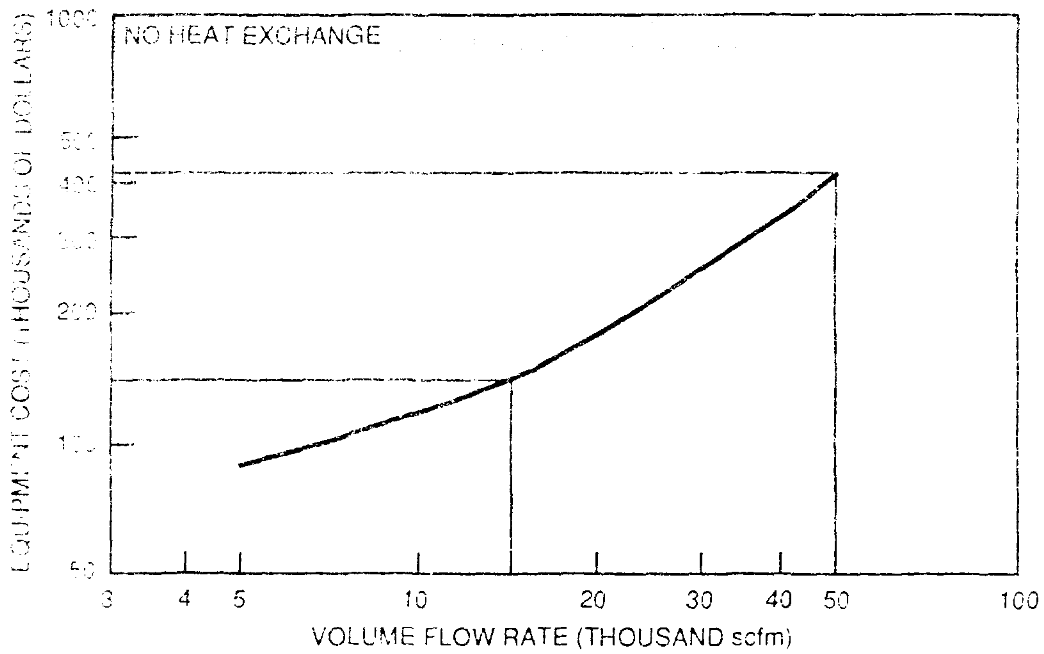

Figure 13. Catalytic Incinerator Cost Estimate

SECTION VII
CPACI FULL-SCALE SYSTEM TECHNICAL EVALUATION AND COST PROJECTION

A. TECHNICAL EVALUATION OF FULL-SCALE SYSTEM

CPACI is a feasible VOC and HAP emissions control technology. The DREs observed during the pilot-scale field testing should be comparable to the DREs attainable by full-scale treatment units. VOC DREs of 99 percent can be expected for properly operated CPACI devices. Full-scale CPACI application should not produce pollutant concentrations in the exhaust stream that are different from those observed in the pilot-scale unit exhaust gas. The increased exhaust gas flow rate from a full-scale unit will result in higher mass emission rates (of any pollutant) than those seen at pilot scale. Particulate, VOC, and TUHC concentrations will not change, but their mass emission rates will increase. The extent of these increases depends upon the size of the emission control systems. CPACI systems designed to treat 50,000 scfm of paint spray booth exhaust would have VOC and particulate mass emission rates, based on pilot-scale data, of 0.095 lb/hr and 1.2 lb/hr, respectively. These emission rates are well below most regulatory standards. For example, in the San Francisco Bay Area the particulate emissions limit for a 50,000-scfm unit is 64 lb/hr (Reference 16). The speciation of VOCs from full-scale systems should be similar to that observed during pilot-scale testing.

Full-scale CPACI systems will consume more power than the pilot-scale systems. As explained in Section VI, manufacturers' data were used to evaluate power consumption. CPACI devices use electricity to power fans, rotor motors, and control systems. Natural gas (or propane) is normally used to bring the catalyst bed to the desired operating temperature. Power consumption by the CPACI has been broken into start-up demands and normal operating demands. Once the unit has reached the desired operating temperature and begins treating VOC-contaminated exhaust gas, its fuel usage decreases because energy is obtained from the catalytic incineration of the organic compounds in the waste gas. The ratio of start-up to operating power consumption is approximately 3:1 for fuel usage and 2:1 for electricity usage. This is important in applications where the CPACI device is not kept running continuously, but started up at the beginning of each work day.

Full-scale CPACI systems will be much larger than the pilot-scale units. Systems designed to handle 50,000 scfm of exhaust gas can weigh 40 tons and require 2,500 square feet of floor space. Hazardous waste will be generated in larger volumes from full-scale than from pilot-scale units. Carbon filters, particulate filters, poisoned catalyst, and spent carbon paper must be periodically disposed of. Larger systems generate larger volumes of this waste, which may require disposal as a hazardous waste.

The reliability of full-scale CPACI technology should be the same as that demonstrated by the pilot-scale unit during the 10-day field testing. Reliability is the consistency with which a system's performance objective is met over time. Under batch or continuous loading, system performance should be satisfactory when the device is operated according to manufacturers' instructions. Fluctuations in VOC concentrations in paint spray booth exhaust may affect CPACI performance, as high concentrations of VOCs in the influent stream may overload the carbon paper and then exhaust to the atmosphere. Table 26 summarizes the technical projection data for a full-scale unit.

B. ECONOMIC EVALUATION OF FULL-SCALE SYSTEM

1. Capital and Installation Costs

Exhaust gas flow rate will have the largest impact on the economics of the CPACI control technology. This is demonstrated in Figure 14, which relates flow rate to cost. Capital cost and installation cost increase linearly with flow rate. Equations describing these relationships are given below. The total cost to purchase and install a CPACI system that treats 50,000 scfm of exhaust gas, for example, would be $1,425,000.

$$\text{Total cost (\$)} = T = 6.9 \times 10^5 + 14.7Q \tag{2}$$

$$\text{Installation cost (\$)} = I = 1.6 \times 10^5 + 3.4Q \tag{3}$$

$$\text{Capital cost (\$)} = C = 5.3 \times 10^5 + 11.3Q \tag{4}$$

where

Q = Flow rate that unit will treat (scfm)

2. Operation and Maintenance Costs

O&M costs for CPACI technology have not been specifically identified because of variations based on geographical location. The estimates based on labor hours, provided in Section VI, should be applicable as order-of-magnitude estimates. The O&M needed to maintain a full-scale unit should be less than the effort needed to operate a pilot-scale unit. Full-scale units have automatic controllers and other features that facilitate operations and maintenance, which do not appear on pilot-scale units. Using the factors provided in Reference 14, annual O&M costs are estimated at $14,900.

3. Utility Costs

Electricity and fuel consumption costs for full-scale CPACI systems of different sizes are presented in Tables 27 and 28. Table 27 presents the daily "start-up" costs. Start-up is assumed to take 45 minutes each working day. A work day consists of two eight-hour shifts, and there are 260 work days in a year. Table 27 presents the daily utility costs during normal operating conditions. Electricity costs are more than 25 percent higher than the natural gas costs. Again, using the example of a 50,000-scfm system, electricity will cost about $30,370/yr while natural gas will cost $22,569/yr. When the start-up costs are added in, the yearly energy

TABLE 26. CPACI FULL-SCALE TECHNICAL SUMMARY.

Parameter	1	2	3	4	5
Flow rate (scfm)	10,000	30,000	50,000	70,000	90,000
Type of catalyst	Platinum	Platinum	Platinum	Platinum	Platinum
Activated carbon (lb)	1,250	3,750	6,250	8,750	11,250
Overall dimensions (ft)	25 x 35	50 x 50	70 x 50	70 x 50	100 x 50
Unit weight (lb)	12,000	100,000	200,000	240,000	300,000
Heat exchanger heat recovery (%)	90	90	90	90	90
Utility Requirements					
Start-up					
Electricity (kW)	54	103	201	272	310
Fuel (natural gas) (MMBtu/hr)	1.19	2.24	3.6	5.0	6.8
Operating					
Electricity (kW)	28	61	93	134	171
Fuel (natural gas) (MMBtu/hr)	0.2	0.7	1.2	1.7	2.2
Water/air/steam	NR[a]	NR	NR	NR	NR

[a] NR — Not required if dry wall filters are used in the paint spray booth instead of a water curtain particulate control system

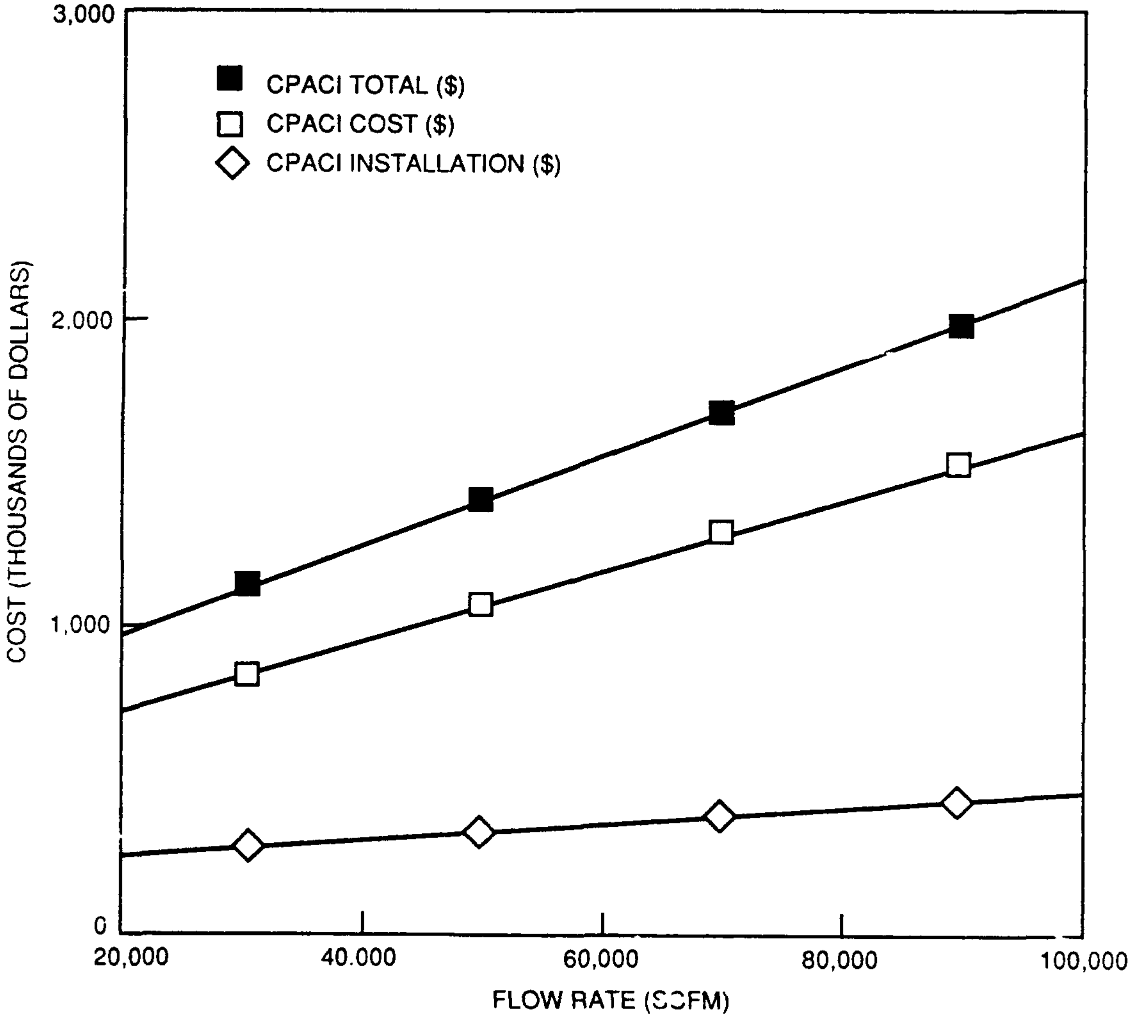

Figure 14. Flow Rate Versus Cost for CPACI

TABLE 27. FULL-SCALE CPACI START-UP UTILITY REQUIREMENTS.

System Flow Rates (scfm)	Electricity Usage (kW)	Energy Costs[a] ($/day)	Energy Costs ($/year)	Fuel Usage (MMBtu/hr)	Energy Costs[b] ($/day)	Energy Costs ($/year)	Total Start-up Costs ($/year)
10,000	54	3.18	827	1.19	4.03	1,048	1,875
30,000	103	6.06	1,576	2.24	7.60	1,976	3,552
50,000	201	11.83	3,076	3.60	12.21	3,170	6,251
70,000	272	16.01	4,163	5.00	16.95	4,407	8,570
90,000	310	18.25	4,745	6.80	23.05	5,993	10,738

[a] Average yearly energy costs from SMUD = $0.0785/kWh

[b] Average yearly energy costs from PG&E for Sacramento area = $4.521/MMBtu

TABLE 28. *FULL-SCALE CPACI OPERATIONAL UTILITY REQUIREMENTS.*

System Flow Rates (scfm)	Electricity Usage (kW)	16-Hr Usage (kW-hr)	Energy Costs[a] ($/day)	Energy Costs ($/year)	Fuel Usage (MMBtu/hr)	16-Hr Usage (MMBtu)	Energy Costs[b] ($/day)	Energy Costs ($/year)	Total Yearly Energy Costs ($/year)[c]
10,000	28	448	35.17	9,144	0.2	3.2	14.47	3,762	14,781
30,000	61	976	76.62	19,921	0.7	11.2	50.64	13,166	37,297
50,000	93	1,488	116.81	30,371	1.2	19.2	86.80	22,568	60,248
70,000	134	2,144	168.30	43,758	1.7	27.2	122.97	31,972	85,772
90,000	171	2,736	214.78	55,843	2.2	35.2	159.14	41,376	109,956

[a] Average yearly energy costs from SMUD = $0.0785/kWh

[b] Average yearly energy costs from PG&E for Sacramento area = $4.521 MMBtu

[c] Includes start-up costs calculated in Table 27

cost for this system is $60,248. Heat exchangers, the low gas flow rate through the catalytic incinerator, and the increased concentration of energy-containing solvents contribute to fuel conservation. Electricity costs are dependent on system fan sizes and will be fixed costs.

4. Replacement and Regeneration Costs

CPACI treatment systems will require periodic filter and catalyst replacement, and regeneration of carbon adsorption paper and granular activated carbon. Manufacturer estimates of catalyst costs are close to those provided in Reference 14. Conservatively, catalyst should be replaced every 5 years for about $3,000 per cubic foot of precious-metal catalyst. The catalyst replacement cost for a 60,000-scfm unit was quoted as $31,000. Pre-filters must be replaced every few months, and the yearly filter replacement costs are about $16,300 for a 60,000-scfm unit, not including disposal costs. The granular activated carbon used to remove high-boiling organic compounds must be regenerated annually at a cost of about $1.00/lb. CPACI systems sized for 60,000 scfm need about 7,600 pounds of granular activated carbon, requiring an annual regeneration cost of $7,600. Carbon paper must also be replaced or regenerated on a regular basis. Carbon paper blocks can last from 5 to 10 years before their replacement is required. The replacement cost for the carbon paper in a 60,000-scfm unit is $170,000. Manufacturers suggest a rotation scheme whereby only half of the blocks are replaced during each replacement period. Replacement costs would then be half—$85,000—for the carbon paper in a 60,000-scfm unit.

Replacing and regenerating catalysts, filters, and carbon can generate waste streams that must be disposed of. The costs of such disposal have not been addressed, since they would vary considerably from region to region. Pre-filters might be disposed of with the filters from the paint spray booth, at little additional cost. Poisoned catalyst will probably need to be disposed of as a hazardous waste, which could prove expensive. Different approaches would be taken in each region to the final disposition of the wastes generated from replacement and regeneration activities.

C. COMPARISON OF CPACI TECHNOLOGY TO STANDARD CONTROL TECHNOLOGIES

CPACI was compared to two standard VOC emission control technologies: regenerable carbon adsorption with catalytic incineration (RCA), and recuperative thermal incineration (RTI). RCA and RTI are standard VOC destruction technologies. CPACI has a VOC DRE equivalent to that of RTI, and generally a much higher DRE than RCA. Regenerating the carbon bed of an RCA system creates an exhaust gas containing waste solvent that must be destroyed by the catalytic incinerator. Technical and economic summaries of carbon adsorption and incineration technologies are provided in Table 29.

For comparison, Table 29 shows the total costs expected for each system over 15 years of operation. CPACI technology has a higher installed cost ($1,572,000) than RTI, but it is still cheaper than RCA. CPACI clearly has lower utility demands and costs—totalling about $72,300

TABLE 29. COMPARISON OF CPACI TO STANDARD VOC CONTROL TECHNOLOGIES — BASIS: 60,000 SCFM SYSTEMS AND 15-YEAR EQUIPMENT LIFE.

Principal Consideration	CPACI	Recuperative Thermal Incineration	Regenerable Carbon Adsorption with Catalytic Incineration
Overall destruction and removal efficiency (%)	>99	>99	95
Reliability issues	Performs well over time; catalyst, carbon paper and filters must be replaced periodically	Performs well over time	Performs well over time; catalyst and carbon need to be replaced periodically
Overall heat recovery (%)	90	70	90
Least-compatible waste	Chlorinated solvents, particulates, heavy metals	Chlorinated solvents, heavy metals	Chlorinated solvents, heavy metals, polar compounds
Environmental medium most affected	Air	Air	Air
Total installed cost	$1,572,500	$ 697,040	$1,962,000
Catalyst replacement (every 5 years)	31,000	NA	27,000
Carbon paper replacement (every 5 years)	95,000	NA	NA
Carbon regeneration	7,600[a]	NA	42,900[b]
Pre-filters replacement (every year)	16,300	NA	NA
Power cost at $0.0785/kWh (annual)	40,140	67,400	105,504
Natural gas cost at $4.521/MMBtu (annual)	32,160	1,150,000	26,720
Net present cost	$2,570,000	$10,090,000	$3,166,000
Treatment cost ($/lb VOCs destroyed)	8.30	32.70	10.70

[a] Carbon regeneration every year
[b] Carbon regeneration every 5 years
NA – Not applicable

annually. Annual O&M costs for each technology are expected to be similar, estimated at $14,900 in Reference 14. Periodic catalyst, carbon and pre-filter replacement or regeneration costs are higher for CPACI technology than for either RTI or RCA systems. This is mainly because RTI and RCA systems utilize few or none of these components. Some carbon adsorption systems don't have catalytic incinerators attached, so capital costs are lower. These systems must regenerate carbon daily and then dispose of the waste solvent. Such disposal is expensive, as much as $600 per drum of solvent.

Over a 15-year period, CPACI technology should be a more economical solution than RTI or RCA. The NPCs of the three systems are as follows: CPACI, $2,570,000; RTI, $10,090,000; and RCA, $3,166,000. Treatment costs ($/lb VOC destroyed) for these systems, based on a daily VOC loading of 80 pounds, are $8.30, $32.70 and $10.70 for CPACI, RTI and RCA, respectively. It should be noted that the main reason for the large NPC and treatment costs for an RTI system is the high utility cost incurred from maintaining a DRE of 99 percent. Were lower DREs acceptable, the fuel costs would be much lower. It should be noted that RTI annual fuel costs would be much lower if a 95-percent DRE was acceptable—approximately $560,000. Figures 15 through 17 are the cash-flow diagrams for CPACI, RTI and RCA, respectively. These diagrams depict the yearly expenditures for each technology.

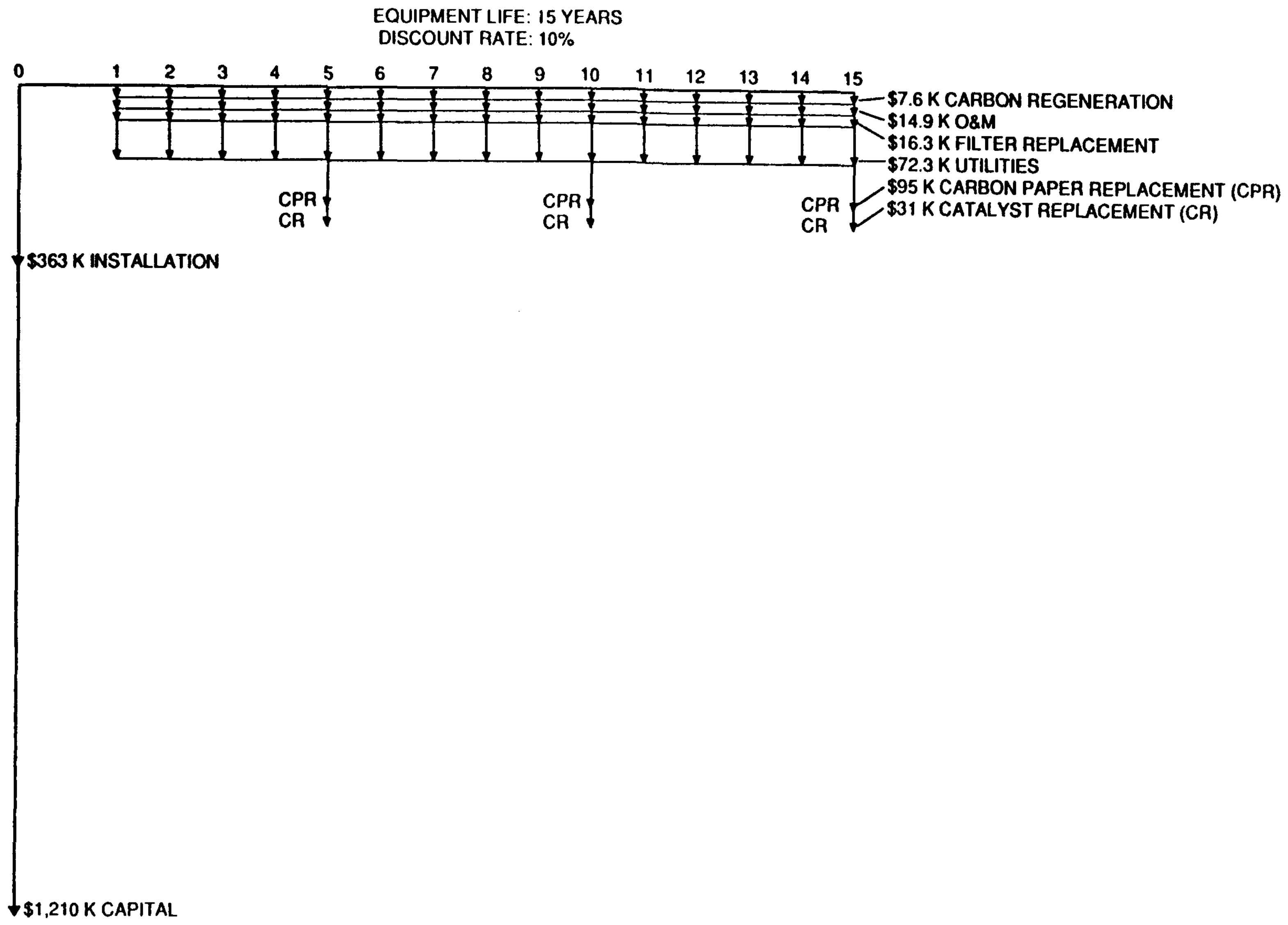

Figure 15. Cash-Flow Diagram for CPACI

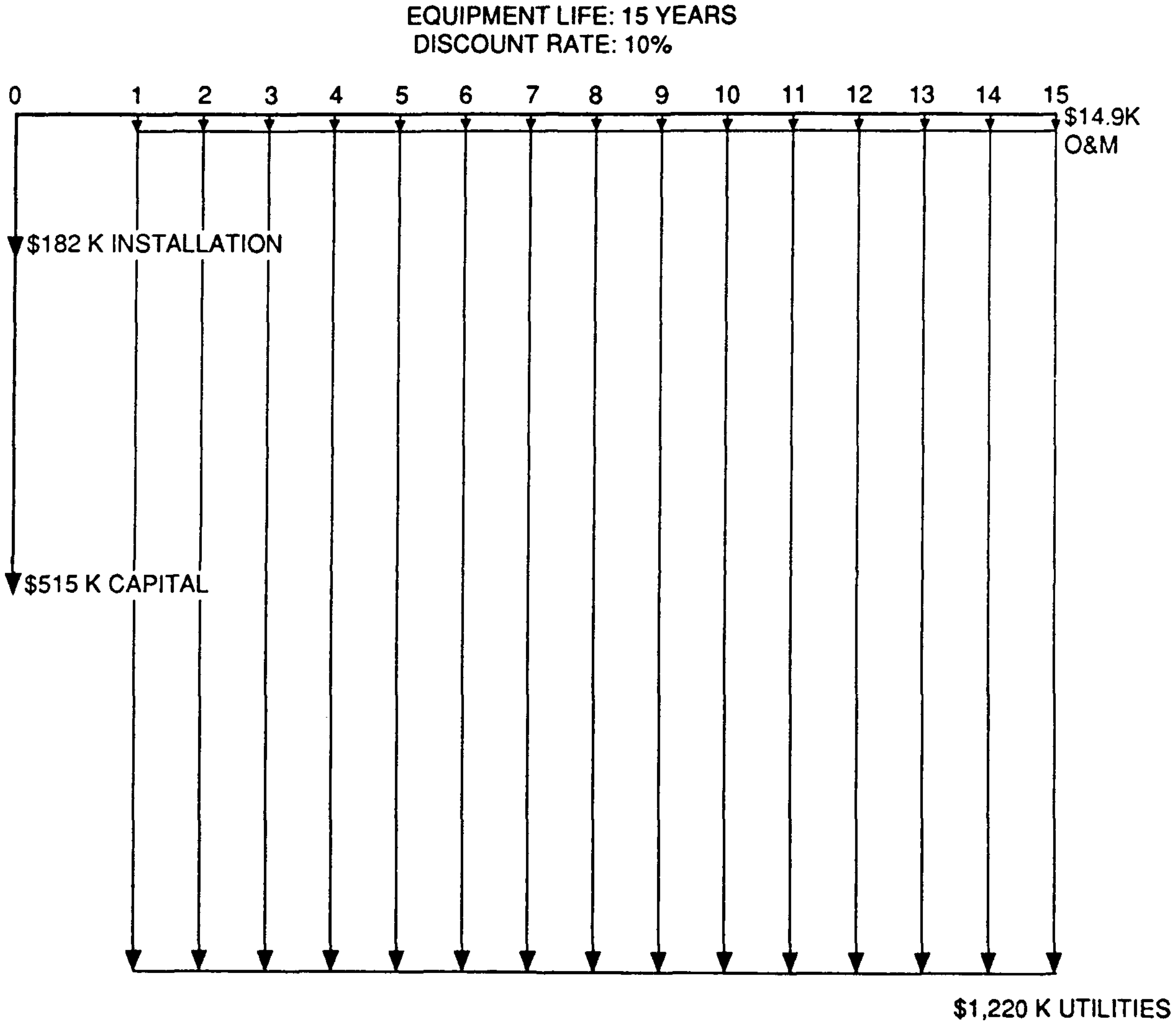

Figure 16. Cash-Flow Diagram for RTI

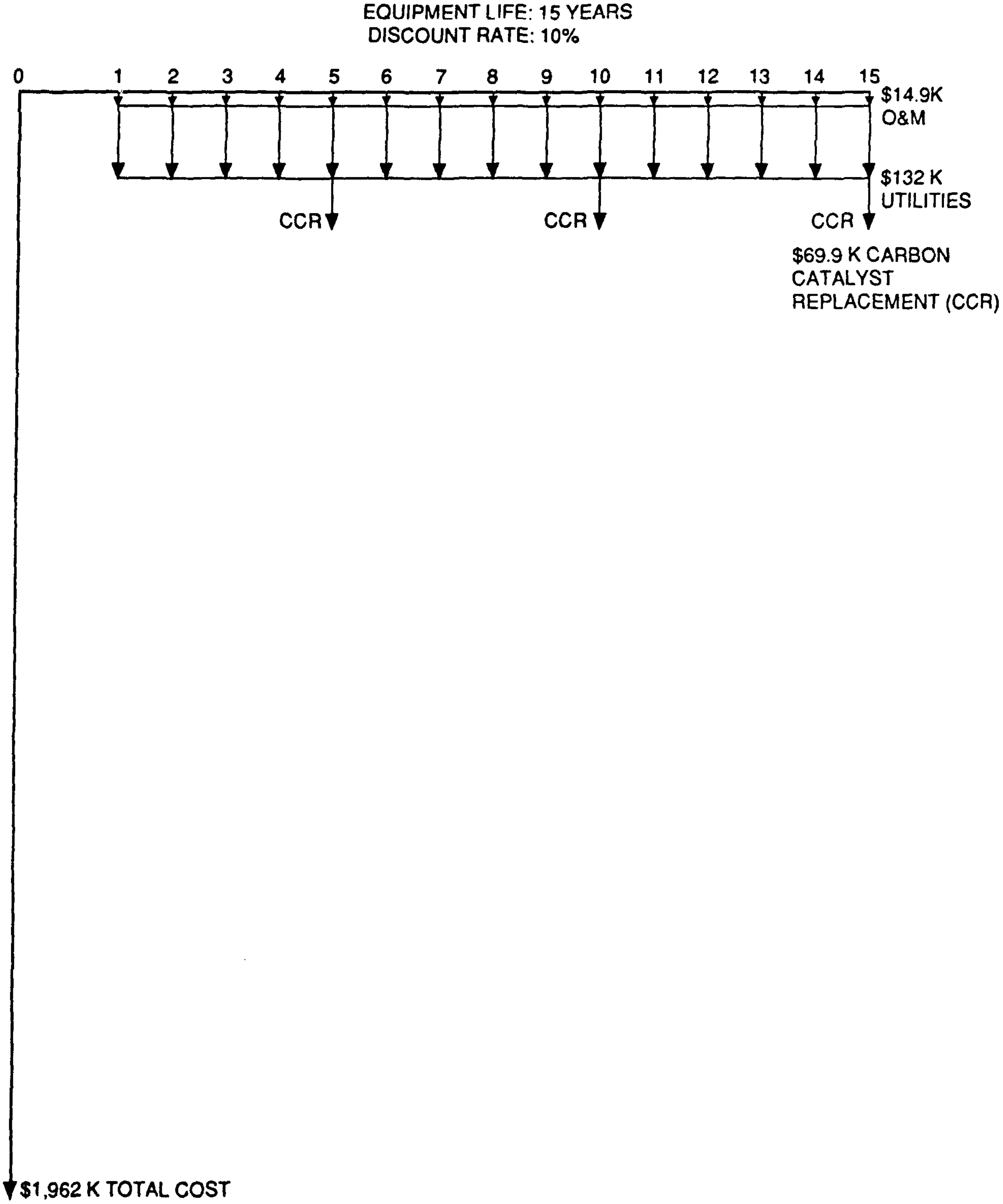

Figure 17. Cash-Flow Diagram for RCA and Catalytic Incineration

SECTION VIII

FBCI FULL-SCALE SYSTEM TECHNICAL EVALUATION AND COST PROJECTION

A. TECHNICAL EVALUATION OF FULL-SCALE SYSTEM

FBCI technology is capable of controlling VOC and HAP emissions from paint spray booths. Pilot-scale field test results for DRE should apply directly to full-scale units. DREs of 99 percent are expected during normal operating conditions. Full-scale application will not alter the pollutant concentrations observed in the pilot-scale exhaust gas. The increased exhaust gas flow rates will result in higher mass emission rates of any pollutant in the exhaust stream. Particulate, TUHC, VOC, CO and NO_x concentrations should not change, but the mass emission rates of these compounds will. The size of the emission control system will determine the magnitude of the increases. Based on pilot-scale data, a full-scale FBCI system designed to treat 50,000 scfm would have particulate mass emissions of 4 lb/hr. This loading rate may or may not be a problem, depending mainly upon the regulations promulgated by the local air pollution control districts. Particulate emissions from an FBCI system will probably consist of the catalyst that has been entrained during the fluidization process. The potential for high metals emission rates needs to be addressed, especially if the catalyst contains chromium oxides. If it is assumed that all particulate emitted from a chromium catalyst bed is chromium oxide, then an emission rate of 4 lb/hr yields a concentration of 0.02 mg/m^3. The OSHA personal exposure limit is 0.5 mg/m^3 (Reference 17). Normal operation of the FBCI system should not emit chromium at significant levels.

VOC emission rates (based on pilot-scale data) for a full-scale unit during normal operating conditions will be about 0.08 lb/hr. The types of organics emitted from a full-scale unit should not be different from those observed in the pilot-scale demonstration. Under normal operating conditions, measurable quantities of specific VOCs should not be found. Periods in which unusually high VOC concentrations are present in the paint spray booth exhaust may contribute to a breakthrough of more stable compounds such as toluene. Small quantities of these compounds may pass through the full-scale system as they did during one test of the pilot-scale unit. It must be pointed out that the referenced breakthrough involved the direct spraying of MEK into the exhaust gas of the booth.

Criteria pollutant concentrations from a full-scale unit will be similar to those observed during the pilot-scale testing, as previously mentioned. CO and NO_x levels are expected to be 59 ppmv and 12 ppmv, respectively.

Full-scale FBCI power usage is based on manufacturer-supplied data. The full-scale system uses electricity to power fans, motors, and control systems. Natural gas or propane is used to bring the catalyst bed to the operating temperature and to maintain it at the desired combustion temperature. After the unit is started, a 1-hour warmup period is needed before VOCs can be introduced. There should not be an excessive startup energy requirement for the FBCI. Power requirements for the FBCI unit should be constant during the operating day. The amount of energy contributed by the dilute solvent mixture in the paint spray booth exhaust is assumed to be negligible. Greater energy conservation is possible when more-efficient heat exchangers are utilized. Assuming FBCI is applied to a paint spray booth operating in a manner similar to that at McClellan AFB, a unit sized to treat 50,000 scfm of waste gas requires about 2,400 kW-hr of electricity and 44 MMBtu each day. The hourly power requirements of different-sized units are shown in Table 30.

A full-scale FBCI system is much larger than the pilot-scale unit. A system designed for handling exhaust gas flow rates of 50,000 scfm can weigh 200 tons and have dimensions of 50 feet long x 26 feet wide x 40 feet high. Such a system requires floor space equalling 1,300 square feet. Dimensions for other sizes of units are also shown in Table 30.

An FBCI system needs its catalyst replaced about every 5 years. Typically, the catalyst must be disposed of as a hazardous waste, but disposal options vary from region to region. The volume of catalyst to be handled depends on the size of the unit. When precious metal is used as a catalyst, 1.5 cubic feet of catalyst are needed per 1000 scfm of exhaust air. Employing base metals as a catalyst requires 5 cubic feet of catalyst per 1000 scfm (Reference 14). Therefore, a 50,000-scfm FBCI system requires 250 cubic feet of base metal catalyst, which will need to be disposed of and changed every 5 years.

The reliability of a full-scale FBCI system should be similar to that demonstrated by the pilot-scale unit during the 10-day field test. Under batch or continuous loading conditions, system performance should be satisfactory when the system is operated according to the manufacturer's instructions. Automatic controls should streamline the operator labor involved in running the unit and minimize the operator expertise required. Fluctuations of exhaust gas flow rate into the system or concentrations of hydrocarbons should not upset the system significantly. The ability of the pilot-scale plant to provide DREs of 96 percent or better while operating at conditions beyond those specified by the manufacturer should be duplicated by the full-scale unit.

B. ECONOMIC EVALUATION OF FULL-SCALE SYSTEM

1. Capital and Installation Costs

Capital and installation costs of FBCI will depend mainly on the exhaust gas flow rate. Figure 18 is a graph of exhaust gas flow rate versus cost. There is an exponential relationship between capital cost and flow rate and installation cost and flow rate. Equations describing these graphical representations are presented below:

TABLE 30. FBCI FULL-SCALE TECHNICAL SUMMARY.

Parameter	1	2	3	4	5
Flow rate (scfm)	10,000	30,000	50,000	70,000	90,000
Type of catalyst	CrO[a]	CrO	CrO	CrO	CrO
Activated carbon	NR	NR	NR	NR	NR
Overall dimensions (ft)	10 x 20 x 33	20 x 30 x 40	50 x 26 x 40	60 x 32 x 45	60 x 30 x 40
Unit weight (lb)	65,000	100,000	200,000	240,000	300,000
Heat exchanger heat recovery (%)	70	70	70	70	70
Utility Requirements					
Start-up					
Electricity (kW)	30	93	149	224	276
Fuel (natural gas) (MMBtu/hr)	0.42	1.20	2.00	2.78	3.56
Operating					
Electricity (kW)	30	93	149	224	276
Fuel (natural gas) (MMBtu/hr)	0.42	1.20	2.00	2.78	3.56
Water/air/steam	NR	NR	NR	NR	NR

[a] CrO – Chromium oxide
NR – Not required

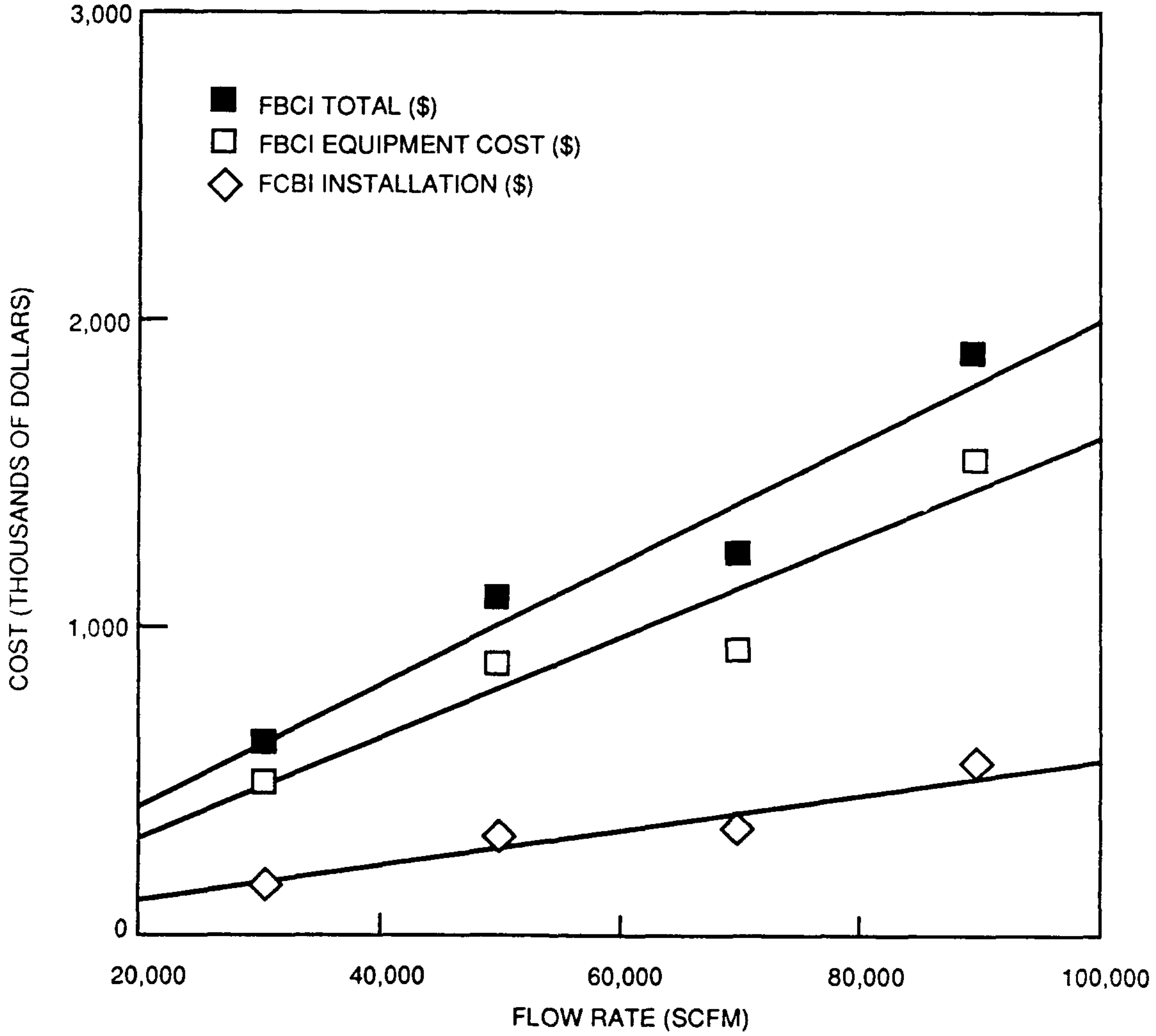

Figure 18. Exhaust Gas Flow Rate Versus Cost for FBCI

$$\text{Total cost (\$)} = T = 37.15*Q^{0.944} \tag{5}$$

$$\text{Installation cost (\$)} = I = 7.44*Q^{0.944} \tag{6}$$

$$\text{Capital cost (\$)} = C = 29.745*Q^{0.944} \tag{7}$$

where

Q = Flow rate into unit (scfm)

These equations are study estimates and are accurate to within ±30 percent. The total cost to purchase and install a FBCI that treats 50,000 scfm of exhaust gas, for example, would be $1,013,000.

FBCI systems may be purchased with different types of catalyst. Catalyst prices vary, which can affect capital cost to some extent. For example, if a 50,000-scfm system used precious metal at a cost of $3,000 per cubic foot, initial catalyst expense would be $225,000 (based on a ratio of 1.5 cubic feet of catalyst per 1000 scfm of gas treated). The cost for base metal catalyst needed to meet the same requirements is $150,000 ($600 per cubic foot of catalyst and 5 cubic feet of catalyst per 1000 scfm of gas treated).

2. Operation and Maintenance Costs

Operation and maintenance costs for FBCI technology have not been specifically identified because of variations based on geographical location. The estimates based on labor hours that were provided in Section VI should be applicable as order-of-magnitude estimates. Full-scale systems require less operator labor than the pilot-scale units that were field tested. Automatic controllers and other features that facilitate operations and maintenance are standard on full-scale units. Based on a labor rate of $9/hr (typical pay for a WG Level 3 employee in the San Francisco Bay Area), annual O&M costs are $14,900.

3. Utility Costs

Table 31 presents electricity and fuel consumption costs for full-scale FBCI systems of different sizes. Pilot-scale testing did not show any significant difference in fuel consumption between startup periods and normal operation. This observation was verified by manufacturer-supplied data. Utility costs were based on a 260-day year, with two 8-hour shifts on each day and one additional hour for the system to warm up. Electricity costs for the FBCI are more than 30 percent greater than fuel costs. Annual natural gas costs for a 50,000-scfm unit are $37,600, while annual electricity costs are $48,700. Total annual utility costs, including startup costs, are $91,700. Fuel costs can be lowered by using heat exchangers with better heat recovery efficiencies. However, there is a point beyond which the savings from fuel conservation are outweighed by the capital cost of a better heat exchanger (Reference 14).

TABLE 31. FULL-SCALE FBCI OPERATIONAL UTILITY REQUIREMENTS.

System Flow Rates (scfm)	Electricity Usage (kW)	16-Hr Usage (kW-hr)	Energy Costs[a] ($/day)	Energy Costs ($/year)	Fuel Usage (MMBtu/hr)	16-Hr Usage (MMBtu)	Energy Costs[b] ($/day)	Energy Costs ($/year)	Total Yearly Energy Costs ($/year)[c]
10,000	30.00	480.00	37.68	9,797	0.42	6.72	30.38	7,899	18,802
30,000	93.21	1,491.36	117.07	30,438	1.20	19.20	86.80	22,568	56,320
50,000	149.14	2,386.24	187.32	48,703	2.00	32.00	144.67	37,614	91,712
70,000	223.71	3,579.36	280.98	73,054	2.78	44.48	201.09	52,284	133,172
90,000	275.91	4,414.56	346.54	90,101	3.56	56.96	257.52	66,954	166,871

[a] Average yearly energy costs from SMUD = $0.0785/kWh

[b] Average yearly energy costs from PG&E for *Sacramento area* = $4.521/MMBtu

[c] Includes one hour per day of warmup

4. Catalyst Replacement

Catalyst must periodically be replaced in FBCI units. Catalyst can be poisoned and become less effective after a few years in operation. Fluidization of the catalyst bed can result in entrainment of catalyst particles. Eventually the lost catalyst needs to be replaced. Some manufacturers suggest replacing catalyst every 5 years, while others say every 2 years. The magnitude of replacement costs depends on the amount and frequency of catalyst replacement. A 60,000-scfm unit in which catalyst is replaced every 2 years will incur a biennial cost of $61,200.

C. COMPARISON OF FBCI TECHNOLOGY TO STANDARD CONTROL TECHNOLOGIES

FBCI technology was compared to both RTI and RCA VOC control technologies. Table 32 provides economic and technical summaries. The VOC DREs of FBCI and RTI are comparable (99 percent), but the RTI consumes far more fuel to achieve this. RCA has a lower DRE (95 percent) than FBCI technology. Each technology can treat the range of VOCs typically emitted from USAF paint spray booths. Limitations of the three technologies are also similar, as shown in Table 32. Operation and maintenance demands of each system are approximately the same. FBCI technology requires catalyst replacement at least every 2 years. RCA has carbon and catalyst that must be maintained regularly. As RTI does not use carbon or catalyst, the maintenance required for the RTI will be less than that required for the other two systems.

Economic information for the three technologies is provided in Table 32 and plotted as cash-flow diagrams in Figures 19, 20, and 21. Total installed cost for FBCI systems ($1,203,500) will be between that of RTI systems and RCA systems. Net present cost of the FBCI system is $2,369,000. This is less than the net present cost (NPC) of either RTI or RCA systems, as seen in Table 32. Figures 19 through 21 illustrate the differences between the annual utilities costs for each technology. FBCI systems have the lowest annual utility costs of the three options, which is the main reason that FBCI's NPC is lower than those of the two standard technologies. Again, it should be noted that RTI annual fuel costs would be much lower if a 95-percent DRE was acceptable—approximately $560,000.

The three cash-flow diagrams were used to generate the NPCs in Table 32. The NPCs were then used to calculate a treatment cost based on a 15-year economic life and a VOC loading of 80 lb/day. Treatment costs for FBCI systems are $7.70/lb of VOCs destroyed. This is substantially lower than the $32.70/lb calculated for RTI and $10.70/lb for RCA. Based on the lower NPC and the lower treatment cost, FBCI is the best economic option of the three evaluated here. FBCI technology can perform the required task of destroying VOCs at a lower cost.

TABLE 32. COMPARISON OF FBCI TO STANDARD VOC CONTROL TECHNOLOGIES — BASIS: 60,000 SCFM SYSTEMS AND 15-YEAR EQUIPMENT LIFE.

Principal Consideration	FBCI	Recuperative Thermal Incineration	Regenerable Carbon Adsorption with Catalytic Incineration
Overall destruction and removal efficiency (%)	>99	>99	95
Reliability issues	Performs well over time; catalyst must be replaced periodically	Performs well over time	Performs well over time; catalyst and carbon need to be replaced periodically
Overall heat recovery (%)	70	70	90
Least-compatible waste	Chlorinated solvents, particulates, heavy metals	Chlorinated solvents, heavy metals	Chlorinated solvents, heavy metals, polar compounds
Environmental medium most affected	Air	Air	Air
Total installed cost	$1,203,500	$ 697,040	$1,962,000
Catalyst replacement	62,300[a]	NA	27,000[b]
Carbon paper replacement (every 5 years)	NA	NA	NA
Carbon regeneration (every 5 years)	NA	NA	42,900
Pre-filters replacement (every year)	NA	NA	NA
Power cost at $0.0785/kWh (annual)	62,100	67,400	105,504
Natural gas cost at $4.521/MMBtu (annual)	48,000	1,150,000	26,720
Net present cost	$2,369,000	$10,090,000	$3,166,000
Treatment cost ($/lb VOCs destroyed)	7.70	32.70	10.70

[a] Catalyst replacement every 2 years
[b] Catalyst replacement every 5 years
N/A – Not applicable

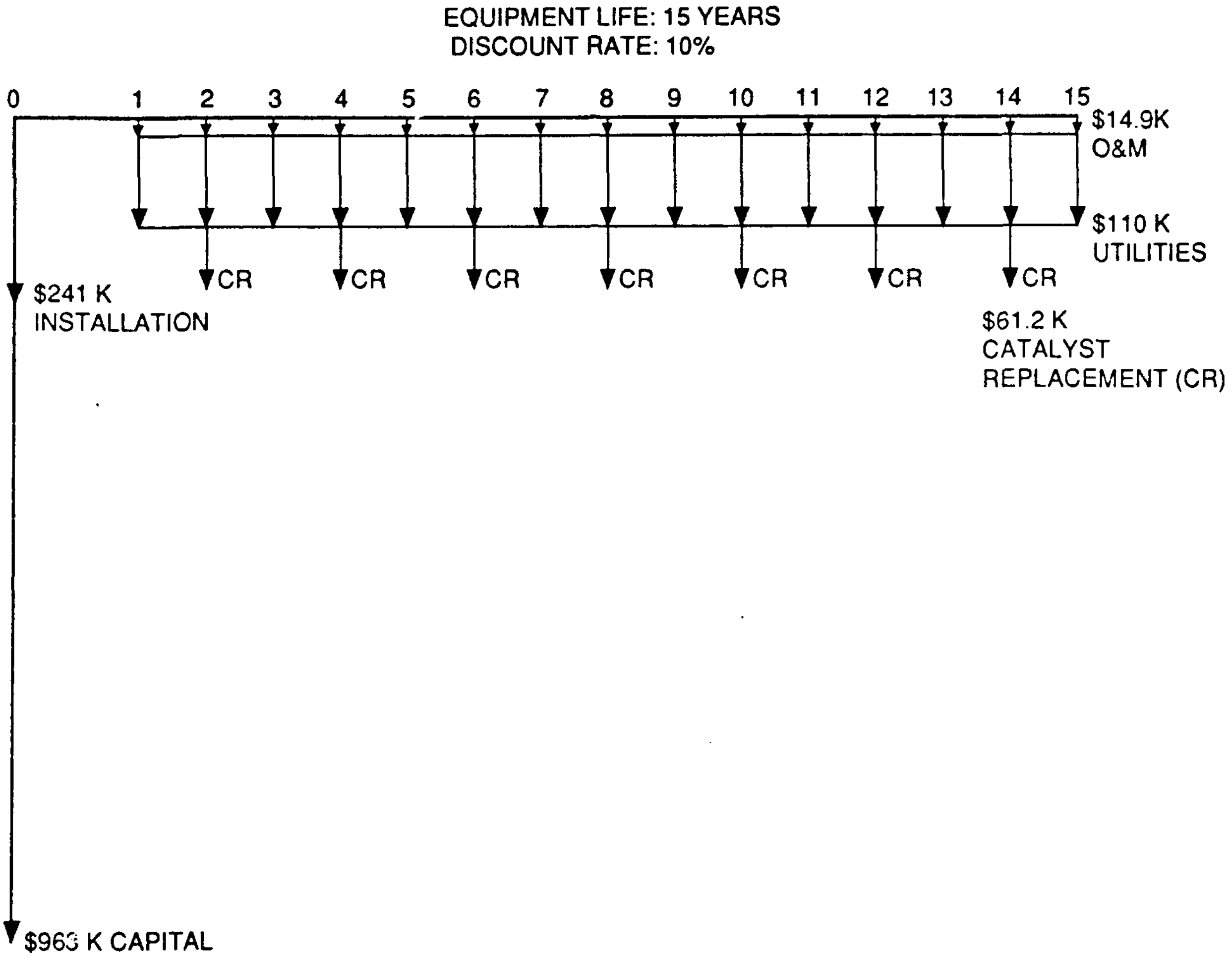

Figure 19. Cash-Flow Diagram for FBCI

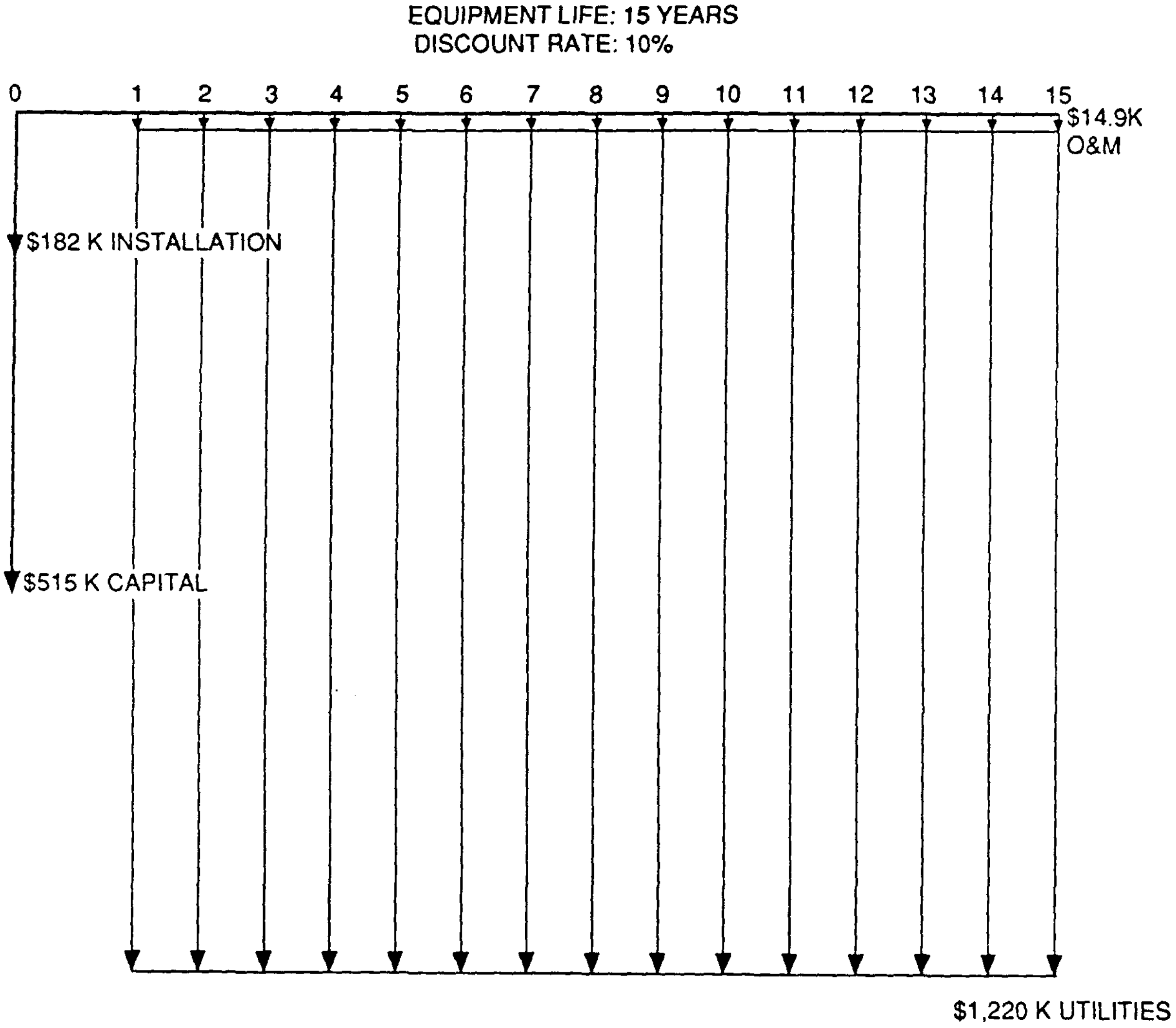

Figure 20. Cash-Flow Diagram for RTI

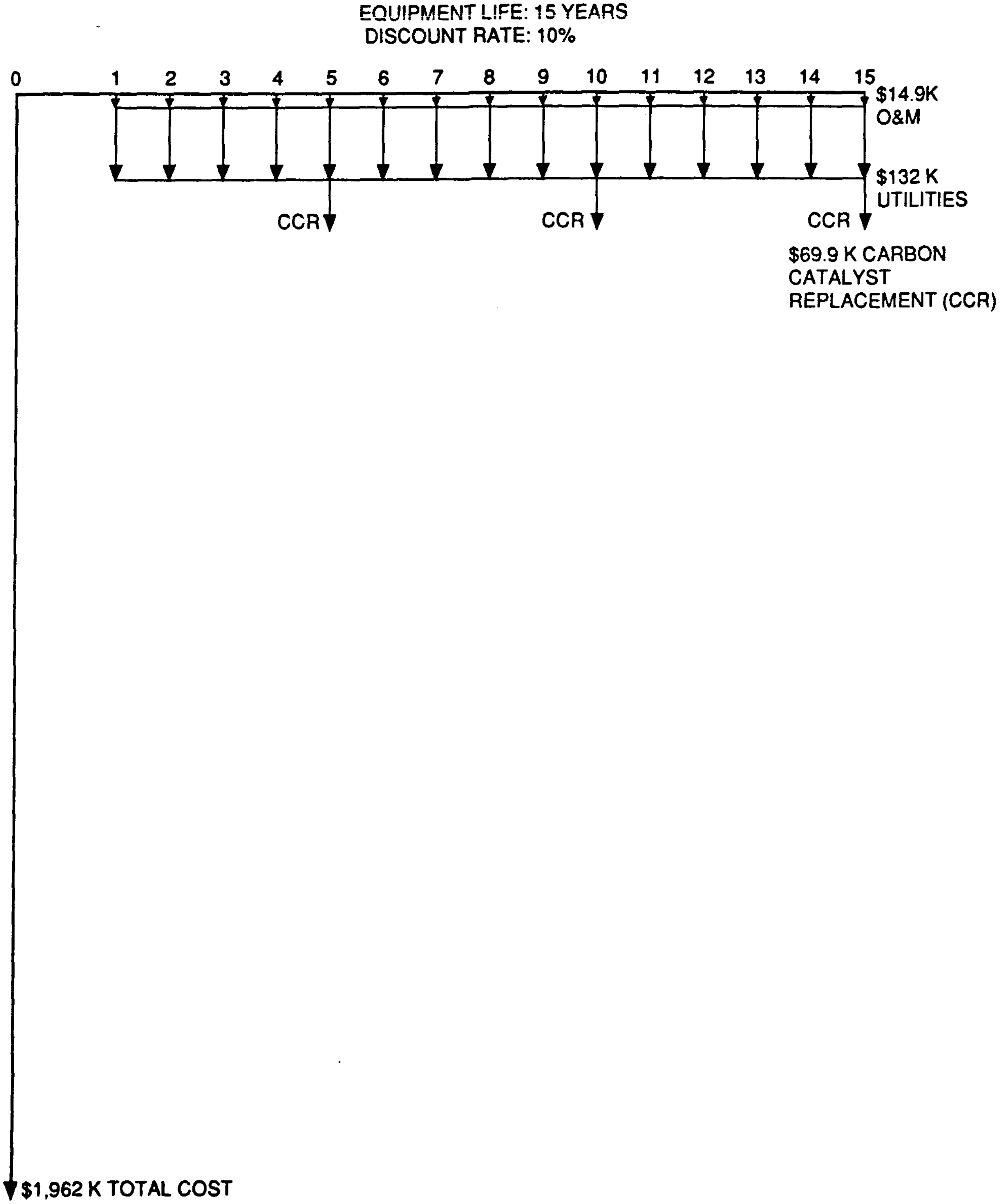

Figure 21. Cash-Flow Diagram for RCA and Catalytic Incineration

SECTION IX

SPECIFICATION CRITERIA FOR SYSTEM SELECTION AND SYSTEM PROCUREMENT

The selection and procurement of air pollution control devices (APCDs) for controlling VOCs from paint spray booths demands an understanding of both technical and regulatory requirements. APCDs can be complex and costly items, so it is desirable that the engineer procuring a system knows what is required to meet the goal of VOC control. The engineer can incorporate much of the information into procurement specifications to solicit bids. This information includes technical, administrative (or regulatory), and standard construction information that a contractor would need to bid properly on a proposal. Section A lists and describes the technical criteria that must be identified. Section B lists and describes the regulatory information that must be understood to make a sound purchasing decision. Standard construction specification criteria are not discussed in this report, since they are fundamental information that engineers are familiar with.

A. TECHNICAL INFORMATION

Table 33 is a list of technical criteria that an engineer should understand when procuring an APCD. If a criterion does not translate directly into a Request for Quotation (RFQ), the engineer should have an opinion concerning the criterion and keep it in mind when writing procurements and evaluating bids. Following are descriptions of each criterion.

1. Maximum Flow Rate

What is the maximum flow rate of paint spray booth exhaust gas that needs treatment? The flow rate greatly affects the size, weight, and cost of an APCD.

2. Destruction and Removal Efficiency (DRE)

What DRE is required? APCDs are available that provide DREs in a wide range that includes greater than 99 percent. The DRE required influences the choice of APCD.

3. Maximum VOC Loading

What VOC concentration is expected in the paint spray booth exhaust gas? Some APCDs operate better when treating high concentrations, while others function better when handling exhaust air containing lower VOC concentrations.

4. VOC Characterization

The VOCs in the exhaust air need to be identified, since different VOCs are treated differently by various APCDs. For example, some APCDs can handle chlorinated solvents, while others cannot.

5. Variability of Exhaust Gas Flow Rate

Flow rates of exhaust gas from a paint spray booth can vary significantly during the course of operation. Will fluctuating flow rates affect the APCD? Some APCDs do not function well during nonsteady-state conditions.

TABLE 33. LIST OF TECHNICAL CRITERIA FOR RFQ.

Criterion	Identification for RFQ	Supplied by Vendor
Maximum Flow Rate	x	
Destruction and Removal Efficiency (DRE)	x	
Maximum VOC Loading	x	
VOC Characterization	x	
Variability of Exhaust Gas Flow Rate	x	
Variability of VOC Loading	x	
Type of Treatment	x	x
Utilities		x
Space for APCDs		x
Equipment Life		x
Reliability		x
Operator Skill		x
Maintenance		x
Catalyst Replacement		x
Carbon Replacement and Regeneration		x
Filters		x
Waste and Hazardous Waste		x
Hazardous Materials		x
Storage Facilities		x
Heat Exchangers		x
Safety Features	x	x
Automatic Controls	x	x
Environmental Impacts		x
Air Sampling Compatibility	x	x
Additional Costs		x
System Flexibility		x

6. **Variability of VOC Loading**

Paint spray booths are often operated intermittently as opposed to continuously. Some APCDs handle this batch loading, which can include minute-by-minute VOC variations, better than others.

7. **Type of Treatment**

After the waste stream has been characterized (flow rate, VOC loading, and type of VOC), the engineer can begin to consider types of treatment systems. For example, is it better to have a technology that destroys VOCs or one that collects and recycles them?

8. **Utilities**

Assess what utilities are available and identify any that need to be installed. Utility needs can include water, sewer, gas, oil, electricity, steam, air, and inert gas.

9. **Space for APCDs**

APCDs can be large and heavy, so it must be decided how much space is available and what type of structural modifications are needed to accommodate the new equipment.

10. **Equipment Life**

APCDs have a life span of 10 to 15 years. Equipment life should be discussed with each bidding vendor.

11. **Reliability**

Many control technologies are new on the market, and they should be evaluated with care. Determine if the APCD has a proven track record for *your* application. Does the company have a proven track record for service? Is the technology fully deployed and are most of the associated problems resolved?

12. **Operator Skill**

APCDs need some time from an operator during each shift—how much time? It is important to know what capabilities the operator must possess to run the system. Must the operator be an experienced combustion engineer, or a skilled mechanic knowledgeable in piping and valves, or both? Must the operator be skilled in computer programming? Will the operator require any special certifications? Will the operator come from the existing labor force or must the person be hired?

13. **Maintenance**

The same questions concerning the operator apply to the personnel responsible for maintenance. Also, how accessible is the unit for maintenance? Is the design well thought out so that repairs can be performed easily and safely?

14. **Catalyst Replacement**

Many APCDs rely on some type of catalyst to augment the thermal destruction of VOCs. When reviewing such a system, it is important to determine what kind of catalyst is used, how much, how often it is replaced, what it costs to replace, and how readily available it is. Is the catalyst a hazardous material and does used catalyst require special disposal procedures?

15. Carbon Replacement and Regeneration

Carbon in some form (granular, paper fiber, powder) is often used in APCDs. Questions similar to those relating to catalyst replacement also apply to carbon. Carbon can also be regenerated, and the frequency and cost of regeneration should be considered.

16. Filters

Many APCDs have prefilters to remove paint overspray from the paint spray booth exhaust. The frequency and cost of filter replacement and disposal must be considered.

17. Waste and Hazardous Waste

VOC control technologies often generate some hazardous waste. Systems using carbon adsorption may generate wastewater. Used catalyst, carbon, and filters must all be properly disposed of. How much waste is generated, and how often, are questions that need answers. Is the waste hazardous, and if so, are specially trained and certified personnel required to handle it? What is the cost of disposal?

18. Hazardous Materials

Some control technologies generate hazardous materials, mainly solvents. These solvents must be collected, stored, and transported safely. What is the cost of this and what level of training must the personnel have? Is there an economic benefit from recycling the hazardous material?

19. Storage Facilities

Additional storage facilities may be needed to store extra filters, recovered solvent, waste materials, or fuel. If fuel oil is used, for example, an underground tank may be needed for storage. Storage facilities will probably need to meet specific building codes.

20. Heat Exchangers

Most VOC control technologies have some type of heat exchanger incorporated into their designs. Heat exchanger costs increase exponentially with heat exchanger efficiencies, but they do decrease fuel costs. It is desirable to know what heat exchanging efficiencies are available for any given APCD.

21. Safety Features

Each system should have safety features that perform emergency shutdowns and alert operators of any problems. In some cases, equipment may need to meet National Fire Prevention Association (NFPA) standards.

22. Automatic Controls

Turnkey systems are standard for VOC control technologies and decrease operator labor. Information about an APCD's automatic controls can help evaluate the ease of operation.

23. Environmental Impacts

The environmental impacts of various APCD options must be considered. Will the systems obtain the desired DRE at all times under normal operating conditions? What happens when the system is operating in upset conditions? Some units continue to function well, while others fail. What air emissions will the APCD have—CO, NO_x, particulate, metals, etc.? Will wastewater be generated that requires treatment before it is discharged? Will the solid wastes generated be an environmental risk in the future?

24. Air Sampling Compatibility

VOC control technologies will be source-tested at some point during their life span, a fact often overlooked. Source-testing is complicated and demands a specific sampling point configuration. Future problems can be avoided if proper sampling locations (and accessibility to them) are designed into the control device. If possible, vendors should provide sampling locations that at least meet the requirements of EPA Methods 25 or 25A. Even better would be sampling locations conforming to EPA Method 5.

25. Additional Costs

Capital costs and installation costs are readily provided by vendors; however, additional, or hidden, costs are often difficult to identify. Carbon, catalyst, and filter replacement can be very expensive, especially if replacement is required annually. Some systems may be very specialized and serviceable only by the vendor. Annual utility demands can vary widely, as can the associated costs. While a system may be quite efficient with gas, it may be less so with electricity; thus, projected energy costs provided by vendors must be carefully evaluated. Determine what utilities and replacement parts are needed throughout the life of the equipment. For example, at some point the system might need a complete overhaul, requiring replacement parts that were not initially planned for or bid upon.

26. System Flexibility

It is best to find a system that has some flexibility, if possible. How wide a range of flow rates can it treat? Can it be adapted to increase DRE, or to add heat exchangers? Will changes in painting schedules affect it? Can it be used with recirculation technologies?

B. ADMINISTRATIVE REQUIREMENTS

Environmental regulations and permitting procedures are issues requiring administrative attention when planning to purchase and install APCDs to control VOCs. In addition, OSHA regulations and permits and, probably, an array of fire, building, and military regulations and permits, may be applicable. In many instances these regulations may actually dictate the choice of control technology.

1. Federal Environmental Regulations

Federal regulations and permits directly apply if state and/or local regulatory agencies are not actively involved.

2. State Environmental Regulations

States may have the authority to establish treatment goals for the APCDs based on pollutant emission levels. Annual operating permits are usually required for APCDs unless waivers can be obtained. State agencies generally require notification of intent to install and operate APCDs. These agencies may require that approval be given to any proposed control system.

3. Local Environmental Regulations

Local agencies, such as air pollution control districts, also have regulations and permitting requirements. These regulations and requirements supersede those of the state and federal governments, but cannot be less stringent than those established by the state and federal governments. Local agencies that regulate wastewater and hazardous waste storage and disposal may also become involved if the chosen control device generates either wastewater or hazardous waste.

Environmental compliance consists of installing and maintaining an approved APCD and keeping its operating permits current. The environmental agencies determine the APCD's performance standards. Their permits establish the frequency and type of air sampling needed to establish compliance with operating permits. Compliance with permitting procedures frequently involves working with local agencies on one aspect of the control device, and with state or federal agencies on others. For example, an air pollution control district may have its own air emission regulations, while state and federal agencies may regulate waste treatment and disposal.

4. Occupational Safety and Health Administration (OSHA) Regulations

OSHA has general health and safety regulations that must be addressed. OSHA's concerns include safe workplace issues and hazardous materials handling. Permits may be required to operate the APCD, and special certifications may be needed by the personnel handling hazardous materials. OSHA may require NFPA-approved safety equipment in ducts and emission control devices.

5. Fire Department Regulations

Installation and operation of a VOC control device may require approval from local fire officials. Safe storage and handling of flammable materials and the design and location of incinerators may be checked by fire department officials. Permits and NFPA-approved safety equipment may also be required.

6. Building and Construction Permits

Building and construction permits may be required for the installation of a VOC emission control device.

SECTION X

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. Technical

- Field-testing of CPACI and FBCI has demonstrated that these technologies can effectively control VOC emissions from USAF paint spray booths.
- Generally, modern VOC control technologies can economically achieve high DREs.
- Other VOC control technologies, such as RTO, are feasible based on manufacturers' literature and on the reported uses of these technologies in the automobile and aircraft manufacturing industries.
- Membrane vapor separation processes, although not field-tested as yet, may be capable of removing VOCs from exhaust gas and collecting the VOCs separately.
- CPACI technology is capable of maintaining VOC DREs of 99 percent under normal operating conditions, and can thus meet most current local, state, and federal regulatory agency requirements.
- CPACI technology has a potential disadvantage deriving from the VOC-concentrating system. The possibility exists that VOCs in the desorption gas can be concentrated in excess of the lower explosive limit (LEL).
- FBCI technology can maintain DREs above 99 percent, and can thus meet most current local, state, and federal regulatory agency requirements.
- Under certain conditions, particulate emissions could be a disadvantage of FBCI.
- Applications in which large amounts of chlorinated solvents are used would be incompatible with CPACI and FBCI because of the potential for elevated HCl emissions.

2. Economic

- CPACI and FBCI have lower treatment costs than standard VOC control technologies with equivalent or near-equivalent technical performance.
- The economics and technical performance of CPACI and FBCI indicate that these technologies are suitable VOC and HAP emission control options for USAF paint spray booths.
- The cost of VOC control can be lowered if flow-reduction techniques are used.

B. RECOMMENDATIONS

- Before purchase of a VOC control device, a careful study should be conducted to ensure the selection of a system that properly matches requirements with capabilities.
- RTO and membrane vapor separation technologies should be technically evaluated, through the field-testing of pilot-scale units, before being selected as VOC control devices for paint spray booths.
- We recommend that research be conducted to evaluate the ability of innovative control technologies to handle specific chemicals. Different technologies will be applicable for different chemical mixtures.
- Whenever possible, capital and O&M costs should be lowered by using flow-reduction techniques in front of control technologies.
- Multiple waste streams should be treated by one control unit, since such will reduce costs.

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APPENDIX A

QUALITY ASSURANCE AND QUALITY CONTROL

To ensure that valid data were collected, the Quality Assurance and Quality Control (QA/QC) Plan was followed. Tests that were subjected to QA/QC criteria established in the QA/QC Plan were NIOSH 1300, Method 25A, Method 2, and BAAQMD Method ST-7. EPA Method 5 tests were required to meet the QA/QC objectives established by the test method.

A. GOALS AND OBJECTIVES FOR QA/QC

Precision, accuracy, and completeness objectives for the tests carried out are shown in Table A-1. QA/QC objectives for the BAAQMD Method ST-7 are the same as for Method 25A. Precision was determined for the charcoal tube results by analyzing duplicate samples and performing matrix spike duplicate analyses of spiked blank charcoal tubes. CEM precision was evaluated by the use of standard reference gases, not duplicate analyses. This is due to the variability of the sampling stream and operating conditions, which make obtaining a duplicate sample impossible. Precision for the Method 2 tests (velocity measurements) was checked by taking duplicate samples.

Accuracy for the NIOSH 1300 tests was assessed as percent recovery of the matrix spikes from the blank charcoal tubes. This assessed extraction efficiency and analytical recovery. Continuous monitoring test accuracy was checked each day by comparing monitors to the expected value of a reference gas.

Completeness was measured as the percentage of valid data obtained divided by the total number of samples collected.

B. QA/QC RESULTS

Relative percent difference (RPD), accuracy (percent recovery), and completeness were determined for each measurement parameter, when applicable. Particulate sampling QA/QC was evaluated by following calibration guidelines established by EPA Method 5.

1. Volume Flow in Ducts

Table A-2 shows the precision for the volume flow measurements in the ducts. Standard deviations or RPDs were calculated for EPA Method 2 flow measurements made at the CPACI Inlet (Site 7) and the FBCI Inlet (Site 8). RPDs were calculated for duplicate measurements, while standard deviations were calculated for triplicate measurements. The RPDs and standard deviations presented in Table A-2 represent all replicate samples taken. The highest RPD found was 13 percent. The highest standard deviation found was 25, or 4.1 percent.

EPA Method 2 flow measurements were generally made with a standard pitot tube. Standard pitot tubes are the references by which accuracies for other flow measurement instruments are checked. Therefore, no special measurements for accuracy were made for the

TABLE A-1. PRECISION, ACCURACY, AND COMPLETENESS OBJECTIVES.

Measurement Parameter	Measurement/ Analytical Method	Reference	Precision Relative Percent Difference	Accuracy (percent recovery)	Completeness
Volume flows in ducts	EPA Method 2 Pitot tube	40 CFR 60 Appendix A	±20	±40	90
Particulate concentrations in ducts	EPA Method 5 Isokinetic sampling	40 CFR 60	NA[a]	NA	90
Organic compound concentrations in air	NIOSH 1300 carbon absorption extraction GC/FID	DHHS (NIOSH)[b] 84-100	±35	70 to 120	90
Hydrocarbon emissions	EPA 25A	40 CFR 60 Appendix A	±20	±20	NA
Hydrocarbon emissions	Organic vapor analyzer	Manufacturer's manual	±20	±20	NA

[a] NA—Not applicable, continuous process

[b] NIOSH Manual of Analytical Methods, Department of Health and Human Services

TABLE A-2. EPA METHOD 2: QA/QC RESULTS.

Date	Run Number	Site Number	RPD (%)	Standard Deviation
5/11/89	Test 5	7	0.69	
		8	5.0	
5/12/89	Test 8	7		19
		8	2.1	
	Test 9	7	11	
		8	3.3	
5/15/89	Test 10	7	13	
	Test 12	7		5.7
5/16/89	Test 13	7	0.00	
		8	0.00	
5/17/89	Test 16	7	0.15	
		8	3.4	
	Test 17	7	1.4	
		8	2.8	
	Test 18	7		19
		8		25
5/18/89	Test 19	7		5.7
		8		5.5
	Test 20	7	2.5	
		8	0.18	
	Test 21	7	2.6	
		8	4.5	
5/19/89	Test 22	7	3.3	
		8	1.8	
	Test 23	7	0.86	
		8	0.27	
	Test 24	8	9.5	

flow rate measurements. All measurements made using S-type pitot tubes did not need special reference checks. The pitot tubes used conform to EPA Method 2 specifications.

Completeness for the flow rate measurements was 100 percent. One hundred thirty-seven velocity traverses were performed, and 33 replicate measurements were made. Replicate measurements were usually taken at Sites 7 and 8, since these sites were the points at which regular monitoring was performed during measurement of airflow into each treatment unit.

2. Particulate Concentration Measurements

Particulate concentration measurements by Method 5 are subject to the calibration procedures established in EPA Method 5. RPDs and accuracy evaluations are not relevant because the complexity of the sampling method precludes simultaneous duplicate tests. Completeness for particulate concentration measurements was 100 percent.

3. Organic Compound Concentrations by NIOSH 1300

Table A-3 shows the RPDs, standard deviations, and percent recoveries obtained for the NIOSH 1300 test results. This table presents these values by charcoal tube size, front or back half of charcoal tube, spike level used, and chemical used for the spike. RPDs for the NIOSH 1300 tests ranged from 0.48 to 5.3 percent, and the highest average for a charcoal tube was 3.95 percent. This occurred for large charcoal tubes spiked with low levels of methoxyacetone. The highest percent recovery averaged 124 percent and was for methoxyacetone in the small charcoal tubes using a low-level spike. The lowest recovery averaged 91.6 percent. Ninety-one samples were collected and four background samples were not submitted, since they were collected at an inappropriate flow rate.

4. Hydrocarbon Emissions by EPA Method 25A and BAAQMD ST-7

Table A-4 shows the RPDs and accuracies for the continuous measurements of hydrocarbons. The average standard deviation for the hydrocarbon monitors was 0.8, or 3 percent. The average accuracy for all hydrocarbon monitors was 3.6 percent. The standard deviation for the ST-7 method was 8.63, or 1.3 percent. The accuracy of the ST-7 method was 3.3 percent. Completeness of testing was 100 percent.

a. QA/QC Discussion

(1) Volume Flow in Ducts. The QA/QC objectives for volume flow measurements were met. The RPDs are all within 20 percent, as established in the QA/QC plan. Accuracy is within the objective of 40 percent, since measurements were made with a standard pitot tube. To calculate DREs and VOC emission rates, flow rate measurements of the influent air were used. Variation in flow measurements were noticed during testing of the pilot-scale devices. Changes of as much as 50 dscfm were observed for the influent air to each device. This variation can cause the DREs to change by as much as 2 percent. Therefore, calculated DREs can be expected to vary by ±2 percent. These variations in flow rates were found during only the first 2 days of testing. During the second day of testing, it was discovered that flow rates

TABLE A-3. NIOSH: QA/QC RESULTS.

Compound	Relative Percent Difference		Percent Recovery	
	Front	Back	Front	Back
Large Tubes, Low Levels				
2-Butanone (MEK)	2.4	0.48	96.9	93.3
Methoxyacetone	5.3	2.6	107	103
Toluene	3.1	2.1	92.4	102
Butyl acetate	2.8	1.1	97.7	94.3
2-Ethoxyethyl acetate	2.9	1.1	105	104
Large Tubes, Medium Levels				
2-Butanone (MEK)	1.2	2.5	93.7	90.4
Methoxyacetone	1.1	3.4	113	107
Toluene	2.2	2.2	96.1	95.9
Butyl acetate	1.2	1.8	96.1	92.7
2-Ethoxyethyl acetate	1.1	1.6	104	100
Small Tubes, Low Levels				
2-Butanone (MEK)	3.7	3.2	97.2	103
Methoxyacetone	3.2	3.9	126	122
Toluene	4.1	3.0	97.9	106
Butyl acetate	3.1	3.1	98.3	97.9
2-Ethoxyethyl acetate	2.8	3.5	106	104

TABLE A-4. QA/QC RESULTS FOR TUHC MEASUREMENTS.

QA/QC	EPA Method 25A Measurements[a]	BAAQMD ST-7 Measurements[b]
Standard Deviation	0.8 (3%)	8.6 (1.3%)
Mean	25.1 ppm	679 ppm
Accuracy (percent)	±3.6	±3.3

[a] Method 25A Reference Gas Value: 26 ppm
[b] ST-7 Reference Gas Value: 657 ppm

were being affected by wind gusts because of an exposed area of ducting. After correction of the problem, fluctuations in flowrate were not significant.

(2) **Particulate Concentration Measurements.** Particulate concentration measurements were made according to EPA Method 5 specifications. All samples were collected isokinetically and instrument calibrations were acceptable.

The five samples collected that had isokinetics outside the specified ±10 percent range were still used. Four of the five samples were from the CPACI incinerator exhaust. The deviations from isokinetics had little impact on evaluation of particulate concentrations, since only a few were out of specification.

(3) **Organic Compound Concentrations by NIOSH 1300.** RPDs and percent recoveries for the NIOSH 1300 measurements met the objectives established in the QA/QC plan. QA/QC objectives of ±35 percent for the RPDs and 70 to 120 percent for percent recovery were met, except for the percent recovery of methoxyacetone in the small charcoal tubes. The 124 percent recovery does not significantly affect results. The higher recovery would result in calculations that yield lower DREs, thus resulting in conservative errors.

(4) **Hydrocarbon Emissions by EPA Method 25A and BAAQMD ST-7.** Standard deviations and accuracies for hydrocarbon emissions measurements met the objectives established in the QA/QC plan. QA/QC objectives of ±20 percent for both standard deviations and accuracies were met.

(5) **Organic Vapor Analyzer (OVA).** The OVA was not used during the test period. Therefore, QA/QC objectives do not apply. The instrument developed a calibration problem before the test began, and Acurex deemed that the unit would not be reliable. A third TUHC analyzer was used and placed on the CPACI carbon paper exhaust. Three tests were run on 10 May 1989 before a TUHC monitor could be installed.

APPENDIX B

TECHNICAL APPROACH/DATA REDUCTION METHODS

A. DREs AND ORGANIC EMISSION RATES

The DREs for each pilot-scale unit were calculated by combining NIOSH data with CEM data. This blending of data allowed a VOC emission rate to be calculated as well. NIOSH and CEM results pertaining to the influent waste stream were also used.

1. Type of Data Used

The following information was used to calculate DREs and VOC mass emission rates:

- Chemical composition as detailed from NIOSH sampling data of the inlet waste stream
- Flow rates of solvent-laden air entering each unit
- Flow rates of exhaust gas from each unit
- Concentration of organic carbon in the inlet stream (BAAQMD Method ST-7 results)
- Concentration of TUHC in exhaust gas from each unit (EPA Method 25A results)

2. Assumptions

Calculating the DREs and the organic emission rates involved the following assumptions:

- The organic speciation and relative composition of the exhaust gas is the same as the influent gas
- All values that appear as 0 ppmv TUHC will be read as 0.5 ppmv, the lower detection limit
- Flow rate of the flue gas from the carbon paper adsorber is the same as the flow rate of the influent gas

3. Approach Used

- Use NIOSH test data to determine what organic compounds are present in the waste stream
- Determine the percent composition of the solvent-laden gas
- Determine the fraction of carbon in each organic compound present
- Calculate the lb organic carbon/hr entering the unit. Use the following equation from BAAQMD Method ST-7:

$$\text{lb } C_{org}/\text{hr} = 1.86\text{E-}6 \times Q_0 \times C_{ppmv} \qquad \text{(B-1)}$$

Q_0 = influent flow rate (dscfm)

C_{ppmv} = ppmv organic carbon measured by Method ST-7

- Determine the lb VOC/hr entering the unit. Use NIOSH speciation data combined with ST-7 data

$$\text{lb VOC/hr} = \text{lb } C_{org}/\text{hr} / \Sigma_1^n f_n C_n \qquad \text{(B-2)}$$

Where: $\underline{n}$ = an organic chemical present in the influent stream
f_n = the fraction of $\underline{n}$th organic chemical present in the influent stream
C_n = percent of C in the $\underline{n}$th chemical present

- Calculate the lb organic carbon/hr in the exhaust gas. Use TUHC measurements supplied as ppmv as propane. Divide this by 3 to convert the data into ppmv organic carbon. Apply Equation (B-1) to the adjusted TUHC data.
- Use Equation (B-2) to determine the lb VOC/hr being emitted
- Use Equation (B-3) determine the DRE of VOCs

$$\text{DRE} = [(\text{Mass Flow Rate In} - \text{Mass Flow Rate Out})/\text{Mass Flow Rate In}] \times 100 \qquad \text{(B-3)}$$

- CPACI system overall DREs and VOC emission rates will incorporate the results from the incinerator and carbon paper adsorber

Example Calculations for FBCI:

- Find organic compounds that are present in influent waste stream

Date: 6 May 1989, NIOSH Test No. 13

NIOSH Results		**% of Total**
MEK	0.9 µg/L	12
2-ethoxyethyl acetate	6.5 µg/L	88
Total	7.4 µg/L	100

- **Determine fraction of carbon in each compound**

	C_n
MEK	**0.6663**
2-ethoxyethyl acetate	**0.5453**

- Calculate lb C_{org}/hr entering the unit

$$\text{lb } C_{org}/\text{hr} = 1.86 \times 10^{-6}\, Q_o \cdot C_{ppmv}$$

$$C_{ppmv} = 39 \text{ ppmv} \quad \text{(from ST-7 data)}$$

$$Q_o = 524 \text{ dscfm} \quad \text{(from velocity traverses)}$$

Inlet Mass Flow Rate

$$\text{lb } C_{org}/\text{hr} = 0.038$$

(from BAAQMD ST-7)

- Determine the lb VOC/hr entering the unit

$$\text{lb VOC/hr} = \text{lb } C_{org}/\text{hr} \div (f_1 \cdot C_1 + f_2 C_2 \; . \; . \; . \; . + f_n\, C_n)$$

$f_1 = f_{MEK} = 0.12$

$f_2 = f_{2\text{-ethoxyethyl acetate}} = 0.88$

$C_1 = 0.6663$

$C_2 = 0.5453$

$C_{org} = 0.038$ lb/hr

$$\text{lb VOC/hr} = 0.038 + ((0.12)(0.6663) + (0.88)\,(0.5453)) = 0.068$$

- Calculate lb C_{org}/hr for effluent gas
  - TUHC measurement: 0.7 ppmv as propane
  - Convert to ppmv as organic carbon. Divide TUHC measurement by 3.
    - 0.7/3 = 0.2 ppmv
  - Use Equation (B-1) again
  - lb C_{org}/hr = $1.86 \times 10^{-6}\, Q_o\, C_{ppmv}$
    - $Q_o = 684$
    - lb C_{org}/hr = $1.86 \times 10^{-6}\,(684)(0.2) = 3 \times 10^{-4}$
- Determine the lb VOC/hr being emitted. Use Equation (B-2). Assume percent chemical composition of exhaust gas is similar to influent waste stream.

$$\text{lb VOC/hr} = \text{lb } C_{org}/\text{hr} + \Sigma_1^n\, f_n\, C_n$$

So

$$\text{lb VOC/hr} = 2.5 \times 10^{-4} + ((0.12)(0.6663) + 0.88\,(0.5453))$$

$$\text{lb VOC/hr} = 2.5 \times 10^{-4}$$

- Determine DRE of VOCs

$$\text{DRE} = \frac{\text{Mass Flow Rate In} - \text{Mass Flow Rate Out}}{\text{Mass Flow Rate In}} \times 100\%$$

$$\text{DRE} = \frac{0.068 - 3 \times 10^{-4}}{0.068} \times 100 = 99.5\%$$

B. CEM DATA REDUCTION APPROACH

Instantaneous readings of each parameter were recorded on strip charts over each hour-long sampling event. These readings were integrated to find average values for each event using the data reduction approach shown in Table B-1. Instrument drift and sampling system bias are incorporated as given by Equation 6C-1 of EPA Method 6C (40 CFR Part 60, Appendix A). Table B-1 presents the raw data used in Equation 6C-1, the equation itself, and the final corrected average results for each sampling event.

C. NIOSH DATA REDUCTION APPROACH

Results of the GC/MS analysis for each sample were divided by the volume of gas collected. This yielded a concentration (μg/L) of organic compound in the gas stream sampled.

D. METHOD 5 DATA REDUCTION APPROACH

Particulate emissions were determined by the direct use of EPA Method 5. Raw data and calculations for each sampling run are given in Appendix C.

The measurements for the Method 5 analysis are:

- Pressure differential across the orifice meter
- Stack gas temperature
- Sampling temperature at the gas meter
- Stack gas pitot pressure differential (i.e., velocity pressure)
- Filter dry weight gain
- Probe wash dry weight
- Water condensate to fine stack gas moisture
- Stack gas O_2 and CO_2 to determine stack gas molecular weight

The step-by-step procedure of how these parameters are used to determine particle emission rate is shown in Table B-2, the isokinetic performance worksheet, and particulate calculations. The amount of moisture in the stack is determined from the volume of liquid captured in the impingers and the volume of gas sampled, converted to standard conditions (68°F, 29.92 inches Hg). The molecular weight of the stack gas is calculated from the amount of CO_2, O_2, and N_2 in the stack gas, which was determined from the CEM monitors. The stack gas velocity calculation also depends on the molecular weight. After weighing the particulate

TABLE B-1. DATA REDUCTION APPROACH FOR CEM MEASUREMENTS.

Data Reduction Steps

- Count squares beneath curve
- Calculate average reading over time
- Find average zero sampling system calibration response
- Find average upscale gas sampling system calibration response
- Use Equation 6C-1 from Method 6C to calculate effluent gas concentration, dry basis, ppm

Equation 6C-1:

$$C_{gas} = (C - C_o) \times \frac{C_{ma}}{C_m - C_o}$$

C_{gas} = Effluent gas concentration, dry basis, ppm

C = Average gas concentration indicated by gas analysis, dry basis, ppm

C_o = Average of initial and final system calibration bias check responses for the zero gas, ppm

C_m = Average of initial and final system calibration bias check responses for the upscale calibration gas, ppm

C_{ma} = Actual concentration of the upscale calibration gas, ppm

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TABLE B-2. ISOKINETIC PERFORMANCE WORKSHEET AND PARTICULATE CALCULATIONS.

Plant______________________________ Performed by__________________

Date ______________________________

Sample Location____________________

Test No./Type______________________

Barometric Pressure (in. Hg)	P_b	
Meter volume (std), $17.64\left(\frac{V_m}{\alpha}\right)\left(\frac{P_b + \frac{\Delta H}{13.6}}{T_m + 460}\right)$ $17.64\left(\frac{(\underline{\quad\quad})}{(\underline{\quad\quad})}\right)\left(\frac{(\underline{\quad\quad}) + \frac{(\underline{\quad\quad})}{13.6}}{(\underline{\quad\quad}) + 460}\right)$	$V_{m\ std}$	
Volume of liquid collected (grams)	Vl_c	
Volume of liquid at standard condition (scf) $Vl_c \times 0.04707$	$V_{w\ std}$	
Stack gas proportion of water vapor $\frac{V_{w\ std}}{V_{w\ std} + V_{m\ std}}, \frac{(\underline{\quad\quad})}{(\underline{\quad\quad}) + (\underline{\quad\quad})}$	B_{wo}	
Molecular weight, stack gas dry (lb/lb-mole) $(\%\ CO_2 \times 0.44) + (\%\ O_2 \times 0.32) + (\%\ N_2 + \%\ CO \times 0.28)$ $(\underline{\quad\quad} \times 0.44) + (\underline{\quad\quad} \times 0.32) + (\underline{\quad\quad} + \underline{\quad\quad} \times 0.28)$	M_d	
Molecular weight, stack gas wet (lb/lb-mole) $Md(1-B_{wo}) + 18(B_{wo}),\ (\underline{\quad\quad})(1-\underline{\quad\quad}) + 18(\underline{\quad\quad})$	M_s	
Absolute stack pressure (in. Hg) $P_b + \frac{P_{stack}\ (\text{in. } H_2O)}{13.6},\ (\underline{\quad\quad}) + \frac{(\underline{\quad\quad})}{13.6}$	P_s	

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TABLE B-2. ISOKINETIC PERFORMANCE WORKSHEET AND PARTICULATE CALCULATIONS (CONCLUDED).

Temperature stack gas, average (^{o}F)	T_s	
Stack velocity (fps) $85.49\ (C_p)\ (\sqrt{\Delta P}_{s\ avg})\ \sqrt{\dfrac{T_s avg + 460}{P_s\ \ M_s}}$ $85.49\ (\_\_\_)(\sqrt{\quad})\ \sqrt{\dfrac{(\_\_\_) + 460}{(\_\_\_)(\_\_\_)}}$	$V_{s(avg)}$	
Total sample time (minutes)	θ	
Nozzle diameter, actual (inches)	N_d	
Percent isokinetic (%) $\dfrac{17.33\ (T_s + 460)(V_w\ std + V_m\ std)}{\theta\quad V_s\quad P_s\quad N_d^2}$ $\dfrac{17.33\ (\_\_\_ + 460)((\_\_\_) + (\_\_\_))}{(\_\_\_)(\_\_\_)(\_\_\_)(\_\_\_^2)}$	%I	
Area of stack (ft^2) $\pi = 3.1416$ $\pi r^2 \div 144,\quad \pi(\_\_\_)^2 \div 144$	A_s	
Stack gas volume at standard conditions (dscfm) $60\ (1 - B_{wo}) Vs_{avg}\ A_s \left(\dfrac{528}{T_s\ avg + 460}\right)\left(\dfrac{Ps}{29.92}\right)$ $60\ (1 - \_\_\_)(\_\_\_)(\_\_\_)\left(\dfrac{528}{\_\_\_ + 460}\right)\left(\dfrac{(\_\_\_)}{(29.92)}\right)$	Q_s	
Particulate matter concentration, dry (gr/dscf) $15.432\ \dfrac{M_p(grams)}{Vm_{std}},\qquad 15.432\ \dfrac{(\_\_\_)}{(\_\_\_)}$	$C_{s(std)}$	
Emission rate of particulate matter (lb/hr) $0.00857\ (Q_s)\ C_{s(std)},\ 0.00857\ (\_\_\_)(\_\_\_)$	E_p	

mass in the dried filter and in the probe wash, the particulate concentration and emission rate for each run are determined.

E. POWER CONSUMPTION, DATA REDUCTION

The first task was to categorize the raw data into one of the three previously identified test conditions. Since the operating conditions of the control unit fluctuated, only data that fell within the three operating conditions were used. In some cases, it was necessary to use engineering judgment because the operating set points and the actual readings fell within different categories.

1. CPACI

The total power consumed and the rate of usage for each time period were calculated for pertinent test conditions. The power used in kW-hr for each time period was added up. The total power used was then divided by the interval time to obtain the mean rate of usage. This allows data from different time durations to be compared. In some cases a daily average had to be used because insufficient data were collected for specific time periods.

2. FBCI

The amount of propane used for each time period was obtained by the difference in the gas meter readings (cubic feet). This amount was divided by the time interval and converted into Btu/hr by using the lower heating value of propane = 2283 Btu/ft^3 (obtained from Mark's Standard Handbook, pp. 4-54).

F. POWER/VOCs DESTROYED RATIO

The fuel-use data (and data on the amount of VOCs destroyed) were used to calculate destruction efficiencies for each unit. The amount of VOCs destroyed was calculated by subtracting the outlet from the inlet data. This quantity was then divided into the fuel-use rate to obtain the amount of energy used per lb of VOC destroyed (MMBtu/lb VOC).

APPENDIX C
DRE

1. CPACI
2. FBCI

DIRECTORY OF SITE REFERENCE NUMBERS

Site Number	Site
1	Common Inlet
4	FBCI Exhaust
5	CPACI Carbon Paper Exhaust
6	CPACI Incinerator Exhaust
7	CPACI Inlet
8	FBCI Inlet

TABLE C-1. VOC DREs AND EMISSION RATES, McCLELLAN AIR FORCE BASE, CPACI.

Date	NIOSH Test Number	Inlet Flow Rate (dscfm)	Inlet (ppmv)	Inlet (lb C/hr)	Fraction Solvent Composition Based on NIOSH Data[a]										Inlet (lb VOC/hr)	Incinerator Exhaust Flow Rate (dscfm)	Incinerator Exhaust (ppmv)	Incinerator Exhaust (lb C/hr)	Incinerator Exhaust (lb VOC/hr)	Incinerator DRE
					MEK	EAc	MeAc	MIBK	Tolu	BAc	Ebnz	Xyl	EtAc	MeEt						
5/10/89	2	340	103	0.065	0.62	0	0	0.14	0.05	0.07	0.01	0.08	0.01	0	0.092	35	NA	NA	NA	NA
5/10/89	3	507	123	0.116	0.62	0	0	0.13	0.05	0.07	0.01	0.08	0.01	0	0.164	40	9.3	0.00069	0.000980	99.4
5/10/89	4	503	219	0.205	0.62	0	0	0.13	0.05	0.07	0.01	0.08	0.01	0	0.290	40	11.0	0.00082	0.001160	99.6
5/11/89	5	435	98	0.079	0.62	0	0	0.13	0.05	0.07	0.01	0.08	0.01	0	0.112	39	1.73	0.00013	0.000177	99.8
5/11/89	6	525	84	0.082	0.16	0	0	0	0.83	0	0	0	0	0	0.094	38	2.53	0.00018	0.000205	99.8
5/11/89	7	517	28	0.027	0.50	0	0	0.10	0.34	0.04	0	0	0	0	0.036	40	2.3	0.00017	0.000227	99.4
5/12/89	8	529	125	0.123	0.40	0	0	0.09	0.14	0.17	0.02	0.06	0.08	0	0.174	40	5.77	0.00043	0.000607	99.7
5/12/89	9	535	30	0.030	0.40	0	0	0.09	0.14	0.17	0.02	0.06	0.08	0	0.042	42	9.87	0.00077	0.001091	97.4
5/15/89	10	626	305	0.355	0.12	0	0	0	0	0	0	0	0.87	0	0.641	42	15.73	0.00123	0.002216	99.7
5/15/89	11	700	61	0.079	0.22	0	0	0	0	0	0	0	0.77	0	0.139	28	17.7	0.00092	0.001607	98.8
5/15/89	12	601	84	0.094	0.41	0	0	0.14	0.06	0.11	0.02	0.11	0.12	0	0.134	41	2.57	0.00020	0.000279	99.8
5/16/89	13	441	39	0.032	0.40	0	0	0.11	0.06	0.10	0.02	0.10	0.18	0	0.046	39	2.23	0.00016	0.000233	99.5
5/16/89	14	405	32	0.024	0.40	0	0	0.11	0.06	0.10	0.02	0.10	0.18	0	0.035	38	1.47	0.00010	0.000150	99.6
5/17/89	16	675	82	0.103	0.76	0	0	0	0.23	0	0	0	0	0	0.142	43	3.9	0.00031	0.000430	99.7
5/17/89	17	668	155	0.193	0.76	0	0	0	0.23	0	0	0	0	0	0.266	43	3.93	0.00031	0.000434	99.8
5/17/89	18	587	168	0.183	0.18	0	0	0.05	0.20	0.13	0	0.02	0.04	0.34	0.279	33	2.53	0.00016	0.000236	99.9
5/18/89	19	517	33	0.032	0.18	0	0	0.05	0.20	0.13	0	0.02	0.04	0.34	0.048	41	0.77	0.00006	0.000089	99.8
5/18/89	20	279	30	0.016	0.01	0	0.20	0.01	0	0.04	0.01	0.07	0.60	0	0.027	32	1.3	0.00008	0.000131	99.5
5/18/89	21	303	106	0.060	0.64	0	0	0.15	0.01	0.08	0.01	0.08	0	0	0.085	27	1.4	0.00007	0.000100	99.9
5/19/89	22	715	126	0.168	0.71	0	0	0.02	0.11	0.03	0	0.01	0.10	0	0.244	44	0.63	0.00005	0.000075	100.0
5/19/89	23	695	752	0.972	0.33	0	0	0.08	0.14	0.20	0	0.13	0.01	0.08	1.366	41	NA	NA	NA	NA

(continued)

[a]MEK = Methyl ethyl ketone (2-Butanone)
EAc = Ethyl acetate
MeAc = Methoxyacetone
MIBK = 4-Methyl-2-pentanone
Tolu = Toluene
BAc = Butyl acetate
Ebnz = Ethylbenzene
Xyl = Xylenes
EtAc = 2-Ethoxyethyl acetate
MeEt = 2-Methoxyethoxyethanol
NA = Not available

TABLE C-1. VOC DREs AND EMISSION RATES, McCLELLAN AIR FORCE BASE, CPACI (CONCLUDED).

Date	NIOSH Test Number	Inlet Flow Rate (dscfm)	Inlet (ppmv)	Inlet (lb C/hr)	Fraction Solvent Composition Based on NIOSH Data^a										Carbon Paper Exhaust Flow Rate (dscfm)	Carbon Paper Exhaust (ppmv)	Carbon Paper Exhaust (lb C/hr)	Carbon Paper Exhaust (lb VOC/hr)	Adsorp. Effic.	CPACI Total DRE
					MEK	EAc	MeAc	MIBK	Tolu	BAc	Ebnz	Xyl	EtAc	MeEt						
5/10/89	2	340	103	0.065	0.62	0	0	0.14	0.05	0.07	0.01	0.08	0.01	0	304	NA	NA	NA	NA	NA
5/10/89	3	507	123	0.116	0.62	0	0	0.13	0.05	0.07	0.01	0.08	0.01	0	507	NA	NA	NA	NA	99.4
5/10/89	4	503	219	0.205	0.62	0	0	0.13	0.05	0.07	0.01	0.08	0.01	0	503	NA	NA	NA	NA	99.6
5/11/89	5	435	98	0.079	0.62	0	0	0.13	0.05	0.07	0.01	0.08	0.01	0	435	0.2	0.000161	0.000229	99.8	99.6
5/11/89	6	525	84	0.082	0.16	0	0	0	0.83	0	0	0	0	0	525	0.17	0.000166	0.000190	>99.8	>99.6
5/11/89	7	517	28	0.027	0.50	0	0	0.10	0.34	0.04	0	0	0	0	517	0.17	0.000163	0.000217	>99.4	>98.8
5/12/89	8	529	125	0.123	0.40	0	0	0.09	0.14	0.17	0.02	0.06	0.08	0	529	0.17	0.000167	0.000236	>99.9	>99.5
5/12/89	9	535	30	0.030	0.40	0	0	0.09	0.14	0.17	0.02	0.06	0.08	0	535	0.17	0.000169	0.000239	>99.4	>96.9
5/15/89	10	626	305	0.355	0.12	0	0	0	0	0	0	0	0.87	0	626	2.53	0.002945	0.005313	99.2	98.8
5/15/89	11	700	61	0.079	0.22	0	0	0	0	0	0	0	0.77	0	700	0.17	0.000221	0.000386	>99.7	>98.6
5/15/89	12	601	84	0.094	0.41	0	0	0.14	0.06	0.11	0.02	0.11	0.12	0	601	0.17	0.000190	0.000271	>99.8	>99.6
																				>99.1
5/16/89	13	441	39	0.032	0.40	0	0	0.11	0.06	0.10	0.02	0.10	0.18	0	441	0.17	0.000139	0.000201	>99.6	98.1
5/16/89	14	405	32	0.024	0.40	0	0	0.11	0.06	0.10	0.02	0.10	0.18	0	405	0.47	0.000354	0.000511	98.5	>99.5
5/17/89	16	675	82	0.103	0.76	0	0	0	0.23	0	0	0	0	0	675	0.17	0.000213	0.000294	>99.8	>99.7
5/17/89	17	668	155	0.193	0.76	0	0	0	0.23	0	0	0	0	0	668	0.17	0.000211	0.000291	>99.9	>99.8
5/17/89	18	587	168	0.183	0.18	0	0	0.05	0.20	0.13	0	0.02	0.04	0.34	587	0.17	0.000185	0.000282	>99.9	>99.1
5/18/89	19	517	33	0.032	0.18	0	0	0.05	0.20	0.13	0	0.02	0.04	0.34	750	0.17	0.000237	0.000361	>99.3	>98.9
5/18/89	20	279	30	0.016	0.01	0	0.20	0.01	0	0.04	0.01	0.07	0.60	0	279	0.17	0.000088	0.000150	>99.4	>99.7
5/18/89	21	303	106	0.060	0.64	0	0	0.15	0.01	0.08	0.01	0.08	0	0	303	0.17	0.000095	0.000137	>99.8	>99.8
5/19/89	22	715	126	0.168	0.71	0	0	0.02	0.11	0.03	0	0.01	0.10	0	715	0.17	0.000226	0.000329	>99.9	NA
5/19/89	23	695	752	0.972	0.33	0	0	0.08	0.14	0.20	0	0.13	0.01	0.08	695	NA	NA	NA	NA	NA

^a MEK = Methyl ethyl ketone (2-Butanone)
EAc = Ethyl acetate
MeAc = Methoxyacetone
MIBK = 4-Methyl-2-pentanone
Tolu = Toluene
BAc = Butyl acetate
Ebnz = Ethylbenzene
Xyl = Xylenes
EtAc = 2-Ethoxyethyl acetate
MeEt = 2-Methoxyethoxyethanol
NA = Not available

TABLE C-2. VOC DREs AND EMISSION RATES, McCLELLAN AIR FORCE BASE, FBCI.

Date	NIOSH Test Number	Inlet Flow Rate (dscfm)	Inlet (ppmv)	Inlet (lb C/hr)	Fraction Solvent Composition Based on NIOSH Data[a]										Inlet (lb VOC/hr)	Outlet Flow Rate (dscfm)	Outlet (ppmv)	Outlet (lb C/hr)	Outlet (lb VOC/hr)	Unit DRE
					MEK	EAc	MeAc	MIBK	Tolu	BAc	Ebnz	Xyl	EtAc	MeEt						
5/10/89	2	468	103	0.089	0.62	0	0	0.14	0.05	0.07	0.01	0.08	0.01	0	0.127	720	0.7	0.00094	0.0013	98.9
5/10/89	3	348	123	0.080	0.62	0	0	0.13	0.05	0.07	0.01	0.08	0.01	0	0.113	543	0.17	0.00017	0.00024	>99.8
5/10/89	4	446	219	0.182	0.62	0	0	0.13	0.05	0.07	0.01	0.08	0.01	0	0.258	543	0.17	0.00017	0.00024	>99.9
5/11/89	5	402	98	0.073	0.62	0	0	0.13	0.05	0.07	0.01	0.08	0.01	0	0.104	553	0.17	0.00017	0.00025	>99.8
5/11/89	6	495	84	0.077	0.16	0	0	0	0.83	0	0	0	0	0	0.089	679	0.17	0.00021	0.00025	>99.7
5/11/89	7	494	28	0.026	0.50	0	0	0.10	0.34	0.04	0	0	0	0	0.034	679	0.17	0.00021	0.00029	>99.2
5/12/89	8	535	125	0.124	0.40	0	0	0.09	0.14	0.17	0.02	0.08	0.08	0	0.176	773	0.17	0.00024	0.00035	>99.8
5/12/89	9	891	30	0.039	0.40	0	0	0.09	0.14	0.17	0.02	0.06	0.08	0	0.055	948	0.17	0.00030	0.00042	>99.2
5/16/89	13	524	39	0.038	0.12	0	0	0	0	0	0	0	0.87	0	0.069	684	0.23	0.00029	0.00053	99.2
5/16/89	14	524	32	0.031	0.22	0	0	0	0	0	0	0	0.77	0	0.054	684	0.17	0.00022	0.00038	>99.3
5/17/89	16	584	82	0.089	0.4	0	0	0.14	0.06	0.11	0.02	0.11	0.12	0	0.127	794	0.17	0.00026	0.00036	>99.7
5/17/89	17	580	155	0.167	0.40	0	0	0.11	0.06	0.10	0.02	0.10	0.18	0	0.242	794	0.17	0.00025	0.00036	>99.8
5/17/89	18	611	188	0.191	0.40	0	0	0.11	0.06	0.10	0.02	0.10	0.18	0	0.276	794	1.03	0.0015	0.0022	99.2
5/18/89	19	339	33	0.021	0.76	0	0	0	0.23	0	0	0	0	0	0.029	438	0.17	0.00014	0.00019	>99.3
5/18/89	M5-13	297	45	0.025	0.76	0	0	0	0.23	0	0	0	0	0	0.034	423	0.4	0.00031	0.00043	98.7
5/18/89	20	565	30	0.032	0.18	0	0	0.05	0.20	0.13	0	0.02	0.04	0.34	0.048	726	0.53	0.00072	0.0011	97.7
5/18/89	M5-14	565	110	0.116	0.18	0	0	0.05	0.20	0.13	0	0.02	0.04	0.34	0.176	726	0.53	0.00072	0.0011	99.4
5/18/89	21	620	108	0.122	0.01	0	0.2	0.02	0.01	0.00	0.04	0.01	0.07	0.6	0.208	771	0.23	0.0033	0.00056	99.7
5/19/89	22	328	128	0.077	0.64	0	0	0.15	0.01	0.08	0.01	0.08	0	0	0.110	638	0.17	0.00020	0.00029	>99.7
5/19/89	23	369	752	0.516	0.71	0	0	0.02	0.11	0.03	0.00	0.01	0.10	0	0.752	639	1.93	0.0023	0.0033	99.6
5/19/89	24	570	216	0.229	0.33	0	0	0.08	0.14	0.20	0	0.13	0.01	0.08	0.322	723	0.43	0.00068	0.00081	99.7

[a]MEK = Methyl ethyl ketone (2-Butanone)
EAc = Ethyl acetate
MeAc = Methoxyacetone
MIBK = 4-Methyl-2-pentanone
Tolu = Toluene
BAc = Butyl acetate
Ebnz = Ethylbenzene
Xyl = Xylenes
EtAc = 2-Ethoxyethyl acetate
MeEt = 2-Methoxyethoxyethanol