FINAL
COMPREHENSIVE TECHNICAL REPORT FOR THE EVALUATION OF SOIL VAPOR EXTRACTION AND TREATMENT USING INTERNAL COMBUSTION ENGINE TECHNOLOGY

JULY 1998

AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE (AFCEE)
TECHNOLOGY TRANSFER DIVISION

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FINAL

COMPREHENSIVE TECHNICAL REPORT FOR THE EVALUATION OF SOIL VAPOR EXTRACTION AND TREATMENT USING INTERNAL COMBUSTION ENGINE TECHNOLOGY

Prepared for

AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE
TECHNOLOGY TRANSFER DIVISION
BROOKS AIR FORCE BASE, TEXAS

July 1998

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PREFACE

Parsons Engineering Science, Inc. (Parsons ES) was contracted by the Air Force Center for Environmental Excellence (AFCEE) Technology Transfer Division (ERT) to perform a demonstration of internal combustion engine (ICE) technology at four demonstration sites throughout the United States including:

- Site ST-04, Bolling Air Force Base (AFB), Washington D.C.;
- Site ST-35, Davis-Monthan AFB, Arizona;
- Site SS-42, Luke AFB, Arizona; and
- Site ST-12, Williams AFB, Arizona.

The work was performed for AFCEE/ERT under Contract F41624-94-D-8136, Delivery Order 28.

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INTRODUCTION

This document was prepared by Parsons Engineering Science, Inc. (Parsons ES) for the Air Force Center for Environmental Excellence (AFCEE) as part of a demonstration of the internal combustion engine (ICE) technology for extraction and treatment of soil vapors contaminated with nonchlorinated volatile organic compounds (VOCs) at four demonstration sites throughout the United States. The demonstration sites include (Figure 1.1):

- Former Car Care Center at Building 41 (Site ST-04), at Bolling Air Force Base (AFB) in Washington, D.C.;
- Fuel Pumphouse No. J3 (Site ST-35), at Davis-Monthan AFB, Arizona;
- Bulk Fuel Storage Yard (Site SS-42), at Luke AFB, Arizona; and
- Liquid Fuels Storage Area (Site ST-12), at Williams AFB, Arizona.

This Comprehensive Technical Report (CTR) summarizes the results of the four demonstrations that have been previously detailed in the following reports:

- *Draft Site-Specific Evaluation Report and Corrective Action Plan for Building 41, Former Car Care Center, Bolling Air Force Base, Washington DC* (April 1997);
- *Final Site-Specific Evaluation Report for the Evaluation of Vapor Extraction and Treatment Using Internal Combustion Engine Technology at Site ST-35 Fuel Pumphouse No. J3, Davis-Monthan Air Force Base, Arizona* (November 1997);
- *Final Site-Specific Evaluation Report for the Evaluation of Vapor Extraction and Treatment Using Internal Combustion Engine Technology at Site SS-42, Luke Air Force Base, Arizona* (January 1998); and
- *Final Site-Specific Evaluation Report for the Evaluation of Vapor Extraction and Treatment Using Internal Combustion Engine Technology at Site ST-12, Williams Air Force Base, Arizona* (April 1998).

A summary of site demonstration durations and final disposition of the units is provided in Table 1.1.

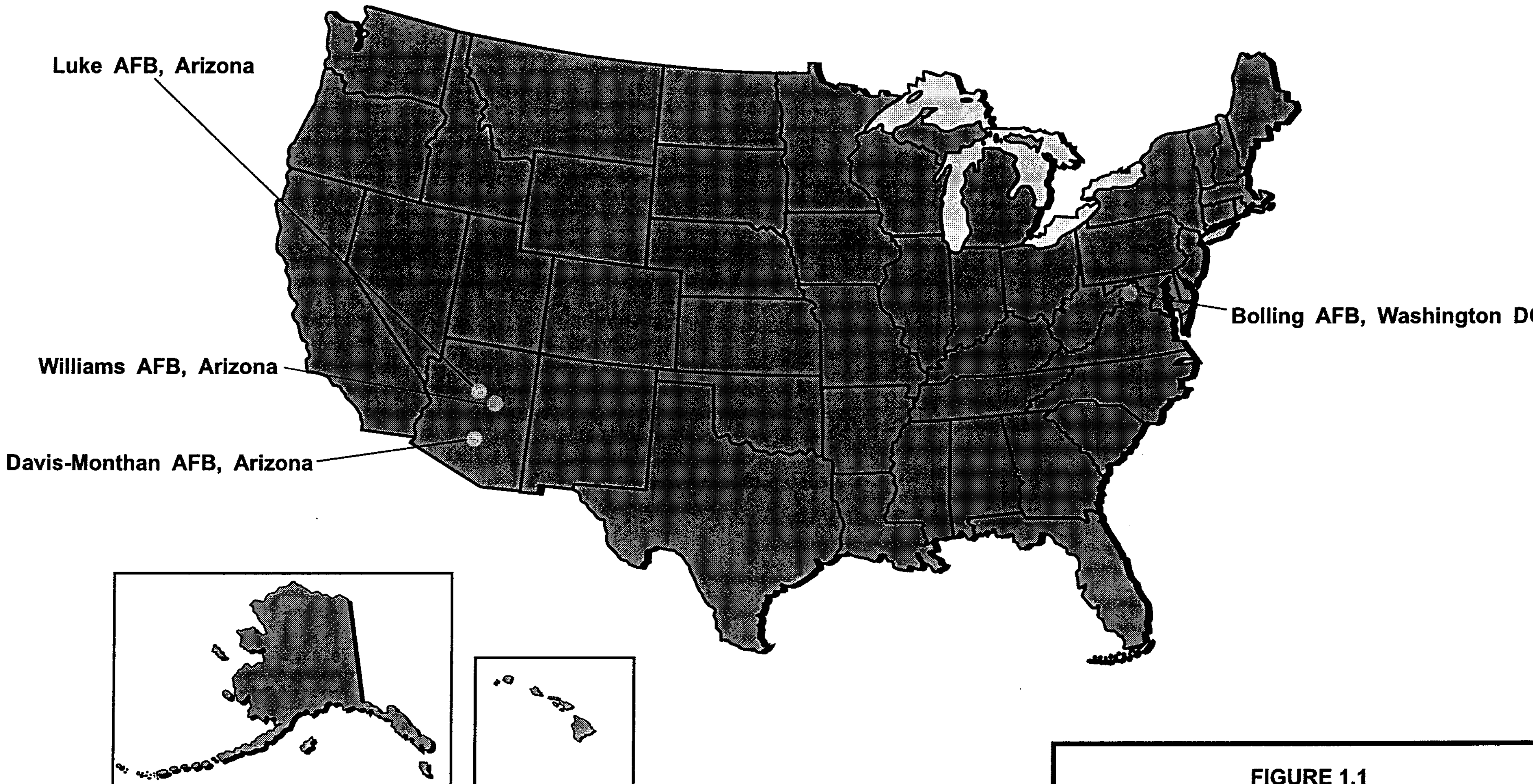

FIGURE 1.1

DEMONSTRATION SITE LOCATIONS

ICE Demonstration
Comprehensive Technical Report

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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TABLE 1.1
SITE DEMONSTRATION DURATIONS AND ICE UNIT DISPOSITION
ICE DEMONSTRATION
COMPREHENSIVE TECHNICAL REPORT

Location	Demonstration Site	Operating/Reporting Period	Transfer Date	Transfer Contract No.
Bolling AFB	Former Car Care Center at Building 41 (Site ST-04)	November 14, 1996 - June 23, 1997[a/]	November 7, 1997	Parsons ES F11623-94-D-0024 Delivery Order RL49
Davis-Monthan AFB	Fuel Pumphouse No. J3 (Site ST-35)	September 1, 1995 - July 24, 1997[b/]	[b/]	[b/]
Luke AFB	Bulk Fuel Storage Yard (Site SS-42)	August 6, 1996 - October 31, 1997[c/]	October 31, 1997	Parsons ES F41689-96-D-0710 Delivery Order 5029
Williams AFB	Liquid Fuels Storage Area (Site ST-12)	February 6, 1997 - December 9, 1997[d/]	October 3, 1997	Geo/Resource Consultants, Inc., San Francisco, California F41624-94-D-8060 Delivery Order 008

[a/] ICE unit turned off on June 23, 1997 to advance the site to closure.

[b/] Data through July 24, 1997 are included in this report. The ICE unit is currently operating under this contract and it is expected that it will continue to operate through September 30, 1998. At that time, operation of the ICE unit will cease under this contract and it is anticipated that operation will continue under a new contract.

[c/] Data through October 31, 1997 are included in this report. The ICE unit is currently operating under the new contract.

[d/] Data through October 3, 1997 were collected by Parsons ES and data collected between October 4 and December 9, 1997 were collected by Geo/Resource Consultants, Inc. The ICE unit is currently operating under the new contract.

1.1 SCOPE AND OBJECTIVE OF DEMONSTRATION

Under contract to AFCEE, Parsons ES collected cost and performance data to demonstrate the effectiveness of SVE technology using a modified ICE to extract and destroy fuel hydrocarbons at four Air Force sites. This CTR is intended to summarize the results of the demonstrations by presenting:

- Analytical data collected during the demonstrations;
- ICE cost and performance data collected during the demonstrations;
- An analysis of the ICE vapor treatment efficiency and cost comparison to other technologies;
- An assessment of the applicability of this technology based on vapor treatment efficiency and cost; and
- An overview of lessons learned and recommendations resulting from this demonstration.

1.2 REPORT ORGANIZATION

This CTR is divided into five sections and two appendices. A summary of the report contents follows:

- **Section 1**: Introduction and brief summary of this CTR;
- **Section 2**: A description of the ICE treatment technology;
- **Section 3**: A detailed summary of the field demonstration results;
- **Section 4**: Conclusions regarding the overall performance of the SVE/ICE systems;
- **Section 5**: Recommendations regarding the use of ICE technology at Department of Defense (DoD) installations;
- **Section 6**: Listing of the references cited in this document;
- **Appendix A**: Vendor Information - RSI ICE Unit Pilot Test Letter Report;
- **Appendix B**: Site Analytical Data Tables; and
- **Appendix C**: Vapor Treatment Technology Cost Comparison.

SECTION 2

DESCRIPTION OF TECHNOLOGY

2.1 INTERNAL COMBUSTION ENGINE

Vapor extraction and combustion is an innovative technology that uses an ICE with advanced emission controls to extract and burn nonchlorinated hydrocarbon vapors from the vadose zone (unsaturated zone). Vapors are extracted from the subsurface by the intake manifold vacuum of the engine via vent wells (VWs) screened in contaminated intervals. The extracted vapors are then burned as fuel to run the engine. To maintain constant/smooth operation of the engine, auxiliary fuel is used to supplement the extracted vapors when necessary. The ICE exhaust gases pass through one or two standard in-series two- and three-way catalytic converters for complete oxidation before being discharged to the atmosphere.

The ICE units supplied for this demonstration were manufactured by the now-insolvent VR Systems, Inc. (VRS), formerly of Anaheim, California. Previously, VRS manufactured "state-of-the-art" vapor treatment systems in three sizes: the single-engine models V2C (4 cylinder) and V3 (8 cylinder), and the dual-engine model V4 (2 x 8 cylinders each). Currently, EnviroSupply (EVS) of Fountain Valley, California, distributes rebuilt VRS Model V3 and V4 units. In addition, Remediation Service International (RSI) of Santa Paula, California, currently manufactures units that are comparable to the VRS Model V3 and V4 units (Generation II Model V3® and Generation II Model V4®). The following discussion focuses on the capabilities of currently available 8-cylinder ICE units. The single, 4-cylinder engine Model V2C has proven effective during short-duration (1- to 5-day) pilot studies, but has not been found to be suitable for long-term operation. This smaller engine is therefore not discussed further in this report.

2.2 SYSTEM CAPABILITIES AND COSTS

2.2.1 Capabilities

General performance specifications for the a single-engine (V3) and dual-engine (V4) VRS ICE unit are provided in Table 2.1. System flow-rate as a function of the influent vapor oxygen concentration as measured at Luke AFB is illustrated in Figure 2.1. System fuel usage as a function of engine speed (revolutions per minute [RPM]) for a single-engine VRS Model V3 is provided in Figure 2.2. A general schematic diagram of a dual-engine ICE unit (i.e., VRS Model V4) is provided as Figure 2.3.

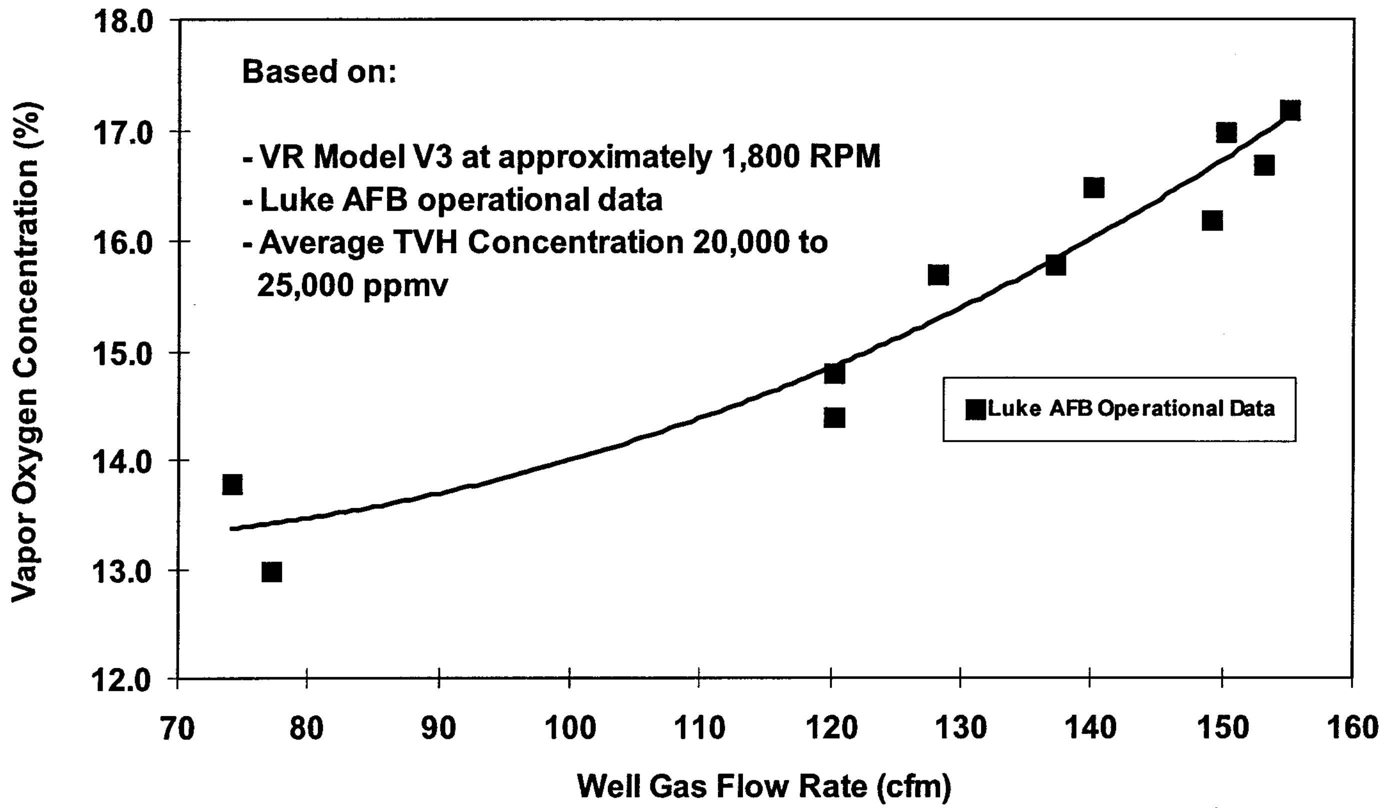
TABLE 2.1
GENERAL PERFORMANCE SPECIFICATIONS FOR VRS MODEL V3 AND V4 ICE UNITS
ICE DEMONSTRATION
COMPREHENSIVE TECHNICAL REPORT

Feature	V3 (single-engine)	V4 (dual-engine)
Max. Hydrocarbon Destruction Rate	55 lbs/hr	110 lbs/hr
Destruction Efficiency for TVH/BTEX[a/]	>99%	>99%
Engine Size in Cubic Inch Displacement	460	2x460
Flow Rate in Cubic Feet/Minute[b/]	50 - 150	100-300
Max. Vacuum in Inches of Mercury/Approx. Inches of Water	18/245	18/245
Required Soil Gas Hydrocarbon concentration (ppmv as gasoline)[c/]	30,000 - 40,000	30,000 - 40,000

a/ TVH = total volatile hydrocarbons; BTEX = benzene, toluene, ethylbenzene, and xylenes.

b/ Actual flow rate is highly dependent on site conditions such as soil type and influent soil gas TVH concentrations.

c/ The approximate influent vapor TVH concentration in parts per million, volume per volume (ppmv) required to sustain >99% destruction efficiency without the addition of supplemental fuel (e.g., propane or natural gas) to maintain efficient engine operation (depending on the percent oxygen and British thermal unit [BTU] value of the influent soil vapors).



NOTE:

The vacuum applied at the well head will be dependent on the relative permeability of the soil and influent well gas oxygen concentration. Well head vacuums applied at Luke AFB during this demonstration ranged from 26 to 74 inches of water (gage). As the oxygen concentration rises in the well gas, a reduction in make-up air (ambient) is needed to maintain optimum combustion conditions. Thus, more of the manifold vacuum is applied at the well head.

FIGURE 2.1

WELL GAS FLOW RATE AS FUNCTION OF INFLUENT VAPOR OXYGEN CONCENTRATION (VRS MODEL V3)

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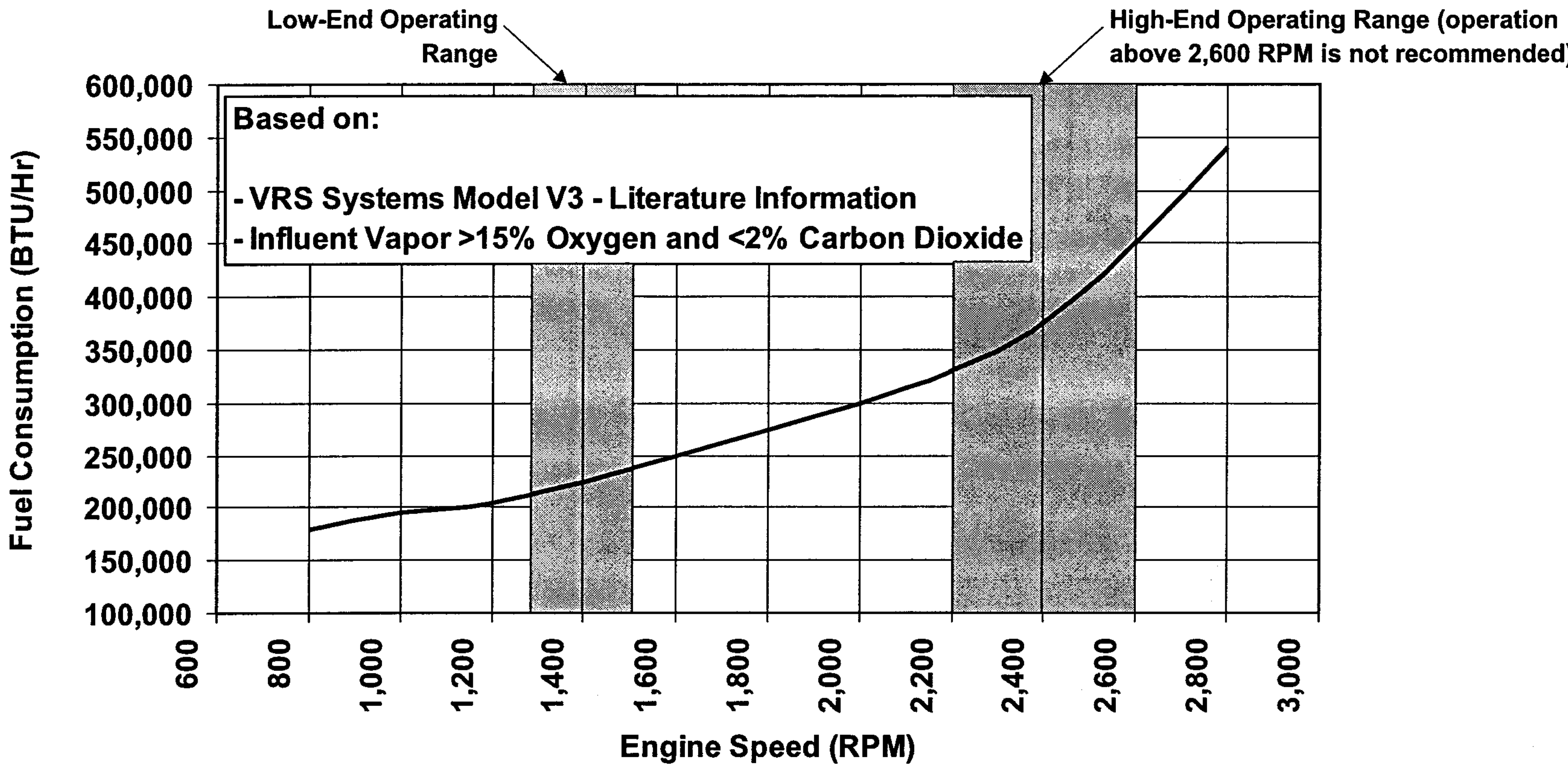

FIGURE 2.2

SYSTEM FUEL USAGE AS A FUNCTION OF ENGINE SPEED (VRS MODEL V3)

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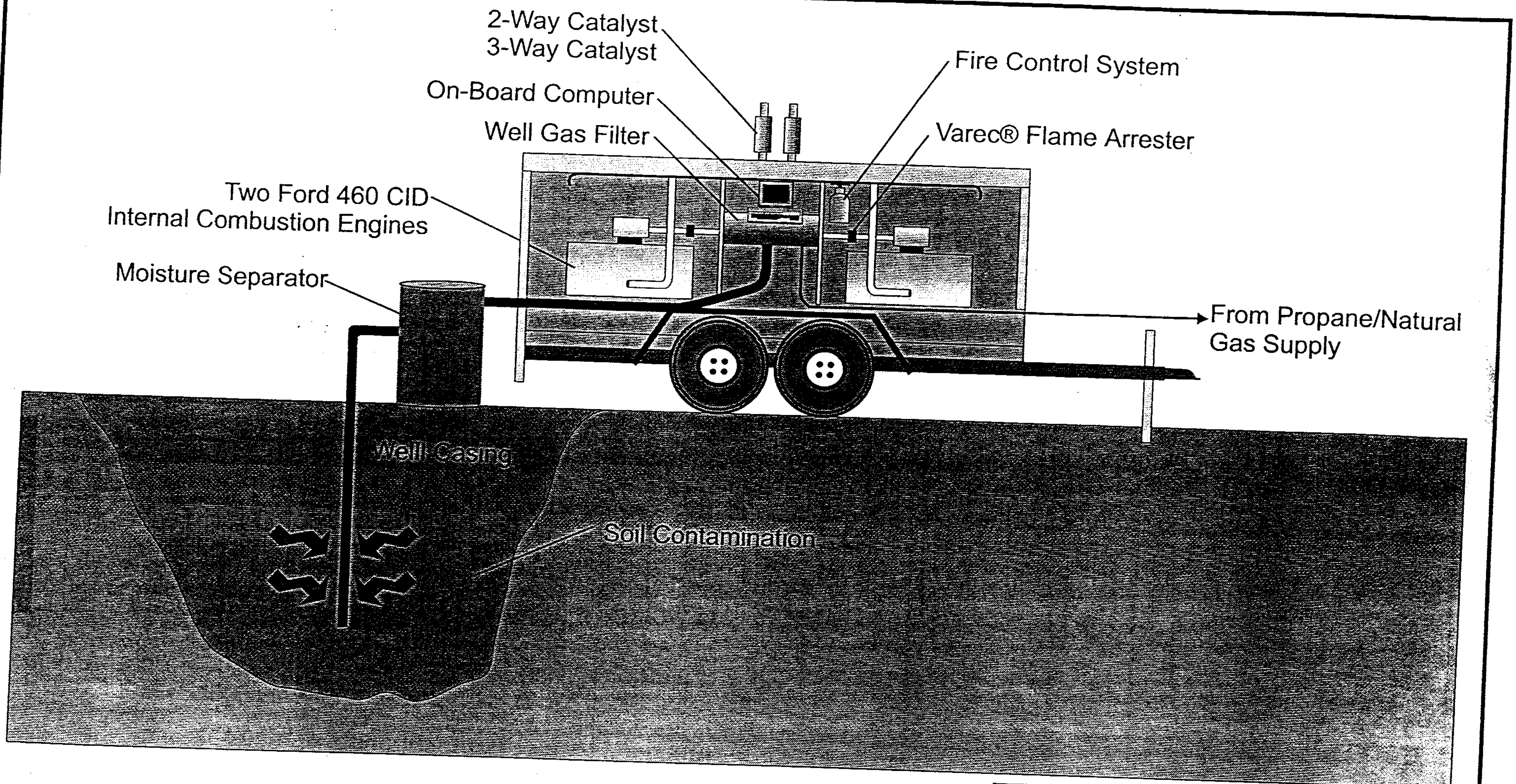

FIGURE 2.3

GENERAL LAYOUT OF A DUAL-ENGINE ICE UNIT

ICE Demonstration
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The engines in the VRS and RSI units are modified Ford® gasoline-powered engines. Each ICE system is equipped with an on-board computer system that provides the necessary monitoring for engine control. The VRS models are equipped with a 16-channel data reporting system which can monitor the engine's oil pressure/temperature, coolant temperature, exhaust temperature, exhaust percent oxygen, and engine speed and performance (extraction flow rate, well vacuum, supplemental fuel consumption, air/fuel ratio, and in the VRS units, engine hours). Both VRS and RSI ICE units are equipped with automatic engine shutdown systems. Monitored by the onboard computer, the engine can be programmed to shut down automatically if one or more of the following conditions occurs: engine overspeed, high/low battery voltage, high coolant temperature, high oil temperature, low oil pressure, fire, or high water level in the SVE well gas filter assembly. The computer can be programmed to store and report the reason for automatic engine shutdown.

ICE units are equipped with a flame arrestor to protect the vapor extraction system from "flash back" from the engine. The ICE systems are also equipped with a fire control system that includes a dry-chemical extinguisher that discharges automatically in the event of fire.

External electrical power is not required for these systems because the electronic ignition, and on-board computer are battery-powered. The engine alternator/voltage regulator maintains the charge of the battery. The ICE units can be equipped with a cellular phone modem for remote monitoring and to make necessary adjustments to engine speed to optimize engine performance and minimize supplemental fuel consumption. The remote monitoring capability allows for adjustments to be made while the unit is operating.

Supplemental fuel (propane or natural gas) is used to provide smooth operation of the engine as extracted soil gas total volatile hydrocarbon (TVH) concentrations fluctuate. Sustained soil vapor TVH concentrations in excess of 30,000 to 40,000 parts per million, volume per volume (ppmv) (depending on the oxygen, carbon dioxide, and British thermal unit [BTU] content of the influent fuel vapors) generally are sufficient to sustain the engine speed without the need for supplemental fuel. On-board microprocessors can regulate the fuel requirements of the engine through a master control unit. The control unit makes adjustments in the supplemental fuel flow to compensate for the changing influent hydrocarbon concentrations and to maintain the stoichiometric air-to-fuel ratio. This is illustrated in Figure 2.1. When hydrocarbon vapor is initially being extracted from the subsurface, oxygen concentrations are generally low, thus, the engine needs to compensate (i.e., maintain proper air to fuel ratio) by using a larger volume of dilution air which results in lower flow rates at the well head. As the oxygen concentration increases in the subsurface through the movement of cleaner air towards the extraction well, a smaller volume of dilution air is then required, allowing vapor extraction rates to increase at the well head. By maintaining the proper air/fuel ratio, the TVH vapor destruction/removal efficiency (DRE) typically exceeds 99 percent. RSI also manufactures an optional load bank that can be used to control the load on the engine to increase fuel consumption. The load bank may increase mass hydrocarbon destruction rates by as much as 25 to 30 percent (using a 25-kilowatt load bank at 2,200 RPM). Verification testing is being performed at this time by RSI.

As stated previously, the ICE units used during this demonstration were manufactured by the now insolvent VRS Systems. To evaluate other potential vendors, a limited field demonstration of the RSI Generation II Model V3 unit was completed at Williams AFB, Arizona in January 1998. The demonstration was performed primarily to determine if the technology incorporated into RSI's air/fuel auto-controlled carburetor system was capable of similar performance to that achieved by VRS units during this demonstration. A letter report detailing the test is included as Appendix A. In summary, during the short duration of the test, RSI's ICE unit exceeded the performance of the operating VRS Model V4 unit at Williams AFB based on destruction/removal efficiency. In addition, it was noted that RSI's carburetor and program logic controller (PLC) have fewer components that can fail compared to the VRS units which may lead to greater reliability and maintainability. Therefore, although long-term operation data are not available, it appears that RSI's units could be used in support of future Air Force projects using ICE technology.

2.2.2 Special Considerations/Limitations

Environmental conditions can limit the application and performance of ICEs. Limitations pertaining to the ICE technology, and appropriate corrective actions (CAs) to rectify related system problems, are listed below:

- The optimum ambient temperature operating range for the ICE unit is 0 to 43 degrees Celsius (°C) (32 to 110 degrees Fahrenheit [°F]).
- Relative humidity of the extracted air stream should be less than 95 percent or noncondensing.

  CA: If a high water table exists or condensation occurs in the extraction hose, then a water knock-out chamber can be installed in-line between the vapor extraction well and the ICE unit to prevent high-water shut down of the system. This water knock-out chamber can be configured to gravity drain accumulated water back to the VW. Piping can be configured to drain water from the knock-out chamber into the influent vapor line, which is graded toward the extraction well.

- The ICE will require supplemental fuel (propane or natural gas) during start up and at some point during cleanup operations.

  CA: Optimize engine speed and vapor flow rate to reduce excessive supplemental fuel consumption.

- The basic engine warranties are limited and most do not cover accessories such as the starter, alternator, plugs, wires, etc.

  CA: If factory-recommended maintenance is conducted, VRS had demonstrated an engine life expectancy of approximately 15,000 hours. This equates to around 1.7 years of continuous operation, 24 hours per day, at 1,600 to 2,000 rpm. An engine rebuild costs approximately $5,000, which equates to approximately $0.33 per hour of operation. Additional engine rebuild costs may be incurred due to shipping and other miscellaneous items.

- Noise associated with the operation of the engine could be considered a potential concern for sites near residential areas or other occupied buildings. The noise level varies with engine speed.

  CA: Noise abatement in areas where noise is a concern can be effected by instituting one or more of the following actions: programming the computer to adjust engine speeds at certain times of day to minimize local noise impacts; constructing a 6- or 8-foot privacy fence around the unit; and, if necessary, installing noise-suppression insulation inside of the fence.

- Soil type is a consideration for areas where low-permeability soil conditions are present and where minimal vapor flow rates from the soil are expected.

  CA: The radius of vacuum influence and vapor extraction rates from the VWs (determined during pilot testing) should be taken into consideration during equipment selection.

2.2.3 Vendor Costs

Table 2.2 provides a summary of the capital, rental, operating, and maintenance costs provided by EVS and RSI. EVS distributes the former VRS-manufactured Model V3 and V4 ICE units. RSI manufactures ICE units that are comparable in the short term as noted in Appendix A, in design and efficiency to the VRS Model V3 and V4 units.

2.3 REGULATORY ACCEPTANCE

The regulatory acceptance of this technology for treatment of hydrocarbon vapors in soil gas has been widespread. A list of jurisdictions where VRS units have been tested and/or are currently operating was compiled by VRS and is summarized in Table 2.3.

For long-term testing (more than a 1- to 5-day pilot test), regulatory approval is generally required. Approval for long-term extracted soil vapor treatment is site-specific (geographically) and may or may not require an air emissions permit application. In some areas, only a work plan or letter notification may be necessary. For shorter-term, 1- to 5-day pilot test, permits usually are not required. Local regulatory officials should be contacted to verify local policy.

TABLE 2.2
CAPITAL AND OPERATING COSTS
FOR 8-CYLINDER ICE UNITS [a/]
ICE DEMONSTRATION
COMPREHENSIVE TECHNICAL REPORT

Item	Cost	
	V3 (single-engine)	V4 (dual-engine)
Purchase (rebuilt - new)[b/]	\$45,000 - \$60,035	\$65,000 - \$107,000
Rental (Monthly)	\$3,000 - \$4,000	\$5,000 - \$8,000
Mobilization/Demobilization (to Phoenix, Arizona from vendor)	\$600 - \$750	\$600 - \$750
Approximate Fuel Costs at 100 Percent Supplemental Fuel (per day)[c/]	\$76	\$152
Monthly Service/Maintenance[d/]	\$550 - \$600	\$600 - \$750

a/ VR Systems, Inc. is no longer in business. EnviroSupply (EVS) of Fountain Valley, California, rebuilds and distributes the former VR Systems, Inc. used Model V3 and V4 line of ICE units. Remediation Service, International (RSI) of Santa Paula, California, currently manufactures new units that are comparable to the VR Systems, Inc. V3 and V4 models. All cost data are for December 1997.

b/ Warranties may be included in purchase price. Typically, warranties cover everything but consumables, and vary from 3 months to 1 year depending on item.

c/ Based on an engine speed of 1,800 revolutions per minute (rpm) and assuming all British thermal units (BTUs) are supplied by supplemental fuel (propane) at \$1.07/gallon. These data were supplied by RSI.

d/ Monthly service estimate includes: engine oil, oil filters, air filter(s), spark plugs, well gas filter(s), and labor. These costs are estimates from both EVS and RSI and assumes the service will be provided by local technicians.

TABLE 2.3
REGULATORY ACCEPTANCE OF ICE TECHNOLOGY
SVE/ICE DEMONSTRATION
COMPREHENSIVE TECHNICAL REPORT

Permitted	1- to 5-Day Pilot Testing
Arizona	Alabama
California:	Colorado
Great Basin Valleys	Georgia
Lake Tahoe	Kansas
Mountain Counties	Louisiana
North Central Coast	Oklahoma
North Coast	Michigan
Northwest Plateau	Missouri
Sacramento Valley	Montana
San Diego	Nevada
San Francisco Bay	North Carolina
San Joaquin Valley	Tennessee
South Central Coast	Texas
South Coast	Utah
Southeast Desert	Alberta, Canada
Florida	
Hawaii	
Idaho	
Illinois	
Massachusetts	
New Jersey	
New Mexico	
New York	
Ohio	
Oregon	
Pennsylvania	
Washington	
Ontario, Canada	
Mexico	
Argentina	

SECTION 3

FIELD DEMONSTRATION RESULTS

3.1 SITE BACKGROUND AND REGULATORY REQUIREMENTS

The following sections provide a brief overview of each demonstration site's history and background. The major site characteristics of each site pertaining to SVE/ICE application are summarized on Table 3.1. More detail regarding each site can be found in the individual site specific evaluation reports referenced in Section 1 of this report.

3.1.1 Bolling AFB, Washington, DC

Site ST-04 served as an auto repair and fueling facility for Bolling AFB from 1936 through 1982. During this period, the facility used several underground storage tanks (USTs) for storage of gasoline and waste oils. The waste oil tanks were abandoned in place in the early 1980s, and removed in 1995. The gasoline USTs were removed in 1983 and 1994.

The top 5 to 15 feet of soil consists of a continuous bed of sand and silt. A 3- to 5-foot layer of clay interbedded with silt underlies these soils with gravel present at approximately 20 feet below ground surface (bgs). Groundwater at Site ST-04 typically is encountered at depths of 16 to 20 feet bgs. Groundwater contamination consists of mobile light non-aqueous-phase liquids (LNAPL) and dissolved fuel contamination. Mobile LNAPL is thought to occur in discontinuous lenses on the water table. In soil samples collected near the water table, the maximum detected soil total volatile hydrocarbons (TVH) and benzene, toluene, ethylbenzene, and xylenes (BTEX) concentrations were 16,000 milligrams per kilogram (mg/kg) and 670 mg/kg, respectively. The maximum TVH and benzene concentrations detected in soil gas were 580,000 parts per million by volume (ppmv) and 14,000 ppmv, respectively, in a sample collected from a 9.5- to 10-foot bgs interval.

Two vapor extraction/air injection VWs and two vapor monitoring points (VMPs) were installed in September 1996 to support this demonstration. The treatability demonstration began operation in November 1996. In lieu of submitting permit applications, a discharge limitation of 1 pound per day (lb/day) of total hydrocarbons was required by the Washington D.C. Environmental Regulation Administration (DCERA) (now the DC Environmental Health Administration [DCEHA]). After approximately 7 months of operation, the ICE system was shut down (June 1997) to advance the site to closure. However, due to negotiations with the regulating agencies, an expanded vapor extraction system will be operated at the site coupled with air sparging to further reduce source area hydrocarbon concentrations. Site closure will be dependent on regulator acceptance of the proposed risk-based approach at the site.

TABLE 3.1
ICE TECHNOLOGY DEMONSTRATION SITES
ICE DEMONSTRATION
COMPREHENSIVE TECHNICAL REPORT

Demonstration Site	Geology	Depth to Groundwater (ft bgs[a/])	Maximum Soil TPH[b/] Concentration (mg/kg)[c/]	Initial Estimated Contaminated Soil Volume (yd^3)[d/]	Initial Influent Vapor TVH[e/] Concentration (ppmv)[f/]
Bolling AFB	intermixed fine- and coarse-grained deposits	20	16,000	43,000	123,000
Davis-Monthan AFB	intermixed fine- and coarse-grained deposits	300	320,000	220,000	43,000
Luke AFB	intermixed fine- and coarse-grained deposits	320	12,000	9,300	38,500
Williams AFB	fine-grained subunits intermixed with coarse-grained beds	200	35,000	100,000	140,000

[a/] ft bgs = feet below ground surface.
[b/] TPH = total petroleum hydrocarbons.
[c/] mg/kg = milligram per kilogram.
[d/] yd^3 = cubic yard.
[e/] TVH = total volatile hydrocarbons.
[f/] ppmv = parts per million by volume.

3.1.2 Davis-Monthan AFB, Arizona

Site ST-35 is a jet fuel pumphouse consisting of nine 40,000-gallon and one 50,000-gallon USTs containing JP-8 jet fuel (JP-4 prior to 1993), and an underground piping system that conveys the fuel to a fueling island. In 1985, a leak was detected in an underground fuel line, and an estimated 220,000 cubic yards of soil was found to be contaminated.

The stratigraphy between the surface and 350 feet bgs is composed of interbedded sand, gravel, silt and clay layers. The dominant soil type in the upper 260 feet is a sandy clay. The 260-foot bgs to 350-foot bgs interval is dominated by sands and gravel. A clay layer present at approximately 250 feet to 260 feet bgs acted to retard the downward migration of the contaminants and caused lateral spreading of the contamination. Groundwater is present at a depth of approximately 300 feet bgs. A maximum total fuel hydrocarbon concentration of 320,000 mg/kg and a maximum soil gas hydrocarbon vapor concentration of 140,000 milligrams per liter (mg/L) were measured at the site in the vadose zone.

Following the pilot testing of different technologies, SVE utilizing ICE technology was selected to be evaluated to determine the technical merit and potential cost savings at this site. A full-scale SVE system with ICE technology was installed at the site in July and August 1995. The system included six VWs installed at various depths to better focus the remediation efforts. The system began operation in September 1995 using a VRS Model V4. In October 1996, the Model V4 was replaced with a VRS Model V3 because of decreased influent TVH concentrations which lead to higher corresponding auxiliary fuel usage. During operations, the Arizona Pima County Department of Environmental Quality required that an air pollution exemption be obtained to operate the ICE system at the site. The main performance requirement of the exemption used during the ICE evaluation was that the control system be capable of reducing actual emissions of the targeted regulated air pollutant(s) below a *de minimis* level of 2.4 lbs TVH per day.

Between February and July of 1997, it was noted that the ICE unit was using a higher percentage of supplemental fuel than it had previously (from approximately 3 to 6-percent to 8 to 15-percent). The system was shut down in July 1997 for further analysis and possible site closure. The concentrations at the site rebounded and a decision was made to continue to operate the ICE unit to further remediate contaminated vadose zone soils. The ICE unit was optimized to run on minimal supplemental fuel (versus maximum flow from the vent wells) and will operate until it is no longer cost effective. The system was restarted in December 1997 and is currently operating at the site.

3.1.3 Luke AFB, Arizona

Site SS-42 is located at the Bulk Fuels Storage Yard in the eastern portion of Luke AFB. The site focuses on a former oil/water separator and associated 1,000-gallon UST system that received condensate from two adjacent aboveground jet fuel storage tanks. The oil/water separator system and aboveground storage tanks (ASTs) were installed in 1954. Prior to 1960, aviation gas and jet propulsion fuel, grade 4 (JP-4) were delivered to the bulk fuels storage area by rail car and off-loaded to the ASTs through a hydrant system. In 1992, a leak-detection system was installed for the oil/water separator system in response to a detected fuel release. In September 1993, the oil/water separator and associated 1,000-gallon UST were removed.

Soils underlying the surficial fill consist of interbedded sand, silt, and clay deposits. Below 100 feet bgs the well-graded sand units are no longer in sequence with the interbedded sandy clays being dominant to a maximum sampled depth of 200 feet bgs. Groundwater is present at a depth of approximately 320 feet bgs. Soil total petroleum hydrocarbon (TPH) analytical results collected in May 1995 during the installation of the bioventing/SVE wells ranged from 4.3 mg/kg in a sample from 150 feet bgs, to a maximum of 12,000 mg/kg in a sample at 70 feet bgs. The maximum soil BTEX concentration of 414 mg/kg also was detected in soil sample from 70 feet bgs. Soil gas samples collected at the site determined that the total fuel concentrations ranged from approximately 12,000 to 57,000 ppmv.

A SVE system using a VRS Model V3 ICE was installed in August 1996. The system was manifolded to three existing vapor injection/extraction VWs completed at varying depths to focus the extraction vapor flow rates in the most contaminated soil intervals. Startup of the Model V3 ICE demonstration system occurred on August 6, 1996. During operation of the ICE unit, the Arizona Maricopa County Division of Air Pollution Control initially required that the actual emissions of TVH from the ICE not exceed 3.0 lbs/day, but were revised on July 23, 1997 to include the alternative requirement that the DRE be equal to or greater than 99 percent. The system operated through October 1997 as part of this demonstration. The system is currently operating under a new contract and discussions with ADEQ regarding site closure will occur in the future.

3.1.4 Williams AFB, Arizona

Site ST-12 is a former liquid fuels storage area located at the former Williams AFB (now the Williams Gateway Airport, Mesa, Arizona). The site has been impacted primarily by releases of jet propulsion fuel (JP-4) and aviation gasoline (AVGAS), which were attributable to multiple documented fuel spills and leaks between 1977 and 1989, and possibly to other undocumented fuel spills and leaks that have occurred since Williams AFB initiated operations in 1942.

Soils in the vadose zone consist primarily of fine-grained subunits with varying percentages of silt and clay with minor amounts of fine sand. The observed thickness of these subunits ranged from 2 feet to 20 feet. Coarse-grained beds are generally very poorly sorted ranging from clay to cobbles with observed thickness of less than 2 feet to 25 feet. Groundwater elevations have steadily increased since 1989, due to the decrease in agricultural use of the surrounding area, with the current depth to water being 200 to 210 feet bgs. During a 1993 deep soils investigation, 384 soil samples were collected from 16 soil boreholes. TPH as JP-4 were detected in 227 of the 384 soil samples collected at concentrations ranging from 0.42 to 35,000 mg/kg. The maximum TPH concentration of 35,000 mg/kg was detected in a soil sample from 174 feet bgs. The maximum soil BTEX concentration of 1,151 mg/kg was detected in a soil sample from 195 feet bgs. Groundwater contamination consists of mobile LNAPL and dissolved fuel contamination. Mobile LNAPL thickness data have been collected from site wells since 1990. The maximum measured thickness has been 15 feet. Initial volume estimates of LNAPL in the subsurface at Site ST-12 range from 0.65 to 1.4 million gallons.

An SVE system using a VRS Model V4 ICE (designated "V4-A") was installed in February 1997. The system used a previously constructed VW which was screened through the LNAPL-water table interface to focus on LNAPL recovery. A second VRS Model V4 ICE (designated "V4-B") was started in April 1997. During operation, the Arizona Maricopa County Division of Air Pollution Control initially required that the actual emissions of TVH from the ICE unit not exceed 3.0 lbs/day, but were revised on July 23, 1997 to include the alternative requirement that the DRE be equal to or greater than 99 percent. The demonstration period ended in October 1997 at which time the operation of the SVE/ICE system was transferred to Geo/Resource Consultants, Inc. (GRC) San Francisco, California (Contract No. F41624-94-D08060) for continued remediation of the site. Data between October and December 1997 were obtained from GRC and are included in this CTR.

3.2 DEMONSTRATION PROTOCOL AND CONDITIONS

3.2.1 Demonstration Protocol

The demonstration protocol included all or part of the following eight common tasks performed at each site:

- Each demonstration began with a site meeting and technology briefing to Base officials. This provided a time for questions to be raised regarding the operating of the system, regulatory requirements, and ultimate objectives of the demonstration and of the individual sites.
- A site-specific work plan was prepared describing where and how the test would be conducted with the exception of Davis-Monthan AFB, which already had an operational system. The work plan provided a brief overview of the site history and characteristics on how they relate to the demonstration. The work plan provided detail on start-up and extended operation monitoring and maintenance.
- With the exception of Bolling AFB, VWs and monitoring points were previously existing at the sites in support of other treatability studies.
- A baseline soil gas survey was conducted to aid in assessing the overall effectiveness of vapor extraction over time. Soil gas was measured using hand-held instruments in the field for oxygen (GasTech®), carbon dioxide (GasTech®), and TVH (GasTech®/Horiba), concentrations.
- Start-up procedures consisted of a 5 to 10 day start-up test to ensure that the ICE unit was operating properly:
  - ⇒ During the initial testing, air flow rates, vacuum, and other system parameters (e.g., engine speed) were adjusted to optimize vapor extraction rates and treatment efficiency.

⇒ Field and laboratory samples of the influent and effluent vapor stream for TVH and BTEX were collected to ensure proper operation of the ICE unit.

⇒ In addition to ICE unit testing, a radius of vacuum influence test was performed to evaluate system effectiveness. Performance monitoring included measuring pressure responses and changes in soil gas oxygen, carbon dioxide, and TVH concentration at the VW(s) and VMPs.

- After the start-up period and optimization of the ICE system, extended operation and performance evaluation began:

  ⇒ In general, extended system operation consisted of daily confirmation of operation by base personnel and monthly site visits by Parsons ES technicians to perform vapor sampling and routine maintenance.

  ⇒ VRS performed daily remote monitoring of the systems to determine if the units were operating and to record/download engine performance data. This remote monitoring was not continued after VRS became insolvent (December 1996). Remote monitoring was replaced by daily confirmation of ICE unit operation by base personnel.

  ⇒ Monthly sampling events consisted of collecting influent and effluent vapor samples for laboratory analysis for BTEX and TVH. Periodically (10-percent of the total samples collected), quality assurance/quality control samples in the form of field duplicates were collected to assess the laboratory performance.

  ⇒ System operational parameters monitored on a monthly basis included system flow-rates, well vacuums, engine speed, and auxiliary fuel usage.

  ⇒ Routine maintenance of the ICE systems consisted of:

    – replacing the spark-plugs;
    – changing the oil and replacing the oil filter;
    – replacing the air filter;
    – checking/replacing the fan belts and hoses, as necessary;
    – checking/refilling the coolant, as necessary;
    – checking the charging system; and
    – checking/replacing the well gas filter as necessary;

  ⇒ In addition to monthly monitoring of the ICE units, soil gas measurements including pressure response, oxygen, carbon dioxide and TVH concentrations were measured at select VMPs to ascertain the effectiveness of the SVE system (e.g., radius of influence, and soil gas TVH reduction).

- After completing the demonstration, the ICE units were transferred to another Air Force contract or the demonstration was extended for continued operation of the ICE units (see Table 1.1).

3.2.2 ICE Configuration

In general, the ICE configuration at each site consisted of the following:

- Vapors were extracted from a single or multiple VWs with individual flow-control (i.e., gate valves) and influent samples ports located at the well head.
- Vapors were transmitted to the trailer mounted ICE unit via manifolded polyvinyl chloride (PVC) piping originating at the VWs.
- Prior to entering the ICE unit, the vapor stream was passed through a moisture separator to remove particulates and condensate.
- The vapors were than passed through the ICE unit for thermal destruction with primary treatment in the engine cylinders and secondary treatment in the exhaust catalytic converters. Associated with the ICE unit was auxiliary fuel in the form of propane (250 or 500 gallon storage tank) or natural gas to provide additional fuel as necessary.
- Following treatment, the vapor stream passed through the exhaust system which included an effluent sample port and exhaust stack 8 to 9 feet above grade.

3.2.3 System Influent Hydrocarbon Vapor Concentrations and Flow Rates

Average influent concentrations and flow rates for all of the systems are summarized on Table 3.2. The ICE units treated vapor streams as high as 140,000 ppmv TVH (Williams AFB) to as low as 4,200 ppmv TVH (Bolling AFB). Flow rates generally ranged from 50 to 150 cfm. During operation of the ICE units, influent concentrations decreased significantly from concentrations measured at startup. Reductions in extracted vapor concentrations as high as 93-percent were measured at Bolling AFB to a smaller reduction of 37-percent at Davis-Monthan AFB. These reductions in soil gas concentrations are a function of a reduction in the mass of contamination remaining in site soils. Additionally, the extraction flow rate increased during this process due to an increase in soil gas oxygen concentrations which reduced the amount of dilution air required by the system.

3.3 OBSERVED PERFORMANCE

Site-specific data tables detailing ICE system performance are provided in Appendix B. The following sections provide a summary of hydrocarbon removal rates, hydrocarbon DREs, and reliability and maintainability of the ICE systems.

TABLE 3.2
ICE TECHNOLOGY DEMONSTRATION TESTING CONDITIONS
ICE DEMONSTRATION
COMPREHENSIVE TECHNICAL REPORT

Demonstration Site	Unit Type	Days of Actual Operation	Avg. Flow Rate (cfm)[a/]	Avg. Influent Concentration (ppmv TVH)[b/]
Bolling AFB[c/]	1-Model V4[d/] 1-Model V3	193	94	8,500
Davis-Monthan AFB	1-Model V4[e/] 1-Model V3	634	109	25,500
Luke AFB	1-Model V3	327	91	20,150
Williams AFB	2-Model V4			
Unit V4-A		≈257	99	57,300
Unit V4-B		≈125	84	45,500

[a/] cfm = cubic feet per minute.
[b/] ppmv TVH = part per million by volume of total volatile hydrocarbons.
[c/] AFB = Air Force Base.
[d/] A Model V4 ICE unit operated at the site from November 13, 1996 to January 21, 1997.
[e/] A Model V4 ICE unit operated at the site from September 1, 1995 to October 31, 1996.

3.3.1 Hydrocarbon Removal Rates

The total amount of TVH removed during the ICE operation for each site is presented in Figure 3.1. A summary of demonstration results are presented in Table 3.3. The ICE systems removed between 57,000 lbs of TVH (Bolling AFB) and 747,000 lbs of TVH (Davis-Monthan AFB) at each site during this demonstration. The combined total for all four sites approaches 1,831,000 lbs of TVH which is equivalent to approximately 305,000 gallons of hydrocarbon (assuming a density of 6 lb TVH/gallon hydrocarbon) that has been removed from these sites. Average removal rates summarized in Table 3.2 ranged from 290 lb/day (Model V3 at Bolling AFB) to 2,100 lb/day (Unit V4-A at Williams AFB). Peak removal rates during the start-up of V4-A at Williams AFB exceeded 2,600 lb/day. Combined peak removal rates for both systems at Williams AFB exceeded 4,300 lb/day shortly after start-up of V4-B.

3.3.2 Hydrocarbon Destruction/Removal Efficiencies

DREs for the ICE systems were calculated using the following equation:

$$DRE = \left(\frac{Concentration_{Influent} - Concentration_{Effluent}}{Concentration_{Influent}} \right) x100\%$$

The ICE systems DRE ranged from a low of 96.4 to greater than 99.9 percent during these demonstrations. Daily TVH emissions from each demonstration site are illustrated on Figure 3.2. Average daily TVH emission rates ranged from 0.8 lb/day (Davis-Monthan AFB) to 2.9 lb/day (V4-A at Williams AFB). For all ICE units, an increase in emissions was observed around 180 to 200 days of operation (6 months). This increase coincides with the time when non-routine maintenance activities such as replacing the oxygen sensor is required to maintain peak engine performance.

Increased emissions from the ICE units during the demonstration may be due to the following:

- Change in soil gas chemistry (i.e., oxygen and carbon dioxide concentrations) of the incoming soil vapor which leads to a difficulty for the engine to maintain a proper air to fuel ratio (i.e., ratio required for stoichiometric combustion).
- DRE's tend to decrease throughout the period between maintenance activities. When maintenance activities were performed prior to sampling, measured DREs remained high. When maintenance activities were performed after sampling, measured DREs were lower than when measured during normal operating conditions in some instances.
- Aging of the catalytic converters (i.e., secondary treatment) in these units led to increased emissions in some instances. This was verified by field sampling pre- and post-catalytic converter TVH concentration and measuring converter temperatures. As the catalysts age, the catalysts become "fouled" which reduces the operating temperature. This leads to decreased destruction in the converters and higher emissions.

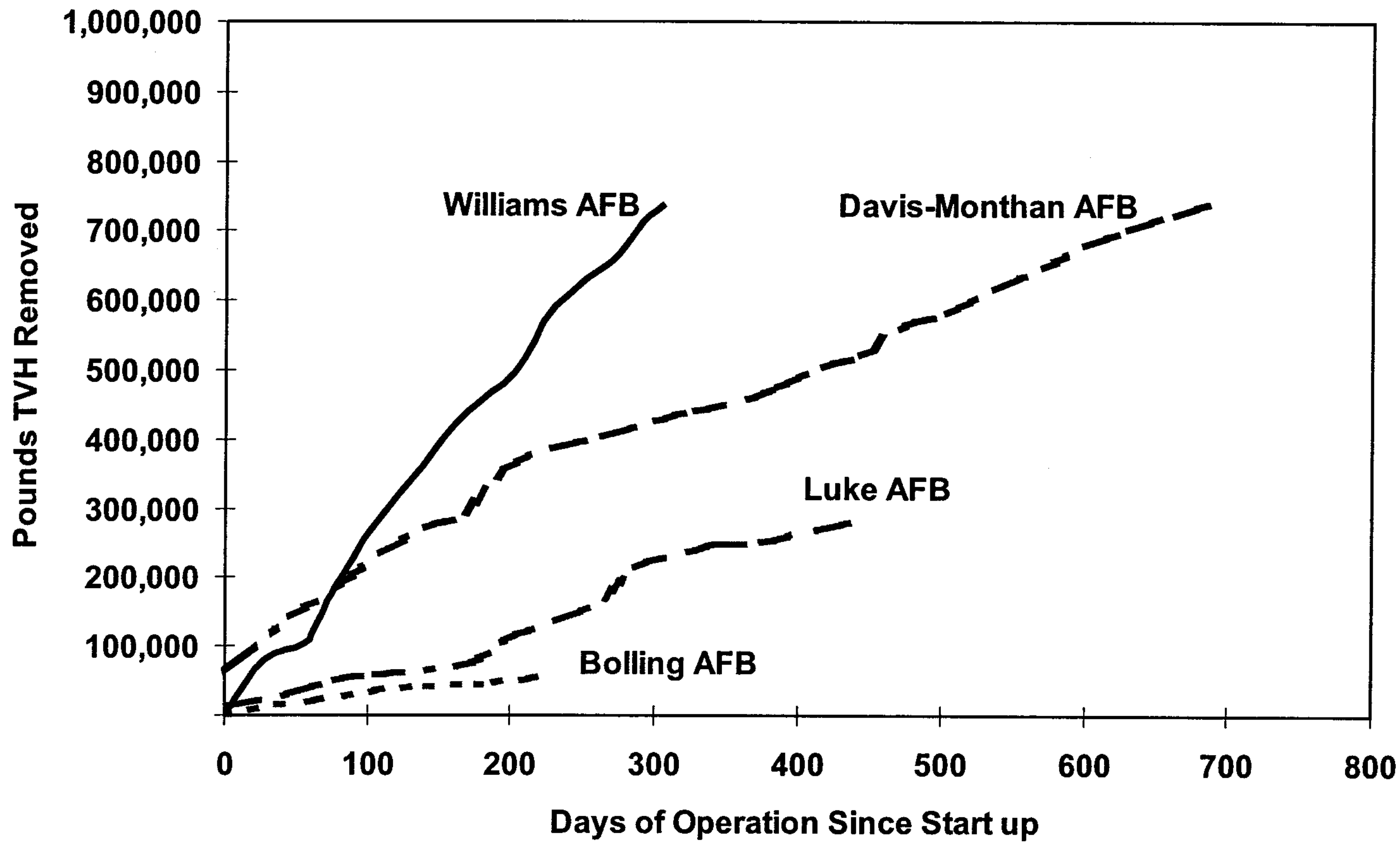

FIGURE 3.1

CUMMULATIVE POUNDS OF TOTAL VOLATILE HYDRCARBONS REMOVED

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TABLE 3.3
ICE TECHNOLOGY DEMONSTRATION RESULTS
ICE DEMONSTRATION
COMPREHENSIVE TECHNICAL REPORT

Demonstration Site	Avg. TVH[a/] Removal Rate (lb/day)[b/]	Avg. Cost Per Pound TVH Removed ($/lb)[c/]	Avg. TVH Emission Rate (lb/day)	Avg. DRE[d/] (%)	Operational Efficiency[g/] (%)
Bolling AFB[e/]	304	0.98	2.1[f/]	>99.4	85
Davis-Monthan AFB	1,200	0.15	0.8	>99.9	91
Luke AFB	880	0.29	0.9	>99.9	72
Williams AFB					
Unit V4-A	2,100	0.09	2.9	>99.8	84
Unit V4-B	1,700	0.16	1.6	>99.8	51

a/ TVH = total volatile hydrocarbons.
b/ lb/day = pounds TVH per day.
c/ $/lb = cost per pound of TVH.
d/ DRE = destruction/removal efficiency.
e/ AFB = Air Force Base.
f/ The calculated average TVH emission rate is elevated due to higher than normal emissions in May and June, 1997.
g/ Operational Efficiency is defined as the percent of calendar days the system actually operated while on-site. This included downtime due to response time, repair, and restart of the systems.

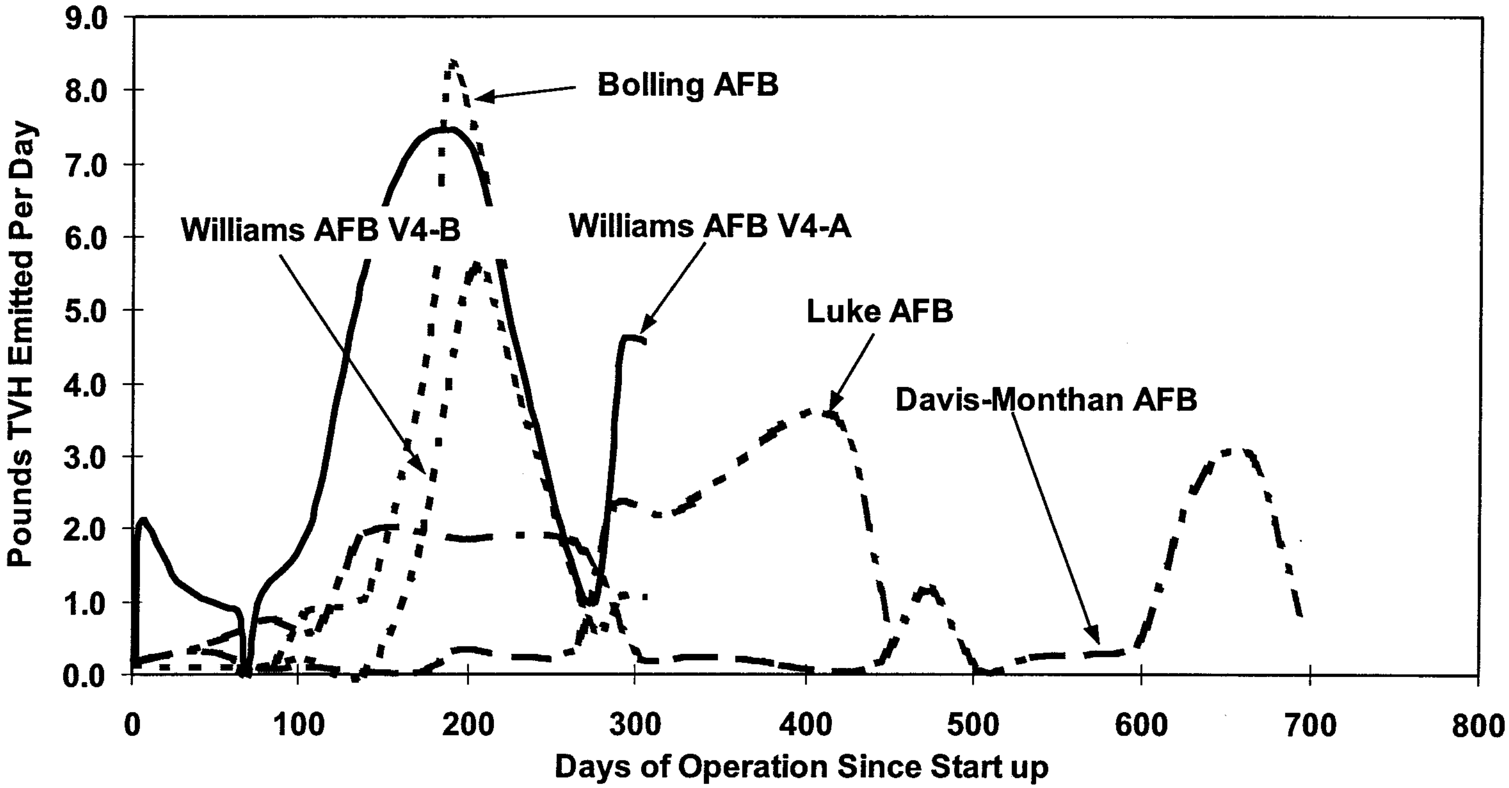

FIGURE 3.2

DAILY TOTAL VOLATILE HYDROCARBONS EMISSIONS

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3.3.3 Reliability and Maintainability

During this demonstration, the ICE systems proved to be operationally reliable. The operational efficiency as a percent of total possible engine hours for the four demonstration sites is illustrated on Figure 3.3. Operational efficiency ranged from a high of 91 percent at Davis-Monthan AFB to a low of 51 percent for unit V4-B at Williams AFB. Major downtime for unit V4-B at Williams AFB was due primarily to low oil pressure (faulty oil sending unit), high battery voltage, and high coolant temperature shutdowns. After the major repairs were completed, operational efficiency increased to 83 percent. The overall average operational efficiencies for all units tested was 82 percent which included response time, repair, and re-start of the systems.

In general, the primary ICE system components with a potential for mechanical problems are the alternator/voltage regulator, the battery (especially in hot climates), and the oxygen sensor. Long-term maintenance requirements include an engine rebuild at approximately 15,000 engine hours. The cost of the rebuild is approximately $5,000 per engine including parts and labor (not including shipping). The catalytic converters require replacement every 5,000 to 10,000 engine hours at an approximate cost of $450 each. Additionally, problems with the on-board computer system may arise due to extreme heat, excessive engine vibrations, high humidity, or dusty areas.

Regular monthly maintenance for each ICE system requires approximately 8 labor hours per month, and includes draining the moisture separator, changing the engine oil and oil filter, replacing the carburetor air filter and spark plugs, and checking engine coolant level, battery charge, water pump, and belts. Approximately 8 additional labor hours per month should be anticipated for unexpected shutdowns and repairs.

3.4 COST INFORMATION

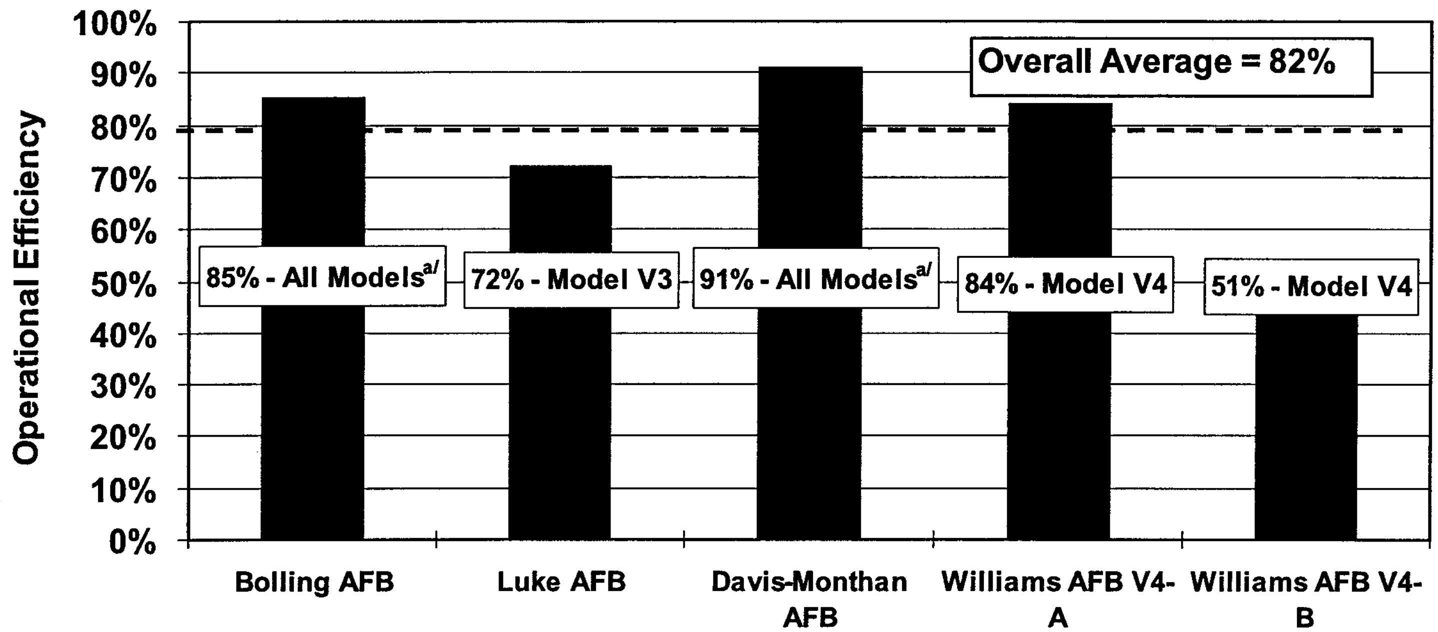
3.4.1 Demonstration Costs

The costs for the ICE demonstration are summarized in Table 3.4. Average operation, maintenance, and monitoring costs for the demonstration ranged between $136 (Luke AFB) to $190 (Bolling AFB) per day.

One of the objectives of this project was to demonstrate the applicability of ICE technology for SVE off-gas treatment. Therefore, increased system monitoring was conducted at these demonstration sites to compile a database that can be used in this technology evaluation. Monitoring costs for ICE systems could be reduced by lowering the frequency at which samples are collected for laboratory analysis and by eliminating daily call-up service, depending on site-specific conditions.

3.4.2 Cost of Remediation

The cost per pound of TVH removed was estimated based on a prorated 30-day month with the capital cost of the ICE unit averaged over an estimated 3-year equipment life (assuming one rebuild). Also included in the daily cost were labor and other direct costs for operation, maintenance, and sampling (including laboratory costs), and actual supplemental fuel cost during operation. The actual costs per pound



[a] Includes both VRS Model V4 and V3.

FIGURE 3.3

AVERAGE OPERATIOAL EFFICIENCY

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TABLE 3.4
ICE TECHNOLOGY DEMONSTRATION COSTS
ICE DEMONSTRATION
COMPREHENSIVE TECHNICAL REPORT

Interagency WBS #[a]	Cost Item	Bolling AFB Subtotal	Davis-Monthan AFB Subtotal[b]	Luke AFB Subtotal	Williams AFB Subtotal
33-07	Capital Costs[c]	$24,800	$85,000	$60,170	$160,700
33-01-XX-01-06	Parsons ES Workplan/Mobilization/Startup Labor	$38,619	$9,928	$13,965	$27,059
33-14-XX-01-06	Analytical	$6,084	$4,952	$3,386	$7,336
33-14-XX-01-06	Monthly Maintenance (subcontracted)[d]	$646	$8,392	$4,629	$926
33-14-XX-01-08	Parsons ES ICE Operating Labor	$1,073	$19,952	$12,524	$18,403
33-13-XX-01-08	Parsons ES Sampling Labor	$13,844	$18,738	$16,403	$13,182
33-14-XX-01-08	Other Direct Costs[e]	$41,565	$7,926	$7,315	$11,737
33-14-XX-01-08	Auxiliary Fuel[f]	$14,968	$8,973	$7,587	$6,160
33-21-XX-01-12	ICE Demobilization	$0	$0	$0	$0
33-21-XX-01-12	Demobilization Labor	$868	$0	$0	$1,336
	TOTAL=	$142,467	$163,861	$125,979	$246,839
	TOTAL POUNDS OF TVH REMOVED =	57,000	747,000	286,000	740,000
	COST PER POUND OF TVH REMOVED [g] =	$2.50	$0.22	$0.44	$0.33
	TOTAL OPERATION, MAINTEANCE, AND MONITORING[h] =	$36,615	$61,007	$44,529	$46,007
	ACTUAL DAYS OF OPERATION=	193	379[b]	327	257
	COST PER DAY=	$190	$161	$136	$179

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TABLE 3.4 (continued)
ICE TECHNOLOGY DEMONSTRATION COSTS
ICE DEMONSTRATION
COMPREHENSIVE TECHNICAL REPORT

a/ USEPA (1995).

b/ Costs for Davis-Monthan AFB include costs associated with the work performed under this demonstration only, with the exception of the capital cost of equipment. Daily operation, maintenance, and monitoring costs are calculated for those calendar days operated under this demonstration contract.

c/ The capital cost includes the base cost for purchased units (Davis-Monthan AFB, Luke AFB, and Williams AFB V4-B) plus additional costs, which include the air/water separator and the installation of the auxiliary fuel line. Unit V4-A at Williams AFB was transferred from Davis-Monthan Air Force Base, Arizona and was purchased under contract F33615-90-D-4014, Delivery Order 14. The costs have been included for the subtotal of Williams AFB. Capital costs for Bolling AFB include 3-year prorated costs for the operation of the VRS Model V2C unit and VRS Model V4 unit. Additional capital costs include rental of a VRS Model V3 unit.

d/ Monthly maintenance costs (subcontracted) include costs incurred for subcontracted maintenance items provided by others.

e/ Other direct costs include travel, per diem, supplies. For Bolling AFB, other direct costs also include well installation (VEW-1 and -2, and VMP-1 and -2)

f/ Auxiliary fuel for the demonstration was either purchased through Parsons ES or by the base.

g/ Cost Per Pound based on total costs incurred during the demonstration period. Differences in the estimated cost per pound presented on Figure 3.4 and that presented on Table 3.4 are caused by different assumptions used in the calculations.

h/ Operation, maintenance, and monitoring costs include analytical, subcontracted monthly maintenance, Parsons ES operating and sampling labor, and auxiliary fuel.

of TVH removed during the demonstration ranged from \$0.04 to \$1.75/lb (Figure 3.4). The higher unit costs represent increased use of supplemental fuel as a result of decreasing extracted hydrocarbon concentrations. This is illustrated in Figure 3.5 where the average cost per pound of TVH removed is plotted as a function of the average influent concentration. As seen by the graph, influent concentrations below 20,000 ppmv TVH are correlated with higher costs per pound removed. As the concentration increases above 20,000 ppmv TVH, costs per pound remain somewhat stable between \$0.10 to \$0.20 per pound of TVH removed. Additionally, the operational efficiency of the unit affected the cost of operation (i.e., if low operational efficiency, the higher the cost per pound TVH removed).

3.4.3 Comparisons of Costs with Other Technologies

Figure 3.6 illustrates a cost comparison between ICE technology, a catalytic oxidation technology (CATOX), thermal oxidation (TOX) technology, and granular activated carbon (GAC) technology. Detail of the cost estimates can be found in Appendix C. Equipment capital costs and estimated consumables (e.g., auxiliary fuel usage, carbon usage) were obtained from vendors of the individual technologies. All costs are based on a 100 scfm soil vapor extraction rate and are calculated for five different influent hydrocarbon concentrations between 1,000 ppmv TVH to 40,000 ppmv TVH. Monthly maintenance and monitoring costs are assumed to be equal. It is understood that these assumptions are a major simplification to what would occur in the field. However, by using these assumptions, general insights can be made regarding the different technologies. More detailed assumptions are presented in Appendix C.

Based on this estimate, ICE technology is similar in costs to that of thermal and catalytic oxidation when influent soil gas concentrations range between 3,000 to 5,000 ppmv TVH. Above these concentrations, ICE technology becomes more cost effective. This is mainly a function of increased loading capability of the ICE unit. At higher influent concentrations, oxidation units require a great deal of dilution air to maintain the influent soil gas at some percentage of the lower explosion limit (LEL) (typically 25 to 40 percent of the LEL). This increases the capital costs because larger units are required. Fuel usage and electricity usage increase with these larger units also. At lower concentrations (less than 3,000 to 5,000 ppmv TVH), the conventional oxidation technologies have an advantage because of lower capital costs and heat recovery options which are not available on the ICE units. At concentrations below 500 ppmv, granular activated carbon may become more cost effective.

Advantages that ICE technology has over more conventional thermal destruction technologies include:

- No extraction blower or electricity hook-up required which reduces capital and operating costs and decreases set-up time; and

- Operation at higher soil gas influent concentrations which allow higher loading rates to be treated at similar well-gas flow rates.

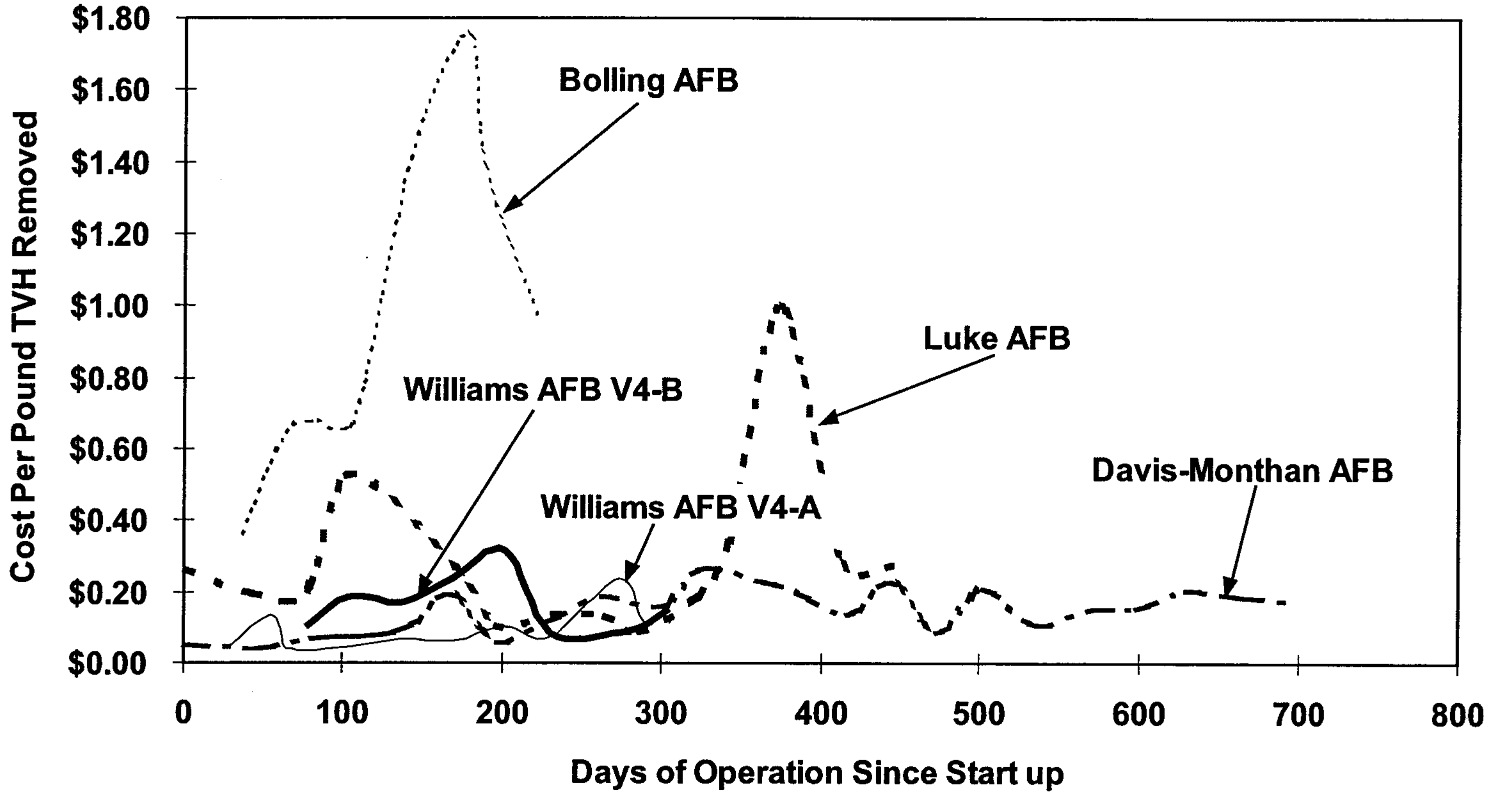

FIGURE 3.4

COST PER POUND OF TOTAL VOLATILE HYDROCARBONS REMOVED

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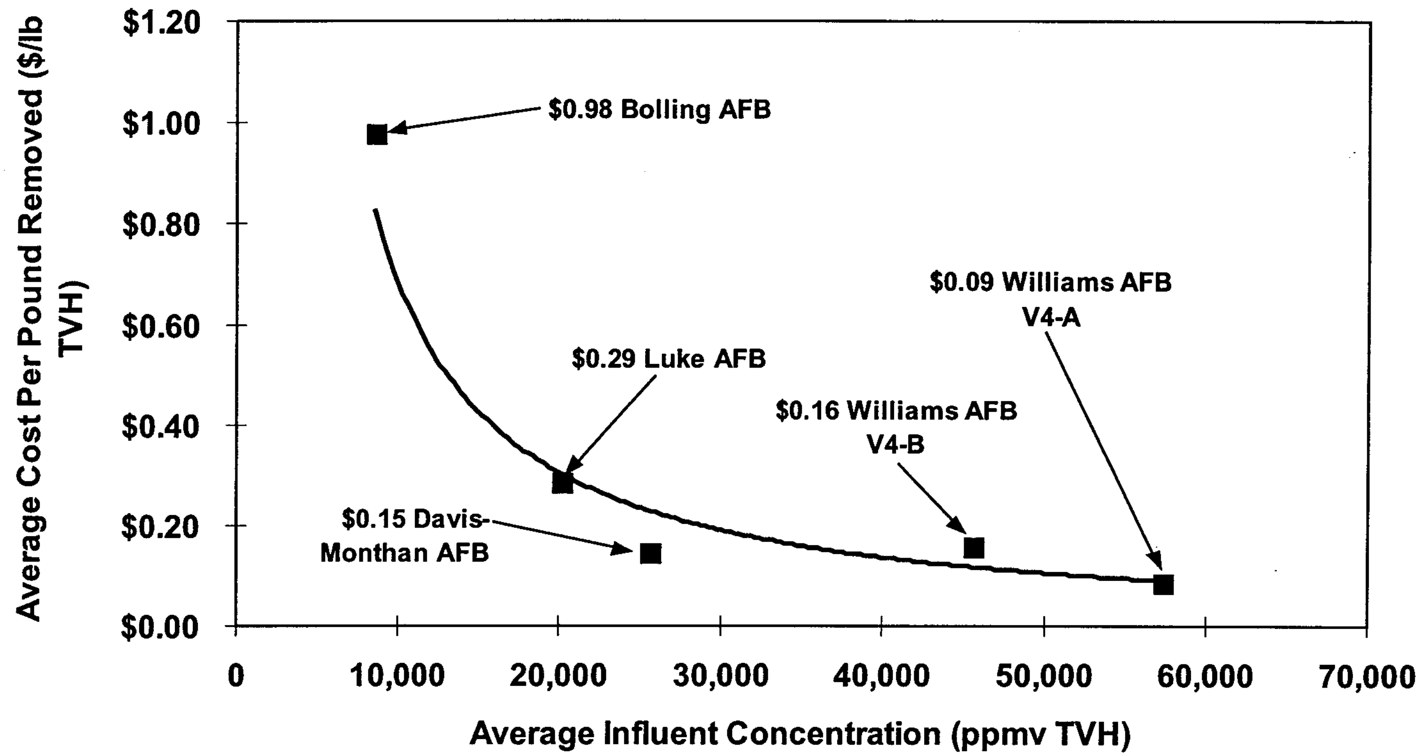

FIGURE 3.5

COST PER POUND OF TOTAL VOLALITE HYDROCARBONS REMOVED VERSUS INFLUENT CONCENTRATION

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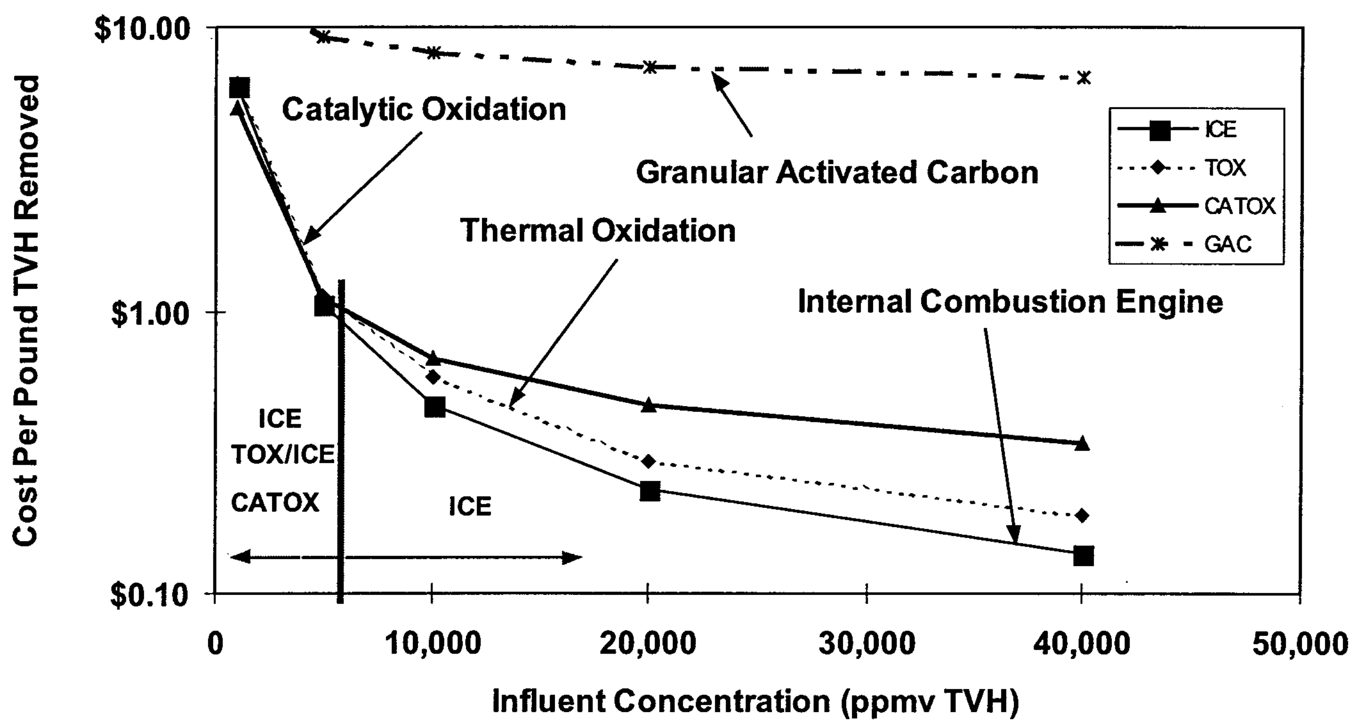

ASSUMPTIONS:

1. See Appendix C.
2. Well gas flow rate approximately 100 cfm.

FIGURE 3.6

COST COMPARISON AS A FUNCTION OF INFLUENT CONCENTRATION

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Disadvantages of ICE technology include:

- No ability for heat recovery, as opposed to other oxidation technologies, which results in higher fuel usages at lower influent soil gas concentration;
- More susceptible to varying influent concentrations (i.e., changes in oxygen and carbon dioxide influent concentrations may cause operational problems) due to the need to maintain stoichiometric combustion ratios; and
- Increased complexity increases maintenance requirements which may also decrease operational efficiency.

SECTION 4

CONCLUSIONS

4.1 TECHNOLOGY PERFORMANCE

The following items summarize the evaluation of the technologies performance during this demonstration:

- The vacuum and flow rate obtained by the ICE units were sufficient to provide effective contaminant removal and radius of influences at the four demonstration sites.
- The ICE units were capable of treating highly concentrated, non-chlorinated vapor streams of up to 140,000 ppmv TVH while maintaining DREs of greater than 99.9-percent.
- Maximum hydrocarbon removal rates of 1,200 (V3) to over 2,400 lb/day (V4) were achieved by the ICE units during the demonstration.
- On average, the ICE units achieved an overall 82 percent operational efficiency.

4.2 LESSONS LEARNED

The following items summarize the lessons learned during this demonstration:

- The ICE units although simple in concept are complex systems that require skilled technicians to properly operate and maintain.
- As the ICE units age, more intensive maintenance to maintain peak operation is required.
- Recommended design changes include the use of pusher as opposed to puller fans and the use of Neihoff® brushless alternators in the ICE units.
- Do not substitute liquid cell batteries with dry cell batteries when performing replacement activities. Upon loss of charge, dry cell batteries require a longer charging period (up to 2 to 3 days) versus liquid cell batteries (3 to 4 hours) to be able to start the engine.
- Extreme surface conditions such as high temperatures in Arizona during the summer months lead to potential operational problems not recognized in cooler climates (i.e., over heating, decreased battery life).
- Elevated carbon dioxide in the extracted vapor stream can lead to higher TVH emissions due to incomplete combustion of the fuel within the units.

- The overall cost effectiveness of ICE technology for off-gas treatment is a function of the concentration of the incoming vapor stream, flow rate, system efficiency, and the operational life of the project. Remediation using ICE technology is a dynamic process which requires a regular assessment of the system effectiveness and the need for adjustments (e.g., running only one engine of a V4 as opposed to two to reduce auxiliary fuel usage when influent concentrations decrease).

- One of the objectives of this project was to demonstrate the applicability of ICE technology for SVE off-gas treatment. Therefore, increased system monitoring was conducted at these demonstration sites to compile a database that could be used in this technology evaluation. Monitoring costs for ICE systems could be reduced by lowering the frequency at which samples are collected for laboratory analysis and by eliminating daily call-up service, depending on site-specific conditions.

- Remote adjustment and monitoring options are useful in operation of the systems. The use of remote start-up capabilities requires the completion of a site-specific safety evaluation assessing all possible hazards and consequences (e.g., potential for deleterious effects due to a propane leak going undetected) prior to utilizing such a feature.

SECTION 5

RECOMMENDATIONS

The Air Force ICE technology demonstration has demonstrated that this technology is effective in treating highly concentrated vapor streams of non-chlorinated hydrocarbons under varying site conditions. Testing has been completed at four different Air Force installations. At all four of these installations, the ICE technology has been retained at the site to provide full-scale systems to complete site remediation.

The ICE units mobility and ability to treat highly concentrated vapor streams suggests that it is generally best suited for initial (0 to 6 months) response at highly contaminated sites. Because the ICE technology is "self-contained," it is well-suited for remote sites or areas where electricity would be expensive to supply to the site. In addition, its applicability should not be limited to SVE technology but should also be considered for treating other vapor streams at contaminated sites (e.g., off-gas from bioslurping, degassing USTs), if hydrocarbon concentrations are greater than 5,000 to 10,000 ppmv.

Based on the cost estimate provided in Section 3.4, ICE technology is similar in costs to that of thermal and catalytic oxidation when influent soil gas concentrations range between 3,000 to 5,000 ppmv TVH. Above these concentrations, ICE technology becomes more cost effective. This comparison will vary depending on site-specific conditions but indicates that ICE technology becomes more cost competitive as influent concentrations increase. Sites which contain a large source of TVH vapors (e.g., vapors emitted from free product or concentrated soil residuals) will be the best candidates for the ICE technology. In contrast, sites which contain limited quantities of fuel hydrocarbon contamination may not be good candidates for the ICE technology, even though initial TVH concentrations could be greater than 5,000 to 10,000 ppmv. At sites with limited quantities of hydrocarbons, vapor concentrations may be rapidly depleted after a few days or weeks of operation and the ICE technology will begin to consume large quantities of supplemental fuel.

All DoD remediation contractors should be required to evaluate ICE technology as a possible off-gas treatment technology for highly concentrated, non-chlorinated vapor streams.

SECTION 6

REFERENCES

Parsons Engineering Science, Inc. (Parsons ES). 1997a. Draft Site-Specific Evaluation Report and Corrective Action Plan for Building 41, Former Car Care Center, Bolling Air Force Base, Washington DC. April.

Parsons ES. 1997b. Final Site-Specific Evaluation Report for the Evaluation of Vapor Extraction and Treatment Using Internal Combustion Engine Technology at Site ST-35 Fuel Pumphouse No. J3, Davis-Monthan Air Force Base, Arizona. November.

Parsons ES. 1998a. Final Site-Specific Evaluation Report for the Evaluation of Vapor Extraction and Treatment Using Internal Combustion Engine Technology at Site SS-42, Luke Air Force Base, Arizona. January.

Parsons ES. 1998b. Final Site-Specific Evaluation Report for the Evaluation of Vapor Extraction and Treatment Using Internal Combustion Engine Technology at Site ST-12, Williams Air Force Base, Arizona. April.

APPENDIX A

VENDOR INFORMATION - RSI ICE UNIT PILOT TEST REPORT

PARSONS ENGINEERING SCIENCE, INC.

1700 Broadway, Suite 900 • Denver, Colorado 80290 • (303) 831-8100 • Fax: (303) 831-8208

January 23, 1998

Major Edward G. Marchand
AFCEE/ERT
3207 North Road, Building 532
Brooks AFB, Texas 78235-5363

RE: Air Force Contract No. F41624-94-D-8136, Order 0028
Air Conformity Determination of Flameless Thermal Oxidation and Internal Combustion Engine for VOC Off-Gas Abatement
Remediation Services International (RSI) Field Demonstration/Evaluation

Dear Major Marchand:

The purpose of this letter is to inform you of the results of Mr. Steve Archabal's [Parsons Engineering Science, Inc. (Parsons ES)], January 15, 1998 field demonstration/evaluation of the Remediation Services International (RSI) Model V3, internal combustion engine (ICE) soil vapor extraction (SVE) system. The demonstration was performed at Site ST-12, Williams AFB, Arizona. On August 12, 1997, an unsuccessful demonstration/evaluation of the RSI Model V3 ICE unit was conducted at Site ST-12, and RSI requested to revisit Site ST-12 to again test their ICE unit. The purpose for conducting the field demonstration was to evaluate the effectiveness of RSI's newly configured air/fuel auto-controlled carburetor system (including an oxygen sensor on the exhaust), and to determine whether or not the system could control post-combustion air emissions as well as the VR Systems internal combustion engine units presently in use by the Air Force. Also witnessing the demonstration was Mr. Michael Joy, general manager for RSI, and Mr. Bob Heagey, vice president of FO Engineering, Inc., who developed the air/fuel controller technology being used on the RSI systems.

Mr. Archabal's observations of the testing procedure are as follow:

- On January 15, 1998, a field demonstration of RSI's Model V3 ICE/SVE system was conducted at Site ST-12, Williams AFB, Arizona. Initially, the ICE system was positioned next to the existing dual-phase extraction (DPE) well No. 1 at the site. RSI supplied propane as the supplemental fuel required to both start the unit and maintain engine operation during the test.

- Prior to starting the test, Mr. Archabal calibrated the Horiba® Emission Analyzer that was used to check the actual emissions as well as the influent well gas concentrations of oxygen (O_2), carbon dioxide (CO_2), and total volatile hydrocarbons (TVH). Following instrument calibration and ICE system warm-up, the testing began.

- The first test included checking the system performance while treating only ambient air and propane (supplemental fuel) to ensure that the engine was operating efficiently prior to extracting and treating well gas. Results of this test showed 0.0 part per million by volume (ppmv) TVH at both the pre- and post-catalytic converter sampling points. This test provided excellent baseline data prior to extracting/treating well gas.

- During the second phase of testing, monitoring of the well gas O_2, CO_2, and TVH concentrations, and pre- and post-catalytic converter TVH concentrations was conducted. The extraction flow rate was 30 to 40 cubic feet per minute (cfm) and the well gas O_2 and CO_2 concentrations were 3.5 and 6.5 percent, respectively. The results from the second phase of testing are as follow:

Horiba® Influent TVH Concentration	36,000 ppmv
Horiba® Total TVH Concentration Pre-Catalytic Converter	200 ppmv
Horiba® TVH Concentrations Post-Catalytic Converter	0.0 ppmv
TVH DRE	100%

- The test performed on well gas ran for approximately 3 hours, during which time several Horiba® measurements were obtained. All results from the sampling conducted were consistent, with the final, post-catalytic-converter emission sampling point results being 0.0 ppmv TVH. It is important to note that the lowest VR unit post-catalytic TVH emissions measured with the Horiba® at DPE-1 well, were 10 to 30 ppmv, with total pre-catalytic TVH readings ranging from 200 to 300 ppmv during vapor extraction.

- Based on these test results, which are predicated on extracting soil vapor from a site considered "worst case," the auto air/fuel controller currently being offered by RSI performed extremely well. Additionally, the time it took to convert onto well gas could be as little as 1 to 2 minutes using the RSI controller, while the VR units require approximately 10 to 15 minutes. At no time during the test did the RSI system shut down due to sudden changes in well gas concentrations, which can happen with the VR units.

- Finally, the RSI carburetor and program logic controller (PLC) have fewer components that can fail compared to the VR units. As a result, when repair/replacement of existing computer and carburetor components is required on the VR units, retrofitting to the RSI technology should be considered. This retrofitting could be done in the field by a qualified technician, eliminating the need to ship the system back to the RSI facility and incurring additional associated costs and downtime.

Parsons ES appreciates your support during this demonstration/evaluation test, and hope these positive results will support future Air Force projects. If you have any questions, please call Steve Archabal at (602) 852-9110 or met at (303) 831-8100.

Sincerely,

PARSONS ENGINEERING SCIENCE, INC.

Peter R. Guest

Peter R. Guest, P.E.
Project Manager

c.c.: Mr. Mike Deaton, HSC/PKVAB
Mr. Steve Archabal, Parsons ES Phoenix
Mr. Jack Sullivan, Parsons ES Oklahoma City

APPENDIX B

SITE ANALYTICAL DATA TABLES

TABLE 1
GALLONS OF HYDROCARBONS REMOVED
SUMMARY OF VR SYSTEMS, MODELS V2C, V4, AND V3
STARTUP OPERATION AT SITE ST-04
BOLLING AFB, WASHINGTON DC

Date of Sampling	Well Number	Days of Operation During Month	Influent TVH[a] Concentration (ppmv)[b]	Flow Rate (scfm)[c]	Pounds TVH Removed	Gallons[d] of Hydrocarbons Removed	Gallons Propane Used[e]	Cost Per Gallon Hydro.Removed[f]
10/17&18/96[g]	1	5	123,000[h]	2	458	76	0	NA[j]
11/14/96[i]	1	1	110,000	40	1,640	273	0	NA[j]
11/15/1996[i]	2	1	15,000	38	212	35	0	NA[j]
12/19/1996[i]	1 and 2	28.3	12,000	120	15,189	2,531	1245	$2.17
1/16/1997[i]	1 and 2	16.5	10,000[k]	102	6,273	1,045	693	$3.88
2/5/1997[l]	1 and 2	15	10,000	108	6,038	1,006	690	$4.09
2/27/1997[l]	1 and 2	22[m]	8,800	89	7,592[n]	1,268	1170	$4.03
4/3/1997[l]	1 and 2	29.5	6,400	78	5,489	915	1580	$8.44
5/8/1997[l]	1 and 2	35[m]	4,200	85	4,657	776	1893	$10.52
5/20/1997[l]	1, 2, and 5R	6[m]	8,400	93	1,747	291	375	$8.29
6/23/1997[l]	1, 2, and 5R	34[m]	7,100	92	8,277	1,380	1894	$5.81
				Total =	57,572	9,598		

[a] TVH = total volatile hydrocarbons.
[b] ppmv = parts per million by volume, as determined by the analytical laboratory.
[c] scfm = standard cubic feet per minute.
[d] gallons = determined using an average weight for fuel removed of 6 pounds per gallon.
[e] Based on ICE unit supplemental fuel totalizing meter.
[f] Through January 16, 1997, costs are based on a prorated 30-day month with a daily operating costs for Model V4 of: $50 for Model V4 ICE system + $60 operation/maintainance/sampling + actual supplemental fuel cost. From February 1997, the cost is based on a prorated $3,800/month lease rate including ICE setup, operation, and maintenance + $30 sampling cost + actual sumplemental fuel cost during month of operation.
[g] A Model V2C ICE was operating during this sampling event (one engine).
[h] Average of two influent samples collected on October 17 and October 18, 1996 (see Table 2).
[i] A Model V4 ICE was operating during this sampling event (two engines).
[j] Cost per gallon not calculated during the short operating period of the Model V2C or for Model V4 ICE startup and extraction well flow optimization activities.
[k] Influent TVH concentration from 2/5/97 sampling event was assumed for 1/16/97 event because an influent sample was not collected on 1/16/97.
[l] A Model V3 ICE was operating during this sampling event (one engine).
[m] Days of operation since previous sampling event.
[n] Calculated using an average influent TVH concentration and average flow rate for the month of February.

TABLE 2
DESTRUCTION EFFICIENCY
SUMMARY OF VR SYSTEMS, MODELS V2C, V4, AND V3
STARTUP OPERATION AT SITE ST-04
BOLLING AFB, WASHINGTON DC

Date Sampled	Well Number	Influent TVH[a] Concentration (ppmv)[b]	Influent TVH[a] Concentration (µg/L)[c]	Effluent TVH Concentration Engine No. 1 (ppmv)	Effluent TVH Concentration Engine No. 1 (µg/L)	Effluent TVH Concentration Engine No. 2 (ppmv)	Effluent TVH Concentration Engine No. 2 (µg/L)	Destruction Efficiency Engine No. 1 (percent)	Destruction Efficiency Engine No. 2 (percent)	Total Daily TVH Emmissions (pounds/day)
10/17/96[d]	1	66,000	270,000	62.0	260.0	-[d]	-[d]	99.90	NA	0.05
10/18/96[d]	1	180,000	750,000	280.0	1200	-[d]	-[d]	99.84	NA	0.22
11/14/96[e]	1	110,000	460,000	7.1	30.0	1.4	5.8	99.99	100.00	0.13
11/15/96[e]	2	15,000	62,000	4.7	20.0	2.8	12	99.97	99.98	0.11
12/19/96[e]	1 and 2	12,000	50,000	-[f]	-[f]	2.6	11	-[f]	99.98	0.12
2/5/1997[g]	1 and 2	10,000	42,000	3.6	15	-[g]	-[g]	99.96	-[g]	0.15
2/27/97[g]	1 and 2	8,800	36,000	27.0	110	-[g]	-[g]	99.69	-[g]	0.88
4/4/97[g]	1 and 2	6,400	27,000	42	170	-[g]	-[g]	99.37	-[g]	1.19
5/8/97	1 and 2	4,200	17,000	150	620	-[g]	-[g]	96.35	-[g]	4.72
5/20/97	1,2, and 5R	8,400	35,000	250	1,000	-[g]	-[g]	97.14	-[g]	8.34
6/23/97	1,2, and 5R	7,100	30,000	160	660	-[g]	-[g]	97.80	-[g]	5.44

[a] TVH = total volatile hydrocarbons.
[b] ppmv = parts per million by volume, as determined by the analytical laboratory.
[c] µg/L = micrograms per liter, as determined by the analytical laboratory.
[d] A Model V2C ICE was operating during this sampling event (one engine).
[e] A Model V4 ICE was operating during this sampling event (two engines).
[f] Effluent samples were not collected from Engine No. 1.
[g] A Model V3 ICE unit (one engine) was installed at the site on January 21, 1997.

TABLE 1
GALLONS OF HYDROCARBONS REMOVED PER MONTH
SUMMARY OF VR SYSTEMS
FULL-SCALE OPERATION AT SITE 35
DAVIS-MONTHAN AFB, TUCSON, AZ

Month	Days of Operation	Average Influent TVH[a] Concentration (ppmv)[b]	Average Flow Rate (scfm)[c]	Pounds TVH Removed	Gallons of Hydrocarbons Removed[d]	Gallons Propane Used[e]	Cost Per Gallon Hydro.Removed[f]
Sep-95	30	41,000	141	64,638	10,773	20	$0.31
Oct-95	31	50,000	137	79,144	13,191	34	$0.25
Nov-95	22	42,000	144	49,591	8,265	100	$0.41
Dec-95	27	28,000	155	43,674	7,279	10	$0.45
Jan-96	30	22,000	150	36,898	6,150	180	$0.56
Feb-96	23	16,500	130	18,387	3,065	300	$1.16
Mar-96	31	38,000	145	63,662	10,610	230	$0.33
Apr-96	30	25,000	110	30,748	5,125	200	$0.68
May-96	31	16,000	106	19,595	3,266	450	$1.13
Jun-96	30	19,000	100	21,244	3,541	30	$0.94
Jul-96	23	19,000[g]	90	14,659	2,443	690	$1.60
Aug-96	28	22,500	77	18,080	3,013	891	$1.36
Sep-96	30	15,000	108	18,048	3,008	291	$1.19
Oct-96	31	21,000	111	26,712	4,452	287	$0.81
Nov-96	27.5	13,000	129	17,228	2,871	373	$1.35
Dec-96	31.0	29,000	130	43,558	7,260	248	$0.52
Jan-97	17.5	23,000	118	17,702	2,950	210	$1.26
Feb-97	28	25,000	134	34,960	5,827	224	$0.64
Mar-97	30	24,000	118	31,665	5,278	1116	$0.92
Apr-97	30	25,000	110	30,748	5,125	1048	$0.93
May-97	28.77	22,000	103	24,298	4,050	1190	$1.22
Jun-97	20.8	23,000	113	20,148	3,358	270	$1.13
Jul-97	23.5	23,000	110	22,159	3,693	367	$1.06
			Total =	747,547	124,591		

[a] TVH = total volatile hydrocarbon.
[b] ppmv = parts per million by volume, as determined by the analytical laboratory.
[c] scfm = standard cubic feet per minute.
[d] gallons = determined using an average weight of 6 pounds per gallon for fuel removed.
[e] Based on propane distributor invoices and/or ICE unit supplemental fuel totalizing meter readings.
[f] Through October 1996, cost is based on 30-day month with a daily operating cost for Model V4 of: $50 for ICE system + 60$ operation/maintainance/sampling + actual supplemental fuel cost (propane @ $0.90/gallon). From November 1996, the cost is based on 30-day month with a daily operating cost for Model V3 of: $55 for ICE system + $60 operation/maintenance/ sampling + actual supplemental fuel cost during month of operation.
[g] Influent sample was collected approximately 2 hours after the system was restarted following a 5-day shutdown period. Therefore, the influent sample may reflect an increased TVH concentration due to hydrocarbon concentration rebound that may have occurred during the 5-day shutdown period.

TABLE 2
TVH DESTRUCTION EFFICIENCY
SUMMARY OF VR SYSTEMS, MODEL V4 AND V3 ICEs
FULL-SCALE OPERATION AT SITE 35
DAVIS-MONTHAN AFB, TUCSON, AZ

Date	Influent TVH[a] Concentration		Effluent TVH Concentration Engine No. 1		Effluent TVH Concentration Engine No. 2		Destruction Efficiency Engine No. 1	Destruction Efficiency Engine No. 2	Total Daily TVH Emissions
Sampled	(ppmv)[b]	(µg/L)[c]	(ppmv)	(µg/L)	(ppmv)	(µg/L)	(Percent)	(Percent)	(Pounds/day)
9/1/95	43,000	180,000	3	12	3	14	99.99	100.00	0.16
9/26/95	39,000	160,000	63	260	28	120	99.84	99.98	2.40
10/17/95	50,000	210,000	7	28	10	42	99.99	100.00	0.43
11/21/95	42,000	170,000	17	71	12	50	99.96	99.99	0.78
12/19/95	28,000	120,000	16	66	6	25	99.95	99.99	0.63
1/18/96	22,000	91,000	42	170	28	120	99.81	99.97	1.95
2/23/96	14,000	58,000	44	180	46	190	99.69	99.92	2.16
3/14/96	38,000	160,000	41	170	28	120	99.89	99.98	1.88
5/20/96	16000	66,000	45	190	-	-	99.71	-[e]	1.81
6/26/96	19,000	79,000	-[d]	-[d]	8	33	-[d]	99.99	0.30
7/24/96	19,000	79,000	3.8	16	10	42	99.98	99.99	0.23
8/30/96	22,500	93,500	7.1	30	-[e]	-[e]	99.97	-[e]	0.21
9/20/96	15,000	62,000	-[d]	-[d]	3.1	13.0	-[d]	99.995	0.13
10/21/96	21,000	87,000	-[d]	-[d]	1.3	5.4	-[d]	99.994	0.05
11/18/96	13,000	54,000	4.2	17	-[f]	-[f]	99.97	-[f]	0.20
12/16/96	29,000	120,000	25	100	-[f]	-[f]	99.92	-[f]	1.2
1/14/97	23,000	95,000	1.8	7.5	-[f]	-[f]	99.99	-[f]	0.08
2/17/97	25,000	100,000	5.5	23	-[f]	-[f]	99.98	-[f]	0.24
3/24/97	24,000	100,000	6.7	28	-[f]	-[f]	99.97	-[f]	0.30
4/21/97	25,000	100,000	11	46	-[f]	-[f]	99.95	-[f]	0.49
5/21/97	22,000	91,000	57	240	-[f]	-[f]	99.74	-[f]	2.54
6/23/97	23,000	96,000	72	300	-[f]	-[f]	99.69	-[f]	3.04
7/24/97	23,000	96,000	21	87	-[f]	-[f]	99.91	-[f]	0.86

[a] TVH = total volatile hydrocarbon.
[b] ppmv = parts per million by volume, as determined by the analytical laboratory.
[c] µg/L = micrograms per liter, as determined by the analytical laboratory.
[d] Engine No. 1 was not operating during this sampling event.
[e] Engine No. 2 was not operating during this sampling event.
[f] A Model V3 ICE unit, which has only one engine, was installed at the site on October 31, 1996.

TABLE 1
GALLONS OF HYDROCARBONS REMOVED PER MONTH
SUMMARY OF VR SYSTEMS, MODEL V3 ICE
FULL-SCALE OPERATION AT SITE SS-42
LUKE AFB, PHOENIX, AZ

Month	Days of Operation	Average Influent TVH[a] Concentration (ppmv)[b]	Average Flow Rate (scfm)[c]	Pounds TVH Removed	Gallons[d] of Hydrocarbons Removed	Gallons Propane Used[e]	Cost Per Gallon Hydro.Removed[f]
Aug-96	14.42	38,500[g]	68	14,156	2,359	313	$1.58
Sep-96	23.46	30,000	71	18,624	3,104	310	$1.20
Oct-96	30.33	22,000	80	19,920	3,320	630	$1.21
Nov-96	21.33	9,900	92	7,218	1,203	427	$3.20
Jan-97	15.50	20,000	120	13,865	2,311	217	$1.61
Feb-97	25.40	28,000	137	36,314	6,052	356	$0.64
Mar-97	26.08	23,000	128	28,616	4,769	522	$0.86
Apr-97	23.10	25,000	140	30,133	5,022	540	$0.82
May-97	31.00	26,000	153	45,961	7,660	583	$0.55
Jun-97	30.00	13,000	155	22,530	3,755	648	$1.13
Jul-97[h]	15.00	13,000	155	11,265	1,878	342	$2.06
Aug-97[h]	10.00	9,900	110	4,059	676	480	$5.98
Sep-97	30.00	9,900	149	16,493	2,749	936	$1.68
Oct-97	31.00	9,900	150	17,158	2,860	1,153	$1.71
			Totals =	**286,313**	**47,719**		

[a] TVH = total volatile hydrocarbon.
[b] ppmv = parts per million by volume, as determined by the analytical laboratory.
[c] scfm = standard cubic feet per minute.
[d] gallons = determined using an average weight of 6 pounds per gallon for fuel removed.
[e] Based on ICE unit supplemental fuel totalizing meter readings when available.
[f] Cost based on a 30-day month with a daily operating cost of: $55 for ICE system + $60 operation/maintenance/ sampling + actual supplemental fuel cost.
[g] Average of two influent TVH samples collected on August 7 and August 8, 1996 (see Table 2).
[h] Data for July and August 1997 are estimates because no samples were collected during those periods because the unit was down due to a computer malfunction.

TABLE 2
VOLATILE HYDROCARBON DESTRUCTION EFFICIENCY
SUMMARY OF VR SYSTEMS, MODEL V3 ICE
FULL-SCALE OPERATION AT SITE SS-42
LUKE AFB, PHOENIX, AZ

Date Sampled	Influent TVH[a] Concentration (ppmv)[b]	Influent TVH[a] Concentration (μg/L)[c]	Effluent TVH Concentration (ppmv)	Effluent TVH Concentration (μg/L)	Destruction Efficiency (Percent)	Total Daily TVH Emmissions (Pounds/day)
8/7/96	49,000	200,000	5.8	24	99.99	0.15
8/8/96	28,000	120,000	8.9	37	99.97	0.23
9/19/96	30,000	120,000	12	50	99.96	0.32
10/22/96	22,000	91,000	2	9	99.99	0.07
11/19/96	9,900	41,000	3.5	14	99.97	0.12
1/23/97	20,000	83,000	1.0	4	100.00	0.04
2/18/97	28,000	120,000	7.0	29	99.98	0.36
3/25/97	23,000	96,000	5.4	22	99.98	0.25
4/28/97	25,000	100,000	8.6	36	99.96	0.45
5/20/97	26,000	110,000	40.0	170	99.85	2.33
6/25/97	13,000	54,000	39.0	160	99.70	2.22
9/23/97	9,900	41,000	64.0	270	99.34	3.61
10/28/97	9,900	41,000	14.0	58	99.86	0.78

[a] TVH = total volatile hydrocarbon.
[b] ppmv = parts per million by volume, as determined by the analytical laboratory.
[c] μg/L = micrograms per liter, as determined by the analytical laboratory.
NOTE: Data for July and August 1997 are estimates because no samples were collected during those periods because the unit was down due to a computer malfunction.

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TABLE 1
GALLONS OF HYDROCARBONS REMOVED PER MONTH
SUMMARY OF VR SYSTEMS MODEL V4 ICE
FULL-SCALE OPERATION AT SITE ST-12
WILLIAMS AFB, ARIZONA

Date Sampled	Engine No.	Days of Operation	Influent TVH[a/] Concentration (ppm)[b/]	Flow Rate (scfm)[c/]	Total Pounds TVH Removed	Gallons of Hydrocarbons Removed[d/]	Therms of Natural Gas Used[e/]	Cost per Gallon Hydro removed[f/]
2/8/97	1A	2	140,000	30	3,131	522	0.0	N/A[g/]
	2A	2	140,000	32	3,339	557	0.0	
2/11/97	1A	3	120,000	36	4,830	805	0.0	N/A[g/]
	2A	3	120,000	36	4,830	805	0.0	
3/5/97	1A	22	100,000	39	31,978	5,330	0.0	$0.25
	2A	22	100,000	38	31,158	5,193	0.0	
4/2/97	1A	10	56,000	40	8,349	1,391	0.0	$0.82
	2A	17	56,000	45	16,322	2,720	0.0	
4/11/97[h/]	1A	9	88,000	40	11,807	1,968	0.0	$0.27
	2A	9	88,000	42	12,398	2,066	0.0	
	1B	Not operating						N/A[g/]
	2B	1	110,000	36	1,476	246	20.2	
4/16/97	1A	5	97,000	40	7,230	1,205	0.0	$0.24
	2A	5	97,000	43	7,773	1,295	0.0	
	1B	Not operating						N/A[g/]
	2B	1	93,000	39	6,759	1,127	85.7	
4/24/97	1A	8	100,000	43	12,821	2,137	0.0	$0.22
	2A	8	100,000	45	13,417	2,236	0.0	
	1B	Not operating						$0.62
	2B	8	76,000	39	8,838	1,473	122.0	
5/22/97	1A	25	72,000	57	38,240	6,373	0.0	$0.27
	2A[i/]	22	72,000	61	36,012	6,002	0.0	
	1B	4	88,000	43	5,641	940	25.6	$1.11
	2B	8	88,000	40	10,495	1,749	51.5	
6/24/97	1A	32	75,000	50	44,725	7,454	86.8	$0.39
	2A	11	75,000	55	16,912	2,819	40.3	
	1B[i/]	15	75,000	40	16,772	2,795	173.0	$1.00
	2B[i/]	4	75,000	41	4,584	764	21.2	
7/25/97	1A	28	57,000	51	30,337	5,056	143.3	$0.37
	2A	31	57,000	53	34,904	5,817	365.7	
	1B[i/]	2	38,000	54	1,530	255	109.4	$1.41
	2B	21	38,000	46	13,681	2,280	479.2	
8/27/97	1A	33	33,000	51	20,700	3,450	568.4	$0.61
	2A	33	33,000	57	23,135	3,856	293.4	
	1B	Not operational during period						$1.91
	2B	20	28,000	56	11,688	1,948	481.3	
9/24/97	1A	28	48,000	58	29,053	4,842	577.3	$0.43
	2A	28	48,000	50	25,046	4,174	368.9	
	1B	15	64,000	55	19,679	3,280	280.8	$0.49
	2B	20	64,000	44	20,991	3,498	460.9	

TABLE 1
GALLONS OF HYDROCARBONS REMOVED PER MONTH
SUMMARY OF VR SYSTEMS MODEL V4 ICE
FULL-SCALE OPERATION AT SITE ST-12
WILLIAMS AFB, ARIZONA

Date Sampled	Engine No.	Days of Operation	Influent TVH[a] Concentration (ppm)[b]	Flow Rate (scfm)[c]	Total Pounds TVH Removed	Gallons of Hydrocarbons Removed[d]	Therms of Natural Gas Used[e]	Cost per Gallon Hydro removed[f]
11/7/1997[j,k]	1A	~~40~~ 37	24,000	38	13,666	2,278	~~1,964.2~~ 845	~~$2.80~~ 1.43
	2A	~~25~~ 30	24,000	38	11,958	1,993	~~1,985.5~~ 649	
	1B	~~41~~ 36	39,000	52	30,669	5,111	1,003.7	~~$0.73~~ 0.52
	2B	~~41~~ 37	39,000	53	31,259	5,210	413.3	
11/24/97	1A	17	33,000	60.8	13,010	2,168	527.1	~~$0.85~~ 0.63
	2A	17	33,000	58.1	12,432	2,072	646.9	
	1B	17	34,000	51	10,913	1,819	510.0	~~$0.91~~ 0.64
	2B	17	34,000	52	11,127	1,854	490.0	
				Total=	725,614	120,933		

a/ TVH = total volatile hydrocarbon.
b/ ppmv = parts per million by volume, as determined by the analytical laboratory.
c/ scfm = standard cubic feet per minute.
d/ gallons = determined using as average weight of 6 pounds per gallon for fuel removed.
e/ Based on natural gas distributor invoices and/or ICE unit supplemental fuel totalizing meter readings (assumes 1 Therm = 100,000 BTUs).
f/ Cost is calculated per ICE unit based on a daily operating cost for Model V4s of: $60 for ICE System (V4A) or $45 for ICE System (V4B) (when appropriate) + $60 operation/maintenance/sampling + supplemental fuel cost (assume $0.55 per therm of natural gas).
g/ Cost per gallon not calculated during Model V4 ICE startup and extraction well flow optimization activities.
h/ A second Model V4 ICE Unit was started-up on April 10, 1997.
i/ This engine not operational during sampling event but was operational during the period.
j/ Systems unilaterally transferred to Geo/Resource Consultants, Inc. on October 3, 1997.
k/ Cost data based on supplemental fuel flow averaging not totalizer readings.

NOTE:
1. CORRECTIONS BASED ON PARSONS ES REVIEW OF FIELD DATA FROM GEO/RESOURCE CONSULTANTS, INC

TABLE 2
TVH DESTRUCTION EFFICIENCY
SUMMARY OF VR SYSTEMS MODEL V4 ICE
FULL-SCALE OPERATION AT SITE ST-12
WILLIAMS AFB, ARIZONA

Date Sampled	Engine No.	Influent TVH[a] Concentration (ppmv)[b]	Influent TVH[a] Concentration (ug/L)[c]	Flow Rate (scfm)[b]	Effluent TVH Concentration (ppmv)	Effluent TVH Concentration (ug/L)	Destruction Efficiency (Percent)	Total Daily TVH Emissions (Pounds/day)	Total Daily TVH Emissions[d] (Pounds/day)
2/8/97	1A	140000	580000	30	18	75	99.99	0.20	0.2
	2A	140000	580000	32	3.4	14	100.00	0.04	
2/11/97	1A	120000	500000	36	76	320	99.94	1.04	2.1
	2A	120000	500000	36	80	330	99.93	1.07	
3/5/97	1A	100000	420000	39	81	340	99.92	1.19	1.3
	2A	100000	420000	38	6.1	25	99.99	0.09	
4/2/97	1A	56000	232800	40	51	212	99.91	0.76	1.0
	2A	56000	232800	46	11	46	99.98	0.19	
4/11/97	1A	88000	360000	40	46	190	99.95	0.68	0.9
	2A	88000	360000	42	8.5	35	99.99	0.13	
	1B	Not operating							
	2B	110000	460000	36	3.4	14	100.00	0.05	
4/16/97	1A	97000	400000	Effluent not sampled.					
	2A	97000	400000	Effluent not sampled.					
	1B	Not operating							
	2B	93000	390000	Effluent not sampled.					
4/24/97	1A	100000	420000	43	61	250	99.94	0.97	1.2
	2A	100000	420000	45	7.7	32	99.99	0.13	
	1B	Not operating							
	2B	76000	320000	39	7.4	32	99.99	0.11	
5/22/97	1A	72000	300000	57	93	390	99.87	2.00	2.2
	2A	Not operating							
	1B	88000	360000	43	4.7	20	99.99	0.08	
	2B	88000	360000	40	10	42	99.99	0.15	
6/24/97	1A	75000	310000	50	200	830	99.73	3.73	5.5
	2A	75000	310000	55	87	360	99.88	1.78	
	1B	Not operating							
	2B	Not operating							
7/25/97	1A	57000	240000	51	110	460	99.81	2.11	9.0
	2A	57000	240000	53	260	1100	99.54	5.24	
	1B	Not operating							
	2B	38000	160000	46	96	400	99.75	1.65	
8/27/97	1A	33000	140000	51	110	460	99.67	2.11	12.8
	2A	33000	140000	57	260	1000	99.29	5.12	
	1B	Not operating							
	2B	28000	120000	56	96	1100	99.08	5.54	
9/24/97	1A	48000	200000	58	150	620	99.69	3.23	8.2
	2A	48000	200000	50	62	260	99.87	1.17	
	1B	64000	270000	55	16	66	99.98	0.33	
	2B	64000	270000	44	210	870	99.68	3.44	

TABLE 2
TVH DESTRUCTION EFFICIENCY
SUMMARY OF VR SYSTEMS MODEL V4 ICE
FULL-SCALE OPERATION AT SITE ST-12
WILLIAMS AFB, ARIZONA

Date Sampled	Engine No.	Influent TVH[a] Concentration (ppmv)[b]	Influent TVH[a] Concentration (ug/L)[c]	Flow Rate (scfm)[d]	Effluent TVH Concentration (ppmv)	Effluent TVH Concentration (ug/L)	Destruction Efficiency (Percent)	Total Daily TVH Emissions (Pounds/day)	Total Daily TVH Emissions[e] (Pounds/day)
11/7/1997[f]	1A	24,000	100000	38	56	230	99.77	0.79	1.6
	2A	24,000	100000	38	12	50	99.95	0.17	
	1B	39,000	160000	52	7.7	32	99.98	0.15	
	2B	39,000	160000	53	25	100	99.94	0.48	
11/24/97	1A	33,000	140000	60.8	180	750	99.46	4.10	5.6
	2A	33,000	140000	58.1	22	91	99.94	0.48	
	1B	34,000	140000	51	2.4	10	99.99	0.05	
	2B	34,000	140000	52	54	220	99.84	1.03	

a/ TVH = total volatile hydrocarbon.
b/ ppmv = parts per million by volume, as determned by the analytical laboratory.
c/ ug/L = micrograms per liter, as determined by the analytical laboratory.
d/ scfm = standard cubic feet per minute.
e/ Combined total for Engine No. 1 and 2 of V4A and Engine No. 1 and 2 of V4B when appropriate.
f/ Systems unilaterally transferred to Geo/Resource Consultants, Inc. on October 3, 1997.

APPENDIX C

VAPOR TREATMENT TECHNOLOGY COST COMPARISON

APPENDIX C

VAPOR TREATMENT TECHNOLOGY COST COMPARISON ASSUMPTIONS

1. Constant influent flow-rate from the vent well at 100 scfm.

2. Constant influent vapor concentrations (in TVH).

3. Well head vacuum requirements are approximately 100-inches of water.

4. Influent oxygen soil gas concentrations are greater than 15-percent and carbon dioxide concentrations are less than 2-percent.

5. Extraction blower/SVE system costs include the cost of the blower only plus $10,000 for additional controls, etc. The capital costs of the TOX units include a combustion air blower for the additional flow required. The CATOX blower costs include the size of blower required to achieve required flow rate and 100 inches of vacuum.

6. Design/labor/installation costs are estimated and assumed the same for each technology.

7. Electrical installation costs are estimated and assumed the same for each technology requiring electricity.

8. Maintenance/monitoring costs are estimated and assumed the same for each technology.

9. Analytical costs are estimated and assumed the same for each technology.

10. Auxiliary fuel usage for ICE unit are estimated based on VRS literature.

11. Auxiliary fuel usage for the TOX and CATOX are estimated by the vendor and include 50-percent heat recovery.

12. The BTU value of the influent vapor stream is estimated at 20,000 BTU/lb TVH removed for all technologies.

13. Auxiliary fuel costs are based on assuming 91,500 BTUs/gal propane at $1.07/gal.

14. Electrical availability is assumed to be 230V, 3-phase power. Cost estimates are based on the following formula:

    (Full Load Amperage Requirements) x (230V) x (1.73 [efficiency factor for 3-phase power]) = Watts

    Watts is converted to KW and multiplied by $0.08/KWH, multiplied by 24 hours/day to get cost per day.

15. Carbon usage rates estimated by the vendor are based on assuming TVH is similar to cyclohexane adsorption properties, 75°F gas temperature and 50-percent relative humidity.

16. Carbon costs are estimated at $2/pound which assumes non-hazardous disposal or regeneration.

APPENDIX C (see assumptions)
COST COMPARISON - 1,000 PPMV TVH
ICE DEMONSTRATION
COMPREHENSIVE TECHNICAL REPORT

System	Internal Combustion Engine	Thermal Oxidation	Catalytic Oxidation	Granular Activated Carbon
Capital:				
Supplier	RSI International	EProducts, Inc.	Catalytic Combustion	EnviroSupply, Inc.
Model No.	Generation II Model V3	HFH-100	SRCO-1G	4-VF-2000 Cannisters
Treatment Unit	$56,000	$47,000	$33,495	$21,600
Total System Flow-Rate (cfm)	100	102	100	100
Extraction Blower/SVE System	-	$13,800	$13,800	$13,800
Design/Labor/Installation	$30,000	$30,000	$30,000	$30,000
Electrical Installation	-	$5,000	$5,000	$5,000
Total Capital Costs =	$86,100	$95,902	$82,395	$70,500
Operating Costs (per day):				
Maintenance/Monitoring	$50	$50	$50	$50
Analytical	$45	$45	$45	$45
Auxillary Fuel Usage (BTU/day)	5,112,000	3,030,000	309,000	0
Auxilliary Fuel	$60	$35	$4	$0
Extraction Blower Power Requirements (HP)	0.0	8.0	7.5	7.5
Electricity	$0	$19	$18	$18
Carbon	-	-	-	$388
Total Operating Costs (per day)=	$155	$150	$117	$501
Total Costs (3-year duration)=	$255,584	$259,728	$210,415	$619,424
Total Cost Per Day (3-year duration)=	$233	$237	$192	$566
Total Pounds TVH Removed (3-years)=	40,811	40,811	40,811	40,811
Cost Per Pound TVH Removed=	$6.26	$6.36	$5.16	$15.18

APPENDIX C (see assumptions)
COST COMPARISON - 5,000 PPMV TVH
ICE DEMONSTRATION
COMPREHENSIVE TECHNICAL REPORT

System	Internal Combustion Engine	Thermal Oxidation	Catalytic Oxidation	Granular Activated Carbon
Capital:				
Supplier	RSI International	EProducts, Inc.	Catalytic Combustion	EnviroSupply, Inc.
Model No.	Generation II Model V3	HFH-200	SRCO-2G	4-VF-2000 Cannisters
Treatment Unit	$56,000	$50,000	$35,145	$21,600
Total System Flow-Rate (cfm)	100	108	200	100
Extraction Blower/SVE System	-	$13,800	$16,000	$13,800
Design/Labor/Installation	$30,000	$30,000	$30,000	$30,000
Electrical Installation	-	$5,000	$5,000	$5,000
Total Capital Costs =	$86,100	$98,908	$86,345	$70,500
Operating Costs (per day):				
Maintenance/Monitoring	$50	$50	$50	$50
Analytical	$45	$45	$45	$45
Auxillary Fuel Usage (BTU/day)	2,140,000	550,000	122,000	0
Auxilliary Fuel	$25	$6	$1	$0
Extraction Blower Power Requirements (HP)	0.0	8.0	15.0	7.5
Electricity	$0	$19	$34	$18
Carbon	$0	$0	$0	$1,546
Total Operating Costs (per day)=	$120	$121	$130	$1,659
Total Costs (3-year duration)=	$217,528	$230,978	$228,724	$1,887,105
Total Cost Per Day (3-year duration)=	$199	$211	$209	$1,723
Total Pounds TVH Removed (3-years)=	204,056	204,056	204,056	204,056
Cost Per Pound TVH Removed=	$1.07	$1.13	$1.12	$9.25

APPENDIX C (see assumptions)
COST COMPARISON -10,000 PPMV TVH
ICE DEMONSTRATION
COMPREHENSIVE TECHNICAL REPORT

System	Internal Combustion Engine	Thermal Oxidation	Catalytic Oxidation	Granular Activated Carbon
Capital:				
Supplier	RSI International	EProducts, Inc.	Catalytic Combustion	EnviroSupply, Inc.
Model No.	Generation II Model V3	HFH-500	SRCO-4G	6-VF-2000 Cannisters
Treatment Unit	$56,000	$59,500	$45,980	$32,400
Total System Flow-Rate (cfm)	100	112	450	100
Extraction Blower/SVE System	-	$13,800	$19,000	$13,800
Design/Labor/Installation	$30,000	$30,000	$30,000	$30,000
Electrical Installation	-	$5,000	$5,000	$5,000
Total Capital Costs =	$86,100	$108,412	$100,430	$81,300
Operating Costs (per day):				
Maintenance/Monitoring	$50	$50	$50	$50
Analytical	$45	$45	$45	$45
Auxillary Fuel Usage (BTU/day)	0	550,000	274,000	0
Auxilliary Fuel	$0	$6	$3	$0
Extraction Blower Power Requirements (HP)	0.0	8.0	30.0	7.5
Electricity	$0	$19	$66	$18
Carbon	$0	$0	$0	$2,834
Total Operating Costs (per day)=	$95	$121	$164	$2,947
Total Costs (3-year duration)=	$190,125	$240,482	$279,905	$3,308,594
Total Cost Per Day (3-year duration)=	$174	$220	$256	$3,022
Total Pounds TVH Removed (3-years)=	408,113	408,113	408,113	408,113
Cost Per Pound TVH Removed=	$0.47	$0.59	$0.69	$8.11

APPENDIX C (see assumptions)
COST COMPARISON - 20,000 PPMV TVH
ICE DEMONSTRATION
COMPREHENSIVE TECHNICAL REPORT

System	Internal Combustion Engine	Thermal Oxidation	Catalytic Oxidation	Granular Activated Carbon
Capital:				
Supplier	RSI International	EProducts, Inc.	Catalytic Combustion	EnviroSupply, Inc.
Model No.	Generation II Model V3	HFH-500	SRCO-12G	6-VF-2000 Cannisters
Treatment Unit	$56,000	$59,500	$70,085	$32,400
Total System Flow-Rate (cfm)	100	309	910	100
Extraction Blower/SVE System	-	$13,800	$22,100	$13,800
Design/Labor/Installation	$30,000	$30,000	$30,000	$30,000
Electrical Installation	-	$5,000	$5,000	$5,000
Total Capital Costs =	$86,100	$108,609	$128,095	$81,300
Operating Costs (per day):				
Maintenance/Monitoring	$50	$50	$50	$50
Analytical	$45	$45	$45	$45
Auxillary Fuel Usage (BTU/day)	0	550,000	555,000	0
Auxilliary Fuel	$0	$6	$6	$0
Extraction Blower Power Requirements (HP)	0.0	8.5	60.0	7.5
Electricity	$0	$20	$130	$18
Carbon	$0	$0	$0	$5,224
Total Operating Costs (per day)=	$95	$122	$231	$5,337
Total Costs (3-year duration)=	$190,125	$241,971	$381,434	$5,925,644
Total Cost Per Day (3-year duration)=	$174	$221	$348	$5,412
Total Pounds TVH Removed (3-years)=	816,226	816,226	816,226	816,226
Cost Per Pound TVH Removed=	$0.23	$0.30	$0.47	$7.26

APPENDIX C (see assumptions)
COST COMPARISON - 40,000 PPMV TVH
ICE DEMONSTRATION
COMPREHENSIVE TECHNICAL REPORT

System	Internal Combustion Engine	Thermal Oxidation	Catalytic Oxidation	Granular Activated Carbon
Capital:				
Supplier	RSI International	EProducts, Inc.	Catalytic Combustion	EnviroSupply, Inc.
Model No.	Generation II Model V4	HFH-1000	SRCO-20G	8-VF-2000 Cannisters
Treatment Unit	$91,000	$81,000	$88,430	$43,200
Total System Flow-Rate (cfm)	100	716	1,820	100
Extraction Blower/SVE System	-	$13,800	$34,200	$13,800
Design/Labor/Installation	$30,000	$30,000	$30,000	$30,000
Electrical Installation	-	$5,000	$5,000	$5,000
Total Capital Costs =	$121,100	$130,516	$159,450	$92,100
Operating Costs (per day):				
Maintenance/Monitoring	$50	$50	$50	$50
Analytical	$45	$45	$45	$45
Auxillary Fuel Usage (BTU/day)	0	960,000	1,110,000	0
Auxilliary Fuel	$0	$11	$13	$0
Extraction Blower Power Requirements (HP)	0.0	8.5	120.0	7.5
Electricity	$0	$56	$260	$18
Carbon	$0	$0	$0	$9,666
Total Operating Costs (per day)=	$95	$162	$368	$9,779
Total Costs (3-year duration)=	$225,125	$308,285	$562,104	$10,800,434
Total Cost Per Day (3-year duration)=	$206	$282	$513	$9,863
Total Pounds TVH Removed (3-years)=	1,632,452	1,632,452	1,632,452	1,632,452
Cost Per Pound TVH Removed=	$0.14	$0.19	$0.34	$6.62