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THE INTERNAL COMBUSTION ENGINE USED AS A LOW-COST SOIL VAPOR TREATMENT TECHNOLOGY

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The information presented herein is intended for discussion at the "Remediation Technologies Symposium, October 15-17, 2003, Banff, Alberta, Canada, pursuant to a request from an ESAA member, as the environmental remediation and treatment methodologies which are described in this text are not widely known nor currently practiced throughout Canada.]

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THE INTERNAL COMBUSTION ENGINE USED AS A LOW-COST SOIL VAPOR EXTRACTION AND TREATMENT TECHNOLOGY

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ABSTRACT

A low-cost and innovative soil vapor extraction (SVE) technology using a modified internal combustion engine (ICE) to extract and destroy nonchlorinated fuel hydrocarbons was demonstrated at multiple United States Air Force (USAF) installation sites. The ICE SVE systems used during the demonstrations were equipped with advanced emissions controls, and manufactured by VR Systems, formerly of Anaheim, California. Remediation Service, Int'l (RSI) of Ventura, California, currently manufactures the ICE systems being used by the USAF. A 3-year, multi-site demonstration project using the ICE SVE technology was conducted by the USAF Center for Environmental Excellence to compare cost and performance data from the ICE SVE system to traditional fuel hydrocarbon vapor treatment technologies.

This paper presents a description of the ICE SVE technology, and case study results for three sites in Arizona and one site in the District of Columbia, where remediation of the vadose zone (unsaturated) soils was required. The destruction/removal efficiency (DRE) of the ICE SVE system averaged greater than 99.9 percent. Results of the full-scale ICE SVE system operated at Davis-Monthan Air Force Base (AFB) in Arizona, removed more than 700,000 pounds of total volatile hydrocarbons (TVH) during the initial 21 months of operation at an average cost of $0.14 per pound. The ICE SVE system that operated at Luke AFB, Arizona removed 169,000 pounds of TVH during the initial 9 months of operation at an average cost of $0.23 per pound. At Bolling AFB, Washington D.C., the ICE SVE system removed over 47,000 pounds of TVH during the initial 7 months of operation at an average cost of $0.54 per pound. At Williams AFB, Arizona, the ICE SVE system removed over 200,000 pounds of TVH during the initial 4 months of operation at an average cost of $0.06 per pound. The higher cost per pound represent lower influent TVH concentrations and increased use of supplemental fuel as a result of decreasing extracted hydrocarbon concentrations over the study period. The TVH removal rates ranged from 378 to 3,417 pounds per day at a weighted average influent TVH vapor concentration ranging from 10,000 to 90,000 parts per million, volume per volume (ppmv).

1. INTRODUCTION

A low-cost and innovative soil vapor extraction (SVE) system using modified internal combustion engines (ICEs) to extract and destroy fuel hydrocarbons from vadose zone soils was successfully demonstrated at multiple United States Air Force (USAF) sites. The ICE systems with advanced emissions controls were manufactured by VR Systems, Inc., formerly of Anaheim, California. Remediation Service, Int'l (RSI) of Ventura, CA currently manufactures the ICE systems being used by the USAF. The sites were contaminated with either JP-4 jet fuel or gasoline constituents, and are located in Arizona and the District of Columbia. Parsons Engineering Science, Inc. (Parsons Es), under contract with the Air Force Center for Environmental Excellence (AFCEE), collected cost and performance data to compare the ICE technology to traditional vapor treatment technologies and provided recommendations for full-scale treatment system designs, including projected operating and capital costs.

This paper presents a description of the ICE technology, a history and description of four sites that are successfully being remediated using the ICE technology, performance data for the ICE systems, and a comparison of the performance and cost of each system.

2. DESCRIPTION OF ICE TECHNOLOGY

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. Vapors are extracted from the subsurface using 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. The ICE exhaust gases pass through a standard catalytic converter for complete oxidation before being discharged to the atmosphere. VR Systems, Inc. manufactured vapor recovery systems in three sizes: the single-engine V2C and V3, and the dual-engine V4. The performance specifications for the three VR Systems units, are provided in Table 1. A schematic diagram of a Model V4 is provided as Figure 1.

TABLE 1. PERFORMANCE SPECIFICATIONS
FOR VR SYSTEMS MODELS V2C, V3, AND V4

Feature	V2C	V3	V4
Max. Hydrocarbon Destruction Rate	12 lbs/hr	35 lbs/hr	70 lbs/hr
Destruction Efficiency for TVH/BTEX [a/]	>99%	>99%	>99%
Engine Size in Cubic Inch Displacement	140	460	920 (2 x 460)
Max. Flow Rate in Cubic Feet/Min	25	70	140
Max. Vacuum in Inches of Mercury/Approx. Inches of Water	20/270	20/270	20/270
Required Soil Gas Hydrocarbon Concentration (ppmv as gasoline)[b/]	30,000	30,000	30,000

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

b/ Per vendor specifications, the recommended influent vapor concentration in parts per million,volume per volume (ppmv) required to sustain >99% destruction efficiency without the addition of supplemental fuel (e.g., natural gas) to maintain efficient engine operation.

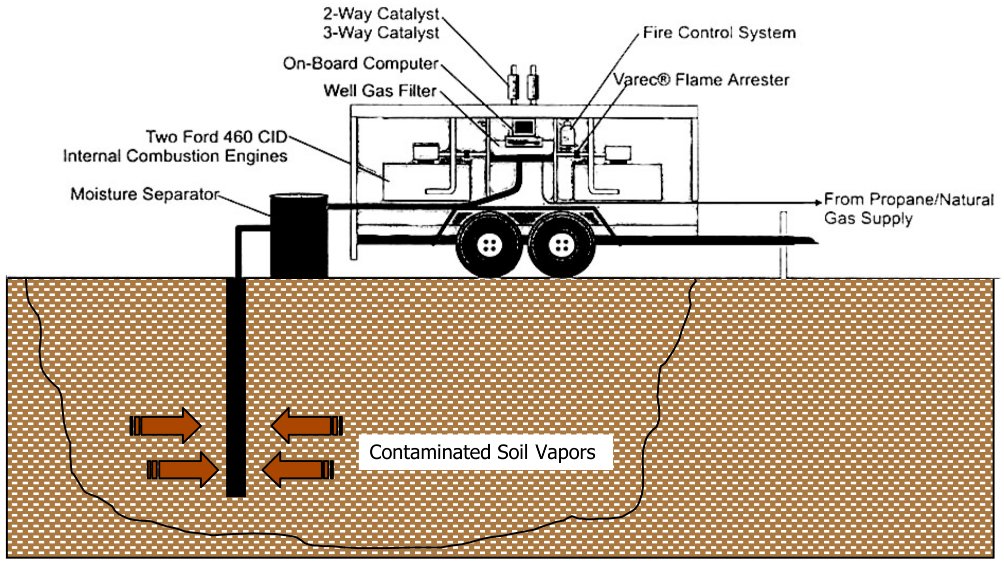

FIGURE 1.

The engines in the VR Systems/RSI units are modified Ford® gasoline-powered engines. Each ICE/SVE system is equipped with an on-board computer system that provides the necessary monitoring for automated engine control. The data collection/reporting system monitors the engine's oil pressure, coolant temperature, exhaust temperature, exhaust percent oxygen, and engine speed and performance (extraction flow rate, inches of vacuum, supplemental fuel consumption, air/fuel ratio, and engine hours).

External electrical power is not required for these systems, because of the 12-volt, closed loop battery-powered technology. The ICE units are equipped with a phone modem for remote monitoring and to make necessary adjustments to the engine's speed, well vacuum, and extraction flow rate to optimize engine performance and minimize supplemental fuel consumption. The remote monitoring capability allows for adjustments to be made while the unit is operating, and/or for the ICE unit to be shut down or started remotely.

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. Soil vapor TVH concentrations in excess of 30,000 to 40,000 parts per million, volume per volume (ppmv) are [depending on the British thermal unit (BTU) value of the influent soil vapors] generally sufficient to sustain the engine speed without the need for supplemental fuel. The on-board computer regulates the fuel requirements of the engine through a patented, oxygen sensor control loop. The computer controlled system makes adjustments automatically in the supplemental fuel flow to compensate for the changing influent hydrocarbon concentrations, and to maintain the stoichiometric air-to-fuel ratio. By maintaining the proper air/fuel ratio, the TVH vapor destruction/removal efficiency (DRE) typically exceeds 99 percent, usually eliminating the need for air emissions permitting.

The regulatory acceptance of this technology for treatment of hydrocarbon vapors in soil gas has been widespread. The ICE technology has been approved for air treatment in the District of Columbia, Arizona, California, and 26 other states.

3. SITE HISTORIES AND DESCRIPTIONS

The following sections provide an overview of the history, site description, and ICE operation for each of the four demonstration sites.

2.1 Davis-Monthan AFB, Arizona

History

Site 35 is a jet fuel pumphouse consisting of nine 40,000-gallon and one 50,000-gallon underground storage tanks (USTs) previously containing JP-4 jet fuel, and an underground piping system that conveys the fuel to a fueling island adjacent to the USTs. In 1985, a leak was detected in an underground fuel line, and an estimated 1.7 million cubic feet of soil was found to be contaminated. From 1989 to 1993, remedial investigations and feasibility studies were completed under the U.S. Air Force Installation Restoration Program (IRP). The remedial alternative selected for the site included SVE followed by air injection bioventing.

Site Description

Based on previous site investigations, soil contamination extended from near the ground surface to a depth of approximately 260 feet below ground surface (bgs). A maximum total fuel hydrocarbon concentration of 320,000 milligrams per kilogram (mg/kg) and a maximum soil gas TVH concentration of 140,000 milligrams per liter (mg/L) were measured at the site. Groundwater, which occured at approximately 300 feet below ground surface at the time of the investigatioin, had not been impacted by the jet fuel release.

ICE Operations

In 1993, a pilot-scale SVE test was performed, and based on the results, a full-scale SVE system was designed that consisted of a series of 28 vapor extraction wells (VWs), a blower system, a moisture separator, thermal oxidizer and catalytic oxidizer air treatment systems, a propane tank, and associated piping and controls. The system was designed to operate at a maximum flow rate of 3,000 standard cubic feet per minute (scfm) with an operation period of 4 to 6 years in the SVE mode, then 2 years in a bioventing (low-flow air injection) mode. The construction/installation cost was estimated to be $1.72 million, with an operating cost of $23,400 per month for 4 to 6 years, for a total SVE remediation cost of between $2.84 and $3.40 million (excluding the 2-year period of bioventing treatment).

Because of the prohibitively high cost for full-scale SVE treatment using the proposed thermal/catalytic oxidation technology, AFCEE contracted with Parsons ES to review alternative treatment technologies, including bioventing and the use of an ICE system for vapor extraction and treatment. Results from a 1-year bioventing pilot test indicated that biological degradation rates for fuel residuals were too slow (10 to 50 mg/kg/yr) to remediate the highly contaminated soils.[1] Following the bioventing pilot test, the ICE/SVE technology was evaluated to determine the technical feasibility and potential cost savings of this technology. A redesigned, full-scale SVE system using an ICE unit was installed in July and

August 1995.[1] The system included the installation of six VWs completed at varying depths to focus vapor extraction in the most contaminated soil intervals, and seven vapor monitoring points (VMPs) at various locations across the site, to monitor remediation progress. A remotely monitored, automated valving and flow rate control system was fabricated for this site so that the vapor flow from individual extraction wells could be remotely blended to provide optimum engine performance and mass TVH removal with a minimum of supplemental fuel use.

Start-up of a Model V4 ICE system occurred in September 1995, and the system operated through October 1996. On October 31, 1996, approximately 450 days from start-up, the decreased extracted TVH concentrations and the resulting increased supplemental fuel use led to a decision to replace the dual-engine Model V4 ICE with a single-engine Model V3 ICE system, which currently is operating at the site.

2.2 Bolling AFB, Washington, DC

History

The former Car Care Center at Building 41 served as an auto repair and fueling facility for Bolling AFB from 1936 through 1982. During this period, the station used several USTs for storage of gasoline and waste oils. The waste oil tanks were abandoned in place in the early 1980s, and removed in 1995. Site personnel have indicated that spills from, and overfilling of, the former USTs located north and west of Bldg. 41 were the most likely sources of the subsurface fuel contamination documented at the site.

Site Description

The maximum detected soil TVH concentration was 16,000 mg/kg in a soil sample collected at 20 to 21 feet bgs. The maximum detected soil total benzene, toluene, ethylbenzene and xylenes (BTEX) concentration was 670 mg/kg, in a soil sample from 18 to 20 feet bgs. The maximum TVH concentration detected in soil gas was 580,000 ppmv in a sample collected from the 9.5- to 10-foot bgs interval during installation of two vapor extraction/air injection VWs and two VMPs that were installed in September 1996 to support the ICE demonstration at this site. Groundwater at the former Car Care Center was encountered at depths of 18 to 20 feet bgs. Groundwater contamination consists of mobile light nonaqueous-phase liquid (LNAPL) and dissolved fuel contamination. Mobile LNAPL was historically observed in site monitoring wells at a maximum measured thickness of 0.81 foot; however, attempts to recover the mobile LNAPL have not been productive, and only approximately 500 gallons of mobile LNAPL had been recovered.

ICE Operations

A demonstration to test the effectiveness of the ICE/SVE system to extract and treat volatile fuel hydrocarbons began in November 1996. Initially, a dual-engine Model V4 ICE system began extracting vapors from two VWs, and operated at the site from November 13, 1996 until January 16, 1997. To reduce operating costs, once TVH concentrations and mass removal rates were reduced, the Model V4 ICE system was replaced with a single engine Model V3, until site closure could be proposed.

2.3 Luke AFB, Arizona

History

Site SS-42 is located at the bulk fuels storage yard at Luke AFB in Arizona. A former oil/water separator and associated 1,000-gallon UST system that received condensate from two adjacent aboveground storage tanks (ASTs) were previously used at this site. The oil/water separator system and ASTs were installed in 1954. Prior to 1960, aviation gas and JP-4 were delivered to the bulk fuels storage area by rail car and off-loaded through a hydrant system to the ASTs. From 1960 to 1993, the fuel delivery system consisted of a combination of aboveground and underground distribution pipelines. In 1992, a fuel release from the oil/water separator system was detected. In September 1993, the oil/water separator and associated 1,000-gallon UST were removed.[2]

Site Description

In May 1995, three air injection VWs and four multi-depth VMPs were installed and sampled near the former oil/water separator as part of a bioventing treatability study.[2]
Total petroleum hydrocarbon (TPH) results from soil sampling ranged from 4.3 mg/kg in a sample from 150 feet bgs to a maximum of 12,000 mg/kg in a sample from 70 feet bgs. The maximum detected soil BTEX concentration was 414 mg/kg in a soil sample from 70 feet bgs. A sample at 200 feet bgs had a TPH concentration of 5.2 mg/kg, and no detected BTEX. At the time of the investigation, groundwater occurred beneath the site at a depth of approximately 320 feet bgs. Groundwater sampling data indicated that the groundwater beneath the site had not been impacted by the release of petroleum hydrocarbons.[2]

ICE Operations

A demonstration of the Model V3 ICE/SVE system to extract and treat fuel hydrocarbons began at this site on August 6, 1996. The system was shut down from November 21, 1996 until January 16, 1997 because chlorinated solvents were thought to be present in the soil gas. The ICE system was restarted on January 16, 1997, and operated until site closure activities commenced.

2.4 Williams AFB, Arizona

History

Site ST-12 was a former liquid fuel storage area located at the former Williams AFB in Arizona. The site had been impacted primarily by releases of JP-4 and 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 may have occurred since Williams AFB initiated operations in 1942.

Site Description

During a 1993 deep soils investigation, 384 soil samples were collected from 16 soil boreholes. TPH as JP-4 was detected in 227 of the 384 samples 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.

Depth to groundwater has steadily decreased since 1989, due to the decrease in agricultural use of the surrounding area, with the depth to water at 200 to 210 feet bgs during the ICE demonstration period. Groundwater contamination consisted of mobile LNAPL and dissolved fuel contamination. Mobile LNAPL thickness data had been collected from site wells since 1990 with a maximum measured thickness of 15 feet. Volume estimates of LNAPL in the subsurface at Site ST-12 have ranged from 0.65 to 1.4 million gallons.[3]

ICE Operations

A demonstration to test the effectiveness of the ICE/SVE system to extract and treat volatile fuel hydrocarbons from the unsaturated soils began in February 1997. One dual-phase extraction (DPE) well and four VMPs were installed in September 1996. Two dual-engine Model V4 ICE systems operated at the site during the demonstration period. The first ICE system (V4A) was started on February 6, 1997, and the second system (V4B) was started in April 1997.

4. FIELD DEMONSTRATION RESULTS

During operation of the ICE systems at each site, monthly sampling events, that included collecting influent and effluent samples from the ICE systems, were conducted by Parsons ES to evaluate the performance of each system. The influent and effluent vapor streams of the ICE systems were sampled using 1-liter SUMMA® canisters, and samples were analyzed by Air Toxics, Ltd. of Folsom, California for TVH and BTEX using USEPA Method TO-3. This section provides a summary of TVH mass removal rates and costs, TVH DREs, and reliability and maintainability of the ICE systems.

3.1 Hydrocarbon Removal Rates

The total pounds of TVH removed for each site are presented in Figure 2 as a function of total days from startup, and the TVH removal rate (pounds per day) and average influent TVH concentration are presented in Table 2.

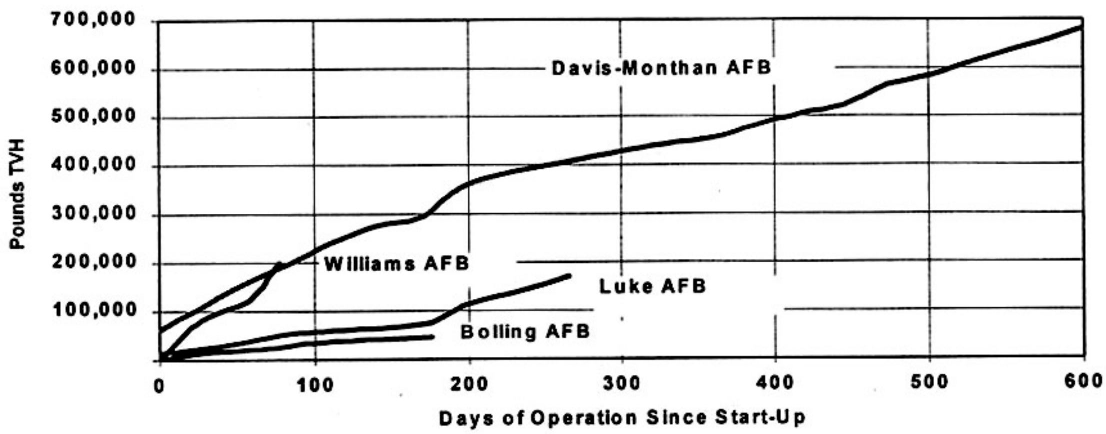

FIGURE 2.

TABLE 2. AVERAGE INFLUENT TVH CONCENTRATIONS AND AVERAGE DAILY TVH REMOVAL RATES

Site Name	Weighted Average Influent TVH Concentration (ppmv)	Average Daily TVH Removal Rate (pounds/day)
Davis-Monthan AFB, AZ	24,000	1,249
Bolling AFB, DC	8,800	321
Luke AFB, AZ	21,000	940
Williams AFB, AZ	90,000	3,417

The total pounds of TVH removed during the demonstration period ranged from 47,550 pounds at Bolling AFB (378 pounds per day) during the initial 148.3 days of actual operation, to over 700,000 pounds at Davis-Monthan AFB (1,249 pounds per day) during the initial 561 days of actual operation. Site ST-12 at Williams AFB had the highest average TVH soil gas concentrations (90,000 ppmv weighted average), which was capable of supporting two Model V4 ICE units with less than 10 percent supplemental fuel required to maintain smooth operation of the engines. The average TVH removal rate at Site ST-12 was 3,417 pounds per day. Approximately 169,000 pounds of TVH was removed at Site SS-42, Luke AFB, during the initial 179.6 days of actual operation, with an average TVH removal rate of 940 pounds per day.

3.2 Hydrocarbon Removal Costs

The cost per pound of TVH removed was estimated based on a prorated 30-day month with the capital cost of each ICE unit averaged over an estimated 3-year equipment life. 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 observed during operation. For example, the capital costs for the Model V3 ICE units operated at Bolling AFB and Luke AFB were $60,170. The capital costs for the two Model V4 ICE units operated at Williams AFB were $85,000 (ICE unit V4A) (includes engine rebuild), and

$75,954 (ICE unit V4B). The V4A unit at Williams AFB was also used during the initial 450 days of the ICE demonstration at Davis-Monthan AFB.

The actual cost per pound of TVH removed and treated by the ICE systems ranged from $0.04 to $0.93 per pound (Figure 3). The average cost per pound of TVH removed ranged from $0.06 per pound at Site ST-12, Williams AFB to $0.54 per pound at the former Car Care Center, Bolling AFB. The higher costs per pound represent lower influent TVH concentrations and increased use of supplemental fuel as a result of decreasing extracted hydrocarbon concentrations. Where appropriate, the ICE systems were optimized to increase influent TVH concentrations and mass removal rates, and decrease supplemental fuel use. For example, at Davis-Monthan AFB on October 31, 1996, approximately 450 days after start-up, and at Bolling AFB on January 21, 1997, approximately 60 days after startup, the decreased extracted TVH concentrations and the resulting increased supplemental fuel use led to decisions to replace the dual-engine Model V4 ICE units with a single-engine Model V3 ICE system at each of these sites.

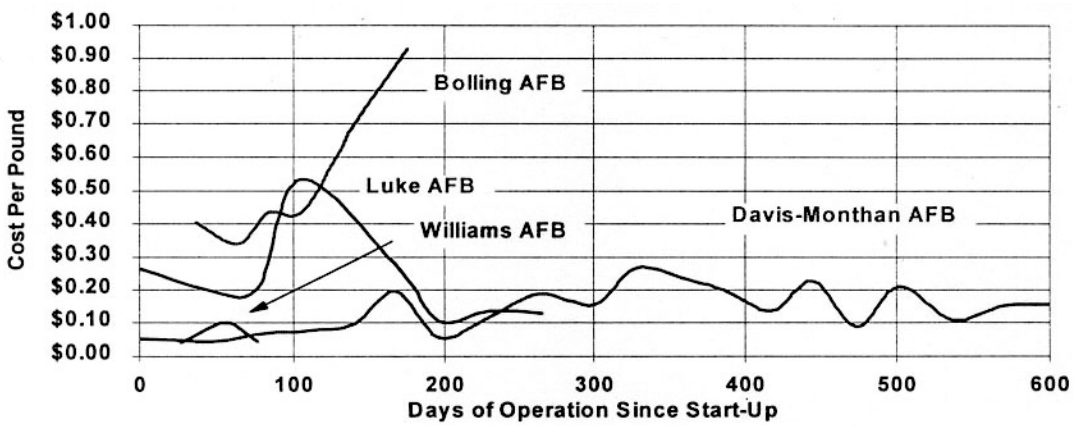

FIGURE 3.

3.3 Hydrocarbon Destruction/Removal Efficiencies

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

$$DRE = \frac{\text{Concentration}_{\text{Influent}} - \text{Concentration}_{\text{Effluent}}}{\text{Concentration}_{\text{Influent}}} \text{ X } 100$$

The influent and effluent vapor streams of the ICE systems were sampled using 1-liter SUMMA™ canisters, and samples were analyzed by Air Toxics, Ltd. of Folsom California for TVH and BTEX using USEPA Method TO-3. Each of the ICE systems averaged a 99.8 percent DRE of the extracted TVH vapor stream.

The ICE/SVE systems used at each site met the air emission standards set for the respective regulating authorities, with the exception of one sampling event at Bolling AFB which was due to an oxygen sensor that required replacement. The average daily TVH air emissions observed for each of the ICE units are shown in Table 3, and the total daily TVH emissions are shown in Figure 4.

TABLE 3. DAILY TVH EMISSIONS

Site Name	Average Daily TVH Emissions (pounds/day)	Air Emissions Standards (pounds/day)
Davis-Monthan AFB, AZ	0.70	2.4 (Pima County, AZ)
Bolling AFB, DC	0.84	1.0 (DC Air Resources Div.)
Luke AFB, AZ	0.22	3.0 (Maricopa County)
Williams AFB, AZ	1.28	3.0 (Maricopa County)

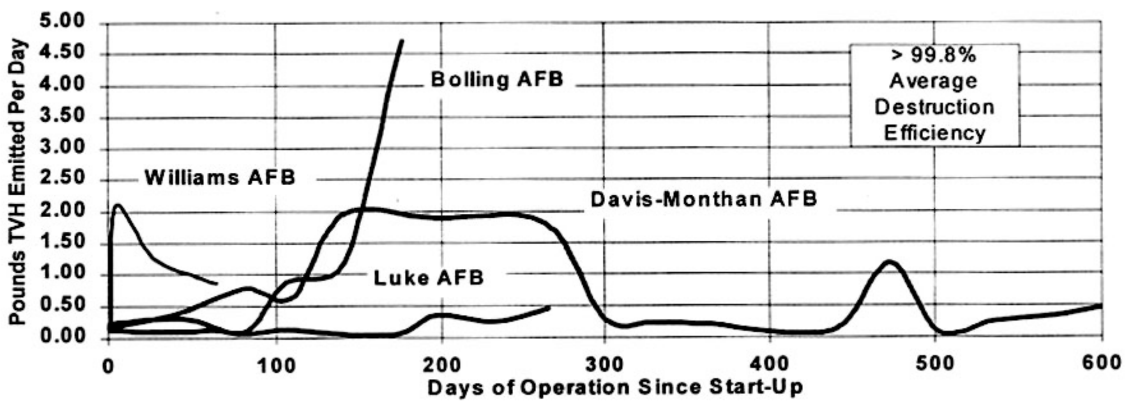

FIGURE 4.

3.4 Reliability and Maintainability

The ICE systems proved to be a reliable SVE technology. The operational efficiency as a percent of total possible engine hours is presented for each site in Table 4.

TABLE 4. SYSTEM RELIABILITY

Site Name	Model ICE System(s) Operating at Site	Operational Efficiency (Percent)
Davis-Monthan AFB, AZ	V4, V3	87
Bolling AFB, DC	V4, V3	84
Luke AFB, AZ	V3	86
Williams AFB, AZ	2 V4s	82

The primary ICE system components with a potential for mechanical problems include the alternator/battery (especially in hot climates), carburetor, and oxygen sensor. Long-term maintenance issues include an engine rebuild typically being required following 10,000 to 15,000 engine hours. The cost of the engine rebuild is approximately $10,000. The catalytic converters require replacement after approximately every 4,000 engine hours at an approximate cost of $800 each.

Regular monthly maintenance for the ICE systems requires approximately 8 hours per month, and includes checking/draining the moisture separator of condensate, changing the engine oil and oil filter, replacing the carburetor air filter and spark plugs, and checking engine coolant level, battery/alternator charging system, belts and water pump. Approximately 4 to 8 additional hours per month should be anticipated for unexpected shutdowns.

4. CONCLUSIONS

The DRE evaluation showed that each of the ICE units were 99.9 percent efficient at removing TVH from the extracted soil vapors. The ICE/SVE systems used at each site met the air emission standards for each regulating authority. The actual cost per pound of TVH removed and treated by the ICE systems ranged from $0.04 to $0.93 per pound. The average cost per pound of TVH removed ranged from $0.06 per pound at Site ST-12, Williams AFB to $0.54 per pound at the former Car Care Center, Bolling AFB. The higher costs per pound represent lower influent TVH concentrations and increased use of supplemental fuel as a result of decreasing extracted hydrocarbon concentrations. The TVH removal rate ranged from 321 to 3,417 pounds per day, with a weighted average influent TVH concentration ranging from 8,800 to 90,000 ppmv.

The ICE systems proved to be a reliable SVE and vapor treatment technology. The operational efficiency (including downtime for system service) as a percent of total possible engine hours for each of the four Air Force demonstration sites ranged from 82 to 87 percent. Regular monthly maintenance for the ICE systems requires approximately 8 hours per month, and approximately 4 to 8 additional hours per month should be anticipated for unexpected shutdowns.

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