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Solar-Powered Systems for Environmental Remediation

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Solar-powered Systems for Environmental Remediation

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Abstract

This study assesses the market and specific applications for solar-powered environmental remediation. To assist in the assessment, system specifications and a mathematical model of system performance and life-cycle cost were developed for the most promising markets and remediation technologies. An overview of existing remediation technologies, and an evaluation of the blower technology used to create the mathematical system model are provided. A review of the potential markets for environmental remediation showed that the single most promising target market is Department of Defense sites. Results indicate that solar-powered systems can compete most effectively with grid-connected systems for low-power applications in remote locations. However, the results indicated that for certain applications solar-powered systems could compete with grid-connected systems when grid extensions as short as 100 feet are required. These initial results are promising enough that field-testing of four types of solar-powered remediation systems is recommended. It is thought that successful field demonstrations would open additional markets in the private sector.

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Acknowledgments

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Acronyms and Abbreviations

AFCEE	Air Force Center for Environmental Excellence
BLM	Bureau of Land Management
BRAC	Base Realignment and Closure
CERCLA	Comprehensive Environmental Response Cleanup and Liabilities Act
cfd	cubic feet per day
cfm	cubic feet per minute
DOD	depth of discharge
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
GOCO	government-owned/contractor-operated
IT	International Technology Corporation
LNAPLs	lighter-than-water, nonaqueous-phase liquids
LUST*	leaking underground storage tanks
NASA	National Aeronautics and Space Administration
NELP	Navy Environmental Leadership Program
NOAA	National Oceanographic and Atmospheric Administration
NPL	National Priorities List
PES	Public Energy Systems
RCRA	Resource Conservation and Recovery Act
scfm	standard cubic feet per minute
SVE	soil vapor extraction
SVOCs	semivolatile organic compounds
UPS	uninterruptible power supply
USPC	AeroVironment, Inc. Universal Solar Pump Controller
UST	underground storage tanks
VOCs	volatile organic compounds

* Standard industry acronym

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Executive Summary

The objective of this study was to assess the market and specific applications for solar-powered remediation, and to develop design specifications to address the market. This study was a joint effort between AeroVironment Inc., a developer and manufacturer of power electronics for global markets including solar applications, and ATC-AVES, an environmental services company.

Concept System Definition

The solar-powered remediation concept involves using solar electric power to operate conventional remediation equipment. Figure 1 is an illustration of two types of solar-powered soil remediation venting systems. On the left is a system that operates on a diurnal cycle; that is, the power to the motor is equivalent to the energy available from the sun. Consequently, peak flow rates occur at mid-day and lower flow rates occur in the morning and evening hours. For continuous or variable-cycle operation, a larger solar array and battery energy storage can be used as shown on the right. For both types of systems, the process may be reversed (i.e., air can be blown into the ground) to accommodate the specific type of remediation required.

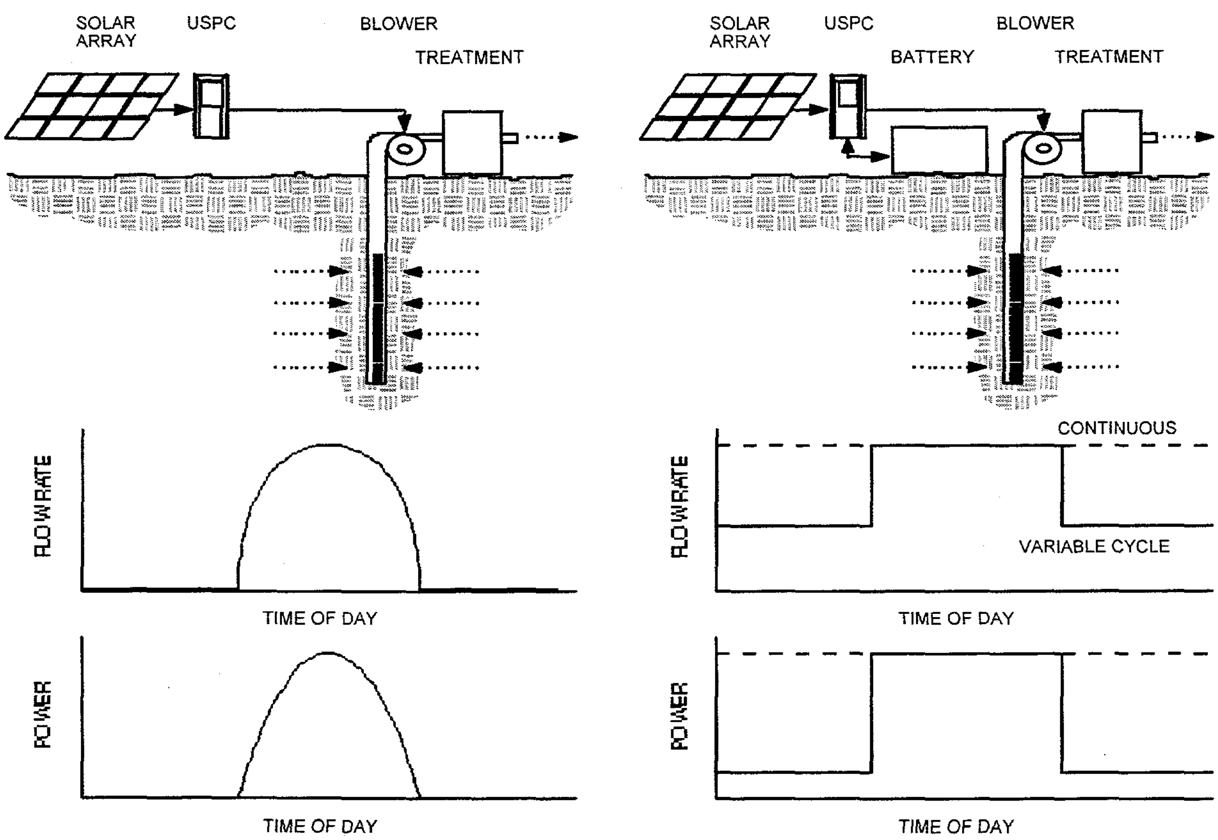

Figure 1. Illustrations of the solar-powered remediation concepts for diurnal (left) and both variable cycle and continuous operation (right).

Six systems, based on the recommended target systems identified in Section 1, were evaluated using a numerical simulation. Table 1 presents the relevant system parameters and summarizes the findings from this analysis.

Table 1. Summary of Solar-powered Remediation System Parameters, Performance, and Life-cycle Cost

	System					
	1 Diurnal	2 Variable Cycle	3 Continuous	4 Diurnal	5 Variable Cycle	6 Continuous
Blower Rating (HP)	1.1	1.1	1.1	2.5	2.5	2.5
Peak Load (W)	1,050	1,050	1,050	2,250	2,250	2,250
Solar Array Rating (W)	1,250	2,000	5,100	2,650	4,150	11,100
Power Electronics	UPSC-2000	UPSC-2000	UPSC-2000	UPSC-2000	UPSC-2000	UPSC-2000
Battery	-	G12V42AhSP	T105	-	T105	T105
Battery Pack Capacity (Wh)	-	13,104	33,852	-	33,852	67,704
Total Flow (cfd)	29,600	52,800	82,500	63,400	113,300	177,000
Initial System Price	$ 14,600	$ 25,600	$ 59,100	$ 28,600	$ 49,200	$ 124,900
Life Cycle Cost (10yr)	$ 14,600	$ 32,500	$ 64,300	$ 28,600	$ 54,600	$ 146,200

The following assumptions were used:

- The total solar resource is 6 kWh/m^2 for a 12-hour day.
- The blower parameters are taken from the manufacturer's rated flow at 40 in. H_2O and full speed.
- The power available from the solar array is the rated value at 1000 W/m^2 at a cost of $6.00/W.
- Lead-acid batteries were used with a maximum depth of discharge (DOD) of 20%.
- Labor costs for assembly are included.
- Total system costs are representative of wholesale costs plus typical commercial mark-up.

Target Remediation Technologies

Several remediation technologies were evaluated to select appropriate technologies for solar applications. The best fit can be characterized as those technologies that require low power (i.e., less than 3 hp) and do not require continuous operation to be effective. Bioventing, for example, is well suited to diurnal operation and many experts argue that cycling may actually be beneficial to the process. Because this technology relies on aerobic stimulation, the effectiveness of the process is most dependent on the zone of influence that is governed by wellhead pressure and peak flow rate, not by total volumetric flow rate. A diurnal system, capable of achieving the same peak flow rates and pressure for only a short time, would therefore be comparable to a conventional grid-connected system. The advantage of a diurnal system is that much less energy is required, which makes solar power a viable energy alternative. Table 2 summarizes the compatibility of each target remediation technology with the three solar-powered system concepts and the respective constraints for equivalency to a conventional system.

Table 2. Remediation Technology and Solar-powered System Compatibility Matrix

Technology	*Constraints*	*Equiv. Sys.*	*Diurnal*	*Variable*	*Continuous*	*Comments*
Soil Vapor Extraction	Min. Pres. Total Flow	Same Pump	Not a Fit	Good Fit*	Equivalent	Process dependent on minimum pressure for volitalization. Equivalent solar system needs to achieve same total flow.
Bioventing	Peak Pres. Peak Flow	Same Pump	Good Fit	Good Fit	Equivalent	Aerobic process depends on periodic introduction of Oxygen for equivalent zone of influence. Solar system must achieve same peak flow and pressure for some period of time.
Biopiles - Ex Situ SVE	Peak Pres. Peak Flow	Same Pump	Good Fit	Good Fit	Equivalent	Aerobic process depends on periodic introduction of Oxygen for equivalent zone of influence. Solar system must achieve same peak flow and pressure for some period of time.
Air Sparging	Peak Pres. Peak Flow	Same Pump	Good Fit	Good Fit	Equivalent	Aerobic process depends on periodic introduction of Oxygen for equivalent zone of influence. Solar system must achieve same peak flow and pressure for some period of time.
Biosparging	Peak Pres. Peak Flow	Same Pump	Good Fit	Good Fit	Equivalent	Aerobic process depends on periodic introduction of Oxygen for equivalent zone of influence. Solar system must achieve same peak flow and pressure for some period of time.
Groundwater Pumping	Min. Pres. Total Flow	Same or Larger Pump	Good Fit	Good Fit	Equivalent	Minimum power required to lift water. Equivalent solar system needs to achieve same total flow.

* *Recent experience suggests that "pulsing" the process does not have a significant negative impact on system performance.*

Target Markets

Both the private and public market sectors were addressed. The most promising initial target market for the solar-powered remediation system is the public sector, specifically the Department of Defense (DoD). The DoD is considered the most promising target market for three reasons. First, the DoD is the single largest group of potential clients with the most relevant problems in remote sites. Second, the majority of DoD problems are related to volatile organic compounds (VOCs), which are wastes amenable to remediation using the solar-powered concept. And third, most DoD services have innovative technology programs and are quick to adopt new technologies. Examples of DoD programs that are involved in technology development and assessment include the following:

- Navy Environmental Leadership Program (NELP) and Port Hueneme National Hydrocarbon Test Center.
- Air Force Center for Environmental Excellence (AFCEE), in Texas, Wright Patterson in Ohio, and Edwards Air Force Base California.
- Air Force Chlorinated Test Center at Dover Air Force Base.
- Army Environmental Center at Aberdeen, Maryland.

The total market potential for solar-powered systems within the DoD can only roughly be estimated. A total of about 8,000 sites currently require remediation, most of which require one of the technologies amenable to solar power. A portion of the more remote sites pose no immediate risk to people or to the environment and therefore may be allowed to recover naturally due to the high cost of remediation. Assuming an average of five systems per site, solar system utilization of five installations over 10 years, and an average solar system price of $20,000, the maximum total potential market for solar-powered equipment is about $160 million. If the solar-powered system is cost competitive in only 10% of these cases, the potential market is $16 million over several years. If the solar-powered system can compete against grid-connected systems with line extensions on the order of 100 feet, the market potential could even be several times higher when considering the private sector and other government agencies. Unfortunately, at this time there is insufficient market data to categorize DoD installations by the cost of grid connections.

Competitive Assessment

A comparison of the monthly cost of power to the end user is presented in Figure 2. These costs represent the price paid by the end user for access to, and supply of, electrical power amortized over the period of operation. The data for customer- (i.e., end-user) owned solar systems is presented in Figures 2(a) and 2(b) for the 1.1-hp and 2.5-hp blowers respectively. Figures 2(c) and 2(d) show the results for customer-leased systems.

Perhaps the most important result of this investigation is that a solar-powered system can be very cost effective compared to grid-supplied power for even short grid-extensions. As would be expected, the general result is that solar-powered systems are most competitive for lower power and more remote systems.

It should be noted that with sufficiently low system costs, amortized over several years and multiple installations, the solar system may be able to compete effectively in both the public and private sectors. After the solar-powered system gains credibility through trials in DoD and other public agencies, the private sector would adopt the technology if the economic benefits are demonstrable. The market potential in the private sector is many times larger (130,000 sites that involve VOCs for the public and private sectors combined according to the Environmental Protection Agency [EPA]), although solar-powered systems would compete effectively for only a portion of these sites.

Recommendations

Based on the results of this study, namely that solar-powered remediation systems can, in certain applications, compete with grid-connected remediation systems, AeroVironment recommends demonstrating four concept systems in the field. The four systems, two diurnal and two variable cycle, would be installed at selected cleanup sites provided by willing participants from existing DoD programs.

The goals of the field test would be to

- achieve credibility in target markets,
- establish final system technical and performance guidelines,
- validate economic and technical viability, and
- create market awareness.

The principal elements of a project to further this concept toward commercialization would involve

- a more detailed system specification and design,
- modifications of the power electronics to incorporate battery management,
- demonstration system construction (4 units),
- field installations,
- monitoring and refinement,

- analysis of results, and
- reporting.

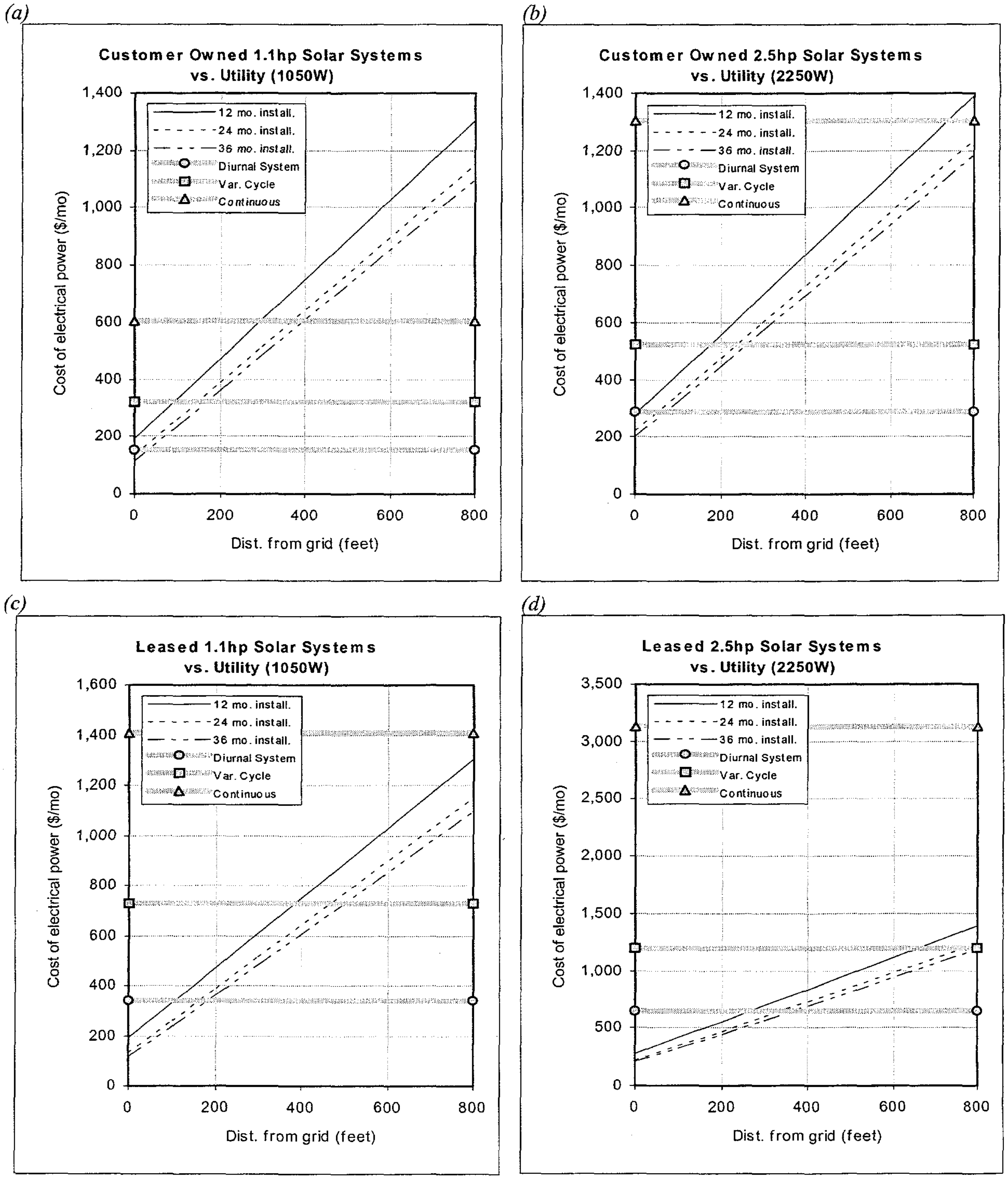

Figure 2. Comparative monthly cost of power for solar-powered system versus grid-supplied power.

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1. Introduction

Purpose

The purpose of this study was to assess the market and specific applications for solar-powered environmental remediation, and to develop design specifications to address the market. The solar-powered remediation concept involves using solar electric power to operate conventional remediation equipment. This study was a joint effort between AeroVironment Inc., a developer and manufacturer of power electronics for global markets including solar applications, and ATC-AVES, an environmental services company.

Description of Remediation Technologies

The worldwide environmental market varies widely—from the use of pollution prevention technologies that minimize the potential impact of current and future manufacturing practices as required by the Resource Conservation and Recovery Act (RCRA), to remediation of pollution caused by past manufacturing or waste management practices as required by the Comprehensive Environmental Response Cleanup and Liabilities Act (CERCLA), usually referred to as Superfund. Our immediate interest is in addressing technologies that may be suitable for application of the solar-powered remediation system concept. The most appropriate technologies are those requiring operation of pumps for air or water which are commonly used in cleaning up hazardous waste sites, although we may find there are other uses for the system. These technologies are described in the text below and summarized in Table 3 and discussed below.

Table 3. Summary of Common Remediation Technologies Being Considered for the Solar-powered System Concept

					Motor Power		Suitable
Technology	Medium	Type of Equipment	Typical Flow	Typical Pressure	Range	Typical	Cycles
In Situ							
Soil Vapor Extraction	V	centrifigal blower		up to 2 inHg or 27 inH_2O (low vac.)			C
		regenerative blower	up to 500 cfm	8 inHg or 109 inH_2O (low vac.)	1 hp	5 hp	C, D
		positive displace. blower		12 inHg or 163 inH_2O (med. vac.)	to	to	C
		liquid ring vacuum pump		25 inHg or 340 inH_2O (high vac.)	30 hp	7.5 hp	C
Bioventing	V	blower	5 to 90 cfm	20 to 100 in H2O	1 to 5 hp	2 to 3 hp	Y, D
Air Sparging	L	blower and/or compressor	1 to 25 cfm/point	1 to 10 inH_2O (coarse sed.)	.5 to 5 hp	3 hp to	Y, D
				12 to 120 inH_2O (fine sediment)	2.5 to 15 hp	7.5 hp	
Biosparging	L	blower and/or compressor	.25 to 2.5 cfm/point	1 to 120 inH_2O	0.5 to 10 hp	2 to 7.5 hp	Y, D
Bioslurping	L,V	regenerative blower	up to 500 cfm (vapor)	< 8 inHg or 109 inH_2O (low. vac.)		10 hp	
		lobe pump	up to 80 gpm (water)	from 8 to 15 inHg (med. vac.)	5 to 30 hp	to	C
		liquid ring vacuum pump		*>15 inHg or 19 ft H_2O (high vac.)*		*20 hp*	
Ex Situ							
Ex situ SVE	V	centrifigal blower		2 inHg or 27 inH_2O (low vac.)		2.5 hp	
or		regenerative blower	5 cfm/piping run	8 inHg or 109 inH_2O (low vac.)	.5 to 15 hp	to	Y, C, D
Biopiles		positive displace. blower		12 inHg or 163 inH_2O (med. vac.)		7.5	
Groundwater Pump and Treat	L	pump (submersible ,etc.)	1 to 600 gpm	varies with depth	0.25 to 25 hp	.5 to .75 hp	Y, D
Bioreactors	L,V	*pump (submersible ,etc.)*	*1 to 600 gpm*	NA	*0.25 to 25 hp*	*.5 to .75 hp*	C
Air Stripping	L	pump (submersible ,etc.)	1 - 20 gpm	pressure drop	.25 to 2 hp		Y, D
		"	20 to 75 gpm	in tower	1 to 5 hp	.5 to 3 hp	Y, D
		"	100 to 600 gpm	0.25 to 0.5 inH_20/ft of tower	5 to 30 hp		Y, D
		blower			1.5 hp/ ft diam		Y, D
Ion Exchange	L	pump (submersible ,etc.)	1 to 600 gpm	varies with depth	1 to 25 hp	.5 to .75 hp	Y, D

L: liquid
V: *vapor*
gpm: gallons per minute
cfm: cubic feet per minute

vac: vacuum
inHg: inches of mercury
inH2O: inches of water
hp: horse power

Y: diurnal operation (no batteries)
C: *continuos operation (with batteries 24 hrs.)*
D: variable cycling (using batteries)
NA: Information not available

In Situ Soil Vapor Extraction

Soil vapor extraction (SVE), also known as soil venting or vacuum extraction, is an accepted and recognized technology for remediating soils contaminated with volatile and semivolatile organic compounds (VOCs and SVOCs). In situ SVE is an unsaturated (vadose) zone remediation technology in which a vacuum is applied to the soil to induce the controlled flow of air and remove contaminants from the soil. In this technology, the vacuum is applied to the soil matrix to create a negative pressure gradient that causes movement of vapors toward extraction wells. The SVE process takes advantage of the volatility of the contaminants to allow mass transfer from adsorbed, dissolved, and free phases in the soil to the vapor phase, where it is removed under vacuum and treated above ground. Vertical (to 300 feet) or horizontal vents can be used. SVE is typically applicable only to volatile compounds with a Henry's law constant greater than 0.01 or a vapor pressure greater than 0.5 mm mercury (0.02 in. Hg).

Air-flow requirements will dictate vacuum equipment selection and air emission control equipment sizing. Air-flow requirements are defined by modeling, pilot testing levels, and/or literature review to determine adequate air flow across the entire site. The vacuum needed to produce a desired air flow defines the type and size of vacuum pumps or blowers that are required. This information is generally based on a scale-up of the field pilot test results. In general, centrifugal blowers should be used for high-flow (up to 280 standard cubic feet per minute [scfm]), low-vacuum (less than 2 in. Hg or 30 in. H_2O) applications. Regenerative-type blowers typically are used in low-vacuum (less than 8 in. Hg or 109 in. H_2O) and high-flow applications. Positive-displacement blowers are used in medium-vacuum applications (less than 12 in. Hg or 163 in. H_2O) and liquid-ring pumps are used to induce flow in high-resistance applications (less than 25 in. Hg or 340 in. H_2O). Other types of blowers and vacuum pumps, such as rotary-vane and gear pumps, have been used successfully for SVE but tend to be less common. Due to the continuos operation of SVE, vacuum equipment should be protected by a thermal overload shut-off. Vacuum equipment systems should be designed with dilution valves to adjust the applied vacuum and to dilute the recovered vapors for vapor treatment, if required.

SVE is not suitable for diurnal operation but may work satisfactorily with a variable-cycle system if the wellhead pressure at the low power condition is sufficiently low to cause volatilization. For this technology, a solar system would have to be compared to a grid-connected system on the basis of comparable total mass flow rates and wellhead pressure, so a continuous operation system is the best fit. Typical installations operate from 6 to 18 months.

Bioventing

Bioventing is a process that uses an approach similar to SVE in terms of system configuration, but with a different objective. The intent of bioventing is to induce airflow to provide oxygen to maximize the aerobic biodegradation of the compounds (in contrast to volatilization). Bioventing stimulates the natural in situ biodegradation of petroleum hydrocarbons in soil by providing oxygen to existing soil microorganisms. Only sufficient quantities of oxygen (air) are injected to maintain aerobic conditions. Good soil permeability, moderate temperatures, and sufficient nutrients are needed for this technology to work well. This technology has been successfully used to remediate soils contaminated by petroleum hydrocarbons, nonchlorinated solvents, some pesticides, wood preservatives, and other organic chemicals.

Important parameters in bioventing are wellhead pressure and induced vapor flow rate. Wellhead pressure is the pressure (or vacuum) that is required at the top of the vent well to produce the desired induced air stream flow rate from the well. Although wellhead pressure is usually determined through field pilot studies, it can be estimated and typically ranges from 3 to 100 in. H_2O vacuum (0.2 to 7 in. Hg) for extraction and 10 to 50 psi for injection. Less permeable soils generally require higher vacuums or pressure to produce a reasonable radius of influence.

Induced vapor flow rate is the volumetric flow rate of soil vapor that will be induced by each extraction or injection well and establishes the oxygen delivery rate to the in situ treatment area. The induced vapor flow rate, radius of influence, and wellhead pressure are all interdependent (a certain vapor flow rate requires a certain wellhead pressure and radius of influence). Typical induced flow rates can range from 1 to 100 cubic feet per minute (cfm).

The type and size of the blower selected should be based on (1) the vacuum or pressure required to achieve design pressure at the wellheads (including upstream and downstream piping losses) and (2) the total flow rate. The flow-rate requirements should be based on the sum of the flow rates from the contributing extraction or injection wells. Centrifugal blowers should be used for high-flow, low-pressure applications (less than 20 in. H_2O or 1.5 in. Hg). Regenerative and turbine blowers should be used when a higher pressure or vacuum (up to 80 in. H_2O or 6 in. Hg) is needed. Rotary-lobe and other positive-displacement blowers should be used when a very high pressure or vacuum (greater than 80 in. H_2O or 6 in. Hg) is needed. Rotary-lobe blowers are not generally applicable to bioventing systems. Typically, 1- to 5-hp blowers are adequate.

Bioventing is well suited to diurnal operation and many experts argue that cycling may actually be beneficial to the process. Because this technology relies on aerobic stimulation, the effectiveness of the process is most dependent on the zone of influence that is governed by wellhead pressure and peak flow rate, not total volumetric flow rate. A diurnal system, capable of achieving the same peak flow rates and pressure, would therefore be comparable to a conventional grid-connected system. Variable-cycle systems would also be suitable using the same pump. Installations are typically in operation from 12 to 36 months.

Air Sparging

Air sparging is an in situ remedial technology that reduces the concentration of volatile constituents in petroleum products that are adsorbed to soils and dissolved in groundwater. This technology, which is also known as "in situ air stripping" and "in situ volatilization," involves the injection of contaminant-free air into the subsurface saturated zone (water saturated formation), enabling a phase transfer of hydrocarbons from a dissolved state to a vapor phase; the air is then vented through the unsaturated zone. Air is injected under pressure below the water table to increase groundwater oxygen concentrations and enhance the rate of biological degradation of organic contaminants by naturally occurring microbes. VOC stripping is also enhanced by air. Air sparging is typically used in conjunction with SVE or bioventing, to enhance removal of the volatile component under consideration. Air sparging is also used to remove nonhalogenated VOCs, SVOCs, and fuels from groundwater.

The sparging air flow rate required to provide sufficient air flow to enhance mass transfer is site specific and is determined via the pilot test. Typical air-flow rates range from 1 to 25 scfm per injection point or injection well with total system flow rates as high as 250 cfm. Pulsing the air flow (turning the system on and off at specific intervals) may provide better distribution and mixing of the air in the contaminated saturated zone, thereby allowing for greater contact with the dissolved phase contaminants making this technology suitable for diurnal operation. The effectiveness of the process is most dependent on the zone of influence that is governed by wellhead pressure and peak flow rate, not total volumetric flow rate. A diurnal system, capable of achieving the same peak flow rates and pressure for a short time, would therefore be comparable to a conventional grid-connected system. Variable-cycle and continuous-operation systems would also be suitable using the same pump. Systems are in operation from 6 to 36 months.

Sparging air pressure is the pressure at which air is injected into the saturated zone (below the water table). It is heavily dependent on the type of geology. The saturated zone requires pressures greater than the static water pressure (1 psi for every 2.3 ft of hydraulic head), and head necessary to overcome capillary forces of the water in the soil pores near the injection point. In reality, the air entry pressure will be higher for fine sediments (12 to 120 in. H_2O) than coarse sediments (1 to 10 in. H_2O).

Biosparging

Biosparging is an in situ remediation technology that uses indigenous microorganisms to biodegrade organic constituents in the saturated zone (water saturated formation). In biosparging air (or oxygen) and nutrients (if needed) are injected (at very low flow rates) into the saturated zone to increase the biological activity of the indigenous microorganisms. Biosparging can be used to reduce the concentration of petroleum constituents that are dissolved in groundwater, adsorbed to soil below the water table, and within the capillary fringe.

Biosparging is similar to air sparging. However, while air sparging removes constituents primarily through volatilization, biosparging promotes biodegradation of constituents rather than volatilization (generally by using lower flow rates than used in air sparging).

The biosparging air-flow rate required to provide sufficient air flow to enhance biological activity is site specific and will be determined via the pilot test. Typical air-flow rates range from 0.25 to 2.5 scfm per injection point or injection well. Pulsing the air flow (turning the system on and off at specific intervals) is also done in biosparging and may allow for diurnal operation. The effectiveness of the process is most dependent on the zone of influence that is governed by wellhead pressure and peak flow rate. Total volumetric flow rate is of less importance as long as sufficient oxygen is introduced. A diurnal system, capable of achieving the same peak flow rates and pressure for a short time, would therefore be comparable to a conventional grid-connected system. Variable-cycle and continuous-operation systems would also be suitable using the same pump. Typically, the SVE extraction rates range from 1.25 to 5 times greater than the biosparging rate. These systems normally operate for a period of 12 to 36 months.

Biosparging air pressure is the pressure at which air is injected into the saturated zone (below the water table). It is heavily dependent on the type of geology. The saturated zone requires pressures greater than the static water pressure (1 psi for every 2.3 ft of hydraulic head) and head necessary to overcome capillary forces of the water in the soil pores near the injection point. A typical system will be operated at approximately 1 to 120 in H_2O.

Bioslurping

Bioslurping is a new in situ technology that teams vacuum-enhanced free product recovery with bioventing. Bioslurping thus simultaneously recovers free-product fuel from the water table and capillary fringe while promoting aerobic bioremediation in the vadose zone of subsurface soils. This is accomplished by using a vacuum that removes free fuel and vapor while venting the soils to stimulate contaminant biodegradation. Biodegradation is further assisted due to the decrease in fuel volume and increase in contaminant accessibility.

Bioslurping can improve free-product recovery efficiency without extracting large quantities of ground water. Bioventing of vadose zone soils is achieved by drawing air into the soil by withdrawing soil gas via the recovery well. The system is designed to minimize environmental discharge of ground water and soil gas. When free-product removal activities are completed, the bioslurping system is easily converted to a conventional bioventing system to complete the remediation. The operation and maintenance duration for bioslurping varies from 12 to 36 months, depending on specific site conditions.

Bioslurping equipment is primarily designed for remediating petroleum hydrocarbons and other medium- to low-viscosity, relatively volatile organic compounds. Bioslurping is most effective in fine- to medium-grained soils where there is a significant amount of hydrocarbon product to recover, and involves minimal physical drawdown and groundwater extraction.

Observed operating ranges for a typical bioslurping system include 20 to 28.5 in. of mercury (272 to 388 in. H_2O) vacuum at the pump; 1 to 20 in. of mercury (14 to 272 in. H_2O) vacuum at the wellhead; flow rates to 525 cfm hydraulic flow rates to 180 L/min. (40 gpm); and depths of product removal to 45 m below grade. Results include elevated product-to-water ratios and removal of volatile contaminants within water and vapor discharge streams to required guidelines.

This technology does not lend itself to operation on a diurnal cycle. Only the continuous process solar system using an equivalent pump would be applicable although the power levels required are generally too high (from 5 hp and up).

Biopiles, or Ex Situ SVE

Ex situ SVE or biopiles (also known as biocells, bioheaps, biomounds, and compost piles) are used to reduce the concentration of petroleum constituents in excavated soils through the use of biodegradation. This technology involves heaping contaminated soils in piles (or "cells") and stimulating aerobic microbial activity within the soils by aeration and/or addition of minerals, nutrients, and moisture. The enhanced microbial activity results in degradation of adsorbed petroleum-product constituents through microbial respiration. Biopiles are above-ground, engineered systems that use oxygen, generally from air, to stimulate the growth and reproduction of aerobic bacteria which, in turn, degrade the petroleum constituents adsorbed to soil.

Biopiles are aerated most often by forcing air to move via injection or extraction through slotted or perforated piping placed throughout the pile. Soil is excavated and placed over a network of aboveground piping to which a vacuum is applied to encourage volatilization of organics. The process includes a system for handling off-gases, and sometimes a leachate collection and treatment system. The target contaminant group for biopiles is VOCs. Advantages over in situ SVE include that the excavation process forms increased passageways, shallow groundwater no longer limits the process, leachate collection is possible, and treatment is more uniform and more easily monitored.

Equipment usually includes blowers or fans, similar to in situ SVE, which will be attached to the aeration piping manifold. Typical flow rates are 5 cfm of air flow per piping run. Total flow rates of 100 cfm are typical. Systems are in operation from 6 to 24 months. Diurnal operation is compatible with this process. Because this technology relies on aerobic stimulation, the effectiveness of the process is most dependent on the zone of influence that is governed by wellhead pressure and peak flow rate for a short time, not total volumetric flow rate. A diurnal system, capable of achieving the same peak flow rates and pressure, would therefore be comparable to a conventional grid-connected system. Variable-cycle and continuous-operation systems would also be suitable using the same pump.

Groundwater Pumping (Pump and Treat)

Until the very recent past, almost all installed groundwater cleanup systems involved variations of the technology called "pump and treat." Pump and treat systems operate by pumping groundwater to the surface, removing the contaminants, and either recharging the treated water back into the groundwater or discharging it to a surface water body or municipal sewage plant. The most important equipment for groundwater pumping is the pump. Depending on the flow rate (1 to 750 gpm) and how deep the groundwater is, the size of pump could be from 0.5 to 25 hp. Most sites require rates of 1 to 10 gpm per well. Once groundwater has been pumped to the surface, contaminants can be removed to very low levels with established technologies used to treat drinking water and wastewater (e.g., air stripping, ion exchange, carbon adsorption, free product recovery, bioreactors, etc.). For all the treatments discussed here, electrical power is used to move the fluid. A diurnal cycle is suitable for all the treatment technologies but, unlike bioventing, the process performance depends on the total volume of water pumped. Therefore, a diurnal system would have to pump the same amount of water as a conventional grid-connected system. A brief description of some of the treatment technologies used to treat the groundwater after it has been pumped to the surface is provided below.

Bioreactors (Liquid-phase Bioremediation)

The use of bioreactors is a pump and treat technology. Liquid-phase bioremediation is the application of surface bioreactors to the treatment of water contaminated with hazardous chemicals. Bioreactors support the growth and retention of desired microorganisms under optimized process conditions. The bioreactors are designed for specific target compounds. Systems are in operation from 2 to 7 years. Neither diurnal or variable-cycle operation are suitable for this technology.

Air Stripping

Air stripping is also a pump and treat technology. Volatile organics are partitioned from groundwater by greatly increasing the surface area of the contaminated water exposed to air (Henry's Law). Types of aeration methods include packed towers, diffused aeration, tray aeration, and spray aeration. Compounds that have been successfully separated from water using air stripping include BTEX, chloroethane, TCE, DCE, and PCE. This technology can achieve greater than 99% efficiency with a 20-ft tower. A major operating cost of air strippers is the electricity required for the groundwater pump, the sump discharge pump, and the air blower. Systems are in operation from 3 to 7 years.

Ion Exchange

Ion exchange is a pump and treat technology or a water treatment technology. Ion exchange removes ions from the aqueous phase by the exchange of cations or anions between the contaminants and the exchange medium. Ion-exchange materials may consist of resins made from synthetic organic materials that contain ionic functional groups to which exchangeable ions are attached. They also may be inorganic and natural polymeric materials. After the resin capacity has been exhausted, resins can be regenerated for re-use. Ion exchange can remove dissolved metals and radionuclides from aqueous solutions as well as nitrate, ammonia nitrogen, and silicate. Systems are in operation from 3 to 7 years. Diurnal operation is suitable for this technology.

Liquid-phase Carbon Adsorption

Carbon adsorption is a pump and treat technology. Groundwater is pumped through a series of vessels containing activated carbon to which dissolved contaminants adsorb. When the concentration of contaminants in the effluent from the bed exceeds a certain level, the carbon can be regenerated. Adsorption by activated carbon has a long history of use in treating municipal, industrial, and hazardous wastes. The target contaminant groups are SVOCs and explosives as well as halogenated VOCs, fuels, and pesticides. Systems are in operation from 3 to 7 years. Diurnal operation is suitable for this technology.

Free Product Recovery

Free product recovery is a pump and treat technology. It is used when lighter-than-water, nonaqueous-phase liquids (LNAPLs) such as petroleum products, float on top of the groundwater table. Free product (undissolved liquid-phase organics) can be removed from subsurface formations, either by active methods (e.g., pumping) or a passive collection system. Free product recovery is used primarily in cases where a fuel hydrocarbon lens more than 20 centimeters (8 inches) thick, is floating on the water table. The free product is generally drawn up to the surface by a pumping system. The target contaminant groups for free product recovery are SVOCs and fuels. Systems are in operation from 2 to 7 years. Diurnal operation is suitable for this technology but the required period of operation is proportional to the recovery rate.

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2. Regenerative Blower Characterization Tests

A regenerative blower similar to ones used in the remediation field was purchased for evaluation and to provide test data for models used in sizing concept systems. The variable speed motor controller used for this project has been tested extensively with submersible water pumps, but there was no experience running blowers. The variable speed data from the blower (flow rate as a function of power), was the building block for the simulation model and was used to determine total volume of air pumped in a given day, for either diurnal- or variable/continuous-cycle concept remediation systems.

Test Set-up

The regenerative blower evaluation test apparatus setup is shown in Figure 3. Power to the system is supplied by a high-voltage DC supply connected to AeroVironment's variable speed motor controller, the Universal Solar Pump Controller (USPC). Variable voltage settings are used to simulate the performance points of a solar array. The output of the USPC is directly connected to the blower motor. A portable computer is connected to the RS232 port of the USPC to display system wattage, speed, and other pertinent information about motor operation. The inlet and outlet ports of the blower are fitted with PVC piping to facilitate air flow control and monitoring. During the compression mode testing, a pressure gauge and throttling valve are attached to the outlet port of the blower and a hot-wire anemometer is inserted into the unrestricted inlet air stream to monitor air flow. During the vacuum mode testing, a vacuum gauge and throttling valve are attached to the inlet port of the blower and the hot-wire anemometer is inserted into the unrestricted outlet air stream. Reference checks of data points were made using 208-VAC utility power in place of the USPC output power.

Test Procedure

The test apparatus was first configured in the compression mode. With the USPC set to operate at a specified fixed speed, air speed from the hot-wire anemometer and pressure meter data were recorded at different points using the throttling valve to restrict air flow through the blower. Air-flow rate calculations for the cross section of the pipe provided cfm values.

The test apparatus was then reconfigured for the vacuum mode of operation and data was again taken by the same method. Readings for air speed and pressure were not observed to be sensitive to tube inlet shape or meter location for these tests.

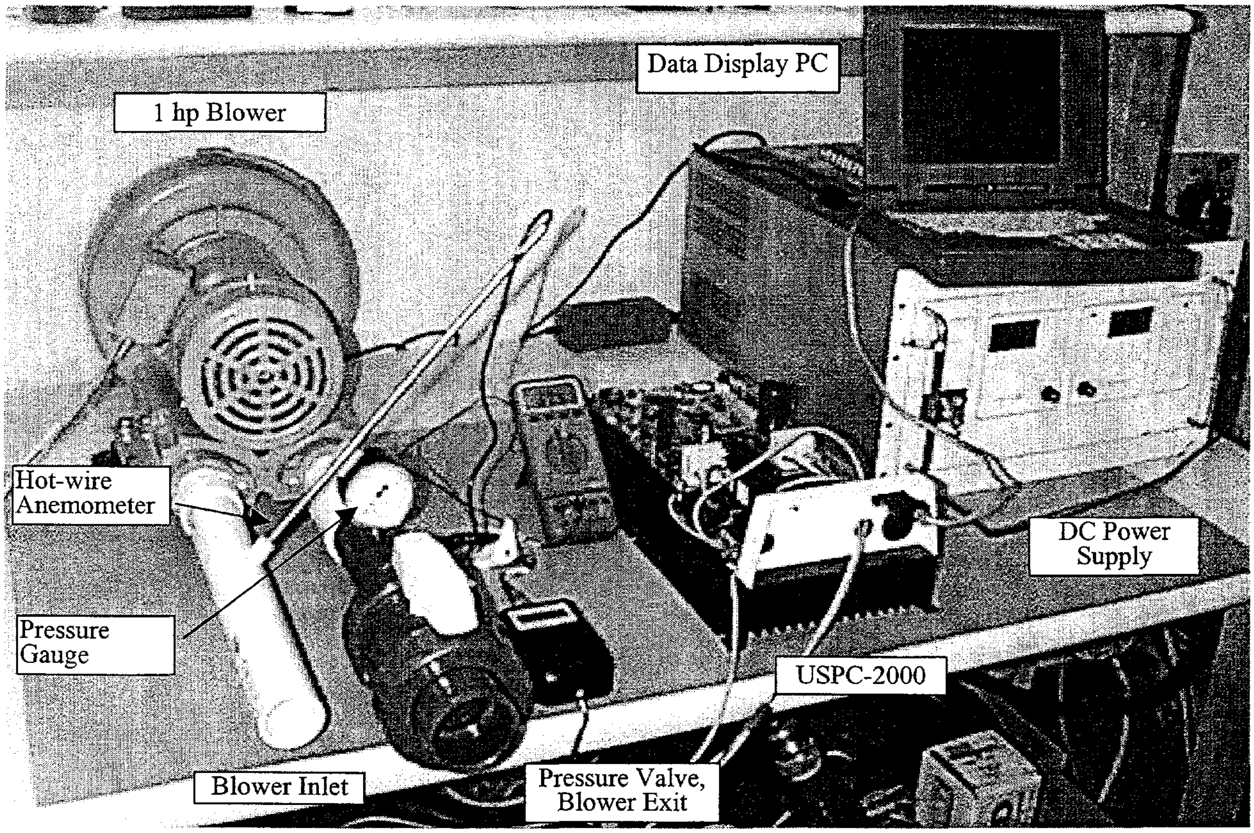


Figure 3. Test apparatus shown in the pressurizing configuration.

Test Results

The three sets of data shown in Table 4 were made at 60 Hz. The manufacturer's data was taken from the catalog used to order the blower. The utility data was taken at 208 VAC. The USPC data was taken at 230 VAC. The blower motor is rated for 200- to 230-VAC operation.

As can be observed from the data, at zero pressure, the manufacturer's data is higher than that measured with AeroVironment's test setup. This may indicate that the manufacturer did not pipe the blower, but rather performed flow readings at the unrestricted blower port itself. From 10 to 40 in. H_2O, the utility and USPC data match well and converge with the manufacturer's data at 40 in. H_2O. The data points at 50 in. H_2O are near the nonlinear endpoints of the flow curve for this blower and as such are less useful. The same effect can be seen in the vacuum (negative pressure) case.

Table 4. Comparison of Manufacturer's Data to Test Data—Flow in cfm at Given Pressures at 60 Hz

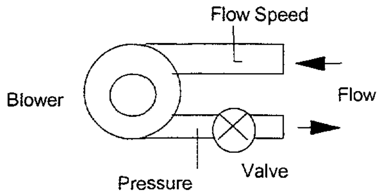
Pressure (in. H_2O)	Manufacturer's Data	208-VAC Utility Connect	USPC @ 230 VAC
50	30	38	45
40	55	53	56
30	69	60	63
20	79	68	68
10	88	76	77
0	98	78	Higher than 78 cfm meter capability
-10	85	67	68
-20	70	64	65
-30	62	53	54
-40	45	43	45
-50	13	15	18

Four variable-speed test cases were then conducted at speeds from 20 to 60 Hz. Test Cases 1 and 2 are constructions of the blower performance polars for the pressurized and vacuum modes of operation, respectively. Test Cases 3 and 4 are variable speed blower performance characterizations for a fixed blockage, simulating the pressure drop through a porous media, in the pressurized and vacuum modes. Results for each test case are described below.

Overall, this evaluation indicated that the solar control of remediation technology is both possible and practical using the USPC as a system controller. The data taken supports this premise and shows that the performance of the USPC-driven system equals that of a grid-connected system. It was also concluded that this data could be used to generate a math model to simulate system performance. The development of this math model is described in Section 3.

Test Case 1 Results: Pressurizing Configuration Performance Characterization

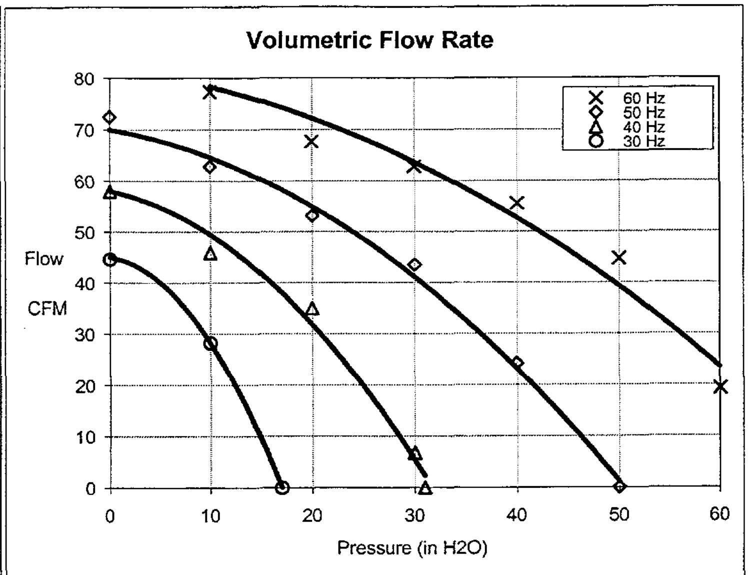
Air Blower Performance Characterization
(Pressurizing Configuration)
(Speed Held Constant While Varying Pressure)

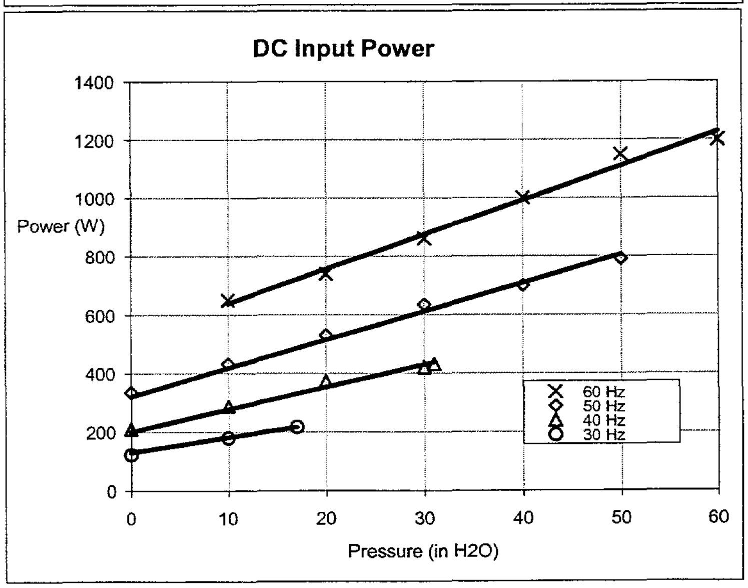


Blower:	Fuji 1.1HP regenerative blower, Model No. VFC 404A-7W, 230VAC 3ph
Flow Meter:	Omega hot-wire anemometer, Model No. HHF 52
Pressure Gauge:	Noshok 1% press. guage, 0-60 in.H2O
Power Source:	DC Power Supply
Controller:	USPC-2000

1.5 = Flow meas. tube diameter (in)
0.0123 = Cross sectional area (ft^2)
2.42 = Conversion from m/s to CFM

Freq. (Hz)	Pressure (in.H2O)	Power (W)	Flow (m/s)	(CFM)
60	10	650	32	77.3
60	20	740	28	67.6
60	30	860	26	62.8
60	40	1000	23	55.5
60	50	1150	18.5	44.7
60	60	1200	8	19.3
50	0	335	30	72.5
50	10	431	26	62.8
50	20	530	22	53.1
50	30	634	18	43.5
50	40	700	10	24.2
50	50	790	0	0.0
40	0	210	24	58.0
40	10	287	19	45.9
40	20	373	14.5	35.0
40	30	420	2.8	6.8
40	31	430	0	0.0
30	0	123	18.5	44.7
30	10	180	11.7	28.3
30	17	217	0	0.0

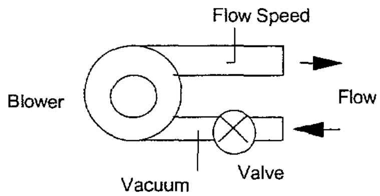




Test Case 2 Results: Vacuum Configuration Performance Characterization

Air Blower Performance Characterization
(Vacuum Configuration)

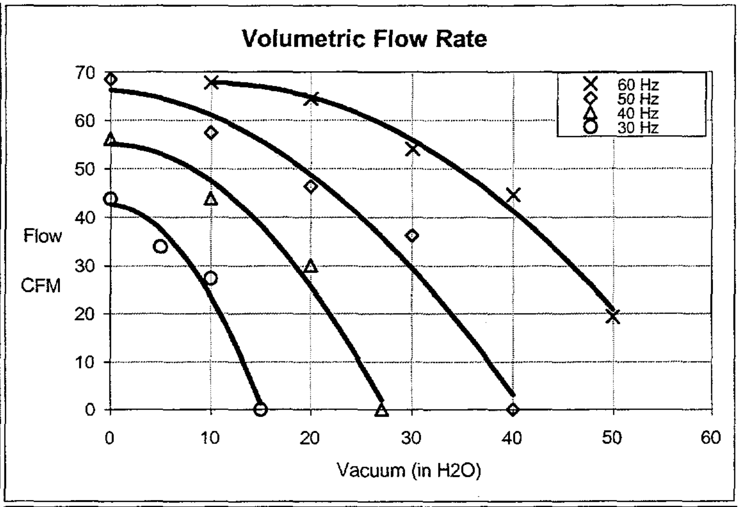
(Speed Held Constant While Varying Vacuum)

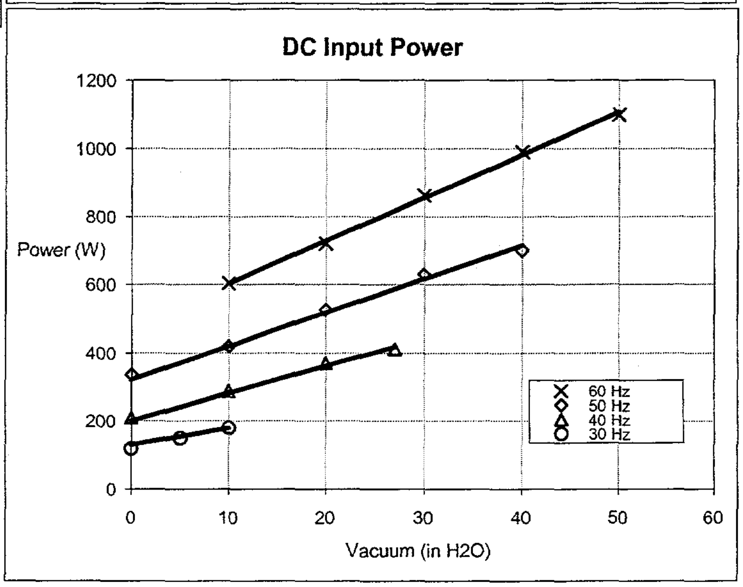


Blower:	Fuji 1.1HP regenerative blower, Model No. VFC 404A-7W, 230VAC 3ph
Flow Meter:	Omega hot-wire anemometer, Model No. HHF 52
Pressure Gauge:	Noshok 1% vac. guage,0-60 in.H2O
Power Source:	DC Power Supply
Controller:	USPC-2000

1.5 = Flow meas. tube diameter (in)
0.0123 = Cross sectional area (ft^2)
2.42 = Conversion from m/s to CFM

Freq. (Hz)	Vacuum (in.H2O)	Power (W)	Flow (m/s)	Flow (CFM)
60	10	604	28.1	67.9
60	20	720	26.7	64.5
60	30	862	22.4	54.1
60	40	990	18.5	44.7
60	50	1100	8	19.3
50	0	335	28.4	68.6
50	10	420	23.8	57.5
50	20	526	19.2	46.4
50	30	630	15	36.2
50	40	700	0	0.0
40	0	210	23.3	56.3
40	10	287	18.2	44.0
40	20	370	12.4	29.9
40	27	411	0	0.0
30	0	120	18.2	44.0
30	5	150	14	33.8
30	10	180	11.3	27.3
30	15	207	0	0.0

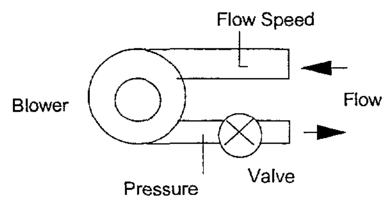




Test Case 3 Results: Fixed-blockage, Variable-speed Performance Characterization (Pressurizing Configuration)

Air Blower Performance Characterization (Pressurizing Configuration)

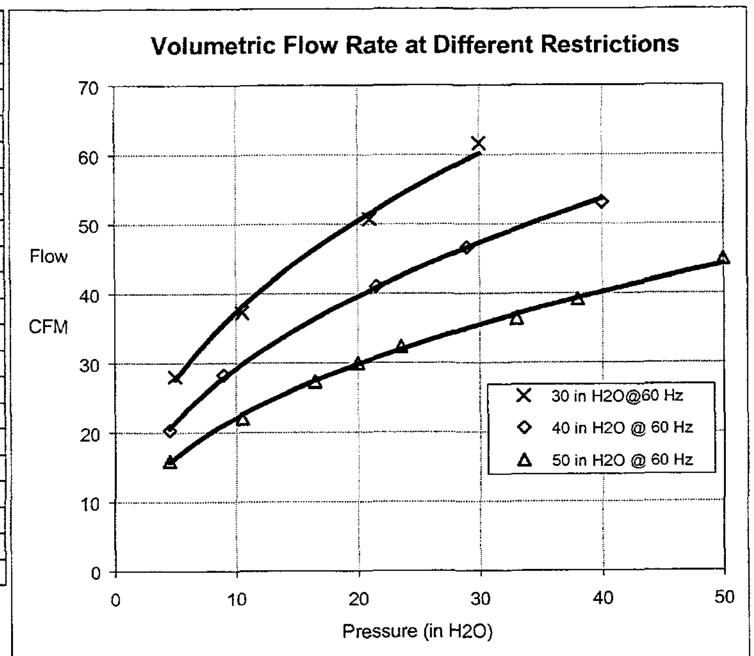
(Fixed Blockage, Variable Speed)

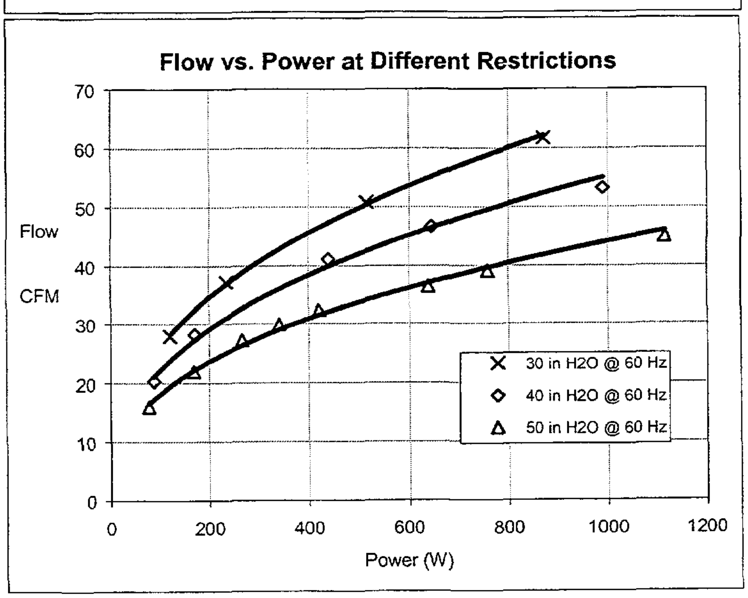


Blower:	*Fuji 1.1HP regenerative blower,* Model No. VFC 404A-7W, 230VAC 3ph
Flow Meter:	Omega hot-wire anemometer, Model No. HHF 52
Pressure Gauge:	Noshok 1% press. guage,0-60 in.H2O
Power Source:	DC Power Supply
Controller:	USPC-2000

1.5 = Flow meas. tube diameter (in)
0.0123 = Cross sectional area (ft^2)
2.42 = Conversion from m/s to CFM

Freq. (Hz)	Pressure (in.H2O)	Power (W)	Flow (m/s)	Flow (CFM)
	50 in H2O @ 60 Hz			
60	50	1115	18.6	44.9
52.5	38	760	16.2	39.1
49.1	33	640	15.1	36.5
41.8	23.5	420	13.4	32.4
38.5	20	340	12.4	29.9
34.9	16.5	266	11.3	27.3
28.5	10.5	168	9.1	22.0
19.1	4.5	78	6.6	15.9
	40 in H2O @ 60 Hz			
60	40	990	22	53.1
52	29	645	19.3	46.6
44.5	21.5	440	17	41.1
29.4	9	170	11.7	28.3
21	4.5	88	8.4	20.3
	30 in H2O @ 60 Hz			
60	30	872	25.5	61.6
49	21	515	21	50.7
35.7	10.5	235	15.4	37.2
25.8	5	120	11.6	28.0

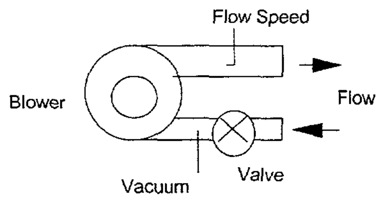




Test Case 4 Results: Fixed-blockage, Variable-speed Performance Characterization (Vacuum Configuration)

Air Blower Performance Characterization (Vacuum Configuration)

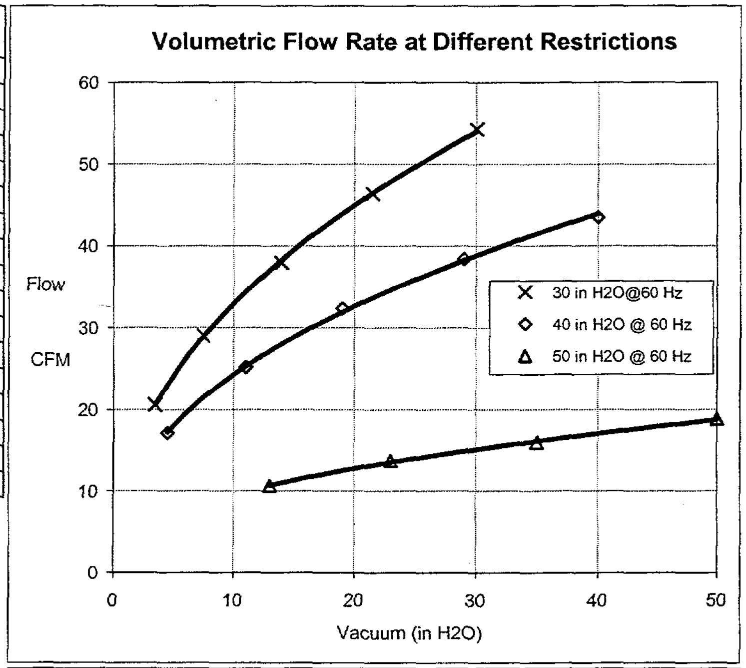
(Fixed Blockage, Variable Speed)

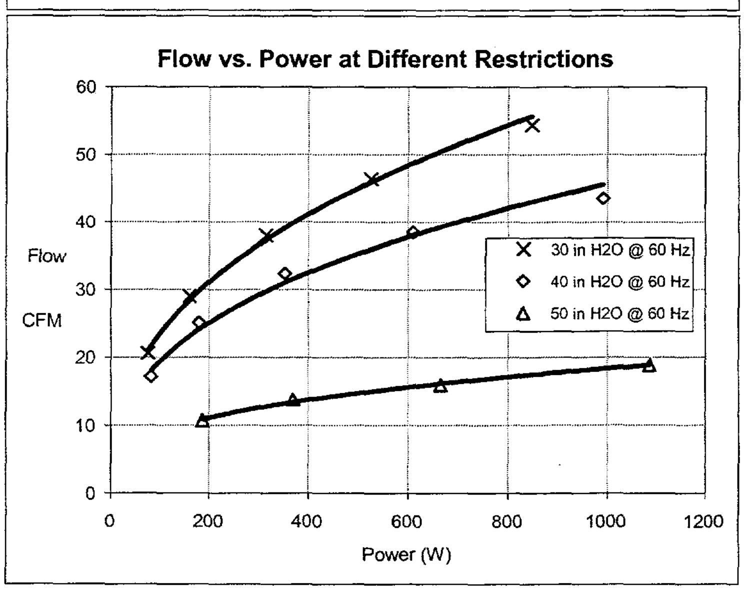


Blower:	Fuji 1.1HP regenerative blower, Model No. VFC 404A-7W, 230VAC 3ph
Flow Meter:	Omega hot-wire anemometer, Model No. HHF52
Pressure Gauge:	Noshok 1% vac. guage,0-60 in.H2O
Power Source:	DC Power Supply
Controller:	USPC-2000

1.5 = Flow meas. tube diameter (in)
0.0123 = Cross sectional area (ft^2)
2.42 = Conversion from m/s to CFM

Freq. (Hz)	Pressure (in.H2O)	Power (W)	Flow (m/s)	Flow (CFM)
	50 in H2O @ 60 Hz			
60.1	50	1087	7.8	18.8
49.9	35	665	6.6	15.9
40	23	370	5.7	13.8
30	13	188	4.4	10.6
	40 in H2O @ 60 Hz			
60.1	40	992	18	43.5
49.9	29	610	15.9	38.4
40.1	19	354	13.4	32.4
30	11	180	10.4	25.1
19.9	4.5	82	7.1	17.1
	30 in H2O @ 60 Hz			
60.1	30	848	22.5	54.3
49.9	21.5	526	19.2	46.4
40.2	14	315	15.7	37.9
29.9	7.5	160	12	29.0
19.9	3.5	76	8.5	20.5





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3. Development of Solar-powered Remediation System Model

A simple numerical simulation (in the time domain) was created using spreadsheet software and was used to predict the performance of candidate concepts for solar-powered remediation systems. To obtain credible results, the simulation incorporated representative models of the system components. Because this was a concept-level study, a high-fidelity simulation was not necessary. The models and assumptions used for each functional element of the simulation model are described in this section. Cost models and technology tradeoffs using this simulation are considered in later sections.

Math Model Development

Figure 4 is a functional diagram of the battery-augmented, solar-powered remediation system. The diurnal system is identical except that there is no battery energy storage. Power is provided to the system by the solar array. The USPC converts DC power to AC for driving the load. For the battery-augmented system, the USPC will also manage the battery used for energy storage. For this study, the primary load is a regenerative blower of the type commonly used for bioremediation.

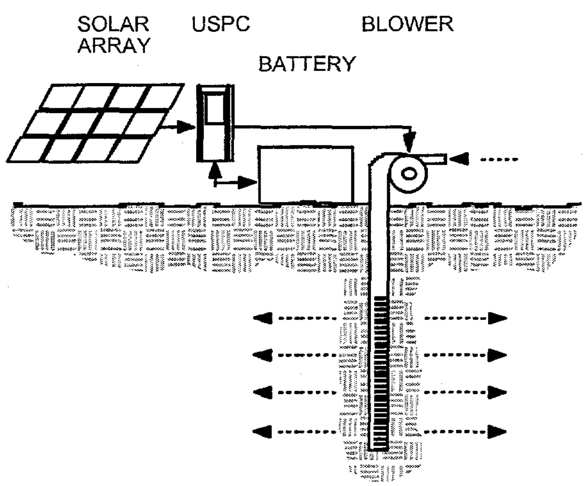


Figure 4. Functional diagram of the battery-augmented, solar-powered remediation system.

Solar Insolation and Array (Power Available)

A 12-hour, 6-kWh/m^2, standard solar day for a fixed array was used as the reference solar radiation profile. This profile was then scaled to provide the integrated total solar insolation desired for each test case in the parametric study. The solar radiation at any given time step is calculated using the expression,

$$R_t = R_{tref} * (I_{total} / 6) \quad (1)$$

where R_t is the solar radiation (W/m^2) at time t, R_{tref} is the reference radiation (W/m^2) at time t, and I_{total} is the desired total insolation for the specific test case (kWh/m^2).

The power available from the solar array at a given time is then,

$$P_{solar} = R_t * (Array\ Rating / 1000) \quad (2)$$

where P_{solar} is the available power from the array (W), and *Array Rating* is the desired solar array rated power (W) referenced to 1000 W/m^2.

Batteries

For this performance model, several battery parameters were used:

Nominal Voltage	(V)
Maximum Charging Voltage	(V)
Capacity	(Ah)
Depth of Discharge	(%)

For the continuous operating cycle, all excess solar power goes into charging the battery at a rate

$$I_{charge} = (P_{solar} - P_{load}) / V_{charge} \quad (3)$$

where I_{charge} is the charging current (A), P_{load} is the power required for the load (W), and V_{charge} is the maximum charging voltage. In low-light conditions, the battery supplies power to supplement the solar and at night the battery supplies all the power. The current from the battery at night and low-light conditions is

$$I_{discharge} = (P_{load} - P_{solar}) / V_{nominal} \quad (4)$$

where $I_{discharge}$ is the discharging current (A) and $V_{nominal}$ is the nominal battery pack voltage. The voltage efficiency is accounted for using this method and current efficiency is accounted for by allowing a 2-hour period where the battery is at full charge. Note that at night $P_{solar} = 0$.

Power Electronics

The power electronics technology used for this project was AeroVironment's USPC, a highly versatile variable-speed motor controller with demonstrated electronic efficiency of over 95% over most of its operating range. The USPC incorporates peak-power tracking, which ensures that all the power from the solar array is available. Battery charging is accomplished using the DC power bus downstream of the clamping circuit on the USPC. For the configurations of interest, the maximum current potential of the array is less than the maximum charging current for the battery. With proper matching of the array and the battery voltage, minimal DC-bus voltage regulation is required; consequently, power conversion losses are not expected during battery charging. This is the simplest possible system configuration yielding the highest possible system electrical efficiency. An inverter power conversion efficiency of 95% was assumed for this study.

Blower

For this study, a generalized model for the variable-speed performance of a regenerative blower was required. Specifically, the model must account for the change in pressure and flow rate associated with flow through a porous media as a function of motor speed (power). Unfortunately, manufacturer-supplied information on blowers is limited to flow rate as a function of fixed pressure rise at a motor speed of 60 Hz. Therefore, we constructed a semi-empirical model based in part on theory and in part on tests of representative blowers, which were described in Section 2. The desired result was an expression for blower volumetric flow rate as a function of available power,

$$Flow = a * P_{avail}^{b} \quad (5)$$

where *Flow* is the volumetric flow rate in cfm, *a* is a power law coefficient derived from a specific blower specification and operating point, P_{avail} is the power available (W), and *b* is the power law exponent derived empirically from the blower tests.

The results from Test Case 3 were curve fit using Equation 1 to obtain values for *a* and *b*. Three conditions relevant to the remediation application were analyzed–Case 1 = 50, Case 2 = 40, and Case 3 = 30 in. H_2O pressure with the pump operating at 60 Hz. Table 5 shows the values for *a* and *b* that best fit the test data for each case. The results show that the exponent can be approximated by a single value (0.39). As expected, the coefficient *a* is most likely a function of the specific blower model and flow blockage.

Table 5. Best Fit Coefficients for Equation 5

Case:	1	2	3	
Pressure:	50	40	30	(in H_2O)
Flow:	44.9	53.1	61.1	(cfm)
a:	3.0545	3.5563	4.2113	
b:	0.3864	0.3969	0.3974	

Given a blower performance specification appropriate to the application (i.e., flow rate at a given pressure and at 60 Hz), Equation 5 may be used to compute a value for *a* if the actual power used is known. Unfortunately, the published rating (typically given in terms of rated current) is rarely accurate and usually only appropriate to a maximum load condition. Therefore, an estimate of the actual power required must be made.

The power represented by the flow for an adiabatic process can be described by Equation 6 where P_1 is the ambient pressure, P_2 is the pressure after work is done, V_1 is the volumetric flow rate, and γ is the ratio of the specific heats for air ($\gamma = 1.4$).

$$P_{ideal} = P_1 * V_1 * (1 - (P_2/P_1)^{(\gamma-1/\gamma)}) * (\gamma / \gamma - 1) \quad (6)$$

The actual power consumed by a compressor is expressed in terms of the power in the flow corrected by the motor and compressor efficiencies,

$$P_{actual} = P_{ideal} * \eta_{motor} * \eta_{blower} \quad (7)$$

where P_{actual} is the actual power required, and η_{motor} and η_{blower} are the motor and blower efficiencies.

Motor efficiencies are about 70% for standard 230-VAC, 3-phase induction motors of this power level. Regenerative blower efficiencies are typically between 30 and 35%. To validate this assumption, the data from Test Case 3 were evaluated. Table 6 and Figure 5 show the blower efficiencies for the three flow-restriction valve settings as a function of power (speed). These data indicate that a single value may be used to represent blower efficiency over a large range of power and restrictions.

Performance curves for the three test points in Test Case 3 were generated using Equations 5-7 and are presented in Figure 6. A motor efficiency of 70% and a blower efficiency of 34% were used based on the results shown in Figure 5.

Figure 7 shows the results of using the published blower specifications to construct the performance polars. The comparison with the measured test data is very good for the 40- and 30-in. H_2O cases, but rather poor for the 50-in. H_2O case. This is due to the significant disagreement between the test results and published specifications, which were documented in Section 2.

Table 6. Blower efficiencies for Three Fixed-blockage, Variable-speed Test Cases

Measurements (Fixed blockage, variable speed)						Calculations			
Flow		Pressure			Power	Ideal	Total	Motor	Fan
CFM	m^3/s	in H2O	N/m^2	P2	Watts	Power	Eff.	Eff.	Eff.
50in H2O @ 60Hz									
44.9	0.0212	50.0	12400	112000	1120	253	0.227	0.7	0.324
39.1	0.0185	38.0	9460	110000	760	169	0.222	0.7	0.318
36.5	0.0172	33.0	8210	108000	640	138	0.215	0.7	0.307
32.4	0.0153	23.5	5850	106000	420	87.6	0.209	0.7	0.298
29.9	0.0141	20.0	4980	105000	340	69.0	0.203	0.7	0.290
27.3	0.0129	16.5	4110	104000	266	52.1	0.196	0.7	0.280
22.0	0.0104	10.5	2610	103000	168	26.9	0.160	0.7	0.229
15.9	0.0075	4.5	1120	101000	78	8.4	0.107	0.7	0.153
40in H2O @ 60Hz									
53.1	0.0251	40.0	9950	110000	990	241	0.244	0.7	0.348
46.6	0.0220	29.0	7220	107000	645	155	0.240	0.7	0.343
41.1	0.0194	21.5	5350	105000	440	102	0.232	0.7	0.331
28.3	0.0134	9.0	2240	102000	170	29.7	0.175	0.7	0.249
20.3	0.0096	4.5	1120	101000	88	10.7	0.121	0.7	0.174
30in H2O @ 60Hz									
61.6	0.0291	30.0	7470	107000	872	211	0.243	0.7	0.347
50.7	0.0239	21.0	5230	105000	515	123	0.238	0.7	0.341
37.2	0.0176	10.5	2610	103000	235	45.5	0.193	0.7	0.276
28.0	0.0132	5.0	1240	101000	120	16.4	0.136	0.7	0.195

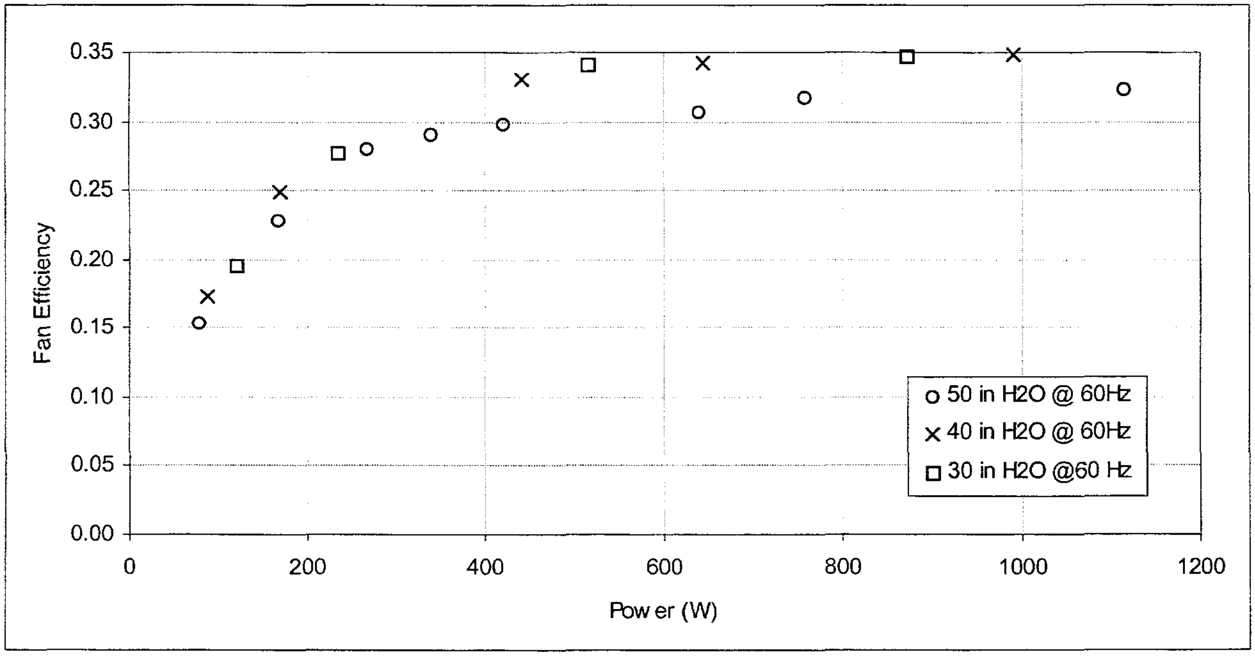


Figure 5. Blower efficiencies for three fixed-blockage, variable-speed test cases plotted as a function of power. The results show that a single value may be used to represent blower efficiency over a large range of powers and blockages. (Assumptions: adiabatic ideal power, motor efficiency of 70%.)

Reference Data (Blower specs @ 60Hz):

	Case			
Case:	A	B	C	
Flow:	44.9	53.1	61.1	(CFM)
Pressure:	50	40	30	(in H2O @ 60 Hz)

1	in H2O =	248.84 N/m^2
1	f^3/m =	0.000472 m^3/s
1.4	= gamma, air	
3.5	= gam/(gam-1)	
100000	= 1 atm (N/m^2) = P1	
0.7	= motor efficiency	
0.34	= fan efficiency	

Calculated Power (adiabatic eqn & efficiencies):

Flow:	0.0212	0.0251	0.0288	(m^3/s)
Pressure:	112442	109953.6	107465.2	(N/m^2)
Ideal Power:	*252.7*	*241.1*	*209.8*	(W)
Est. Actual:	1061.9	1012.9	881.4	(W)

Comparison of Calculate Power-Law Coefficient to Experimental Curve-fit:

"a" Calc.	2.97	3.57	4.34
"a" Exp. Fit.	3.0545	3.5563	4.2113

Comparison of Calculated Power-Law Exponent to Experimental Curve-fit:

"b" Calc.	0.39	0.39	0.39
"b" Exp. Fit.	0.3864	0.3969	0.3974

Calculated Polars, (Flow = a x Power^b):

Power	Flow (CFM)		
(W)	A	B	C
1200	47.1	56.7	68.9
1000	43.9	52.8	64.2
800	40.2	48.4	58.8
700	38.2	46.0	55.8
600	35.9	43.3	52.6
500	33.5	40.3	49.0
400	30.7	37.0	44.9
300	27.4	33.0	40.1
200	23.4	28.2	34.3
100	17.9	21.5	26.1
50	13.6	16.4	20.0
25	10.4	12.5	15.2
0	0.0	0.0	0.0

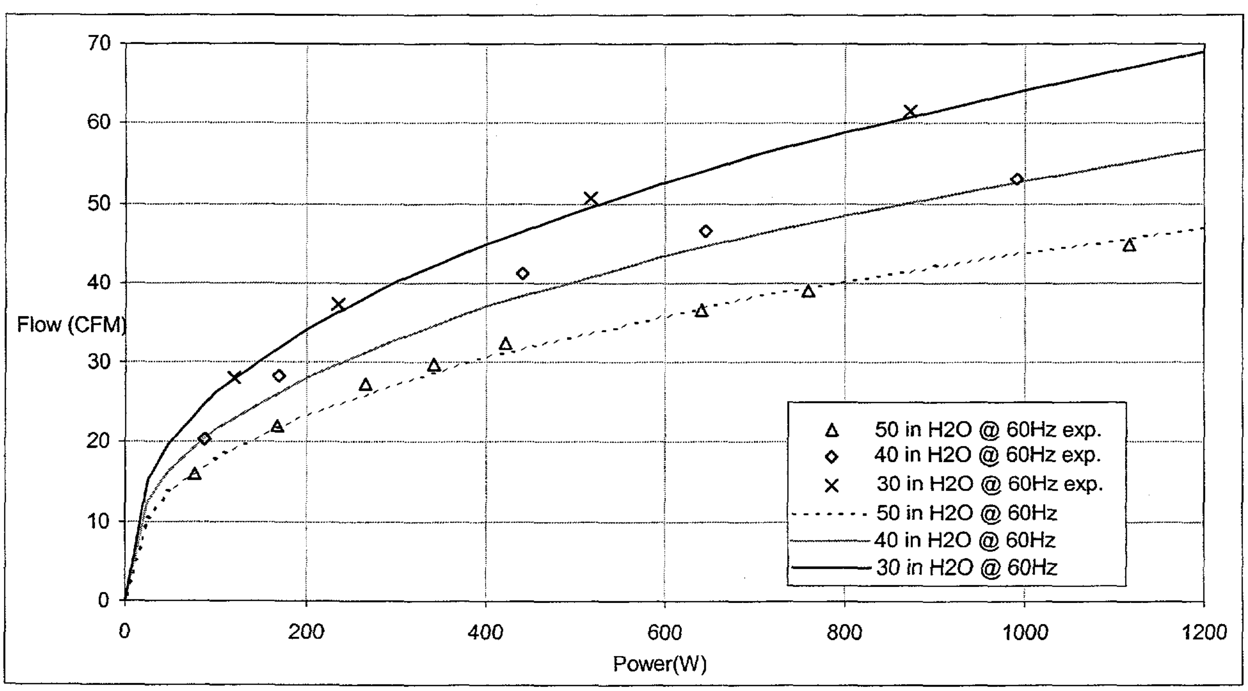


Figure 6. Calculation of blower performance using the semi-empirical model. Comparison of blower performance with experimental results.

Reference Data (Blower specs @ 60Hz):

	Case			
Case:	A	B	C	
Flow:	30	55	69	(CFM)
Pressure:	50	40	30	(in H2O @ 60 Hz)

1 in H2O = 248.84 N/m^2
1 f^3/m = 0.000472 m^3/s
1.4 = gamma, air
3.5 = gam/(gam-1)
100000 = 1 atm (N/m^2) = P1
0.7 = motor efficiency
0.34 = fan efficiency

Calculated Power (adiabatic eqn & efficiencies):

Flow:	0.0142	0.0260	0.0326	(m^3/s)
Pressure:	112442	109953.6	107465.2	(N/m^2)
Ideal Power:	168.9	249.7	236.9	(W)
Est. Actual:	709.5	1049.2	995.4	(W)

Comparison of Calculate Power-Law Coefficient to Experimental Curve-fit:

"a" Calc.	2.32	3.65	4.67
"a" Exp. Fit.	3.0545	3.5563	4.2113

Comparison of Calculated Power-Law Exponent to Experimental Curve-fit:

"b" Calc.	0.39	0.39	0.39
"b" Exp. Fit.	0.3864	0.3969	0.3974

Calculated Polars, (Flow = a x Power^b):

Power	Flow (CFM)		
(W)	A	B	C
1200	36.8	58.0	74.2
1000	34.3	54.0	69.1
800	31.4	49.5	63.4
700	29.8	47.0	60.1
600	28.1	44.2	56.6
500	26.2	41.2	52.8
400	24.0	37.8	48.4
300	21.4	33.8	43.2
200	18.3	28.8	36.9
100	14.0	22.0	28.2
50	10.7	16.8	21.5
25	8.1	12.8	16.4
0	0.0	0.0	0.0

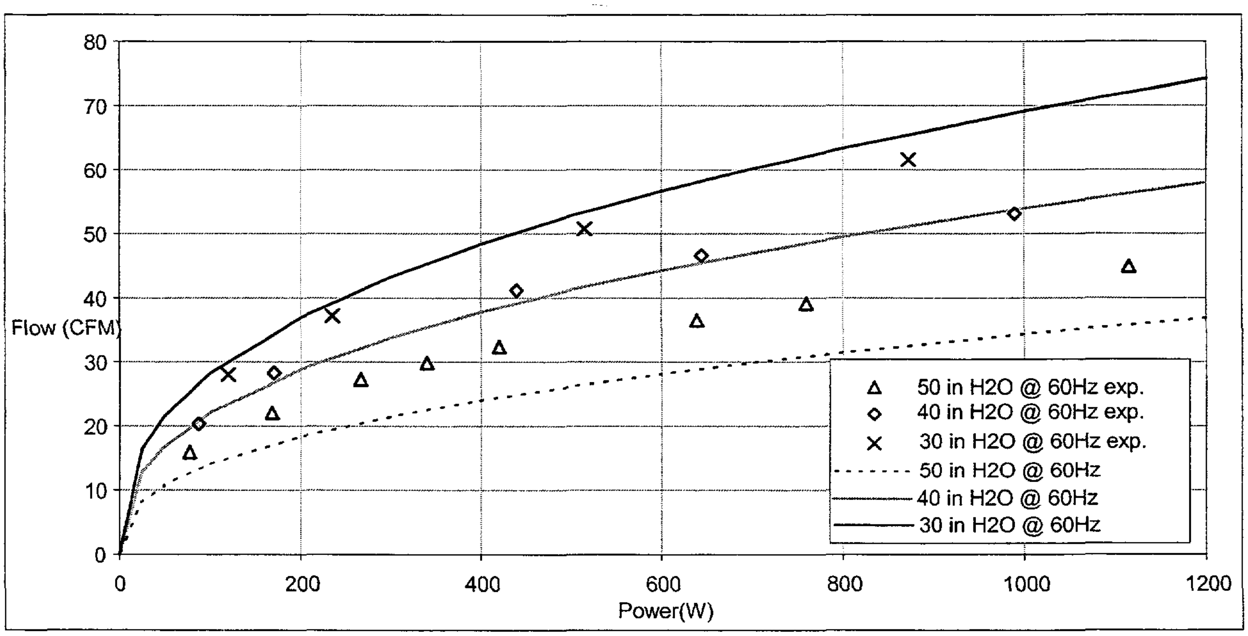


Figure 7. Comparison of math-model generated blower performance to test data. The large discrepancy between the measured test results and the math-model generated results for the 50-in. H_2O case reflects the significant disagreement between the measured and published performance for this blower.

4. Concept System Design and Specifications

This section describes the solar-powered remediation system concept and component specifications. Three system operational types are presented–diurnal, variable cycle, and continuous–for two power ratings each. System performance and specifications are predicted for each system type using a numerical simulation based on the math model defined in Section 3. The resulting specifications are used to determine system life-cycle costs, which are discussed in Section 5.

Concept Description

Figure 8 is an illustration of two types of solar-powered soil remediation venting systems. On the left is a system that operates on a diurnal cycle, that is, the power to the motor is equivalent to the energy available from the sun. Peak flow rates occur at mid-day and lower flow rates occur in the morning and evening hours. For continuous or variable-cycle operation, a larger solar array and battery energy storage can be used as shown on the right. For both types of systems, the process may be reversed (i.e., air can be blown into the ground) to accommodate the specified type of remediation required.

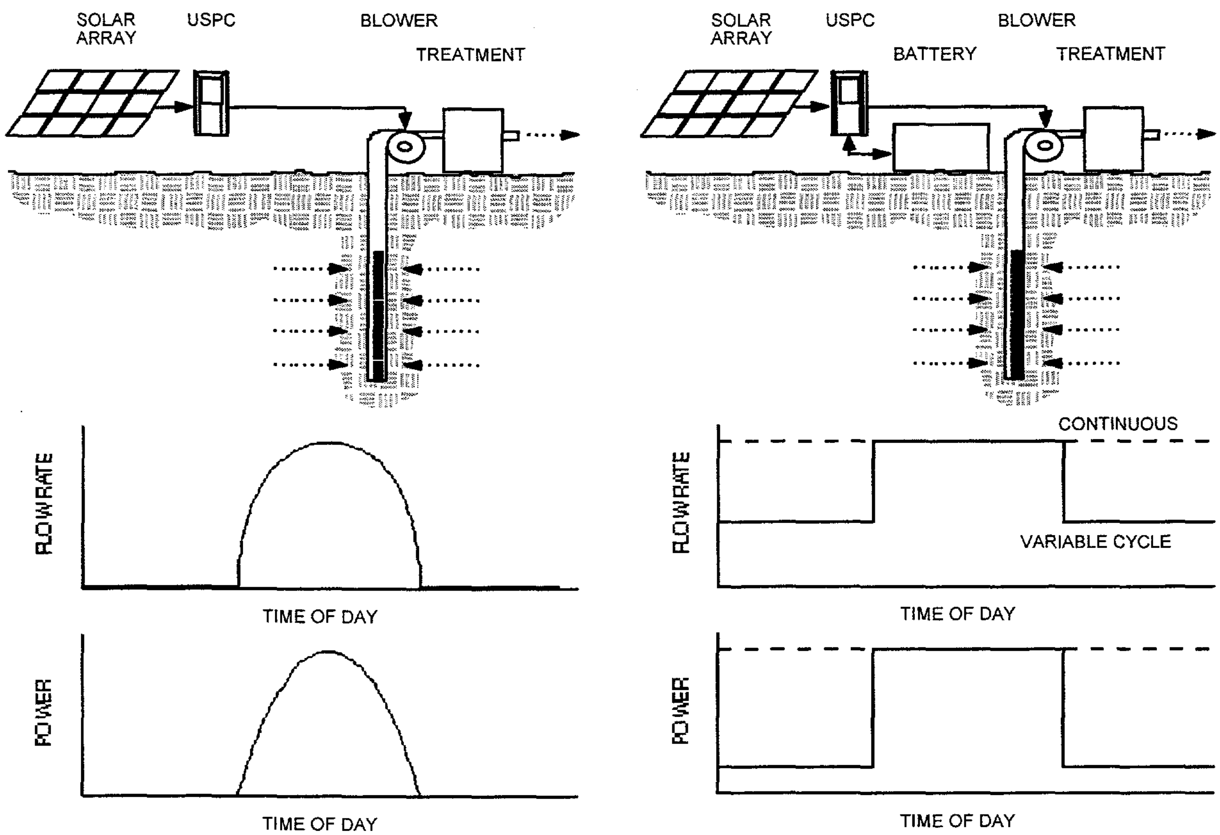


Figure 8. Illustrations of the solar-powered remediation concepts for diurnal (left) and both variable-cycle and continuous operation (right).

The key components of a solar-powered venting system are

- solar panels and support structure,
- a power converter to change the solar panel DC current to AC for the blower,
- the blower, and
- batteries.

Solar panels are a proven and reliable technology that convert solar radiation to electricity. They are commercially available and typically guaranteed for 20 years. Unlike a utility connection, the solar panels can be moved to a new location, thus greatly reducing the cost of future installations. The solar array can be supported by a modular aluminum structure that can be set up, taken down, and moved easily, or the array can be mounted on a trailer for easy set up and relocation.

The power converter changes the DC power from the solar panels or batteries to AC electrical power. Although there are several converters available to perform this function, only the AeroVironment USPC, which matches the load (by varying the motor speed) to the power available from a PV array, is specifically designed for outdoor industrial uses, and to operate large (greater than 1/3 hp) induction motors of almost any type.

The blower used is an explosion-proof regenerative blower. This blower is used because its pressure-flow curves closely match the needs of the remediation industry. The possible presence of volatile vapors necessitates that the blower be explosion proof.

Deep-cycle batteries are needed for the variable- and continuous-cycle systems. Cost, maintenance, and adequate life are the driving factors when choosing batteries. Because the systems remain at one site for a year or more, weight and volume are less important.

System Design Specifications and Predicted Performance

To assess the technical and economic competitiveness of the solar-powered system concept, general specifications are recommended. Three types of systems are considered, each targeting different remediation technology characteristics:

- ***Diurnal systems***–These systems operate only when power is available from the sun and represent the least expensive and most efficient type of system. The diurnal system is suitable for remediation technologies amenable to cycling without a degradation in the effectiveness in the fundamental processes. For aerobic processes, equivalent peak wellhead pressures and flow rates are required for at least a short interval to achieve the same zone of influence. For pump and treat processes, the diurnal system must deliver the same quantity of groundwater to the treatment process.
- ***Variable-cycle systems***–These systems use batteries to store energy during daylight hours for use at night and under low-light conditions. These systems employ a variable cycle in which maximum blower performance is achieved only during a few hours each day and 50% flow rates are available during the remainder of each day. This type of system is most suitable for sites or processes that require a minimum performance threshold to maintain effectiveness on a continual basis, and some higher performance requirement on a periodic basis to maintain an effective zone of influence. For aerobic processes, equivalent peak wellhead pressures and flow rates are required for at least a short interval. For pump and treat processes, the minimum

performance condition must be capable of pumping water with an equivalent total delivery of groundwater.

- ***Continuous-duty systems***–These types of systems operate the remediation equipment continuously, as if operating from utility power. These systems are analogous to conventional grid-connected systems and are most suitable for remediation processes requiring certain controlled operating conditions.

Each of these system types was evaluated using blowers rated at 1.1 hp and 2.5 hp, which represent the most directly applicable portion of the target market. Table 7 summarizes the compatibility of each remediation technology with the three solar-powered system concepts and the respective constraints for equivalency to a conventional system.

Table 7. Remediation Technology and Solar-powered System Compatibility Matrix

Technology	*Constraints*	*Equiv. Sys.*	*Diurnal*	*Variable*	*Continuous*	*Comments*
Soil Vapor Extraction	Min. Pres. Total Flow	Same Pump	Not a Fit	Good Fit*	Equivalent	Process dependent on minimum pressure for volitalization. Equivalent solar system needs to achieve same total flow.
Bioventing	Peak Pres. Peak Flow	Same Pump	Good Fit	Good Fit	Equivalent	Aerobic process depends on periodic introduction of Oxygen for equivalent zone of influence. Solar system must achieve same peak flow and pressure for some period of time.
Biopiles - Ex Situ SVE	Peak Pres. Peak Flow	Same Pump	Good Fit	Good Fit	Equivalent	Aerobic process depends on periodic introduction of Oxygen for equivalent zone of influence. Solar system must achieve same peak flow and pressure for some period of time.
Air Sparging	Peak Pres. Peak Flow	Same Pump	Good Fit	Good Fit	Equivalent	Aerobic process depends on periodic introduction of Oxygen for equivalent zone of influence. Solar system must achieve same peak flow and pressure for some period of time.
Biosparging	Peak Pres. Peak Flow	Same Pump	Good Fit	Good Fit	Equivalent	Aerobic process depends on periodic introduction of Oxygen for equivalent zone of influence. Solar system must achieve same peak flow and pressure for some period of time.
Groundwater Pumping	Min. Pres. Total Flow	Same or Larger Pump	Good Fit	Good Fit	Equivalent	Minimum power required to lift water. Equivalent solar system needs to achieve same total flow.

* *Recent experience suggests that "pulsing" the process does not have a significant negative impact on system performance.*

Six systems, based on the remediation technologies most suited to solar-powered remediation were evaluated using a numerical simulation based on the math model described in Section 3. (That is, systems able to operate on a diurnal or variable cycle. Systems needing continuous operation are probably too expensive to be practical. See Section 1.) These systems are numbered according to the definitions listed in Table 8.

Table 8. System Numbers and Definitions

	System Number	
Cycle	1.1 hp	2.5 hp
Diurnal	1	4
Variable	2	5
Continuous	3	6

Component Selection

Solar Panels and Support Structure

The solar panels used can be single-crystal, poly-crystal, or thin-film PV technology. For a 208-V, 3-phase motor, they need to be connected in series for an array-rated voltage of about 350-V (at operating temperature). The array is mounted on an aluminum "skid" that can be easily transported and set up in the field. Skid mounting is less expensive than mounting the arrays on trailers.

USPC Power Electronics

For a diurnal system, the USPC operates as it would when it is used to operate water pumps (the more solar power available, the more water or air pumped), so no modifications are needed. The USPC performs peak power tracking by modulating motor speed. The USPC is greater than 95% efficient over most of its operating range, which makes the conversion from solar to AC power extremely efficient.

For the variable- and continuous-cycle systems, a battery pack is connected to the DC bus of the USPC. To use the USPC in this application, the maximum battery equalization voltage needs to be less than 400 V. The USPC contains a regulating circuit that can be software controlled to limit battery voltage when charging (voltage can be periodically raised to accomplish equalization). In variable-speed operation, the software in the USPC can be modified to operate the blower at the speed that corresponds to 50% flow at night and 100% flow and speed during the day. In continuous operation, the USPC operates the blower at full speed regardless of time of day. Battery voltage can be monitored and the system operation modified or shut down if the voltage falls below a specified value, such as during extended cloudy periods. Thus, minor modifications to the USPC are required to accommodate the variable- and continuous-operation modes.

Blower

The blowers selected for this study were a 1.1-hp and a 2.5-hp regenerative blower, which are similar to those used at many remediation sites. The variable-speed performance was modeled and described in Section 3. A 208-VAC, 3-phase motor closely matches the operating voltages for the USPC used with batteries. A battery pack with a 400-V equalization limit will have approximately a 325-V nighttime operating point (which is close to full speed on a 208-V motor).

Battery Selection

Solar-charged batteries in remote locations present a variety of challenges for battery selection. The batteries need to have very good cycle life, tolerate cycling at various DODs due to weather, and tolerate cycling in warm or hot climates. Also, the charging time is somewhat limited with solar power, and shallower DODs may be needed to permit full recharge of the battery. For this study, we were primarily interested in commercially available components, so we primarily investigated batteries with a proven record of performance.

The driving factors for selecting batteries were as follows:

- Availability
- Cost
- Maintenance
- Adequate cycle life

Table 9 shows the battery chemistries considered. Both nickel-iron and nickel-cadmium have the ideal chemistry for this application–long life and deep DOD for a large number of cycles–but cost and availability ruled these out. Lithium-ion and nickel-metal hydride have good specific power and energy for mobile applications, but these attributes are not important in this application. Zinc-bromide is a good chemistry for this system, but its laboratory status eliminated it as a potential candidate. Availability and cost reduced the desirability of all the chemistries except for lead-acid.

Table 9. Battery Chemistries Considered

	Pros	Cons
Lead-acid	Inexpensive. Field tested.	Shallow DOD.
Nickel-iron	Superior life (> 10 years in this application). Deep DOD possible.	Not readily available, must be imported from China. Frequent watering needed. 3-5 times the cost of lead-acid.
Nickel-cadmium	Long life.	Frequent watering needed. 3-5 times the cost of lead-acid.
Lithium-ion		Laboratory status. Proper charging is critical.
Nickel-metal hydride		Cost.
Zinc-bromide	Deep DOD possible.	Laboratory status. Accessory pump and controls not field proven.

With lead-acid selected as the preferred battery chemistry, the next step was to evaluate which technology would work the best—flooded, gel, or absorbed glass mat (AGM) cells, which are shown in Table 10. True deep-discharge flooded cells have been available for some time; they have been used at solar and other remote sites for back-up power. Gel and AGM batteries were developed to provide a maintenance-free, sealed battery that did not need a separate vented room. Initially, these batteries were designed for the uninterruptible power supply (UPS) and electric vehicle industries. However, the UPS industry only needed standby power, not the regular cycling that a true deep-discharge battery could offer. Consequently, batteries developed for this industry tended to have below average deep cycling capability. Recently, a few gel and AGM batteries have been designed for deep cycling. These batteries are low maintenance and cycle almost as well as flooded cells, but are more susceptible to damage from misuse and high-temperature cycling.

Table 10. Comparison of Lead-acid Deep-cycle Technologies

Lead-acid Deep-cycle Technologies	Pros	Cons
Flooded	Excellent deep cycle capability. Excellent cycling ability in a hot environment. Resistant to misuse. Low cost.	Maintenance– Water replacement. Cleaning terminals.
Gel	Very little maintenance.	Poor performance in hot weather. Less robust than flooded.
AGM	Very little maintenance.	Poor performance in hot weather. Less robust than flooded.

The Ah discharges for the various systems, which are based on results from the numerical simulation discussed under the heading "Numerical Simulation–System Sizing, Performance, and Cost Prediction" in this section, are shown in Table 11.

Table 11. Ah Discharges for Various Systems

System #	2	3	5	6
Daily Ah Discharge	8	45	16	100

Given the daily Ah requirement, several battery models were investigated to select the lowest cost and best performing battery. The life cycles used reflect manufacturer's data at the given DOD (none higher than 30%) and at 95°F and a 10-hour discharge rate. Manufacturers usually rate battery cycle life as a function of DOD at 25°C (77°F) and at a favorable discharge rate (about a 1- to 2-hour rate for a battery discharged to 30% DOD). Raising the temperature 8°C can cut the cycle life for the flooded battery about 5% and 25 to 50% for the gel and AGM batteries. Discharging to 30% DOD at the 10-hour rate can cut the cycle life of the flooded battery about 25% and 25% to 50% for the gel and AGM batteries.

The economic comparison of the batteries is shown in Table 12. The initial cost is the list price for the first pack and the 10-year cost is the list price for the number of packs needed over the 10-year life of the system. Packs are rounded up to the nearest whole pack and a minimum of two packs are used because one lead-acid pack will not last for 10 years in a remote environment.

Table 12. Economic Comparison of Lead-acid Technologies

Daily Ah	Model	Technology	Ah	Battery Voltage	Price $	Predicted Life Cycles	@ DOD %	Initial Cost $	10-yr Cost $	# Battery Packs in 10 yr
8	27TMH	Flooded	115	12	105	1925	7	2730	5500	1.9
8	DC-22F	Flooded	50	12	50	640	16	1300	7800	5.7
8	G12V42AhSP	Absorbed Glass Mat	42	12	105	1500	19	2730	8200	2.4
8	T105	Flooded	217	6	82	6000	4	4264	8600	0.6
8	GC12V100B	Gel	90	12	166	3000	9	4308	8700	1.2
8	G12V70AhSP	Absorbed Glass Mat	70	12	167	2250	11	4342	8700	1.6
16	27TMH	Flooded	115	12	105	1350	14	2730	8200	2.7
16	T105	Flooded	217	6	82	6000	7	4264	8600	0.6
16	GC12V100B	Gel	90	12	166	3000	18	4308	8700	1.2
45	T105	Flooded	217	6	82	2150	21	4264	8600	1.7
45	L16	Flooded	350	6	197	2400	13	10244	20500	1.5
100	T105	Flooded	217	6	82	1650	23	8528	25600	2.5
100	L16	Flooded	350	6	197	2275	14	20488	41000	1.6

Batteries are sorted in order from least 10-year cost to most expensive. The 27TMH and the DC-22F batteries should only be selected if there is monthly access to the site as they need frequent watering. The other flooded batteries are available in models with extra electrolyte capacity, prolonging maintenance intervals to at least every six months. The gel and AGM batteries should be thoroughly tested in the field before widespread use. These batteries are not as robust as the flooded cells and are more prone to high-temperature failure.

The batteries selected for each of the systems under consideration are shown in Table 13. The 27TMH and the DC-22F batteries were not chosen because of their frequent maintenance needs. With only a small price penalty in System 2, the T105 battery would have worked for all four of the systems.

Table 13. Batteries Selected for Systems under Consideration

System	2	3	5	6
Selected Battery	G12V42AhSP	T105	T105	T105

Battery Accessories

Accessories to enhance battery life or prolong maintenance intervals include a watering system to keep flooded batteries full and insulated battery containers to keep them cool. Watermaster makes an automatic watering system for about $20 per cell, or $120 for a 12-V battery. This, along with proper sealing of the terminals, would extend the maintenance interval of flooded cells to once a year. If battery maintenance is a key selection criterion, the cost of the watering system would have to be weighed against the cost of an insulated battery box that the low maintenance batteries would need in a hot environment. Some AGM batteries are susceptible to hot spots and thermal runaway in hot temperatures. Zomeworks makes a "cool cell" designed to maintain the battery temperature 20 to 30°F below the ambient high temperature. The price for a 100-Ah cool-cell system is $12,680.

Numerical Simulation - System Sizing, Performance, and Cost Prediction

The numerical simulation described in Section 3 was used to determine the appropriate solar array rating and battery size to achieve the desired performance for each of the six target systems. These specifications were then used to determine the life-cycle cost of each system configuration. The results of the numerical simulations for each of the six target systems are provided below and include a detailed system specification. The total system cost and performance were also calculated and presented.

The following assumptions were used in the calculations:

- The total solar resource is 6 kWh/m^2, 12-hour day.
- The blower parameters are taken from the manufacturer's rated flow at 40 in. H_2O and full speed (B is 1.1-hp data and C is 2.5-hp data).
- The power available from the solar array is the rated value at 1000 W/m^2 and the cost is $6.00/W.
- Lead-acid batteries were used with a maximum DOD of 20%. The specific batteries selected are shown in Table 13. Battery hardware cost is $1.00/Ah.
- The cost for an aluminum support structure for the PV array is $1.00/W PV and the cost per trailer (each trailer can carry 1800 W) is $4500.
- USPC cost is $1200.
- Labor costs for assembly are included.
- No battery accessories are included.
- Total system costs are representative of wholesale costs plus typical commercial mark-up.
- For this study, a stationary array structure was selected instead of trailers to reduce system cost.

System 1. 1.1-hp Blower, Diurnal Cycle

Solar Resource

6 Sun Hours
6 kWh/day/m^2

Blower Parameters

B Enter case A, B, or C (from Comp Model) (in. H20 Pressure at 60 Hz.)

Power Consumption

1049 W, Load at full speed
0% Flow Rate, non-daylight hours
0.00 W, Load at reduced flow rate
7,418 Wh/day, Load variable cycle
y Diurnal (y or n, n for battery)

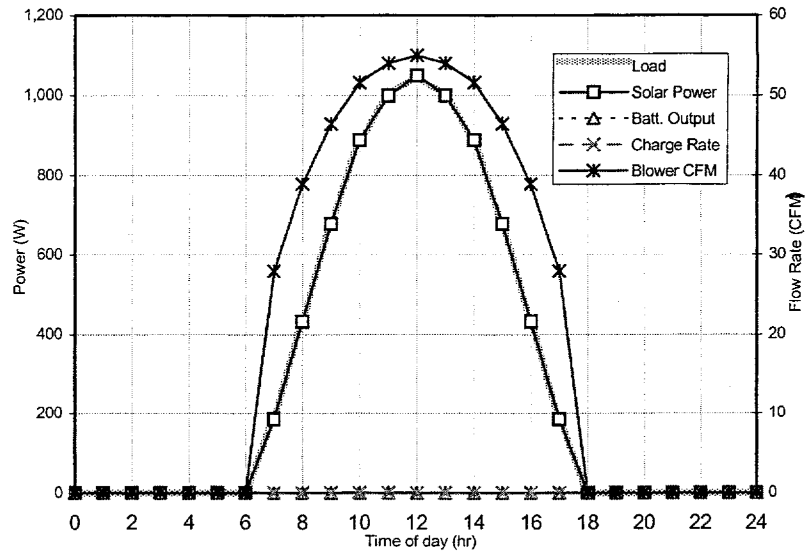
Power Available from Solar Array

1250 W, array rating
7,418 Wh/day needed by system
1234 W, array rating (calc)

Battery Energy Storage Required

30% losses from energy storage
20% Allowable discharge
15.4 Volts, max. battery voltage
12.8 Volts, nominal battery voltage
0.0 Ah/Battery
400 Volts, max. pack voltage
26 Batteries in series
1 Parallel String(s) of Batteries
0.7 lb./Ah
332.8 Volts, Nominal Pack Voltage
0 Ah Pack rating
0 Wh, Required
0 Wh, Req'd pack size w/DoD
0 Ah, Needed Pack rating
0 lb., Battery Pack Weight

Simulation



Time (hr)	Insolation (W/m^2)	Load (W)	Solar Power (W)	Batt. Output (W)	Battery Energy (Ah)	Charge Rate (W)	Blower CFM (ft^3/min)
0	0	0	0	0	0	0	0.00
1	0	0	0	0	0	0	0.00
2	0	0	0	0	0	0	0.00
3	0	0	0	0	0	0	0.00
4	0	0	0	0	0	0	0.00
5	0	0	0	0	0	0	0.00
6	0	0	0	0	0	0	0.00
7	150	185	185	0	0	0	27.96
8	350	432	432	0	0	0	38.91
9	550	679	679	0	0	0	46.41
10	720	889	889	0	0	0	51.55
11	810	1,000	1,000	0	0	0	53.98
12	850	1,049	1,049	0	0	0	55.00
13	810	1,000	1,000	0	0	0	53.98
14	720	889	889	0	0	0	51.55
15	550	679	679	0	0	0	46.41
16	350	432	432	0	0	0	38.91
17	150	185	185	0	0	0	27.96
18	0	0	0	0	0	0	0.00
19	0	0	0	0	0	0	0.00
20	0	0	0	0	0	0	0.00
21	0	0	0	0	0	0	0.00
22	0	0	0	0	0	0	0.00
23	0	0	0	0	0	0	0.00
24	0	0	0	0	0	0	0.00
	Total Wh	7,418	7,418	0			

Max DOD
Total Ah used 0.0

Total Manufacturers Price **$14,625**

10 Year Price **$14,625**

Total Volume Pumped (ft^3) **29,558**

System 2. 1.1-hp Blower, Variable Cycle

Solar Resource

6 Sun Hours
6 kWh/day/m^2

Blower Parameters

B Enter case A, B, or C (from Comp Model) (in. H20 Pressure at 60 Hz.)

Power Consumption

1049 W, Load at full speed
50% Flow Rate, non-daylight hours
177.41 W, Load at reduced flow rate
10,537 Wh/day, Load variable cycle
n Diurnal (y or n, n for battery)

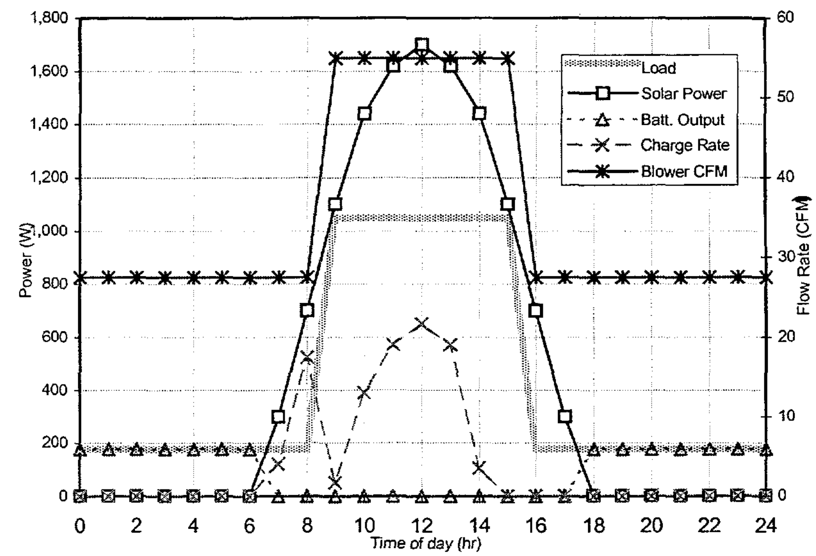
Power Available from Solar Array

2000 W, array rating
11,283 Wh/day needed by system
1880 W, array rating (calc)

Battery Energy Storage Required

30% losses from energy storage
20% Allowable discharge
15.4 Volts, max. battery voltage
12.8 Volts, nominal battery voltage
40.0 Ah/Battery
400 Volts, max. pack voltage
26 Batteries in series
1 Parallel String(s) of Batteries
0.7 lb./Ah
332.8 Volts, Nominal Pack Voltage
40 Ah Pack rating
2,484 Wh, Required
12,418 Wh, Req'd pack size w/DoD
37 Ah, Needed Pack rating
728 lb., Battery Pack Weight

Simulation



Time (hr)	Insolation (W/m^2)	Load (W)	Solar Power (W)	Batt. Output (W)	Battery Energy (Ah)	Charge Rate (W)	Blower CFM (ft^3/min)
0	0	177	0	177	36	0	27.50
1	0	177	0	177	35	0	27.50
2	0	177	0	177	35	0	27.50
3	0	177	0	177	34	0	27.50
4	0	177	0	177	34	0	27.50
5	0	177	0	177	33	0	27.50
6	0	177	0	177	33	0	27.50
7	150	177	300	0	33	123	27.50
8	350	177	700	0	34	523	27.50
9	550	1,049	1,100	0	34	51	55.00
10	720	1,049	1,440	0	35	391	55.00
11	810	1,049	1,620	0	37	571	55.00
12	850	1,049	1,700	0	38	651	55.00
13	810	1,049	1,620	0	40	571	55.00
14	720	1,049	1,440	0	40	106	55.00
15	550	1,049	1,100	0	40	0	55.00
16	350	177	700	0	40	0	27.50
17	150	177	300	0	40	0	27.50
18	0	177	0	177	39	0	27.50
19	0	177	0	177	39	0	27.50
20	0	177	0	177	38	0	27.50
21	0	177	0	177	38	0	27.50
22	0	177	0	177	37	0	27.50
23	0	177	0	177	37	0	27.50
24	0	177	0	177	36	0	27.50
	Total Wh	10,537	12,020	2,484			

Max DOD 18.7%
Total Ah used 7.5

Total Manufacturers Price **$25,638**

10 Year Price **$32,475**

Total Volume Pumped (ft^3) **52,800**

System 3. 1.1-hp Blower, Continuous Operation

Solar Resource

6 Sun Hours
6 kWh/day/m^2

Blower Parameters

B Enter case A, B, or C (from Comp Model) (in. H20 Pressure at 60 Hz.)

Power Consumption

1049 W, Load at full speed
100% Flow Rate, non-daylight hours
1049.16 W, Load at reduced flow rate
26,229 Wh/day, Load variable cycle
n Diurnal (y or n, n for battery)

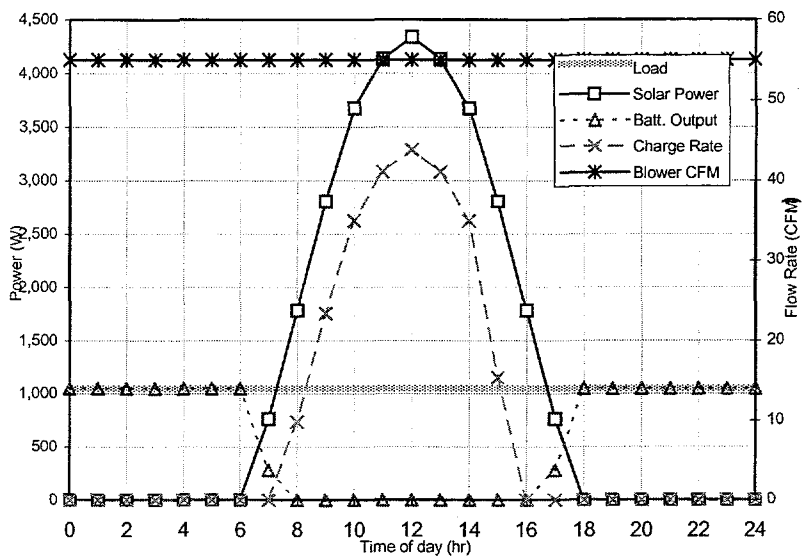
Power Available from Solar Array

5100 W, array rating
30,806 Wh/day needed by system
5134 W, array rating (calc)

Battery Energy Storage Required

30% losses from energy storage
20% Allowable discharge
15.4 Volts, max. battery voltage
12.8 Volts, nominal battery voltage
230.0 Ah/Battery
400 Volts, max. pack voltage
26 Batteries in series
1 Parallel String(s) of Batteries
0.7 lb./Ah
332.8 Volts, Nominal Pack Voltage
230 Ah Pack rating
15,257 Wh, Required
76,283 Wh, Req'd pack size w/DoD
229 Ah, Needed Pack rating
4,186 lb., Battery Pack Weight

Simulation



Time (hr)	Insolation (W/m^2)	Load (W)	Solar Power (W)	Batt. Output (W)	Battery Energy (Ah)	Charge Rate (W)	Blower CFM (ft^3/min)
0	0	1,049	0	1,049	204	0	55.00
1	0	1,049	0	1,049	201	0	55.00
2	0	1,049	0	1,049	198	0	55.00
3	0	1,049	0	1,049	194	0	55.00
4	0	1,049	0	1,049	191	0	55.00
5	0	1,049	0	1,049	188	0	55.00
6	0	1,049	0	1,049	185	0	55.00
7	150	1,049	765	284	184	0	55.00
8	350	1,049	1,785	0	186	736	55.00
9	550	1,049	2,805	0	190	1756	55.00
10	720	1,049	3,672	0	197	2623	55.00
11	810	1,049	4,131	0	205	3082	55.00
12	850	1,049	4,335	0	213	3286	55.00
13	810	1,049	4,131	0	221	3082	55.00
14	720	1,049	3,672	0	227	2623	55.00
15	550	1,049	2,805	0	230	1150	55.00
16	350	1,049	1,785	0	**230**	0	55.00
17	150	1,049	765	284	229	0	55.00
18	0	1,049	0	1,049	226	0	55.00
19	0	1,049	0	1,049	223	0	55.00
20	0	1,049	0	1,049	220	0	55.00
21	0	1,049	0	1,049	217	0	55.00
22	0	1,049	0	1,049	213	0	55.00
23	0	1,049	0	1,049	210	0	55.00
24	0	1,049	0	1,049	207	0	55.00
	Total Wh	26,229	30,651	15,257			

Max DOD 19.9%
Total Ah used 45.8

Total Manufacturers Price

$59,075

10 Year Price

$64,325

Total Volume Pumped (ft^3) **82,500**

System 4. 2.5-hp Blower, Diurnal Cycle

Solar Resource

6 Sun Hours
6 kWh/day/m^2

Blower Parameters

C Enter case A, B, or C (from Comp Model) (in. H20 Pressure at 60 Hz.)

Power Consumption

2251 W, Load at full speed
0% Flow Rate, non-daylight hours
0.00 W, Load at reduced flow rate
15,915 Wh/day, Load variable cycle
y Diurnal (y or n, n for battery)

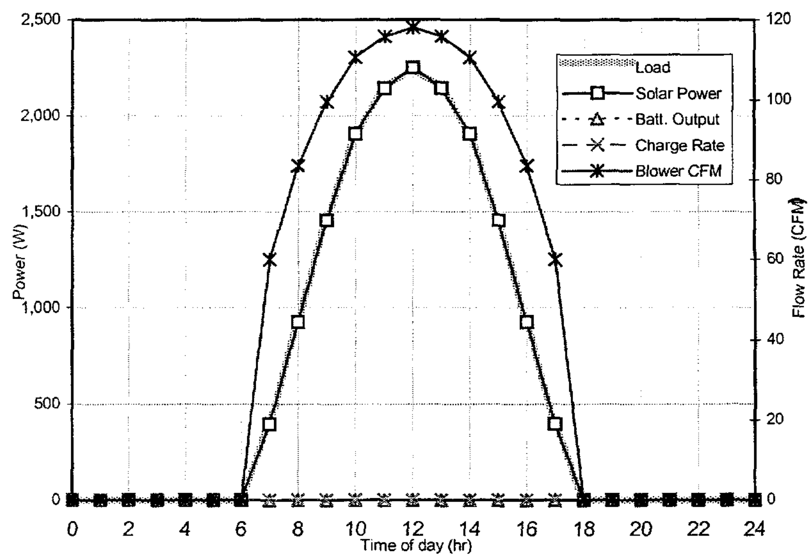
Power Available from Solar Array

2650 W, array rating
15,915 Wh/day needed by system
2648 W, array rating (calc)

Battery Energy Storage Required

30% losses from energy storage
20% Allowable discharge
15.4 Volts, max. battery voltage
12.8 Volts, nominal battery voltage
0.0 Ah/Battery
400 Volts, max. pack voltage
26 Batteries in series
1 Parallel String(s) of Batteries
0.7 lb./Ah
332.8 Volts, Nominal Pack Voltage
0 Ah Pack rating
0 Wh, Required
0 Wh, Req'd pack size w/DoD
0 Ah, Needed Pack rating
0 lb., Battery Pack Weight

Simulation



Time (hr)	Insolation (W/m^2)	Load (W)	Solar Power (W)	Batt. Output (W)	Battery Energy (Ah)	Charge Rate (W)	Blower CFM (ft^3/min)
0	0	0	0	0	0	0	0.00
1	0	0	0	0	0	0	0.00
2	0	0	0	0	0	0	0.00
3	0	0	0	0	0	0	0.00
4	0	0	0	0	0	0	0.00
5	0	0	0	0	0	0	0.00
6	0	0	0	0	0	0	0.00
7	150	397	397	0	0	0	59.99
8	350	927	927	0	0	0	83.48
9	550	1,456	1,456	0	0	0	99.57
10	720	1,907	1,907	0	0	0	110.60
11	810	2,145	2,145	0	0	0	115.80
12	850	2,251	2,251	0	0	0	118.00
13	810	2,145	2,145	0	0	0	115.80
14	720	1,907	1,907	0	0	0	110.60
15	550	1,456	1,456	0	0	0	99.57
16	350	927	927	0	0	0	83.48
17	150	397	397	0	0	0	59.99
18	0	0	0	0	0	0	0.00
19	0	0	0	0	0	0	0.00
20	0	0	0	0	0	0	0.00
21	0	0	0	0	0	0	0.00
22	0	0	0	0	0	0	0.00
23	0	0	0	0	0	0	0.00
24	0	0	0	0	0	0	0.00
Total Wh		15,915	15,915	0			

Max DOD
Total Ah used 0.0

Total Manufacturers Price **$28,625**

10 Year Price **$28,625**

Total Volume Pumped (ft^3) **63,414**

System 5. 2.5-hp Blower, Variable Cycle

Solar Resource

6 Sun Hours
6 kWh/day/m^2

Blower Parameters

C Enter case A, B, or C
(from Comp Model)
(in. H20 Pressure at 60 Hz.)

Power Consumption

2251 W, Load at full speed
50% Flow Rate, non-daylight hours
380.62 W, Load at reduced flow rate
22,608 Wh/day, Load variable cycle
n Diurnal (y or n, n for battery)

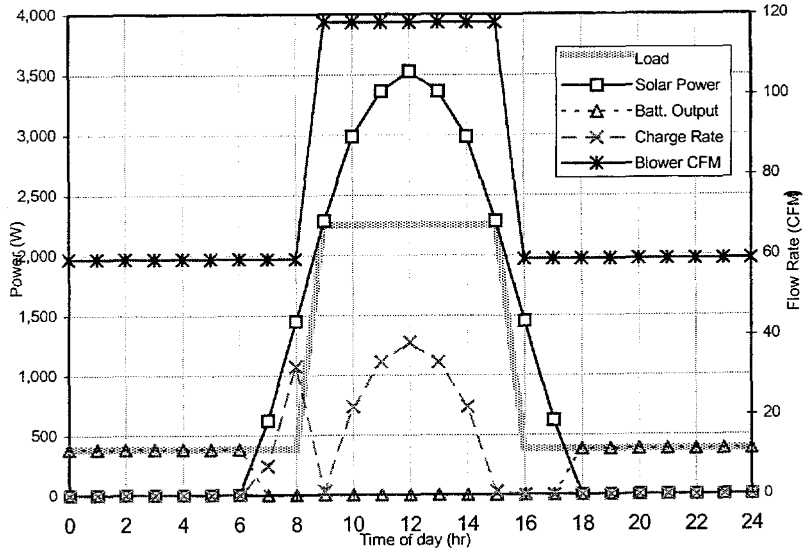
Power Available from Solar Array

4150 W, array rating
24,206 Wh/day needed by system
4034 W, array rating (calc)

Battery Energy Storage Required

30% losses from energy storage
20% Allowable discharge
15.4 Volts, max. battery voltage
12.8 Volts, nominal battery voltage
80.0 Ah/Battery
400 Volts, max. pack voltage
26 Batteries in series
1 Parallel String(s) of Batteries
0.7 lb./Ah
332.8 Volts, Nominal Pack Voltage
80 Ah Pack rating
5,329 Wh, Required
26,643 Wh, Req'd pack size w/DoD
80 Ah, Needed Pack rating
1,456 lb., Battery Pack Weight

Simulation



Time (hr)	Insolation (W/m^2)	Load (W)	Solar Power (W)	Batt. Output (W)	Battery Energy (Ah)	Charge Rate (W)	Blower CFM (ft^3/min)
0	0	381	0	381	71	0	59.00
1	0	381	0	381	70	0	59.00
2	0	381	0	381	69	0	59.00
3	0	381	0	381	67	0	59.00
4	0	381	0	381	66	0	59.00
5	0	381	0	381	65	0	59.00
6	0	381	0	381	64	0	59.00
7	150	381	623	0	65	242	59.00
8	350	381	1,453	0	67	1072	59.00
9	550	2,251	2,283	0	67	32	118.00
10	720	2,251	2,988	0	69	737	118.00
11	810	2,251	3,362	0	72	1111	118.00
12	850	2,251	3,528	0	75	1277	118.00
13	810	2,251	3,362	0	78	1111	118.00
14	720	2,251	2,988	0	80	737	118.00
15	550	2,251	2,283	0	80	32	118.00
16	350	381	1,453	0	80	0	59.00
17	150	381	623	0	80	0	59.00
18	0	381	0	381	79	0	59.00
19	0	381	0	381	78	0	59.00
20	0	381	0	381	77	0	59.00
21	0	381	0	381	75	0	59.00
22	0	381	0	381	74	0	59.00
23	0	381	0	381	73	0	59.00
24	0	381	0	381	72	0	59.00
	Total Wh	22,608	24,942	5,329			

Max DOD 20.0%
Total Ah used 16.0

Total Manufacturers Price **$49,200**

10 Year Price **$54,575**

Total Volume Pumped (ft^3) **113,280**

System 6. 2.5-hp Blower, Continuous Operation

Solar Resource

6 Sun Hours
6 kWh/day/m^2

Blower Parameters

C Enter case A, B, or C (from Comp Model) (in. H20 Pressure at 60 Hz.)

Power Consumption

2251 W, Load at full speed
100% Flow Rate, non-daylight hours
2250.92 W, Load at reduced flow rate
56,273 Wh/day, Load variable cycle
n Diurnal (y or n, n for battery)

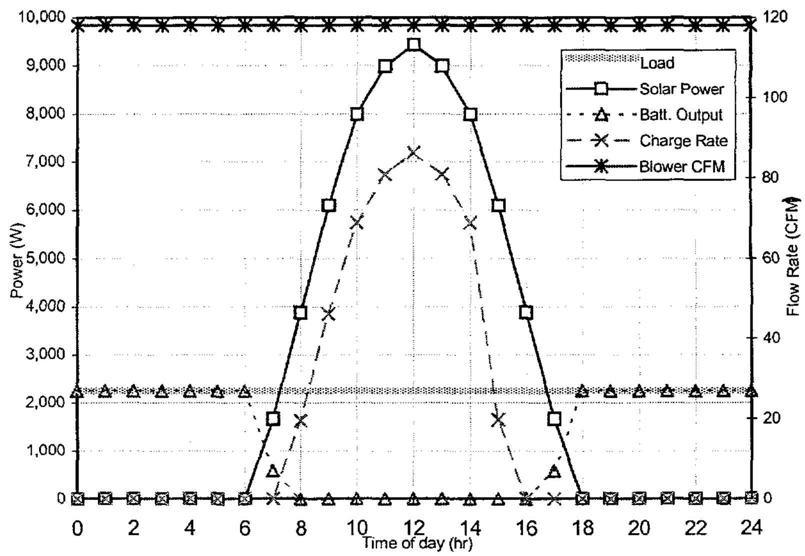
Power Available from Solar Array

11100 W, array rating
66,078 Wh/day needed by system
11013 W, array rating (calc)

Battery Energy Storage Required

30% losses from energy storage
20% Allowable discharge
15.4 Volts, max. battery voltage
12.8 Volts, nominal battery voltage
220.0 Ah/Battery
400 Volts, max. pack voltage
26 Batteries in series
2 Parallel String(s) of Batteries
0.7 lb./Ah
332.8 Volts, Nominal Pack Voltage
440 Ah Pack rating
32,685 Wh, Required
163,424 Wh, Req'd pack size w/DoD
491 Ah, Needed Pack rating
8,008 lb., Battery Pack Weight

Simulation



Time (hr)	Insolation (W/m^2)	Load (W)	Solar Power (W)	Batt. Output (W)	Battery Energy (Ah)	Charge Rate (W)	Blower CFM (ft^3/min)
0	0	2,251	0	2,251	384	0	118.00
1	0	2,251	0	2,251	377	0	118.00
2	0	2,251	0	2,251	371	0	118.00
3	0	2,251	0	2,251	364	0	118.00
4	0	2,251	0	2,251	357	0	118.00
5	0	2,251	0	2,251	350	0	118.00
6	0	2,251	0	2,251	344	0	118.00
7	150	2,251	1,665	586	342	0	118.00
8	350	2,251	3,885	0	346	1634	118.00
9	550	2,251	6,105	0	356	3854	118.00
10	720	2,251	7,992	0	370	5741	118.00
11	810	2,251	8,991	0	387	6740	118.00
12	850	2,251	9,435	0	405	7184	118.00
13	810	2,251	8,991	0	422	6740	118.00
14	720	2,251	7,992	0	436	5741	118.00
15	550	2,251	6,105	0	440	1650	118.00
16	350	2,251	3,885	0	440	0	118.00
17	150	2,251	1,665	586	438	0	118.00
18	0	2,251	0	2,251	431	0	118.00
19	0	2,251	0	2,251	425	0	118.00
20	0	2,251	0	2,251	418	0	118.00
21	0	2,251	0	2,251	411	0	118.00
22	0	2,251	0	2,251	404	0	118.00
23	0	2,251	0	2,251	398	0	118.00
24	0	2,251	0	2,251	391	0	118.00
	Total Wh	56,273	66,711	32,685			

Max DOD 22.3%
Total Ah used 98.2

Total Manufacturers Price **$124,850**

10 Year Price **$146,225**

Total Volume Pumped (ft^3) **177,000**

Results of the Numerical Simulation

Table 14 summarizes the costs and predicted performance for the six systems. The diurnal system has the clear advantage of being a lower cost and minimum maintenance system. For many of the target remediation technologies described in Section 6, process effectiveness depends on the peak flow rate and pressure, not total volume. Therefore, a solar system operated on a diurnal cycle using a 1-hp pump would be just as effective as the same pump operated continuously from utility power. However, not all remediation technologies are amenable to diurnal operation.

For remediation technologies requiring a minimum nominal operating point between cycles to be effective, Systems 2 and 5 (the variable-cycle systems) are options, although at significantly higher cost. The continuous operation systems, Systems 3 and 6, are the least cost effective but would be necessary for some remediation technologies. Note that these are analogous to the potential competing technologies mentioned in Section 6.

Table 14. Cost and Performance Summary for the Six Systems

	System					
	1	2	3	4	5	6
Equipment Cost[1]	$15,000	$26,000	$59,000	$29,000	$49,200	$125,000
10-yr Life-cycle Cost[2]	$15,000	$33,000	$64,000	$29,000	$55000	$146,000
Cubic Feet/Day (cfd)[3]	30,000	53,000	83,000	63,000	113,000	177,000
cfd/$ (equipment cost)	2.0	2.1	1.4	2.2	2.3	1.4
cfd/$ (life-cycle cost)	2.0	1.6	1.3	2.2	2.1	1.2

1. Equivalent to manufacturer's price.
2. The total cost for the end user over 10 years (two battery packs total).
3. The total volume of product pumped in a day.

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5. Economic Analysis of Solar-powered Remediation Systems

For this study, only the difference in cost to the end user for accessing and supplying electrical power is needed to determine the market potential of the solar-powered remediation system concept. The cost of remediation site preparation, plumbing, wells, blowers, and even periodic maintenance and monitoring is assumed to be the same for either the solar-powered or grid-supplied systems. The period of operation is also the same for the majority of the applicable remediation technologies described in Section 1.

This section examines the life-cycle cost of a solar-powered system versus the cost of grid-supplied power from the perspective of the end user. The comparison is performed for each of the six solar system configurations defined in Section 4. Two cases are addressed for the solar system concept—customer-owned and customer-leased equipment. The results are summarized in Table 15.

For customer-owned systems, the end user of the system purchases the unit directly from the manufacturer. The life-cycle cost is equal to the purchase price plus the cost of installing and maintaining the system over 10 years (see Section 4 for the life-cycle cost discussion). A total of eight installations is assumed over the life of the system. It is also assumed that the solar system is skid mounted and anchored to the ground for easy installation. The cost per month to the end user is therefore equal to the life-cycle cost plus installation costs amortized over 10 years. No inflation, interest, or cost-of-money calculations are considered in this analysis.

For customer-leased systems, an equipment rental enterprise purchases the unit from the manufacturer and leases the equipment to the customer. This is a common practice in the environmental services business for blowers, filters, and other equipment. Here, it is assumed that the leasing party recovers the life-cycle cost in 4 years, which defines the lease price. The cost to the end user is the lease price plus the installation cost amortized over the installation period. Again, no inflation, interest, or cost-of-money calculations are considered in this analysis.

Table 15. Computation of Costs for Customer-owned and Customer-leased Systems

	1.1-hp Systems			2.5-hp Systems		
	Diurnal 1	Var. Cycle 2	Continuous 3	Diurnal 4	Var. Cycle 5	Continuous 6
Life-Cycle Cost	15,000	33,000	64,000	29,000	55,000	146,000
Cost of Installation/Removal	500	750	1,000	750	1,000	1,250
Case I—Customer-owned						
Life-cycle Cost	15,000	33,000	64,000	29,000	55,000	146,000
Life of System (years)	10	10	10	10	10	10
Installations per Lifetime	8	8	8	8	8	8
Cost of all Installations	4,000	6,000	8,000	6,000	8,000	10,000
Total System Cost	19,000	39,000	72,000	35,000	63,000	156,000
Cost per Month w/Install	158	325	600	292	525	1,300
Case II—Customer-leased						
Leaser Cost	15,000	33,000	64,000	29,000	55,000	146,000
Cost Recovery Period (years)	4	4	4	4	4	4
Lease Price per Month	313	688	1,333	604	1,146	3,042
Installation Cost	500	750	1,000	750	1,000	1,250
Lease Period (months)	15	15	15	15	15	15
Cost per Month w/Install	346	738	1,400	654	1,213	3,125

Cost of Grid-supplied Power to the End User

The cost of access and supplying grid power for the 1050-W and 2250-W loads is addressed in this section. The cost of grid-supplied power can vary widely depending on the specifics of the installation. Factors influencing cost include the specific utility cost structures, terrain, load, and type of hook-up. Recent sample cost data for three actual remediation sites located in the Los Angeles area is provided in Table 16. These sites are in the metropolitan area (i.e., not remote). The sample sites are intended to operate for about 12 months. The data do not include the cost of power. The 15% mark-up is what the customer is typically charged by the contractor providing the leased equipment.

Table 16. Sample Grid Hook-up Cost Data for Three Sites Located in the Los Angeles Area

	Site A	Site B	Site C
Distance to Grid (ft)	90	100	100
Cost of Hook-up	$2,500	$1,200	$4,000
Cost of Poles (per month)	$20	$125	$---
Total Cost for 12 Months	$2,740	$2,700	$4,000
Mark-up (15%)	$411	$405	$600
Total Cost for 12 Months	$3,151	$3,105	$4,600
Total Cost per Month	$263	$250	$383

A representative model was constructed to reflect the cost of a grid connection as a function of the basic charges, distance from the grid, cost for poles, period of operation, and the cost of electricity for the two loads under consideration. The resulting data is presented in Figure 9 for the 1050-W load, and Figure 10 for the 2250-W load. The results were calculated for typical durations of remediation site clean up (12, 24, and 36 months on average). The sample site data, including the calculated cost of electricity at $0.10/kWh, is also shown. A cost of $2.50/ft was assumed (values between $1.50 and $5.00 are common in the U.S.).

Cost of power from utility (1050W Load)

Basic charges	$	1,200	/ site
Cost per foot	$	2.50	/ ft
Cost for poles	$	1.00	/ ft / mo
Cost of electricity	$	0.10	/ kWh
Contractor mark-up		15%	
Power Required		1050	W

Cost per month

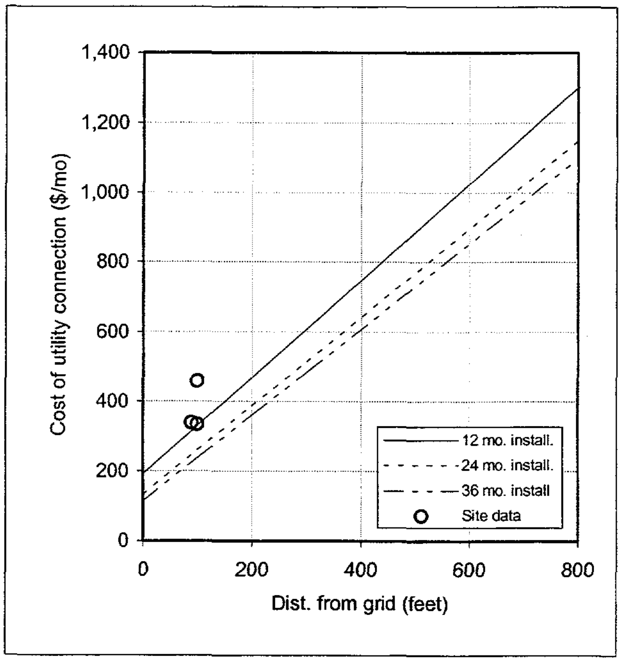
	Period of installation		
Dist. (ft)	12	24	36
0	190.60	133.10	113.93
100	329.56	260.08	236.92
200	468.52	387.06	359.91
300	607.48	514.04	482.89
800	1302.27	1148.93	1097.82

Sample utility tie costs from actual sites

	Site A	Site B	Site C
Distance to grid (ft)	90	100	100
Cost of hook-up	$ 2,500	$ 1,200	$ 4,000
Cost of poles (/mo)	$ 20	$ 125	$ -
Total cost for 12 mo.	$ 2,740	$ 2,700	$ 4,000
Mark-up	$ 411	$ 405	$ 600
Cost of electricity	$ 907	$ 907	$ 907
Total price for 12 mo.	$ 4,058	$ 4,012	$ 5,507
Total price per mo.	$ 338	$ 334	$ 459

Total cost

	Period of installation		
Dist. (ft)	12	24	36
0	2,287	3,194	4,102
100	3,955	6,242	8,529
200	5,622	9,289	12,957
300	7,290	12,337	17,384
800	15,627	27,574	39,522



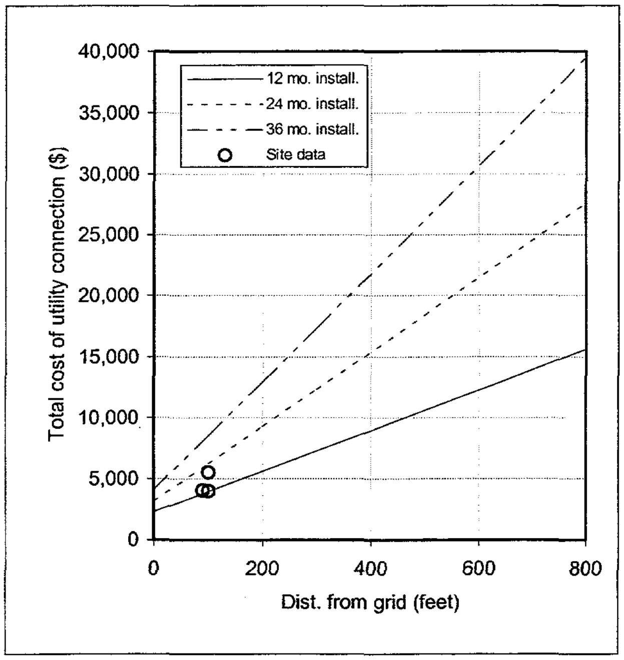


Figure 9. Calculated cost of grid-supplied power for a 1050-W load (1.1-hp blower) and comparison with actual site data.

Cost of power from utility (2250W Load)

Basic charges	$	1,200	/ site
Cost per foot	$	2.50	/ ft
Cost for poles	$	1.00	/ ft / mo
Cost of electricity	$	0.10	/ kWh
Contractor mark-up		15%	
Power Required		2250	W

Cost per month

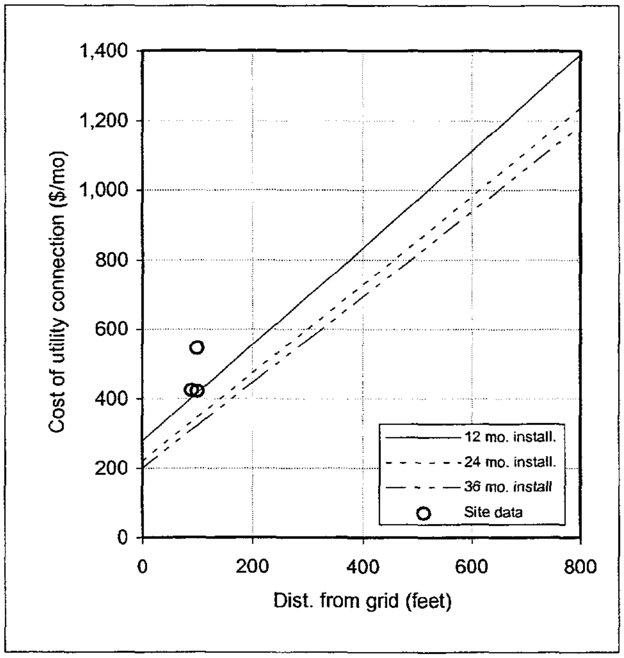
	Period of installation		
Dist. (ft)	12	24	36
0	277.00	219.50	200.33
100	415.96	346.48	323.32
200	554.92	473.46	446.31
300	693.88	600.44	569.29
800	1388.67	1235.33	1184.22

Sample utility tie costs from actual sites

	Site A	Site B	Site C
Distance to grid (ft)	90	100	100
Cost of hook-up	$ 2,500	$ 1,200	$ 4,000
Cost of poles (/mo)	$ 20	$ 125	$ -
Total cost for 12 mo.	$ 2,740	$ 2,700	$ 4,000
Mark-up	$ 411	$ 405	$ 600
Cost of electricity	$ 1,944	$ 1,944	$ 1,944
Total price for 12 mo.	$ 5,095	$ 5,049	$ 6,544
Total price per mo.	$ 425	$ 421	$ 545

Total cost

	Period of installation		
Dist. (ft)	12	24	36
0	3,324	5,268	7,212
100	4,992	8,316	11,640
200	6,659	11,363	16,067
300	8,327	14,411	20,495
800	16,664	29,648	42,632



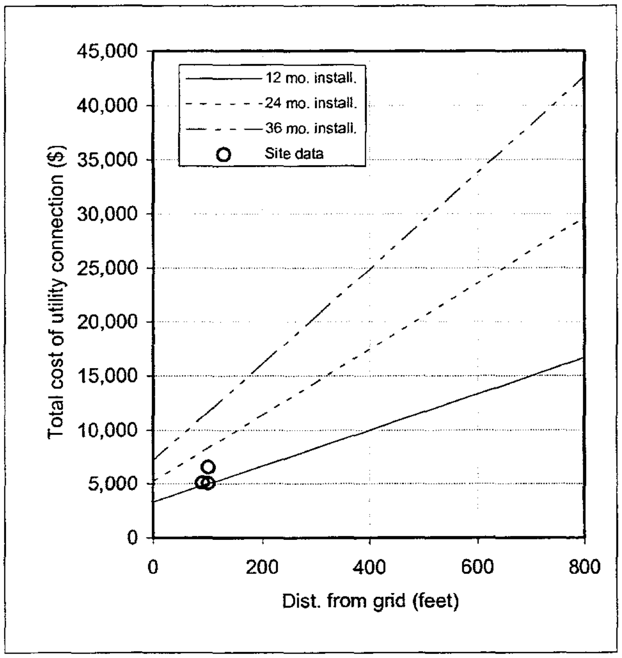
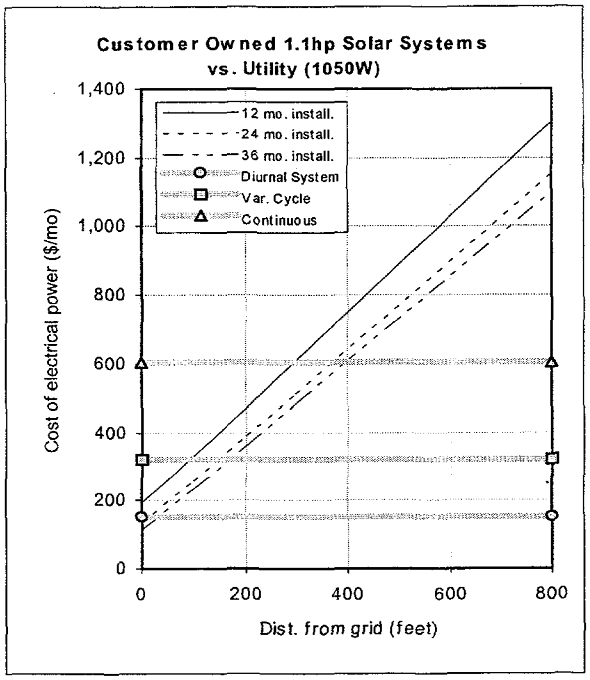


Figure 10. Calculated cost of grid-supplied power for a 2250-W load (2.5-hp blower) and comparison with actual site data.

Comparison—Solar-powered vs. Grid-connected Systems

The monthly cost of power to the end user is compared in **Error! Reference source not found.**. The data for customer- owned systems is presented in Figures 11(a) and 11(b) for the 1.1-hp and 2.5-hp blowers, respectively. Figures 11(c) and 11(d) show the results for customer-leased systems.

(a)



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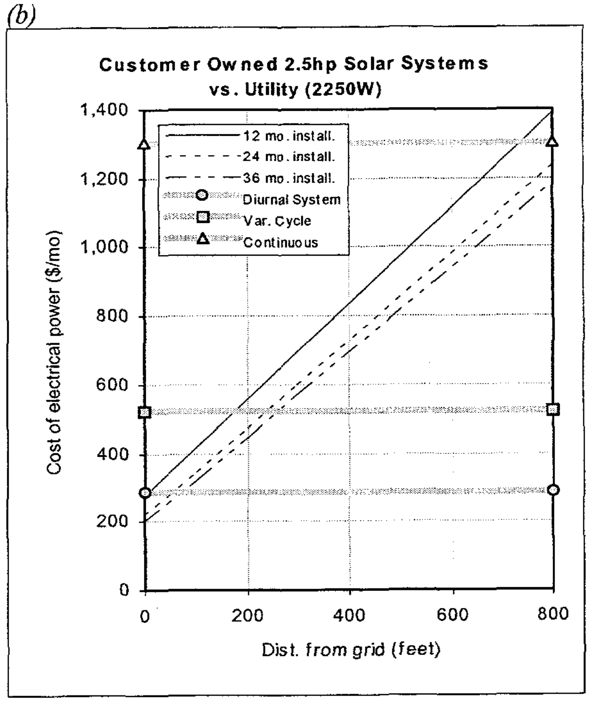
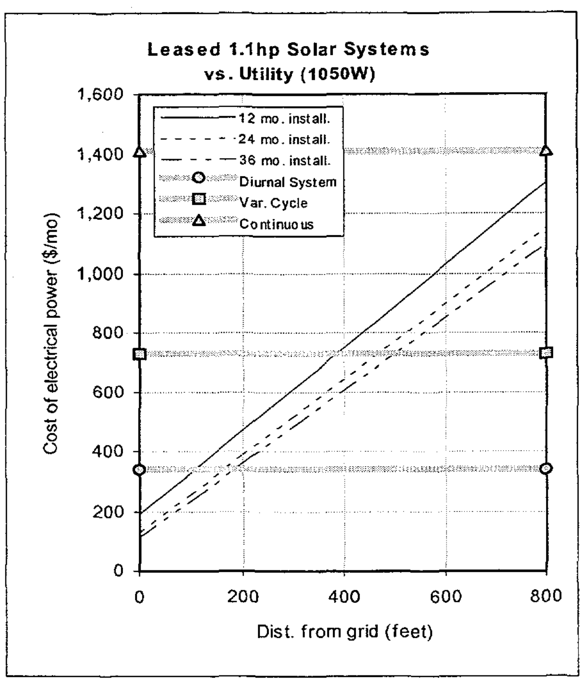


(c)



(d)

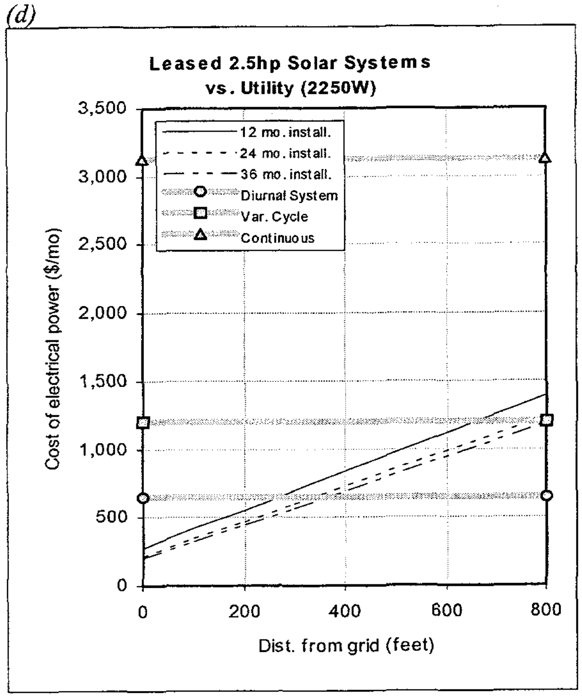


Figure 11. Comparative monthly cost of power for solar-powered vs. grid-connected systems.

Discussion of Economic Analysis

Perhaps the most important result of this investigation is that a solar-powered system can be cost effective when compared to grid-supplied power for even short grid-extensions. As would be expected, the general result is that solar-powered systems are most competitive for lower power and more remote systems.

The most promising application is for the diurnal system used with a remediation technology such as bioventing which is amenable to intermittent operation. For this situation, the solar-powered system may compete effectively for a majority of the potential remediation sites, greatly expanding the market potential for solar applications. For example, an end user with a sufficiently large number of sites requiring bioventing over a span of 10 or more years would be better off buying and using the diurnal solar systems than connecting to the grid in most cases. The DoD and other government agencies are good examples of this situation. However, because most private end users have only a few sites, leasing the systems will be the most suitable option, in which case the diurnal solar system becomes cost effective when grid extensions exceed 100 ft. for a 1.1-hp system, and 250 ft. for a 2.5-hp system.

One surprising result was that the variable-cycle solar systems may also be able to compete effectively with grid-connected systems because a large number of remediation sites require grid extension on the order 100 to 400 feet. Using variable-cycle systems opens the markets for remediation technologies such as SVE. It should be noted that both the diurnal- and variable-cycle system options depend on using a technology that allows the operation of standard AC blowers at variable speeds using solar panels.

The cost analysis provided is representative only for remediation processes that involve blowing or sucking air. The results would be significantly different for groundwater (i.e., pump and treat) processes because the cost comparison would be based on an equivalent amount of fluid pumped (rather than air) and the well depth introduces another significant independent variable.

6. Market and Needs Assessment

General environmental market information and remediation technologies are explored in this section to identify suitable target markets and technologies for the solar-powered remediation system concept. The results of this study were used to define the general specifications for the systems used in the numerical simulations and cost evaluations. An extensive survey of the world wide web, existing trade literature, and interviews was conducted to determine if there has been any prior effort to use solar electric energy to power remediation systems. Key agencies in target markets were also interviewed to assess the level of interest in the solar-powered system concept.

Identification and Description of General Market Segments

In the U.S., over half a million sites with potential contamination have been reported to state or federal agencies during the past 15 years. To date, over 300,000 sites have either been cleaned up or require no further action. However, nationwide approximately 217,000 hazardous waste sites remain that require some sort of remediation. The total cost to remediate these remaining sites is estimated to be about $187 billion, approximately $7 to $10 billion per year for the next 20 to 30 years.

Most of these contaminated sites are left over from the Cold War and from poor environmental practices and consist of hazardous wastes that are toxic, corrosive, reactive, or ignitable substances that can affect human health or the environment. The wastes consist of fuels, solvents, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons and are the targets of the current remediation efforts. Another environmental problem found in the U.S. is the Department of Energy's (DOE's) radioactive waste sites. These sites consist mainly of mixed wastes that have organic, inorganic, and radioactive chemical substances, which due to their special nature are not considered in this report.

The remediation market consists of two main sectors—the private (privately or publicly owned commercial or industrial sites) and the public (federal, state, or local government sites). In the U.S., these two sectors are in turn subdivided into eight subsectors, which are described below. A site can have one or several wellheads and equipment installations as defined in this report.

- **National Priorities List (NPL), or Superfund, sites**—These are older sites being cleaned up under state and/or federal contracts and guidelines. These sites may be owned by and may be the responsibility of federal, state, municipal, or private entities. Superfund sites comprise a wide variety of contaminants and conditions, but are mostly large, complex sites near population centers. There are roughly 547 NPL sites remaining to be cleaned up at a rate of 30 sites per year. The total cost of remediation is estimated at $7 billion.
- **RCRA corrective action sites**—These are newer sites being cleaned up under State and/or Federal contracts and guidelines. These sites may be owned by and may be the responsibility of federal, state, municipal or private entities. RCRA sites comprise a wide variety of contaminants and conditions, but are mostly large, complex sites near population centers. There are approximately 3000 RCRA sites. It is estimated that it will take 30 years to complete construction, and an additional 128 years for monitoring and groundwater treatment. This is the second largest market at $39 billion, however, the customer base is large and the majority of sites will have easy access to grid electricity.

- **Underground storage tanks (UST) sites**—Although now uniformly regulated under RCRA, UST sites were regulated under a wide spectrum of federal, state, and local guidelines. Leaking UST (LUST*) site cleanups are still regulated at the local level by a variety of agencies. Most UST or LUST sites are or were (if removed) composed of single or small clusters of UST. These sites are perhaps the single largest class of hazardous waste sites in the U.S. and worldwide in terms of numbers and volume of contamination. There are roughly 165,000 LUST sites remaining to be remediated. Collectively, regional-scale groundwater contamination from many LUST sites has created major Superfund sites. LUST sites will include a wide variety of liquid contaminants and, although mostly found near population centers, will be widespread due to the ubiquitous use of UST for storing fuel and other chemicals. A total of $21 billion is the estimated cost of remediation for the remaining sites. The majority of these sites will be near a source of utility power.
- **DoD sites**—Defense facilities range from large active bases (essentially small cities) to extensive undeveloped training areas to small remote sites such as radio relay towers. DoD sites also include many closed facilities of varying size and infrastructure which may or may not have been transferred to non-DoD agencies (either public or private sector) due to the Base Realignment and Closure (BRAC) Program. These sites may also include government-owned/contractor-operated (GOCO) facilities. Consequently, hazardous waste sites at DOD facilities will include essentially every problem encountered elsewhere, plus some uncommon problems such as explosives, chemical or biological warfare agents, and radioactive waste. Because of the relevance to their individual missions, the three services have been given charters to investigate remedial technologies applicable to three separate classes of hazardous waste: hydrocarbon fuels (Navy), explosives (Army), and chlorinated solvents (Air Force). However, all services (including the Marines and Coast Guard) have a full spectrum of hazardous waste site types. Moreover, the U.S. Army Corps of Engineers has been the primary federal contracting service for cleanup of a variety of non-military federal sites as well as Army facilities and a number of state- or private-sector-owned sites. The other military services also have contracting mechanisms for cleanups on their respective facilities. There are 8336 DoD sites remaining to be remediated representing approximately $29 billion over the next 20 years.
- **DOE sites**—DOE facilities range from large active research or weapons facilities to extensive undeveloped testing areas to small remote sites such as radio relay towers. Former DOE sites of varying size and infrastructure also exist due to the closure of these facilities. These sites may also include GOCO facilities. Consequently, hazardous waste sites at DOE facilities will include essentially every problem encountered elsewhere, plus some uncommon problems such as explosives and radioactive and mixed waste. The DOE has contracting mechanisms for cleanup of DOE facilities and the Corps of Engineers appears to be providing some support as well. However, the DOE generally places greater emphasis on containment rather than treatment of many sites. Altogether, there are roughly 10,500 sites in this segment representing $63 billion over 75 years. Many of the problems currently have no proven cleanup technology, for example nuclear and large-scale groundwater sites.

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* Standard industry acronym

- **Other federal agencies' sites**—There are many "civilian" federal agencies (non-DoD or DOE) that may have or be responsible for hazardous waste sites. The most promising of these include the Bureau of Land Management (BLM), Bureau of Reclamation, Coast Guard, Department of Transportation (DOT), Federal Aviation Administration (FAA), National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), Immigration and Naturalization Service (INS), National Park Service, Bureau of Indian Affairs (BIA), and National Forest Service. A number of these agencies have hazardous waste sites at remote locations. There are over 700 facilities, each with several sites requiring remediation.
- **State and local government sites**—Many state or local government agencies have hazardous waste sites, some in remote areas, or are responsible for cleanups of orphan sites in remote areas. Such agencies include police, parks, water, power, transportation, and highway maintenance departments. Major state-owned universities are also participants in research programs that may have hazardous waste sites in remote testing facilities. There are roughly 29,000 sites needing attention, many of which will not require remediation.
- **Private-sector sites**—Most private-sector hazardous waste sites, most commonly commercial or industrial sites, are likely to be within areas with substantial power resources. However, some DoD or DOE contractors are likely to own or have owned large tracts of land for research, development, testing, and evaluation of weapon systems or other federally funded programs and which may now contain hazardous waste sites. Some major private universities are also participants in research programs that may have hazardous waste sites in remote testing facilities.

The single largest problem in the U.S., in terms of the volume of contamination, is related to hydrocarbon fuels. Hydrocarbon fuels are also the most widely distributed type of contamination. Nearly every segment of the remediation market will have hazardous waste sites contaminated by fuels. This is probably true worldwide as well. The next most important problem is related to chlorinated solvents which, although not as voluminous or as widespread as hydrocarbon fuels, are significantly more toxic than hydrocarbon fuels pound for pound and therefore of greater concern. Many Superfund, RCRA, UST, DoD, DOE, and industrial (manufacturing) sites, and some commercial sites (e.g., dry cleaners) may have chlorinated solvent contamination.

The DoD accounted for the use of vast amounts of petroleum fuels and releases consisting of gasoline, diesel fuel, and aviation fuels. These petroleum products were used at facilities that were both close to electrical power and, more importantly, in remote areas used for training and systems testing, and for radar or communications stations. To a lesser degree, federal and state forest service agencies and transportation departments are thought to have smaller releases of petroleum substances into the environment at remote sites. The BLM, Bureau of Reclamation, and BIA are also thought to represent a relatively small market for the cleanup of small petroleum fuel releases and old mine waste tailings.

Sites that are contaminated with both hydrocarbon fuels and chlorinated solvents are amenable to remediation technologies supported by the USPC/solar-powered system. The technologies that would address these types of volatile organic contaminants include in situ treatment or on-site treatment technologies where air, vapors, or liquids are moved by pressure or vacuum systems. The types of remediation systems best suited for the treatment of volatile organic contaminants were discussed in Section 1.

The 1996 environmental budgets for the U.S. Navy, Marines, Coast Guard, Air Force, and Army were reviewed to establish the dollar value of the potential solar-powered remediation market segment that they may represent. The DoD estimates a total of 8336 sites on 1561 installations that will require remediation of contaminated materials. The majority of sites requiring remediation is generally distributed evenly among the three services (Army, Air Force, and Navy). These sites include currently and formerly used defense sites. Of $187 billion in total remediation costs for the U.S., it is estimated that $28.6 billion will be needed to cleanup DoD sites. The estimated cost to remediate sites within individual DoD divisions is as follows:

- Army = $10.6 billion
- Air Force = $7.4 billion
- Navy = $5.6 billion
- Defense Logistics Agency = $0.4 billion
- Defense Nuclear Agency = $0.1 billion
- Formerly used defense sites = $4.5 billion

Based on quantity of sites and remoteness of location it is believed that the U.S. Army has by far the greatest number of sites thought to be amenable to solar-powered remediation. Not only were there a large number of Army petroleum-fuel-contaminated sites, but also a large quantity of remote landfills on Army facilities were identified that are thought to represent a potential market segment for leachate collection systems. The other military branches, such as the Air Force, Navy, and Marines as well as DOE and other federal agencies, were found to have a small potential since most of the affected fuel or solvent sites were determined to have electrical power available from either public or private utilities or generator sets for pumps to transfer the petroleum from the tanks to the end-use vehicle.

Identification of Target Markets

The market potential for solar-powered remediation systems is directly related to the relative cost of accessing and using electrical power. The type and rating of the remediation equipment, and therefore the power requirement, can be considered the same for both the grid-supplied and solar-powered options.

Providing grid power to a site can be very expensive (on the order of $1.50 to $5.00 per foot, plus installation, poles, and maintenance fees, plus the cost of electricity at $0.10/kWh). In one recent example, the cost of running a line from the utility pole 90 feet to bioventing equipment was over $3,000. In either case, the cost of providing electrical power via the utility or extracting the contaminated material can vary greatly depending on the distance from the grid, local topography, and other factors.

The cost of a solar-powered system is roughly proportional to the energy required. Therefore, remediation technologies requiring the least amount of energy should be considered first. As discussed in Section 1, the most suitable technologies are bioventing, biosparging, and groundwater pumping since these techniques require the least power and are amenable to diurnal and variable-cycle operation.

Thus, in general, solar-powered systems will be most competitive for applications with remote locations and low power requirements. Therefore, market segments having a large number of remote sites would be a priority although the competitiveness of the solar-powered system must be assessed on a site-by-site basis.

The most promising initial target customers for the solar-powered remediation system is the public sector, specifically the DoD. The DoD is considered the most promising target market for three reasons. First, the DoD is the single largest group of potential clients with the most relevant problems in remote sites. Second, the majority of DoD problems are related to VOCs (wastes that are amenable to remediation using the solar-powered concept). And third, most DoD services have innovative technology programs and are early adopters of new technologies. The private sector does not typically explore new remediation technology and very few state governments participate. Examples of DoD programs that are involved in technology development and assessment are listed below.

- Navy Environmental Leadership Program (NELP) and Port Hueneme National Hydrocarbon Test Center.
- Air Force Center for Environmental Excellence (AFCEE), in Texas, Wright Patterson in Ohio, and Edwards Air Force Base California.
- Air Force Chlorinated Test Center at Dover Air Force Base.
- Army Environmental Center at Aberdeen, Maryland.

The total market potential for solar-powered systems within the DoD can be only roughly estimated. There is a total of about 8,000 sites requiring remediation, most of which require one of the three technologies amenable to solar power. A portion of the more remote sites pose no immediate risk to people or the environment and therefore would be allowed to recover naturally due to the high cost of remediation. Assuming an average of five systems per site, solar system utilization of five installations over 10 years, and an average solar system price of $20,000, the maximum total potential market for solar-powered equipment is about $160 million. If the solar-powered system is cost competitive in only 10% of these cases, the potential market is $16 million spread over several years. If the solar-powered system can compete against a grid-connected system with line extensions on the order of 100 feet, the market potential could even be several times higher when considering the private sector and other government agencies. Unfortunately, there is insufficient market data at this time to segment the DoD installations by the cost of connecting to the grid.

It should be noted that with sufficiently low system costs, amortized over several years and multiple installations, the solar system may be able to compete effectively in both the public and private sectors. After the solar-powered system gains credibility through trials in the DoD and other public agencies, the private sector would adopt the technology if the economic benefits are demonstrable. The market potential in the private sector is again many times larger (130,000 sites that involve VOCs for the public and private sectors combined according to the EPA) although solar-powered systems would compete effectively for a smaller fraction of these.

Identification of Current and Potential Competing Technologies

An extensive survey of the world wide web, existing trade literature, and interviews was conducted to determine if there has been any prior effort to utilize solar electric energy to power remediation systems. The following three companies and agencies have tried some type of remediation technology that use solar energy.

- Public Energy Systems (PES), Green Bay, Wisconsin. In a company profile, PES claims they have a unique solar environmental remediation system that represents a major breakthrough in applied solar technology. They also mention a comprehensive solar research and development program and have done contract work with Sandia National Laboratories and the State of Wisconsin, although nothing specific was mentioned. They construct and evaluate prototypes, including aeration devices and pollution remediation units. We have not been able to contact PES or obtain any additional information.
- International Technology Corporation (IT), Monroeville, Pennsylvania. IT is a full-service environmental management and remediation company. It claims that it has treatment systems powered by renewable energy sources, such as wind-powered bioventing and solar-powered biosparging. These systems were each designed for a specific remote site. The wind-powered system used rooftop vent fans. The solar-powered system used standard solar equipment designed for remote homes.
- Zentox Corporation, Ocala, FL. Zentox commercializes technologies for improving the quality of air, water, and soil environments. Zentox has remote solar-powered systems available as fully-integrated, factory-assembled, hydraulically and electrically pre-tested units. They configure a wide variety of remediation or process equipment types that could be mounted on one or more skids to offer versatile and transportable systems. Their systems use standard solar equipment of the type used for remote homes.

In each case above, where we were able to verify the type of equipment used, the solar-powered system included an off-the-shelf inverter and battery charger typically used in remote home systems. These systems can only operate at a fixed speed (60 Hz) equivalent to the continuous-operation system being investigated in this report. It should be noted that these power electronics were not designed for operating large inductive loads, so system reliability may be a problem with the higher horsepower units. It is encouraging, however, to see that there has already been some interest in using solar energy for remote sites indicating that a market for the remote systems is likely to exist.

A significant advantage of the AeroVironment system is the ability to operate remediation equipment using variable motor speeds on a diurnal cycle. This eliminates the need for batteries and charge controllers and the associated electrical inefficiencies. Typical efficiencies for power inverters at rated power is 85% and roughly 25% of the energy is lost in the charge/discharge process. The AeroVironment diurnal system has a total system efficiency of over 95% over the entire power range. The result is a lower cost system that is directly applicable to many remediation technologies and more economically competitive against grid-connected systems. For remediation processes unsuitable for diurnal operation but amenable to variable-cycle operation (using batteries for energy storage), significantly greater performance for a given amount of available power (solar array) can be achieved by operating the equipment at different speeds to manage energy rather than an on/off duty cycle.

7. Conclusions

The market potential for solar-powered remediation systems is directly related to the relative cost of accessing and supplying power between current practices and an equivalent solar system. Target markets for the solar-powered remediation system will therefore be characterized as having sites with low power requirements (probably less than 3 hp) and a high cost of connection to the utility for power (remote sites).

The most promising initial market for the solar-powered system concept is the public sector, specifically the DoD. The market potential within the DoD for solar-powered systems is estimated to be $16 million over the next several years. With sufficiently low system cost, a solar-powered remediation system could eventually compete in the much larger private market segment, particularly for bioventing as applied to UST cleanup.

Perhaps the most important result of this investigation is that a solar-powered system can be cost effective as compared to grid-supplied power for even short grid extensions. The general result is that solar-powered systems are most competitive for lower power and more remote systems.

The most promising application is for the diurnal system used with a remediation technology such as bioventing, which is amenable to intermittent operation. In this application, the solar-powered system may compete effectively for a majority of the potential remediation sites, greatly expanding the market potential for solar-powered systems. For example, an end user with a sufficiently large number of sites requiring bioventing over a span of 10 or more years would be better off buying and using a diurnal solar systems than connecting to the grid in almost any case. The DoD and other government agencies are good examples of this situation. However, because most private end users have only a few sites, leasing the systems will be the most suitable option, in which case the diurnal system becomes cost effective when grid extensions exceed 100 feet for a 1.1-hp system, and 250 feet for a 2.5-hp system.

One surprising result was that the variable-cycle solar systems may also be able to compete effectively with grid-connected systems because a large number of remediation sites require grid extension on the order 100 to 400 feet. This provides access to markets for remediation technologies such as SVE.

It should be noted that both the diurnal- and variable-cycle system options that include energy storage depend on using a technology that allows the operation of standard AC blowers at variable speeds using solar panels. It is also noted that the cost analysis provided is representative only for remediation processes that involve blowing or sucking air. The results would be significantly different for the groundwater (i.e., pump and treat) processes because the cost comparison would be based on an equivalent amount of fluid pumped (rather than air) and the well depth introduces another significant independent variable.

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