Chevron

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Marketing Department

92 MAR -6 [illegible]:50

March 5, 1992

Mr. Paul Smith
Alameda County Health Care Services
80 Swan Way, Room 200
Oakland, CA 94621

Re: Former Chevron Service Station #9-4816
301 14th Street, Oakland

Dear Mr. Smith:

Enclosed we are forwarding a letter dated March 5, 1992, prepared by our consultant Weiss Associates responding to your letter dated February 25, 1992 in which you expressed legitimate concerns regarding the site remediation proposed at the referenced site. By submittal of this letter, Chevron feels that it has successfully addressed those concerns and are requesting approval of the corrective action work plan.

As you are aware, all permits have been secure and we have scheduled the installation of the system to commence the week of March 9, 1992, and are very anxious to initiate operation of the treatment system. We are committed to aggressively mitigating the contamination that exists beneath the site and will evaluate the effectiveness of the proposed remedial technology with respect to mitigation of the separate-phase hydrocarbons floating on the ground water.

Your expeditious approval is appreciated. If you have any questions or would like to discuss further, please do not hesitate to contact either myself at (510) 842-9581 or Mr. Tom Berry, Weiss Associates at (510) 547-5420.

Very truly yours,
CHEVRON U.S.A. PRODUCTS COMPANY

Nancy Vukelich
Site Assessment and Remediation Engineer

Enclosure

cc: Mr. Eddy So, RWQCB
Mr. R.W. Cosby, 225/1936
Ms B.C. Owen
File (9-4816W1-Addendum)

Ms. Beth Castleberry
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March 5, 1992

Ms. Nancy Vukelich
Chevron U.S.A. Products Company
P.O. Box 5004
San Ramon, CA 94583-0804

Re: Remediation Work Plan
Former Chevron SS #9-4816
301 14th Street
Oakland, California
WA Job # 4-582-83

Dear Ms. Vukelich:

As you requested, Weiss Associates (WA) prepared a Remediation Work Plan dated February 10, 1992 for the site referenced above. As required, you submitted this work plan to the Alameda County Department of Environmental Health (ACDEH) for their review and approval. Based on their review, the ACDEH requested additional information about the proposed work plan in their letter to you dated February 25, 1992.

This letter provides the additional information requested by the ACDEH and supplements our original work plan. The following subjects are discussed:

- Use of soil vapor extraction (SVE) as a means of separate-phase hydrocarbon removal,
- Remediation system schematic,
- Rationale for extraction well location,
- Project schedule,
- Health and Safety Plan,
- Equipment malfunction contingency plan,
- Status of a work plan for further investigation,
- Discussion of dissolved hydrocarbons detected in ground water from monitoring well C-8.

Please note that the ACDEH letter is incorrectly dated as February 25, 1991 and refers to the WA work plan dated as February 10, 1991. Both are 1992 documents. ✓

Separate-phase Hydrocarbon Removal by SVE

Soil vapor extraction can effectively remove separate-phase hydrocarbons from subsurface materials. We have attached three articles which discuss the theory and applicability of SVE (Attachment A). Of particular interest is the case study in the article by Baehr, Hoag, and Marley which shows the success of SVE as a method for removing separate-phase hydrocarbons.

Because the shallow sediments beneath the site are primarily high permeability sands, we anticipate the proposed internal combustion engine (ICE) to work at its optimum capacity. ICE specifications and performance data are provided as Attachment B. We anticipate initial hydrocarbon mass removal rates up to 1,000 lbs per day. An advantage of SVE in high permeability sediments is that it can remediate separate-phase hydrocarbons and dissolved hydrocarbons in ground water through dispersion over a much greater distance from the well than a separate-phase skimming system. Therefore, a skimming system would be redundant. If SVE does not effectively decrease the presence of separate-phase hydrocarbons, we will evaluate the installation of a separate-phase skimming system.

As you are aware, we have obtained the required permits and we are now ready to install and operate the SVE system. We are currently scheduled to install and start the system during the week of March 9, 1992.

Remediation System Schematic

A schematic diagram of the soil vapor extraction system is provided as Attachment C.

Extraction Well Location

We propose vapor extraction from wells CR-1 and C-5. Both wells have over two ft of separate-phase hydrocarbons suggesting that they are at or near the hydrocarbon source. → so does C-3 Additionally, because subsurface sediments are highly permeable, it is likely that vapor extraction from these two wells can effectively influence most, if not all of the site. We will verify the radius of influence by measuring vacuum at the surrounding monitoring wells once the system is started. Extraction from well CR-1 should effectively remove separate-phase hydrocarbons from nearby well C-3. Therefore, extraction from well C-3 does not appear necessary. Additionally, well CR-1 has a larger diameter and therefore a greater screened surface area, it is better suited for extraction than well C-3. If necessary, other wells can be plumbed into the system.

Project Schedule

Pending work plan approval, we have scheduled system installation for the week of March 9, 1992. We anticipate system start-up during the same week. We plan to operate the system 24 hours a day, seven days a week. According to the conditions of the permit from the Bay Area Air Quality Management District (BAAQMD), WA will conduct daily sampling of the system influent and effluent for the first three days and monthly thereafter. The ICE requires weekly oil changes, during which the system will be shut down for a few hours. The propane tank which will provide a supplemental fuel supply if necessary, will require periodic refills. However, this does not require system shut-down. Refill frequency increases as hydrocarbon concentrations drop and, based on our experience, may be necessary up to twice per week.

It is difficult to predict the time necessary to remediate the site, however we anticipate that the ICE will be operating for a few months. To monitor separate-phase hydrocarbon removal, we will measure hydrocarbon thickness in wells CR-1, C-2, C-3, and C-5 monthly in conjunction with system vapor sampling. If no decrease in separate-phase hydrocarbon thickness is observed, we will evaluate a separate-phase hydrocarbon pumping/skimming system. In addition to the required monthly BAAQMD compliance reports, we will submit bi-monthly SVE progress reports which will include hydrocarbon mass removal and separate-phase hydrocarbon thickness measurements. Ground water sampling will continue quarterly to monitor the effectiveness of SVE on dissolved hydrocarbon removal.

We will evaluate obtainable clean-up levels as the system operates and submit a work plan for initiating site closure including confirmatory soil borings when remediation approaches completion.

Health and Safety Plan

The Site Safety Plan, included as Attachment D, provides the necessary information requested in item 4 of the ACDEH letter. This Plan will be provided to all workers who will be performing installation and initial start-up of the system. The Plan addresses, among other subjects; naming of the Site Safety Officer, Project Team Leader and WA Office Advisor; personal protective equipment available to onsite workers; nearest medical facility location with a marked route map; air monitoring equipment; fire protection; and employee training.

Contingency Plan

The proposed remediation system consists of an equipment enclosure, an internal combustion engine (ICE), propane tank, underground and above ground piping, a moisture collection drum, two extraction wells and telephone service. The ICE, propane tank and above ground plumbing will be contained within a fenced enclosure.

A safety/test analysis of the ICE is provided as Attachment E. This system has several safety features that address fire hazards. System operation is continually monitored by an on-board computer which automatically shuts down the system should equipment failure occur due to high engine rpm, high temperature or power loss. The system also features a built-in dual nozzle automatic fire control system and a ground line to reduce ignition hazards. Other safety features of the ICE are a high water level switch in its water trap, which will shut-down the engine if water reaches a preset level, and a propane gas filter lock-off, which uses vacuum pressure from the engine to draw vapors into the engine. The engine automatically shuts off if it runs out of propane.

The propane tank will be inspected by the Fire department. The propane tank has an excess flow shut-off valve which will shut off the propane supply in the event of a high flow fuel leak. The propane tank will be routinely inspected during weekly ICE oil changes, and when the tank is refilled. If a leak occurs in the supply line the tank will be shut off and repairs made as necessary.

WA will perform weekly monitoring of the SVE system to ensure proper operation of the system. This will include checking the vapor knock out drum and draining it if necessary, optimizing engine performance, and visual inspection of equipment and plumbing.

The ICE will have an auto dialer which will be connected to a computer at WA. This will allow WA to monitor system performance and alert WA technician of system shut-down. Appropriate actions will be taken to address failures within the treatment system to allow continuous system operation.

Work Plan for Further Investigation

The ACDEH has requested a work plan for additional investigation to better delineate the extent of hydrocarbon concentrations. As you requested, we will evaluate proper placement of additional well(s) and submit a work plan for your review by the end of April 1992.

Monitoring Well C-8

Data suggests that hydrocarbons in ground water from well C-8 are not related to the 310 14th Street investigation. Ground water samples from monitoring wells C-6 and C-7 which are located closer to the site than C-8, have shown no detectable hydrocarbons. This suggests that hydrocarbons in C-8 originate from a different source. Analyses of ground water from monitoring well C-8 have shown between 5,000 and 6,300 parts per billion (ppb) total petroleum 1 hydrocarbons as gasoline (TPH-G) during 1991. However, only trace concentrations of toluene (28ppb), ethylbenzene (140ppb) and total xylenes (470ppb) have been detected and benzene has not been detected. This chemical signature does not correspond with that found in ground water analyses from onsite wells such as C-1 and C-4 where the lighter hydrocarbons of benzene and toluene comprise a far greater percentage of the total hydrocarbons. This data suggests that hydrocarbons in well C-8 are from an older, more degraded source than found at the site. maybe

ok there levels are <MCL.

WA is pleased to provide remediation services to Chevron U.S.A. Products Company. Please feel free to call if you have any questions or comments or require additional information.

Sincerely,
Weiss Associates

Thomas R. Berry
Thomas R. Berry
Project Geologist

TRB:trb

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Attachments:
A - Articles Regarding Applicability of SVE
B - ICE Product Literature
C - System Schematic
D - Site Safety Plan
E - ICE Safety/Test Analysis

ATTACHMENT A

ARTICLES REGARDING APPLICABILITY OF SVE

OBSERVATIONS OF THE EFFECTS OF SOIL VENTING ON SEPARATE-PHASE HYDROCARBONS

Lance Geselbracht, P.E., Robert Giattino, and Daniel Landry

Pacific Environmental Group, Inc.
Santa Clara, California

Introduction

One of the most prevalent forms of environmental impact today is the introduction of gasoline into the subsurface environment. A large proportion of this problem occurs where gasoline is distributed, both at the retail and wholesale level. In most cases, gasoline enters the subsurface environment as a result of surface spills or leaking underground fuel storage tanks and transport lines. At some point after the unwanted gasoline release, the subsurface environment comes to a new equilibrium which includes vapor and liquid phase gasoline in the unsaturated zone, liquid phase gasoline floating on the groundwater surface, and dissolved gasoline constituents within the groundwater. This scenario is illustrated in Figure 1.

Once impact to the subsurface environment has been discovered, site investigation is required to characterize the extent and nature of the problem. Data is also generated to describe the physical nature of the site in terms of geology and hydrology. In these early stages of the remediation process, immediate source removal and interim remedial action take place.

Interim remedial actions are often implemented to address migration of gasoline and its constituents through the unsaturated and saturated zones. Objectives at this stage of remediation are usually limited to removal of liquid phase gasoline, and migration control of liquid phase gasoline and dissolved gasoline constituents. Interim remedial objectives are achieved by using a combination of media-specific technologies. Petroleum hydrocarbon impact of the unsaturated zone is commonly addressed by excavation, soil vapor extraction, or biodegradation. Bulk liquid phase gasoline is frequently removed by bailing, skimming, or a combined use of groundwater extraction and skimming. Hydraulic containment by groundwater extraction, or installation of a physical barrier are common technologies used to institute migration control.

Where applicable, soil vapor extraction is recognized as a cost effective means for in-situ remediation of gasoline impacted soils. In general, soil vapor extraction is accomplished by applying a vacuum to a field of perforated probes or vadose zone wells in order to establish a subsurface pressure gradient. The resulting air flow through the unsaturated zone mobilizes volatile gasoline components, facilitating their removal. Extracted soil vapor is typically treated by thermal oxidation, or vapor-phase carbon adsorption. Figure 2 presents a basic soil vapor extraction system. Design considerations for vadose zone treatment using soil vapor extraction have been identified by several authors, including Baehr, Hoag and Marley (1988); and Johnson, Kemblowski, et al (1989).

While soil vapor extraction has been shown to be an effective way to mitigate vadose zone impact, it has received little consideration as a method to remove bulk liquid phase gasoline. The remainder of this paper will attempt to establish soil vapor extraction as a method for attenuating liquid phase gasoline plumes and explore the possible advantages over traditional methods.

Field Observations

Data collected from sites where soil vapor extraction is being used to remediate the vadose zone have suggested that bulk liquid phase gasoline removal is taking place. A portion of that data is presented below.

Case 1

Gasoline concentration versus time curves for two sites are shown on Figure 3. Site A has a been characterized as having a liquid phase gasoline plume, impacted soil and impacted groundwater. Site B has been shown to have soil and groundwater impact. Both sites have similar lithology and are undergoing vadose zone remediation. Soil vapor extraction systems at each site were operated under comparable conditions. As seen in Figure 3, the site with the liquid phase gasoline plume displayed significantly higher gasoline concentrations for the first 200 days of operation. The concentration decay trend is similar for both sites. As remediation proceeds, gasoline concentrations fall to an asymptotic level characteristic of diffusion limited transport and site conditions. This data may imply that initial high concentrations were due to a flux contribution from the bulk liquid.

Case 2

At this site, routine tank monitoring disclosed there had been an unwanted release of gasoline. Inventory records were used to approximate the volume lost, approximately 450 gallons. It was found that gasoline had leaked into the subsurface environment through a hole in one of the subsurface fuel storage tanks (Baehr, Hoag, and Marley, 1988). Interim remediation began with removal of bulk liquid phase gasoline through a combination of bailing and enhanced skimming (groundwater depression with skimming). Gasoline recovery took place from a 6-inch diameter well, equipped with a groundwater depression pump.

After about five months of skimming, approximately 79 gallons of liquid phase gasoline was removed. Based on the initial spill amount, enhanced skimming had removed 17 percent of the total volume of gasoline released. Over a 5 month period, the average recovery rate was approximately 0.5 gallons per day. In an attempt to recover more gasoline, a soil vapor extraction system was installed.

Over a 90 day period, the soil vapor extraction system removed approximately 351 gallons of gasoline; 78 percent of the total estimated spill. Gasoline was removed at an average rate of 3.9 gallons per day. Soil vapor extraction significantly reduced the bulk liquid gasoline plume and mitigated residual vadose zone impact. The average removal rate for vapor extraction was 87 percent faster than that of enhanced skimming.

Case 3

At this site, a surface release of toluene (volatile component of gasoline) resulted in impact to the vadose zone, liquid phase toluene on the groundwater surface, and dissolved toluene in groundwater (Clayton, Brody, and Brown, 1989). The maximum separate-phase toluene thickness 20 feet downgradient of the release was 1.5 feet. A soil vapor extraction system was installed to remove toluene from the subsurface.

After 3 months of operation, approximately 1,000 pounds of toluene had been removed by vapor extraction. Separate-phase thicknesses were reduced significantly, and dissolved concentrations were attenuated. Not only did soil vapor extraction achieve its' primary objective, vadose zone remediation, it also achieved the removal of bulk liquid phase toluene and initiated the aquifer restoration.

Theory

In the case of soil vapor extraction, the total mass flux is the sum of flux contributions associated with ordinary (concentration) diffusion, and convection. The system under consideration is shown in Figure 4. Flux associated with convection occurs as vapor sweeps through soil pores, mobilizing vapor-phase gasoline constituents away from liquid phase gasoline residual. The flux of compound (i) resulting from convection in a porous media may be described using Darcy's Law:

$$\text{Flux (i)} = (x_i)\,(B/\mu)\,(\nabla P) \qquad (1)$$

In this application, (x_i) is the vapor-phase mass fraction of (i), (B) is the permeability of the porous media, (μ) is the viscosity of the transport fluid, and (∇P) is the pressure gradient. The functionality of (x_i) is complex; therefore, it is typically assumed to be the vapor concentration associated with vapor-liquid equilibrium (Johnson, et. al, 1988; Baehr, et. al, 1988)

Ordinary diffusion results from the concentration gradients of all substances present in a system. For an example, consider liquid diffusion within residual liquid and bulk liquid gasoline. As volatile gasoline constituents diffuse across the vapor-liquid interface, away from the liquid surface, a localized concentration change occurs within the gasoline mixture. The resulting difference in concentration between the liquid surface and the interior of the liquid residual (or bulk) causes volatile constituents to move towards the vapor-liquid interface. A similar vapor-phase mechanism occurs in the vadose zone pore space. Flux resulting from ordinary diffusion can be described by Fick's Law:

$$\text{Flux (i)} = -D\,(\nabla x_i) \qquad (2)$$

Where (D) is the effective diffusivity, and (∇x_i) is the concentration gradient of (i). An effective vapor-phase diffusivity is shown to account for diffusion in the soil matrix, where pore dimensions may be smaller than the mean free path of diffusing molecules. It is important to note that x_i, and therefore the flux of (i), is ultimately a function of the vapor-liquid equilibrium state of the system.

Design strategy for remediation of the vadose zone has been to intersect the residual plume area with air flow, optimizing conductive and diffusive flux. Any other configuration would not efficiently achieve the vadose zone remedial objective. For example, passing an air flow near the residual plume area would limit the contribution of convective flux, and increase the dependence on diffusive flux. However, field data suggests that passing air over bulk liquid gasoline may be more efficient for the removal of bulk liquid than reliance on pumping.

Consider the transport mechanisms for bulk liquid removal by pumping and soil vapor extraction. The dominating mechanism for transport by pumping is convection. In this case, the resistance to transport is the inverse of the hydraulic conductivity, or the liquid viscosity divided by the permeability coefficient of the porous media through which transport occurs. In the case of soil vapor extraction, the dominating transport mechanism is vapor-phase diffusion, where the resistance to transport is the inverse of the diffusivity. Field observations regarding bulk liquid phase removal indicate that the resistance associated with convective liquid transport is equal to, or greater than that associated with vapor-phase diffusive transport. Once vapor-phase gasoline has diffused into an area where convective transport dominates, the transport resistance becomes negligible compared to the resistance of liquid phase convective transport. This supports the supposition that soil vapor extraction may be a more efficient means to remove bulk liquid phase hydrocarbons.

Separate-Phase Removal: Soil Vapor Extraction or Pumping

Separate-Phase Pumping

Traditionally there have been two installed methods for the removal of separate phase hydrocarbons from the groundwater surface. These methods are the installation of either a separate-phase hydrocarbon recovery pump or the combination of a groundwater depression pump with a separate-phase recovery pump. These two methods are both feasible technologies in the removal of separate-phase hydrocarbons, but there are deficiencies in performance, cost, and start-up time associated with these methods. We believe the use of soil vapor extraction is at times a more efficient, cost effective means to address separate-phase hydrocarbon removal.

The simplest and most time efficient method of the two traditional methods for separate-phase recovery is the installation of product recovery pumps in existing monitoring wells at the groundwater/separate-phase interface. The recovered separate-phase and groundwater is then properly stored and recycled. This method has both advantages and disadvantages. The advantages are its relatively inexpensive costs to respond to separate-phase removal due to the use of existing wells, the short time required for the installation of these pumps and the ease in acquiring regulatory permits, since no groundwater discharge permits will be required. But there are drawbacks to the use of this method. The recovery efficiency of the separate-phase recovery pump is restricted by its generally small radius of influence which is a result of the limited amount of drawdown the pump can achieve. This fact generally leads to the installation of further extraction wells and more recovery pumps or the installation of a groundwater depression pump in conjunction with a separate-phase recovery pump.

The installation of a groundwater depression pump to assist separate-phase recovery is generally used as a dual purpose remediation method. This method responds to dissolved hydrocarbons as well as increases the radius of influence of the separate-phase recovery system by depressing the water table at the recovery well and enhancing the recovery of separate-phase within a larger radius. The major drawback to this method lies in the discharge of extracted groundwater. The extracted groundwater must be treated and then discharged through either the use of a NPDES permit or to a POTW system. These permits in recent times have become more difficult as well as more time consuming to obtain due to more restrictive discharge requirements. In California, wastewater reclamation requirements imposed due to the last 5 years of drought have added an additional obstacle. Therefore, this method of recovery is becoming a more time consuming method of addressing separate-phase removal, whose primary goal, is source removal in a timely fashion to minimize the impact on groundwater and minimize the time required for closure of the site.

As has been shown in the previous paragraphs there are problems associated with the traditional methods for separate-phase recovery both in efficiency and the time required for the implementation of these systems. Due to these constraints, we propose the use of soil vapor extraction as a method for the recovery of separate-phase hydrocarbons.

Soil Vapor Extraction

Previous sections in this paper have shown soil vapor extraction as a viable method for removing hydrocarbons from soil and the theories by which this mechanism is driven. We have also shown field evidence to support this theory. Therefore, based on these theories and field evidence which supports the use of soil vapor extraction to remove separate-phase hydrocarbons we propose using soil vapor extraction as a separate-phase hydrocarbon recovery method.

The primary advantage to soil vapor extraction lies in the ability to install and permit the treatment method in a shorter period of time and achieve recovery results equal to or greater than the use of a groundwater depression pump in conjunction with a separate-phase recovery pump. The primary goal of separate-phase recovery is source removal, therefore, response time is one of the most important factors in the installation of a recovery system. As we have mentioned previously, delays can occur in acquiring groundwater discharge permits and separate-phase recovery without the benefit of groundwater depression can be an ineffective method for recovery. Permits for soil vent systems in most areas can be obtained within 90 days and source removal can begin. The extracted vapors can be recovered through a vapor recovery system or treated through various existing treatment technologies.

Soil vapor extraction can also be a more cost effective way of removing separate-phase hydrocarbons. Beyond the potential reduction in total remediation costs from the more rapid response to the removal of the contamination source, this technology in many cases is a less costly method for the removal of separate-phase. Soil vapor extraction is in most cases part of the interim remedial action plan for the site and therefore represents no additional capital. Furthermore, by addressing soil vapor extraction as a viable form of separate-phase removal in the interim remedial design, the soil vent system recovery wells can be designed to reflect their use as a separate phase removal method as well as a vadose zone remediation method. Savings in capital and operational costs also occur in eliminating the need for separate-phase recovery equipment and in limiting the extraction of groundwater to plume migration control. The savings incurred will vary depending on the specific site conditions, but in all cases where separate-phase recovery and soil vapor extraction are part of the interim remedial plan, savings will occur.

Conclusions

Based on field observations and theory previously discussed the following conclusions were identified:

- When soil vapor extraction is used to remediate the vadose zone at sites where bulk liquid is present there appears to be flux contributions from the bulk liquid. The major transport mechanism for this process is diffusion.

- Soil vapor extraction appears to remove bulk volatile liquid phase at a greater rate than traditional separate-phase removal methods. This implies, where appropriate, soil vapor extraction should be used to recover bulk separate-phase in lieu of recovery by pumping.

- Further research is required to quantify the role of soil vapor extraction in removing bulk liquid phase hydrocarbons.

- Design criteria needs to be developed to optimize the use of soil vapor extraction in bulk liquid phase hydrocarbon recovery.

There are several advantages to the use of soil vapor extraction in lieu of pumping to recover bulk liquid phase hydrocarbons. These are:

- Reduced remedial response time due to limited permitting constraints, and ease of implementation.

- Reduction of extracted groundwater volumes by restricting groundwater extraction to only migration control objectives.

- Reduced capital cost of remediation by eliminating the need for a separate bulk liquid phase recovery system.

- Groundwater conservation is achieved by reducing the volumes of extracted groundwater.

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REMOVING VOLATILE CONTAMINANTS FROM THE UNSATURATED ZONE BY INDUCING ADVECTIVE AIR-PHASE TRANSPORT

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ABSTRACT

Baehr, A.L., Hoag, G.E. and Marley, M.C., 1989. Removing volatile contaminants from the unsaturated zone by inducing advective air-phase transport *J. Contam. Hydrol.*, 4: 1–26.

Organic liquids inadvertently spilled and then distributed in the unsaturated zone can pose a long-term threat to ground water. Many of these substances have significant volatility, and thereby establish a premise for contaminant removal from the unsaturated zone by inducing advective air-phase transport with wells screened in the unsaturated zone. In order to focus attention on the rates of mass transfer from liquid to vapour phases, sand columns were partially saturated with gasoline and vented under steady air-flow conditions. The ability of an equilibrium-based transport model to predict the hydrocarbon vapor flux from the columns implies an efficient rate of local phase transfer for reasonably high air-phase velocities. Thus the success of venting remediations will depend primarily on the ability to induce an air-flow field in a heterogeneous unsaturated zone that will intersect the distributed contaminant. To analyze this aspect of the technique, a mathematical model was developed to predict radially symmetric air flow induced by venting from a single well. This model allows for in-situ determinations of air-phase permeability, which is the fundamental design parameter, and for the analysis of the limitations of a single well design. A successful application of the technique at a site once contaminated by gasoline supports the optimism derived from the experimental and modeling phases of this study, and illustrates the well construction and field methods used to document the volatile contaminant recovery.

INTRODUCTION

Organic substances, such as hydrocarbons and halogenated hydrocarbons, are introduced into the subsurface in a variety of ways including leaking underground storage tanks, mismanagement of industrial solvents, and accidents involving pipelines and tank trucks. Because of the limited volatility and solubility of these substances under environmental conditions, organic contaminants most commonly enter the subsurface as a liquid phase that is immiscible with both air and water. Remedial actions for large spills of petroleum products generally include an effort to physically recover the

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product accumulated on top of the water table by bailing and/or skimming. However, substantial portions of the spill, can remain because the porous media can retain the immiscible phase by capillary forces. For example, Hoag and Marley (1986) determined residual saturations of a commercial gasoline to be 26 and 44 grams per kilogram of medium and fine sand, respectively, at field moisture conditions.

Unfortunately, the threat posed to ground water may persist even if the immiscible phase is immobile. Using a mathematical model of vapor and solute transport in the unsaturated zone, Baehr (1987) demonstrated that significant amounts of gasoline hydrocarbons can partition into the water in the unsaturated zone. These solutes can enter ground water with recharge or fluctuating water tables. Thus, in environmentally sensitive areas, a secondary recovery method may be required to completely rectify the contamination.

Many organic substances of environmental interest have substantial vapor concentrations comparable to their solubilities. By comparing the saturated vapor concentrations and aqueous solubilities presented in Table 1 and assuming connected air-filled voids, it is reasonable to anticipate that such contaminants could more effectively be recovered from the unsaturated zone by enhancing air-phase transport than by enhancing water-phase transport (e.g., a flushing scheme).

Advective-vapor transport can be induced by withdrawing or injecting air through wells screened in the unsaturated zone. At least one withdrawal well is required to collect and analyze vapors for documenting contaminant recovery. Air laden with organic vapors moves along the induced flow path toward the withdrawal wells, where it is removed from the unsaturated zone and treated and/or released to the atmosphere. Therefore, the success of the method depends on the rate of contaminant mass transfer from the immiscible

TABLE 1

Thermodynamic parameters for selected organic substances

Substance[1]	Molecular weight	Saturated vapor concentration[1] at 20°C (mg L^{-1})	Aqueous solubility[1] at 20°C (mg L^{-1})
Benzene	78	300	1780
Toluene	92	130	515
o-Xylene	106	30	152
n-Hexane	86	630	10
1,1,2-Trichloroethylene	131	410	1100
1,1,1-Trichloroethane	133	690	730
gasoline[2]	100	411	156

[1] Data from MacKay and Shiu (1981). mg L^{-1} = milligrams per liter.

[2] Values for gasoline are based on a weighted average of hydrocarbon properties determined from the gas chromatography analysis of a leaded regular gasoline by Bruell and Hoag (1984).

and water phases to the air phase and on the ability to establish an air-flow field that intersects the distributed contaminant. This method of recovery is called induced venting or in-situ air stripping. Its application has been described by Texas Research Institute (1980), Thorton and Wootan (1982), and Marley and Hoag (1984). However, a formal analysis of the transport processes involved, has not appeared in the literature to date.

The purpose of this paper is to provide such an analysis. First, the results of venting experiments on sand columns residually saturated with gasoline are analyzed by using an equilibrium-based transport model to focus attention on rates of local phase transfer. Next, a mathematical model which predicts air flow to a single well is developed. This model can be used to analyze air-phase pressure measurements collected during an unsaturated zone pump test to estimate permeability and thus can determine the limitations of a single well design. Finally, a successful application of the technique at a site once contaminated by gasoline is presented.

VENTING EXPERIMENTS UNDER STEADY AIR-FLOW CONDITIONS

Three venting experiments were conducted to analyze the rate of mass transfer of gasoline from the immiscible and water phases to the air phase. Steady air flow was maintained in the experiments to focus attention on these phase transfers. The experiments were conducted in column reactors that were 8.9 cm in diameter, 65 cm long, and filled with medium-grained sieved, washed sand to 5 cm below the top (Fig. 1). All experiments were conducted at 21°C. Prior to introducing the gasoline, the entire column length was saturated with distilled water, and then allowed to drain. Residual gasoline saturations were obtained by applying a vacuum to the top of the column, and by allowing a commercial leaded gasoline (density $0.78\,\mathrm{g\ cm^{-3}}$) to saturate the bottom 30 cm of sand. Then the vacuum was shut off and the gasoline was drained by gravity which left a residual saturation. During the course of the experiments, air that entered the bottom of the column was first saturated in water vapor to prevent the column from drying (with respect to water). A detailed description of these and other venting experiments is provided by Marley and Hoag (1984) and Marley (1985).

The three venting experiments had steady air flows, of 1.43, 3.00, and 7.00 L $\mathrm{min^{-1}}$ (liters per minute) respectively. The air-phase specific discharge corresponding to 7.00 L $\mathrm{min^{-1}}$ is 1.9 cm $\mathrm{s^{-1}}$. This is high compared to anticipated specific discharges in field applications, except perhaps in the immediate vicinity of the wells. Therefore, if limitations on the recovery caused by kinetic effects occur, they should be observed within the flow range of these three experiments. The medium-grained sand had a porosity of 0.241, a dry bulk density of $1.71\,\mathrm{g\ cm^{-3}}$ and an average particle diameter of 0.09 cm. The initial water and gasoline retentions for the three experiments are listed on Table 2. It is assumed that the small differences in saturations between experiments do

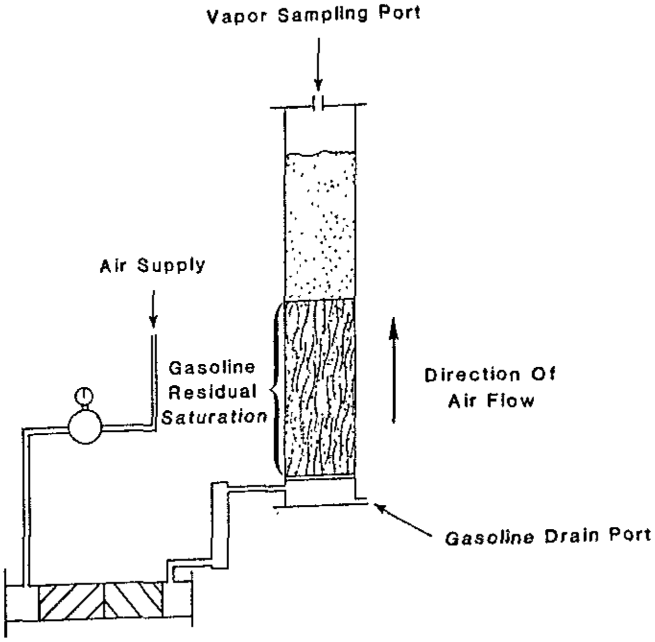


Fig. 1. Column reactor for conducting steady-flow venting experiments.

not interfere with isolating the effect of varying the flow rate. Air leaving the column was analyzed by using a packed column gas chromatograph with a flame ionization detector (GC/FID). This method was developed especially for gasoline analysis by Bruell and Hoag (1984). For this particular gasoline, 51 peaks were identified. Because a commercial gasoline consists of hundreds of individual compounds, some of the peaks, which are referred to as composite constituents in this paper, may correspond to a number of compounds.

Total hydrocarbon vapor fluxes (Table 3) were calculated by summing the 51 concentrations that were measured in the air leaving the column, and then

TABLE 2

Initial water and gasoline retentions for three steady-flow experiments

Experiment	Steady-flow rate ($L\ min^{-1}$)	Water retained by 60 cm of sand (g)	Gasoline retained by 30 cm of moist sand (g)
1	1.43	200	88
2	3.00	221	83
3	7.00	250	85

TABLE 3

Experimentally determined total hydrocarbon vapor fluxes

Experiment 1 $Q = 1.43$ L min^{-1}		Experiment 2 $Q = 3.00$ L min^{-1}		Experiment 3 $Q = 7.00$ L min^{-1}	
t (min)	F (mg min^{-1})	t (min)	F (mg min^{-1})	t (min)	F (mg min^{-1})
				0.75	12600
0.75	2473	0.75	5288	1.33	6141
1.50	2305	1.50	4144	1.83	4908
3.08	1577	3.00	2906	4.00	2466
5.00	1251	5.00	2159	9.00	1348
12.25	881	8.00	1489	17.00	851
16.00	725	12.00	1127	21.75	658
20.25	688	16.00	958	26.33	530
30.00	595	20.00	855	36.00	358
40.00	437	35.00	589	46.00	196
73.00	242	46.00	308	143.00	126
94.00	197	78.00	238	179.00	84
159.00	108	125.00	189	226.00	61
232.00	91	183.00	149	286.00	39
419.00	63	615.00	26	406.00	23
839.00	29	753.00	15	864.00	13
1024.00	13	894.00	8		
1544.00	11	1136.00	7		
2207.00	6				
$\int_0^{2207} Fdt = 89.2$ grams		$\int_0^{1136} Fdt = 83.6$ grams		$\int_0^{864} Fdt = 84.7$ grams	

t = time after commencement of venting.
Q = steady air flow rate mesaured at top of column.
G_T = total hydrocarbon concentration in vented air at top of column obtained by summing the concentrations of the 51 composite constituents determined by GC/FID analysis.
F = flux = $Q\,G_T$.
$\int_0^a Fdt$ = total mass removed from column.

multiplying the sum by the steady air-flow rate. The hydrocarbon mass that was removed was estimated by numerically integrating the flux over the duration of the experiment. Comparing the gravimetrically determined residual saturations listed in Table 2 with the total hydrocarbon vapor fluxes listed in Table 3, shows that essentially all gasoline was removed by venting. It also shows that the GC/FID analysis was sufficient for the purpose of obtaining mass balances. Figure 2 shows the hydrocarbon mass removed from the column as a function of the volume of air passed through the column (obtained by

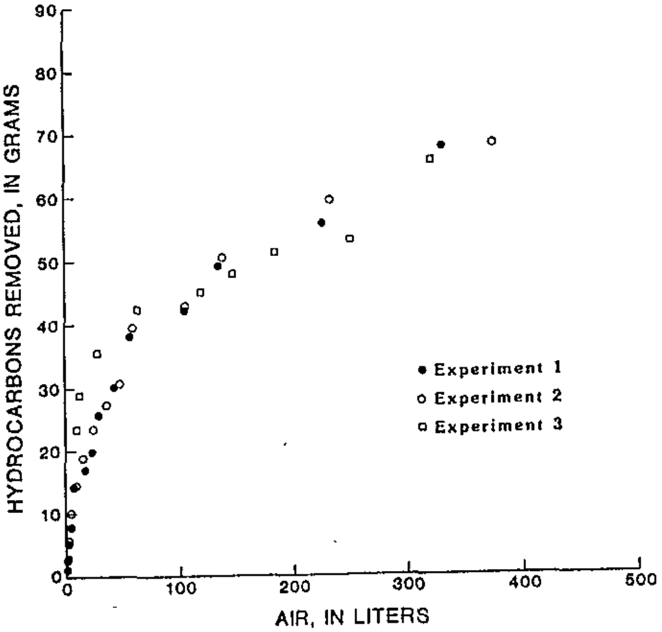


Fig. 2. Hydrocarbon mass removed as a function of the volume of air passed through the column.

multiplying the flow rate by time into the experiment) for each experiment. The coincidence of the plots indicates a proportionality between the removal rate (flux) and air-flow rate over the range of flow rates investigated. Note, however, that the flux (slope of plots), and hence the proportionality constant, declines with time. To describe this phenomenon we hypothesize that the vapor concentration in the air-filled void space is at equilibrium with the residual liquid gasoline for all times, for each experiment. Furthermore, the decline in flux with time, can be attributed to a shift in equilibrium which is caused by the selective removal of more volatile hydrocarbons. This results in an immiscible contaminant that shifts toward a less volatile substance.

To test this hypothesis, the experiments were mathematically simulated with a multiphase-compositional transport model. The model consists of a conservation of mass equation for each constituent of the contaminant. Each constituent can be partitioned into air, immiscible, water and adsorbed phases according to equilibrium relationships. The model is presented in Appendix 1. Under the simulated conditions (high air-flow rates and the presence of an immiscible phase), however, model predictions were found to be insensitive to the degree of partitioning into the water and adsorbed phases. Thus, for the purpose of modeling the steady air-flow experiments, only contaminant partitioning into air and immiscible phase was required. The experimental conditions were also such that advective and dispersive transport mechanisms in the water and immiscible phases as well as dispersive transport in the air phase were negligible. As previously discussed, the 51-peak GC/FID analysis does not allow for the assignment of a single compound for every peak. Therefore, the constituent-specific vapor pressures, required as input for the model, could not be assigned independent of experimental results. These values were assigned by calibrating the model to the data from experiment 1 (the experiment with the lowest air flow rate). This calibration and the selection of constituent-specific properties is further discussed in Appendix 1. If the calibrated model is successful in describing the flux declines in time for higher-flow experiments 2 and 3, then the equilibrium hypothesis would be supported.

Figures 3a, 3b, and 3c compare the experimentally determined total hydrocarbon fluxes (Table 3) to the fluxes predicted by the mathematical model. The ability of the model to describe the experiments conducted at the higher flow rates supports the hypothesis of local equilibrium as an explanation for the declining fluxes as opposed to the development of kinetic effects which would depend on air phase velocities. However, these results, do not provide a rigorous verification of the equilibrium model, detailed in Appendix 1, because of the complex composition of the gasoline. Figures 4a and 4b are the GC/FID chromatograms of the vented air samples for Experiment 3 (flow rate = 7 L min^{-1}) at t = 1.33 and 17 min, respectively. These chromatograms provide experimental evidence of the shift in the composition of the vented air from the lighter, more volatile substances to the heavier, less volatile ones. The horizontal axis of each chromatogram is the retention time relative to that of the toluene peak. Benzene, toluene, and xylenes have been identified for reference.

Equilibrium concentrations for a given air-phase discharge imply that the maximum rate of local phase transfer occurs, however, it is a declining maximum for a multiconstituent contaminant like gasoline. This, together with the observation that essentially all of the gasoline in all the column experiments was eventually removed by vapor stripping, enables us to anticipate that the success of a venting application will depend primarily on the ability to induce a significant air-flow field to intersect the contaminant plume, which, in general, will be distributed in a heterogeneous medium.

MODELING AIR FLOW AND DESIGN CONSIDERATIONS

Compressible flow in porous media has been a subject of investigation for many years in petroleum reservoir engineering. In particular, mathematical models have been used to simulate gas reservoirs dating back to Muskat and Botset (1931). The application of such models to aid in the design of a venting system is exactly analogous and can be thought of in two steps:

(1) Evaluate, in situ, the air permeability of the contaminated unsaturated zone by calibrating a steady-state air-flow model with pressure measurements obtained during pumping tests.

(2) Use the air permeability and a steady-state air-flow model to determine

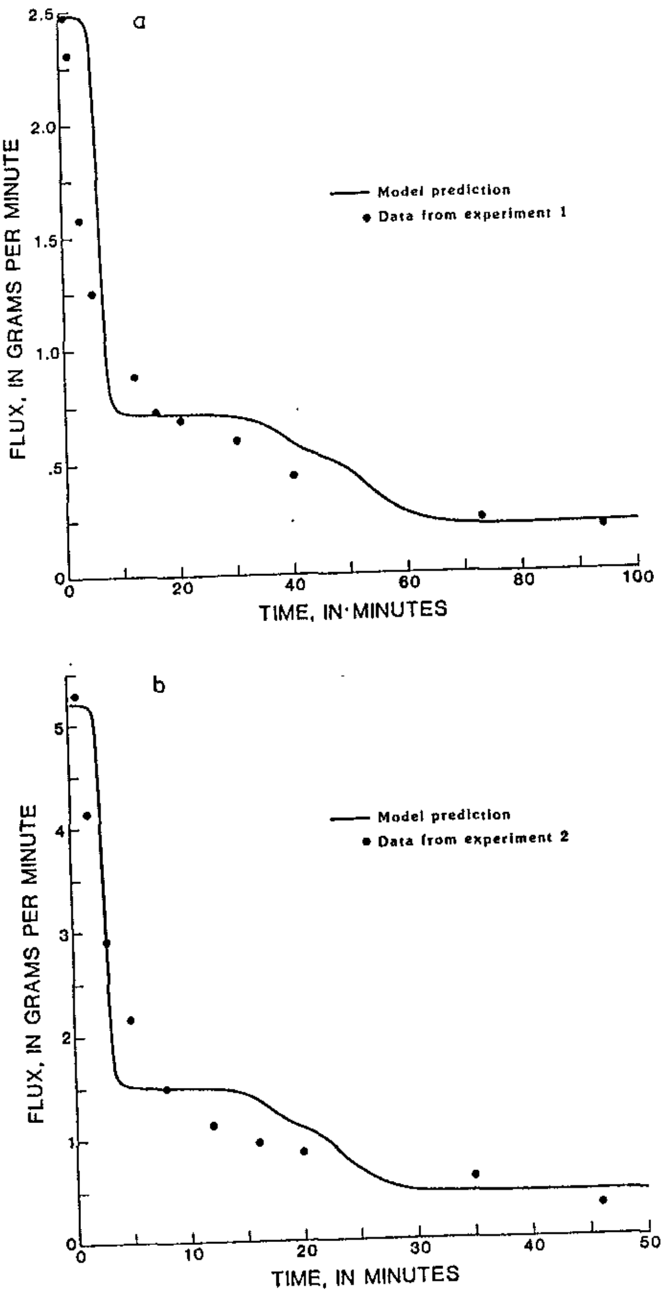


Fig. 3. Comparison of total hydrocarbon fluxes from steady-flow venting experiments to predictions obtained from the mathematical model. (a) flow rate = 1.43 L min^{-1}; (b) flow rate = 3.00 L min^{-1}; (c) flow rate = 7.00 L min^{-1}.

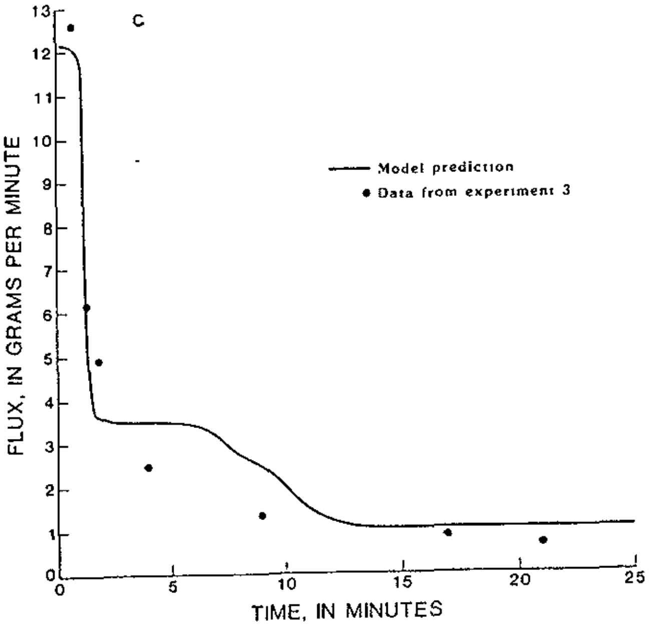


Fig. 3. Continued.

the well spacing and screen intervals of wells in the unsaturated zone required to generate the desired air movement.

An in-situ determination of air-phase permeability is preferred over laboratory determinations to account for variations in prevailing soil-water conditions, the presence of the immiscible organic liquid, and anisotropy and heterogeneity in air-phase permeability. Steady-state pumping tests, which require less data than transient analyses, are sufficient for this application because only the in-situ air permeability is needed for design purposes. The steady-state air-flow model is given by the following partial differential equation:

$$\nabla \cdot (k \nabla P^2) = 0 \qquad (1)$$

where P is air-phase pressure and k is the air-phase permeability tensor. The selection of a coordinate system and appropriate boundary conditions, together with eq. (1) defines the air-flow model. Equation (1) is based on the conservation of mass principle for a compressible fluid, with assumptions of Darcian flow and ideal gas behavior. Details are provided in Appendix 2.

To determine air-phase permeability, a radially symmetric region with a single well. (Fig. 5) is assumed. This implies that the principal axes for the air-permeability tensor are in the radial (r) and vertical (z) directions. Air is injected or withdrawn through the well screen. The unscreened portion of the

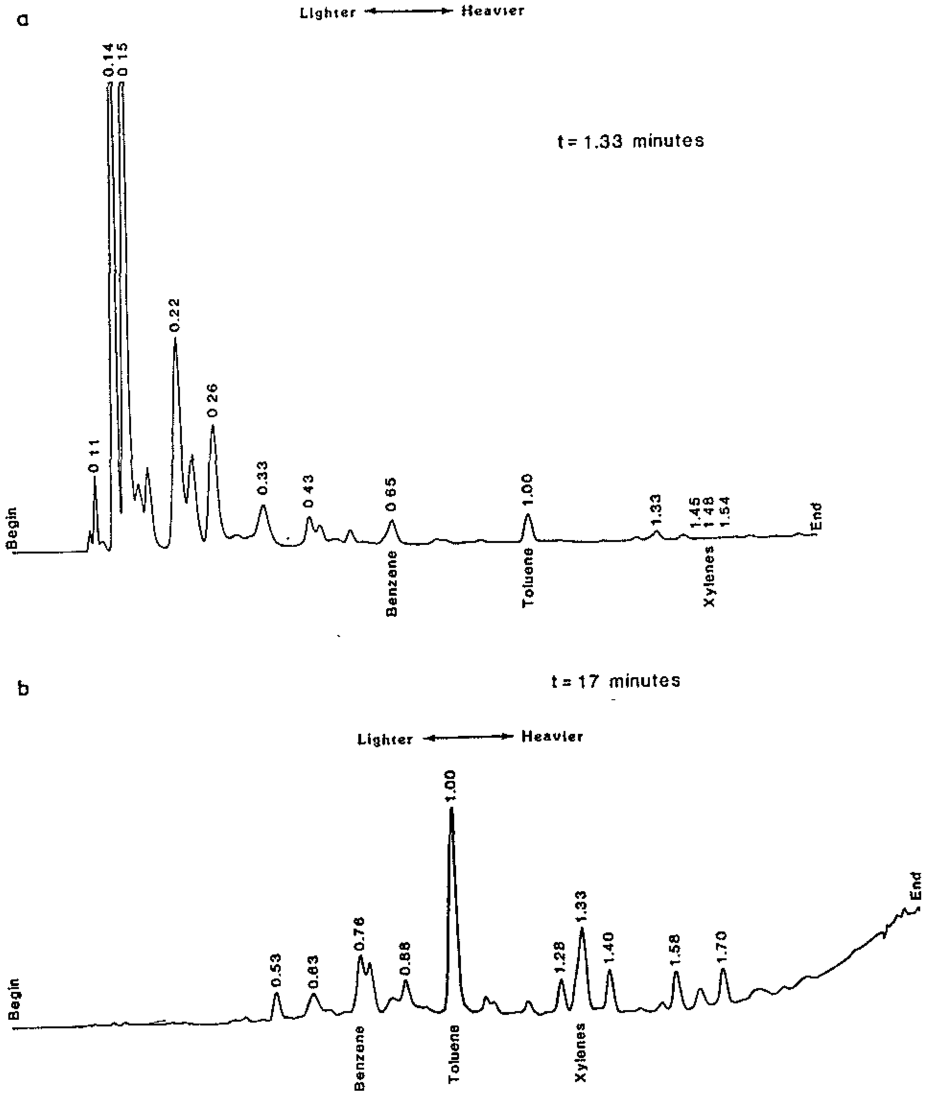


Fig. 4. GC/FID Chromatograms of vented air samples for experiment 3. (a) $t = 1.33$ min; (b) $t = 17$ min.

well is a no-flow boundary. Referring to Fig. 5, the boundary conditions at $r = r_0$ (well diameter) are:

$$P = P_s \qquad \text{for } r = r_0 \text{ and } z_{w1} \leqslant z \leqslant z_{w2} \tag{2}$$

and

$$\frac{\partial P}{\partial r} = 0 \qquad \text{for } r = r_0 \text{ and } z < z_{w1} \text{ or } z > z_{w2} \quad . \tag{3}$$

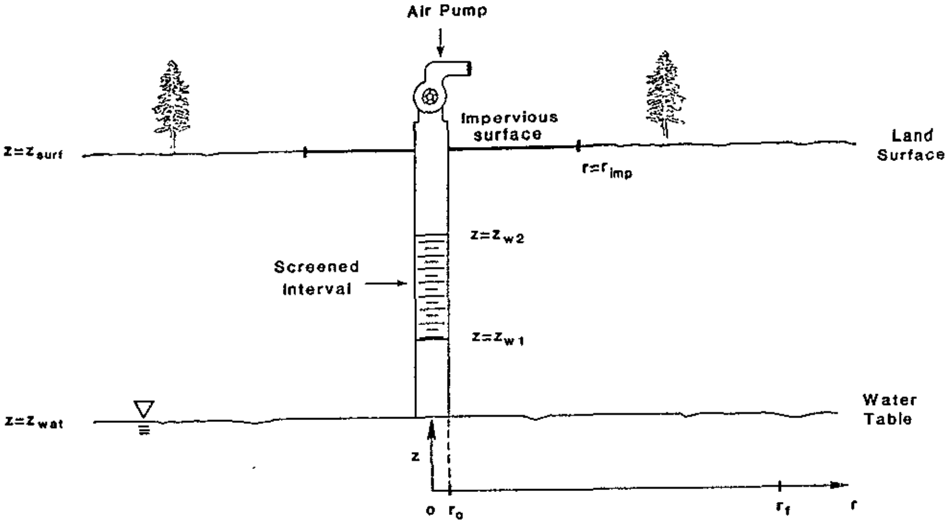


Fig. 5. Radially symmetric region for single-well air flow model

where P_s is the steady pressure along the well screen, located between elevations z_{w1} and z_{w2}. P_s is assumed to be equal to the steady pressure read at the pump. The boundary at $r = r_f$ can be chosen to be unaffected by the well:

$$P = P_{atm} \qquad \text{for } r = r_f \tag{4}$$

where P_{atm} is atmospheric pressure. Pressure measurements (if available) can be used to define the boundary condition at $r = r_f$. The lower boundary, formed by the water table, is impervious to air flow, and is as follows:

$$\frac{\partial P}{\partial z} = 0 \qquad \text{for } z = z_{wat} \text{ and all } r \tag{5}$$

The land surface may be open to the atmosphere or impervious to air flow to simulate paved surfaces. This boundary is:

$$\frac{\partial P}{\partial z} = 0 \qquad \text{for } z = z_{surf} \text{ and } r \leqslant r_{imp} \tag{6}$$

$$P = P_{atm} \qquad \text{for } z = z_{surf} \text{ and } r_{imp} < r < r_f$$

where r_{imp} is the radius of the impervious portion of the land surface.

A numerical solution to eq. (1) subject to boundary conditions (2)–(6) was developed using finite-difference approximations. For the special case of radial flow that is induced by fully screening the well in the unsaturated zone beneath an entirely impervious ground surface, the analytical solution to equation (1) presented by Muskat and Botset (1931) can be used to obtain a horizontal air-phase permeability, averaged over the entire depth of the unsaturated zone. The numerical solution, however, can simulate flow to a partially screened well, and thus, allow for a determination of vertical and horizontal air-phase permeabilities, averaged over protions of the unsaturated zone. Further, the numerical solution allows for evaluating heterogeneous unsaturated zones.

Weeks (1977) describes the use of depth-dependent variations in air pressure caused by natural variations in atmospheric pressure, to calculate the vertical component of air-phase permeability. For the venting application, however, the horizontal, or some composite parameter, is clearly required. Furthermore, Weeks' method does not allow for a focus on a contaminated region at depth. As another historical note, soil scientists (for example, Kirkham, 1946; Evans and Kirkham, 1949; Grover, 1955; and Tanner and Wengel, 1957) have utilized injected air and pressure measurements to evaluate soil permeability but these techniques provide estimates over small regions of soil and are not directly applicable for unsaturated zone evaluation.

After determining air-phase permeability, a flow model based on eq. (1) can be used to determine the well spacings and screen intervals needed to induce the desired air movement. If more than one well is needed, then the radially symmetric geometry implied by boundary conditions (2)–(6) is not adequate. However, the single well analysis can be used to determine if multiple wells are needed. For example, Fig. 6 compares plots of normalized pressures predicted at the well screen, P_s/P_{atm}, as a function of the mass rate of air-phase withdrawal, Q_m, for hypothetical isotropic unsaturated zones of varying air-phase permeability (input parameters defined in Table 4). For reference, a mass withdrawal rate of 1 g s^{-1} corresponds to a volumetric rate of about 50 L min^{-1} (assuming an air-phase density of 1.2×10^{-3} g cm^{-3}). The plots illustrate the limitations of this particular single well design as $P_s/P_{atm} < 0.5$ is assumed infeasible because of pump limitations. Figure 7 shows plots of the theoretical power, Γ, that is required to move air through the porous media corresponding to the same cases illustrated in Fig. 6. As illustrated, the power needed to move significant volumes of air through typical unsaturated zones is quite modest. Actual power requirements will be greater than the calculated theoretical power because of motor and pump inefficiencies. Appendix 3 describes the

TABLE 4

Input parameters for single well model used to obtain the plots of Figs. 6 and 7

Boundary characterization (refer to fig. 5)

$r_w = 7.62$ cm
$r_{atm} = r_t = 5000$ cm
$P(r_t) = P_{atm} = 1$ atmosphere
$z_{wat} = 0$
$z_{w_1} = 30$ cm
$z_{w_2} = 180$ cm
$z_{surf} = 560$ cm

Air-phase Properties

$T = 10°C$ (temperature)
$\mu = 1.76 \times 10^{-4}$ g cm^{-1} sec^{-1} (dynamic viscosity)
$\omega = 28.8$ g $mole^{-1}$ (average molecular weight)

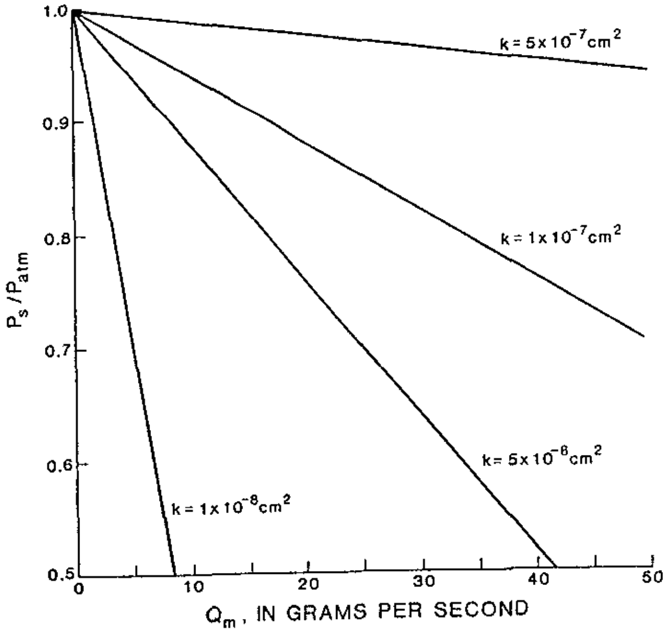


Fig. 6. Normalized air-phase pressure at a single well as a function of mass withdrawal rate for selected values of permeability.

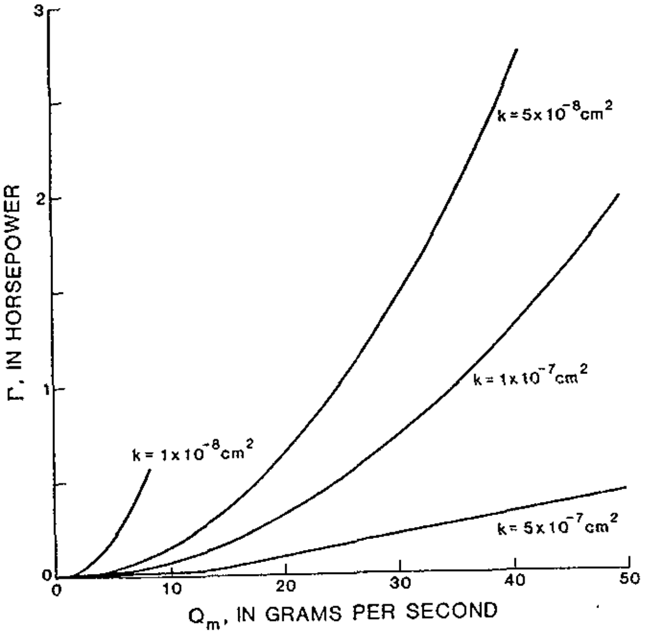


Fig. 7. Theoretical power required to move air as a function of mass withdraw rate for selected values of permeability.

application of the air-flow model to compute well pressures (Fig. 6) and the theoretical power (Fig. 7).

REHABILITATION OF A GASOLINE-CONTAMINATED UNSATURATED ZONE

The experimental and modeling investigations reported here establish a premise for organic contaminant removal from the unsaturated zone by induced vapor transport. Experiments conducted under steady air-flow conditions indicate that residual saturations of gasoline can be completely removed by vapor transport; air-flow modeling indicates that significant volumes of air can be moved through realistic unsaturated zones with modest power requirements. The following application of the technique at a gasoline-contaminated unsaturated zone beneath a service station provides evidence that the optimistic findings of these separate analyses can be translated into a successful field application.

While conducting a general monitoring program an oil company discovered gasoline contamination beneath a service station. Inventory records indicated that over a period of approximately 4 months 1480–1850 L of gasoline leaked to the subsurface through a hole in the bottom of a tank. An attempt to physically recover the lost product by using a water-table skimming system resulted in the removal of only 300 L of the product over a 5-month period. It was determined that the remaining product posed a threat to an active water-supply well that is located 150 m from the service station property line. Therefore, a secondary recovery method was sought.

The unsaturated zone beneath the service station was approximately 5.5 m thick consisting of fine to medium sands of glacial lake origin. The in situ air phase permeability (assuming isotropy) in the gasoline contaminated region was $k = 7.0 \times 10^{-8}$ cm^2 (as determined by a pumping test that was designed according to the parameters of Table 4). For the test, the mass withdrawal rate, $Q_m = 11.1\,\mathrm{g\,s^{-1}}$ corresponded to a normalized pressure of $P_s/P_{atm} = 0.9$.

The venting system consisted of three identically constructed wells, including the well used to determine the in-situ air-phase permeability. The wells were spaced 9.0 m apart. Figure 8 illustrates the well construction, and Fig. 9 provides a site plan showing the locations of the three vacuum wells, the unsuccessful skimming-system pump, and the locations of vapor probes used to determine total hydrocarbon vapor distributions in the unsaturated zone. The vapor probes were set 1 m above the water table. Additional site plan details are provided by Hoag and Cliff (1985). The design was constrained by the requirement that all wells had to be within property boundaries. Although air injection could have been used to increase air flow for the given configuration of venting boreholes, air was withdrawn from *all* three boreholes to obtain samples at each location.

The three venting wells were pumped simultaneously for 90 days from June to September, 1985. A volumetric withdrawal rate of 566 L min^{-1} (measured at

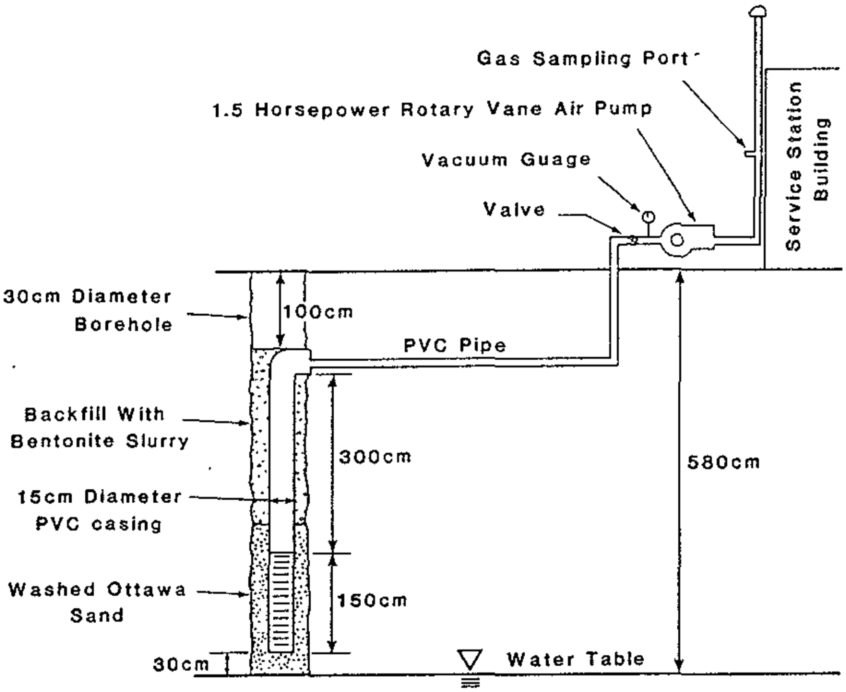


Fig. 8. Well construction in a gasoline contaminated unsaturated zone.

atmosphere pressure) was maintained at each well by using a 1.5-horsepower, rotary carbon vane, oil-less air pump. An oil-less pump was used to prevent contamination of the samples taken from the vented air, thus allowing for documentation of hydrocarbon recovery. Cumulative hydrocarbon recovery, in approximate liquid equivalents from each borehole is plotted as a function of time in Fig. 10. The liquid equivalent was obtained by multiplying the total hydrocarbon concentration in the vented air by the volumetric withdrawal rate and dividing by the density of the liquid gasoline (0.78 g cm^{-3}). Gas-tight syringes were used to obtain and store the samples that were transported to the University of Connecticut Hazardous Waste Laboratory. The total hydrocarbon concentration was determined by GC/FID analysis within 1 day of sample collection.

An estimated 1330 L of product were removed from the unsaturated zone with induced vapor transport; 300 L were recovered by the skimming operation. Therefore, an estimated total of 1630 L was recovered. Recalling that the spill was estimated between 1480 and 1850 L, we conclude that the venting operation was successful. Figures 11a and 11b provide an independent verification of the success of the venting by comparing the vapor plumes associated with the spill shortly before (11a) and shortly after (11b) the venting operation. The vapor plumes were determined with a network of gas-sampling probes (see Figs. 11a

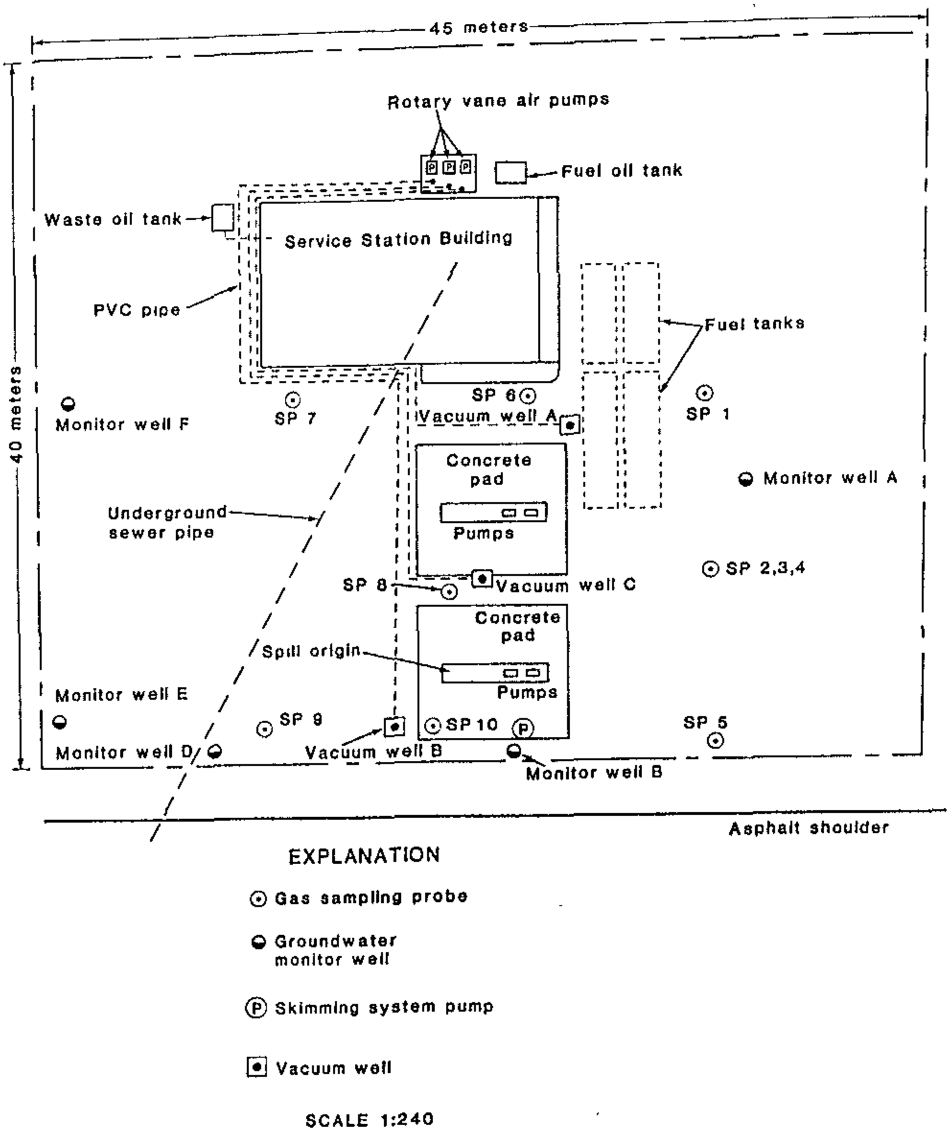


Fig. 9. Service station site plan.

and 11b) located about a meter above the water table. The venting performance also was measured with a physical parameter, the apparent (uncorrected) product thickness, as measured with a steel tape in a ground-water monitoring well located near well A (Fig. 12). This measure of success is of particular significance because near the water table air flows would be reduced or nonexistent because of the presence of both water and immiscible phases in the porespace. This success in the liquid-saturated regions within and adjacent to the capillary zone may be attributed to the upward movement of bulk gasoline

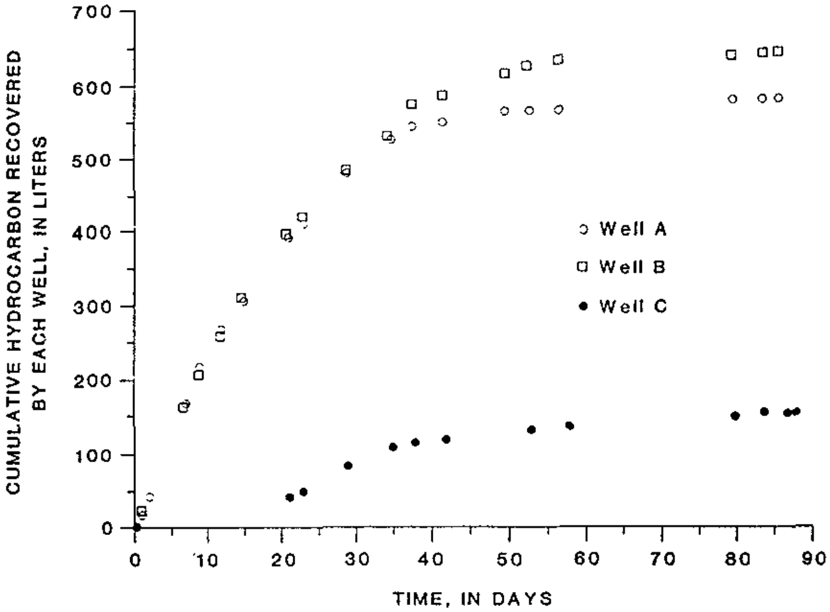


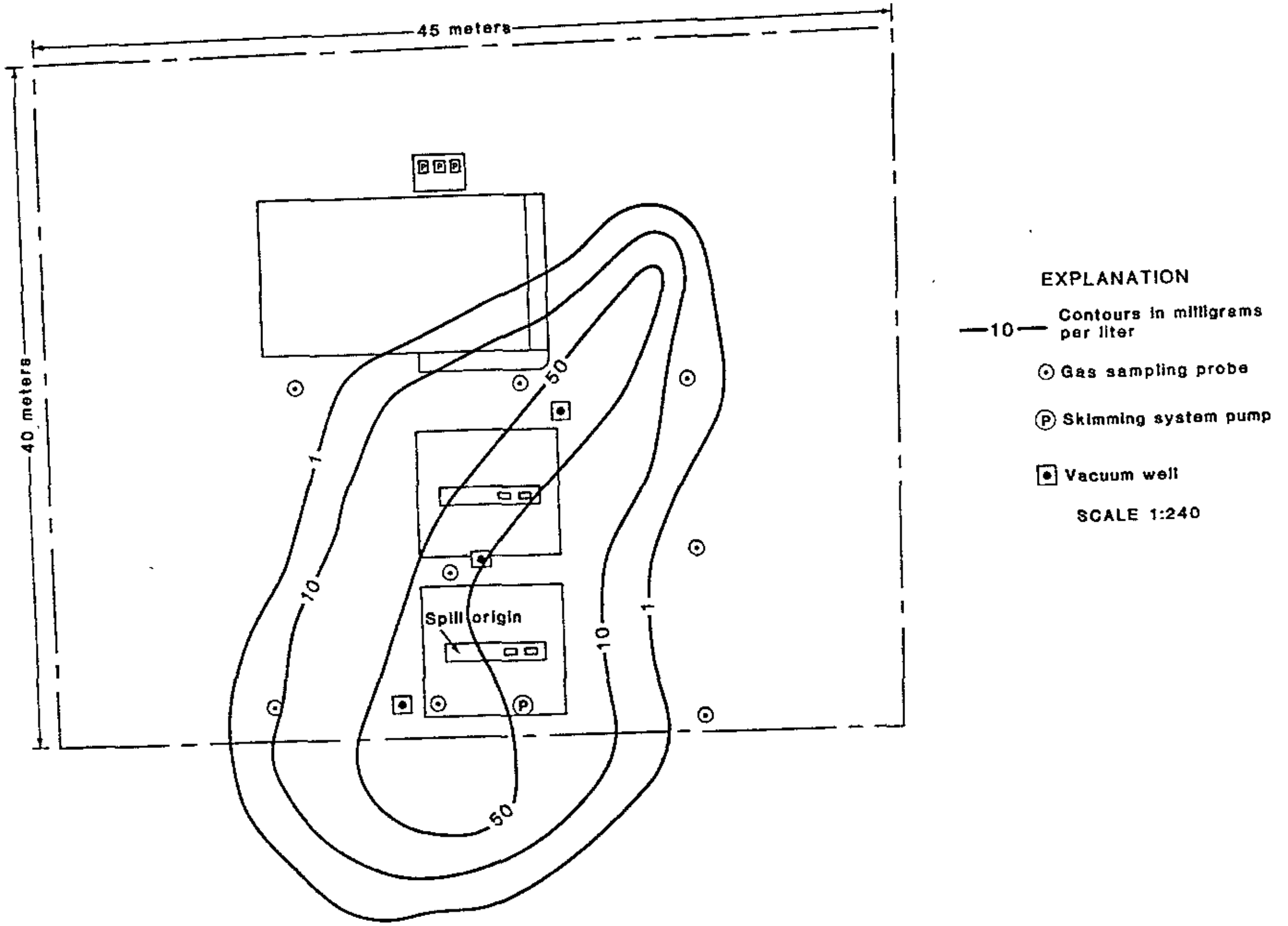
Fig. 10. Cumulative gasoline hydrocarbons recovered in liquid equivalents from three wells.

induced by a gradient in capillary forces resulting from venting. Another possible mechanism is upward vapor diffusion caused by concentration gradients, due to the induced air-flow field.

The declining slope of the cumulative recovery curves of Fig. 10 indicate declining recovery rates at each venting well. After 50 days of operation, the vapor recovery was negligible. It is reasonable to anticipate that these declines in recovery rates can be attributed, in part, to shifts in the composition of the remaining product toward heavier, less volatile substances as was observed in the steady air-flow column experiments. Figures 13a and 13b are the GC/FID chromatograms of air samples taken from withdrawal well A at days 1 and 30, respectively. These chromatograms provide verification of a compositional shift for the field experiment that is similar to that observed in the steady air-flow column experiments.

SUMMARY AND RECOMMENDATIONS

Experiments were conducted with homogeneous columns of moist sands residually saturated with a gasoline and vented under steady air flow to analyze liquid to air-phase transfers, which are requisite for air-phase removal. An equilibrium-based transport model was able to describe experimental hydrocarbon removal at flows corresponding to interstitial velocities higher than those that would be associated with most field applications. This equilibrium assumption suggests that local advective transport is linearly related to air-phase specific discharge at a given time. The results, although encouraging,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SERVICE STATION SITE PLAN

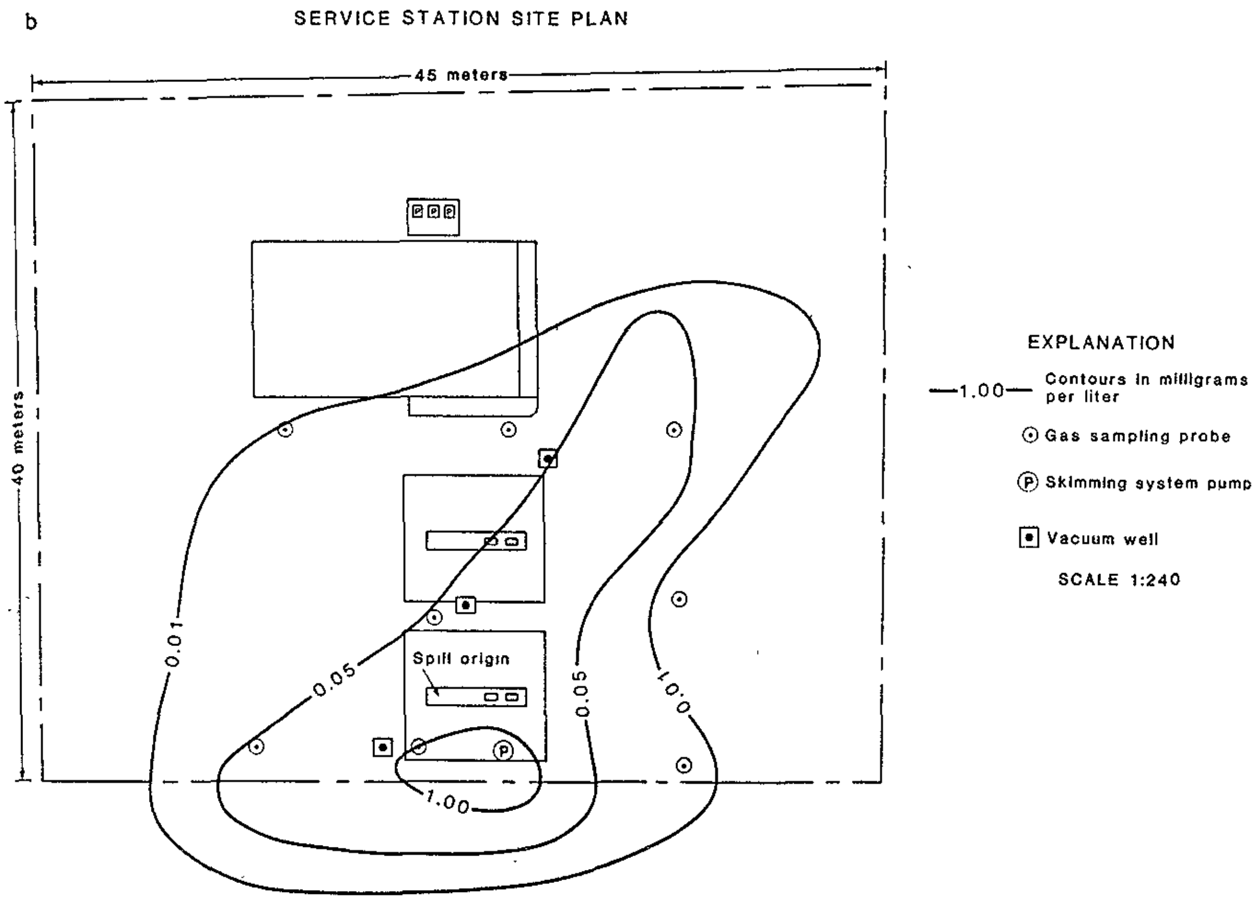

Fig. 11. Comparison of total hydrocarbon vapor plume before and after venting operation contour labels in milligram per liter. (a) Before; (b) after.

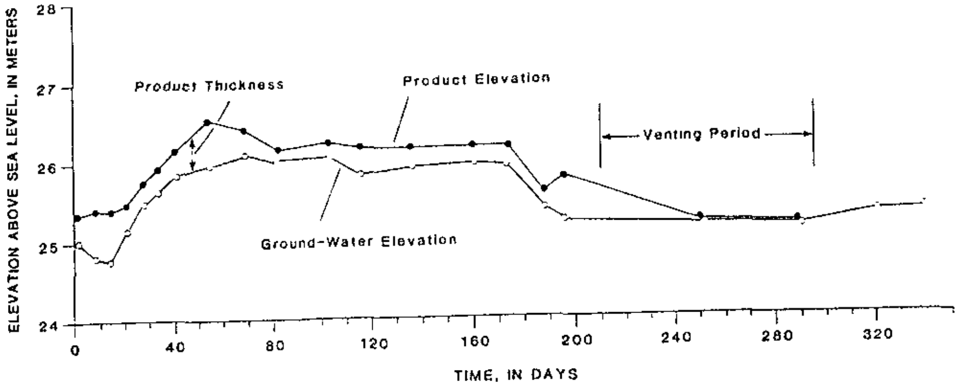

Fig. 12. Apparent product thickness near venting well A.

do not provide a rigorous verification of the equilibrium model because of the complex composition of the commercial gasoline used in the experiments. Such a verification is perhaps impossible for gasoline; however, venting experiments using a pure liquid such as benzene or trichloroethylene are suggested for further research. Nonetheless, the equilibrium-like behavior combined with the fact that essentially all residual gasoline saturations were removed by vapor stripping in all sand column experiments, enables us to anticipate that the success of a venting application to recover substances (with volatility comparable to gasoline-ranged hydrocarbons) will depend primarily on the ability to induce a significant air-flow field that will intersect the contaminant distributed in a heterogeneous unsaturated zone.

The air-phase permeability is the fundamental design parameter required to predict the air-flow field. An in-situ determination of this parameter can be obtained by calibrating a radially symmetric air-flow model with pressure measurements. Then air-flow models can be applied to determine the venting configuration needed to produce the desired amount of air movement. In particular, the same radially symmetric flow model developed to determine in-situ air-phase permeability can be applied to determine if multiple wells are required. Although not fully discussed in this paper, the model can be applied to analyze the effects of heterogeneity on the air-flow field. It should be noted, however, that an air-flow pump test designed to evaluate this aspect would require substantial instrumentation.

An induced venting system rehabilitated the gasoline-contaminated subsurface beneath a service station. The recovery was documented directly by analyzing air removed from withdrawal wells screened in the unsaturated zone. In addition, the success of the application was indirectly determined by mapping the vapor plume associated with the spill and measuring the apparent product thickness before and after the venting period. These two indirect measures would be of particular importance for cases where spill estimates are unavailable.

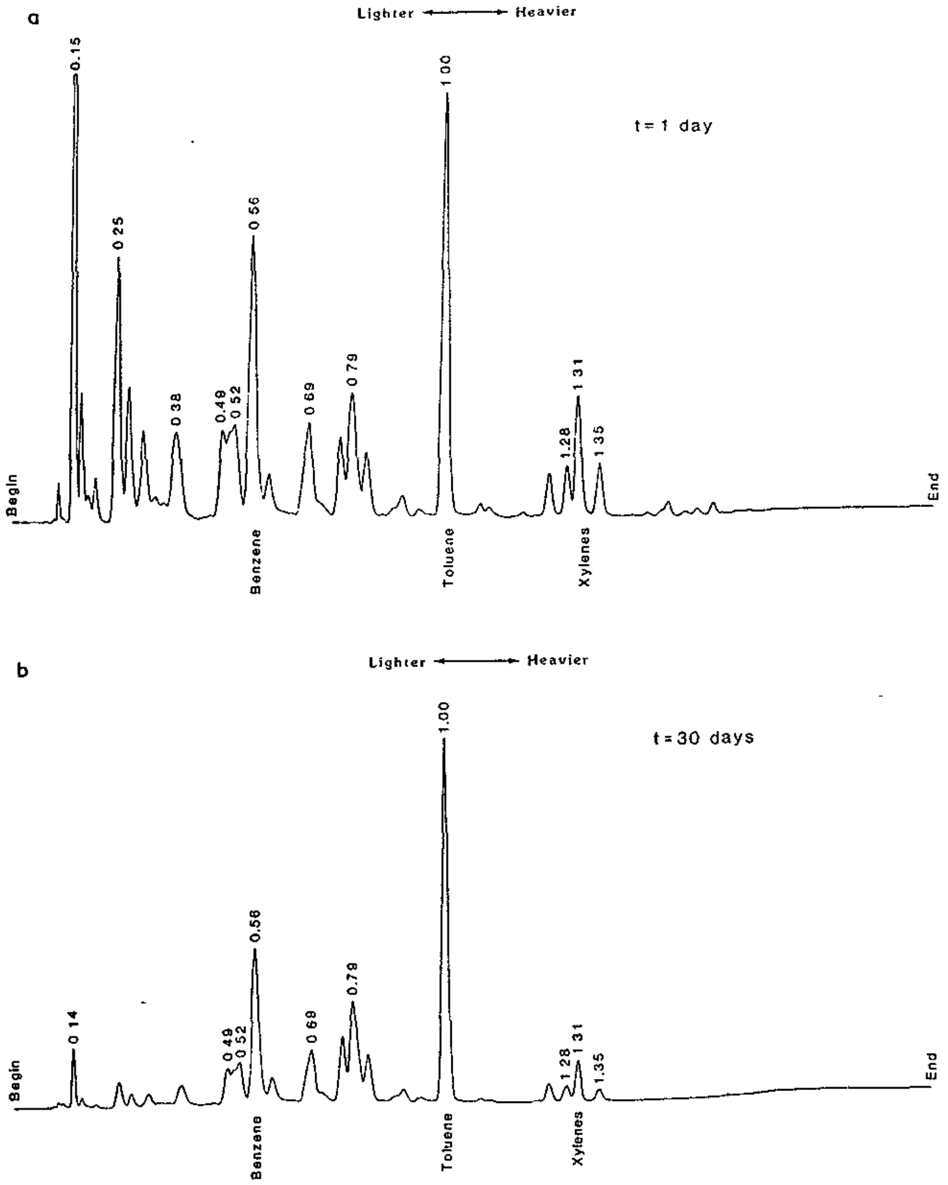

Fig. 13. GC/FID chromatograms of vented air samples from withdrawal well. (a) $t = 1$ day; (b) $t = 30$ days.

The experimental, modeling, and field evidence presented in this study, together with the simplicity of venting designs and the modest power requirements for moving air in permeable environments point toward a cost-effective technology, even in cases where withdrawn air requires treatment before it is released to the atmosphere. Thus, air-venting techniques should be considered when a secondary recovery method is required.

Appendix 1: Mathematical model describing steady-flow venting experiments

The following system of equations was obtained by generalizing the multiphase compositional transport model of Baehr and Corapcioglu (1987) to include advective air-phase transport:

$$\frac{\partial}{\partial t}[G_k\theta_a + C_k\theta_w + I_k\theta_i + S_k\rho_b] + \frac{\partial}{\partial z}[qG_k] = 0, \quad k = 1, 2, \ldots, N \qquad \text{(A1)}$$

where z is the coordinate along the column length; t is time; k is the constituent index; N is the number of constituents; G_k, C_k, I_k and S_k are the concentrations of the k^{th} constituent in the air, water, immiscible, and adsorbed phases respectively; θ_a, θ_w and θ_i are the volumetric contents of the air, water and immiscible phases, respectively; ρ_b is the soil bulk density; and q is the air-phase specific discharge. The conditions of the experiments were such that advective and dispersive transport mechanisms in the water and immiscible phases, as well as dispersive transport mechanisms in the air phase, were negligible. Because of the small air-phase pressure gradient required to maintain flow rates, the density of the air phase was essentially constant throughout the column, and thus, q was assumed constant under the experimental conditions of steady air flow. The following equilibrium model relates the phase concentrations and is based on the following three assumptions: (1) the immiscible phase is an ideal solution of its constituents; (2) Henry's Law describes the water-air phase equilibria; and (3) adsorption on soil is governed by aqueous-phase partitioning. These three assumptions are quantified as follows:

$$\begin{aligned} G_k &= H^k_{ai}\,\chi_{ki} && \text{for } z \text{ where } \theta_i > 0 \qquad \text{(A2)} \\ C_k &= H^k_{wa}\,G_k && \text{for all } z \\ S_k &= H^k_{sw}\,C_k && \text{for all } z \\ k &= 1, 2, \ldots, N \end{aligned}$$

where H^k_{ai} is the vapor concentration over pure k^{th} constituent, H^k_{wa} is the Henry's Law partition coefficient, H^k_{sw} is the adsorption isotherm coefficient, and χ_{ki} is the mole fraction in the immiscible phase for the k^{th} constituent. The mole fraction χ_{ki} is related to immiscible phase concentrations as follows:

$$\chi_{ki} = \frac{I_k/\omega_k}{\sum_{k=1}^{N} I_k/\omega_k} \qquad \text{(A3)}$$

where ω_k is the molecular weight of the k^{th} constituent. The appropriate boundary conditions are for the bottom of the column ($z = 0$):

$$G_k = 0 \quad t > 0 \text{ and } k = 1, 2, \ldots, N \qquad \text{(A4)}$$

and for the top of the column ($z = L$):

$$\frac{dG_k}{dz} = 0 \qquad t > 0 \text{ and } k = 1,2, \ldots, N \tag{A5}$$

The initial condition for $0 < z < L$ is given by:

$$G_k = H^k_{al} \chi_{kl} \qquad t = 0 \text{ and } k = 1,2, \ldots, N \tag{A6}$$

The system of equations was solved numerically by adapting the finite-difference algorithm described by Baehr and Corapcioglu (1987) to include advective air-phase transport.

Under the simulated conditions (high air-flow rates and the presence of an immiscible phase) model predictions were found to be insensitive to the degree of partitioning into the water and adsorbed phases. Predictions obtained by assigning H^k_{wa}, the Henry's Law coefficient of benzene (the highest among hydrocarbons) to all constituents were essentially identical to predictions obtained by assuming that the constituents do not partition in water. Thus, for the purpose of modeling the steady air-flow experiments, one only needs to select values for H^k_{al} and the water and adsorbed partitions of equation (A1) can be neglected. To obtain the model predictions of Fig. 3, it was assumed that gasoline consists of five ($N=5$) composite constituents with properties as defined in Table A1. The values chosen for the constituent vapor concentrations, H^k_{al} were obtained by calibrating the model to the data from experiment 1, the experiment with the lowest air-flow rate.

TABLE A1

Composite constituent inputs for the simulation of steady air-flow experiments

Composite Constituent	ω_k[1] (g mole^{-1})	$I_k(t=0)$[1] (g cm^{-3})	H^k_{al}[2] (g L^{-1})	υ_k[3] (cm^3 g^{-1})
1	58	0.081	8.4	1.6
2	77	0.091	1.5	1.4
3	79	0.103	0.96	1.4
4	96	0.275	0.20	1.3
5	110	0.229	0.05	1.1

[1] The GC/FID analysis (Bruell and Hoag, 1984) of the gasoline included an assignment of a molecular identity to each of the 51 peaks. Each of the 51 peaks were assigned to 1 of the 5 composite constituents. The value for ω_k for each composite constituent was obtained by averaging over the values for the peaks assigned to the composite constituent. The values for $I_k(t = 0)$ were obtained by summation.

[2] Assigned by model calibration to experiment 1.

[3] υ_k is the specific volume of the k^{th} constituent required to model the rate of change in θ_l (Corapcioglu and Baehr, 1987). The value assigned to each composite constituent was obtained by averaging over the values for the peaks assigned to the composite constituent.

Appendix 2: Derivation of basic air flow equation

Equation (1) is derived as follows. We start with the steady-state conservation of mass equation for a compressible fluid:

$$\nabla \cdot (\rho q) = 0 \tag{A7}$$

and a Darcian relationship:

$$q = \frac{-\rho g}{\mu} k \nabla \Phi \tag{A8}$$

where ρ, q, and μ are the density, specific discharge vector, and viscosity for the air phase; g is the acceleration of gravity, and k is the air phase permeability tensor. Head, Φ, is defined for compressible fluids (Hubbert, 1940), by:

$$\Phi = z + \frac{1}{g} \int_{P_0}^{P} \frac{\mathrm{d}P}{\rho(P)} \tag{A9}$$

where z is elevation, P is air-phase pressure and P_0 is a reference air phase pressure.

The ideal gas law relates pressure and density and provides a good approximation at environmental conditions:

$$\rho = \frac{\omega P}{RT} \tag{A10}$$

where ω is the average molecular weight of the air phase, T is temperature and R is the universal gas constant. Upon substituting eq. (A10) into eq. (A9), assuming an isothermal process, and neglecting elevation head z (an appropriate assumption when analyzing the induced flow of gases, see Muskat and Botset, 1931; Kirkham, 1946) one obtains the following:

$$\Phi = \frac{RT}{\omega g} \ln \frac{P}{P_0} \tag{A11}$$

Substituting eq. (A11) into eq. (A8), neglecting spatial variations in ω and assuming an isothermal porous medium yields:

$$\mathrm{q} = \frac{-k}{\mu} \nabla P \tag{A12}$$

For ideal gases μ is independent of P, and thus, is constant under the assumed isothermal conditions. Thus upon substituting eqs. (A10) and (A12) into eq. (A7) and recognizing that:

$$\tfrac{1}{2} \nabla P^2 = P \nabla P \tag{A13}$$

one obtains eq. (1):

$$\nabla \cdot (k \nabla P^2) = 0$$

Appendix 3: Calculations to obtain borehole pressure and theoretical power as a function of mass withdrawal rate

A. P_s/P_{atm} vs Q_m

For given values of Q_m and k the corresponding value for P_s is determined by requiring that the predicted mass flow through the screen equal Q_m:

$$2\pi r_0 \rho(P_s) \int_{z_{w_1}}^{z_{w_2}} q_0(z)\,\mathrm{d}z = Q_m \tag{A14}$$

where $\rho\ (P_s)$ is the density of air at pressure P_s, as determined by the ideal gas law, and q_0 is the magnitude of the radial component of air-phase specific discharge numerically evaluated at $r = r_0$ using model predictions as follows:

$$q_0\,(z_j) = \frac{k}{\mu}\,\frac{P_{1,j} - P_s}{\Delta r} \tag{A15}$$

where $P_{1,j}$, is the predicted pressure at node (r_1, z_j) where $r_1 = r_0 + \Delta r$. The integration of eq. (A14) is evaluated numerically by using trapezoidal approximations.

B. Γ vs. Q_m

The work, W, performed in the isothermal expansion of a parcel of gas from volume V_1 to volume V_2 is given by the following equation:

$$W = \int_{V_1}^{V_2} P\mathrm{d}V \tag{A16}$$

Substituting the relation for pressure in terms of volume given by the ideal gas law and integrating eq. (A16) yields:

$$W = n\,RT \ln\,(V_2/V_1) \tag{A17}$$

where n is the number of moles of gas. From eq. (A17), assuming an ideal gas and thus an inverse relationship between volume and pressure it follows that the rate at which work is done, or the power, Γ, required to remove air from the soil at the rate Q_m is given as follows:

$$\Gamma = \frac{Q_m}{\omega}\,RT \ln\,(P_{atm}/P_s) \tag{A18}$$

The borehole pressure, P_s, can be expressed in terms of Q_m and k as previously described in part A of this Appendix.

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SOIL VAPOR EXTRACTION
RESEARCH DEVELOPMENTS

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ABSTRACT

Of the in-situ processes developed to date, soil vapor extraction holds perhaps the most widespread application to the remediation volatile and semi-volatile organic chemicals. A wide variety of applications of the technology exists from "design while you dig" to those using sophisticated numerical models. The extent of success in applications of soil vapor extraction are varied based on many factors. Fundamental research needs in the area of soil vapor extraction include diffusion limitation integration into numerical modeling and capillary zone effects of advective air flow and mass transfer limitations. Optimization modeling is essential for more cost effective applications of the technology on a national basis. Emphasis should be placed on funding basic research in the above areas and should not be preceded by demonstration projects.

SECTION 1

INTRODUCTION

Recently, in situ subsurface remediation processes have been the focus of significant attention by the scientific community involved with the clean-up of volatile and semi-volatile environmental contaminants. Of the in situ processes researched to date, vapor extraction holds perhaps the most widespread application to the remediation of these types of organic chemicals frequently found in the subsurface. The vapor extraction process has been successfully employed at many types of sites as a stand alone technology and may also be considered a synergistic technology to other types of in situ subsurface remediation technologies, such as, bioremediation and groundwater pump, skim and treat.

In the past five years, in situ vapor extraction has been applied at many sites by means of significantly different approaches. These range from "black box" DESIGN WHILE YOU DIG TECHNIQUES to those utilizing sophisticated numerical models interfaced with laboratory, pilot and full-scale parameter determination for design purposes. The extent of success in field application of vapor extraction is varied, in many cases related to monitoring and interpretive limitations employed before, during and after the remediation. Because application of the technology is quite recent, many remediations are still in progress, thus final results interpretation and publishing in refereed scientific journals is limited.

Research Milestones in Vapor Extraction

Thorton and Wootan (1982) introduced the concept of vertical vapor extraction and injection wells for the removal gasoline product, as well as, vapor probe monitoring for the quantitative and qualitative analysis of diffused hydrocarbon vapors. A further enhancement of this research was published by Wootan and Voynick (1984), in which various venting geometries and subsequent air flow paths were hypothesized and tested in a pilot sized soil tank. In their first study, 50 percent gasoline removal was achieved, while in their second study up to 84 percent removal of gasoline was observed.

Local Equilibrium Concept--

In controlled laboratory soil column vapor extraction experiments by Marley and Hoag (1984) and Marley (1985), one hundred percent removal of gasoline at residual saturation was achieved for various soil types (0.225 mm to 2.189 mm average diameters), bulk densities (1.44 g/cm to 2.00 g/cm), moisture contents (0 percent to 10 percent v/v) and air flow rates (16.1 $cm^3/(cm^2\text{-}min)$ to 112.5 $cm^3/(cm^2\text{-}min.)$ They also successfully developed an equilibrium solvent-vapor model using Raoult's Law to predict concentrations of 52 components of gasoline in the vapor extracted exhaust of the soil columns.

Baehr and Hoag (1985) adapted a one dimensional three phase (immiscible solvent, aqueous and vapor phases) local equilibrium transport model developed by Baehr (1984) to include air flow as described by Darcy's Law for compressible flow. This first deterministic one dimensional model effectively predicted the laboratory vapor extraction results of Marley and Hoag (1984) and provided the basis for higher dimensional coupled air flow contaminant models for unsaturated zone vapor extraction.

Porous Media Air Flow Modeling--

Because local equilibria prevailed in the above studies, a higher dimensional model, developed by Baehr, Hoag and Marley (1988) was used to model air flow fields under vapor extraction conditions. The three dimensional radially symmetric compressible air flow model is used to design vapor extraction systems using limited lab and/or field air flow pump tests. A steady state in situ pump test determination of air phase permeability is preferred over laboratory tests because an accounting is possible of the presence of an immiscible liquid, anisotropy, soil surface, variations in soil water conditions and heterogeneity in air phase permeabilities. The numerical solution developed can simulate flow to a partially screen well, and allow determinations of vertical and horizontal air phase permeabilities. Heterogeneous unsaturated zones can also be evaluated using the numerical simulation. Analytical solutions to radial flow equations, such as one developed early by Muskat and Botset (1931) are generally restricted to determination of average horizontal air perambulated determination for impervious soil surfaces.

Removal of Capillary Zone Immiscible Contaminants--

Hoag and Cliff (1985) reported that an in situ vapor extraction system was effective in removing 1330 L gasoline at residual saturation and in the capillary zone at a service station and achieved clean up levels to below 3 ppm (v/v) in soil vapor and below detection limits in soils. The entire remediation took less than 100 days. A groundwater elevation and product thickness log for the time period of before, during and after the vapor extraction remediation is graphically shown in Figure 1. On day 250 only a skim of gasoline was present in this well and on day 290 no skim was detected. One year after the vapor extraction remediation took place, groundwater samples were non detected for gasoline range hydrocarbons, reflecting that at least advective dispersive transport and possible natural microbiological activity in the groundwater were mechanisms responsible for this effect.

Field Application of Porous Media Air Flow Models

Baehr, Hoag and Marley (1988) utilized the above site for a field air pump test to determine the horizontal air phase permeability and to simulate the sensitivity of the model to changes in air phase permeabilities utilizing site geometries and boundary conditions. Based upon a full-scale air flow pump test, the air phase permeability for the site was predicted to be $k = 7.0 \times 10^{-8}$ cm^2 for a mass air withdrawal rate of 11.1 g/sec and a normalized pressure of $P_s/P_{atm} = 0.9$. For reference 11.1 g/sec, assuming an air phase density of 1.2×10^{-3} g/cm^3, equals about 555 L/min.

To illustrate the sensitivity of the model to a range of air phase permeabilities, the above service station vapor extraction well geometry, depth to water table, and appropriate boundary conditions were used as input and air phase permeability and mass air withdrawal rates were varied. In Figure 2, the normalized air phase pressure in the well, for various mass air withdrawal rates and air phase permeabilities are shown. Significant increase in the vacuum developed in the wells can be observed for order of magnitude decreases in air phase permeabilities and small increases in the mass air withdrawal rates. Review of Figure 2, indicates that if a mass air withdrawal rate of 40 g/sec was used at the service station site ($k = 7.0 \times 10^{-8}$), the the normalized air phase pressure at the well would be approximately $P_s/P_{atm} = 0.6$, within an acceptable range of operating conditions.

A limitation of the model developed by Baehr and Hoag (1988) is that it is not coupled to contaminant transport. However, for the design of vapor extraction systems for volatile contaminants, this generally is not a fundamental need and can be accomplished by either laboratory venting tests, similar to those developed by Marley and Hoag (1984) or by utilization of the one dimensional coupled model developed by Baehr and Hoag (1985).

SECTION 2

RESEARCH NEEDS

A fundamental need of vapor extraction modeling occurs in the area of capillary zone/unsaturated zone interaction when immiscible phases are present on or in the capillary fringe. While air phase modeling alone is probably adequate for most vapor extraction system system design purposes, particularly if a full three-dimensional model is used with optimization modeling, a rigorous modeling effort to couple air phase flow and immiscible contaminant transport, particularly in the capillary zone, will provide strategic insight to vapor extraction operation and planning.

To assess research needs in this area, two basic vapor extraction systems applications should be considered: 1. Immiscible contaminant with density less that 1.0 (petroleum range hydrocarbons); and 2. Immiscible contaminants with density greater than 1.0 (halogenated compounds).

Generalized subsurface phase distributions for immiscible liquids with densities less than that of pure water are illustratively shown in Figure 3. A typical vapor extraction system installation in this type of subsurface and contaminant condition is found in Figure 4. In the case study presented by Hoag and Cliff (1985), as detailed above, pump and skim was employed at the site for the first 210 days of the remediation with only 300 L gasoline removed (i.e. mostly through manual bailing). Thus, an important question should be: Was vapor extraction alone necessary in this case or were both pump and skim and vapor extraction required for optimal or even effective remediation of immiscible contaminants? To answer this question requires an understanding of air-immiscible liquid-water three phase conduction and distribution in the porous media, particularly in the capillary fringe areas at a site. Additionally, the site history of groundwater fluctuation and immiscible contaminant behavior in the capillary fringe is essential information necessary to answer the above question. Parker, Lenhard and Kuppusamy (1986) and Lenhard and Parker (1986) provide a parametric model for three-phase conduction and measurements of saturation-pressure relationships for immiscible contaminants in the unsaturated and capillary zones. However to date, this author is not aware of the coupling of these types of models to air phase and contaminant transport models.

A more in depth hypothetical examination of the possible relationships near the capillary fringe will illustrate the importance of this zone in determining the need for pump and treat and the importance of solute mass transfer from the capillary zone into the saturated flow regime. In the case of a recent spill of an immiscible contaminant with density less than water, when relatively steady groundwater flow prevails, a zone may exists on the capillary fringe of floating product, as shown in Figure 5. Infiltrating water, under draining conditions will reach an equilibrium with the immiscible liquid resulting in a saturated solute condition. For hypothetical purposes only, if it is assumed that only vertical groundwater flow exists in the capillary zone, the rate of solute input to the saturated zone will be limited by the rate of infiltration and C_s. If it assumed, again for illustrative purposes, that a horizontal flow boundary exists at the groundwater table, then mass transfer of solute from the capillary zone into the saturated zone will have only limited effects on the rate of solute input into the saturated zone. When considering the quantities of water infiltrating through the capillary zone per year in comparison to saturated flow rates, the above assumptions may be valid. The result is relatively, inefficient transfer of solutes from the capillary fringe zone to the saturated zone. Thus, in this scenario, pump and treat systems may not be necessary to remove the immiscible contaminants and advective dispersive dilution may be adequate to protect groundwater resources. Without knowledge a priori of the immiscible liquid distribution and interaction with the capillary zone, and advective-dispersive transport characteristics at a site, this approach may be risky. An alternative, however may be close monitoring of groundwater in the saturated zone near the spill area, as vapor extraction proceeds. If the scenario in Figure 5 exists at a site then solute concentrations in groundwater will decrease with time and no pump, treat and skim system may be necessary, to achieve desired levels of remediating in soil and groundwater. If near field transport of solutes from the spill area increases steadily with time, then groundwater pumping may be necessary to employ at that time.

In the case of an immiscible contaminant with a density less than water with impingement on the saturated zone by penetration of the capillary zone, the potential for solute transfer from the unsaturated zone to the saturated zone is greatly increased. This scenario may be result from the depression of the capillary zone in a spill event where considerable quantities of an immiscible contaminant are spilled, such as that shown in Figure 3. Alternatively, fluctuating groundwater tables may result from a rise in the groundwater table through wetting (imbibition) of the capillary zone as described by characteristic curves for a given porous media and immiscible contaminant. Remembering that immiscible contaminants become immobilized once at residual saturation, the result of wetting the capillary zone may result in the condition shown in Figure 6. The net result of this scenario is that saturated solute concentrations exists at the top of the horizontal flow zone of the saturated zone. This boundary condition enables substantially greater mass transfer of solute into the saturated zone, principally resulting from the upper flow boundary being the immiscible contaminant itself. In Figure 5, the upper boundary was only solute at less than C_s, and solubilization was limited to that achieved through infiltration. Clearly, the difference in these two situations greatly affects the rate of solute input into the saturated zone and should affect remedial action responses. Unless the solute transport phenomena from an immiscible phase into the saturated zone is understood and physically defined at a site, then neither optimal remediation systems can be designed nor saturated zone solute transport models can be effectively utilized to predict the impact of immiscible liquid remediation on saturated zone solute transport.

Immiscible phase boundary conditions presented in Figures 5 and 6 also greatly effect the vapor diffusive flux rates from the capillary zone into the unsaturated zone. Bruell (1987) and Bruell and Hoag (1986) rigorously investigated the effect of immiscible liquid phase boundary conditions on subsequent hydrocarbon diffusive flux rates of benzene. For a given column geometry (diffusive path length of 47.6 cm), diffusive flux rates for benzene at 20 °C for an immiscible phase boundary condition similar to that shown in Figure 5, resulted in benzene diffusive flux rates of 24.9 mg/cm^2-min and 6.1 mg/cm^2-min, for dry and wet (i.e. field capacity moisture content) concrete sand, respectively. Thus, moisture content played a significant role in reducing the effective porosity of the concrete sand. When residual saturation immiscible liquid phase boundary conditions were investigated the maximum benzene diffusive flux rate was 26.6 mg/cm^2-min, however the diffusive path length was only 22.4 cm. The moisture content in the residually saturated zone was 3.2 percent(v/v). When capillary zone immiscible liquid phase boundary conditions were investigated, the maximum benzene diffusive flux rate was reduced to 4.8 mg/cm^2-min with a diffusive path length of 22.4 cm. The moisture content in the capillary zone reflected saturated conditions (i.e. $O_w = n$.) This research demonstrated that the immiscible liquid phase boundary condition greatly affects the diffusive flux rates of hydrocarbons that occur in the unsaturated zone. As the moisture content increases, then the diffusive flux rates of contaminants will decrease. The net result of these boundary conditions affects the concentrations of hydrocarbon vapors detected using soil gas assessment techniques and the rates of hydrocarbon recovery utilizing in situ vapor extraction.

With reference to Figures 6 and knowing that advective air flowrates also decrease with increasing moisture content, creates a circumstance in the area of the capillary zone where advective air flow may not be in direct contact with the immiscible phase. Thus, diffusion in this case, will be the controlling mechanism of contaminant removal during vapor extraction. In the case depicted in Figure 5, it is likely that some advective air flow will contact the immiscible phase, greatly increasing vapor extraction efficiency.

In the case of an immiscible liquid with a density greater than that of water, contaminant distribution is significantly different given a hypothetical spill to the subsurface. Penetration of the capillary and saturated zones by the immiscible liquid is likely, given sufficient spill volumes as shown is Figure 7. Of great importance is the occurrence of groundwater flow through the immiscible liquid phase in the saturated zone, resulting in substantially greater solubilization rates of the immiscible phase and greater groundwater contamination potential than in the cases presented in Figures 5 and 6.

A typical in situ remedial action response to the dense immiscible liquid phase contamination is given in Figure 8. Simultaneous vapor extraction and groundwater pumping are necessary to expose immiscible phase contaminants to advective air flow and to increase diffusive flux rates of contaminants in the vicinity of the groundwater table at time = T_2. In this case, dewatering of the saturated zone in the area of immiscible phase contaminants is desirable. Long-term plume management interceptor pumping strategies, such as those developed by Ahlfeld, Mulvey, Pinder and Wood (1988) and Ahlfeld, Mulvey and Pinder (1988) should be implemented to optimally circumvent uncontrolled groundwater contamination and to maximize groundwater contaminant recovery rates. Strategies to maximize saturated zone dewatering in the vicinity of the immiscible phase liquids must be developed to properly implement this approach. Additionally, in situ bioremediation may be considered as an additionally technology to further degrade the immiscible liquid, if complete subsurface dewatering is not possible.

SECTION 3

SUMMARY

Significant advances have been made in the past five years in the understanding of volatile and semi-volatile contaminant behavior as related to vapor extraction technologies. Coupled modeling of both contaminant behavior and advective air flow, however remains limited to one dimensional systems. Given the significant hydrogeological complexity of porous media and subsequent heterogeneous distributions of immiscible phase contaminants, the design utility of higher dimensional coupled models is questionable. Higher dimensional advective air flow models are being used to design vapor extraction systems. These models are generally dependent on site specific parameters best determined in field air pumping tests, unless uniform hydrogeologic conditions prevail with quantifiable boundary conditions necessary for model design predictions. Three dimensional models are being adapted to deal with non-radial symmetry and will be necessary to rigorously model multiple extraction well and extraction well/injection well applications.

Significant modeling and experimental research is needed to further understand immiscible contaminant behavior in the capillary zone and adjacent boundary conditions. The interaction of immiscible phase liquids in the capillary zone with unsaturated zone infiltration and saturated zone transport must be the focus of this research. The approach should include both hydrogeologic characteristics and testing procedures necessary to determine the influencing factors. Chemical fate and transport in the unsaturated zone under natural and advective air flow conditions must also be better understood to wore effectively apply optimal in situ remediation processes.

Emphasis should be placed on basic research in the above areas, to be followed at the appropriate time by demonstration level projects. When demonstration level projects precede basic research needs, as has frequently been the case in the past five years, the result generally do not properly reflect necessary parameter control or monitoring and either inconclusive or misleading results may be generated.

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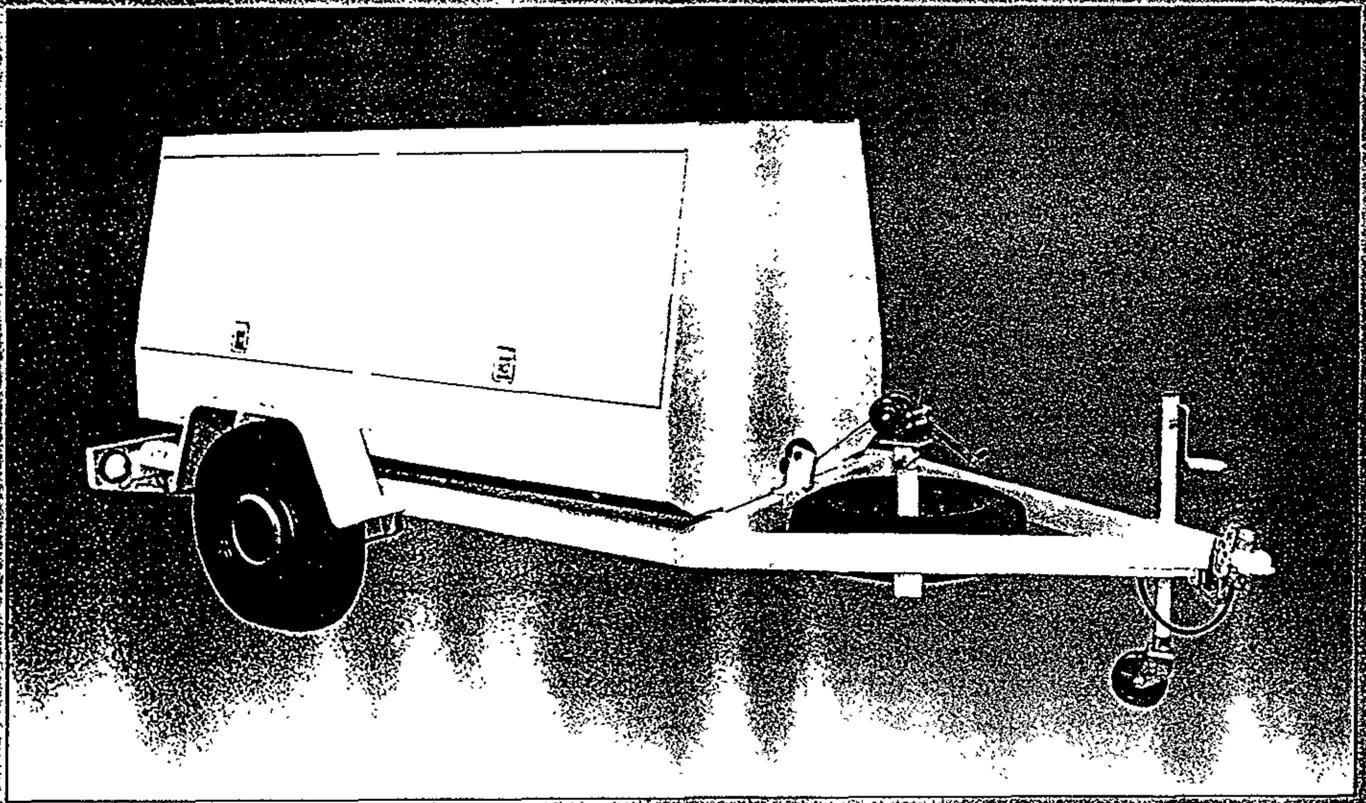
ATTACHMENT B

ICE PRODUCT LITERATURE

State-of-the-Art Soil Remediation System



U.S. PAT #4846134

BACT-1

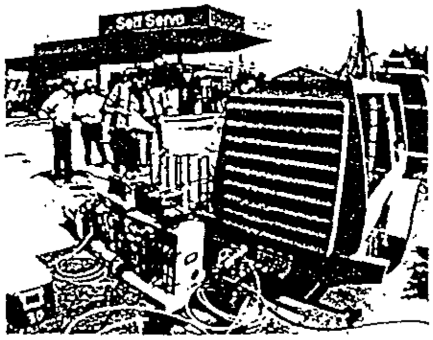
VR systems inc.

Technology In Support of the Environment

Now, BACT-I provides you with a method of economically and efficiently decontaminating soils. *Faster - More Efficient - More Cost Effective* than excavation, carbon or platinum catalyst treatment and no need for disposal of contaminants. Performance verified by over 30,000 hours of field operation and independent laboratory test results.

NO EXTERNAL VACUUM PUMP NEEDED

The VR Systems Inc. BACT-I utilizes a specially configured dual-fuel internal combustion engine. BACT-I simultaneously draws the vapors from the ground, burns them and purifies the exhaust. Emissions discharged to atmosphere meet or better air quality requirements.



One method of BACT-I recovery is the use of well casings embedded within the contaminated soil zone. Wells drilled for the purpose of soil testing may often be utilized. In another method, the soil is excavated and placed over a gallery of perforated pipes. This approach additionally allows storage tank removal and soil backfill to be completed without a delay for soil cleanup.

SIMPLE, POSITIVE OPERATION

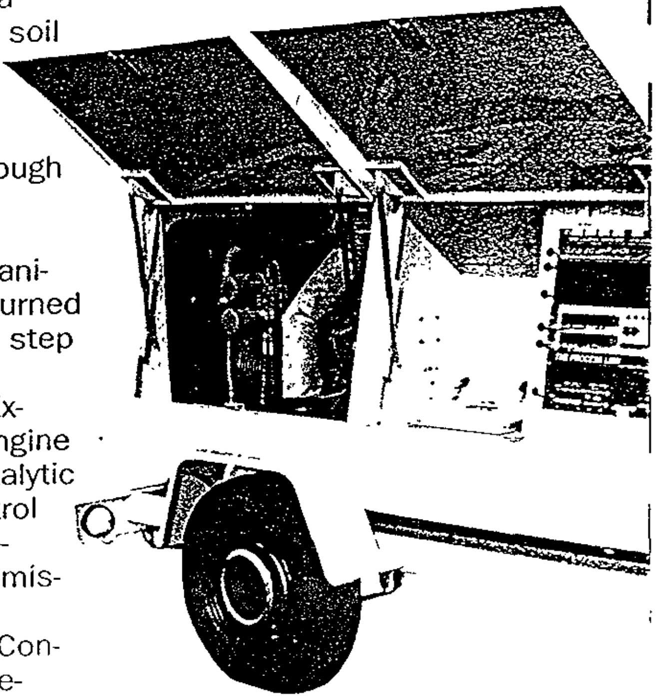
Vacuum from the engine (23" Hg available) applied to the well casing creates a pressure gradient in the soil surrounding the casing. Heavy hydrocarbons are volatilized and migrate through the soil and through perforations in the well casing. The vapors are drawn into the intake manifold of the engine and burned as fuel. This is the first step in rendering the vapors environmentally safe. Exhaust gases from the engine then pass through a catalytic converter emission control system. This system reduces the levels of all emissions to well below the current "Best Available Control Technology" limits required for release to atmosphere.

AUTOMATIC CONTROL

A VR Systems trained technician is required only for startup and shutdown of a BACT-I Model V3 unit. The balance of operation is in automatic mode, protected by a fenced area, with no attendant required.

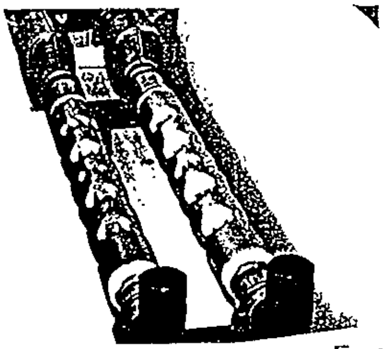
GREATER EFFICIENCY

The special BACT-I engine alone normally burns non-methane hydrocarbon vapors (300,000 ppm-plus concentrations) with 99.9-percent efficiency. Addition of the platinum-based catalytic converters reduces products of combustion to acceptable levels set by air quality management standards.



FULLY COMPUTERIZED

The BACT-1 Model V3C unit may be started, stopped and monitored - equipment diagnostics and emission sampling (optional) on a 24-hour basis using the remote base comand computer. Up to 16 engines can be monitored by one computer.

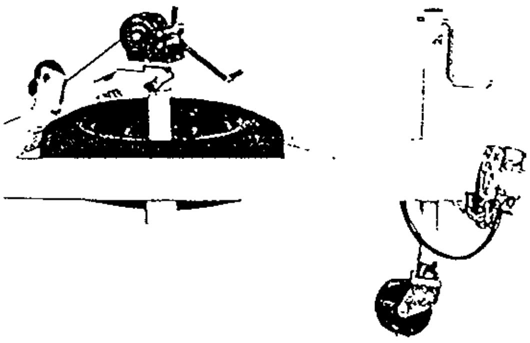


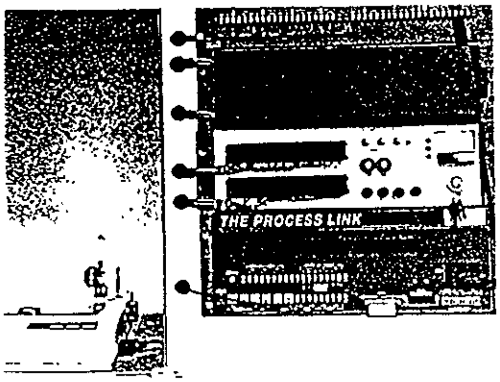
TEST RESULTS

A recent emission performance test with the BACT-I Model V3 was performed by an independent laboratory for South Coast Air Quality Management District. The definitive sampling and analysis showed the following results:

	Engine Intake	Total Exhaust after Catalyst
Total Hydrocarbons	318,832 ppm	16 ppm
(HC destruction efficiency - percent		99.99)
CO	5 ppm	<1 ppm
NOX	(Engine Exhaust 58 ppm)	33 ppm
Benzene	995 ppm	ND* (<6.0 ppb)
Ethylbenzene	125 ppm	ND* (<5.0 ppb)
Toluene	1005 ppm	13.7 ppb
Xylenes	1550 ppm	<11.5 ppb

*ND indicates that the species was not detected at the analytical detection limit shown in parentheses. ppb (parts per billion)





SUPERIOR TO PRIOR TECHNIQUES

By comparison with the BACT-I method, other techniques have proved to be extremely expensive, time consuming and difficult to utilize. BACT-I solves the problems encountered with activated carbon treatment or with the catalyst bed. There are no hazardous wastes generated that must be disposed of. Water vapor in the intake from the well does not adversely affect the engine performance. By contrast, activated carbon loses much of its absorptive capacity in the presence of water. The cost and complexity of the use of large catalytic converter beds is totally avoided by the small sized and self contained BACT-I system.

LOWEST COST WITH BACT-I

In addition to its high efficiency and small size, a key benefit inherent in the BACT-I is the low cost per pound of VOC removed, only a fraction of the cost of any other technique or system.

OUTSTANDING SAFETY

The safety record of properly equipped and operated propane engines equals or exceeds that of gasoline powered engines. BACT-I has a built-in dual nozzle automatic fire control system. The on board computer system automatically shuts down the engine should equipment failure occur.

REGULATORY AGENCY APPROVAL

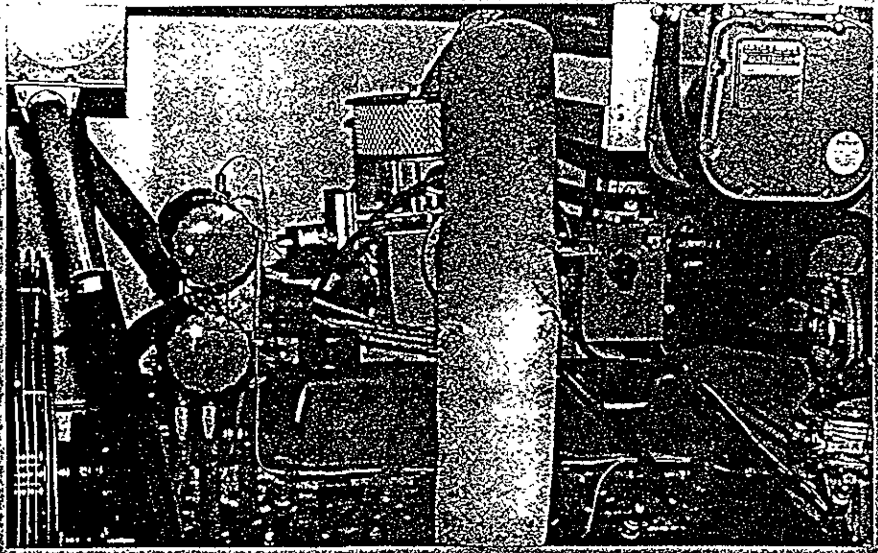
The BACT-I procedure and equipment has the approval of local health departments and major air pollution districts and agencies including the South Coast Air Quality Management District (Los Angeles, CA) and the Bay Area Air Quality Management District (San Francisco, CA) among many others.

PRACTICAL FOR ALL LOCATIONS

Trailer or stand-mounted BACT-I units allow for easy installation and removal from even the most congested, high-traffic locations. They can be safely operated without interference with normal service station functions and without risk to station personnel or customers. Typical set-up time is 20 minutes or less.

STORAGE TANK EVACUATION

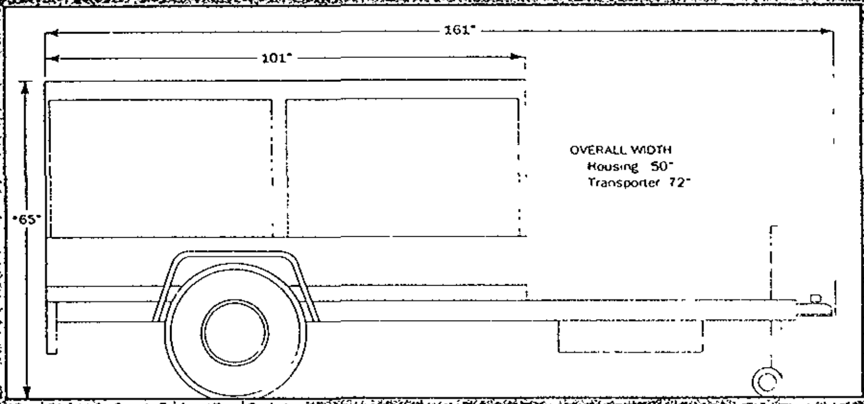
The BACT-I is the simple, speedy solution for the removal of hydrocarbon fumes that remain in a storage tank when the liquid fuel has been pumped out. Purging will be required in the Los Angeles area (SCAQMD) after January 1, 1990, before tanks can be removed from the ground.



SPECIFICATIONS

BACT-I Model V3 and V3C U.S. PAT # 4846134
ENGINE: 7.5 liter V-8 industrial engine
CATALYTIC SYSTEM: 3-way/2-way catalytics
COMPUTER: State-of-the-art data acquisition system for monitoring and control

DIMENSIONS



* Same Height On Stands For Long Term Operation
DIMENSIONS ARE APPROXIMATE AND SUBJECT TO CHANGE WITHOUT NOTICE

VRsystems inc.
Technology In Support of the Environment.
VR Systems Inc. 1338 N. Knollwood Circle, Anaheim, California 92801
Telephone (714) 826-0483 FAX (714) 826-8746

UNDERGROUND
WaynePerry
CONSTRUCTION INC.
SPECIALISTS

C.S.C. LIC. NO. 300345 E.P.A. CAD 053841102
8301 W. COMMONWEALTH AVE. ■ BUENA PARK, CALIFORNIA 90621
(714) 826-0352

BACT-1 Case Study

The attached viewgraphs show an example of a successful soil remediation project utilizing the BACT-1 soil venting engine for excavated soil cleanup and in-situ soil venting. Over 700 cubic yards of gasoline contaminated soil were excavated during a tank replacement project. This soil was placed in an above-grade gallery and vented using the BACT-1 to meet air quality regulations. After remediation, the soil was sent to a Class III landfill for cover soil. Following tank replacement, tank zone wells were used for in-situ venting of the soil surrounding the tank hole.

Wayne Perry Construction offers BACT-1 sale or lease; service/maintenance agreements, pre-installation permitting and permit compliance for above-grade and in-situ soil venting. We also offer turnkey soil venting systems including wells, permitting and construction.

If the BACT-1 Soil Venting Engine meets your soil remediation needs, please call:

Mr. Ron Perry
Wayne Perry Construction, Inc.
8301 W. Commonwealth Ave.
Buena Park, CA 92621
(714) 826-0352

We would be happy to answer technical questions or discuss site-specific information.

Vapor Extraction Equipment

VR Systems B.A.C.T. 1
Soil Venting Engine

July, 1990

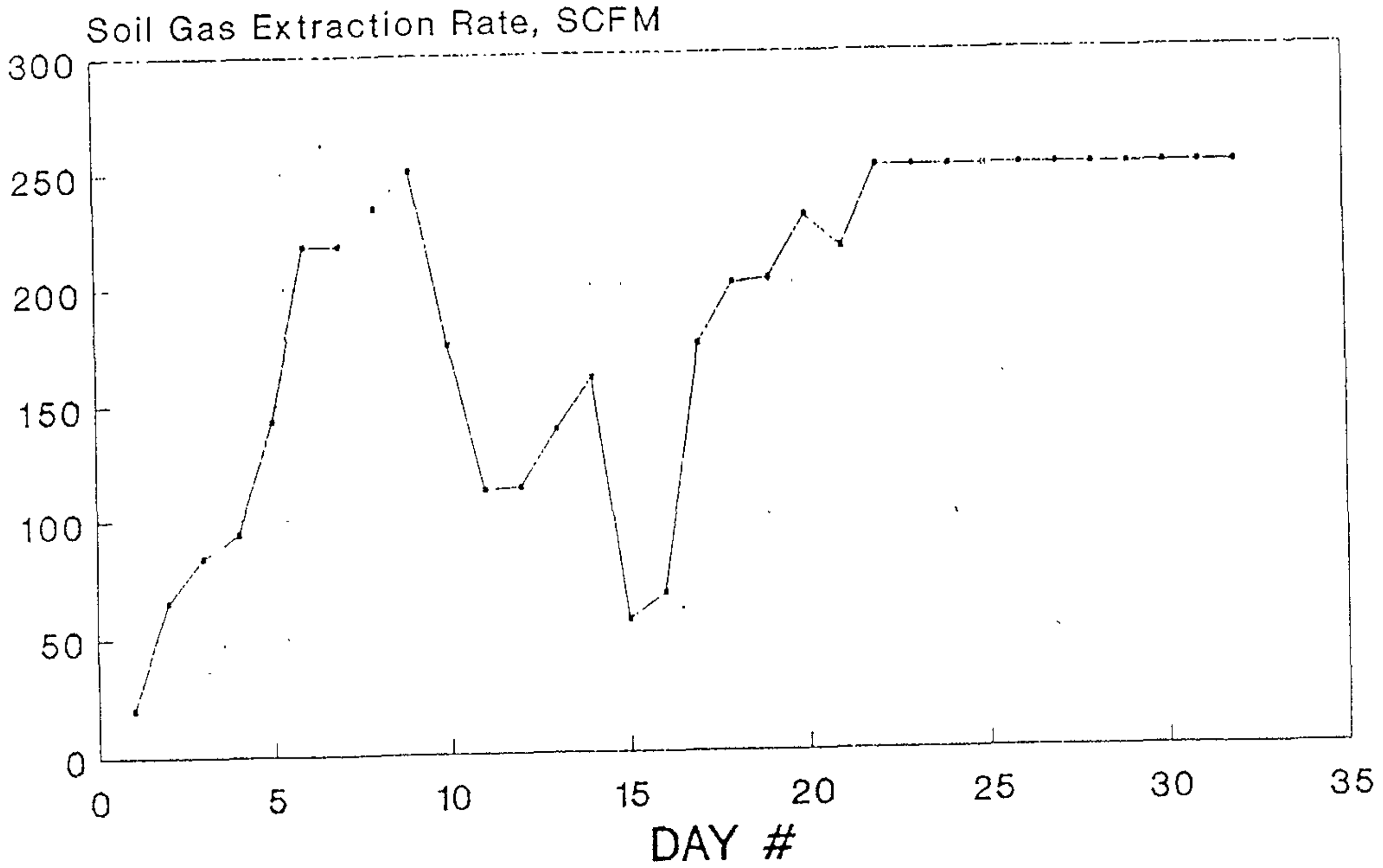
VR SYSTEMS MODEL V-3 (BACT 1)

Vapor Extraction System

- Max. Firing Rate: 880,000 BTU/hr
- Max. Flow Rate: 250 SCFM
- Max. HC Vapor Concentration: 250,000 ppmV
- Max. Vacuum: 150 in. w.c. (11 in. Hg.)
- Size: 101" long x 50" wide x 65" high
- Supplemental Fuel: Propane or LPG
- Setup Time: approx. 1/2 hour
- Typical Emissions: HC .... < 20 ppm
  CO .... < 300 ppm
  NOx ... 5 - 30 ppm
  BTEX .. < 100 ppb

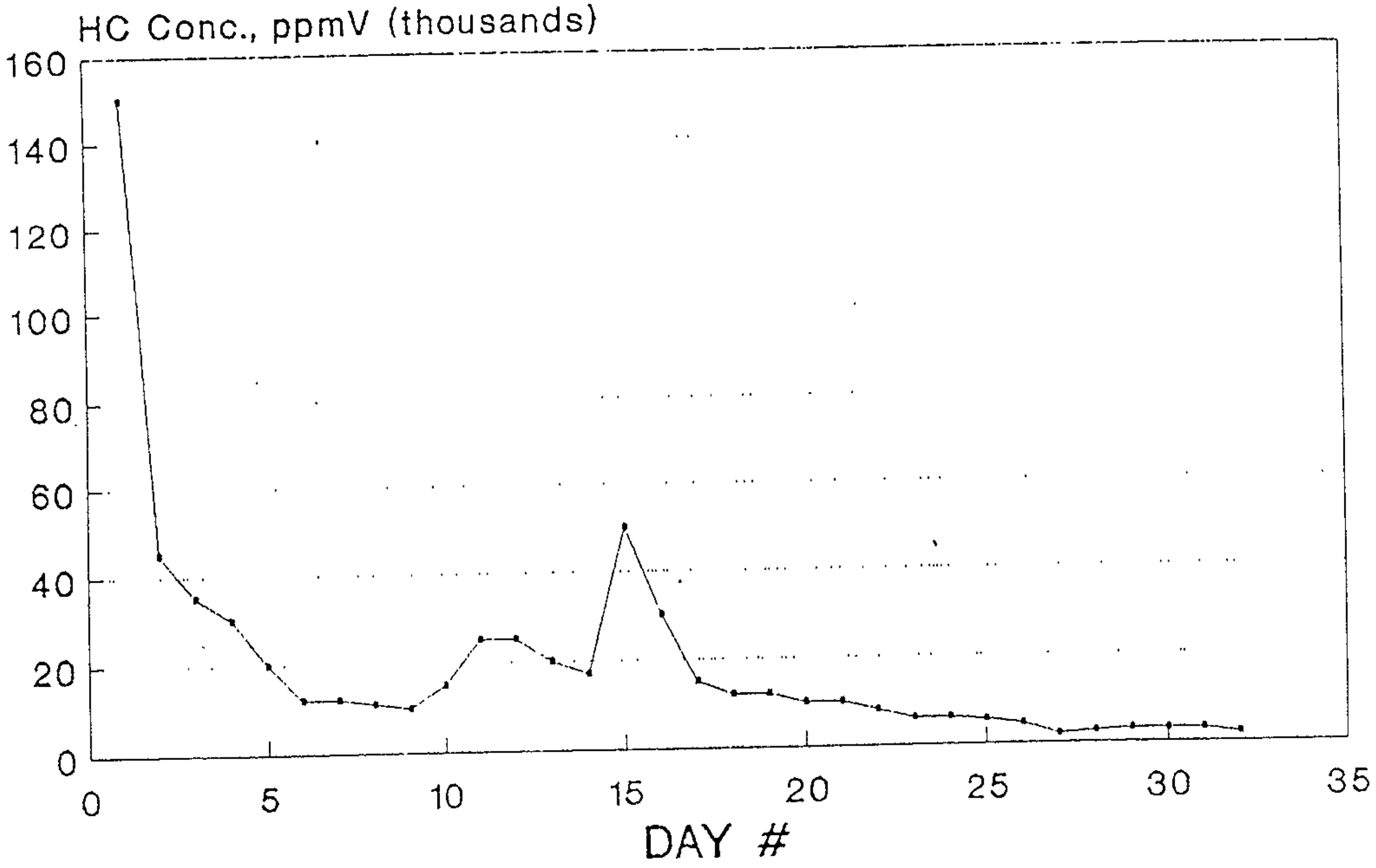
U.S. Pat. No. 4,846,134

SOIL VENTING - TANK ZONE WELLS
VR SYSTEMS MODEL V-3 (BACT - 1)



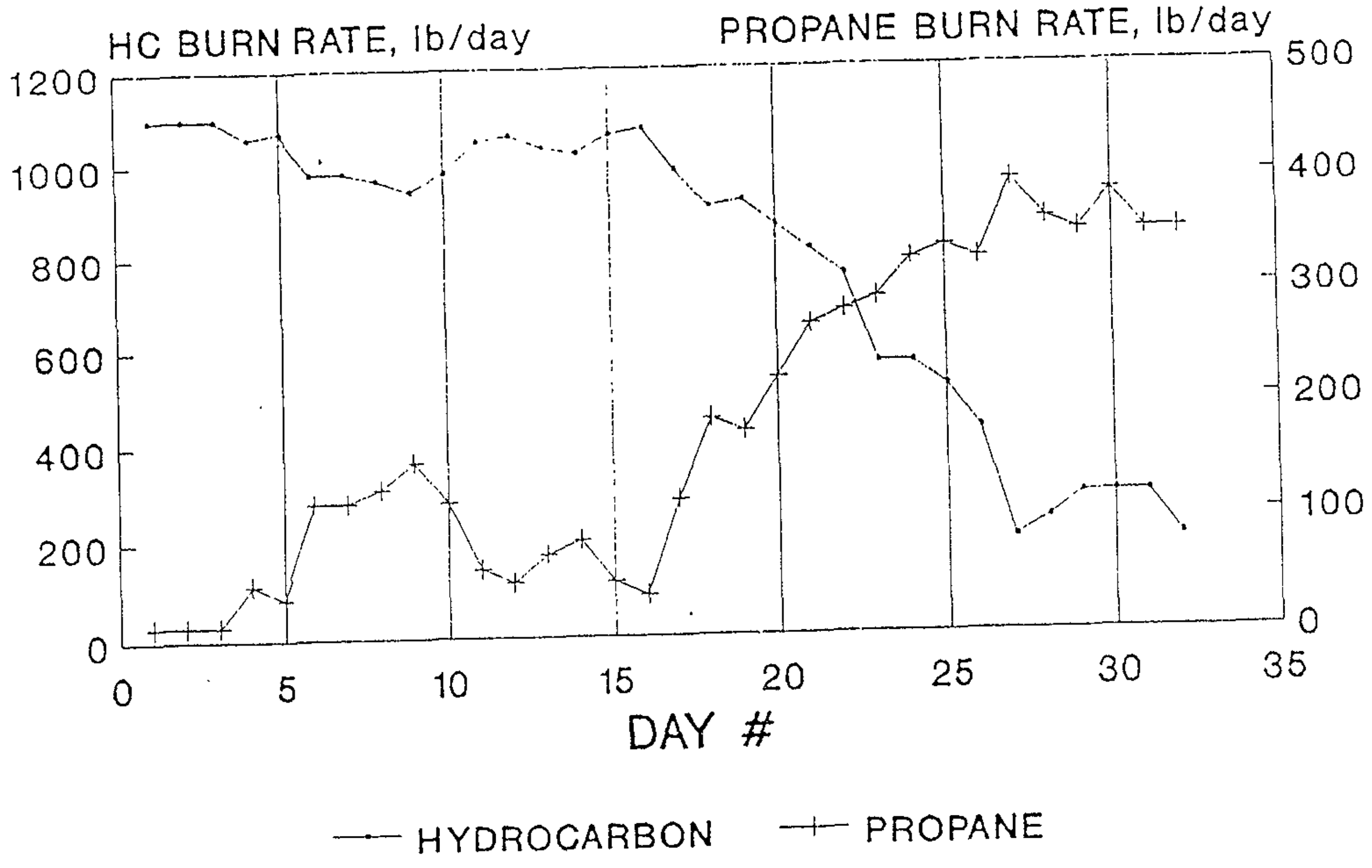
California Remediation Site

SOIL VENTING - TANK ZONE WELLS
VR SYSTEMS MODEL V-3 (BACT - 1)



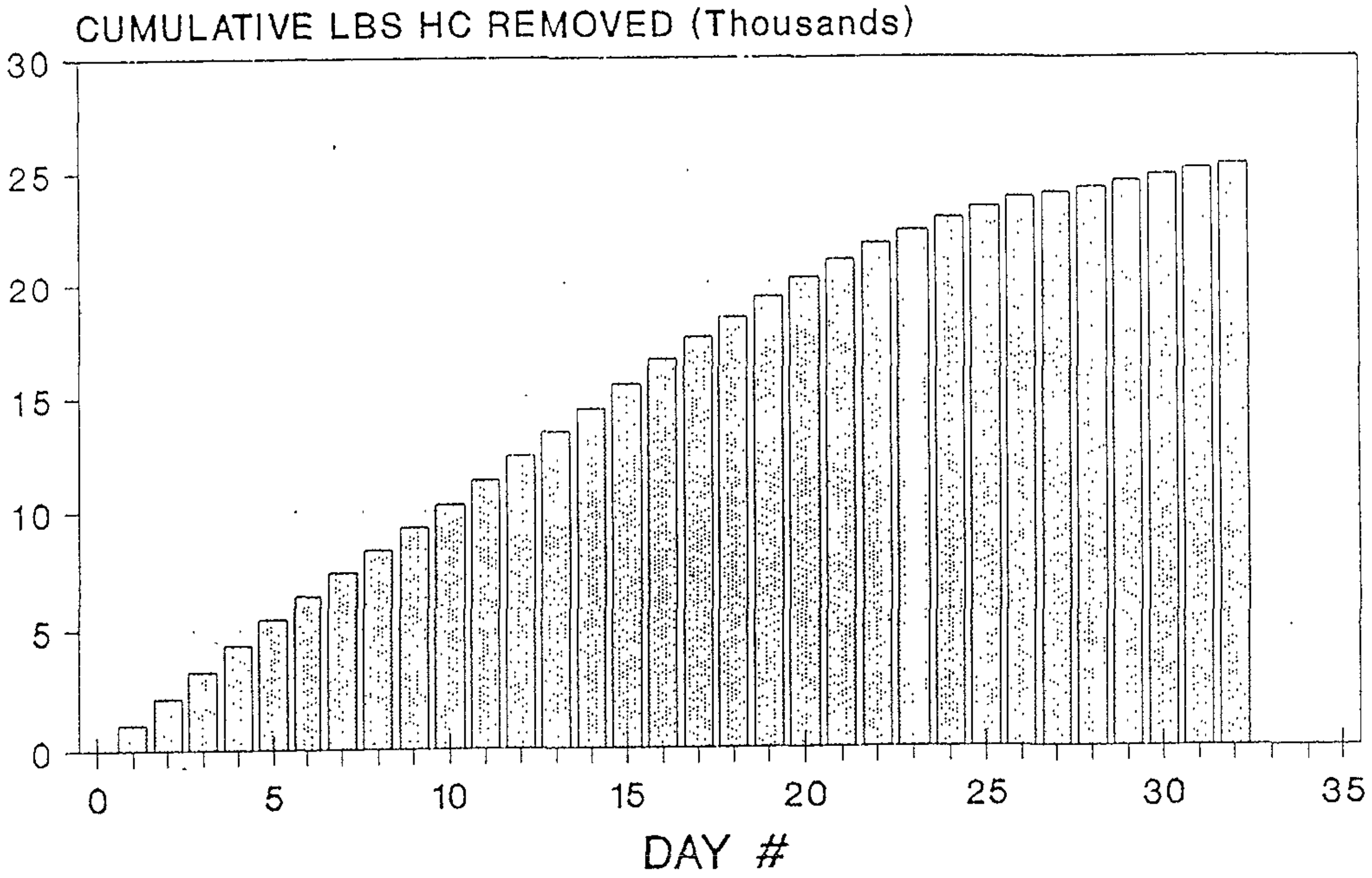
California Remediation Site

SOIL VENTING - TANK ZONE WELLS
VR SYSTEMS MODEL V-3 (BACT - 1)



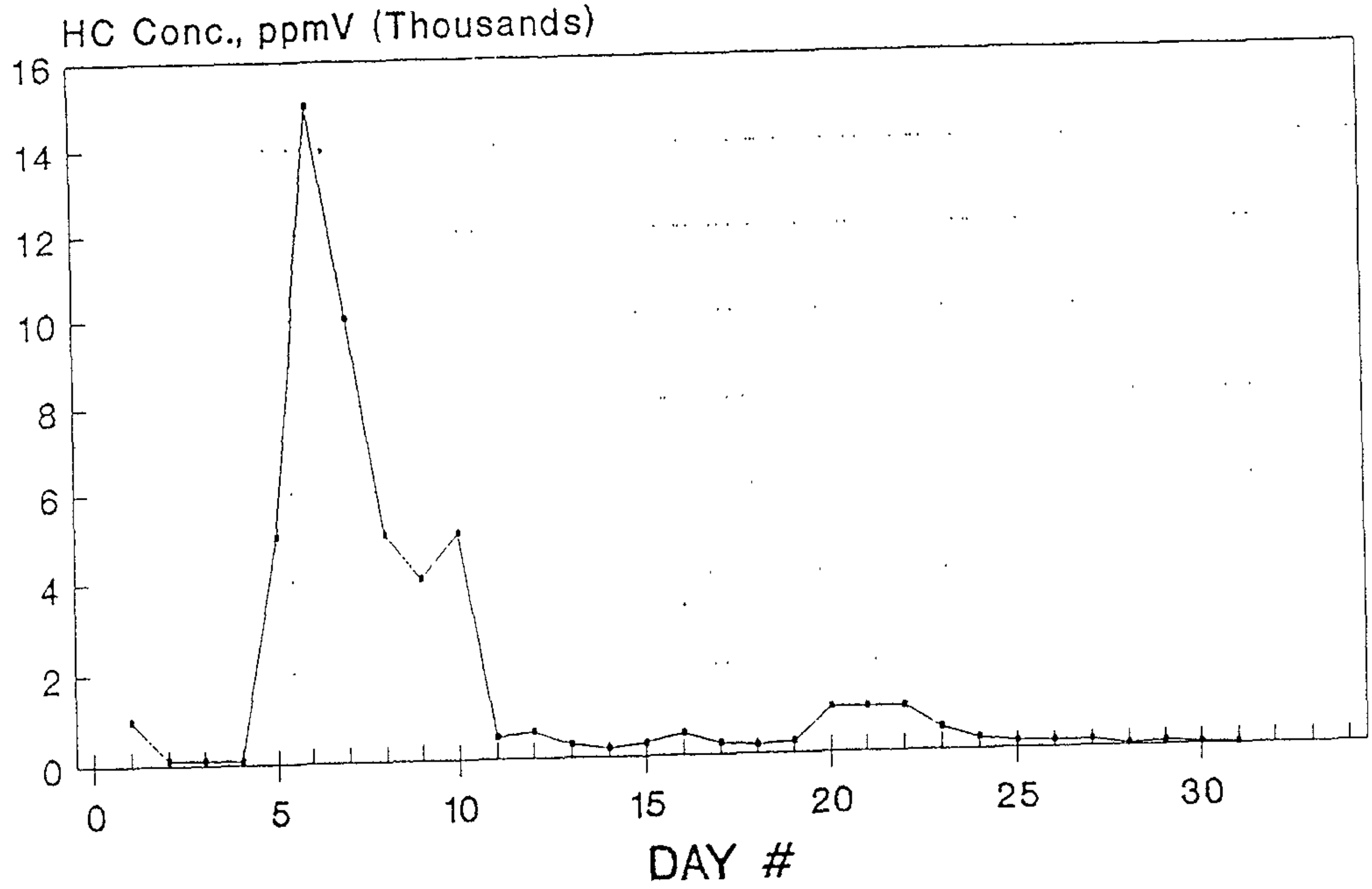
California Remediation Site

SOIL VENTING - TANK ZONE WELLS
VR SYSTEMS MODEL V-3 (BACT -1)



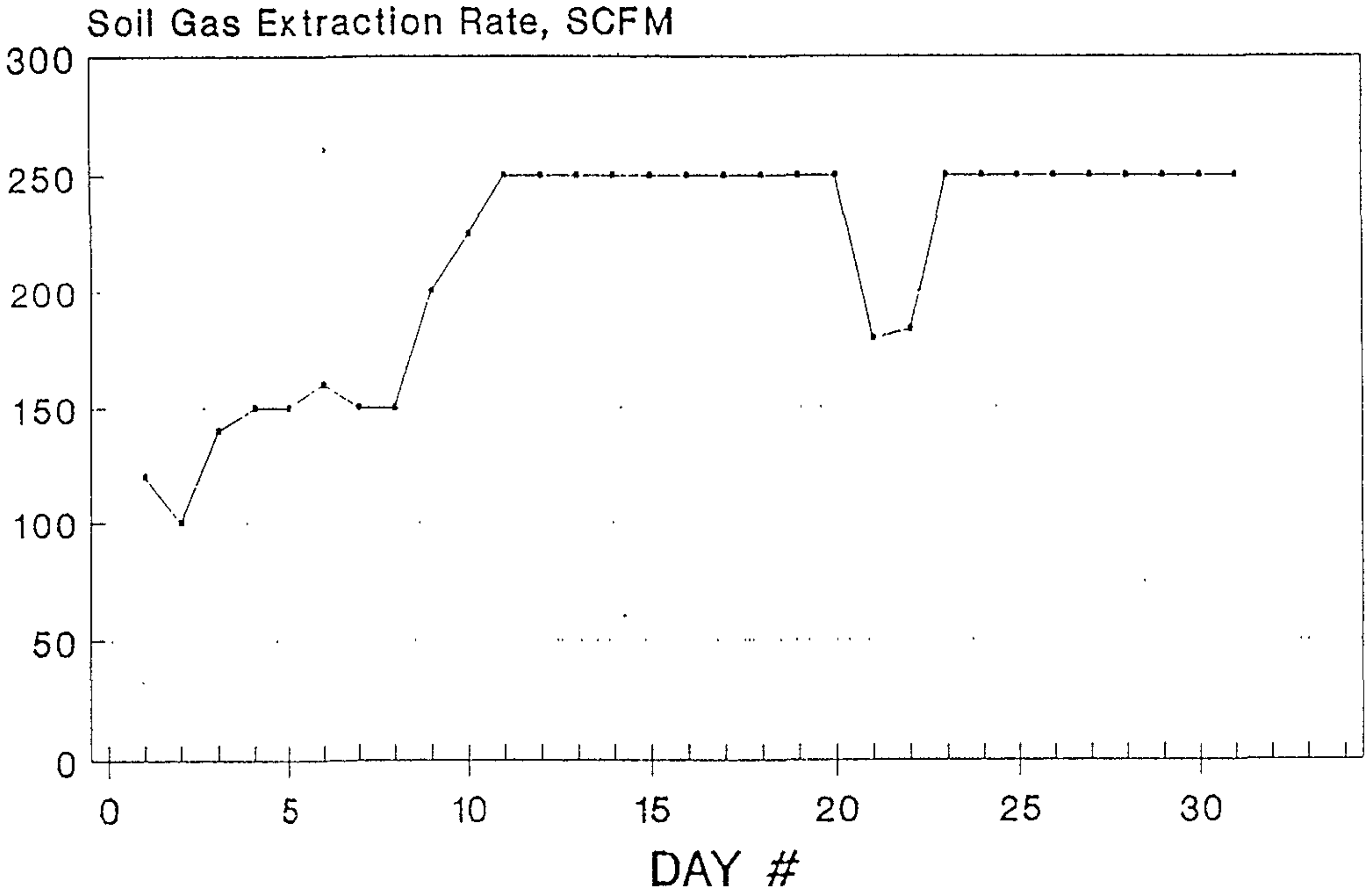
California Remediation Site

SOIL VENTING - ABOVE GRADE
VR SYSTEMS MODEL V-3 (BACT - 1)



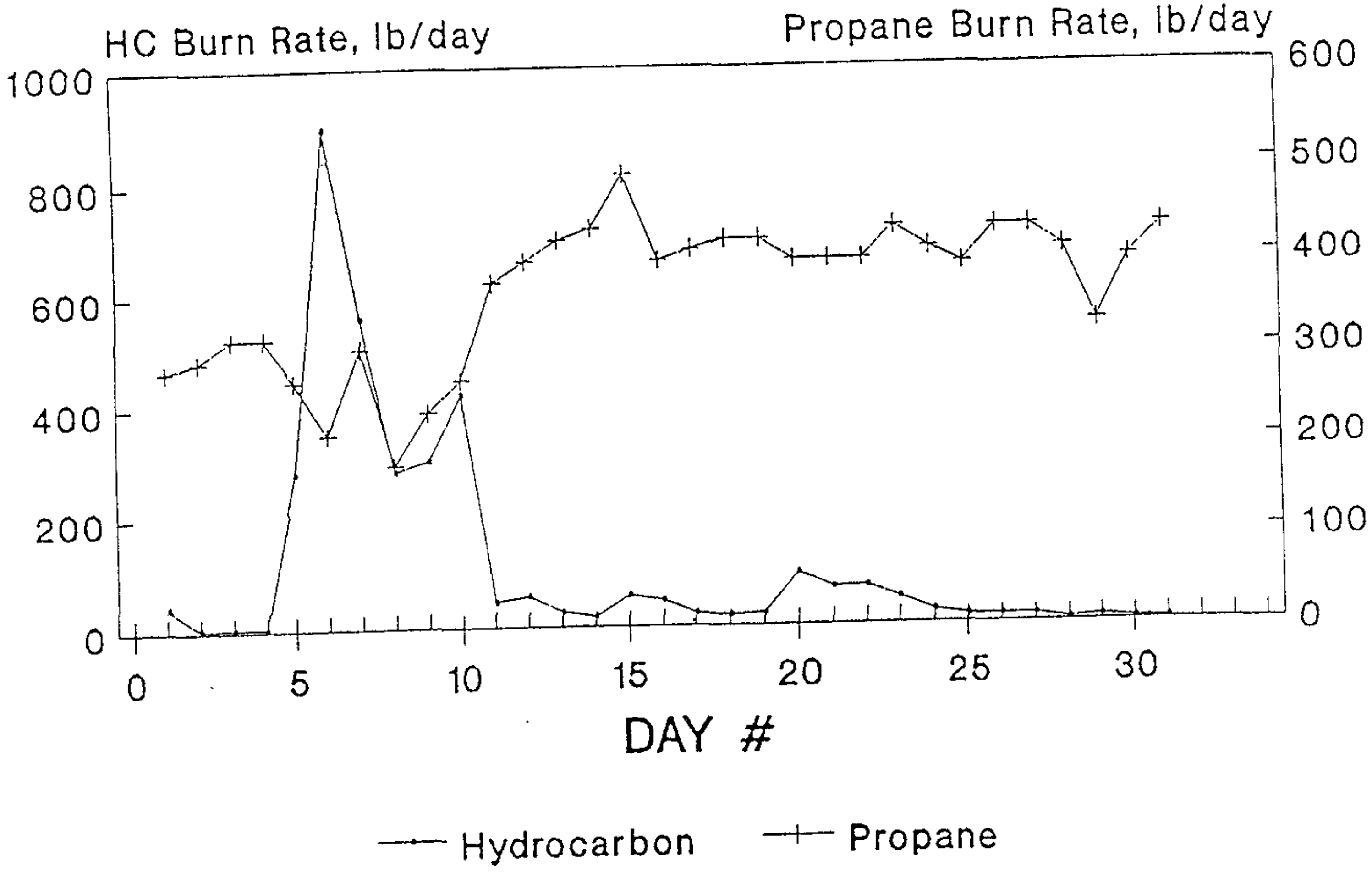
California Remediation Site

SOIL VENTING - ABOVE GRADE
VR SYSTEMS MODEL V-3 (BACT - 1)



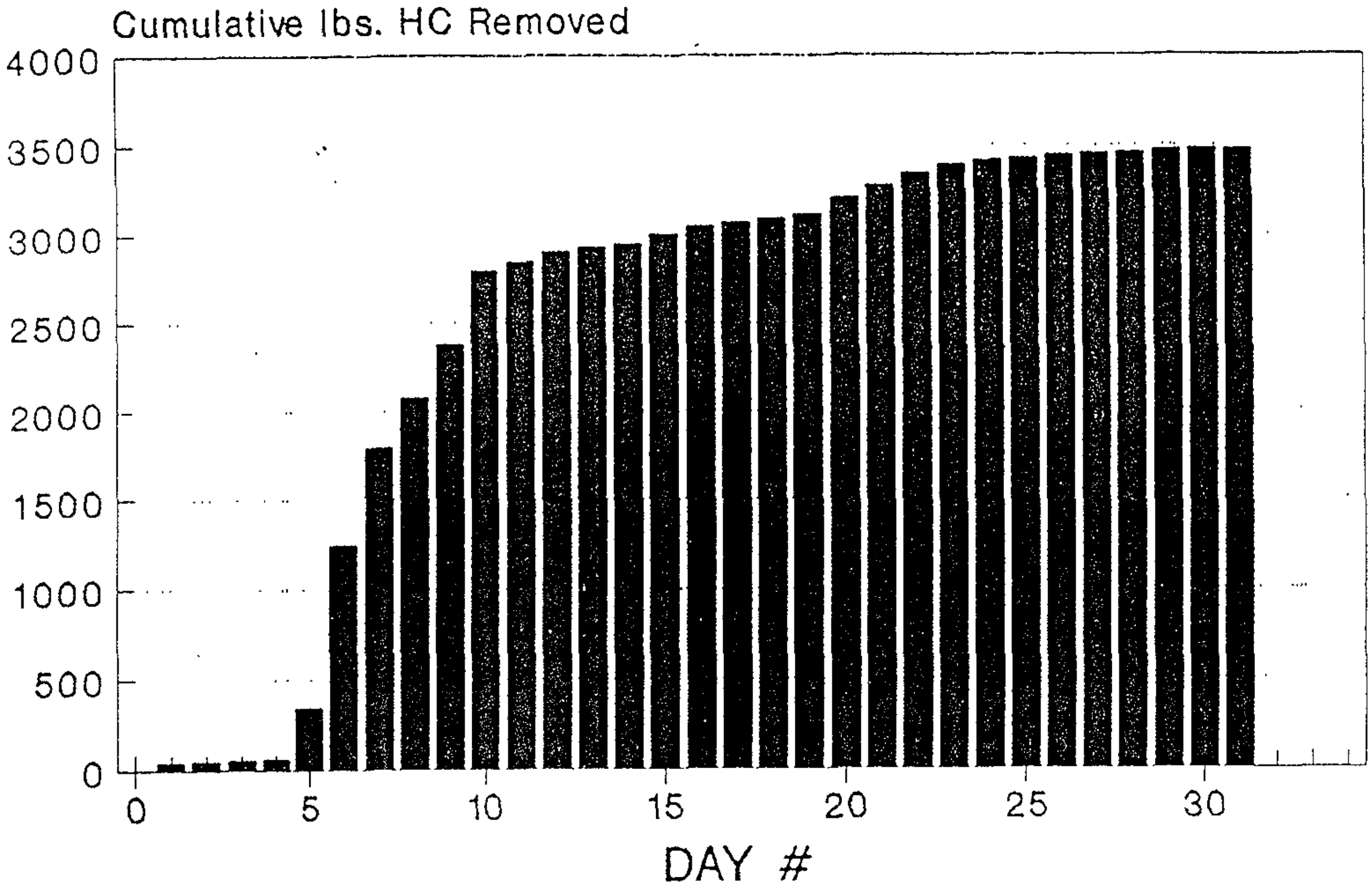
California Remediation Site

SOIL VENTING - ABOVE GRADE
VR SYSTEMS MODEL V-3 (BACT - 1)



California Remediation Site

SOIL VENTING - ABOVE GRADE
VR SYSTEMS MODEL V-3 (BACT - 1)



California Remediation Site

VR systems inc.

V3 STANDARD FEATURES

- * FIRE CONTROL SYSTEM
- * INPUT FLAME ARRESTER
- * AUTO SHUT DOWN
  - High Water Temperature
  - High Oil Temperature
  - Low Oil Level
- * AUTOMATIC OIL LEVEL REGULATOR
- * "0" PRESSURE COOLANT SYSTEM
  - (Safety & Long Life)
- * 16 ITEM PRINTOUT CAPABILITY
- * WELL GAS FLOW METER
- * EASILY TRANSPORTED - ONE MAN SETUP
- * SHUTDOWN/CALL-UP CAPABILITY
- * PERMIT ABILITY IN SCAQMD
  - Soil Remediation (Various Locations)
  - Underground Tank Degassing (Various Locations)
  - Above Ground Tank Degassing (In Progress)
- * L.A. CITY FIRE DEPARTMENT
  - General Approval
- * 20 MINUTE INSTALLATION CAPABILITY
- * SLIDE IN/SLIDE OUT ENGINE PACKAGE
- * LARGE SERVICE DOORS
- * PERMANENT STAND OR TRANSPORTABILITY
- * PRINTER AND PRINTER STAND
- * 15' X 2" VAPOR HOSE
- * 50' STATIC REELS

AVAILABLE OPTIONS

- * LCD MONITOR W/DISC DRIVE
  - For Report Accumulation
- * INVERTER PACKAGE
  - For "Stand Alone" Capability
- * MONITORING BY MODEM
- * FOXBORO OVA
- * KIT FOR NATURAL GAS OPERATION

11/90

KNOLLWOOD CIRCLE • ANAHEIM, CALIFORNIA 92801 • TELEPHONE (714) 826-0483

VR systems inc.

PRICE SHEET

1. **MODEL V3 VAPOR EXTRACTION SYSTEM** $71,000.00

   Price Includes The Standard Accessory Package[1] Including Transporter & Stand

2. **MODEL V3 VAPOR EXTRACTION SYSTEM** 69,500.00

   Standard Accessory Package With Stand Only (No Transporter)

3. **MODEL V4 VAPOR EXTRACTION SYSTEM (TWIN ENGINE)** 96,000.00

   Standard Accessories Package[2] Including Transporter and Stand

4. **ACCESSORIES**

V3 Transporter	2,100.00
Modem For Remote Monitoring	400.00
Inverter for "Stand Alone" Capability	550.00
Foxboro OVA	8,247.00
Weather Cover	Quote On Request
Sound Shields	Quote On Request

TRAINING: Machine pricing includes a one (1) day Training Program on operation and Maintenance at our facility in Anaheim. Field Training and set-up is available and quoted on request.

CONDITIONS: Prices are quoted F.O.B., our plant, Anaheim, California and are subject to all applicable sales taxes. DMV charges for the V3 Transporter are approximately $100.00, and for the V4 Transporter are approximately $160.00. Transporters shipped out of state will be issued a Certificate of Origin at no charge.

Freight charges quoted and billed at available rates in effect at time of shipment.

TERMS: 25% down with accompanying Purchase Order, balance, including shipping charges are all due upon shipment.

On Approved Credit, 25% down with accompanying Purchase Order, with balance due 30 days from delivery date.

---

[1] Standard Accessory Package: Printer & Stand, 15' of 2" Vac. Hose, 15' LPG High Pressure Hose, Static Reel (50').

[2] Standard Accessory Package: 80 column x 25 Line Display, 3½" (720K) Disk Drive, 15' of 3" Vac. Hose, 15' LPG High Pressure Hose, Static Reel (50'), and Inverter Package.

PRICES ARE SUBJECT TO CHANGE WITHOUT NOTICE EFFECTIVE 10/90

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VR systems inc.

5-17-90

SOURCE TESTS
UNDERGROUND SOIL VENTING DATA SHEETS

8-16-90 TESTS

SECTION 1.0

INTRODUCTION AND SUMMARY

Energy Systems Associates (ESA) was contracted by Wayne Perry Construction, Inc. to conduct emissions performance testing of a gasoline vapor extraction and treatment system at , Downey, California. This system consisted of a VR Systems engine with Aftermarket catalysts.

Emission tests were conducted to comply with South Coast Air Quality Management District rules and regulations for:

- total hydrocarbons
- non-methane hydrocarbons by GC/MS
- NOx, CO, CO_2, O_2
- lead and lead compounds (total lead)
- flow rate

Emissions tests were performed on August 16, 1989. Testing was performed by Mike Schmitt and Russel Pence of ESA. David E. Potts served as Wayne Perry Construction's testing coordinator. Henrique Nascimento of the SCAQMD witnessed portions of the testing.

The results of the tests are summarized in Table 1-1. Table 1-2 summarizes emissions of trace organic species. Detailed results are presented in the Appendices.

TABLE 1-1
SUMMARY OF EMISSION RESULTS
VR SYSTEMS ENGINE WITH AFTERMARKET CATALYST
DOWNEY, CALIFORNIA (AUGUST 16, 1989)

	Engine Intake	Engine Exhaust	3-Way Catalyst Exhaust	2-Way Catalyst Exhaust
Temperature, °F	90			950
H_2O %	8.5*			12.7
Flow rate, wacfm	171			308
Flow rate, dscfm	55			99
O_2%	7.9*	1.5	0.5	6.5
CO_2 %	8.7*	12.7	13.7	9.6
NOx: ppm		28	76	71
ppm @ 3% O_2		26	67	88
lb/hr				0.0511
CO: ppm	5*	7,240	43	< 1
ppm @ 3% O_2	7	6,680	38	< 1
lb/hr	0.0012			0.0004
HC:				
CH_4, ppm	252	13	44	121
NMHC, ppm as CH_4	45,810	9	19	35
NMHC, ppm @ 3% O_2	63,077	8	17	44
NMHC, lb/hr as CH_4	6.374			0.0088
Destruction efficiency, %				99.86
Lead:				
micrograms per dscf	0.075*			0.518
micrograms per dscf @ 3% O_2	0.103			0.644
lb/hr	5.45×10^{-7}			6.78×10^{-6}

* from August 15, 1989 testing

BENZENE EMISSIONS SOURCE TEST

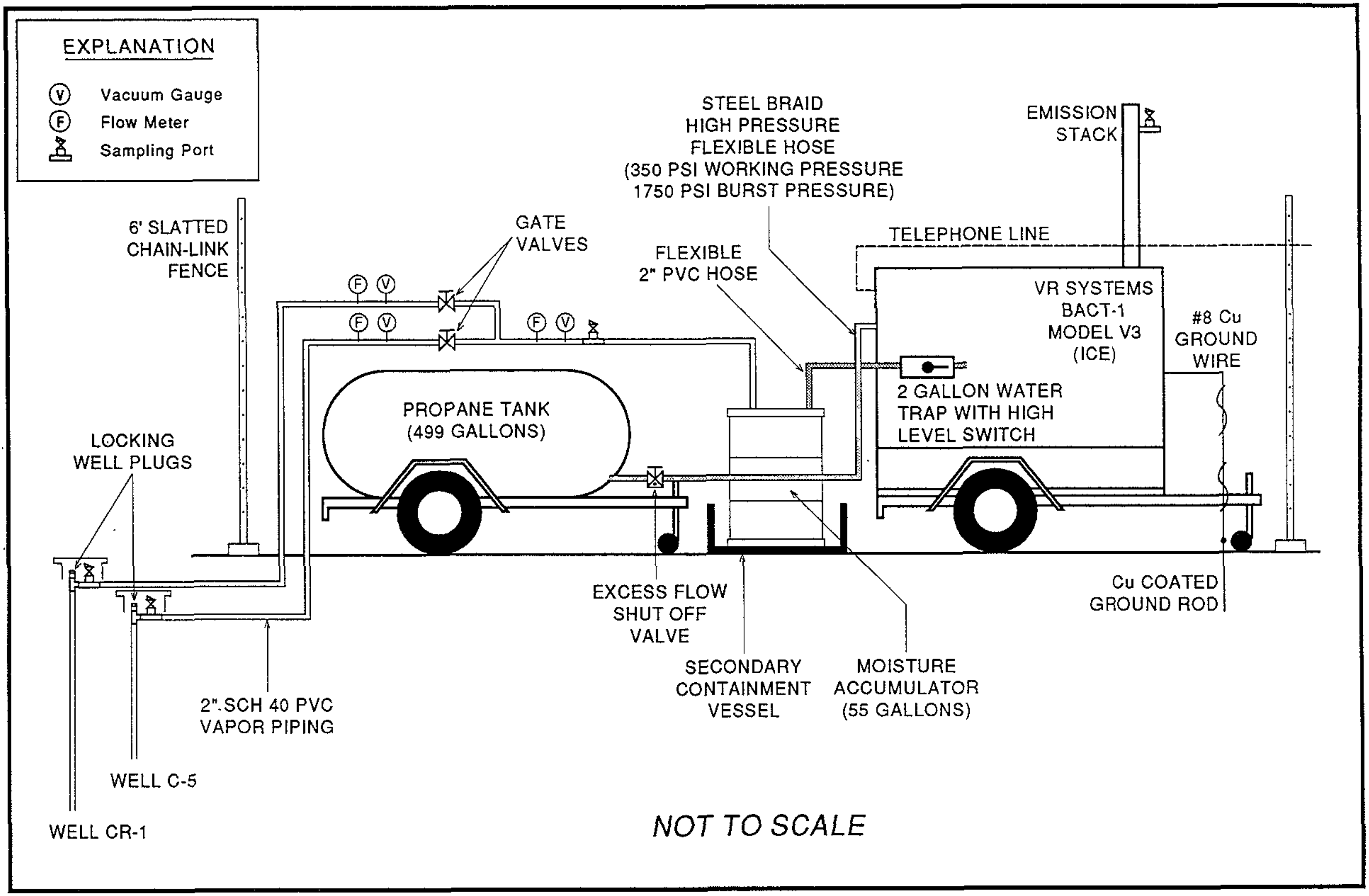
TABLE 1-2
SUMMARY OF EMISSIONS TESTS FOR TRACE ORGANIC SPECIES
WAYNE PERRY, DOWNEY, AFTERMARKET CATALYST
AUGUST 16, 1989

Species	Engine Inlet	2-Way Catalyst Exhaust
benzene:	125 ppm	ND (< 6.0) ppb
lb/hr	0.0800	ND (< 0.00001)
1,2-dichloroethane:	ND (< 20.0) ppm	ND (< 6.0) ppb
lb/hr	ND (< 0.01700)	ND (< 0.00001)
ethylbenzene:	ND (< 25.0) ppm	ND (< 5.0) ppb
lb/hr	ND (< 0.0231)	ND (< 0.00001)
toluene:	205 ppm	8.4 ppb
lb/hr	0.1660	0.00001
xylenes:	445 ppm	ND (< 10) ppb
lb/hr	0.4110	ND (< 0.00001)

ND indicates that the species was not detected.
Values in parentheses indicate the analytical detection limit for these samples

ATTACHMENT C

SYSTEM SCHEMATIC



Attachment C. Process Flow Diagram - Former Chevron Service Station #9-4816, 301 14th Street, Oakland, California

3/3/92

ATTACHMENT D

SITE SAFETY PLAN

Site Safety Plan

Date: February 28, 1992
Job # 4-582-83

A. Site Description

Client: Chevron USA, Inc.
Location 301 14th Street, Oakland, California
Area affected [X] 150 ft x 100 ft [ ] ______ acres
Surrounding land use [X] Residential [ ] Agricultural [ ] Industrial [X] Commercial
Topography [X] Flat [ ] Hilly [ ] Open Excavation [X] Paved [ ] Unpaved
Weather conditions ______

B. Work to be Performed: Soil Vapor Extraction and treatment with internal combustion engine.

C. On Site Control [X] A safe perimeter has been established. Its boundaries are defined by [ ] tape [ ] traffic cones [X] other Fencing has been installed around the site.

[X] The contamination reduction zone is designated as follows: The area within site fencing.

[X] The support zone is designated as follows: The area within site fencing.

D. Hazard Evaluation

[X] The following substances are known or suspected to be on site.
[X] Concentration range in water (mg/l) and soils (mg/kg) are as shown. Ground water results from latest quarterly sampling event from Alton Geoscience consultants to Chevron USA.

Substance	Free-Phase	In Ground Water	In Soil	TWA
TPH-Gasoline	approx. 2.5 ft	310 - 8,700	ND - 6,100	300 ppm
Benzene	not applicable	130 - 1,500	ND - 1.9	10 ppm
Toluene	not applicable	11 - 1,200	ND - 57	100 ppm
Ethyl Benzene	not applicable	2.6 - 150	ND - 120	100 ppm
Xylene	not applicable	6.8 - 580	ND - 740	100 ppm
Total Lead	not applicable	ND	ND	notapplicable

[X] Material Safety Data Sheets (MSDS) for the substances at the site are attached.
[ ] Air concentrations may exceed 10% of the Lower Explosive Limit (LEL).
[ ] Air concentrations may exceed OSHA Permissible Exposure Levels (PEL) 8 hour Time Weighted Average (TWA) for the following substances: OSHA levels are above air permit levels. The ICE will not be operated if air concentrations exceed air permit levels. Consequently, OSHA levels will never be exceeded.

General Safety Hazards:

[ ] Underground utilities and/or process lines have been identified. A line detector survey is [not] required.
[ ] Nitrogen cylinders or tanks will be used. Safety and operating instructions have been reviewed.
[X] Personnel are aware of safety hazards associated with lifting heavy items, moving machinery parts, slipping, falling and operating or working near electrical equipment.
[X] Propane tank (499 gallons). MSDS for propane is attached.
[ ] Confined space entry is required. All personnel have reviewed confined space entry procedures. A confined space entry checklist has been completed and it is attached to this plan.

E. Air Monitoring

The following air monitoring instruments shall be used on site at the specified intervals:

[X] Combustible Gas Indicator System LEL sensor shuts off engine for air concentrations exceeding 10% LEL
[ ] Oxygen Indicator Work will be performed in open spaces, therefore, no oxygen monitoring will be necessary.
[X] Organic Vapor Meter or OVM/FID will be used during trenching activities
[X] Color Tubes (Refer to Attached Flow Chart): Refer to attached Hazard Evaluation Logic Diagram

Substance	Concentration Range	Pump Strokes
Benzene	1 - 20 ppm	10 strokes at 50mL/stroke

F. Personal Protective Equipment

The required personal protection level is: D. Specific protective equipment to be worn is as follows: Hard hats and Steel toe boots. Level of protection will increase to C by SSO if concentrations exceed PEL's.

Protective clothing materials for the involved substances are Nitrile gloves, boots and splash shield (only if skin contact with gasoline is likely).

Respiratory protection shall consist of half face respirator if needed Protection Factor = 10.

The required respiratory cartridge is organic vapor. Use 3M brand NIOSH appr'd. TC-23C-435.

This cartridge is expected to provide adequate protection for 8 hours.

[X] All personnel at the site have been trained in the proper use and care of protective equipment. All personnel have 40 hour SARA training and 8 hour refresher courses records on file at WA Human Resources Department.

G. Decontamination Procedures

Personnel and equipment leaving the site shall be decontaminated as follows:

Soap and water for personnel and steam cleaning for equipment.

H. Heat Stress Monitoring

The expected air temperature will be 60° F. Adjusted air temperature [Tadj = Tair(F) + (13 x % sunshine)] is not expected to exceed 70° F.

[ ] A Health Alert Warning (air temperatures likely to exceed 95° F) has [not] been issued by the weather service.

[X] Workers are trained to recognize heat stress symptoms.

[X] The Site Safety Officer will monitor pulse rate and temperature of workers showing signs of heat stress and modify the work schedule accordingly. A disposable oral thermometer is part of the field kit. No team member will work if his/her oral temperature exceeds 100.6° F.

[X] Drinking water and disposable cups are available during work.

I. Emergency Procedures

Personnel Injury: The Site Safety Officer and Project Team Leader should evaluate the nature of the injury and contact should be made for an ambulance and with the designated medical facility (if required). An incident report form should be filed.

Fire/Explosion: The fire department shall be alerted if necessary. All personnel shall be moved to a safe distance from the involved area. There is [not] an alarm system at the facility. [ ] The client has explained to us the procedures to be followed if their alarm is activated.

Oral communications are possible at all times. [ ] A [horn] [megaphone] will be used to issue emergency signals.

Emergency escape routes have been identified as follows:

North along Harrison St., then left onto 15th St., and right onto Broadway. Proceed for about 1 mile on Broadway then turn left onto 30th Street. Proceed two blocks uphill to Summit, than go right for 1/2 block. Hospital is on right.

J. Emergency Medical Care

Hospital Providence Hospital, at 3100 Summit,

phone (510)835-4500 is located 5 minutes from this location. A map of alternative routes to this facility is attached. First-aid equipment is available on site at the following locations:

First-aid kit	In WA vehicle
Emergency eye wash	In WA vehicle
Other	Fire extinguisher, located in equipment enclosure.

List of emergency phone numbers:

	Agency/Facility	Phone #	Contact (if applicable)
Police	Oakland Police	911	
Fire	Oakland Fire Dept.	911	
Client	Chevron USA	(510)842-9581	Nancy Vukelich

Any injuries sustained while working are covered under Worker's Compensation insurance. Any injured WA employee should inform the medical care facility that this is a worker's comp claim and that our policy is Firemans' Fund #8 09 WZP 8053 17 65. Copies of the Doctor's report on injury should be forwarded to our carrier Fireman's Fund, P.O. Box 1799, Rohnert Park, CA 94927-9908.) WA employees must also notify Beth Springston at WA (510-547-5420) the same day so that this claim can be filed properly.

Any injured sub-contractor employee will be covered under their employer's policy. If they do not know their information, call Beth Springston at WA. She has certificates of the insurance policy for all approved sub-contractors.

Emergency medical information is presented in the attached MSDS.

All site personnel have read the plan and are familiar with its provisions. The following personnel are designated to carry out job functions at the site:

	Name	Signature
Project Team Leader	Tom Berry	
Site Safety Officer	Jim Martin	
Field Team Leader		
Field Team Member		
Field Team Member		
WA Office Advisor	Fatima Lelic	

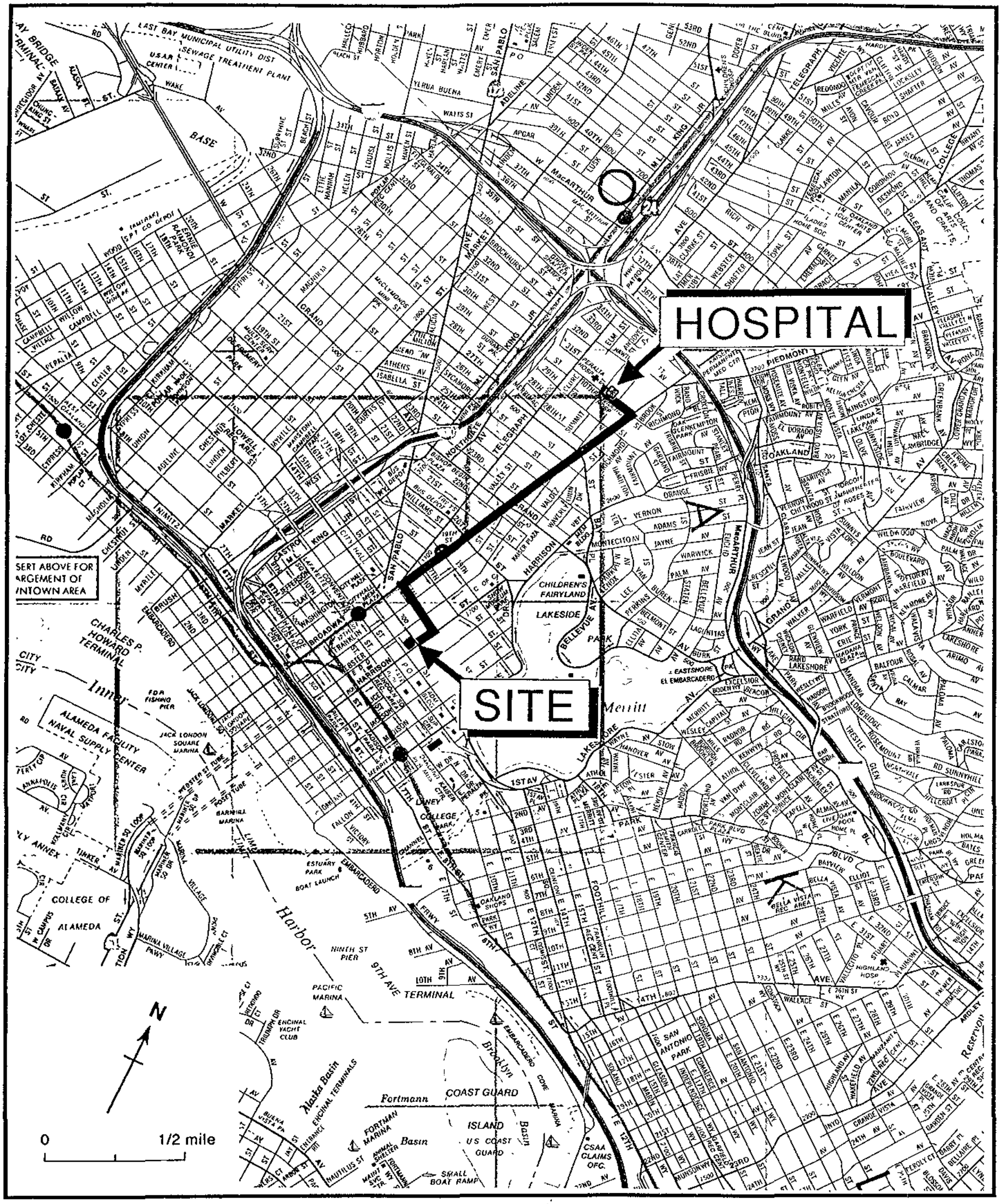
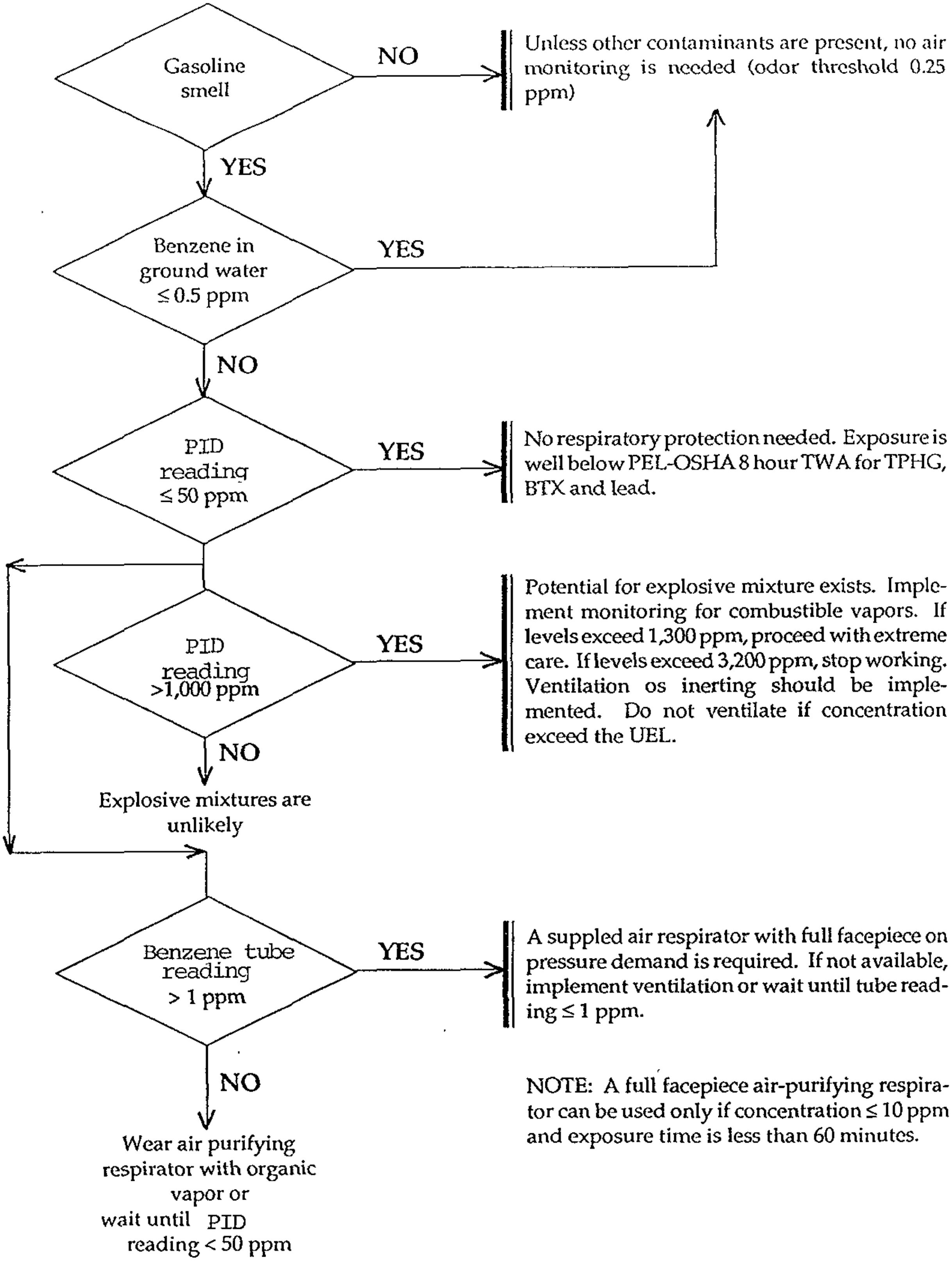


Figure 1. Hospital Route Map - Chevron Service Station #9-4816, 301 14th Street, Oakland, California

3/3/92

Hazard Evaluation - Gasoline and BTX



Unless other contaminants are present, no air monitoring is needed (odor threshold 0.25 ppm)

No respiratory protection needed. Exposure is well below PEL-OSHA 8 hour TWA for TPHG, BTX and lead.

Potential for explosive mixture exists. Implement monitoring for combustible vapors. If levels exceed 1,300 ppm, proceed with extreme care. If levels exceed 3,200 ppm, stop working. Ventilation os inerting should be implemented. Do not ventilate if concentration exceed the UEL.

A suppled air respirator with full facepiece on pressure demand is required. If not available, implement ventilation or wait until tube reading ≤ 1 ppm.

NOTE: A full facepiece air-purifying respirator can be used only if concentration ≤ 10 ppm and exposure time is less than 60 minutes.

GASOLINES: AUTOMOTIVE (<4.23g lead/gal)

GAT

Common Synonyms

Motor spirit
Petrol

Watery liquid — Colorless to pale brown or pink — Gasoline odor

Floats on water Flammable, irritating vapor is produced

Stop discharge if possible. Keep people away
Shut off ignition sources and call fire department
Stay upwind and use water spray to "knock down" vapor
Isolate and remove discharged material
Notify local health and pollution control agencies

Fire

FLAMMABLE
Flashback along vapor trail may occur.
Vapor may explode if ignited in an enclosed area
Extinguish with dry chemical, foam, or carbon dioxide
Water may be ineffective on fire
Cool exposed containers with water

Exposure

CALL FOR MEDICAL AID

VAPOR
Irritating to eyes, nose and throat.
If inhaled, will cause dizziness, headache, difficult breathing or loss of consciousness
Move to fresh air.
If breathing has stopped, give artificial respiration
If breathing is difficult, give oxygen

LIQUID
Irritating to skin and eyes
If swallowed, will cause nausea or vomiting
Remove contaminated clothing and shoes
Flush affected areas with plenty of water
IF IN EYES, hold eyelids open and flush with plenty of water
IF SWALLOWED and victim is CONSCIOUS, have victim drink water or milk.
DO NOT INDUCE VOMITING

Water Pollution

HARMFUL TO AQUATIC LIFE IN VERY LOW CONCENTRATIONS.
Fouling to shoreline
May be dangerous if it enters water intakes.

Notify local health and wildlife officials
Notify operators of nearby water intakes

1. RESPONSE TO DISCHARGE

(See Response Methods Handbook)

Issue warning high flammability
Evacuate area
Disperse and flush

2. LABEL

2.1 **Category:** Flammable liquid
2.2 **Class:** 3

3 CHEMICAL DESIGNATIONS

3.1 **CG Compatibility Class:** Miscellaneous Hydrocarbon Mixtures
3 2 **Formula** (Mixture of hydrocarbons)
3.3 **IMO/UN Designation:** 3 1/1203
3 4 **DOT ID No.:** 1203
3 5 **CAS Registry No.:** Data not available

4. OBSERVABLE CHARACTERISTICS

4.1 **Physical State (as shipped):** Liquid
4 2 **Color:** Colorless to brown
4.3 **Odor** Gasoline

5. HEALTH HAZARDS

5.1 **Personal Protective Equipment** Protective goggles, gloves
5.2 **Symptoms Following Exposure:** Irritation of mucous membranes and stimulation followed by depression of central nervous system Breathing of vapor may also cause dizziness, headache, and incoordination or, in more severe cases, anesthesia, coma, and respiratory arrest. If liquid enters lungs, it will cause severe irritation, coughing, gagging, pulmonary edema, and, later, signs of bronchopneumonia and pneumonitis Swallowing may cause irregular heartbeat
5.3 **Treatment of Exposure.** INHALATION maintain respiration and administer oxygen, enforce bed rest if liquid is in lungs INGESTION do NOT induce vomiting; stomach should be lavaged (by doctor) if appreciable quantity is swallowed EYES. wash with copious quantity of water SKIN wipe off and wash with soap and water
5.4 **Threshold Limit Value** 300 ppm
5 5 **Short Term Inhalation Limits:** 500 ppm for 30 min
5.6 **Toxicity by Ingestion.** Grade 2, LD_{50} = 0 5 to 5 g/kg
5.7 **Late Toxicity:** None
5.8 **Vapor (Gas) Irritant Characteristics:** Vapors cause a slight smarting of the eyes or respiratory system if present in high concentrations The effect is temporary
5.9 **Liquid or Solid Irritant Characteristics:** Minimum hazard If spilled on clothing and allowed to remain, may cause smarting and reddening of the skin.
5.10 **Odor Threshold.** 0 25 ppm
5.11 **IDLH Value:** Data not available

6. FIRE HAZARDS

6.1 **Flash Point:** —36°F C C.
6.2 **Flammable Limits in Air:** 1.4%-7 4%
6.3 **Fire Extinguishing Agents:** Foam, carbon dioxide, dry chemical
6 4 **Fire Extinguishing Agents Not to be Used:** Water may be ineffective
6.5 **Special Hazards of Combustion Products:** None
6.6 **Behavior in Fire:** Vapor is heavier than air and may travel considerable distance to a source of ignition and flash back
6.7 **Ignition Temperature** 853°F
6.8 **Electrical Hazard:** Class I, Group D
6.9 **Burning Rate:** 4 mm/min
6.10 **Adiabatic Flame Temperature:** Data not available
6.11 **Stoichiometric Air to Fuel Ratio:** Data not available
6.12 **Flame Temperature** Data not available

7. CHEMICAL REACTIVITY

7 1 **Reactivity With Water:** No reaction
7.2 **Reactivity with Common Materials:** No reaction
7.3 **Stability During Transport:** Stable
7.4 **Neutralizing Agents for Acids and Caustics:** Not pertinent
7.5 **Polymerization.** Not pertinent
7.6 **Inhibitor of Polymerization:** Not pertinent
7.7 **Molar Ratio (Reactant to Product):** Data not available
7.8 **Reactivity Group:** 33

8. WATER POLLUTION

8.1 **Aquatic Toxicity:**
90 ppm/24 hr/juvenile American shad/TL_m/fresh water
91 mg/1/24 hr/juvenile American shad/TL_m/salt water
8.2 **Waterfowl Toxicity:** Data not available
8.3 **Biological Oxygen Demand (BOD):** 8%, 5 days
8.4 **Food Chain Concentration Potential.** None

9 SHIPPING INFORMATION

9.1 **Grades of Purity** Various octane ratings, military specifications
9.2 **Storage Temperature:** Ambient
9.3 **Inert Atmosphere.** No requirement
9.4 **Venting.** Open (flame arrester) or pressure-vacuum

10 HAZARD ASSESSMENT CODE

(See Hazard Assessment Handbook)

A-T-U-V-W

11. HAZARD CLASSIFICATIONS

11.1 **Code of Federal Regulations:** Flammable liquid
11.2 **NAS Hazard Rating for Bulk Water Transportation:**

Category	Rating
Fire	3
Health	
Vapor Irritant	1
Liquid or Solid Irritant	1
Poisons	2
Water Polution	
Human Toxicity	1
Aquatic Toxicity	2
Aesthetic Effect	2
Reactivity	
Other Chemicals	0
Water	0
Self Reaction	0

11 3 **NFPA Hazard Classification:**

Category	Classification
Health Hazard (Blue)	1
Flammability (Red)	3
Reactivity (Yellow)	0

12. PHYSICAL AND CHEMICAL PROPERTIES

12.1 **Physical State at 15°C and 1 atm:** Liquid
12.2 **Molecular Weight:** Not pertinent
12.3 **Boiling Point at 1 atm:**
140—390°F
= 60—199°C = 333—472°K
12.4 **Freezing Point:** Not pertinent
12.5 **Critical Temperature:** Not pertinent
12.6 **Critical Pressure:** Not pertinent
12.7 **Specific Gravity:**
0 7321 at 20°C (liquid)
12.8 **Liquid Surface Tension:**
19-23 dynes/cm
= 0 019—0 023 N/m at 20°C
12.9 **Liquid Water Interfacial Tension:**
49-51 dynes/cm
= 0 049—0 051 N/m at 20°C
12 10 **Vapor (Gas) Specific Gravity:** 3 4
12.11 **Ratio of Specific Heats of Vapor (Gas)** (est) 1.054
12.12 **Latent Heat of Vaporization.**
130—150 Btu/lb = 71—81 cal/g
= 3 0 — 3.4 X 10^5 J/kg
12.13 **Heat of Combustion** —18,720 Btu/lb
= —10,400 cal/g = 435 1 X 10^5 J/kg
12 14 **Heat of Decomposition:** Not pertinent
12.15 **Heat of Solution:** Not pertinent
12.16 **Heat of Polymerization** Not pertinent
12.25 **Heat of Fusion:** Data not available
12.26 **Limiting Value:** Data not available
12.27 **Reid Vapor Pressure** 7 4 psia

NOTES

JUNE 1985

GAT

GASOLINES: AUTOMOTIVE (<4.23g lead/gal)

12.17 SATURATED LIQUID DENSITY

Temperature (degrees F)	Pounds per cubic foot
45	46.270
50	46.130
55	46.000
60	45.850
65	45.710
70	45.560
75	45.400
80	45.240
85	45.080
90	44.910
95	44.750
100	44.570
105	44.390
110	44.210
115	44.030

12.18 LIQUID HEAT CAPACITY

Temperature (degrees F)	British thermal unit per pound-F
10	.459
15	.462
20	.464
25	.467
30	.470
35	.472
40	.475
45	.478
50	.480
55	.483
60	.486
65	.488
70	.491
75	.494
80	.496
85	.499
90	.502
95	.504
100	.507
105	.510

12.19 LIQUID THERMAL CONDUCTIVITY

Temperature (degrees F)	British thermal unit-inch per hour-square foot-F (estimate)
40	.909
50	.900
60	.891
70	.883
80	.874
90	.865
100	.856
110	.847
120	.838
130	.829
140	.821
150	.812
160	.803
170	.794
180	.785
190	.776

12.20 LIQUID VISCOSITY

Temperature (degrees F)	Centipoise
46	.521
48	.514
50	.507
52	.500
54	.494
56	.487
58	.481
60	.475
62	.469
64	.463
66	.457
68	.451
70	.446
72	.440
74	.435
76	.430
78	.424
80	.419
82	.414
84	.410
86	.405
88	.400
90	.396
92	.391
94	.387
96	.382

12.21 SOLUBILITY IN WATER

Temperature (degrees F)	Pounds per 100 pounds of water
	INSOLUBLE

12.22 SATURATED VAPOR PRESSURE

Temperature (degrees F)	Pounds per square inch
	DATA NOT AVAILABLE

12.23 SATURATED VAPOR DENSITY

Temperature (degrees F)	Pounds per cubic foot
	NOT PERTINENT

12.24 IDEAL GAS HEAT CAPACITY

Temperature (degrees F)	British thermal unit per pound-F
	DATA NOT AVAILABLE

BENZENE

BNZ

Common Synonyms

Benzol
Benzole

Watery liquid — Colorless — Gasoline-like odor

Floats on water Flammable, irritating vapor is produced Freezing point is 42°F

Avoid contact with liquid and vapor Keep people away
Wear goggles and self contained breathing apparatus
Shut off ignition sources and call fire department
Stop discharge if possible
Stay upwind and use water spray to "knock down" vapor
Isolate and remove discharged material
Notify local health and pollution control agencies

Fire

FLAMMABLE
Flashback along vapor trail may occur
Vapor may explode if ignited in an enclosed area.

Wear goggles and self contained breathing apparatus
Extinguish with dry chemical foam, or carbon dioxide
Water may be ineffective on fire
Cool exposed containers with water

Exposure

CALL FOR MEDICAL AID
VAPOR
Irritating to eyes, nose and throat
If inhaled, will cause headache, difficult breathing, or loss of consciousness

Move to fresh air
If breathing has stopped, give artificial respiration
If breathing is difficult, give oxygen
LIQUID
Irritating to skin and eyes
Harmful if swallowed

Remove contaminated clothing and shoes
Flush affected areas with plenty of water
IF IN EYES, hold eyelids open and flush with plenty of water
IF SWALLOWED and victim is CONSCIOUS, have victim drink water or milk

Water Pollution

HARMFUL TO AQUATIC LIFE IN VERY LOW CONCENTRATIONS.
May be dangerous if it enters water intakes

Notify local health and wildlife officials
Notify operators of nearby water intakes

1. RESPONSE TO DISCHARGE

(See Response Methods Handbook)

Issue warning high flammability
Restrict access

2. LABEL

2.1 **Category:** Flammable liquid
2.2 **Class:** 3

3 CHEMICAL DESIGNATIONS

3.1 **CG Compatibility Class:** Aromatic Hydrocarbon
3.2 **Formula:** C_6H_6
3.3 **IMO/UN Designation:** 3 2/1114
3.4 **DOT ID No.:** 1114
3 5 **CAS Registry No.:** 71-43 2

4. OBSERVABLE CHARACTERISTICS

4 1 **Physical State (as shipped):** Liquid
4.2 **Color:** Colorless
4 3 **Odor:** Aromatic, rather pleasant aromatic odor, characteristic odor

5. HEALTH HAZARDS

5.1 **Personal Protective Equipment:** Hydrocarbon vapor canister, supplied air or a hose mask, hydrocarbon-insoluble rubber or plastic gloves, chemical goggles or face splash shield, hydrocarbon-insoluble apron such as neoprene
5.2 **Symptoms Following Exposure:** Dizziness, excitation, pallor, followed by flushing, weakness, headache, breathlessness, chest constriction Coma and possible death
5.3 **Treatment of Exposure:** SKIN flush with water followed by soap and water; remove contaminated clothing and wash skin. EYES flush with plenty of water until irritation subsides INHALATION remove from exposure immediately Call a physician IF breathing is irregular or stopped, start resuscitation, administer oxygen
5.4 **Threshold Limit Value:** 10 ppm
5.5 **Short Term Inhalation Limits:** 75 ppm for 30 min
5.6 **Toxicity by Ingestion:** Grade 3, LD_{50} = 50 to 500 mg/kg
5.7 **Late Toxicity:** Leukemia
5.8 **Vapor (Gas) Irritant Characteristics:** If present in high concentrations, vapors may cause irritation of eyes or respiratory system The effect is temporary
5.9 **Liquid or Solid Irritant Characteristics.** Minimum hazard If spilled on clothing and allowed to remain, may cause smarting and reddening of the skin
5.10 **Odor Threshold:** 4 68 ppm
5 11 **IDLH Value:** 2 000 ppm

6. FIRE HAZARDS

6.1 **Flash Point.** 12°F C C
6.2 **Flammable Limits in Air:** 1 3%-7 9%
6.3 **Fire Extinguishing Agents:** Dry chemical, foam, or carbon dioxide
6.4 **Fire Extinguishing Agents Not to be Used:** Water may be ineffective
6.5 **Special Hazards of Combustion Products:** Not pertinent
6.6 **Behavior in Fire:** Vapor is heavier than air and may travel considerable distance to a source of ignition and flash back
6.7 **Ignition Temperature:** 1097°F
6.8 **Electrical Hazard:** Class I, Group D
6.9 **Burning Rate:** 6 0 mm/min
6.10 **Adiabatic Flame Temperature:** Data not available
6.11 **Stoichiometric Air to Fuel Ratio:** Data not available
6.12 **Flame Temperature:** Data not available

7. CHEMICAL REACTIVITY

7.1 **Reactivity With Water:** No reaction
7.2 **Reactivity with Common Materials.** No reaction
7.3 **Stability During Transport:** Stable
7.4 **Neutralizing Agents for Acids and Caustics:** Not pertinent
7.5 **Polymerization:** Not pertinent
7.6 **Inhibitor of Polymerization.** Not pertinent
7.7 **Molar Ratio (Reactant to Product)** Data not available
7.8 **Reactivity Group:** 32

8. WATER POLLUTION

8.1 **Aquatic Toxicity:**
5 ppm/6 hr/minnow/lethal/distilled water
20 ppm/24 hr/sunfish/TL_m/tap water
8.2 **Waterfowl Toxicity:** Data not available
8 3 **Biological Oxygen Demand (BOD):** 1 2 lb/lb, 10 days
8.4 **Food Chain Concentration Potential:** None

9 SHIPPING INFORMATION

9 1 **Grades of Purity:**

Industrial pure	99+%
Thiophene-free	99+%
Nitration	99+%
Industrial 90%	85+%
Reagent	99+%

9.2 **Storage Temperature:** Open
9.3 **Inert Atmosphere.** No requirement
9.4 **Venting** Pressure-vacuum

10. HAZARD ASSESSMENT CODE

(See Hazard Assessment Handbook)

A-T-U-V-W

11. HAZARD CLASSIFICATIONS

11.1 **Code of Federal Regulations:** Flammable liquid
11.2 **NAS Hazard Rating for Bulk Water Transportation:**

Category	Rating
Fire	3
Health	
Vapor Irritant	1
Liquid or Solid Irritant	1
Poisons	3
Water Pollution	
Human Toxicity	3
Aquatic Toxicity	1
Aesthetic Effect	3
Reactivity	
Other Chemicals	2
Water	1
Self Reaction	0

11.3 **NFPA Hazard Classification.**

Category	Classification
Health Hazard (Blue)	2
Flammability (Red)	3
Reactivity (Yellow)	0

12. PHYSICAL AND CHEMICAL PROPERTIES

12.1 **Physical State at 15°C and 1 atm:** Liquid
12.2 **Molecular Weight:** 78 11
12.3 **Boiling Point at 1 atm:** 176°F = 80.1°C = 353 3°K
12.4 **Freezing Point:** 42.0°F = 5 5°C = 278 7°K
12.5 **Critical Temperature:** 552.0°F = 288 9°C = 562 1°K
12.6 **Critical Pressure:** 710 psia = 48 3 atm = 4.89 MN/m^2
12.7 **Specific Gravity:** 0.879 at 20°C (liquid)
12 8 **Liquid Surface Tension:** 28.9 dynes/cm = 0 0289 N/m at 20°C
12.9 **Liquid Water Interfacial Tension:** 35 0 dynes/cm = 0 035 N/m at 20°C
12.10 **Vapor (Gas) Specific Gravity:** 2 7
12.11 **Ratio of Specific Heats of Vapor (Gas):** 1 061
12.12 **Latent Heat of Vaporization:** 169 Btu/lb = 94 1 cal/g = 3 94 X 10^5 J/kg
12.13 **Heat of Combustion** —17,460 Btu/lb = —9698 cal/g = —406 0 X 10^5 J/kg
12.14 **Heat of Decomposition** Not pertinent
12.15 **Heat of Solution** Not pertinent
12.16 **Heat of Polymerization:** Not pertinent
12 25 **Heat of Fusion:** 30 45 cal/g
12.26 **Limiting Value** Data not available
12.27 **Reid Vapor Pressure** 3 22 psia

NOTES

BNZ

BENZENE

12.17 SATURATED LIQUID DENSITY

Temperature (degrees F)	Pounds per cubic foot
55	55.330
60	55.140
65	54.960
70	54.770
75	54.580
80	54.400
85	54.210
90	54.030
95	53.840
100	53.660
105	53.470
110	53 290
115	53.100
120	52.920
125	52.730
130	52.540
135	52.360
140	52.170
145	51.990
150	51.800
155	51.620
160	51.430
165	51.250
170	51.060
175	50.870

12.18 LIQUID HEAT CAPACITY

Temperature (degrees F)	British thermal unit per pound-F
45	.394
50	.396
55	.398
60	.400
65	.403
70	.405
75	.407
80	.409
85	.411
90	.414
95	.416
100	418

12.19 LIQUID THERMAL CONDUCTIVITY

Temperature (degrees F)	British thermal unit-inch per hour-square foot-F
75	.988
80	.981
85	.975
90	.969
95	.962
100	956
105	.950
110	.944
115	.937
120	.931
125	.925
130	.919
135	.912
140	.906
145	.900
150	.893
155	.887
160	.881
165	.875
170	.868

12.20 LIQUID VISCOSITY

Temperature (degrees F)	Centipoise
55	.724
60	.693
65	.665
70	.638
75	.612
80	.588
85	.566
90	544
95	.524
100	.505
105	.487
110	.470
115	.453
120	.438

12.21 SOLUBILITY IN WATER

Temperature (degrees F)	Pounds per 100 pounds of water
77.02	.180

12.22 SATURATED VAPOR PRESSURE

Temperature (degrees F)	Pounds per square inch
50	.881
60	1.171
70	1.535
80	1.989
90	2.547
100	3.227
110	4.049
120	5.033
130	6.201
140	7.577
150	9.187
160	11.060
170	13.220
180	15.700
190	18.520
200	21.740
210	25.360

12.23 SATURATED VAPOR DENSITY

Temperature (degrees F)	Pounds per cubic foot
50	.01258
60	.01639
70	.02109
80	.02681
90	.03371
100	.04196
110	.05172
120	.06317
130	.07652
140	.09194
150	.10960
160	.12980
170	.15270
180	.17850
190	.20750
200	.23970
210	.27560

12.24 IDEAL GAS HEAT CAPACITY

Temperature (degrees F)	British thermal unit per pound-F
0	.204
25	.219
50	.234
75	.248
100	.261
125	.275
150	.288
175	.301
200	.313
225	.325
250	.337
275	.349
300	.360
325	.371
350	.381
375	.392
400	.402
425	.412
450	.421
475	.431
500	.440
525	.449
550	.457
575	.465
600	.474

TOLUENE

TOL

Common Synonyms

Toluol
Methylbenzene
Methylbenzol

Watery liquid Colorless Pleasant odor

Floats on water Flammable, irritating vapor is produced

Stop discharge if possible Keep people away
Shut off ignition sources and call fire department
Stay upwind and use water spray to "knock down" vapor
Avoid contact with liquid and vapor
Isolate and remove discharged material
Notify local health and pollution control agencies

Fire

FLAMMABLE.
Flashback along vapor trail may occur
Vapor may explode if ignited in an enclosed area.
Wear goggles and self contained breathing apparatus
Extinguish with dry chemical, foam, or carbon dioxide
Water may be ineffective on fire
Cool exposed containers with water

Exposure

CALL FOR MEDICAL AID

VAPOR
Irritating to eyes, nose and throat
If inhaled, will cause nausea, vomiting, headache, dizziness, difficult breathing, or loss of consciousness.
Move to fresh air
If breathing has stopped, give artificial respiration
If breathing difficult, give oxygen

LIQUID
Irritating to skin and eyes
If swallowed, will cause nausea, vomiting or loss of consciousness.
Remove contaminated clothing and shoes
Flush affected areas with plenty of water
IF IN EYES, hold eyelids open and flush with plenty of water
IF SWALLOWED and victim is CONSCIOUS, have victim drink water or milk
DO NOT INDUCE VOMITING

Water Pollution

Dangerous to aquatic life in high concentrations.
Fouling to shoreline
May be dangerous if it enters water intakes

Notify local health and wildlife officials
Notify operators of nearby water intakes

1. RESPONSE TO DISCHARGE

(See Response Methods Handbook)

Issue warning-high flammability
Evacuate area

2. LABEL

2.1 **Category:** Flammable liquid
2.2 **Class:** 3

3. CHEMICAL DESIGNATIONS

3.1 **CG Compatibility Class:** Aromatic Hydrocarbon
3.2 **Formula:** $C_6H_5CH_3$
3.3 **IMO/UN Designation:** 3 2/1294
3.4 **DOT ID No.:** 1294
3.5 **CAS Registry No.:** 108-88 3

4. OBSERVABLE CHARACTERISTICS

4.1 **Physical State (as shipped):** Liquid
4.2 *Color: Colorless*
4.3 **Odor:** Pungent, aromatic, benzene-like, distinct, pleasant

5 HEALTH HAZARDS

5.1 **Personal Protective Equipment:** Air-supplied mask, goggles or face shield, plastic gloves.
5.2 **Symptoms Following Exposure** Vapors irritate eyes and upper respiratory tract, cause dizziness, headache, anesthesia, respiratory arrest Liquid irritates eyes and causes drying of skin If aspirated, causes coughing, gagging, distress, and rapidly developing pulmonary edema If ingested causes vomiting, griping, diarrhea, depressed respiration
5.3 **Treatment of Exposure:** INHALATION remove to fresh air, give artificial respiration and oxygen if needed, call a doctor. INGESTION do NOT induce vomiting, call a doctor. EYES: flush with water for at least 15 min. SKIN: wipe off, wash with soap and water.
5.4 **Threshold Limit Value:** 100 ppm
5.5 **Short Term Inhalation Limits:** 600 ppm for 30 min
5.6 **Toxicity by Ingestion:** Grade 2; LD_{50} = 0.5 to 5 g/kg
5.7 **Late Toxicity:** Kidney and liver damage may follow ingestion
5.8 **Vapor (Gas) Irritant Characteristics:** Vapors cause a slight smarting of the eyes or respiratory system if present in high concentrations. The effect is temporary
5.9 **Liquid or Solid Irritant Characteristics:** Minimum hazard If spilled on clothing and allowed to remain, may cause smarting and reddening of the skin
5.10 **Odor Threshold:** 0 17 ppm
5.11 **IDLH Value:** 2,000 ppm

6 FIRE HAZARDS

6.1 **Flash Point:** *40°F C C; 55°F O C*
6.2 **Flammable Limits in Air:** 1 27%-7%
6.3 **Fire Extinguishing Agents:** Carbon dioxide or dry chemical for small fires, ordinary foam for large fires
6.4 **Fire Extinguishing Agents Not to be Used:** Water may be ineffective
6.5 **Special Hazards of Combustion Products:** *Not pertinent*
6.6 **Behavior in Fire:** Vapor is heavier than air and may travel a considerable distance to a source of ignition and flash back
6.7 **Ignition Temperature:** 997°F
6.8 **Electrical Hazard:** Class I, Group D
6.9 **Burning Rate:** 5.7 mm/min
6.10 **Adiabatic Flame Temperature.** Data not available

(Continued)

7 CHEMICAL REACTIVITY

7.1 **Reactivity With Water:** No reaction
7.2 **Reactivity with Common Materials:** No reaction
7.3 **Stability During Transport:** Stable
7.4 **Neutralizing Agents for Acids and Caustics:** Not pertinent
7.5 **Polymerization:** Not pertinent
7.6 **Inhibitor of Polymerization:** Not pertinent
7.7 **Molar Ratio (Reactant to Product):** Data not available
7.8 **Reactivity Group:** 32

8. WATER POLLUTION

8.1 **Aquatic Toxicity:** 1180 mg/l/96 hr/sunfish/TL_m/fresh water
8.2 **Waterfowl Toxicity:** Data not available
8.3 **Biological Oxygen Demand (BOD):** 0%, 5 days; 38% (theor), 8 days
8.4 **Food Chain Concentration Potential:** None

9. SHIPPING INFORMATION

9.1 **Grades of Purity:** Research, reagent, nitration-all 99 8 + %, industrial contains 94 + %, with 5% xylene and small amounts of benzene and nonaromatic hydrocarbons, 90/120 less pure than industrial
9.2 **Storage Temperature:** Ambient
9.3 **Inert Atmosphere** No requirement
9.4 **Venting:** Open (flame arrester) or pressure-vacuum

10. HAZARD ASSESSMENT CODE

(See Hazard Assessment Handbook)

A-T-U

11. HAZARD CLASSIFICATIONS

11.1 **Code of Federal Regulations:** Flammable liquid
11.2 **NAS Hazard Rating for Bulk Water Transportation:**

Category	Rating
Fire	3
Health	
Vapor Irritant	1
Liquid or Solid Irritant	1
Poisons	2
Water Pollution	
Human Toxicity	1
Aquatic Toxicity	3
Aesthetic Effect	2
Reactivity	
Other Chemicals	1
Water	0
Self Reaction	0

11.3 ***NFPA Hazard Classification:***

Category	Classification
Health Hazard (Blue)	2
Flammability (Red)	3
Reactivity (Yellow)	0

12. PHYSICAL AND CHEMICAL PROPERTIES

12.1 **Physical State at 15°C and 1 atm:** Liquid
12.2 **Molecular Weight:** 92.14
12.3 **Boiling Point at 1 atm:** 231.1°F = 110.6°C = 383.8°K
12.4 **Freezing Point:** —139°F = —95 0°C = 178 2°K
12.5 **Critical Temperature:** 605.4°F = 318 6°C = 591 8°K
12.6 **Critical Pressure:** 596 1 psia = 40.55 atm = 4.108 MN/m^2
12.7 **Specific Gravity:** 0.867 at 20°C (liquid)
12.8 **Liquid Surface Tension:** 29.0 dynes/cm = 0.0290 N/m at 20°C
12.9 **Liquid Water Interfacial Tension:** 36 1 dynes/cm = 0.0361 N/m at 25°C
12.10 **Vapor (Gas) Specific Gravity:** Not pertinent
12.11 **Ratio of Specific Heats of Vapor (Gas):** 1 089
12.12 **Latent Heat of Vaporization:** 155 Btu/lb = 86.1 cal/g = 3 61 X 10^5 J/kg
12.13 **Heat of Combustion:** —17,430 Btu/lb = —9686 cal/g = —405.5 X 10^5 J/kg
12.14 ***Heat of Decomposition:*** *Not pertinent*
12.15 **Heat of Solution:** Not pertinent
12.16 **Heat of Polymerization:** Not pertinent
12.25 **Heat of Fusion:** 17 17 cal/g
12.26 **Limiting Value:** Data not available
12.27 **Reid Vapor Pressure:** 1.1 psia

6. FIRE HAZARDS (Continued)

6.11 **Stoichiometric Air to Fuel Ratio:** Data not available
6.12 **Flame Temperature:** Data not available

TOLUENE

12.17 SATURATED LIQUID DENSITY

Temperature (degrees F)	Pounds per cubic foot
—30	57.180
—20	56.870
—10	56.550
0	56.240
10	55.930
20	55.620
30	55.310
40	54.990
50	54.680
60	54.370
70	54.060
80	53.750
90	53.430
100	53.120
110	52.810
120	52.500

12.18 LIQUID HEAT CAPACITY

Temperature (degrees F)	British thermal unit per pound-F
0	.396
5	.397
10	.399
15	.400
20	.402
25	.403
30	.404
35	.406
40	.407
45	.409
50	.410
55	.411
60	.413
65	.414
70	.415
75	.417
80	.418
85	.420
90	.421
95	.422
100	.424
105	.425
110	.427
115	.428
120	.429
125	.431

12.19 LIQUID THERMAL CONDUCTIVITY

Temperature (degrees F)	British thermal unit-inch per hour-square foot-F
0	1.026
10	1.015
20	1.005
30	.994
40	.983
50	.972
60	.962
70	.951
80	.940
90	.929
100	.919
110	.908
120	.897
130	.886
140	.876
150	.865
160	.854
170	.843
180	.833
190	.822
200	.811
210	.800

12.20 LIQUID VISCOSITY

Temperature (degrees F)	Centipoise
0	1.024
5	.978
10	.935
15	.894
20	.857
25	.821
30	.788
35	.757
40	.727
45	.700
50	.673
55	.649
60	.625
65	.603
70	.582
75	.562
80	.544
85	.526
90	.509
95	.493
100	.477

12.21 SOLUBILITY IN WATER

Temperature (degrees F)	Pounds per 100 pounds of water
68.02	.050

12.22 SATURATED VAPOR PRESSURE

Temperature (degrees F)	Pounds per square inch
0	.038
10	.057
20	.084
30	.121
40	.172
50	.241
60	.331
70	.449
80	.600
90	.792
100	1.033
110	1.332
120	1.700
130	2.148
140	2.690
150	3.338
160	4.109
170	5.018
180	6.083
190	7.323
200	8.758
210	10.410

12.23 SATURATED VAPOR DENSITY

Temperature (degrees F)	Pounds per cubic foot
0	.00070
10	.00103
20	.00150
30	.00212
40	.00296
50	.00405
60	.00547
70	.00727
80	.00954
90	.01237
100	.01584
110	.02007
120	.02518
130	.03127
140	.03850
150	.04700
160	.05691
170	.06840
180	.08162
190	.09675
200	.11400
210	.13340

12.24 IDEAL GAS HEAT CAPACITY

Temperature (degrees F)	British thermal unit per pound-F
0	.228
25	.241
50	.255
75	.268
100	.281
125	.294
150	.306
175	.319
200	.331
225	.343
250	.355
275	.367
300	.378
325	.389
350	.400
375	.411
400	.422
425	.432
450	.443
475	.453
500	.462
525	.472
550	.482
575	.491
600	.500

ETHYLBENZENE

ETB

Common Synonyms

Phenylethane
EB

Liquid — Colorless — Sweet gasoline-like odor

Floats on water Flammable, irritating vapor is produced

Avoid contact with liquid and vapor Keep people away
Wear goggles, self-contained breathing apparatus, and rubber overclothing (including gloves)
Shut off ignition sources and call fire department
Stop discharge if possible
Stay upwind and use water spray to knock down vapor
Isolate and remove discharged material
Notify local health and pollution control agencies

Fire

FLAMMABLE
Flashback along vapor trail may occur.
Vapor may explode if ignited in an enclosed area
Wear goggles, self contained breathing apparatus, and rubber overclothing (including gloves)
Extinguish with dry chemical, foam or carbon dioxide
Water may be ineffective on fire
Cool exposed containers with water

Exposure

CALL FOR MEDICAL AID

VAPOR
Irritating to eyes, nose and throat
If inhaled, will cause dizziness or difficult breathing
Move to fresh air
If breathing has stopped give artificial respiration
If breathing is difficult, give oxygen

LIQUID
Will burn skin and eyes
Harmful if swallowed
Remove contaminated clothing and shoes
Flush affected areas with plenty of water
IF IN EYES, hold eyelids open and flush with plenty of water
IF SWALLOWED and victim is CONSCIOUS, have victim drink water or milk
DO NOT INDUCE VOMITING

Water Pollution

HARMFUL TO AQUATIC LIFE IN VERY LOW CONCENTRATIONS
Fouling to shoreline
May be dangerous if it enters water intakes

Notify local health and wildlife officials
Notify operators of nearby water intakes

1. RESPONSE TO DISCHARGE

(See Response Methods Handbook)

Mechanical containment
Should be removed
Chemical and physical treatment

2. LABEL

2.1 **Category:** Flammable liquid
2.2 **Class:** 3

3 CHEMICAL DESIGNATIONS

3.1 **CG Compatibility Class:** Aromatic hydrocarbon
3.2 **Formula:** $C_6H_5CH_2CH_3$
3.3 **IMO/UN Designation:** 3 3/1175
3.4 **DOT ID No.:** 1175
3.5 **CAS Registry No.:** 100-41-4

4. OBSERVABLE CHARACTERISTICS

4.1 **Physical State (as shipped):** Liquid
4.2 **Color:** Colorless
4.3 **Odor:** Aromatic

5 HEALTH HAZARDS

5.1 **Personal Protective Equipment:** Self-contained breathing apparatus, safety goggles
5.2 **Symptoms Following Exposure:** Inhalation may cause irritation of nose, dizziness, depression Moderate irritation of eye with corneal injury possible Irritates skin and may cause blisters
5.3 **Treatment of Exposure:** INHALATION if ill effects occur, remove victim to fresh air, keep him warm and quiet, and get medical help promptly, if breathing stops, give artificial respiration. INGESTION induce vomiting only upon physician's approval, material in lung may cause chemical pneumonitis SKIN AND EYES: promptly flush with plenty of water (15 min for eyes) and get medical attention, remove and wash contaminated clothing before reuse
5.4 **Threshold Limit Value:** 100 ppm
5.5 **Short Term Inhalation Limits:** 200 ppm for 30 min
5.6 **Toxicity by Ingestion:** Grade 2, LD_{50} = 0 5 to 5 g/kg (rat)
5.7 **Late Toxicity:** Data not available
5.8 **Vapor (Gas) Irritant Characteristics:** Vapors cause moderate irritation such that personnel will find high concentrations unpleasant The effect is temporary
5.9 **Liquid or Solid Irritant Characteristics:** Causes smarting of the skin and first-degree burns on short exposure; may cause secondary burns on long exposure
5.10 **Odor Threshold:** 140 ppm
5.11 **IDLH Value:** 2,000 ppm

6. FIRE HAZARDS

6.1 **Flash Point** 80°F O C , 59°F C C
6.2 **Flammable Limits in Air:** 1 0%-6 7%
6.3 **Fire Extinguishing Agents:** Foam (most effective), water fog, carbon dioxide or dry chemical
6.4 **Fire Extinguishing Agents Not to be Used** Not pertinent
6.5 **Special Hazards of Combustion Products.** Irritating vapors are generated when heated
6.6 **Behavior in Fire:** Vapor is heavier than air and may travel considerable distance to the source of ignition and flash back
6.7 **Ignition Temperature:** 860°F
6.8 **Electrical Hazard:** Not pertinent
6.9 **Burning Rate:** 5 8 mm/min
6.10 **Adiabatic Flame Temperature** Data Not Available

(Continued)

7 CHEMICAL REACTIVITY

7.1 **Reactivity With Water:** No reaction
7.2 **Reactivity with Common Materials** No reaction
7.3 **Stability During Transport:** Stable
7.4 **Neutralizing Agents for Acids and Caustics:** Not pertinent
7.5 **Polymerization:** Not pertinent
7.6 **Inhibitor of Polymerization:** Not pertinent
7.7 **Molar Ratio (Reactant to Product):** Data Not Available
7.8 **Reactivity Group:** 32

8. WATER POLLUTION

8.1 **Aquatic Toxicity:** 29 ppm/96 hr/bluegill/TL_m/fresh water
8.2 **Waterfowl Toxicity:** Data not available
8.3 **Biological Oxygen Demand (BOD):** 2.8% (theor), 5 days
8.4 **Food Chain Concentration Potential:** None

9. SHIPPING INFORMATION

9.1 **Grades of Purity:** Research grade 99 98%, pure grade 99 5%, technical grade, 99.0%
9.2 **Storage Temperature:** Ambient
9.3 **Inert Atmosphere:** No requirement
9.4 **Venting:** Open (flame arrester) or pressure-vacuum

6 FIRE HAZARDS (Continued)

6.11 **Stoichiometric Air to Fuel Ratio:** Data Not Available
6.12 **Flame Temperature:** Data Not Available

10. HAZARD ASSESSMENT CODE

(See Hazard Assessment Handbook)

A-T-U

11 HAZARD CLASSIFICATIONS

11.1 **Code of Federal Regulations:** Flammable liquid
11.2 **NAS Hazard Rating for Bulk Water Transportation:**

Category	Rating
Fire	3
Health	
Vapor Irritant	2
Liquid or Solid Irritant	2
Poisons	2
Water Polution	
Human Toxicity	1
Aquatic Toxicity	3
Aesthetic Effect	2
Reactivity	
Other Chemicals	1
Water	0
Self Reaction	0

11.3 **NFPA Hazard Classification:**

Category	Classification
Health Hazard (Blue)	2
Flammability (Red)	3
Reactivity (Yellow)	0

12. PHYSICAL AND CHEMICAL PROPERTIES

12.1 **Physical State at 15°C and 1 atm:** Liquid
12.2 **Molecular Weight:** 106 17
12.3 **Boiling Point at 1 atm:** 277.2°F = 136 2°C = 409 4°K
12.4 **Freezing Point:** —139°F = —95°C = 178°K
12.5 **Critical Temperature:** 651 0°F = 343.9°C = 617.1°K
12.6 **Critical Pressure:** 523 psia = 35 6 atm = 3 61 MN/m^2
12.7 **Specific Gravity:** 0.867 at 20°C (liquid)
12.8 **Liquid Surface Tension:** 29 2 dynes/cm = 0 0292 N/m at 20°C
12.9 **Liquid Water Interfacial Tension:** 35 48 dynes/cm = 0 03548 N/m at 20°C
12.10 **Vapor (Gas) Specific Gravity:** Not pertinent
12.11 **Ratio of Specific Heats of Vapor (Gas):** 1.071
12.12 **Latent Heat of Vaporization:** 144 Btu/lb = 80.1 cal/g = 3 35 X 10^5 J/kg
12.13 **Heat of Combustion:** —17,780 Btu/lb = —9877 cal/g = —413.5 X 10^5 J/kg
12.14 **Heat of Decomposition:** Not pertinent
12.15 **Heat of Solution:** Not pertinent
12.16 **Heat of Polymerization:** Not pertinent
12.25 **Heat of Fusion:** Data Not Available
12.26 **Limiting Value:** Data Not Available
12.27 **Reid Vapor Pressure:** 0 4 psia

ETHYLBENZENE

12.17
SATURATED LIQUID DENSITY

Temperature (degrees F)	Pounds per cubic foot
40	54.990
50	54.680
60	54.370
70	54.060
80	53.750
90	53.430
100	53.120
110	52.810
120	52.500
130	52.190
140	51.870
150	51.560
160	51.250
170	50.940
180	50.620
190	50.310
200	50.000
210	49.690

12.18
LIQUID HEAT CAPACITY

Temperature (degrees F)	British thermal unit per pound-F
40	.402
50	.404
60	.407
70	.409
80	.412
90	.414
100	.417
110	.419
120	.421
130	.424
140	.426
150	.429
160	.431
170	.434
180	.436
190	.439
200	.441
210	.443

12.19
LIQUID THERMAL CONDUCTIVITY

Temperature (degrees F)	British thermal unit-inch per hour-square foot-F
-90	1.065
-80	1.056
-70	1.047
-60	1.037
-50	1.028
-40	1.018
-30	1.009
-20	1.000
-10	.990
0	.981
10	.971
20	.962
30	.953
40	.943
50	.934
60	.924
70	.915
80	.906
90	.896
100	.887
110	.877
120	.868
130	.859
140	.849
150	.840
160	.830

12.20
LIQUID VISCOSITY

Temperature (degrees F)	Centipoise
40	.835
50	.774
60	.719
70	.670
80	.626
90	.586
100	.550
110	.518
120	.488
130	.461
140	.436
150	.414
160	.393
170	.374
180	.356
190	.340
200	.325
210	.311

12.21
SOLUBILITY IN WATER

Temperature (degrees F)	Pounds per 100 pounds of water
68.02	.020

12.22
SATURATED VAPOR PRESSURE

Temperature (degrees F)	Pounds per square inch
80	.202
100	.370
120	.644
140	1.071
160	1.713
180	2.643
200	3.953
220	5.747
240	8.147
260	11.290
280	15.320
300	20.410
320	26.730
340	34.460
360	43.800
380	54.950

12.23
SATURATED VAPOR DENSITY

Temperature (degrees F)	Pounds per cubic foot
80	.00370
100	.00654
120	.01099
140	.01767
160	.02734
180	.04087
200	.05926
220	.08363
240	.11520
260	.15510
280	.20490
300	.26570
320	.33910
340	.42620
360	.52850
380	.64720

12.24
IDEAL GAS HEAT CAPACITY

Temperature (degrees F)	British thermal unit per pound-F
-400	-.007
-350	.026
-300	.060
-250	.093
-200	.125
-150	.157
-100	.187
-50	.217
0	.246
50	.274
100	.301
150	.327
200	.353
250	.377
300	.401
350	.424
400	.446
450	.467
500	.487
550	.507
600	.525

m-XYLENE

XLM

Common Synonyms

1, 3-Dimethylbenzene
Xylol

Watery liquid | Colorless | Sweet odor

Floats on water. Flammable, irritating vapor is produced

Stop discharge if possible. Keep people away
Call fire department
Avoid contact with liquid and vapor.
Isolate and remove discharged material
Notify local health and pollution control agencies

Fire

FLAMMABLE
Flashback along vapor trail may occur
Vapor may explode if ignited in an enclosed area
Wear self-contained breathing apparatus
Extinguish with foam, dry chemical, or carbon dioxide
Water may be ineffective on fire
Cool exposed containers with water

Exposure

CALL FOR MEDICAL AID

VAPOR
Irritating to eyes, nose, and throat.
If inhaled, will cause headache, difficult breathing, or loss of consciousness.
Move to fresh air.
If breathing has stopped, give artificial respiration
If breathing is difficult, give oxygen

LIQUID
Irritating to skin and eyes
If swallowed, will cause nausea, vomiting, or loss of consciousness
Remove contaminated clothing and shoes
Flush affected areas with plenty of water
IF IN EYES, hold eyelids open and flush with plenty of water
IF SWALLOWED and victim is CONSCIOUS, have victim drink water or milk.
DO NOT INDUCE VOMITING

Water Pollution

HARMFUL TO AQUATIC LIFE IN VERY LOW CONCENTRATIONS
Fouling to shoreline
May be dangerous if it enters water intakes

Notify local health and wildlife officials
Notify operators of nearby water intakes

1. RESPONSE TO DISCHARGE

(See Response Methods Handbook)

Issue warning-high flammability
Evacuate area
Should be removed
Chemical and physical treatment

2. LABEL

2.1 **Category:** Flammable liquid
2.2 **Class:** 3

3. CHEMICAL DESIGNATIONS

3.1 **CG Compatibility Class:** Aromatic Hydrocarbon
3.2 **Formula:** $m\text{-}C_6H_4(CH_3)_2$
3.3 **IMO/UN Designation:** 3.2/1307
3.4 **DOT ID No.:** 1307
3.5 **CAS Registry No.:** 108-38-3

4. OBSERVABLE CHARACTERISTICS

4.1 **Physical State (as shipped):** Liquid
4.2 **Color:** Colorless
4.3 **Odor:** Like benzene, characteristic aromatic

5. HEALTH HAZARDS

5.1 **Personal Protective Equipment:** Approved canister or air-supplied mask; goggles or face shield, plastic gloves and boots.
5.2 **Symptoms Following Exposure:** Vapors cause headache and dizziness. Liquid irritates eyes and skin. If taken into lungs, causes severe coughing, distress, and rapidly developing pulmonary edema. If ingested, causes nausea, vomiting, cramps, headache, and coma, can be fatal. Kidney and liver damage can occur
5.3 ***Treatment of Exposure:*** INHALATION: remove to fresh air; administer artificial respiration and oxygen if required; call a doctor. INGESTION: do NOT induce vomiting, call a doctor. EYES: flush with water for at least 15 min. SKIN: wipe off, wash with soap and water.
5.4 **Threshold Limit Value:** 100 ppm
5.5 **Short Term Inhalation Limits:** 300 ppm for 30 min
5.6 **Toxicity by Ingestion:** Grade 3, LD_{50} = 50 to 500 g/kg
5.7 **Late Toxicity:** Kidney and liver damage
5.8 **Vapor (Gas) Irritant Characteristics:** Vapors cause a slight smarting of the eyes or respiratory system if present in high concentrations. The effect is temporary.
5.9 **Liquid or Solid Irritant Characteristics:** Minimum hazard. If spilled on clothing and allowed to remain, may cause smarting and reddening of the skin.
5.10 **Odor Threshold:** 0.05 ppm
5.11 **IDLH Value:** 10,000 ppm

6. FIRE HAZARDS

6.1 **Flash Point:** 64°F C.C.
6.2 **Flammable Limits in Air:** 1.1%-6.4%
6.3 **Fire Extinguishing Agents:** Foam, dry chemical, or carbon dioxide
6.4 **Fire Extinguishing Agents Not to be Used:** Water may be ineffective.
6.5 **Special Hazards of Combustion Products:** Not pertinent
6.6 **Behavior in Fire.** Vapor is heavier than air and may travel considerable distance to a source of ignition and flash back
6.7 **Ignition Temperature:** 986°F
6.8 **Electrical Hazard:** Class I, Group D
6.9 **Burning Rate:** 5.8 mm/min
6.10 **Adiabatic Flame Temperature:** Data not available
6.11 **Stoichiometric Air to Fuel Ratio:** Data not available
6.12 **Flame Temperature:** Data not available

7. CHEMICAL REACTIVITY

7.1 **Reactivity With Water:** No reaction
7.2 **Reactivity with Common Materials:** No reaction
7.3 **Stability During Transport:** Stable
7.4 **Neutralizing Agents for Acids and Caustics:** Not pertinent
7.5 **Polymerization:** Not pertinent
7.6 **Inhibitor of Polymerization.** Not pertinent
7.7 **Molar Ratio (Reactant to Product):** Data not available
7.8 **Reactivity Group:** 32

8. WATER POLLUTION

8.1 **Aquatic Toxicity:** 22 ppm/96 hr/bluegill/TL_m/fresh water
8.2 **Waterfowl Toxicity:** Data not available
8.3 **Biological Oxygen Demand (BOD):** 0 lb/lb, 5 days, 0% (theor.), 8 days
8.4 **Food Chain Concentration Potential.** Data not available

9. SHIPPING INFORMATION

9.1 **Grades of Purity:** Research 99.99%, Pure 99.9%; Technical 99.2%
9.2 **Storage Temperature:** Ambient
9.3 **Inert Atmosphere:** No requirement
9.4 **Venting:** Open (flame arrester) or pressure-vacuum

10. HAZARD ASSESSMENT CODE

(See Hazard Assessment Handbook)

A-T-U

11. HAZARD CLASSIFICATIONS

11.1 **Code of Federal Regulations:** Flammable liquid
11.2 **NAS Hazard Rating for Bulk Water Transportation:**

Category	Rating
Fire	3
Health	
Vapor Irritant	1
Liquid or Solid Irritant	1
Poisons	2
Water Pollution	
Human Toxicity	1
Aquatic Toxicity	3
Aesthetic Effect	2
Reactivity	
Other Chemicals	1
Water	0
Self Reaction	0

11.3 **NFPA Hazard Classification:**

Category	Classification
Health Hazard (Blue)	2
Flammability (Red)	3
Reactivity (Yellow)	0

12. PHYSICAL AND CHEMICAL PROPERTIES

12.1 **Physical State at 15°C and 1 atm:** Liquid
12.2 **Molecular Weight:** 106.16
12.3 **Boiling Point at 1 atm:** 269.4°F = 131.9°C = 405.1°K
12.4 **Freezing Point:** −54.2°F = −47.9°C = 225.3°K
12.5 **Critical Temperature:** 650.8°F = 343.8°C = 617.0°K
12.6 **Critical Pressure:** 513.8 atm = 34.95 psia = 3.540 MN/m^2
12.7 **Specific Gravity:** 0.864 at 20°C (liquid)
12.8 **Liquid Surface Tension.** 28.6 dynes/cm = 0.0286 N/m at 20°C
12.9 **Liquid Water Interfacial Tension.** 36.4 dynes/cm = 0.0364 N/m at 30°C
12.10 **Vapor (Gas) Specific Gravity:** Not pertinent
12.11 **Ratio of Specific Heats of Vapor (Gas):** 1.071
12.12 **Latent Heat of Vaporization:** 147 Btu/lb = 81.9 cal/g = 3.43×10^5 J/kg
12.13 **Heat of Combustion:** −17,554 Btu/lb = −9752.4 cal/g = -408.31×10^5 J/kg
12.14 **Heat of Decomposition.** Not pertinent
12.15 **Heat of Solution:** Not pertinent
12.16 **Heat of Polymerization:** Not pertinent
12.25 **Heat of Fusion:** 26.01 cal/g
12.26 **Limiting Value:** Data not available
12.27 **Reid Vapor Pressure:** 0.34 psia

NOTES

XLM

m-XYLENE

12.17 SATURATED LIQUID DENSITY

Temperature (degrees F)	Pounds per cubic foot
15	55.400
20	55.260
25	55.130
30	54.990
35	54.850
40	54.710
45	54.570
50	54.430
55	54.290
60	54.160
65	54.020
70	53.880
75	53.740
80	53.600
85	53.460
90	53.320
95	53.180
100	53.050

12.18 LIQUID HEAT CAPACITY

Temperature (degrees F)	British thermal unit per pound-F
40	.387
50	.393
60	.398
70	.404
80	.410
90	.415
100	.421
110	.426
120	.432
130	.437
140	.443
150	.448
160	.454
170	.460
180	.465
190	.471
200	.476
210	.482

12.19 LIQUID THERMAL CONDUCTIVITY

Temperature (degrees F)	British thermal unit-inch per hour-square foot-F
35	.962
40	.953
45	.944
50	.935
55	.926
60	.917
65	.908
70	.899
75	.890
80	.881
85	.873
90	.864
95	.855
100	.846

12.20 LIQUID VISCOSITY

Temperature (degrees F)	Centipoise
15	.938
20	.898
25	.862
30	.827
35	.794
40	.764
45	.735
50	.708
55	.682
60	658
65	.635
70	.613
75	.592
80	.572
85	.554

12.21 SOLUBILITY IN WATER

Temperature (degrees F)	Pounds per 100 pounds of water
	INSOLUBLE

12.22 SATURATED VAPOR PRESSURE

Temperature (degrees F)	Pounds per square inch
60	.090
70	.127
80	.177
90	.242
100	.326
110	.434
120	.571
130	.743
140	.956
150	1.219
160	1.538
170	1.924
180	2.388
190	2.939
200	3.590
210	4.355
220	5.247
230	6.282
240	7.476
250	8.846
260	10.410

12.23 SATURATED VAPOR DENSITY

Temperature (degrees F)	Pounds per cubic foot
60	.00172
70	.00238
80	.00324
90	.00435
100	.00577
110	.00754
120	.00975
130	.01247
140	.01577
150	.01977
160	.02455
170	.03023
180	.03691
190	.04473
200	.05382
210	.06431
220	.07635
230	.09009
240	.10570
250	.12330
260	.14310

12.24 IDEAL GAS HEAT CAPACITY

Temperature (degrees F)	British thermal unit per pound-F
0	.247
25	.260
50	.273
75	.286
100	.299
125	.311
150	.324
175	.336
200	.348
225	.360
250	.371
275	.383
300	.394
325	.406
350	.417
375	.427
400	.438
425	.449
450	.459
475	.469
500	.479
525	.489
550	.499
575	.508
600	.517

PROPANE

PRP

Common Synonyms
Dimethylmethane

Liquefied compressed gas　Colorless　Odorless may have skunk odor added

Liquid floats and boils on water　Flammable visible vapor cloud is produced

Stop discharge if possible　Keep people away
Shut off ignition sources and call fire department
Stay upwind and use water spray to "knock down" vapor
Notify local health and pollution control agencies

Fire

FLAMMABLE
Containers may explode in fire
Flashback along vapor trail may occur
Vapor may explode if ignited in an enclosed area
Stop flow of gas if possible
Cool exposed containers and protect men effecting shut off with water
Let fire burn

Exposure

CALL FOR MEDICAL AID

VAPOR
Not irritating to eyes, nose or throat
If inhaled, will cause dizziness, difficult breathing, or loss of consciousness
Move to fresh air
If breathing has stopped, give artificial respiration
If breathing is difficult, give oxygen

LIQUID
May cause frostbite
Flush affected areas with plenty of water
DO NOT RUB AFFECTED AREAS

Water Pollution

Not harmful to aquatic life

1. RESPONSE TO DISCHARGE

(See Response Methods Handbook)
Issue warning-high flammability
Restrict access
Evacuate area

2. LABEL

2.1 **Category:** Flammable gas
2.2 **Class:** 2

3. CHEMICAL DESIGNATIONS

3.1 **CG Compatibility Class:** Paraffin
3 2 **Formula:** $CH_3CH_2CH_3$
3.3 **IMO/UN Designation:** 2 0/1978
3 4 **DOT ID No.:** 1978
3 5 **CAS Registry No :** 74 98 6

4. OBSERVABLE CHARACTERISTICS

4 1 **Physical State (as shipped):** Liquefied compressed gas
4.2 **Color:** Colorless
4.3 **Odor:** Faint gassy

5. HEALTH HAZARDS

5 1 **Personal Protective Equipment:** Self-contained breathing apparatus for high concentrations of gas
5.2 **Symptoms Following Exposure:** Vaporizing liquid may cause frostbite　Concentrations in air greater than 10% cause dizziness in a few minutes　1% concentrations give the same effect in 10 min　High concentrations cause asphyxiation
5 3 **Treatment of Exposure:** Remove to open air　If victim is overcome by gas, apply artificial respiration　Guard against self-injury if confused
5.4 **Threshold Limit Value:** Asphyxiant
5.5 **Short Term Inhalation Limits:** Data not available
5.6 **Toxicity by Ingestion:** Not pertinent
5 7 **Late Toxicity:** None
5 8 **Vapor (Gas) Irritant Characteristics:** Vapors are nonirritating to the eyes and throat
5 9 **Liquid or Solid Irritant Characteristics:** No appreciable hazard. Practically harmless to the skin because it evaporates quickly
5.10 **Odor Threshold.** 5,000-20,000 ppm
5.11 **IDLH Value:** 20,000 ppm

6. FIRE HAZARDS

6 1 **Flash Point.** —156°F C C
6 2 **Flammable Limits in Air:** 2 1%-9.5%
6.3 **Fire Extinguishing Agents.** Stop flow of gas　For small fires use dry chemicals　Cool adjacent areas with water spray.
6.4 **Fire Extinguishing Agents Not to be Used:** Water
6.5 **Special Hazards of Combustion Products:** Not pertinent
6.6 **Behavior in Fire:** Containers may explode　Vapor is heavier than air and may travel a long distance to a source of ignition and flash back
6.7 **Ignition Temperature:** 842°F
6 8 **Electrical Hazard:** Class I, Group D
6 9 **Burning Rate:** 8 2 mm/min
6 10 **Adiabatic Flame Temperature:** 2419 (Est)

(Continued)

7 CHEMICAL REACTIVITY

7.1 **Reactivity With Water:** No reaction
7.2 **Reactivity with Common Materials:** No reaction
7.3 **Stability During Transport:** Stable
7.4 **Neutralizing Agents for Acids and Caustics:** Not pertinent
7.5 **Polymerization:** Not pertinent
7.6 **Inhibitor of Polymerization:** Not pertinent
7.7 **Molar Ratio (Reactant to Product)** Data not available
7.8 **Reactivity Group:** 31

8. WATER POLLUTION

8.1 **Aquatic Toxicity:** None
8.2 **Waterfowl Toxicity:** None
8.3 **Biological Oxygen Demand (BOD):** None
8.4 **Food Chain Concentration Potential:** None

9. SHIPPING INFORMATION

9.1 **Grades of Purity:** Research, instrument, or Pure. 99.35+ % Technical. 97.50 %
9.2 **Storage Temperature:** Ambient
9.3 **Inert Atmosphere:** No requirement
9.4 **Venting:** Safety relief

10 HAZARD ASSESSMENT CODE

(See Hazard Assessment Handbook)

A-B-C-D-E-F-G

11. HAZARD CLASSIFICATIONS

11.1 **Code of Federal Regulations:** Flammable gas
11.2 **NAS Hazard Rating for Bulk Water Transportation:**

Category	Rating
Fire	4
Health	
Vapor Irritant	0
Liquid or Solid Irritant	0
Poisons	0
Water Polution	
Human Toxicity	0
Aquatic Toxicity	0
Aesthetic Effect	0
Reactivity	
Other Chemicals	0
Water	0
Self Reaction	0

11.3 **NFPA Hazard Classification:**

Category	Classification
Health Hazard (Blue)	1
Flammability (Red)	4
Reactivity (Yellow)	0

12. PHYSICAL AND CHEMICAL PROPERTIES

12.1 **Physical State at 15°C and 1 atm:** Gas
12.2 **Molecular Weight:** 44 09
12.3 **Boiling Point at 1 atm:** —43.8°F = —42 1°C = 231.1°K
12.4 **Freezing Point:** —305 9°F = —187.7°C = 85.5°K
12.5 **Critical Temperature:** 206 0°F = 96.67°C = 369.67°K
12.6 **Critical Pressure:** 616.5 psia = 41.94 atm = 4 249 MN/m^2
12.7 **Specific Gravity:** 0.590 at —50°C (liquid)
12.8 **Liquid Surface Tension:** 16 dynes/cm = 0 016 N/m at -47°C
12.9 **Liquid Water Interfacial Tension:** (est) 50 dynes/cm = 0 05 N/m at —50°C
12.10 **Vapor (Gas) Specific Gravity:** 1 5
12.11 **Ratio of Specific Heats of Vapor (Gas):** 1.130
12 12 **Latent Heat of Vaporization:** 183 2 Btu/lb = 101 8 cal/g = 4 262 X 10^5 J/kg
12.13 **Heat of Combustion** —19,782 Btu/lb = —10,990 cal/g = —460 13 X 10^5 J/kg
12.14 **Heat of Decomposition:** Not pertinent
12.15 **Heat of Solution:** Not pertinent
12.16 **Heat of Polymerization:** Not pertinent
12.25 **Heat of Fusion:** Data not available
12.26 **Limiting Value:** Data not available
12.27 **Reid Vapor Pressure:** 190 psia

6. FIRE HAZARDS (Continued)

6.11 **Stoichiometric Air to Fuel Ratio:** 15.60 (Est)
6.12 **Flame Temperature:** Data not available

JUNE 1985

PRP

PROPANE

12.17
SATURATED LIQUID DENSITY

Temperature (degrees F)	Pounds per cubic foot
—180	41 480
—175	41.290
—170	41.100
—165	40.910
—160	40.720
—155	40.530
—150	40 340
—145	40 150
—140	39 960
—135	39 770
—130	39.580
—125	39.390
—120	39.190
—115	39.000
—110	38.810
—105	38.620
—100	38.430
—95	38.240
—90	38.050
—85	37.860
—80	37.670
—75	37.480
—70	37.290
—65	37.100
—60	36.910
—55	36.720

12.18
LIQUID HEAT CAPACITY

Temperature (degrees F)	British thermal unit per pound-F
—50	.546

12.19
LIQUID THERMAL CONDUCTIVITY

Temperature (degrees F)	British thermal unit-inch per hour-square foot-F
	NOT PERTINENT

12.20
LIQUID VISCOSITY

Temperature (degrees F)	Centipoise
—145	433
—140	.413
—135	.395
—130	.378
—125	.362
—120	.347
—115	.333
—110	.321
—105	.309
—100	.297
—95	287
—90	.277
—85	.268
—80	259
—75	251
—70	.243
—65	.236
—60	.229
—55	.222
—50	.216
—45	210

12.21
SOLUBILITY IN WATER

Temperature (degrees F)	Pounds per 100 pounds of water
	INSOLUBLE

12.22
SATURATED VAPOR PRESSURE

Temperature (degrees F)	Pounds per square inch
—230	002
—220	.004
—210	.009
—200	.019
—190	039
—180	.074
—170	.134
—160	.230
—150	.380
—140	.605
—130	.931
—120	1.393
—110	2.029
—100	2.886
—90	4.017
—80	5.480
—70	7.344
—60	9.680
—50	12.570
—40	16.090
—30	20.340
—20	25.400

12.23
SATURATED VAPOR DENSITY

Temperature (degrees F)	Pounds per cubic foot
—230	.00003
—220	00007
—210	.00015
—200	.00031
—190	.00060
—180	.00109
—170	.00190
—160	.00315
—150	.00504
—140	.00777
—130	.01160
—120	01685
—110	02384
—100	.03296
—90	.04463
—80	.05929
—70	.07741
—60	.09948
—50	.12600
—40	.15750
—30	.19440
—20	.23730

12.24
IDEAL GAS HEAT CAPACITY

Temperature (degrees F)	British thermal unit per pound-F
0	.349
25	.365
50	.381
75	.397
100	.413
125	.429
150	.444
175	.459
200	.474
225	.489
250	.504
275	.519
300	.533
325	.548
350	.562
375	.576
400	.590
425	.603
450	.617
475	.630
500	.643
525	.657
550	.669
575	.682
600	.695

ATTACHMENT E

ICE SAFETY/TEST ANALYSIS

SAFETY/TEST ANALYSIS
OF THE BACT-1 MODEL V3
VAPOR RECOVERY SYSTEM

prepared for

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REGISTERED PROFESSIONAL ENGINEER
ARTHUR EDELSTEIN
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QUALITY
STATE OF CALIFORNIA

September, 1990

Arthur Edelstein
Chief Operating Officer

1. INTRODUCTION

The following test program/safety analysis is performed under P.O. #4980 to VR Systems. It describes the potential hazards and the system features that have been incorporated to improve safety and minimize the potential for fire or explosion. It is based on analysis and test of the BACT-1 system, information contained in the operating instructions manual, information in products literature, and conversations with Tom Davis and Dale Henderson of VR Systems.

In addition, system operation was observed at two sites; a tank degassing operation was witnessed at a site in Seal Beach, California and a soil remediation operation was witnessed at a site located at Carmenita and Rosecrans in Norwalk, California.

2. SYSTEM DESCRIPTION

The BACT-1, Model V3 is a system that utilizes a basic internal combustion engine, supplemented with propane gas, to extract and burn vapors from underground gas storage tanks and contaminated soils. After preparing the well head for soil remediation, or the tank for degassing, the BACT-1 system is connected via a 2 or 3 inch hose. Vacuum from the engine creates a pressure differential which extracts the vapors from the tank or from the soil. LPG gas is used to supplement the combustion process and ensure a consistent combustion of the vapors.

The system is process controlled by a KAYE Process Link data acquisition system which provides system monitoring for efficient operation, recording of data and emergency shutdown in the event of a system fault or failure.

The following is a list of system faults which will result in shut down of the system:

a) Engine RPM - The system will shut down if the engine speed is above 300 RPM and the oil pressure is below 40 psi for more than 10 seconds or if the engine speed exceeds 3000 RPM.

b) Oil Pressure - see above.

c) Oil Temperature - The engine will shut down if the oil temperature exceeds 240°F.

d) Coolant Temperature - The system will shut down if the engine coolant temperature exceeds 220°F.

e) Fire - If a fire or excessive temperatures are sensed in the engine compartment, the system will shut down and a fire suppression system is activated.

f) High Water Level - Water in the suction line is separated from the vapors and removed by the water trap. When the water trap is filled to capacity, it can no longer remove the moisture which will be passed into the engine. To prevent this, a level indicator has been installed so that if the water reaches a preset level in the trap, the system will shut down.

g) LPG Disconnect - Vacuum pressure from the engine opens a valve in the LPG filter lock-off which allows the vapors to enter the engine carburetion system. With the vacuum line disconnected, the engine simply runs out of gas and shuts down. Similarly, if the line from the LPG tank is cut or disconnected, the engine will continue to operate only until the remaining gas in the line is consumed.

h) Power Loss - If external 120 V power to the system is lost, the engine will shut down.

i) Battery Voltage - The system will shut down if battery voltage is less than 11.9 volts and the engine speed is greater than 1800 RPM; or if battery voltage is greater than 16.5 volts.

3. CODE COMPLIANCE

It was discovered, in researching the applicable codes and standards for a unique machine like the BACT-1, that there is only limited application to this type of process. Only one, a section prescribing clearances from combustibles for incinerators might apply and is reproduced below.

Uniform Fire Code

Article 11 - General Provisions Against Fire

Section 11.109 - Clearance between incinerators and combustibles. A minimum clearance of 10 feet shall be maintained between incinerators and all rubbish, dry grass, weeds, vegetation and any other combustible material.

Though the above code applies to incinerators the intent is clear and the application can be inferred to any system that generates high temperatures. VR Systems recognizes this and has specified the 10 foot requirement in the operation instructions manual.

4. SUMMARY

The safety/test analysis of the BACT-1 Model V3 system consisted of evaluation and inspections of the system in operating and non operating settings, including start-up and shutdown operations. The review of_the BACT-1 vapor recovery system reveals many good safety features and there appears to be a very low risk of fire or an explosion occurring during routine operation of the equipment. Some of the key safety features and practices taken in the design and system setup are listed in Section 4.1 below.

4.1 Safety Features

4.1.1 Emergency Shutdowns

The system operation parameters and sensor output signals are input to the system computer which trigger system shutdowns.

4.1.2 Static Line

The system is bonded with a static line to reduce the potential for ignition of explosive vapors by static discharge.

4.1.3 Flame Arresters

Flame arresters are employed at the tank connection during degassing and in the engine compartment between the engine intake and vapor filter.

4.1.4 Accessible Operating Instructions

The operating instructions are conveniently mounted in place over the microcontroller area in addition to being contained in the operating instructions manual. These minimize the chances of an operator attempting to operate the machine without instructions if, for example, the operations manual was lost or misplaced.

4.1.5 Low Maintenance

The system requires low maintenance which results in low repair frequency. This reduces the change for human error leading to an unwanted event during start-up, shutdown or maintenance.

4.2 Operational Procedures

The Operational Procedures for VR Systems BACT-1 Model V3, V3C Permitted by SCAQMD pursuant to Rule 1149 Tank Degassing, Rule 1166 Soil Vapor Extraction have been previously reviewed and approved by the Los Angeles Fire Department. They are included in Appendix B for reference.

4.3 Safety Hazards

The BACT-1 system has a proven safety record. Product literature states that over 30,000 hours of accident free service have been performed. As stated earlier, the probability of fire or explosion is very low while the system is operating at steady-state. However, the most likely time for an accident occurs during start-up, shutdown or maintenance as a result of human error.

The operation start-up and shutdown procedures describe, in detail, the proper steps required for safe start-up and shutdown of the system.

As part of the analysis, the following list of questions was formulated to evaluate the hazards associated with non steady-state operation of the system.

a) It is possible for a fire to start after the fire extinguishing system has emptied.

b) Is the system "jimmy proof"? Can the system interlocks be easily bypassed should an operator wish to continue operation with a system fault present?

c) Can the system be restarted after shutdown without system failures being corrected (i.e. by reset)?

d) Does the computer represent a single point failure mode, i.e. could damage to the computer cause system shutdowns to malfunction?

5. DISCUSSION

5.1 Resolution of Safety Hazard Questions

a) Fire Re-start - The volume of dry chemical fire suppressant supplied with the system matches that required by the compartment volume and the expected amount of fuel that would be available to burn in a compartment fire. The likelihood of a second fire starting or a re-start of the initial fire appears very remote.

b) Override of Interlocks - The only way a set point can be modified, which in effect would override the shut down, is to reprogram the computer. This can only be performed by VR Systems.

c) Unauthorized System Re-start - The interlocks and system shutdowns described in Section 2. function as a result of set points being exceeded. In all cases except fire and power failure, the system can be re-started, but the microprocessor will read the same fault and shut down the engine immediately if the fault is not corrected.

d) Computer Failure - If damage to the microprocessor were to occur, it would most likely happen as a result of an outside event external to the system. Damage to the microprocessor could result in a loss of system control.

The parameters necessary for fire or an explosion to occur: ignition source, fuel and oxygen, are not normally present in quantities that present a hazard if system control were lost. The intent of most of the system shutdowns are to prevent damage to the engine. Shut down of the system is a vital step in minimizing the potential for a catastrophic event to occur. It is a reasonable expectation, that because of the sensitivity of the computer to the system faults, that an outside fire or explosion would cause the system to shut down.

5.2 System Shutdown Testing

System testing was performed to verify system shutdown for the system faults specified in Sections 5.2.1 - 5.2.5, below. The test report is contained in Appendix A.

5.2.1 LPG Cutoff

The LPG vacuum line was disconnected to test for engine shutdown.

5.2.2 Power Failure

Engine shutdown was verified during a power failure.

5.2.3 Operating Parameters

Oil pressure and temperature, RPM, battery voltage and coolant temperature values that were out of the specified operating range were input to the system computer to test for shutdown.

5.2.4 Fire

The response of a fire sensor to a fire in the engine compartment was simulated by shorting the wires together which normally close a switch and activate the fire suppression system in addition to shutting down the engine.

5.2.5 Liquid in Suction Line

System shutdown as a result of a high level of water in the water trap was simulated by removing the water level sensor and manually raising the float. As the water level rises, the float rises until it reaches a level which closes a switch and triggers system shutdown.

5.3 Actual System Operation

The operation of the BACT-1 system was witnessed in both modes; a tank degassing process was observed at Seal Beach, CA by NTS personnel and Capt. Jonathan Hall of the L.A.F.D. and soil remediation was observed during some preliminary soil and ground water level testing being performed for VR System customers at a site in Norwalk.

The utilization of static lines was observed. One static line was fed from a reel contained in the BACT-1 unit and connected at the hose/well head union. Another static line was connected opposite the first connection at the well head and clipped to a grounded conduit approximately 25 feet away.

APPENDIX A

SYSTEM SHUTDOWN VERIFICATION TESTING

ABSTRACT

On September 13, 1990 the VR System BACT-1, Model V3 Vapor Extraction System, was tested to verify system shutdown as a result of system faults. In the test, faults were simulated by either manually closing a switch or changing the set points to levels outside the normal operating range, and were input into the system computer. In every case, the computer read the faulty inputs and shut down the system.

I. OBJECTIVE

The objective of the test was to verify the system shutdowns of the VR Systems BACT-1, Model V3 Vapor Extraction System.

II. INTRODUCTION

A BACT-1, Model V3 System, Serial No. 23, was tested at VR Systems, located at 1338 Knollwood Circle, Anaheim, CA. Testing was performed by introducing set points outside the normal operating ranges of the system and verifying that the system would shut down. Emergency shutdowns, as a result of fire and power outage, were verified as well.

The test data was recorded by the system computer printer. A copy of the printed output is provided at the end of the report.

III. TEST RESULTS

A list of the shutdown tests performed and the results are described below:

A. System Operating Parameters Exceeded

1. **Engine Overspeed** - Engine RPM is fed into the computer via coil pulses, much like a tachometer. A set point of 2000 RPM was entered into the microprocessor and the engine RPM was increased above that point. At 2001 RPM the engine shut down.

2. **Low Oil Pressure** - A set pint of 80 psi was entered into the microcontroller. The real operating pressure was 70 psi. This was read as a fault and the system was shut down immediately. It was necessary to test for shutdown at a pressure higher than the normal set point to avoid having to drain oil out of the reservoir and operate the engine with less than the recommended oil in the system.

3. **High Oil Temperature** - The nominal operating oil temperature is approximately 150°F. A set point of 140°F was entered into the system, which resulted in immediate shutdown.

4. **High Engine Coolant Temperature** - The nominal operating coolant temperature is approximately 140°F. A set point of 138°F was entered into the system, which resulted in immediate shutdown.

5. **Low Battery** - Shutdown due to a low battery was demonstrated by checking the charging voltage. A set point of 13.4 volts was entered. The actual amperage was 13.5 volts, which shut down the engine.

B. Water in Suction Line

To simulate a high water level to the system microcontroller, the level sensor was removed and the float switch was manually raised to represent high water level. The engine was shut down.

C. Fire Suppression

The fire suppression system operation was simulated by shorting two sensor wires together, which represents the switch closing after a fire in the engine compartment was sensed. The engine was shut down and would not re-start. This satisfied the two-point requirement of the fire suppression shutdown.

D. LPG Cutoff

LPG cutoff was verified twice. The vacuum line to the filter lock-off was disconnected before startup and during operation. In the first case the engine would not start, and in the second, shutdown resulted in approximately two to three seconds. The two to three second delay was a result of the engine combusting the vapors that remained in the carburetion system after disconnection.

E. Power Failure

Power was removed from the BACT-1 System during operation by disconnecting the 120V plug at the receptacle, at which time the engine shut down.

IV. CONCLUSIONS

The design set points for the operation allow for a 10 point hysteresis on the actual values being monitored. This corresponds to ±10 RPM, ±1 psi, ±1°F, etc. The actual response of the system to faults in testing exceeded these tolerances, as in the overspeed shutdown where the system shut down at 2001 RPM at a set pint of 2000.

Based on the test results discussed in Section III, the system shutdowns do function as stated by the manufacturer, VR Systems, and will terminate the vapor recovery operation under the foreseeable fault conditions as designed.