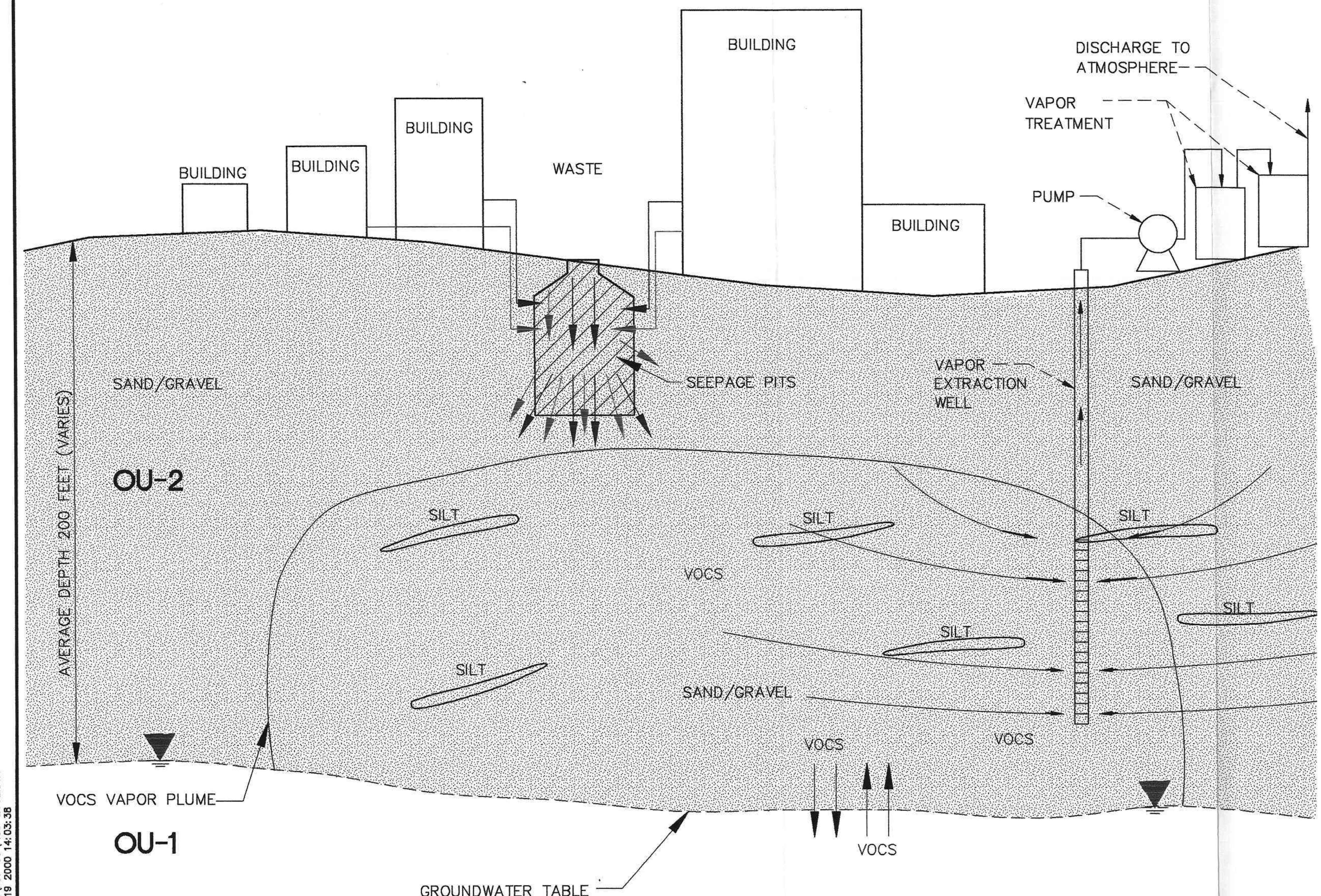
Previous



Explanation

KEY

WATER

VOCS

VOCS VOLATILE ORGANIC COMPOUNDS

NOTES:

1. Contaminants discharged to seepage pits over 30 years ago.
2. Seepage pits normally constructed of unmortared brick.
3. Large amounts of water also discharged to pits.

NOT TO SCALE

FIGURE 3–2

SVE APPLICATION AT OU–2

Jet Propulsion Laboratory
Pasadena, California

FOSTER WHEELER ENVIRONMENTAL CORPORATION

4.0 DEVELOPMENT AND SCREENING OF REMEDIAL ALTERNATIVES

In this section, potential remedial alternatives are assembled using various process options associated with SVE, which was selected as the presumptive remedy in Section 3.0 (refer to Subsection 3.3.1). The potential remedial alternatives are then subjected to a screening process in which their effectiveness, implementability, and cost are evaluated. The retained remedial alternatives are subjected to a more detailed evaluation in Section 5.0 using the nine Superfund evaluation criteria. Also included in this section is a description of the SVE pilot test conducted at OU-2, and a summary of the results.

The final configuration of the remedial alternative selected for implementation will be based on performance criteria presented in the ROD. Any additional information and data acquired during remedial design, such as from pilot testing, will also be considered when the final design is developed. The project details described in this FS are conceptual and have been assumed only for cost estimating and remedial alternative comparisons. Other technologies and configurations are possible. In accordance with EPA guidance, cost estimates developed at this stage in the FS process are approximate (plus 50 to minus 30 percent), and based on designs that are not yet well defined.

4.1 DEVELOPMENT OF REMEDIAL ALTERNATIVES

The development of alternatives must conform to requirements identified in CERCLA, as amended, and to the extent possible in the National Contingency Plan (40 CFR Part 300). CERCLA Section 121(b) identifies the following statutory preferences when developing and evaluating remedial alternatives.

- Remedial actions that involve treatments that permanently and significantly reduce the volume, toxicity, or mobility of contaminants or hazardous substances are preferred over alternatives that only prevent exposure.
- Off-site transport and disposal of hazardous substances or contaminated materials without treatment is considered the least favored remedial action for sites where practical treatment technologies are available.
- Remedial actions using permanent solutions, innovative treatment technologies, or resource recovery technologies shall be assessed.

These requirements will be taken into consideration in developing the alternatives for the JPL site.

For the purposes of this FS, the remedial alternatives consist of process options associated with treatment of VOC waste streams extracted via SVE. SVE is paired with the various process options to form remedial alternatives, which are then screened on the basis of effectiveness, implementability, and cost.

As per EPA guidance, the "No Action" alternative is carried through the FS screening processes to provide a baseline for comparison with other alternatives. The "No Action" alternative consists of leaving the site "as is." Under this alternative, no remedial activities would be undertaken at OU-2 in the future, and the pilot plant currently operational would be taken off line.

Based on the analysis presented in Section 3.0 and above, the general alternatives for OU-2 at JPL include:

- No Action
- In Situ Soil Vapor Extraction

These alternatives include soil-vapor monitoring via the quarterly monitoring program (currently in place) to assess the VOC concentration trends over time.

As noted above, additional technologies that are required for treatment of waste streams from SVE are considered below. Vapors extracted from the well(s) will contain VOCs, and the vapor stream will require treatment prior to discharge to the atmosphere.

Using the EPA *Remediation Technologies Screening Matrix and Reference Guide* (EPA, 1993c), the following technologies were identified as being appropriate for VOC removal from the off-gas stream:

- Thermal Oxidation
- Catalytic Oxidation
- Carbon Adsorption
- VOC Adsorbing Resins

The choice of off-gas treatment method may depend on the concentrations of contaminants and may change if these concentrations vary by an order of magnitude, either across the site or with time.

4.1.1 Development of Alternatives

Alternatives were developed using the "No Action" alternative, and in situ SVE (the presumptive remedy) plus the possible process options for treating waste streams. As noted above, all alternatives include soil monitoring, so that the degree of remediation can be evaluated. Natural attenuation will occur regardless of human effort; therefore, it is expected to occur to some extent in each alternative as well.

Four alternatives were developed for SVE, each specifying a different process option for off-gas treatment.

The alternatives developed for consideration at JPL OU-2 are:

Alternative 1:	No Action
Alternative 2:	In Situ SVE Treatment
Alternative 2a:	Thermal Oxidation Off-Gas Treatment
Alternative 2b:	Catalytic Oxidation Off-Gas Treatment
Alternative 2c:	Granular Activated Carbon Adsorption Off-Gas Treatment
Alternative 2d:	VOC Adsorbing Resins Off-Gas Treatment

4.2 PILOT TEST

In situ SVE was identified during the RI stage as being a potentially feasible technology for remediation of the VOC-impacted soils in OU-2. Implementation of in situ SVE requires collection of site-specific data, typically through implementation on a field pilot scale. This was recognized by the RPMs during the RI process, and a field scale pilot test was implemented starting in April of 1998. This testing confirmed the feasibility of in situ SVE in remediating VOC-impacted soils, and provided design parameters for future full-scale implementation. Detailed descriptions of the pilot test and results obtained to date are provided in Appendix A. A summary of relevant information is provided in the following sections.

4.2.1 Test Setup

The pilot test was performed on a test vapor extraction well (VE-1) installed at the location shown in Figure 4-1 that is at the approximate center of the area with the highest VOC concentrations. The well is screened across the depth of contamination, from approximately 45 feet bgs to 185 feet bgs. It consists of three discrete casings that are screened at different depths [Screen A (44 to 84 feet bgs), Screen B (94 to 134 feet bgs), and Screen C (145 to 185 feet bgs)] as shown in Figure 4-2. This allows a better distribution of vacuum across the screened interval and allows for extraction from specific depths as opposed to the entire screened depth.

The test consisted of applying a vacuum on various combinations of these casings, monitoring flow rates and VOC concentrations in extracted vapors, and measuring vacuum responses in the soil vapor monitoring wells surrounding VE-1. Locations of the wells that were monitored are shown in Figure 4-1. As noted in the RI report (Foster Wheeler, 1999b), each well consists of multiple soil vapor sampling tips at various depths. These wells were also monitored for VOCs as part of the ongoing soil vapor monitoring program, which provided additional information in terms of SVE effectiveness. A vacuum blower was used to extract soil vapors from VE-1, and the vapors were treated with four vapor-phase granular activated carbon (GAC) vessels as shown in Figure 4-3.

The test consisted of a short-term portion (Tests 1 and 2) from April 1998 to June 1998, and a long-term portion (Test 3) beginning in November 1998 (this test is ongoing).

4.2.2 Test Results

The test results indicated that SVE is indeed a feasible technology for remediation of the VOC-impacted soils at OU-2. Following are some of the key results of the pilot test:

- All three screens were able to extract significant quantities of soil vapor with flow-rates ranging from 157 to 174 cubic feet per minute (cfm) from each screen at vacuums ranging from 44 to 80 inches of water.
- Vacuum responses were noted as far as 771 feet away. For the long-term portion of the test, a response equal to 1 percent of the exerted vacuum was observed at least 550 feet away. To be conservative, a radius of influence (ROI) of 400 feet was assumed based on radius of remedial influence (RORI). The RORI is defined as the distance at which VOC levels in the soil vapor monitoring probes were reduced by 50 percent as a result of SVE.
- VOC concentrations in the extracted vapor decreased by over 95 percent over the duration of the test.
- VOC removal rates of up to 0.1 pound per hour were noted for CCl_4, with an overall removal of approximately 200 pounds of VOCs between May 1998 and October 1999. An additional 800 pounds of VOCs were also removed, based on exhaustion of the primary carbon vessels on two occasions (see Appendix A).

4.2.3 SVE Effectiveness

As noted above, vacuum responses were noted as far as 700 feet away from VE-1 during the early portions of the test, indicating a ROI of at least 700 feet. This is somewhat higher than the typical ROI at most sites (10 to 200 feet depending on soil type). This led to an extension of the test from an originally intended duration of 10 weeks, to approximately 12 months. Furthermore, the observation of vacuum responses does not necessarily imply that remediation (i.e., removal of VOCs) is occurring within the area encompassed by the ROI. Hence, the actual changes in VOC levels in the various soil-vapor monitoring probes were evaluated over time to provide a better measure of SVE effectiveness. This effectiveness was measured in terms of the radius of remedial influence (RORI), which is defined as the distance which significant reduction in VOCs (as evidenced by soil vapor levels) is observed.

Four soil-vapor monitoring events (May/June 1998, October 1998, March 1999, and October 1999) were used to evaluate SVE effectiveness. It is noted here that two events were actually conducted in May/June 1998. However, because they were conducted only one month apart, they were considered together for the purpose of assessing SVE effectiveness, and the highest concentration for each sampling probe was used. VOC levels (CCl_4 and Freon) for the four events for selected soil vapor monitoring probes are shown on Figure 4-4. Based on Figure 4-4, VOC levels have reduced significantly as a result of the SVE pilot test. Contours for CCl_4 and Freon are shown in Figures 4-5 and 4-6, respectively, for the four events. These figures also reflect the significant reduction in VOC levels as a result of the pilot test.

As shown in Appendix A, reductions of greater than 50 percent were observed as far as 400 feet away (in the same range as the ROI) for Freon in Zone 3. The corresponding distance for Freon in Zone 2 is greater than 1,000 feet. The effectiveness for CCl_4 is greater than for Freon, with a reduction of 80 to 90 percent occurring at 400 feet. To be conservative, a RORI of 400 feet is assumed.

4.3 SCREENING OF REMEDIAL ALTERNATIVES

In this section, the remedial alternatives listed above are described and evaluated on the basis of effectiveness, implementability, and cost, the same criteria used in Section 3.3. The focus of the following screening is enlarged to include the effects of the remedial process on its surroundings as well as its technical feasibility. Alternatives with favorable composite evaluations will be retained for further consideration during the detailed analysis presented in Section 5.0.

Effectiveness—The effectiveness criterion evaluates the ability of an alternative to provide protection to human health and the environment. This includes both immediate and long-term considerations. According to EPA guidance (EPA, 1988a), the effectiveness screening includes the following criteria:

- The ability to protect the groundwater beneath the site, i.e., meet cleanup levels for soil that are protective of beneficial use of the groundwater.
- The degree of permanent reduction in toxicity, mobility, or volume.
- The magnitude of risks to the public, site workers, or the environment during implementation.
- The ability to attain remediation goals.

It should be noted that evaluating effectiveness with regard to direct protection of human health is not required for soils at this site because the risk assessment found no human health risks associated with surface soils [OU-2 RI report (Foster Wheeler, 1999b)]. In addition, mitigation of potential human health risks due to exposure to contaminants via groundwater is the subject of the OU-1/OU-3 FS (Foster Wheeler, 1999c).

Implementability—Implementability is a measure of both the technical and administrative feasibility of each alternative, particularly with respect to construction, operation, and maintenance. Implementability criteria include the following:

- The extent to which a process can be constructed, reliably operated, and meet technology-specific regulations
- How easily operation, maintenance, replacement, and monitoring of technical components can be achieved after the remediation period is complete.
- The difficulty in obtaining approvals from other offices and agencies.
- The availability of treatment, storage, and disposal services and capacity.
- The requirements for, and availability of, specific equipment and technical specialists.

Cost—During the alternative screening, order of magnitude cost estimates are used to provide comparisons between alternatives, rather than to define the cost of specific alternatives. The following considerations are used for the cost screening at this level:

- Comparative cost increase or decrease with respect to the benefit derived from one alternative versus another.
- Comparative capital and operation and maintenance (O&M) costs for the alternatives.

4.3.1 Alternative 1: No Action, Monitoring

The No Action alternative is evaluated for this FS in accordance with NCP protocols (40 CFR Part 300). This alternative stipulates that no additional remedial activities will be implemented by JPL. Under this alternative, no remedial activities are undertaken at the site, the current SVE pilot system is taken off-line, and a soil-vapor monitoring program is instituted to assess temporal changes in contaminant concentrations and distributions.

Advantages and disadvantages of the No Action alternative are evaluated in the following paragraphs.

Effectiveness—This alternative does not provide protection of groundwater, since there are no provisions to prevent the VOC plume from continuing to migrate to the water table. No reduction in toxicity, mobility, or volume of contaminants will result from this alternative with the exception of incidental reductions in volume or toxicity due to natural processes.

There are no risks to the public, site workers, and the environment resulting from implementation of this alternative, since no actions will take place. Remediation goals will not be met in the foreseeable future if no action is taken.

Implementability—The No Action alternative is easily implemented since no new construction is required. Soil-vapor monitoring will require field operations similar to those undertaken during the RI and is already proven to be technically implementable at this site. In addition, soil vapor sampling tips are already in place for future soil vapor sample collection.

The No Action alternative is not likely to be acceptable to local governments and the public because the VOC plume will continue to act as a source of groundwater contamination. As discussed in the JPL OU-1 and OU-3 FS report (Foster Wheeler, 1999c), this groundwater may impact surrounding communities if no remedial action is taken.

Cost—The only costs associated with the No Action alternative are those for the soil vapor monitoring program. These fall into the O&M category, and will continue periodically for at least 5 years.

Conclusion—The No Action alternative represents the baseline to which all other remedial alternatives are compared. Thus, as required by the NCP, the No Action alternative will be carried into the detailed evaluation in Section 5.0.

4.3.2 Alternative 2: In Situ SVE, Monitoring

Under Alternative 2, VOCs in the vadose zone are treated with in situ SVE. As explained in Section 3.3, in situ SVE has been identified by USEPA as a presumptive remedy for sites with VOCs present in soil. Based on discussions presented in Sections 3.3.1 and 4.2, SVE can be performed as an in situ process (thereby increasing economic effectiveness), is amenable to conditions at JPL, and has been shown to be effective at JPL in a pilot study. In situ SVE has, therefore, been selected as the presumptive remedy, and does not require further evaluation in this section. The ongoing soil-vapor monitoring program will be used to assess changes in contaminant concentrations and extent over time.

The soil vapors extracted by the SVE system constitute a waste off-gas stream, and contain the VOCs removed from the vadose zone. These VOCs must be removed before the off-gas can be discharged to the atmosphere. Four different options for vapor treatment are considered, and are evaluated in the following section.

4.3.3 Off-Gas Treatment

Alternative 2 requires off-gas treatment as part of the treatment train. Four off-gas treatment options are evaluated in the following subsections to determine which are most appropriate at this site.

4.3.3.1 Alternative 2a: Thermal Oxidation Off-Gas Treatment

Thermal oxidation is a process in which organic contaminants are destroyed in a combustor at temperatures of approximately 1,800°F (1,000°C). The primary advantage of thermal oxidation is that contaminants are chemically degraded into nontoxic compounds. This process is typically applied to streams with contaminant concentrations greater than 12,000 parts per million by volume (ppmv). Vapor/liquid separators are used prior to thermal oxidation units to remove noncombustible components from the treatment stream.

Effectiveness—Thermal oxidation effectively removes VOCs, SVOCs, and fuel hydrocarbons from gaseous streams. However, it is typically targeted toward treatment of non-halogenated compounds and can be problematic when used on waste streams containing chlorinated materials such as those present at JPL (EPA, 1993b). This is mainly because hydrochloric acid (HCl) is generated, which is highly corrosive, and can damage various system components. Furthermore, since halogenated compounds are present, the system would be Resource Conservation and Recovery Act (RCRA) regulated as a hazardous waste incinerator, which would require extensive permitting.

Conclusion—All four of the constituents of interest at the JPL OU-2 site are chlorinated, and the presence of chlorine makes thermal oxidation inappropriate for the waste stream at this site due to the production of HCl. Based on low effectiveness, this treatment process is eliminated from further consideration in this FS.

4.3.3.2 Alternative 2b: Catalytic Oxidation (Halogenated) Off-Gas Treatment

Catalytic oxidation uses a catalyst to treat air streams containing halogenated organics, typically at concentrations less than 12,000 ppmv. During treatment, the air stream is preheated to approximately 840°F (450°C) and then passed through the catalyst bed where it is oxidized. The contaminants and oxygen are adsorbed onto the catalyst surface where they react to produce carbon dioxide, water, and hydrogen chloride or hydrogen fluoride gas (for the VOCs at this site). The exhaust typically requires scrubbing (usually with water) to remove the chloride and fluoride, prior to final discharge to the atmosphere.

Effectiveness—While catalytic oxidation can remove halogenated VOCs from an air stream, it may not be able to reach the fairly low levels that would be required by the SCAQMD and may require additional polishing of air stream prior to discharging to atmosphere (typically GAC). The major advantage of this process is that it permanently destroys the contaminants resulting in complete toxicity removal. Since the discharge from the catalytic oxidation system will contain halogenated acids (as halogenated VOCs are the primary constituents of concern), this method will require additional treatment options for addressing halogenated acids (typically scrubbing). Risks to the public and site workers during implementation are well controlled and are negligible if the system is operated correctly.

Implementability—This process has been used successfully in the past, and can be installed and operated reliably. While no permits would be required, the "substantive" requirements of a Permit to Construct/Operate from the South Coast Air Quality Management District (SCAQMD) would have to be met.

The constituents of interest at the JPL OU-2 site are halogenated, primarily with chlorine, but also with fluorine (Freon 113). Emissions from the oxidation unit will, therefore, contain hydrogen chloride and hydrogen fluoride, and they would require scrubbing prior to discharge to the atmosphere. This would result in another waste stream (water). Also, since the halogenated volatiles do not have a very high calorific value, the catalytic unit will require heat energy (either natural gas or electricity). Some specialized training may be required for operating personnel. Oxidation units are available to treat a large range of flow rates.

Cost—This process option is rated as 'Better' by the EPA, indicating that a general cost range, based on past experience, is less than $7 per pound of off-gas treated (EPA, 1993b). However, this cost does not reflect the additional costs that would be incurred for scrubbing and the significant amounts of energy (gas or electricity) that would be required. Hence, actual costs are expected to be much higher. Typical costs for a 500 cfm system are on the order of $200,000 (capital), and $5,000 per month for electricity, chemicals, and laboratory analyses.

Conclusion—Catalytic oxidation could be used to treat VOCs in the off-gas stream from the SVE system. However, additional treatment may be required to scrub hydrogen chloride and/or hydrogen fluoride from system emissions. Additional polishing of the exhaust may be needed to comply with SCAQMD requirements. Hence, this option is eliminated from further consideration in this FS.

4.3.3.3 Alternative 2c: Granular Activated Carbon Off-Gas Treatment

This off-gas treatment process uses GAC to capture contaminant molecules from the gas phase. Typically, the GAC is contained in a packed bed through which the off-gas flows. When the carbon becomes saturated with contaminants, it is regenerated in place or removed and regenerated at an off-site facility.

Contaminants treated by GAC include VOCs, SVOCs, fuel hydrocarbons, and pesticides. This process is most effective for contaminants with molecular weights between 50 and 200, boiling points between 75° and 300°F (24° and 150°C), and on air streams with a low moisture content. Carbon adsorption is typically used when contaminant concentrations are less than 1,000 ppmv and is capable of high removal efficiencies.

Effectiveness—GAC is effective in removing halogenated VOCs from a vapor stream. Constituents of interest at this site have molecular weights ranging from 97 (1,1-DCE) to 187 (Freon 113) and boiling points ranging from 98.6°F (1,1-DCE) to 188°F (TCE). Because removal rates with GAC are high, this process is frequently used to bring contaminated streams into compliance with regulations and will be able to reach the levels required by the SCAQMD. This has been confirmed during the pilot test by laboratory analyses of the treated vapors. One minor disadvantage of GAC is that the contaminants are not initially destroyed. The contaminants are removed from the carbon in a regeneration process during which they typically are destroyed.

Risks to the public, site workers, and the environment during implementation are low. GAC treatment is reliable and is not likely to result in unintentional releases of contaminants to the surroundings.

Implementability—GAC is a commonly used vapor treatment process for halogenated VOCs. Construction and operation are readily accomplished, and equipment is available from several vendors. Regeneration service is usually provided by the carbon vendor. Different GAC systems are available for treatment of a large range of flow rates, and only require limited special training. Hence, GAC systems are considered to be easy to implement.

Cost—This process option is rated as 'Better' by the EPA, indicating that a general cost range, based on past experience, is less than $7 per pound of off-gas treated (EPA, 1993b). Typical costs for a 500 cfm system are on the order of $60,000 (capital), and $2,000 per month for electricity, chemicals, and laboratory analyses.

Conclusion—GAC is a viable choice for treatment of the off-gas stream based on selection criteria discussed above and past operating experience. Despite its disadvantages, GAC units typically compare favorably with other off-gas treatment processes and will be retained for further evaluation.

4.3.3.4 Alternative 2d: VOC Adsorbing Resin Off-Gas Treatment

Adsorbing resin treatment systems are similar to GAC treatment systems except that resin systems rely on various synthetic resins to adsorb VOCs rather than activated carbon. In contrast to activated carbon, which will adsorb a wide variety of chemicals, synthetic resins are designed to selectively adsorb particular chemicals or families of chemicals.

Synthetic resins may be regenerated more than 1,000 times without loss of adsorptive capacity, and systems are typically constructed with on-site regenerative systems. This entails two sets of resin beds, one in the adsorption mode and one in the desorption mode. In the desorption process, the adsorbed chemicals are removed by heating and/or the application of a vacuum. The desorbed chemicals are then condensed from the purge stream and recovered.

Effectiveness—Synthetic resins are effective in removing targeted contaminants from the gas stream and would be appropriate for the constituents of interest at this site because they are all from the family of small, halogenated VOCs. One disadvantage of resins is that the contaminants are not destroyed and must be removed from the resin at a later time and further treatment is needed. Synthetic resins typically have a greater tolerance than GAC systems for off-gas streams with high moisture content.

Risks to the public, site workers, and the environment during implementation are low. Resin adsorption systems are not likely to result in unintentional releases of contaminants to the surroundings.

Implementability—Synthetic resin systems have not been widely used for off-gas treatment. Therefore, availability of equipment and materials may be more limited than for GAC. Regulatory acceptance of resin systems may also be more difficult to obtain than for GAC systems because this is a relatively new application of resin adsorption. Resin systems can be applied for a large range of flow rates and may require some special training.

Cost—This process option is not rated by the EPA in the Technology Screening document (EPA, 1993b); however, synthetic resin systems with on-site regeneration generally have greater capital costs than typical GAC systems requiring off-site regeneration or disposal. Although this may be balanced by lower operating costs for the synthetic resin systems, these systems have not been widely used for off-gas treatment because of the significantly high capital cost. Typical costs for a 500 cfm system are on the order of $100,000 (capital), and $3,000 per month for electricity, chemicals, and laboratory analyses.

Conclusion—Synthetic resins are capable of treating halogenated VOCs in dilute air streams. The higher capital cost is a disadvantage compared to GAC (while resin system performance is about the same as for GAC), which, in turn, results in higher operating costs because of the higher costs for regeneration of resins. Because of the higher cost without significant benefit over GAC, synthetic resins will not be considered further in this FS.

4.3.4 Summary of Off-Gas Treatment Evaluation

Of the four off-gas treatment processes considered for the in situ SVE system at JPL OU-2, one has been retained for further consideration. Results of this evaluation are summarized below:

Off-Gas Treatment	Conclusion
Thermal Oxidation	Reject. Not appropriate for halogenated compounds.
Catalytic Oxidation	Reject. Applicable to constituents of interest at this site. Costs are expected to be on the high side. May require additional side stream treatment, as well as polishing.
GAC	Retain. Proven technology, and proven to be effective for VOC treatment. Applicable to constituents of interest at this site. Less costly compared to other appropriate technologies reviewed.
Synthetic Resin	Reject. Limited performance data. High capital cost with no appreciable benefit in performance over GAC.

Hence, GAC is the preferred treatment for the VOC-containing soil vapors.

4.4 RETAINED ALTERNATIVES

Two alternatives, one consisting of SVE as the presumptive remedy with four variations in terms of off-gas treatment, have been evaluated. The alternatives are developed in more detail in Section 5.0. A more detailed evaluation is then performed to select the preferred alternative for remediation at the JPL OU-2 site.

The alternatives retained for further consideration are listed in the following table.

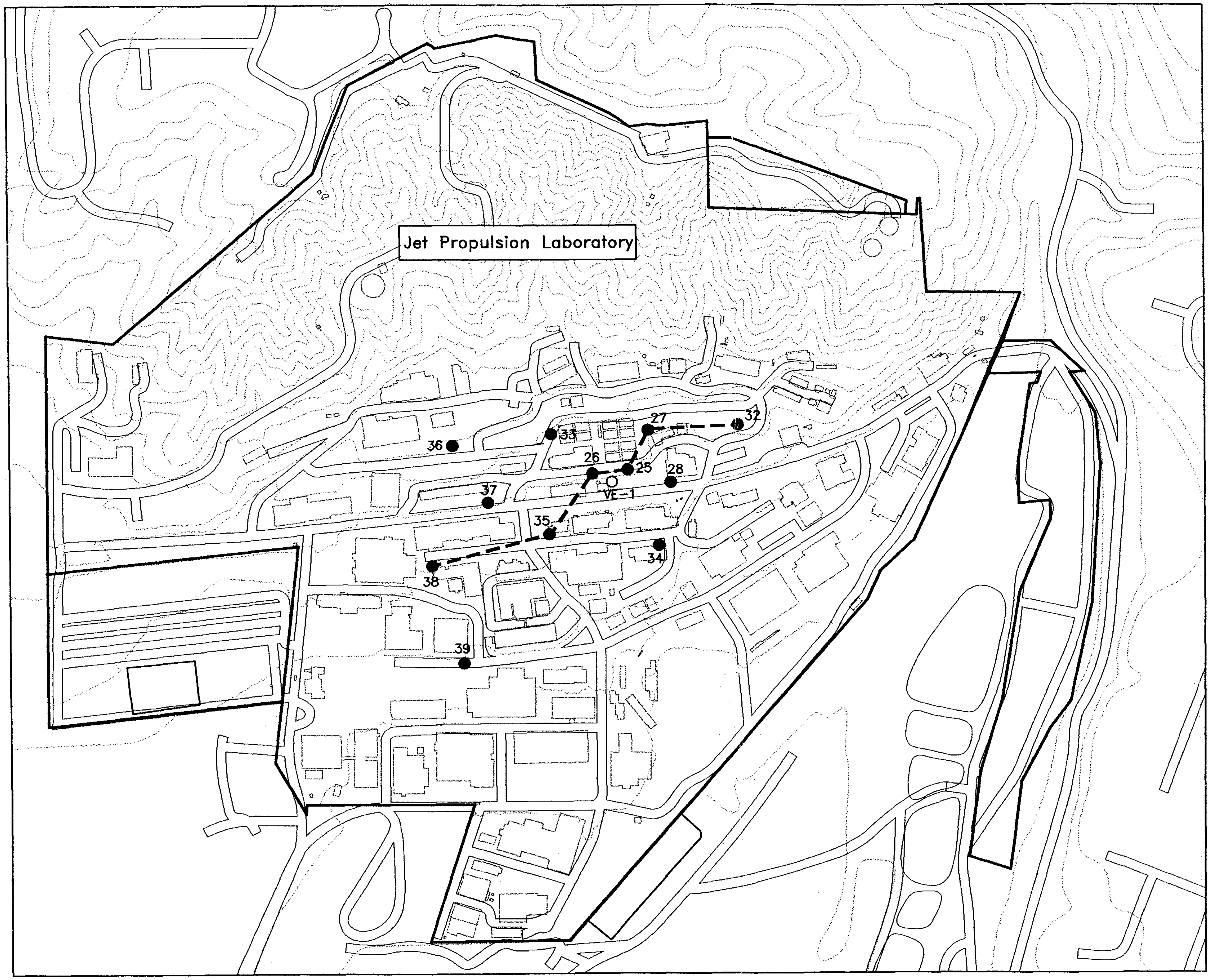
RETAINED ALTERNATIVES	
Alternative	**Description**
Alternative 1	No Action
Alternative 2c	In Situ SVE/GAC Off-Gas Treatment

In reviewing these alternatives against the statutory preferences identified in CERCLA and listed in Section 4.1, it can be seen that:

- Alternative 2c involves treatment that permanently and significantly reduces the volume of contaminants in soil. This is preferred over alternatives that prevent exposure only, of which there are none at this site.
- Alternatives that do no include off-site transport and disposal of hazardous substances or contaminated materials are preferred over those that do. None of the alternatives at JPL OU-2 include off-site transport of untreated materials.
- Remedial actions included in Alternative 2c incorporates permanent solutions and innovative treatment technologies (i.e., in situ SVE), which are preferred over other approaches.

Therefore, the alternatives being carried forward for further consideration at this site are in compliance with the CERCLA preferences.

FIGURES



Explanation

● 39 Soil Vapor Well Installed During RI Investigation

○ VE-1 Vapor Extraction Well

--- Line of Cross Section

N

400 200 0 400

SCALE IN FEET

Source: USGS, 7.5 Minute Topographic Map Pasadena, CA 1966, Revised 1988, 1994.

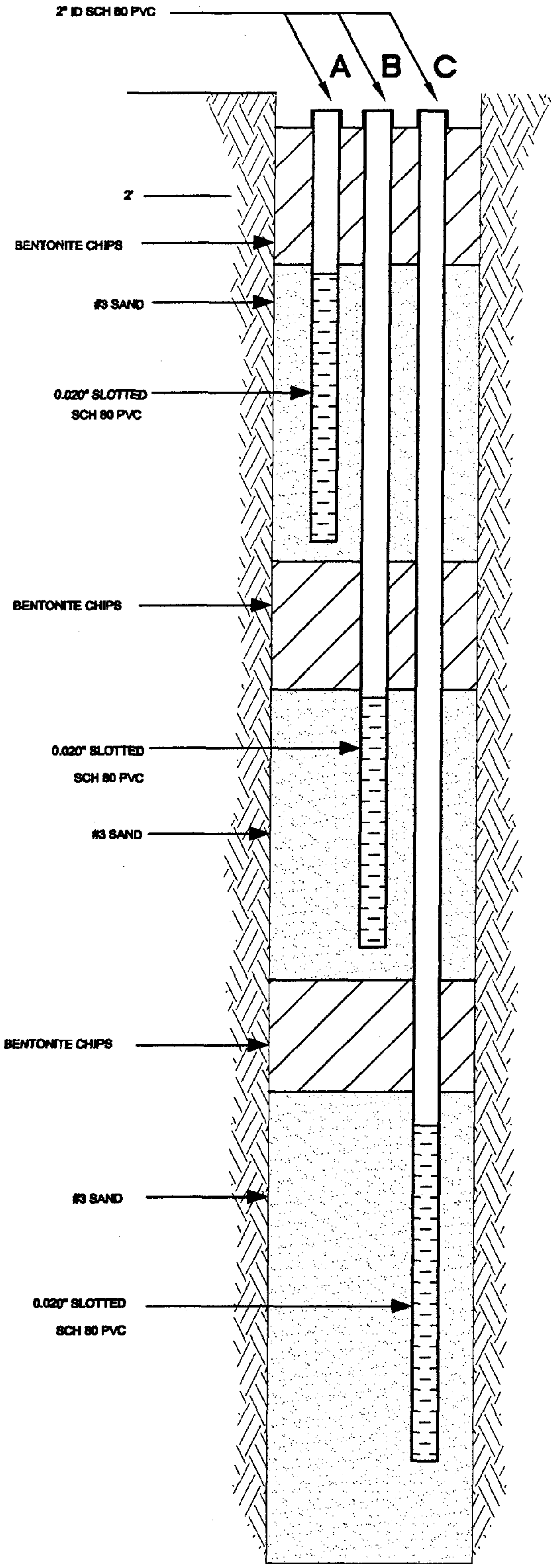
FIGURE 4-1

SOIL VAPOR WELL LOCATIONS

Jet Propulsion Laboratory
Pasadena, California

FOSTER WHEELER ENVIRONMENTAL CORPORATION

I:\1572-JPL\DWG\OU2\FS12-99\FIG4-1.DWG
PLOT/UPDATE: DEC 21 1999 13:56:54



SCREEN A: 44' TO 84' BGS
SCREEN B: 94' TO 134' BGS
SCREEN C: 145' TO 185' BGS

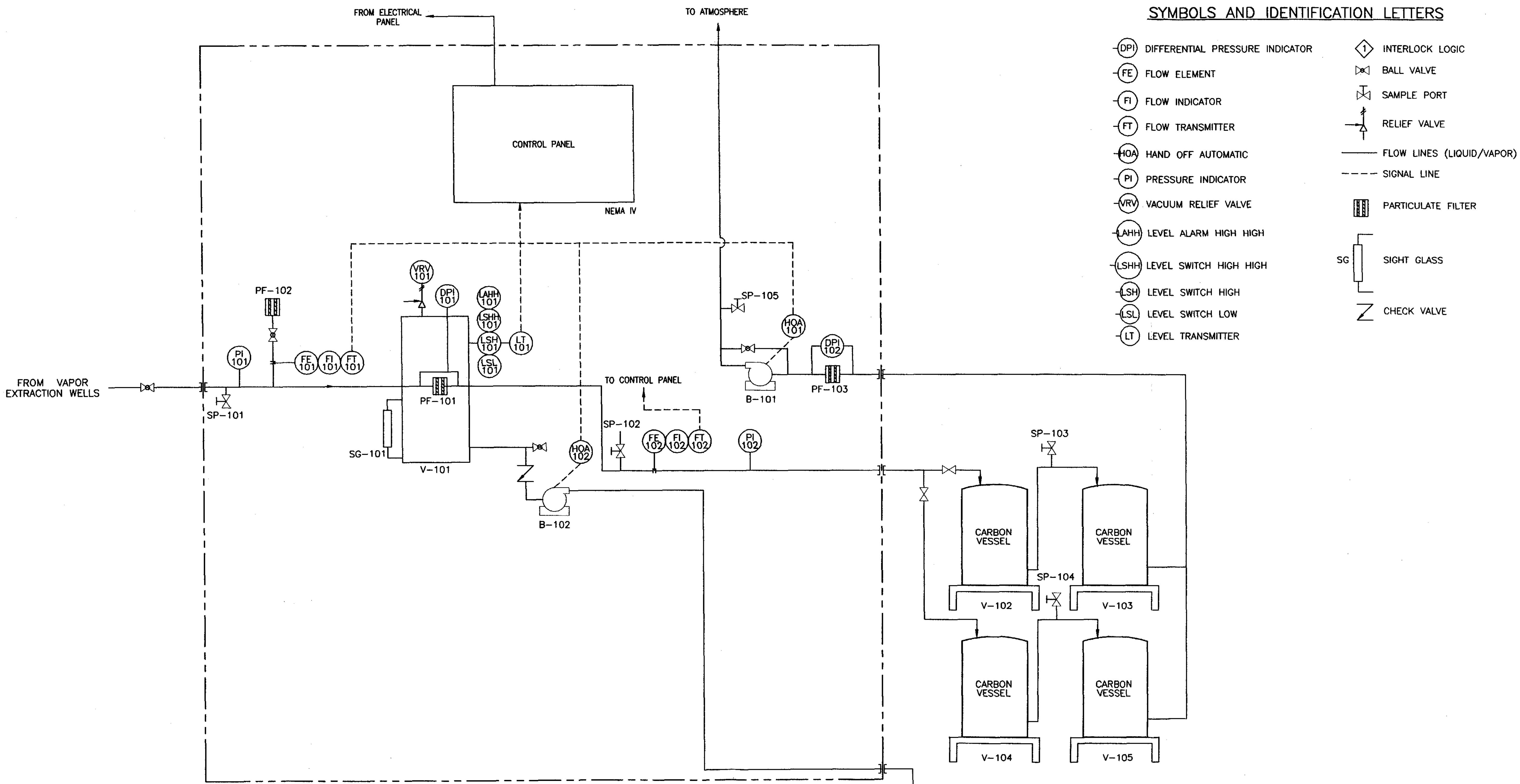
FIGURE 4-2

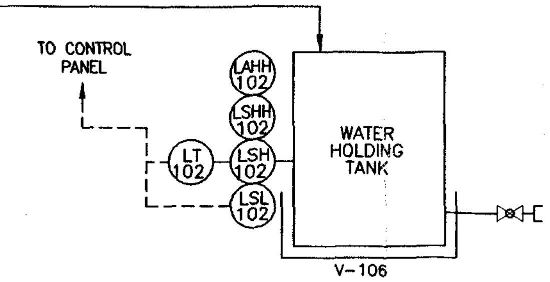
VAPOR EXTRACTION WELL
VE-1

Jet Propulsion Laboratory
Pasadena, California

FOSTER WHEELER ENVIRONMENTAL CORPORATION

I:\1572-JPL\DWG\OU2\FS6-00\FIG4-2.DWG
PLOT/UPDATE: MAY 11 2000 10:06:33





INSTRUMENTATION

NAME	DECRIPTION	RANGE
DPI-101	MAGNEHELIC, PRESSURE INDICATOR	0-10 "H_2O
DPI-102	MAGNEHELLIC PRESSURE INDICATOR	0-10 "H_2O
FE, FI, FT-101	PITOT TUBE, INDICATOR, TRANSMITTER	0-600 scfm
FE, FI, FT-102	PITOT TUBE, INDICATOR, TRANSMITTER	0-600 scfm
PI-101	MAGNEHELIC, VACUUM INDICATOR	0-150 "H_2O
PI-102	MAGNEHELIC, VACUUM INDICATOR	0-150 "H_2O
VRV-101	VACUUM RELIEF	10 "Hg

CONTROLS

1. SHUT DOWN B-101 FOR ALARM HIGHS IN V-101 AND V-106. PROVIDE TWO INDICATING LIGHTS FOR EACH ALARM IN CONTROL PANEL.
2. RECORD FLOWS FROM FT-101, AND 102 ON RECORDER IN CONTROL PANEL.
3. ALL MOTOR STARTERS FOR B-101 AND B-102 SHALL BE INSTALLED IN CONTROL PANEL AND EQUIPPED WITH HOA SWITCHES.
4. LSH-101 TURNS ON PUMP B-102.
5. LSHH-101 SHOULD SHUT DOWN B-101 UNTIL RESOLVED.
6. LSHH-102 SHOULD SHUT DOWN B-101 UNTIL RESOLVED.

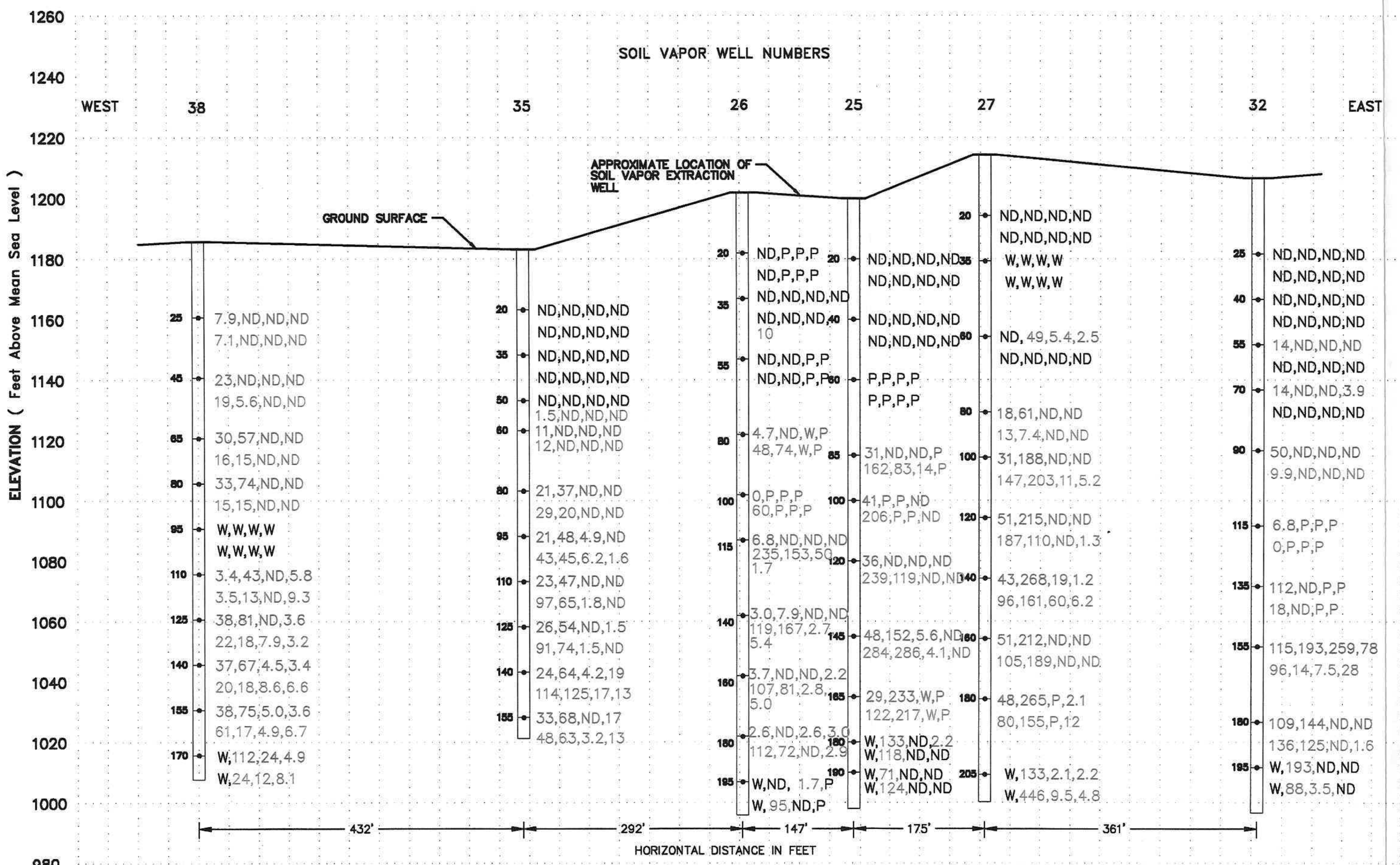
FIGURE 4-3

PIPING AND INSTRUMENTATION DIAGRAM-PILOT TEST

Jet Propulsion Laboratory
Pasadena, California

FOSTER WHEELER ENVIRONMENTAL CORPORATION

I:\1572-JPL\DWG\OU2\FS12-99\FIG4-3.DWG
PLOT/UPDATE: DEC 27 1999 09:12:07



Explanation

25 — Soil Vapor Sample Point and Depth

ND Non-Detect @ Laboratory Detection Limit of 1.0 μg/L-Vapor

P Sample Port Plugged; No Sample Collected

W Sample Port Waterlogged; No Sample Collected

MAY/JUNE 1998*
OCTOBER 1998
MARCH 1999
OCTOBER 1999

13,7.4, ND,ND

MAY/JUNE 1998*
OCTOBER 1998
MARCH 1999
OCTOBER 1999

21,37, ND,ND

31 Total Freon 113

162 Total Carbon Tetrachloride

Notes:

Location of cross-section is shown on Figure 4-1.

See section 4-2 for pilot test details.

*Highest concentration from OU-2 RI soil-vapor sampling Events 6 (May 1998) and 7 (June 1998) is shown. Soil Vapor Well Nos. 25, 26 and 27 were not sampled during Event 7.

HORIZONTAL SCALE: 1"=160'

160 80 0 160

VERTICAL SCALE: 1"=40'

40 20 0 40

FIGURE 4-4

CONCENTRATIONS OF CARBON TETRACHLORIDE AND FREON 113 OVER TIME DURING SOIL VAPOR EXTRACTION PILOT TEST

Jet Propulsion Laboratory
Pasadena, California

FOSTER WHEELER ENVIRONMENTAL CORPORATION

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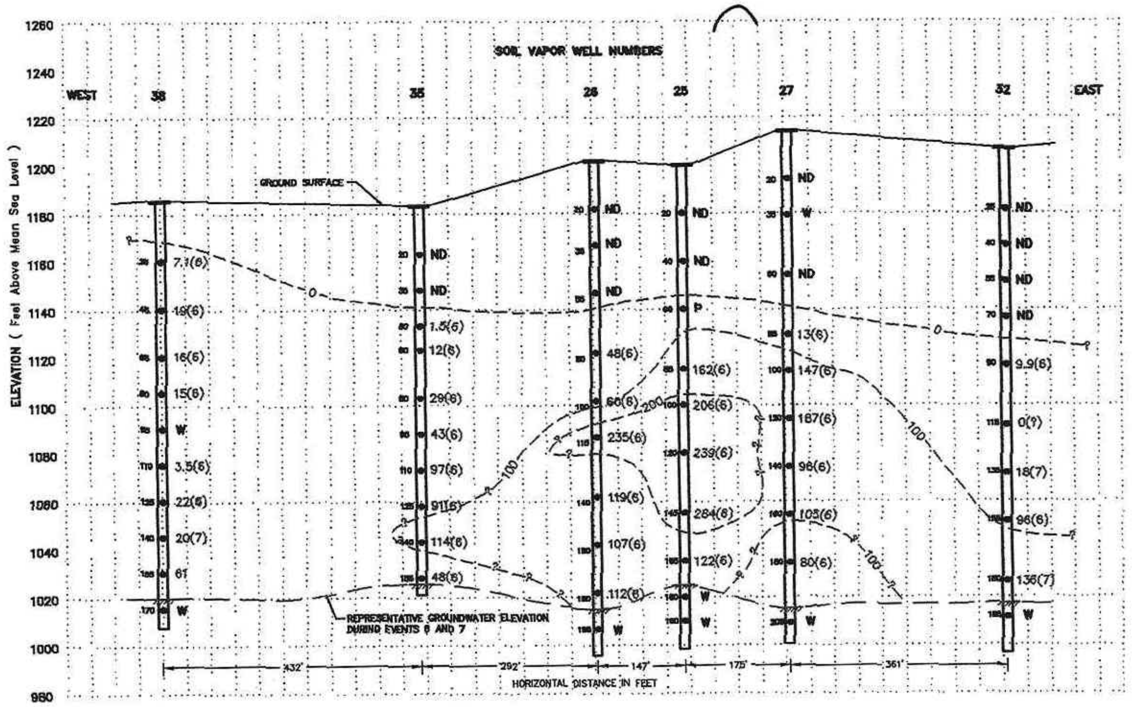
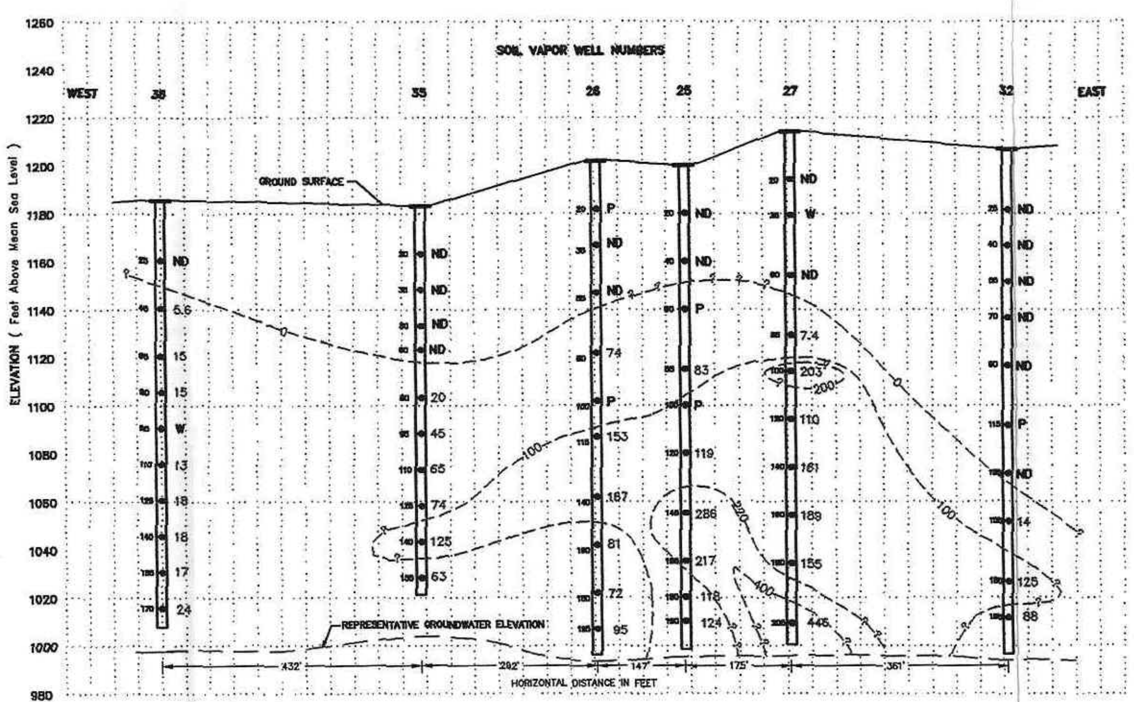


MAY–JUNE 1998



OCTOBER 1998

Explanation

- 25 Soil Vapor Sample Point and Depth
- 187 Concentrations of Carbon Tetrachloride (μg/L–Vapor)
- (6) Indicates Results from Event 6, May 1998
- (7) Indicates Results from Event 7, June 1998
- ND Non–Detect @ Laboratory Detection Limit of 1.0 μg/L–Vapor
- P Sample Port Plugged; No Sample Collected
- W Sample Port Waterlogged; No Sample Collected
- ? Indicates points where spatial control is lacking

Note:

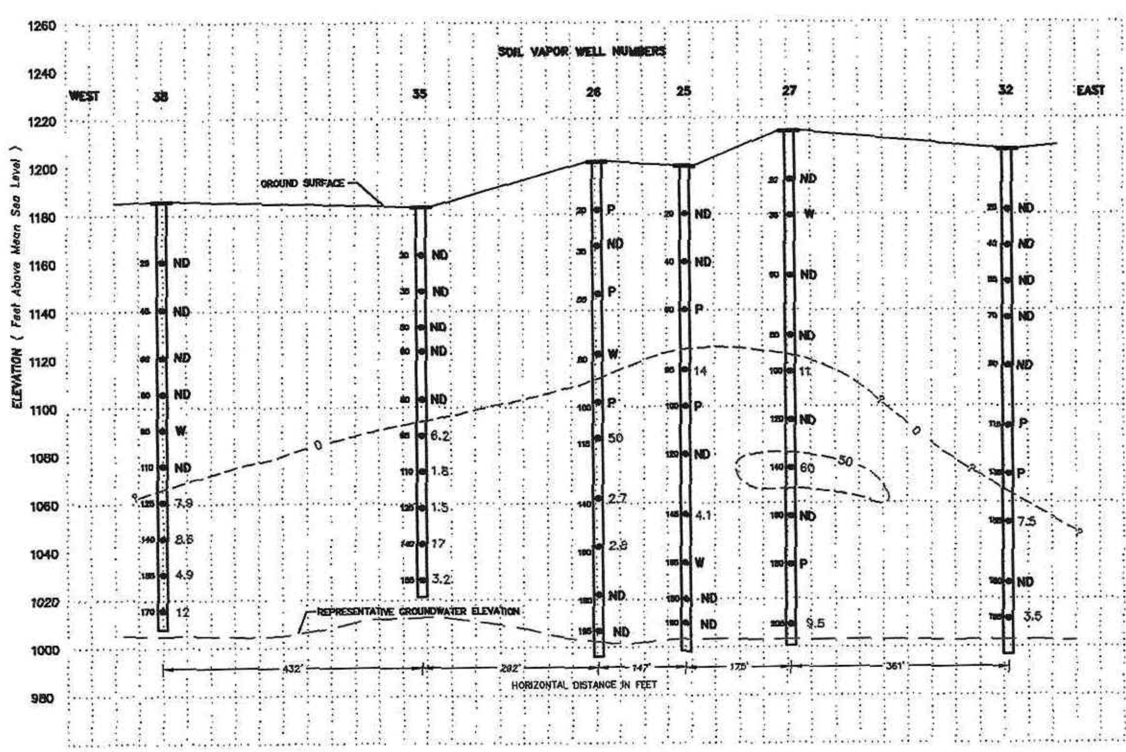
Location of cross–section is shown on Figure 4–1.

HORIZONTAL SCALE: 1"=320'

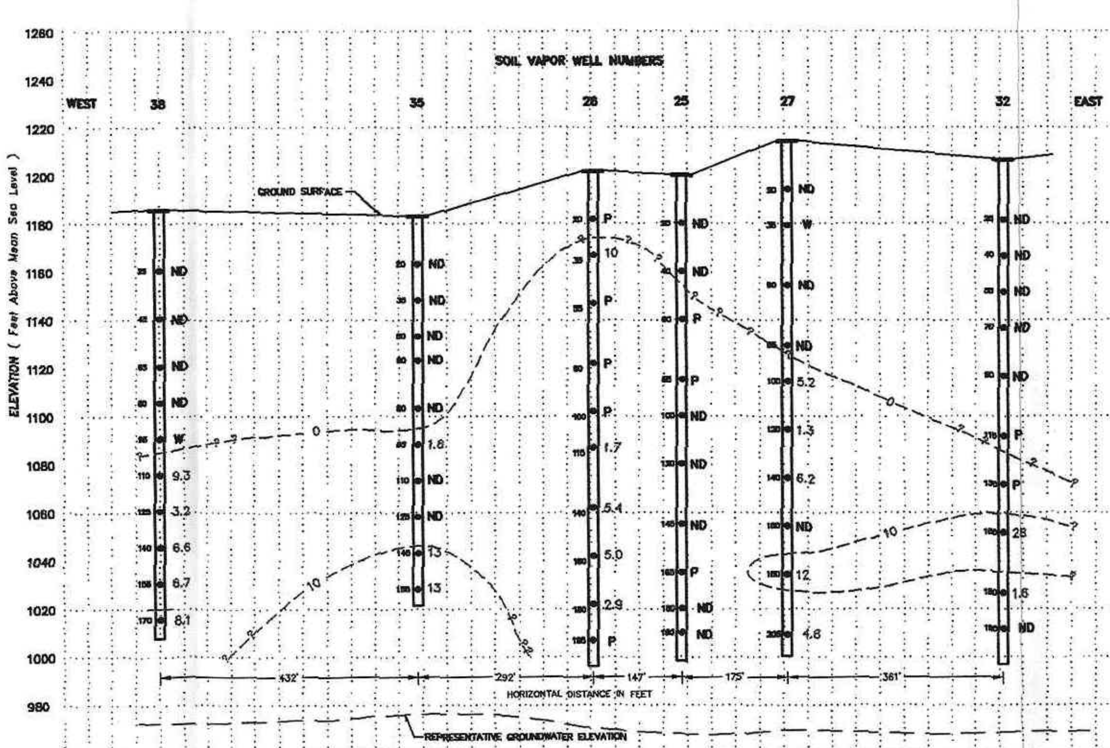
320 160 0 320

VERTICAL SCALE: 1"=80'

80 40 0 80



MARCH 1999



OCTOBER 1999

FIGURE 4–5

REPRESENTATIVE HORIZONTAL AND VERTICAL DISTRIBUTION OF CARBON TETRACHLORIDE

Jet Propulsion Laboratory
Pasadena, California

FOSTER WHEELER ENVIRONMENTAL CORPORATION

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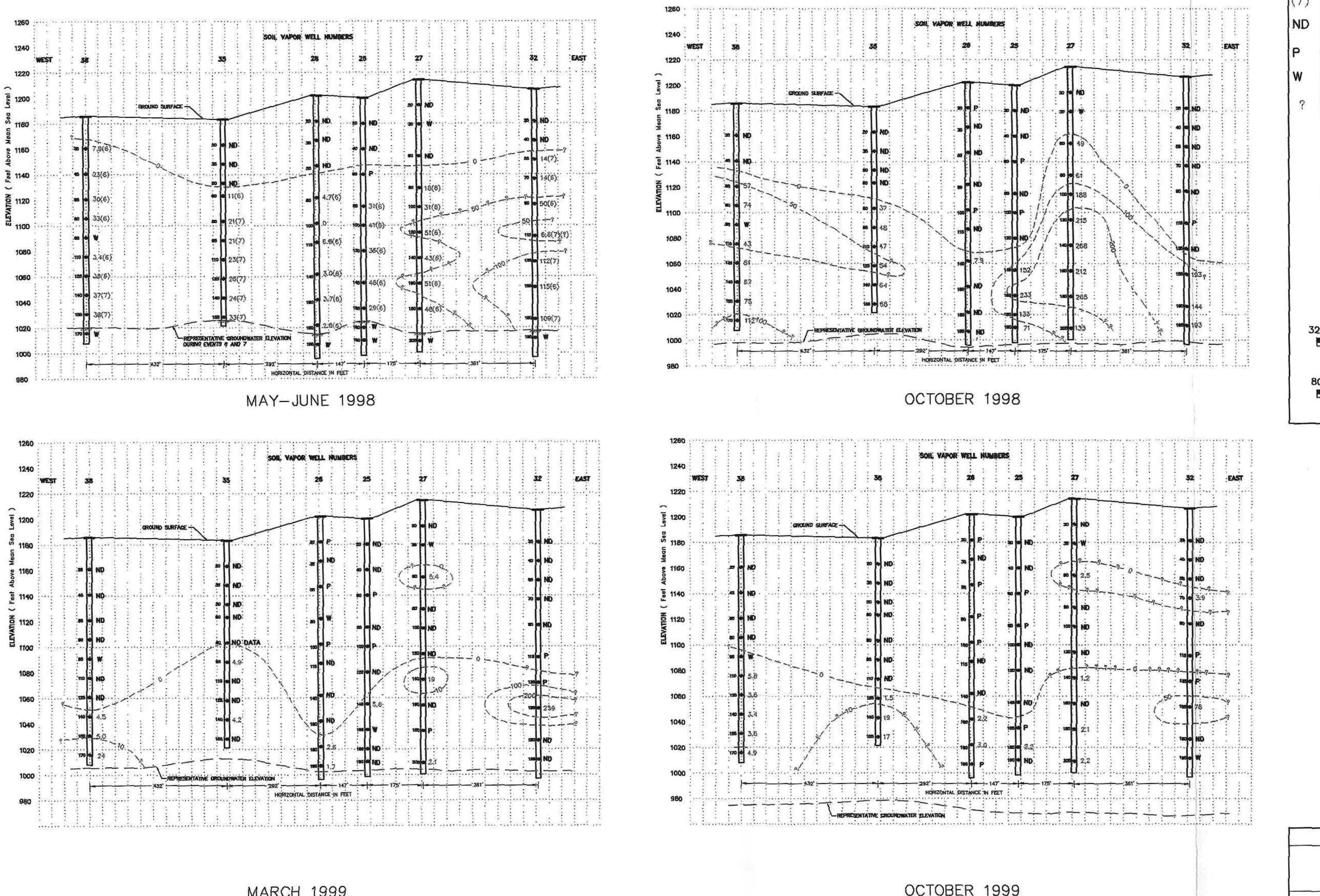

Explanation

- 25 ●— 31: Soil Vapor Sample Point and Depth; Concentrations of Freon 113 (µg/L–Vapor)
- (6) Indicates Results from Event 6, May 1998
- (7) Indicates Results from Event 7, June 1998
- ND Non–Detect @ Laboratory Detection Limit of 1.0 µg/L–Vapor
- P Sample Port Plugged; No Sample Collected
- W Sample Port Waterlogged; No Sample Collected
- ? Indicates points where spatial control is lacking

Note:

Location of cross–section is shown on Figure 4–1.

HORIZONTAL SCALE: 1"=320'

320 160 0 320

VERTICAL SCALE: 1"=80'

80 40 0 80

FIGURE 4–6

REPRESENTATIVE HORIZONTAL AND VERTICAL DISTRIBUTION OF FREON 113

Jet Propulsion Laboratory
Pasadena, California

FOSTER WHEELER ENVIRONMENTAL CORPORATION

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5.0 DETAILED ANALYSIS OF ALTERNATIVES

The remedial alternatives developed in Section 4.0 and retained for the detailed analysis are evaluated in this section. The detailed evaluation of each remedial alternative includes the following:

- Refinement of the remedial alternative using quantitative data, where available.
- Detailed evaluation of the remedial alternatives emphasizing the criteria outlined in EPA guidance [EPA, 1988 (guidance for RI/FS)].
- Evaluation of the remedial alternatives with respect to the statutory preferences in CERCLA Section 121(b), as amended.

This stage is the most detailed in the evaluation process, and for this reason, the alternatives are defined more quantitatively.

5.1 EVALUATION OF ALTERNATIVES

The following criteria from EPA's RI/FS guidance document (EPA, 1988) are used as the basis for the detailed analysis:

- Overall Protection of Human Health and the Environment
- Compliance with ARARs
- Long-term Effectiveness and Permanence
- Reduction of Toxicity, Mobility, or Volume
- Short-term Effectiveness
- Implementability
- Cost
- State Acceptance
- Community Acceptance

Factors considered for each of the evaluation criteria are summarized in Table 5-1.

Of the nine evaluation criteria, only the first seven will be fully evaluated. State and community acceptance will be evaluated during State review of the draft FS, the public comment period, and the post-RI/FS meeting/public comment period. Also, as discussed in Section 1.0, this analysis is required when the presumptive remedy format is used.

The remedial alternatives retained in Section 4.0 for the detailed evaluation are as follows:

Alternative 1:	No Action
Alternative 2c:	In Situ SVE/Off-Gas Treatment with GAC

5.1.1 Alternative 1: No Action

The No Action alternative is included to provide a baseline for comparison with the other alternatives. No remedial activities are planned under this alternative except those that occur naturally. A soil-vapor monitoring program (currently in place) is used to track contaminant concentrations and areal extent in the soil vapor over time.

The monitoring program will consist of collection and analyses of soil-vapor samples from the soil vapor monitoring wells (see Figure 4-1) on a quarterly basis for 5 years. If VOC levels continue to decrease and/or remain stable, the frequency may be reduced to semi-annual or annual before the end of the 5-year period. At the end of the 5-year period, sampling will either be switched to annual or dropped entirely depending on data from the first 5 years. Agency approvals will be obtained for all monitoring strategies.

Overall Protection of Human Health and the Environment

Alternative 1 is protective of human health in terms of exposure to contaminants via direct contact with soils, based on results of the human health risk assessment (Foster Wheeler, 1999b).

Mitigation of potential human health risks associated with exposure to groundwater is being considered in the OU-1/OU-3 FS. Furthermore, it is noted that groundwater extracted by the local purveyors for domestic consumption is currently being treated to meet strict regulatory requirements. Risks associated with the groundwater in the OU-1/OU-3 risk assessment were based on exposure to untreated water, which in reality, never occurs. This has been confirmed by the Agency for Toxic Substances and Disease Registry (ATSDR), which issued a report in 1998 stating that, in effect, there were no human health risks associated with groundwater at the site. It is acknowledged, however, that Alternative 1 is not protective of groundwater because of migration of VOCs from vadose zone soils to groundwater.

Compliance with ARARs

ARARs established for the JPL OU-2 site are presented and discussed in Section 2. As expected, this alternative does not meet chemical-specific ARARs since the constituents of interest are left in place and groundwater beneath the site is not protected. This alternative does meet location-specific ARARs since it does not involve construction activities. It also meets action specific ARARs. In particular, soil vapor monitoring will be used in accordance with RWQCB guidelines.

Long-Term Effectiveness and Permanence

This alternative is not effective over the long-term because the soil contamination continues to migrate into the groundwater. However, human health is protected in the long-term with regard to surface soils based on results of the OU-2 Human Health Risk Assessment.

Reduction of Toxicity, Mobility, and Volume

No remedial treatment is planned with this alternative; therefore, there is no reduction in toxicity, mobility, and volume of contamination in JPL OU-2 soils. While there will be some natural attenuation that reduces the overall toxicity, mobility, and volume of constituents of interest, its impact is not expected to be significant.

Short-Term Effectiveness

Because this alternative is the No Action alternative, no activities are planned. Hence, there are no short-term risks to the community resulting from implementation activities.

Implementability

This alternative is easily implemented since there are no activities associated with Alternative 1.

Cost

The only costs associated with this alternative are those relating to the soil monitoring program. Costs were estimated based on quarterly sampling events for the first 5 years, followed by 25 annual events. Based on these parameters, the approximate cost estimate for Alternative 1 is $1,477,000. Cost calculations are provided in Appendix B. It should be noted that the durations for the quarterly and annual sampling (5 and 25 years) are conservative, and they may be reduced significantly depending on the data obtained.

5.1.2 Alternative 2c: In Situ SVE/GAC Off-Gas Treatment

Alternative 2c uses in situ SVE to treat VOCs in soils in OU-2. For the purpose of this FS, it is assumed that up to 5 new vapor extraction wells, and up to 5 new extraction and treatment systems will be required. A general approach to design, operation, and closure is presented in Appendix C. This approach is based on RWQCB (1996) protocols.

The new wells will be screened similar to the existing well, and will have up to three discrete screens. The depth and extent of the screens will depend on the well's location, and will take into account the variations in water level at the site. At least one screen may extend to depths that are below the "high" water table. Such screens would be operated only when water table is lower than the bottom of the screen, thereby effecting VOC removal from soils that are below water table during wet periods.

The actual number of wells will depend on the results of the SVE pilot test, and the extent of VOC contamination. The systems would be operated until sufficient VOC mass reduction is effected, as evidenced by conformance with specific criteria, which will be determined and agreed upon during the remedial design phase. These criteria would eventually be used as basis of discontinuing operation (i.e., obtaining closure) (see Appendix C).

Also, it is recognized that there is some uncertainty regarding VOC levels to the west of soil vapor well No. 36. Given the RORI of 400 feet, VOCs to the west of soil vapor well No. 36, if any, will be captured by an appropriately placed extraction well.

Alternative 2c includes the same soil vapor monitoring program as described for Alternative 1. Results from the soil-vapor analyses will be used to determine the extent of remediation, if operations should be adjusted, or if a new approach must be taken for the remainder of the remediation. Adjustments include shutting down wells or selected screens within specific wells to enhance remediation.

Overall Protection Of Human Health and the Environment

Alternative 2c is protective of human health from the standpoint that the VOCs in the vadose-zone soils do not pose a threat to human health because there are no direct exposure pathways. The groundwater beneath the site is protected through remediation of the vadose zone, which limits future migration of VOCs to the water table. Treatment of the off-gas stream further protects the environment by removing VOCs before the off-gas stream is released into the atmosphere.

Compliance with ARARs

Alternative 2c is in compliance with all identified chemical-specific, action-specific, and site-specific ARARs as discussed below.

Alternative 2c is in compliance with the chemical-specific ARARs identified in Section 2.0. The MCLs for groundwater are indirectly applicable since SVE will be implemented in a manner that meets the stated RAO of protecting groundwater. The PRGs and SSLs (which are TBCs, see Table 2.1) were used in the risk assessment during the RI (see Section 1.3.9.1). The RWQCB's approach to investigation and clean-up of soil (a TBC) addresses all of the remaining RWQCB ARARs (i.e., this approach is designed to take these ARARs into account).

Location-specific ARARs will be taken into account during the remedial design phase (see Table 2-1). Specifically, as noted in Table 2-1, wastes will be managed in accordance with the Federal Facilities Compliance Act (soil cuttings, decontamination solutions, etc.). System facilities will be situated outside the 100-year flood plain of the Arroyo Creek. Potential locations will be surveyed for historic, archeologic, architectural, and cultural resources during design.

All of the chemical-specific ARARs pertaining to discharge of air will be addressed by the GAC treatment system. Dust generated during well installation (and piping installation, if below grade) will be controlled. The spent carbon and wastewater (entrained moisture in extracted vapor) will be profiled and appropriately disposed. The RWQCB's standards for SVE operation and soil-vapor sampling will be followed.

Long-Term Effectiveness

Alternative 2c is effective in the long-term. The SVE process permanently removes VOCs from the vadose zone. The VOC-laden air is processed through the vapor-phase GAC, which in turn permanently removes the VOCs from the extracted soil vapor. The VOCs are subsequently removed from the carbon, either through thermal regeneration in which the VOCs are destroyed, or through chemical regeneration in which the VOCs are transferred to the regenerating solution. Because contaminants are permanently removed from the soil, existing and future risks to groundwater are reduced. Once remediation is completed (criteria outlined in Appendix C are met), residual VOCs would not be expected to further impact groundwater, and, thus, long-term reliability is achieved.

Reduction of Toxicity, Mobility, and Volume

This alternative permanently and irreversibly removes VOCs from the vadose zone, thus, reducing the volume and mobility of contamination in the soil. Based on pilot study results, the amount of mass removal is expected to be significant. As discussed in Appendix A, the pilot test, which was conducted on an extraction well located in the center of the VOC plume, has already resulted in removal of 1,050 pounds. This removal has caused VOCs in soil-vapor monitoring wells to reduce significantly. Reductions of over 80 percent were observed in sampling tips 400 feet away from the extraction well. The amount of reduction decreased with distance from the well (see Appendix A). Thus, this alternative will reduce the volume of VOCs in the subsurface. In addition, the shutdown criteria (see Appendix C) inherently ensures that impact to groundwater is minimal.

The mobility of VOCs will be reduced within the zone of influence of the extraction well(s), since these VOCs would move towards the extraction well, and eventually be captured by the well. While there is no direct reduction in toxicity as a result of this alternative, the decrease in VOC-vapor volume results in reduction of the amount of toxic material.

Thus, Alternative 2c meets this criterion.

Short-Term Effectiveness

In situ SVE presents very few risks to on-site workers or the community with the exception of possible dust generation during well installation.

Equipment and operations for in situ SVE systems are readily available. The proposed SVE system will be designed such that the wells and the associated piping is under vacuum at all times (the extracted vapor will be "pulled" through carbon vessels by the extraction blower). The portions of the piping that are under pressure will only contain treated vapor. The treatment of the vapors with GAC will remove the majority of the VOCs, thereby minimizing VOC emissions to the atmosphere.

Thus, Alternative 2c meets this criterion.

Implementability

In situ SVE is one of the most commonly used remedial processes for treatment of VOC contamination in soil. Required equipment is readily available from many sources and does not require specialized knowledge for installation. Installing and operating vapor extraction wells requires fewer engineering controls than other technologies such as excavation and incineration, and no difficulties are foreseeable with regard to obtaining approvals from the various agencies.

GAC is the most widely used off-gas treatment for SVE systems. Treatment units are readily available and installation and operation are not difficult. Because the waste (spent carbon) is routinely transported and treated off-site, there are no anticipated issues regarding on-site waste storage and/or disposal services.

Soil vapor sampling is a proven technology, has been successfully tested at JPL, and is readily implemented particularly since numerous soil vapor sampling tips are already in place.

Thus, Alternative 2c meets this criterion.

Cost

Costs associated with this alternative include extraction-well installation, vacuum blowers, well-head GAC units, and the soil monitoring program.

Capital costs include installation of five new extraction wells that would be similar in construction to the existing pilot test extraction well (averaging 200 feet deep and each having three discrete screened intervals). Each well will be equipped with a 500-cfm blower and up to four GAC vessels containing 2,000 pounds of carbon each. Operating and maintenance costs cover power consumption for the blowers and carbon replacement/regeneration for the GAC units. The major pieces of equipment are expected to last for the duration of the treatment period without replacement.

Site engineering and planning are included as 15 percent of the construction cost and a 25 percent contingency is included. A present worth value for this alternative was determined using a 5 percent discount rate and assuming that the SVE system will operate for 5 years. The soil vapor monitoring component is assumed to be the same as for Alternative 1 (i.e., 5 years of quarterly monitoring followed by 25 years of annual monitoring). It should be noted that these durations (for both system operation and monitoring) are conservative and may be reduced depending on the ongoing soil vapor monitoring results.

Based on these parameters, the cost estimate for Alternative 2c is approximately $3,816,600. Cost calculations are presented in Appendix B.

5.2 COMPARATIVE ANALYSIS

Contained in this section is a comparative analysis of the alternatives with respect to each of the seven evaluation criteria. The comparative analysis provides the basis for identifying a preferred alternative for the JPL OU-2 site. A summary of the comparative analysis is presented in Table 5-2.

5.2.1 Overall Protection of Human Health and the Environment

This evaluation criterion involves assessing the degree to which each alternative provides adequate protection of human health and the environment. For this FS, both alternatives are considered protective of human health with regard to exposure to contaminants via direct exposure to soil. This is because the risk assessment indicated that the VOCs in surface soil do not pose a risk to humans. The focus is, therefore, a comparison of how well the alternatives protect the environment, specifically the groundwater. The VOCs in soils have migrated to the water table and are currently impacting groundwater quality. Protection of the environment is taken to be the inhibition of further groundwater contamination.

Alternative 1, the No Action alternative, relies on natural attenuation to reduce VOC concentrations in the vadose zone. This provides negligible protection of the environment. Alternatives 2c uses in situ SVE to remove VOCs from the contaminant plume in soil. This is substantially more protection than is offered by Alternative 1.

5.2.2 Compliance with ARARs

This evaluation criterion is used to evaluate how well each alternative conforms to federal and state ARARs or whether there is adequate justification for invoking waivers to specific ARARs. The ARARs for these remedial alternatives are described in Section 2.

Alternative 1 does not comply with ARARs since there is no VOC removal. Alternative 2c meets all ARARs as discussed in Section 5.1.2.

5.2.3 Long-Term Effectiveness and Permanence

Long-term effectiveness relates to the amount of risk remaining at the site after the remedial action objectives are met. At this site, risk will be reduced if continued migration of contaminants to groundwater is prevented, which is the only concern at this site for OU-2. Alternative 1 does not prevent migration of contaminants into groundwater and offers negligible long-term effectiveness and permanence. Alternative 2c is effective in the long-term because it permanently removes VOCs from the vadose zone.

Both alternatives include longer-term soil vapor sampling for, possibly, up to 30 years. The sampling program poses minimal risks to the community, the environment, or to workers involved in handling environmental samples.

5.2.4 Reduction in Toxicity, Mobility, and Volume

This criterion is a measure of the reduction in toxicity, mobility, and volume of the constituents of interest at a site and also the extent to which the reduction is irreversible. Alternative 1 does not include any treatment, so there is no reduction in toxicity, mobility, or volume except for minor reductions provided by natural attenuation.

Alternatives 2c provides significant reduction in volume by permanently and irreversibly removing VOCs from the vadose zone. This reduces the mobility of the contaminants and the volume of contamination in the soil.

5.2.5 Short-Term Effectiveness

Short-term effectiveness is a measure of the impacts to workers, the community, and the environment during the construction and operating life of the remedial action. Because Alternative 1 does not include either construction or operation of a treatment system, there are no effects on the community, workers, or the environment. For these reasons, Alternative 1 has very few impacts in the short term.

Alternative 2c relies on in situ SVE for treatment, and requires installation of up to five new soil vapor extraction wells. Short-term impacts to workers and the community are limited to possible dust releases during well installation, which would have a negligible impact. SVE system operation would also result in negligible impacts since the system is in situ. The only waste streams generated include spent GAC and entrained water (entrained moisture, which is separated using a knockout tank). VOCs in the off-gas stream are permanently removed from the stream, and emissions will comply with air emission standards. Therefore, Alternative 2c results in only slightly higher short-term risks than the No Action alternative.

5.2.6 Implementability

Implementability is a measure of how easily a remedial action can be installed and operated. At the JPL OU-2 site, Alternative 1 is the easiest alternative to implement because no construction activities are performed.

Implementation of the in situ SVE systems for Alternative 2c is relatively straightforward in that this is the most commonly used process for treating VOC contamination in soil. Required equipment is readily available from many sources and does not require specialized knowledge for installation.

5.2.7 Cost

Cost considerations include capital costs and O&M costs as well as the cost of the soil vapor monitoring program.

Alternative 1 is the least expensive alternative since no activities are planned under this alternative except soil-vapor monitoring. The estimated total cost for Alternative 1 is approximately $1,477,000.

The estimated total cost for Alternative 2c is approximately $3,816,600. This includes installation of the five new vapor extraction wells, five new vapor extraction and treatment systems, operation and maintenance of the existing and new systems for a 5-year period, quarterly soil-vapor monitoring for first 5 years, and annual soil-vapor monitoring for 25 years.

5.3 PREFERRED ALTERNATIVE

Alternative 1, No Action, is not appropriate for the site because no protection of groundwater is provided, and, therefore, the RAO for the site will not be met. Based on the preceding analysis of alternatives, Alternative 2c, In Situ SVE/GAC Off-Gas Treatment, is chosen as the preferred alternative for the JPL OU-2 site.

TABLES

TABLE 5-1

FACTORS FOR DETAILED EVALUATION OF ALTERNATIVES

Overall Protection	How alternative provides human health and environmental protection.
Compliance with ARARs	Compliance with chemical-specific ARARs. Compliance with location-specific ARARs. Compliance with action-specific ARARs. Compliance with other criteria, advisories, and guidance.
Long-Term Effectiveness and Permanence	Reduction of existing risks. Magnitude of future risks. Long-term reliability. Prevention of future exposure to residuals.
Reduction of Toxicity, Mobility, and Volume Through Treatment	Amount of hazardous materials destroyed or treated. Degree of expected reductions in toxicity, mobility, and volume. Degree to which treatment is irreversible. Type and quantities of residuals remaining after treatment.
Short-Term Effectiveness	Time until protection is achieved. Short-term reliability of technology. Protection of community during remedial actions.
Implementability	Ability to operate and construct the technology. Ability to phase into operable units. Ease of undertaking additional remedial actions, if necessary. Ability to monitor effectiveness of remedy. Ability to obtain approvals from other agencies. Coordination with other agencies. Availability of treatment, storage, and disposal services and capacity. Availability of necessary equipment and specialists.
Cost	Construction costs. Operating costs for implementing remedial action. Other capital and short-term costs until remedial action is complete. Costs of operation and maintenance for as long as necessary. Costs of 5-year reviews (if required).
State Acceptance(1)	Features of the alternative the state supports. Features of the alternative about which the state has reservations. Features of the alternative the state strongly opposes.
Community Acceptance(1)	Features of the alternative the community supports. Features of the alternative about which the community has reservations. Features of the alternative the community strongly opposes.

Notes:

(1): Not evaluated in feasibility study because of limited available information. State and community acceptance will be fully addressed in the record of decision (ROD).

TABLE 5-2

DETAILED SCREENING OF ALTERNATIVES

	Alternative 1	Alternative 2c	Comments
Description	• No Action • Soil-Vapor Monitoring	• *In Situ* SVE • GAC Off-Gas Treatment • Soil-Vapor Monitoring	
Overall Protection	• Not protective of environment.	• Protective of environment.	• Protection of human health not needed because no human receptors at this site. Alternative 2c indirectly provides protection by reducing VOCs in the subsurface soils, which in turn reduces the potential for further impact to groundwater.
Compliance with ARARs	• Does not comply with ARARs	• Complies with ARARs	• Compliance for Alternative 2c is either direct, or through design of full-scale SVE systems.
Long-Term Effectiveness	• Not effective in long-term. • Constituents of interest remain at site and will be released to groundwater.	• Very effective in long-term. • Constituents of interest permanently removed from vadose zone.	
Reduction of Toxicity, Mobility, or Volume	• No reduction in toxicity, mobility, or volume of constituents of interest.	• Nearly complete reduction in volume of constituents of interest through SVE. GAC removes, but does not destroy constituents of interest.	• COPCs are transferred to VPGAC for Alternative 2c, but are subsequently removed during regeneration.
Short-Term Effectiveness	• Extremely high short-term effectiveness. • No risks to workers, community, or environment.	• High short-term effectiveness. • Few risks to workers, community, or environment.	• Alternative 1 has highest short-term effectiveness. Alternative 2c highly effective in short-term.
Implementability	• Very easily implemented. • No activities required.	• Easily implemented. • SVE is well-known treatment system. • GAC also well-known, easily implemented.	• Alternative 1 is most easily implemented. • Alternative 2c is easily implemented due to wide acceptance of GAC for off-gas treatment.
Cost	• Approximate cost: $1,477,000	• Approximate cost: $3,816,600	• Alternative 1 is least expensive. • Alternative 2c is most expensive.
Conclusion	• Does not pass first two criteria (threshold criteria).	• Preferred alternative.	• Meets RAOs, complies with ARARs in a cost-effective manner.

Notes:

ARAR – Applicable or relevant and appropriate requirement
COPC – Constituent of potential concern
GAC – Granular activated carbon
RAO – Remedial action objective
SVE – Soil vapor extraction
VOC – Volatile organic compound
VPGAC – Vapor-phase granulated activated carbon

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APPENDIX A

SUMMARY REPORT
SOIL VAPOR EXTRACTION PILOT TEST

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ACRONYMS AND ABBREVIATIONS

amsl	Above mean sea level
bgs	Below ground surface
CCl_4	Carbon tetrachloride
cfm	Cubic feet per minute
1,1-DCA	1,1-Dichloroethane
1,1-DCE	1,1-Dichloroethene
1,2-DCA	1,2-Dichloroethane
DTSC	California Department of Toxic Substances Control
EPA	U.S. Environmental Protection Agency
Freon 113	Trichlorotrifluoroethane
ft	feet
GAC	Granular activated carbon
H_2O	Water
in.	Inch or inches
in. H_2O	Inches of water
JPL	Jet Propulsion Laboratory
lb	Pound
lbs/hr	Pounds per hour
NASA	National Aeronautics and Space Administration
OU-2	Operable Unit 2 (On-Site Contaminant Source Investigation)
PVC	Polyvinyl chloride
RI/FS	Remedial investigation/feasibility study
ROI	Radius of influence
RORI	Radius of remedial influence
RPM	Remedial Project Manager
RWQCB	California Regional Water Quality Control Board, Los Angeles Region
SVE	Soil vapor extraction
TCE	Trichloroethene
VOC	Volatile organic compound

1.0 INTRODUCTION

Presented in this summary report are the results of a long-term soil vapor extraction (SVE) pilot test conducted in Operable Unit 2 (OU-2) at National Aeronautics and Space Administration's (NASA's) Jet Propulsion Laboratory (JPL) facilities. These facilities are located at 4800 Oak Grove Drive in Pasadena, California and are referred to as "JPL" throughout the rest of this document. Figures A.1-1 and A.1-2 are a Site Location Map and Site Facility Map for the site, respectively.

The test was conducted in the parking lot located between Buildings 18 and 79 (Figure A.1-2). Based on previous investigations at the site, subsurface soils in OU-2 are known to be impacted with volatile organic compound (VOC) vapors, primarily carbon tetrachloride (CCl_4). The Remedial Investigation/Feasibility Study (RI/FS) Work Plan (Ebasco, 1993) and its addenda (Foster Wheeler, 1996a and 1996b) identified the investigative work required to adequately characterize the impacted soil. The investigative work identified in the RI/FS Work Plan consisted of installation and sampling of nested soil vapor monitoring wells. The sampling of these wells has indicated the presence of VOC vapors including CCl_4, chloroform, Freon 113, trichloroethene (TCE), 1,1-dichloroethane (1,1-DCA), 1,2-dichloroethane (1,2-DCA), and 1,1-dichloroethene (1,1-DCE).

Based on the soil types at JPL and the nature and extent of contamination, in situ SVE appears to be a feasible technology for remediating the VOC impacted soils in OU-2. In situ SVE was one of the in situ technologies identified as a potential remedial technology for OU-2 in the 1993 RI/FS Work Plan. During ongoing Remedial Project Manager (RPM) meetings (September 4, 1997, and December 3, 1997) attended by representatives from NASA, JPL, Foster Wheeler Environmental Corporation (Foster Wheeler), the U.S. Environmental Protection Agency (EPA), the California Regional Water Quality Control Board, Los Angeles Region (RWQCB), and the California Department of Toxic Substances Control (DTSC), it was agreed that a pilot test would be conducted to confirm the feasibility of using in situ SVE at the site. In addition, the pilot test would also provide design criteria for implementing a full-scale SVE system at the site. The entire test, including setup and demobilization, was initially expected to require approximately 9 weeks to complete. The initial test was to run in two test phases, Test 1 and Test 2.

The test was started in April 1998 and conducted through June 1998 in accordance with the SVE pilot test work plan contained in Addendum Number 2 to the Field Sampling and Analysis Plan for Performing a Remedial Investigation at Operable Unit 2 (Foster Wheeler, 1998). Based on the results of the test it was decided to extend the test for an additional 9 months, as discussed during the RPM Meeting on July 16, 1998. During the extended portion of the test, noted as the third test phase (Test 3), the SVE system operated from November 1998 and continued, with exception of a few temporary shutdowns, through September 1999. Since then, the SVE system has been placed on standby.

Presented in this report are the scope of the pilot test, equipment used for the test, test procedures, and a summary of the data obtained from the test. A supplementary report will be submitted upon completion of the test.

1.1 PILOT TEST OBJECTIVES

The objectives of the SVE pilot test were to:

- Confirm the feasibility of using SVE at JPL.
- Estimate physical design parameters, such as SVE flow rate from the extraction well at different extraction vacuums, radius of influence (ROI) of a single extraction well, and permeability of the soil to air flow.
- Evaluate VOC concentrations in extracted vapor.

1.2 SCOPE OF WORK

To meet the above objectives, one pilot test well (VE-1) with three discrete screened intervals was installed. Twelve existing monitoring points (with multiple sample ports) in the vicinity of this well were used for monitoring purposes. Additional details regarding the test well and the monitoring points are provided in Section 2.0.

The scope of work required to meet the project objectives consisted of three test phases:

1. Test 1 – Short-term tests: three on individual screens, one on all three screens combined.
2. Test 2 – Long-term test on two combinations of screens: one on all three screens combined and one on Screens B and C combined.
3. Test 3 – This was a continuation of Test 2 on Screens B and C combined and Screen C separately.

In addition, VOC concentrations in individual screens and soil vapor monitoring points were monitored periodically to provide additional data pertaining to SVE effectiveness.

Test 1 was started on April 13, 1998, and was completed on May 7, 1998. Test 2 was started on May 11, 1998, and was completed on June 10, 1998. Test 3 was started on November 2, 1998, and was shut down on September 22, 1999. The SVE system is currently on standby.

1.3 REPORT ORGANIZATION

The remainder of the Report is organized into the following sections:

Section 2.0 – Equipment and Materials: describes the equipment and materials used for the test.

Section 3.0 – Test Procedures: describes the general test procedures performed during Test 1, Test 2, and Test 3.

Section 4.0 – Results and Data Analysis/Interpretation: describes the results of the data collected and various data analyses to meet the project objectives.

Section 5.0 – Conclusions: summarizes conclusions of the SVE pilot test.

Section 6.0 – References.

2.0 EQUIPMENT AND MATERIALS

This section provides descriptions of the extraction well, monitoring wells, and treatment/ sampling equipment used in the SVE pilot test.

2.1 WELLS

During the course of the SVE pilot test, two types of wells were used: a SVE well and monitoring wells. The location of these wells is shown in Figure A.1-2.

2.1.1 Extraction Well

A single vapor extraction test well (VE-1) was used for the SVE pilot test. It is located approximately at the center of the highest soil-vapor contamination. The well consists of three discrete screened intervals (i.e., three separate casings in the same borehole) with a bentonite seal between screens. The screens are designated shallowest to deepest as VE-1A (Screen A), VE-1B (Screen B), and VE-1C (Screen C), respectively. Each casing is constructed of Schedule 80 PVC, and is screened (0.020 inch slots) from 44 to 84 feet below ground surface (bgs), 94 to 134 feet bgs; and 145 to 185 feet bgs as shown in Figure A.2-1. Screens A, B, and C each have inside diameters of 2 inches. The annular space between the screens and the borehole is backfilled with Lonestar RMC® No. 3 sand, and the annular space between the blank casing and the borehole is filled with Enviroplug® No. 16 bentonite granules.

2.1.2 Monitoring Wells

Twelve soil vapor monitoring wells (SVW-25, -26, -27, -28, -32, -33, -34, -35, -36, -37, -38, and -39) were used for monitoring (Figure A.1-2). Each well contains discrete depth-specific monitoring points. These were used to monitor vacuum responses and to collect depth-specific soil vapor samples during the test. In total, there were 110 depth-specific monitoring points available. However, because of the fluctuating water table and other unknown factors, some of the probes were plugged and, therefore, were not continuously monitored. Also, access to some of the soil vapor monitoring wells was not always available.

2.2 EXTRACTION/TREATMENT EQUIPMENT

The following subsections provide a description of the extraction/treatment equipment. Figure A.2-2 shows a piping and instrumentation diagram for the pilot test equipment.

2.2.1 Blower Package

Tests 1 and 2

Because of restrictions imposed by the South Coast Air Quality Management District (SCAQMD) Permit to Operate (PTO) (Multiple Locations Permit), extraction blowers operating at the site were limited to a maximum flow rate of 200 cubic feet per minute (cfm) per unit. Hence, two units were used in parallel during the last week of Test 1 and for the entire duration of Test 2. Both extraction systems met the following specifications:

- One trailer mounted, one skid mounted.
- Common 50-gallon knockout tank, level switch, and safety interlock to shut down blower for high water level.
- Vacuum blower, maximum flow 200 cfm, maximum vacuum equivalent to 10 inches of mercury. Blowers 1 and 2 operated at a maximum flow rate of 200 cfm and 100 cfm, respectively.
- Dilution air valve and recirculation air valve to regulate vacuum and flow.

Test 3

For Test 3, the above-mentioned equipment was replaced with a single 20-horsepower positive displacement blower package (skid-mounted). Temporary power connections were provided by JPL.

2.2.2 Treatment System

Tests 1 and 2

The treatment system in Tests 1 and 2 consisted of two 1,000-pound (lb) vapor-phase granular activated carbon (GAC) vessels in series per blower unit (four vessels total). This met the vendor's SCAQMD PTO requirements.

Test 3

The treatment system in Test 3 consisted of two parallel trains of two 2,000-lb vapor-phase GAC vessels in series (four vessels total). In May 1999, the vapor-phase GAC vessels were replaced with vapor-phase GAC vessels fitted with reinforcement boards to withstand higher vacuums.

2.3 SAMPLING/TESTING EQUIPMENT

Various sampling/testing equipment was used for the test, as follows:

- Flow Meter – to measure extracted flow rates.
- Flame Ionization Detector – to analyze extracted soil vapors and treated effluent.

- Tedlar Bags/Summa Canisters – to collect vapor for laboratory analyses.
- Sample Pumps – to collect soil vapor samples.
- Vacuum Gauges – to measure vacuums.
- Vacuum Chamber – to collect vapor samples from the extraction wells and piping while the system was in operation, without contaminating the sample pump.

3.0 TEST PROCEDURES

A general outline of the procedures followed during the performance of Tests 1, 2, and 3 are provided in the following subsections.

3.1 TEST 1 PROCEDURE

Test 1 consisted of applying a vacuum to each of the three-screened intervals of the extraction well individually and all three screens combined (four runs total). During each run, applied vacuum levels were varied on a day-to-day basis. Each vacuum level was applied for an 8-hour day, requiring each run 1 week to complete (baseline sampling/monitoring was performed on day 5). Test 1 ran for 4 weeks total. The vacuum application schedule is further outlined below.

Week	Screen	Day 1	Day 2	Day 3	Day 4
1	VE-1A	Maximum Vacuum	75 percent Maximum Vacuum	50 percent Maximum Vacuum	25 percent Maximum Vacuum
2	VE-1B	Maximum Vacuum	75 percent Maximum Vacuum	50 percent Maximum Vacuum	25 percent Maximum Vacuum
3	VE-1C	Maximum Vacuum	75 percent Maximum Vacuum	50 percent Maximum Vacuum	25 percent Maximum Vacuum
4	VE-1ABC	Maximum Vacuum	75 percent Maximum Vacuum	50 percent Maximum Vacuum	25 percent Maximum Vacuum

Soil vapors were extracted using a single 200 cfm blower and treated using two 1,100-pound carbon vessels in series. Two blowers (an additional 100 cfm blower was added), each followed by a series of carbon vessels (four 1,100-lb carbon vessels total) were used during Week 4 of testing. Field measurements were divided into three categories, Tests 1 and 2: Extraction Well Data (Attachment 1), Tests 1 and 2: Monitoring Well Data (Attachment 2), and Tests 1 and 2: Laboratory Results (Attachment 3). Extraction well data measurements were collected at the extraction well. These measurements included vacuum pressures, flow rates, and extracted vapor concentrations prior to carbon treatment (influent) and after carbon treatment (effluent). In addition, laboratory samples were collected at a minimum of twice per day. All laboratory samples were analyzed for VOCs by EPA Methods 8010/8020 in accordance with RWQCB protocols. Monitoring well data consisted of vacuum response readings at nearby soil vapor monitoring wells SVW-25, -26, and -28. Each monitoring well has a series of depth specific probes where measurements were taken.

3.2 TEST 2 PROCEDURE

Test 2 represented the initial portion of the long-term SVE test. The system was operated continuously for a period of 1 month. Over the first 3 weeks, vacuum pressure of approximately 26 inches of water (in. H_2O) was applied to Screens A, B, and C concurrently, using two blowers. The effluent from each blower was treated by two carbon vessels in series (four 1,100-lb carbon vessels total). During the final week of Test 2, the same vacuum was applied only to Screens B and C concurrently using only one blower[1]. Extracted vapors were treated through a series of two carbon vessels initially and through three carbon vessels during the final days of operation because of potential breakthrough in the primary carbon vessel. Field measurements were essentially identical to those collected during Test 1 and are also presented in Attachments 1, 2, and 3. Toward the end of Test 1, vacuum responses were observed in some of the more distant soil vapor monitoring wells. Hence, for Test 2, vacuum response measurements were also taken at SVW-28, -32, -33, -34, -35, -37, and -38. As can be seen from Figure A.1-2, these are at significant distances from VE-1.

3.3 TEST 3 PROCEDURE

Test 3 represents the final (extended) portion of the long-term SVE test. Test 3 was started on November 2, 1998, shut down on September 22, 1999, and is currently on standby. Vacuum was initially applied only on Screens B and C combined. This optimal combination was chosen after analyzing VOC removal data (see Section 4.0 for data analysis) and based on literature (Shan and others, 1992). During the later portion of the test, vacuum was applied only to Screen C. As with Test 1, field measurements were divided into three categories, Test 3: Extraction Well Data (Attachment 4), Test 3: Monitoring Well Data (Attachment 5) and Test 3: Laboratory Results (Attachment 6). The field measurements are very similar to the data collected during Test 1; however, additional vacuum reading and one additional soil vapor monitoring well (SVW-39) was added. Based on the data review of the initial 3 weeks of operation, the field measurement collection frequency was decreased from that in Tests 1 and 2.

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[1] This was necessitated by mechanical problems with one of the blowers.

4.0 DATA ANALYSIS / INTERPRETATION

Presented in this section are the various data collected to date during the SVE pilot test and an interpretation of this data. All figures generated for Section 4.0 were produced from data in Attachments 1 through 6.

4.1 TEST 1

The primary objective of Test 1 was to determine the effect of applied vacuum on the extraction well screens. Results generated from the data gathered in Test 1 include: vacuum to flow correlations, vacuum response with respect to distance from the extraction well, soil permeability, and VOC removal rates with respect to applied vacuum.

4.1.1 Vacuum versus Flow

As described earlier, Test 1 consisted of applying vacuums to Screens A, B, and C individually and then to Screens A, B, and C combined for four runs at four 8-hour days per run. On day 1 of each run, the blowers were set at maximum capacity. The blower capacity was reduced by 25 percent on day 2, 50 percent on day 3, and 75 percent on day 4 of each run (Table A.3-1). Test 1 extraction well data indicates that extraction flow rates decreased as applied vacuum decreased. Results are plotted as Figure A.4-1 and are discussed in the remainder of this section. Figure A.4-1 was generated based on data presented in Attachment 1.

The maximum applied vacuum to Screen A was recorded at 44 in. H_2O, which produced an extraction flow rate of 174 cfm. As the applied vacuum was reduced (25 percent increments), the flow rate also decreased as expected. The maximum applied vacuum to Screen B was recorded at 70 in. H_2O, which produced an extraction flow rate of 167 cfm. Similar to Screen A, as the applied vacuum on Screen B was reduced the flow rate also decreased. The maximum applied vacuum to Screen C was recorded at 80 in. H_2O, which produced an extraction flow rate of 157 cfm. Applied vacuum to flow rate response was fairly similar to that of Screen B. The results suggest that when extracting from individual screens, Screen A requires the least applied vacuum to produce a given flow rate, while Screen C requires more applied vacuum to produce the same flow rate. Based on this observation, it appears that soil permeability decreases with depth. To further support this conclusion, soil permeability calculations were performed and are presented in Section 4.1.3.

The maximum applied vacuum to Screens A, B, and C combined was recorded at 25 in. H_2O, which produced an extraction flow rate of 277 cfm.

4.1.2 Vacuum Responses

Responses to the applied vacuum at the extraction well were measured at various soil vapor monitoring wells within the vicinity of VE-1. As described in Section 2.1.2, each soil vapor monitoring well contains several depth-specific probes. The probes were used to measure vacuum responses at various depths and distances from the extraction well. Four monitoring zones, based on elevation, have been designated for the purpose of data analysis (Figure A.4-2). Zone 1 includes the subsurface areas at an elevation greater than 1,151 feet above mean sea level (amsl); Zone 2 covers the elevation interval of 1,151 feet to 1,101 feet amsl; Zone 3 covers the elevation interval of 1,051 feet to 1,001 feet amsl; and Zone 4 covers the elevation interval of 1,051 feet to 1,001 feet amsl. Elevations for Zones 2, 3 and 4 were designated to correspond to screened interval elevations at Screens A, B, and C [Screen elevations: A (1,146 feet to 1,106 feet.), B (1,096 feet to 1,056 feet), C (1,046 feet to 1,006 feet)], respectively. For a given monitoring well, the responses at the probes (for each zone) were averaged. Thus, for each monitoring well there is one "average" vacuum response for each of the four zones.

During Test 1, responses were measured in monitoring wells SVW-25, -26, and -28. The results were plotted with respect to distance from VE-1 for all the extracting scenarios (Figures A.4-3 through A.4-6). As expected, the figures show that average vacuum responses were generally highest in the zone that corresponds to the extracting well screen and decreased with distance. For example, Figure A.4-3 illustrates that while extracting from Screen A, the greatest average vacuum responses were noted in Zone 2. Overall, Zone 1 showed the least average vacuum responses, this is expected since there is no extraction screen at the Zone 1 elevation. To some extent, this indicates that surface leakage is minimal based on the lack of responses in Zone 1 for the two closest soil vapor monitoring wells. This may be attributable to the fact that almost 90 percent of JPL is capped. Furthermore, as discussed later, vacuum responses during Tests 2 and 3 were noted in wells at a significant distance from VE-1, which again points to minimal surface leakage.

Based on Figure A.4-3, while extracting from Screen A, Zone 2 showed good vacuum responses in all three monitoring wells. Vacuum response averages in Zone 2 ranged from 0.7 in. H_2O to 1.8 in. H_2O. Zones 1, 3, and 4 did not show good responses with the exception of Zone 1 at well SVW-26 (response of 1.63 in. H_2O).

Based on Figure A.4-4, while extracting from Screen B, Zone 3 showed the best vacuum responses. While extracting from Screen B, vacuum response averages in Zone 3 ranged from 0.38 in. H_2O to 2.05 in. H_2O. Average vacuum responses for the other zones were below 0.85 in. H_2O.

Based on Figure A.4-5, while extracting from Screen C, the best average vacuum responses were recorded in Zone 4 (monitoring points were not available for Zone 4 in SVW-28,). Average vacuum responses in Zone 4 ranged from 1.20 in. H_2O to 2.95 in. H_2O. In addition, Zone 3 showed a significant average vacuum response reading while extracting from Screen C. Average vacuum responses in Zone 3 were recorded as high as 1.37 in. H_2O (SVW-25). Relatively low average vacuum responses were recorded at Zones 1 and 2.

Based on Figure A.4-6, while extracting from all three screens combined, Zones 2, 3, and 4 showed good vacuum responses. Overall, the best average vacuum responses were recorded in Zone 3 where they ranged from 0.53 in. H_2O to 2.63 in. H_2O. For Zone 2 and Zone 4, average vacuum responses ranged, respectively, from 0.0 in. H_2O to 1.9 in. H_2O and from 0.95 in. H_2O to 2.25 in. H_2O. Vacuum responses in Zone 1 were relatively low (less than 0.01 in. H_2O) with the exception of the response at SVW-26, which showed an average vacuum response of 0.95 in. H_2O.

4.1.3 Soil Permeability

Soil permeability is a measure of the ability of soil to allow airflow through its pore spaces. The following mathematical equation can be used to calculate permeability (Johnson and others, 1990):

$$\frac{Q}{H} = \pi \frac{k}{\mu} P_e \frac{[1-(P_m/P_e)^2]}{\ln(R_e/D_m)} \qquad (1)$$

Where:

Q = Flow [cfm, cm^3/s]

H = Screen interval [ft, cm]

K = Soil Permeability to air flow [darcy, cm^2]

μ = Viscosity of air [centipoise, g/cm-s]

P_e = Extraction well vacuum [inches H_2O, g/cm-s^2]

P_m = Monitoring well response [inches H_2O, g/cm-s^2]

R_e = Extraction well radius [ft, cm]

D_m = Distance of monitoring well from extraction well [ft, cm]

π = 3.14

ln = Natural logarithm

Based on equation 1, soil permeability was calculated for the test site. Using data collected during Test 1, soil permeabilities were calculated for Zones 2, 3 and 4. Soil permeability calculations are presented in Table A.4-1. Zone 2 calculations were based on vacuum response data [date and time, respectively (April 13, 1998, 12:15)] from the monitoring probes in Zone 2 of monitoring wells SVW-25, -26, and -28. Similarly, calculations for Zones 3 and 4 were based on vacuum response data (April 20, 1998, 10:00 and April 27, 1998, 14:00) from the monitoring probes in Zones 3 and 4 of monitoring wells SVW-25, -26, and -28. Results indicate that Zone 2 is the most permeable of the three zones. The estimated soil permeability value for Zone 2 is 12.60 darcy. The estimated soil permeability values for Zones 3 and 4 are 6.83 darcy and 5.72 darcy, respectively. These results justify the soil permeability conclusions made in Section 4.1.1.

Note, soil permeability calculations are only justifiable within the radial distance of SVW-28 (167 feet) from VE-1.

4.1.4 VOC Analysis

As discussed previously, the OU-2 RI (Foster Wheeler Environmental, 1999) indicated subsurface soils at OU-2 were impacted by VOCs, primarily CCl_4, Freon 113, TCE, and 1,1-DCE. The majority of the contamination extracted during Test 1 was CCl_4. Trace amounts of Freon 113 were also extracted. A total of approximately 11.1 lbs of VOCs (10.7 lbs of CCl_4 and 0.4 lbs of Freon 113) were extracted during Test 1. Extraction rate calculations are presented in Table A.4-2 and cumulative VOC removals are plotted on Figure A.4-7.

CCl_4 concentrations with respect to applied vacuum are plotted in Figure A.4-8. Since CCl_4 was at the highest concentration, only CCl_4 concentrations were plotted for the purpose of this analysis. The figure suggests that VOC concentrations did not vary significantly with vacuum during Test 1.

4.2 TEST 2

The objectives of Test 2 were to verify the vacuum responses observed during Test 1, to determine the ROI for the site, and to determine VOC removal rates trends over time.

4.2.1 Vacuum Responses

As with Test 1, vacuum responses due to the applied vacuum at the extraction well were measured at monitoring wells within the vicinity of VE-1. However, because of the high vacuum responses observed at distant soil vapor monitoring wells during Test 1, additional monitoring wells (at further distances) were observed during Test 2. Vacuum response measurements were taken at SVW-25, -26, -27, -28, -32, -33, -34, -35, -37, and -38. Since additional monitoring wells were available during Test 2, additional data were available to confirm that significant responses were present in the monitoring zones (Zones 1 to 4) at much further distances. Vacuum responses were noted as far as 771 feet away (SVW-38). Similar to Test 1, the average vacuum response in each zone with respect to distance from VE-1 was plotted for both extracting scenarios (Figures A.4-9 through A.4-10). Again, as in Test 1, the plots suggest that average vacuum responses are generally highest in the zones that correspond to the extracting well screens and decreased with distance. For example, Figure A.4-9 illustrates that when extracting from the combined Screens A, B, and C, Zones 2, 3, and 4 showed significant average vacuum response, whereas Zone 1 generally showed minimal average vacuum responses. These results, along with the decrease with distance, indeed imply that the observed vacuum responses are due to the operation of the SVE system.

To demonstrate that the observed vacuum responses were truly a function of the applied vacuum to the extraction well, vacuum response tests were performed. These tests consisted of cycling the SVE system on and off while recording vacuum responses. The results have been plotted with respect to time (Figures A.4-11 through A.4-20) and clearly show that the vacuum responses were a function of the applied vacuum. It should be noted that in these figures actual vacuum responses were plotted and not the average "zone" vacuum responses. As can be seen in Figure A.4-11 through A.4-20 when the SVE system was shut down and time was allowed for the subsurface to reach equilibrium, the vacuum responses were generally at a minimum (zero or close to zero). Also, when the SVE system was restarted, vacuum responses immediately (within 1 to 2 hours) started to rebound. Similarly, when the SVE system was shut down, vacuum responses immediately decreased in magnitude. Thus, the results of the vacuum response tests confirm that the vacuum responses in the soil vapor monitoring wells were caused by the applied vacuum at the extraction well.

4.2.2 ROI Estimation

The ROI is described as a mathematical estimate of the upper limit of distance at which the effects of extraction can be observed. These effects are usually measured as vacuum responses at the monitoring wells. Generally, the ROI is defined as the distance from the extraction well at which the response is 1.0 percent of the applied vacuum.

To determine ROI at the site, vacuum-response data was normalized and plotted as Figures A.4-21 and A.4-22. Figure A.4-21 indicates that while extracting from Screens A, B, and C combined, the ROIs for Zones 2, 3, and 4 are approximately 665, 950, and 1,000 feet, respectively. Figure A.4-22 indicates that while extracting from Screens B and C combined, the ROIs for Zones 2, 3, and 4 are 215, 900, and 900 feet, respectively.

It is recognized that these ROIs are somewhat higher than expected. As discussed in Section 4.3.3, a different approach (using actual reduction in VOC concentrations in soil vapor monitoring wells) may be warranted.

4.2.3 VOC Analysis

The majority of the contamination extracted during Test 2 was CCl_4. Trace amounts of Freon 113 were also extracted. A total of approximately 62.6 lbs of VOCs (57.0 lbs of CCl_4 and 4.6 lbs of Freon 113) were extracted during Test 2. Extraction rate calculations are presented in Table A.4-3 and cumulative VOC removals are plotted on Figure A.4-23. Generally, the data indicate that the VOC removal rates decreased with time (Figure A.4-24). While applying vacuums to Screens A, B, and C combined, the VOC removal rates ranged from 0.23 pounds per hour (lbs/hr) to 0.10 lbs/hr. While applying vacuums to Screens B and C combined, the VOC removal rates ranged from 0.11 lbs/hr to 0.08 lbs/hr.

Removal rates are a function of extracted flow rates and VOC concentration in the extracted vapors. During Test 2, the two primary carbon vessels were prematurely exhausted on two separate occasions. Testing at the carbon vendor's laboratory indicated high VOC loading although VOC removals based on laboratory analyses of the extracted soil vapor and flow rates did not indicate that carbon capacity had been reached. This indicates that one or more slugs of

VOCs may have been extracted. The amount of VOCs extracted during Tests 1 and 2, based on a 44.6 percent loading as reported by the carbon vendor, is 1,784 pounds (44.6 percent of 4,000 pounds – two vessels each with 1,000 pounds, on two occasions). Attachment 7 shows the results of the analyses on the first batch of exhausted carbon. This is only an estimate and actual VOC removal may have been lower since the analysis was based on carbon samples collected from the vessel near the inlet ports. This also includes the 73.7 pounds based on the laboratory analyes of the vapors. Hence, an estimated 800 pounds (approximately 20 percent loading) of VOCs were assumed to be removed in addition to the 73.7 pounds. Since this removal could not be substantiated by laboratory results of vapor analyses, it was not included in the removal rate calculations.

4.3 TEST 3

The objectives of Test 3 were to confirm the results of Test 2 (verification of vacuum responses, ROI, and VOC removal trends), determine the radius of remediation influence (RORI), and conduct system optimization tests.

4.3.1 Vacuum Responses

For Test 3, vacuum responses due to the applied vacuum at the extraction well were measured at monitoring wells SVW-25, -26, -27, -28, -32, -33, -34, -35, -36, -37, -38, and -39. As with Test 2, vacuum response tests were conducted to demonstrate that the observed vacuum responses were truly a function of the applied vacuum to the extraction well. As with Test 2, the results have been plotted with respect to time (Figures A.4-25 through A.4-34) and once again clearly show that the vacuum responses were a function of the applied vacuum.

4.3.2 ROI Estimation (Vacuum)

Test 3 consisted of extracting from Screens B and C combined from November 2, 1998, through September 8, 1999. The final portion of Test 3 extended from September 8, 1999, through September 22, 1999, and consisted of extracting from Screen C only. As in Test 2, the ROI is defined as the distance from the extraction well at which the response is a minimum of 1.0 percent of the applied vacuum. Plots similar to those generated for Test 2 (normalized vacuum response plots) were prepared to confirm the ROI. These are shown in Figures A.4-35 and A.4-36. Based on Figure A.4-35, while extracting from combined Screens B and C, the ROIs for Zones 2, 3, and 4 are estimated at 65, 460, and greater than 1,000 feet, respectively. Based on Figure A.4-36, while extracting from Screen C only, ROIs for Zones 2, 3, and 4 were reduced to 25, 350, and 520 feet, respectively. The results of the ROI analysis conducted for Test 2 and Test 3 indicate that the ROI for Zones 3 and 4, while extracting from combined Screens B and C is 460 feet. To be conservative, 460 feet is designated as the effective ROI for the site.

4.3.3 RORI Estimation (Remediation)

The ROI, based on vacuum response, is estimated to be on the order of 460 feet for Zones 3 and 4 while extracting from combined Screens B and C. However, this ROI may not be representative of the actual area that the extraction well is capable of remediating based on literature and previous experience. Hence, an alternate method for estimating the influence of remediation was used. This consists of estimating the "radius of remediation influence" (RORI), which is defined as the distance at which a significant the reduction of VOC levels is observed in monitoring wells (as opposed to observed vacuum responses). Since the objective of SVE is to reduce VOC levels in the subsurface, this method is expected to be more realistic than the vacuum response ROI method.

Prior to initiating Test 3 (May 1998) and after the SVE system was placed on standby (October 1999), soil vapor monitoring was conducted to evaluate SVE effectiveness. VOC percent reductions for CCl_4 and Freon 113 concentrations as of October 1999 (compared to May 1998 VOC concentrations) are plotted in Figures A.4-37 through A.4-42, for Zones 2, 3, and 4. For the purpose of this analysis, it has been assumed that an effective RORI will extend to the point of 50 percent VOC reduction. Based on this analysis, reductions of CCl_4 greater than 50 percent extend beyond 1,000 feet for Zones 2 and 3 and at approximately 915 feet for Zone 4. Reductions in Freon 113 greater than 50 percent have been estimated to extend beyond 1,000 feet for Zone 2 and to 400 feet for Zones 3 and 4. The results indicate the remedial effectiveness is much greater for CCl_4 than for Freon 113 with a reduction of 80 to 90 percent of CCl_4 at 400 feet. Since CCl_4 is the primary VOC of concern, the RORI is designated at 400 feet to be conservative.

4.3.4 Pore Volume Exchange Rate

Pore volume exchange rate (PVER) is an indirect means of determining the number of SVE wells required at a site. PVER may be defined as the rate at which one complete pore volume of the impacted soil is exchanged. The number of wells required would then be based on adequate PVER within a removable time frame.

For VE-1, when extracting from B and C, the PVER is estimated as follows:

$$\text{Time for 1 PVER, month} = \frac{\pi \text{ x ROIR}^2 \text{ n x H}}{\text{Q x 1440 min/day x 30 days/month}} \qquad (2)$$

Where:

RORI = 400 feet

n = Soil porosity, assumed to be 0.25

H = Soil column through which flow occurs

Q = Flow = 393 cfm

Based on the lack of response in Zone 1, and the minimal responses in Zone 2, "n" was assumed to be equal to the thickness of Zones 3 and 4 combined, i.e., 100 feet. This translates to 1 PV every 3 months.

4.3.5 VOC Analysis

The majority of the contamination extracted during Test 2 was CCl_4. Trace amounts of Freon 113 and TCE were also extracted. A total of approximately 125.9 lbs of VOCs (113.2 lbs of CCl_4, 11.2 lbs of Freon 113, and 2.5 lbs of TCE) were extracted during Test 2. Extraction rate calculations are presented in Table A.4-4, and cumulative VOC removals are plotted on Figure A.4-43. Test 3 results confirm Test 2 results and indicate that VOC removal rates will decrease over a long period of time (Figure A.4-44). During the initial startup of Test 3, the total VOC removal rates were as high as 0.11 lbs/hr and dropped as low as 0.004 lbs/hr (system in operation). These results indicate that VOC concentrations in the extracted vapor were reduced by over 95 percent over the duration of the test.

4.3.6 System Optimization

During Test 3, the following operational strategies were explored in order to maximize the efficiency of the SVE system (these methods involved equipment upgrades and changes in how the SVE system was being operated):

- Extracting from only Screen C to effect greater remediation in Zone 4, which is closest to the water table.
- Cycling the treatment system on and off for periods of time and monitor effects on system performance.

4.3.6.1 Screen C Extraction

On September 8, 1999, Screen B was closed off and only Screen C remained open. By closing Screen B, the applied vacuum increased from approximately 73 in. H_2O (for combined Screens B and C) to an applied vacuum of approximately 100 in. H_2O. In order to operate the SVE system at increased vacuum, the existing vapor-phase GAC adsorbers were replaced with vessels retrofitted with two reinforcement bands of the same size and configurations. The system operated for 2 weeks with only Screen C open; thus, more time may be needed to evaluate the true effectiveness under these operating parameters. However, preliminary results indicate that extracting from a single screen may reduce the radius of influence (Section 4.3.1) in certain zones.

4.3.6.2 System Cycling

In an effort to increase the system performance, cycling tests were done from May 1999 through July 1999. The VOC removal rates had decreased by approximately an order of magnitude (0.11 lbs/hr to 0.021 lbs/hr) since start-up of Test 3.

In looking at the VOC removal rate data from May through July (Figure A.4-45), the following observations can be made:

- The VOC removal rate initially rebounded following start-up of the system but the magnitude of the rebound decreased with each subsequent shutdown.
- Within each operation interval, the removal rates declined before the system was shut down.
- Overall, removal rates remained at least an order of magnitude below the levels of the initial startup of Test 3 and were consistently lower than the last period prior to cycling.

Based on these observations, cycling did not significantly enhance the performance of the SVE system. However, cycling will be continued to further evaluate its potential in enhancing effectiveness.

5.0 TEST RESULTS AND CONCLUSIONS

The test results indicated that SVE is indeed a feasible technology for remediation of the VOC-impacted soils in OU-2. Following are some of the key results of the pilot test:

- All three screens were able to extract significant quantities of soil vapor with flow-rates ranging from 157 to 174 cfm from each screen at vacuums ranging from 44 to 80 inches of water.
- Vacuum responses were noted as far as 771 feet away. Normalized vacuum responses of greater than or equal to 1 percent were observed at least 460 feet away. To be conservative, a RORI of 400 feet was assumed based on a 50 percent reduction of VOC levels in soil vapors at various distances from the extraction wells.
- VOC concentrations in the extracted vapor were reduced by over 95 percent over the duration of the test.
- VOC removal rates of up to 0.10 lbs/hr were noted for CCl_4 with an overall removal of approximately 180 lbs of CCl_4 between May 1998 and October 1999.
- Total VOC removal rates of up to 0.11 lbs/hr were noted with an overall removal of approximately 200 lbs between May 1998 and October 1999. An additional 850 lbs of VOCs (total) may have been removed on two separate occasions.

6.0 REFERENCES

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TABLES

TABLE A.4-1
SOIL PERMEABILITY CALCULATIONS

Extraction Well = VE-1A				
Monitoring Well Data - Zone 2, 4/13/99 12:15				
Extraction Well Radius (R_e)	inch	1		
	cm	2.54		
Air viscosity (μ)	g/cm-s	0.00018		
		SVW-25	SVW-26	SVW-28
Distance	ft	53.8	101.4	167.4
Distance (D_m)	cm	1639.8	3090.7	5102.4
Screen Interval	ft	40	40	40
Screen Interval	cm	1219.2	1219.2	1219.2
Extraction Flow Rate	cfm	179	179	179
Extraction Flow Rate (Q)	cm^3/s	84479.1	84479.1	84479.1
Extraction Vacuum (gage)	inches H_2O	44	44	44
Extraction Vacuum (abs)	$g/cm\text{-}s^2$	900757.72	900757.72	900757.72
Measured Vacuum (gage)	inches H_2O	1.8	1.25	0.7
Measured Vacuum (abs)	$g/cm\text{-}s^2$	1005502.8	1006867.9	1008233.1
$\ln[R_e/D_m]$		-6.47	-7.10	-7.61
$[1-(P_m/P_e)^2]$		-0.25	-0.25	-0.25
Permeability	cm^2	1.159E-07	1.256E-07	1.326E-07
	darcy	11.71	12.68	13.40
Average Permeability	cm^2	1.25E-07		
	darcy	12.60		

TABLE A.4-1
SOIL PERMEABILITY CALCULATIONS

Extraction Well = VE-1B				
Monitoring Well Data- Zone 3, 4/20/99 10:00				
Extraction Well Radius (R_e)	inch	1		
	cm	2.54		
Air viscosity (μ)	g/cm-s	0.00018		
		SVW-25	SVW-26	SVW-28
Distance	ft	53.8	101.4	167.4
Distance (D_m)	cm	1639.8	3090.7	5102.4
Screen Interval	ft	40	40	40
Screen Interval	cm	1219.2	1219.2	1219.2
Extraction Flow Rate	cfm	162	162	162
Extraction Flow Rate (Q)	cm^3/s	76455.9	76455.9	76455.9
Extraction Vacuum (gage)	inches H_2O	70	70	70
Extraction Vacuum (abs)	$g/cm\text{-}s^2$	836222.86	836222.86	836222.86
Measured Vacuum (gage)	inches H_2O	2.03	2.05	0.25
Measured Vacuum (abs)	$g/cm\text{-}s^2$	1004931.9	1004882.2	1009350
$\ln[R_e/D_m]$		-6.47	-7.10	-7.61
$[1-(P_m/P_e)^2]$		-0.44	-0.44	-0.46
Permeability	cm^2	6.262E-08	6.877E-08	7.155E-08
	darcy	6.32	6.95	7.23
Average Permeability	cm^2	6.76E-08		
	darcy	6.83		

TABLE A.4-1
SOIL PERMEABILITY CALCULATIONS

Extraction Well = VE-1C			
Monitoring Well Data- Zone 4, 4/27/99 14:00			
Extraction Well Radius (R_e)	inch	1	
	cm	2.54	
Air viscosity (μ)	g/cm-s	0.00018	
		SVW-25	SVW-26
Distance	ft	53.8	101.4
Distance (D_m)	cm	1639.8	3090.7
Screen Interval	ft	40	40
Screen Interval	cm	1219.2	1219.2
Extraction Flow Rate	cfm	163	163
Extraction Flow Rate (Q)	cm^3/s	76927.9	76927.9
Extraction Vacuum (gage)	inches H_2O	80	80
Extraction Vacuum (abs)	$g/cm\text{-}s^2$	811401.76	811401.76
Measured Vacuum (gage)	inches H_2O	2.95	1.2
Measured Vacuum (abs)	$g/cm\text{-}s^2$	1002648.3	1006992
$\ln[R_e/D_m]$		-6.47	-7.10
$[1-(P_m/P_e)^2]$		-0.53	-0.54
Permeability	cm^2	5.473E-08	5.862E-08
	darcy	5.53	5.92
Average Permeability	cm^2		5.67E-08
	darcy		5.72

TABLE: A.4-2
TEST 1: VOC ANALYSIS

Week	Day	Date / Time	Operating Hours *hr*	Avgerage Vacuum *in.* H_2O	Average Flowrate *cfm*	CCl4 Average Concentration mg/m^3	CCl4 Removal Rate *lb/hr*	CCl4 Removed *lb*	Cumulative CCl4 Removed *lb*	Freon 113 Average Concentration mg/m^3	Freon 113 Removal Rate *lb/hr*	Freon 113 Removed *lb*	Cumulative Freon 113 Removed *lb*	Total VOCs Removed *lb*
1	1	4/13/98 10:00	6	44	174	157	0.102	0.61	0.61	0	0.000	0.00	0.00	0.61
1	2	4/14/98 10:00	8	32	139	153	0.080	0.64	1.25	11	0.006	0.05	0.05	1.30
1	3	4/15/98 10:00	8	20	102	170	0.065	0.52	1.77	13	0.005	0.04	0.09	1.86
1	4	4/16/98 10:00	8	10	58	170	0.037	0.3	2.07	0	0.000	0.00	0.09	2.16
		4/19/98 10:00	0	0	0		0.000	0	2.07		0.000	0.00	0.09	2.16
2	1	4/20/98 10:00	8	70	167	253	0.158	1.27	3.34	0	0.000	0.00	0.09	3.43
2	2	4/21/98 10:00	8	52	143	260	0.139	1.11	4.45	0	0.000	0.00	0.09	4.54
2	3	4/22/98 10:00	8	34	109	237	0.097	0.77	5.22	0	0.000	0.00	0.09	5.31
2	4	4/23/98 10:00	8	17	60	263	0.059	0.47	5.69	17	0.004	0.03	0.12	5.81
		4/26/98 10:00	0	0	0		0.000	0	5.69		0.000	0.00	0.12	5.81
3	1	4/27/98 10:00	8	80	157	123	0.072	0.58	6.27	0	0.000	0.00	0.12	6.39
3	2	4/29/98 10:00	8	59	136	150	0.076	0.61	6.88	11	0.006	0.04	0.16	7.04
3	3	4/30/98 8:00	8	40	101	140	0.053	0.42	7.3	0	0.000	0.00	0.16	7.46
3	4	4/30/98 16:00	8	20	62	163	0.038	0.3	7.6	3	0.001	0.01	0.17	7.77
		5/3/98 10:00	0	0	0		0.000	0	7.6		0.000	0.00	0.17	7.77
4	1	5/4/98 10:00	8	25	277	151	0.157	1.25	8.85	10	0.010	0.08	0.25	9.10
4	2	5/5/98 10:00	5	19	229	173	0.148	0.74	9.59	13	0.011	0.06	0.31	9.90
4	3	5/6/98 10:00	7	13	166	167	0.104	0.73	10.32	13	0.008	0.06	0.37	10.69
4	4	5/7/98 10:00	7	6	103	167	0.064	0.45	10.77	13	0.005	0.04	0.41	11.18

TABLE A.4-3
TEST 2: VOC ANALYSIS

Week	Day	Date/Time	Anemometer Flowrate ABC	Anemometer Flowrate BC	CCl4 Average Concentration	CCl4 Removal Rate	CCl4 Removed	Cumulative CCl4 Removed	Freon 113 Average Concentration	Freon 113 Removal Rate	Freon 113 Removed	Cumulative Freon 113 Removed	Total VOCs Removed
			cfm	*cfm*	*mg/m3*	*lb/hr*	*lb*	*lb*	*mg/m3*	*lb/hr*	*lb*	*lb*	*lb*
		5/11/98 6:59	0		0	0.000		10.485	0	0.000		0.367	10.852
1	1	5/11/98 7:00	275	--	205	0.211	0.002	10.487	17	0.018	0.000	0.367	10.854
1	1	5/11/98 8:00	274	--	205	0.210	0.211	10.697	17	0.017	0.017	0.385	11.082
1	1	5/11/98 9:00	275	--	205	0.211	0.211	10.908	17	0.018	0.017	0.402	11.310
1	1	5/11/98 11:00	281	--	205	0.216	0.427	11.335	17	0.018	0.035	0.437	11.772
1	1	5/11/98 14:00	273	--	205	0.210	0.638	11.973	17	0.017	0.053	0.490	12.463
1	2	5/12/98 7:00	272	--	100	0.102	2.647	14.619	0	0.000	0.148	0.638	15.257
1	2	5/12/98 9:00	278	--	100	0.104	0.206	14.825	0	0.000	0.000	0.638	15.463
1	2	5/12/98 12:00	274	--	100	0.103	0.310	15.135	0	0.000	0.000	0.638	15.773
1	3	5/13/98 8:00	276	--	120	0.124	2.266	17.401	5	0.005	0.052	0.690	18.091
1	3	5/13/98 10:00	274	--	120	0.123	0.001	17.403	5	0.005	0.000	0.690	18.093
1	3	5/13/98 12:00	282	--	120	0.127	0.250	17.653	5	0.005	0.010	0.700	18.353
1	3	5/13/98 14:00	268	--	120	0.120	0.247	17.900	5	0.005	0.010	0.711	18.611
1	4	5/14/98 7:00	286	--	120	0.128	2.116	20.016	5	0.005	0.088	0.799	20.814
1	4	5/14/98 11:00	285	--	120	0.128	0.513	20.529	5	0.005	0.021	0.820	21.349
1	4	5/14/98 14:00	287	--	120	0.129	0.385	20.914	5	0.005	0.016	0.836	21.750
1	5	5/15/98 9:00	276	--	120	0.124	2.403	23.317	5	0.005	0.100	0.936	24.253
1	5	5/15/98 11:30	278	--	120	0.125	0.311	23.628	5	0.005	0.013	0.949	24.578
1	5	5/15/98 14:30	278	--	120	0.125	0.375	24.003	5	0.005	0.016	0.965	24.968
2	1	5/19/98 14:00	270	--	160	0.162	0.001	24.005	13	0.013	0.000	0.965	24.970
2	2	5/20/98 8:00	253	--	160	0.152	2.820	26.825	15	0.014	0.246	1.211	28.036
2	2	5/20/98 11:00	257	--	160	0.154	0.458	27.283	15	0.014	0.043	1.254	28.537
2	2	5/20/98 14:00	267	--	160	0.160	0.471	27.754	15	0.015	0.044	1.298	29.052
2	3	5/21/98 8:00	264	--	150	0.148	2.774	30.528	0	0.000	0.135	1.433	31.961
2	3	5/21/98 9:29	264		150	0.148	0.220	30.748	0	0.000	0.000	1.433	32.181
2	3	5/21/98 14:45	267		150	0.150	0.001	30.751	0	0.000	0.000	1.433	32.184
2	3	5/21/98 15:00	267	--	150	0.150	0.037	30.788	0	0.000	0.000	1.433	32.221
2	4	5/22/98 7:00	255	--	92	0.088	1.902	32.690	8.2	0.008	0.063	1.496	34.186
2	4	5/22/98 14:00	275	--	92	0.095	0.639	33.329	8.2	0.008	0.057	1.553	34.882
3	1	5/26/98 8:00	252	--	100	0.094	8.508	41.837	10	0.009	0.804	2.357	44.195
3	1	5/26/98 12:00	288	--	100	0.108	0.404	42.242	10	0.011	0.040	2.398	44.639
3	1	5/26/98 14:00	259	--	100	0.097	0.205	42.447	10	0.010	0.020	2.418	44.865

TABLE A.4-3
TEST 2: VOC ANALYSIS

Week	Day	Date/Time	Anemometer Flowrate		CCl4 Average Concentration	CCl4 Removal Rate	CCl4 Removed	Cumulative CCl4 Removed	Freon 113 Average Concentration	Freon 113 Removal Rate	Freon 113 Removed	Cumulative Freon 113 Removed	Total VOCs Removed
			ABC	BC									
			cfm	*cfm*	*mg/m3*	*lb/hr*	*lb*	*lb*	*mg/m3*	*lb/hr*	*lb*	*lb*	*lb*
3	1	5/26/98 16:00	265	--	100	0.099	0.196	42.643	10	0.010	0.020	2.438	45.081
3	1	5/26/98 23:00	268	--	100	0.100	0.698	43.341	10	0.010	0.070	2.508	45.849
3	2	5/27/98 16:01	--	160	160	0.096	0.001	43.343	16	0.010	0.000	2.508	45.851
3	4	5/29/98 7:50	--	160	160	0.096	3.816	47.159	16	0.010	0.382	2.889	50.049
4	1	6/1/98 8:00	--	166	160	0.099	7.047	54.206	15	0.009	0.682	3.572	57.777
4	1	6/1/98 13:30	--	155	160	0.093	0.529	54.735	15	0.009	0.050	3.621	58.356
4	2	6/2/98 6:14	--	155	160	0.093	1.554	56.288	15	0.009	0.146	3.767	60.055
4	2	6/2/98 8:00	--	157	140	0.082	0.001	56.290	15	0.009	0.000	3.767	60.057
4	2	6/2/98 8:30	--	157	140	0.082	0.041	56.331	15	0.009	0.004	3.771	60.102
4	2	6/2/98 11:00	--	158	140	0.083	0.206	56.537	15	0.009	0.022	3.794	60.331
4	2	6/2/98 13:00	--	156	140	0.082	0.165	56.702	15	0.009	0.018	3.811	60.513
4	3	6/3/98 7:00	--	152	140	0.080	1.453	58.155	14	0.008	0.151	3.962	62.117
4	3	6/3/98 10:30	--	158	140	0.083	0.284	58.439	14	0.008	0.028	3.990	62.429
4	3	6/3/98 11:15	--	159	140	0.083	0.062	58.501	14	0.008	0.006	3.996	62.498
4	4	6/4/98 10:15	--	155	120	0.070	1.759	60.261	13	0.008	0.183	4.179	64.440
4	4	6/4/98 12:00	--	158	120	0.071	0.123	60.384	13	0.008	0.013	4.192	64.576
4	4	6/4/98 15:00	--	161	120	0.072	0.215	60.599	13	0.008	0.023	4.216	64.814
4	5	6/5/98 9:30	--	165	140	0.086	1.469	62.068	15	0.009	0.158	4.374	66.442
4	5	6/5/98 12:00	--	162	140	0.085	0.214	62.282	15	0.009	0.023	4.397	66.679
4	5	6/5/98 14:00	--	159	140	0.083	0.168	62.450	15	0.009	0.018	4.415	66.865
5	1	6/8/98 7:10	--	158	120	0.071	5.029	67.479	13	0.008	0.542	4.956	72.435
5	1	6/8/98 10:05	--	159	120	0.071	0.208	67.687	13	0.008	0.023	4.979	72.665
5	1	6/8/98 10:44	--	159	120	0.071	0.046	67.733	13	0.008	0.005	4.984	72.717
5	1	6/8/98 10:45	--	0	0	0.000	0.001	67.734	0	0.000	0.000	4.984	72.718

TABLE: A.4-4
TEST 3: VOC ANALYSIS

Date	Time *hours*	Date/Time	Time Of Operation *min*	Flowrate ABC *cfm*	CCl4 Average Concentration *mg/m3*	CCl4 Removal Rate *lb/hr*	CCl4 Removed *lb*	Cumulative CCl4 Removed *lb*	Freon 113 Average Concentration *mg/m3*	Freon 113 Removal Rate *lb/hr*	Freon 113 Removed *lb*	Cumulative Freon 113 Removed *lb*	TCE Avgerage Concentration *mg/m3*	TCE Removal Rate *lb/h*	Ave. TCE Removed *lb*	Cumulative TCE Removed *lb*	Total VOCs removed *lb/h*	Total VOCs Removed *lb*
11/2/98	10:50	11/2/98 10:50	1330	242	35	0.032	0.70	68.43	0	0.000	0.00	4.98	0	0	0	0	0.032	73.41
11/3/98	9:00	11/3/98 9:00	1380	242	82	0.074	1.71	70.14	0	0.000	0.00	4.98	0	0	0	0	0.074	75.12
11/4/98	8:00	11/4/98 8:00	1470	242	110	0.100	2.44	72.59	11	0.010	0.24	5.22	0	0	0	0	0.110	77.81
11/5/98	8:30	11/5/98 8:30	1410	228	110	0.094	2.21	74.79	13	0.011	0.26	5.49	0	0	0	0	0.105	80.28
11/6/98	8:00	11/6/98 8:00	4410	256	100	0.096	7.05	81.84	12	0.012	0.85	6.33	0	0	0	0	0.107	88.17
11/9/98	9:30	11/9/98 9:30	1410	260	85	0.083	1.95	83.79	0	0.000	0.00	6.33	0	0	0	0	0.083	90.12
11/10/98	9:00	11/10/98 9:00	1440	257	76	0.073	1.76	85.54	10	0.010	0.23	6.56	0	0	0	0	0.083	92.11
11/11/98	9:00	11/11/98 9:00	1440	253	76	0.072	1.73	87.27	9.8	0.009	0.22	6.79	0	0	0	0	0.081	94.06
11/12/98	9:00	11/12/98 9:00	1440	258	73	0.071	1.69	88.97	0	0.000	0.00	6.79	0	0	0	0	0.071	95.75
11/13/98	9:00	11/13/98 9:00	4320	258	67	0.065	4.66	93.63	8.7	0.008	0.61	7.39	0	0	0	0	0.073	101.02
11/16/98	9:00	11/16/98 9:00	2880	258	64	0.062	2.97	96.60	8.9	0.009	0.41	7.80	0	0	0	0	0.070	104.40
11/18/98	9:00	11/18/98 9:00	1440	262	60	0.059	1.41	98.01	8.2	0.008	0.19	8.00	0	0	0	0	0.067	106.01
11/19/98	9:00	11/19/98 9:00	1440	260	54	0.053	1.26	99.27	7	0.007	0.16	8.16	0	0	0	0	0.059	107.43
11/20/98	9:00	11/20/98 9:00	4320	240	68	0.061	4.40	103.68	7.9	0.007	0.51	8.67	0	0	0	0	0.068	112.35
11/23/98	9:00	11/23/98 9:00	15840	262	51	0.050	13.21	116.89	6.7	0.007	1.74	10.41	0	0	0	0	0.057	127.30
12/4/98	9:00	12/4/98 9:00	5760	262	48	0.047	4.52	121.41	8.6	0.008	0.81	11.22	0	0	0	0	0.056	132.63
12/8/98	9:00	12/8/98 9:00	8700	262	38	0.037	5.41	126.82	6.1	0.006	0.87	12.09	0	0	0	0	0.043	138.91
12/14/98	10:00	12/14/98 10:00	12960	262	36	0.035	7.63	134.45	6.1	0.006	1.29	13.38	0	0	0	0	0.041	147.83
12/23/98	10:00	12/23/98 10:00	10080	262	35	0.034	5.77	140.22	5.3	0.005	0.87	14.25	0	0	0	0	0.040	154.48
12/30/98	10:00	12/30/98 10:00	9990	262	30	0.029	4.90	145.13	5	0.005	0.82	15.07	0	0	0	0	0.034	160.20
1/6/99	8:30	1/6/99 8:30	10230	262	16	0.016	2.68	147.81	0	0.000	0.00	15.07	0	0	0	0	0.016	162.88
1/13/99	11:00	1/13/99 11:00	11520	262	21	0.021	3.96	151.76	0	0.000	0.00	15.07	0	0	0	0	0.021	166.83
1/21/99	11:00	1/21/99 11:00	5040	262	24	0.024	1.98	153.74	0	0.000	0.00	15.07	0	0	0	0	0.024	168.81
1/26/99	11:00	1/26/99 11:00	0	0	0	0.000	0.00	153.74	0	0.000	0.00	15.07	0	0	0	0	0.000	168.81
1/28/99	11:00	1/28/99 11:00	20190	131	0	0.000	0.00	153.74	0	0.000	0.00	15.07	0	0	0	0	0.000	168.81
2/11/99	11:30	2/11/99 11:30	11430	131	15	0.007	1.40	155.14	0	0.000	0.00	15.07	0	0	0	0	0.007	170.21
2/19/99	10:00	2/19/99 10:00	0	0	0	0.000	0.00	155.14	0	0.000	0.00	15.07	0	0	0	0	0.000	170.21
3/30/99	12:00	2/19/99 10:00	0	0	0	0.000	0.00	155.14	0	0.000	0.00	15.07	0	0	0	0	0.000	170.21
3/31/99	15:00	3/31/99 15:00	11370	332	13	0.016	3.06	158.21	0	0.000	0.00	15.07	0	0	0	0	0.016	173.28
4/8/99	12:30	4/8/99 12:30	8610	332	13	0.016	2.32	160.53	0	0.000	0.00	15.07	0	0	0	0	0.016	175.60
4/14/99	12:00	4/14/99 12:00	9840	262	0	0.000	0.00	160.53	0	0.000	0.00	15.07	0	0	0	0	0.000	175.60
4/21/99	11:00	4/21/99 11:00	11340	370	0	0.000	0.00	160.53	0	0.000	0.00	15.07	0	0	0	0	0.000	175.60
4/29/99	8:00	4/29/99 8:00	120	369	0	0.000	0.00	160.53	0	0.000	0.00	15.07	0	0	0	0	0.000	175.60
5/3/99	12:00	5/3/99 12:00	0	0	0	0.000	0.00	160.53	0	0.000	0.00	15.07	0	0	0	0	0.000	175.60
5/4/99	1:30	5/4/99 1:30	3450	370	9.8	0.014	0.78	161.31	1.4	0.002	0.11	15.18	2.7	0.0037	0.215	0.21	0.019	176.71
5/6/99	11:00	5/6/99 11:00	7200	374	12	0.017	2.02	163.33	3.2	0.004	0.54	15.72	2.7	0.0038	0.454	0.67	0.025	179.71
5/11/99	11:00	5/11/99 11:00	4350	373	8.3	0.012	0.84	164.17	0	0.000	0.00	15.72	0	0	0	0.67	0.012	180.56
5/14/99	11:30	5/14/99 11:30	8580	375	8.5	0.012	1.71	165.87	0	0.000	0.00	15.72	2	0.003	0.401	1.07	0.015	182.66
5/20/99	10:30	5/20/99 10:30	0	375	6.8	0.010	0.00	165.87	0	0.000	0.00	15.72	0	0	0	1.07	0.010	182.66
5/21/99	12:00	5/21/99 12:00	0	0	0	0.000	0.00	165.87	0	0.000	0.00	15.72	0	0	0	1.07	0.000	182.66
5/26/99	12:00	5/26/99 12:00	0	0	0	0.000	0.00	165.87	0	0.000	0.00	15.72	0	0	0	1.07	0.000	182.66
5/27/99	14:45	5/27/99 14:45	7200	371	0	0.000	0.00	165.87	0	0.000	0.00	15.72	0	0	0	1.07	0.000	182.66
6/1/99	9:30	6/1/99 9:30	8730	371	9.3	0.013	1.88	167.76	2.2	0.003	0.44	16.16	3.2	0.0044	0.65	1.72	0.020	185.64
6/7/99	11:00	6/7/99 11:00	240	397	6.7	0.010	0.04	167.80	0	0.000	0.00	16.16	2.2	0.0033	0.01	1.73	0.013	185.69
6/8/99	12:00	6/8/99 12:00	0	0	0	0.000	0.00	167.80	0	0.000	0.00	16.16	0	0	0	1.73	0.000	185.69
6/30/99	12:00	6/30/99 12:00	0	0	0	0.000	0.00	167.80	0	0.000	0.00	16.16	0	0	0	1.73	0.000	185.69
7/1/99	16:00	7/1/99 16:00	8400	377	3	0.004	0.59	168.39	0	0.000	0.00	16.16	0	0	0	1.73	0.004	186.28
7/7/99	12:00	7/7/99 12:00	8400	377	6.8	0.010	1.34	169.73	0	0.000	0.00	16.16	0	0	0	1.73	0.010	187.63
7/13/99	8:00	7/13/99 8:00	2910	372	6	0.008	0.41	170.14	0	0.000	0.00	16.16	0	0	0	1.73	0.008	188.03
7/15/99	8:30	7/15/99 8:30	4320	373	6.2	0.009	0.62	170.76	0	0.000	0.00	16.16	2.1	0.0029	0.21	1.94	0.012	188.87
7/21/99	10:00	7/21/99 10:00	0	373	0.0	0.000	0.00	170.76	0	0.000	0.00	16.16	0	0	0	1.94	0.000	188.87
7/26/99	12:00	7/26/99 12:00	0	0	0.0	0.000	0.00	170.76	0	0.000	0.00	16.16	0	0	0	1.94	0.000	188.87

TABLE: A.4-4
TEST 3: VOC ANALYSIS

Date	Time *hours*	Date/Time	Time Of Operation *min*	Flowrate ABC *cfm*	CCl4 Average Concentration *mg/m3*	CCl4 Removal Rate *lb/hr*	CCl4 Removed *lb*	Cumulative CCl4 Removed *lb*	Freon 113 Average Concentration *mg/m3*	Freon 113 Removal Rate *lb/hr*	Freon 113 Removed *lb*	Cumulative Freon 113 Removed *lb*	TCE Avgerage Concentration *mg/m3*	TCE Removal Rate *lb/h*	Ave. TCE Removed *lb*	Cumulative TCE Removed *lb*	Total VOCs removed *lb/h*	Total VOCs Removed *lb*
7/27/99	11:00	7/27/99 11:00	4200	373	7.0	0.010	0.68	171.45	0	0.000	0.00	16.16	2.0	0.0028	0.2	2.14	0.013	189.75
7/30/99	9:00	7/30/99 9:00	8640	373	6.0	0.008	1.21	172.65	0	0.000	0.00	16.16	2.0	0.0028	0.4	2.54	0.011	191.36
8/5/99	9:00	8/5/99 9:00	8670	370	5.4	0.007	1.08	173.74	0	0.000	0.00	16.16	0	0.0000	0.0	2.54	0.007	192.44
8/11/99	9:30	8/11/99 9:30	12930	371	5.9	0.008	1.77	175.50	0	0.000	0.00	16.16	0	0.0000	0.0	2.54	0.008	194.21
8/20/99	9:00	8/20/99 9:00	7260	373	5.8	0.008	0.98	176.48	0	0.000	0.00	16.16	0	0.0000	0.0	2.54	0.008	195.19
8/25/99	10:00	8/25/99 10:00	20100	376	5.2	0.007	2.45	178.94	0	0.000	0.00	16.16	0	0.0000	0.0	2.54	0.007	197.64
9/8/99	9:00	9/8/99 9:00	10080	373	5.5	0.008	1.29	180.23	0	0.000	0.00	16.16	0	0.0000	0.0	2.54	0.008	198.93
9/15/99	9:00	9/15/99 9:00	10080	370	2.9	0.004	0.68	180.90	0	0.000	0.00	16.16	0	0.0000	0.0	2.54	0.004	199.61
9/22/99	9:00	9/22/99 9:00	180	373	4.0	0.006	0.02	180.92	0	0.000	0.00	16.16	0	0.0000	0.0	2.54	0.006	199.62
9/23/99	10:00	9/23/99 10:00	0	0	0.0	0.000	0.00	180.92	0	0.000	0.00	16.16	0	0.0000	0	2.54	0.000	199.62

FIGURES

0 .5 mile

Scale
1:24,000

Source: USGS 7.5 Minute Topographic Quadrangle, 1966, Revised 1994

FIGURE A.1-1

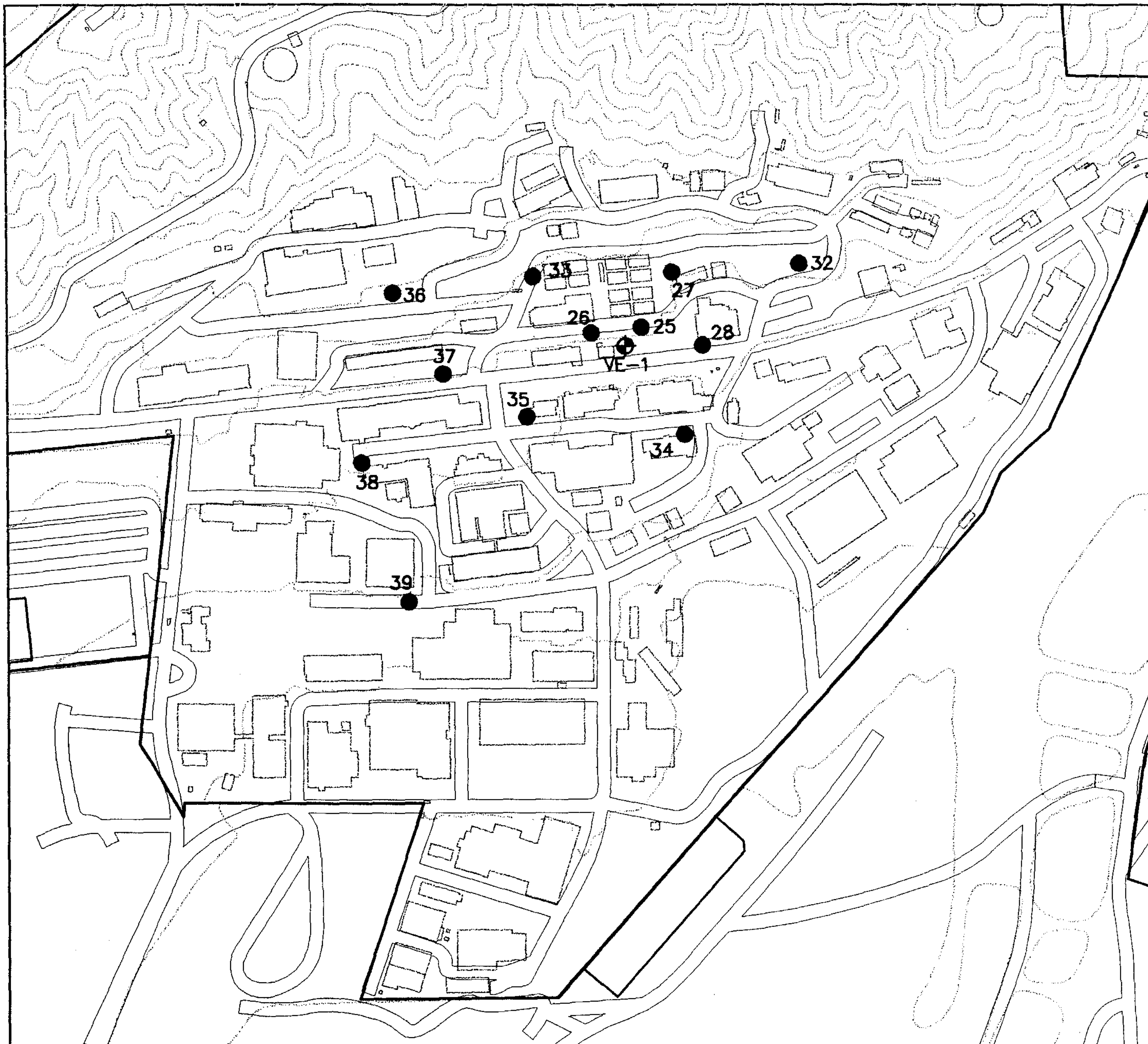
SITE LOCATION MAP
JET PROPULSION LABORATORY

Jet Propulsion Laboratory
Pasadena, California

FOSTER WHEELER ENVIRONMENTAL CORPORATION

I:\1572-JPL\DWG\OU2\FS99\FIGA.1-1.DWG
PLOT/UPDATE: NOV 09 1999 08:15:55

I:\1572-JPL\D...02\FS6-00\JPLFA.1-2.DWG
PLOT/UPDATE: MAY 16 2000 16:11:39



Explanation

- ● 39 Soil Vapor Wells
- ⊕ VE-1 Vapor Extraction Well

400 200 0 400

SCALE IN FEET

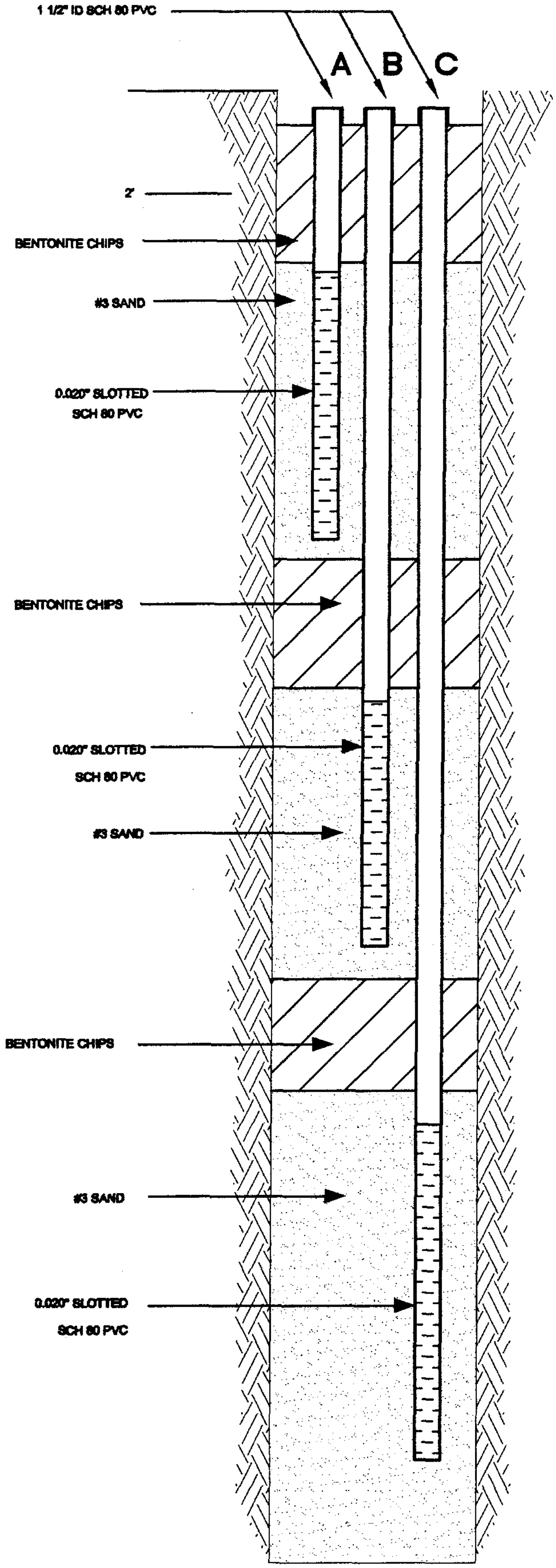
Source: USGS, 7.5 Minute Topographic Map Pasadena, CA 1966, Revised 1988, 1994.

FIGURE A.1-2

SOIL VAPOR WELL LOCATIONS

Jet Propulsion Laboratory
Pasadena, California

FOSTER WHEELER ENVIRONMENTAL CORPORATION



SCREEN A: 44' TO 84' BGS
SCREEN B: 94' TO 134' BGS
SCREEN C: 145' TO 185' BGS

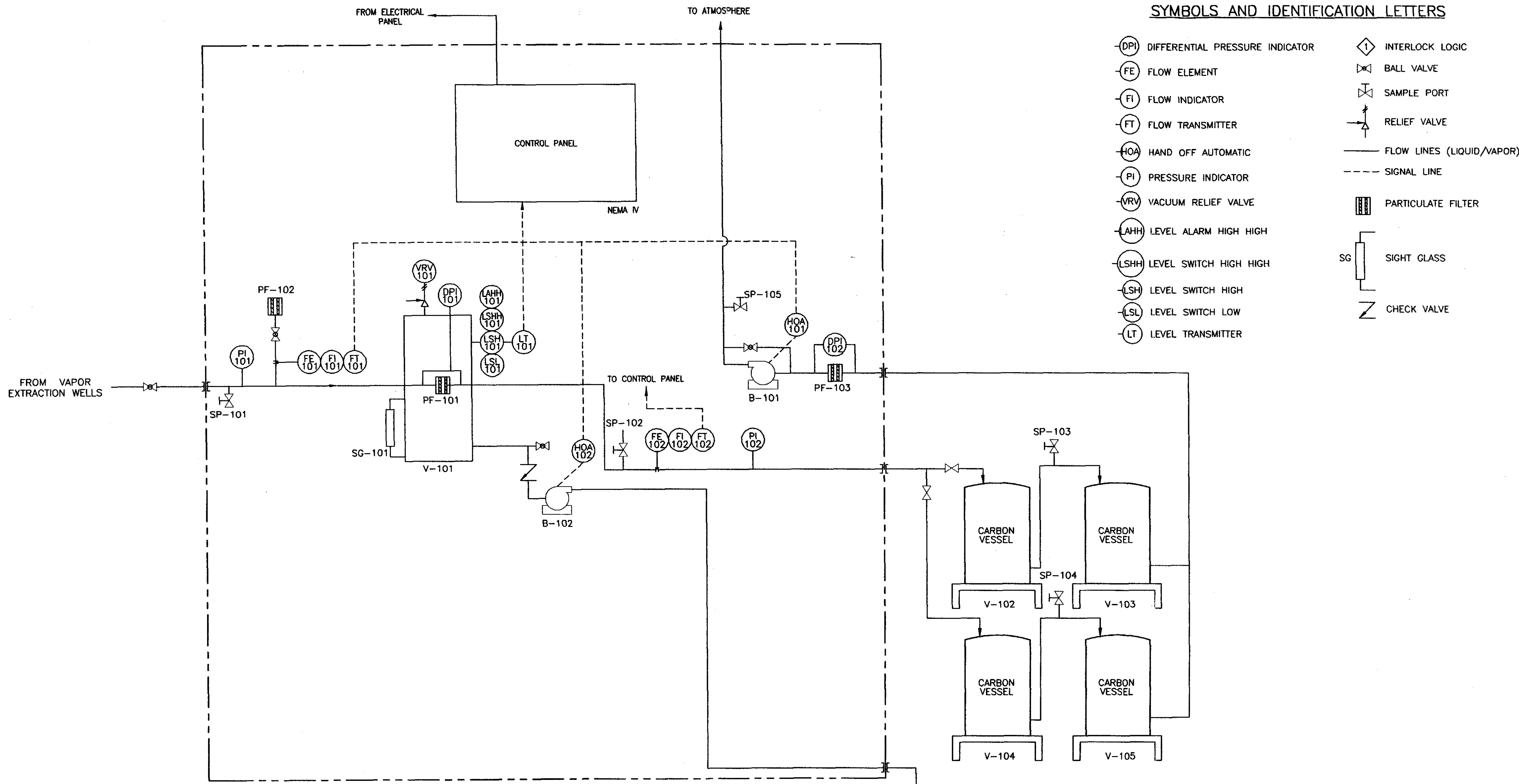
FIGURE A.2-1

VAPOR EXTRACTION WELL
VE-1

Jet Propulsion Laboratory
Pasadena, California

FOSTER WHEELER ENVIRONMENTAL CORPORATION

I:\1572-JPL\DWG\OU2\FS8-00\FIGA2-1.DWG
PLOT/UPDATE: MAY 03 2000 15:54:11



INSTRUMENTATION

NAME	DECRIPTION	RANGE
DPI-101	MAGNEHELIC, PRESSURE INDICATOR	0-10 "H_2O
DPI-102	MAGNEHELLIC PRESSURE INDICATOR	0-10 "H_2O
FE, FI, FT-101	PITOT TUBE, INDICATOR, TRANSMITTER	0-600 scfm
FE, FI, FT-102	PITOT TUBE, INDICATOR, TRANSMITTER	0-600 scfm
PI-101	MAGNEHELIC, VACUUM INDICATOR	0-150 "H_2O
PI-102	MAGNEHELIC, VACUUM INDICATOR	0-150 "H_2O
VRV-101	VACUUM RELIEF	10 "Hg

CONTROLS

1. SHUT DOWN B-101 FOR ALARM HIGHS IN V-101 AND V-106. PROVIDE TWO INDICATING LIGHTS FOR EACH ALARM IN CONTROL PANEL.
2. RECORD FLOWS FROM FT-101, AND 102 ON RECORDER IN CONTROL PANEL.
3. ALL MOTOR STARTERS FOR B-101 AND B-102 SHALL BE INSTALLED IN CONTROL PANEL AND EQUIPPED WITH HOA SWITCHES.
4. LSH-101 TURNS ON PUMP B-102.
5. LSHH-101 SHOULD SHUT DOWN B-101 UNTIL RESOLVED.
6. LSHH-102 SHOULD SHUT DOWN B-101 UNTIL RESOLVED.

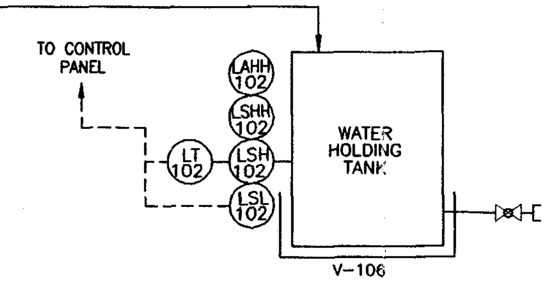


FIGURE A.2-2

PIPING AND INSTRUMENTATION DIAGRAM-PILOT TEST

Jet Propulsion Laboratory
Pasadena, California

FOSTER WHEELER ENVIRONMENTAL CORPORATION

I:\1572-JPL\DWG\OU2\FS12-99\FIGA2-2.DWG
PLOT/UPDATE: DEC 21 1999 14:04:17

FIGURE A.4-1
TEST 1: VACUUM VS FLOW RATE

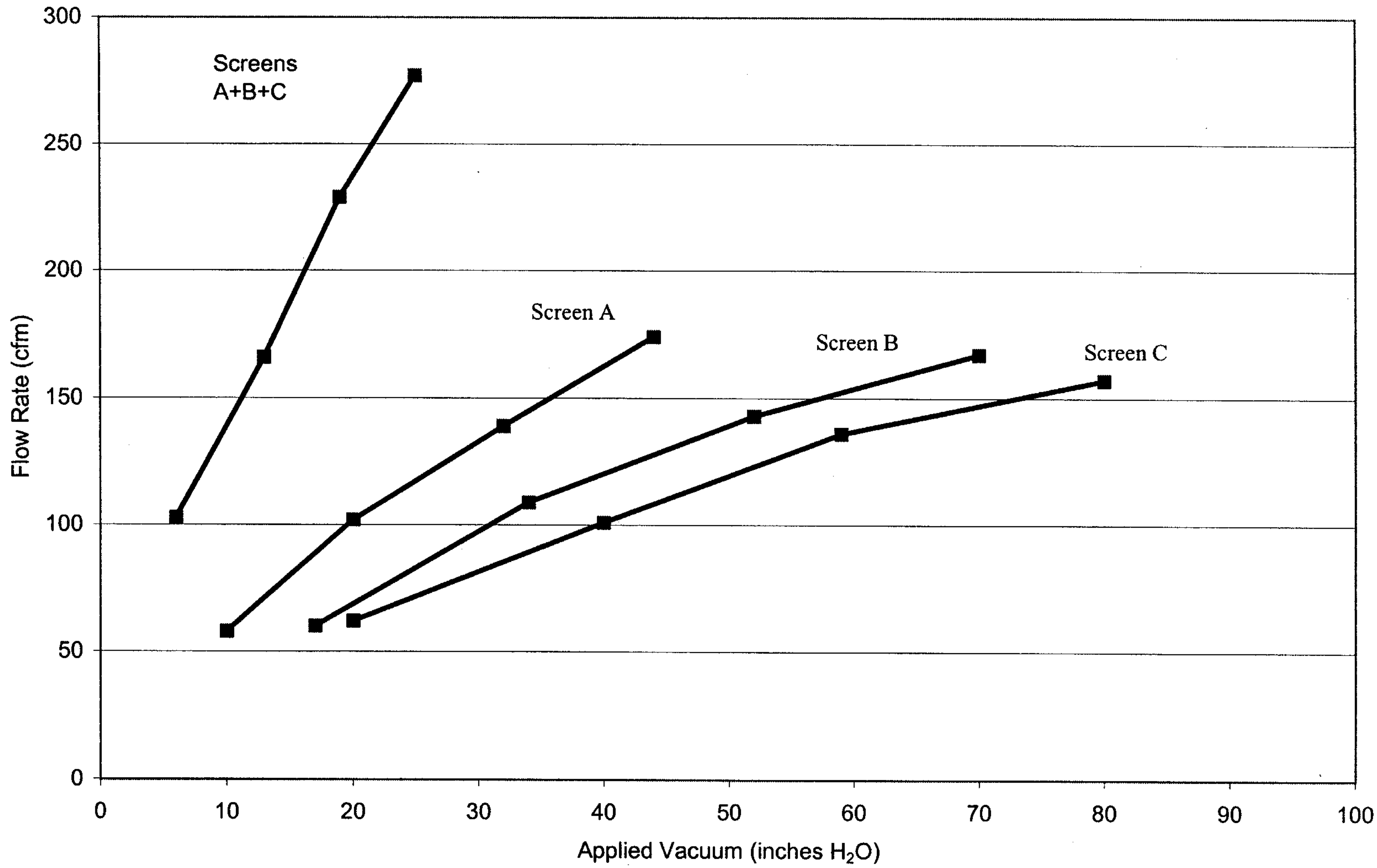
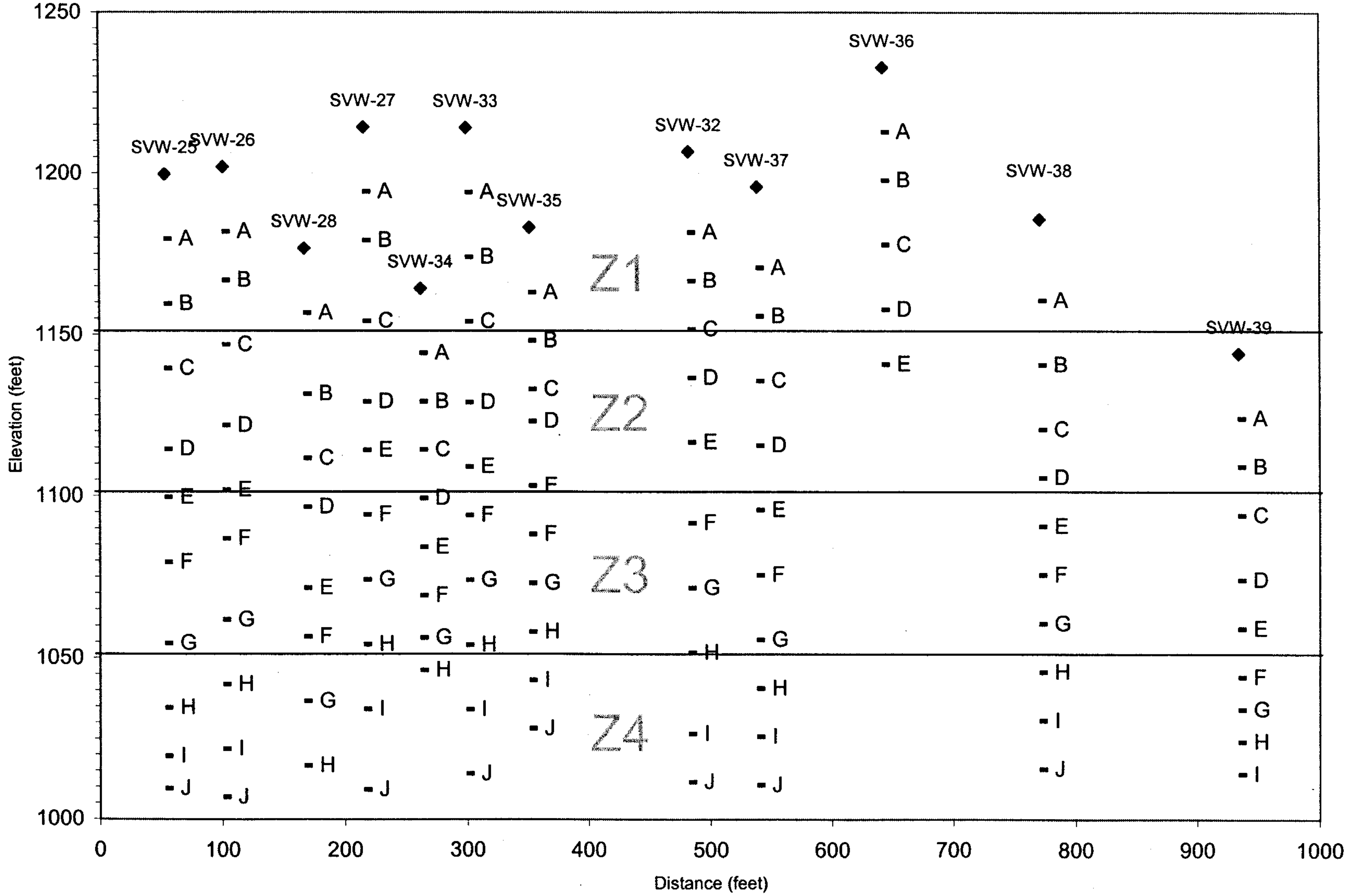
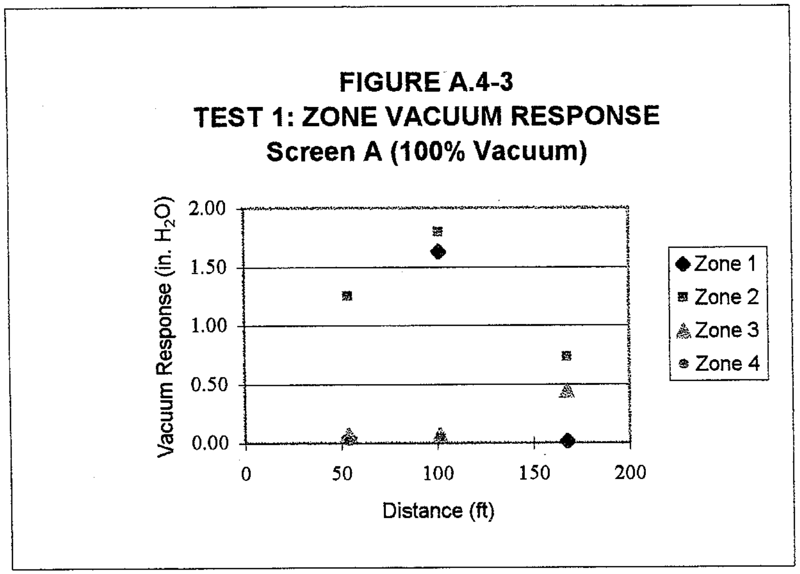
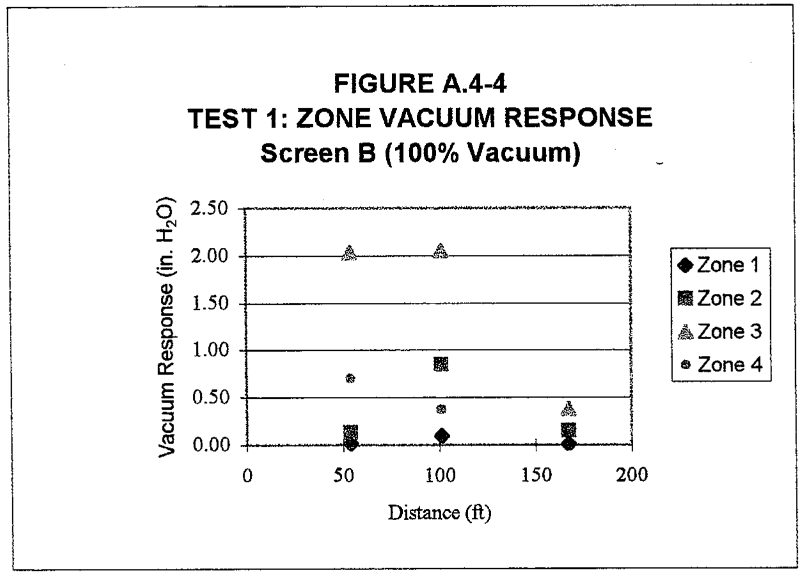


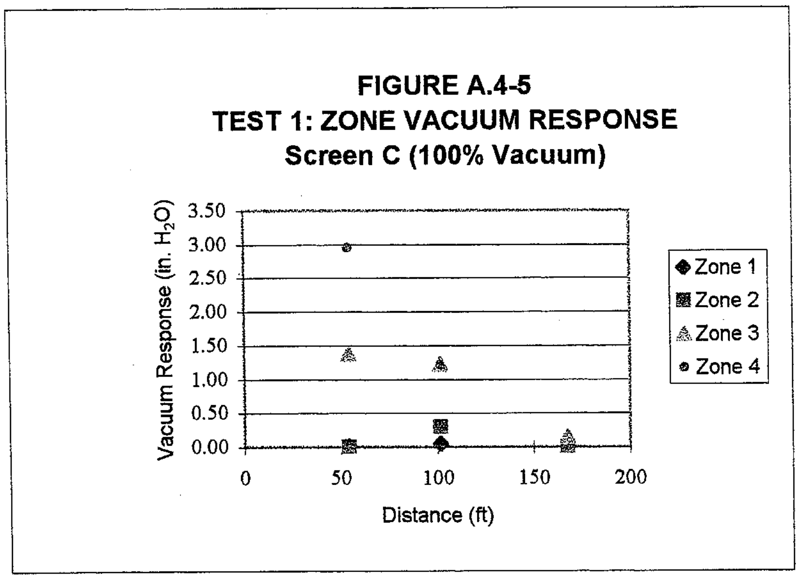
FIGURE A.4-2
JPL MONITORING WELL LOCATIONS AND DEPTHS

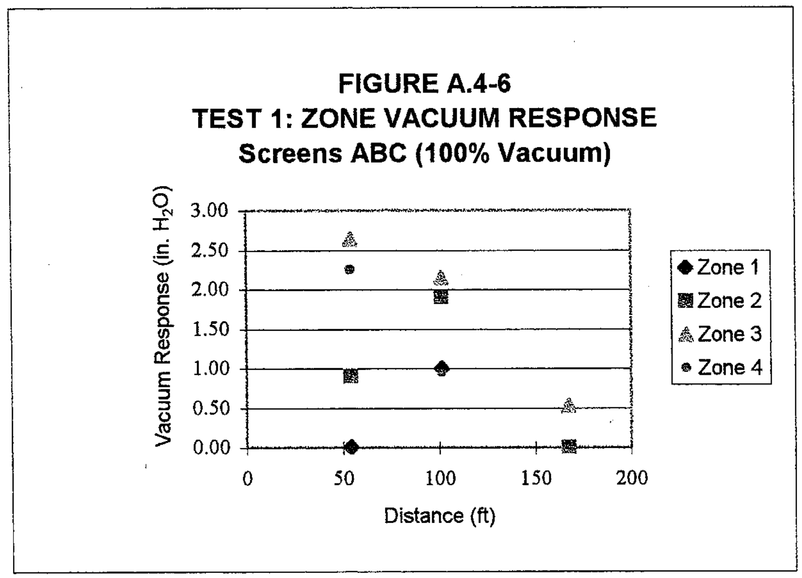


Datasht / Figure A.4-2









Mwdata.xls/Test 1 Vacuum response plots

FIGURE A.4-7
TEST 1: DAILY AVERAGE CUMULATIVE VOCs REMOVED

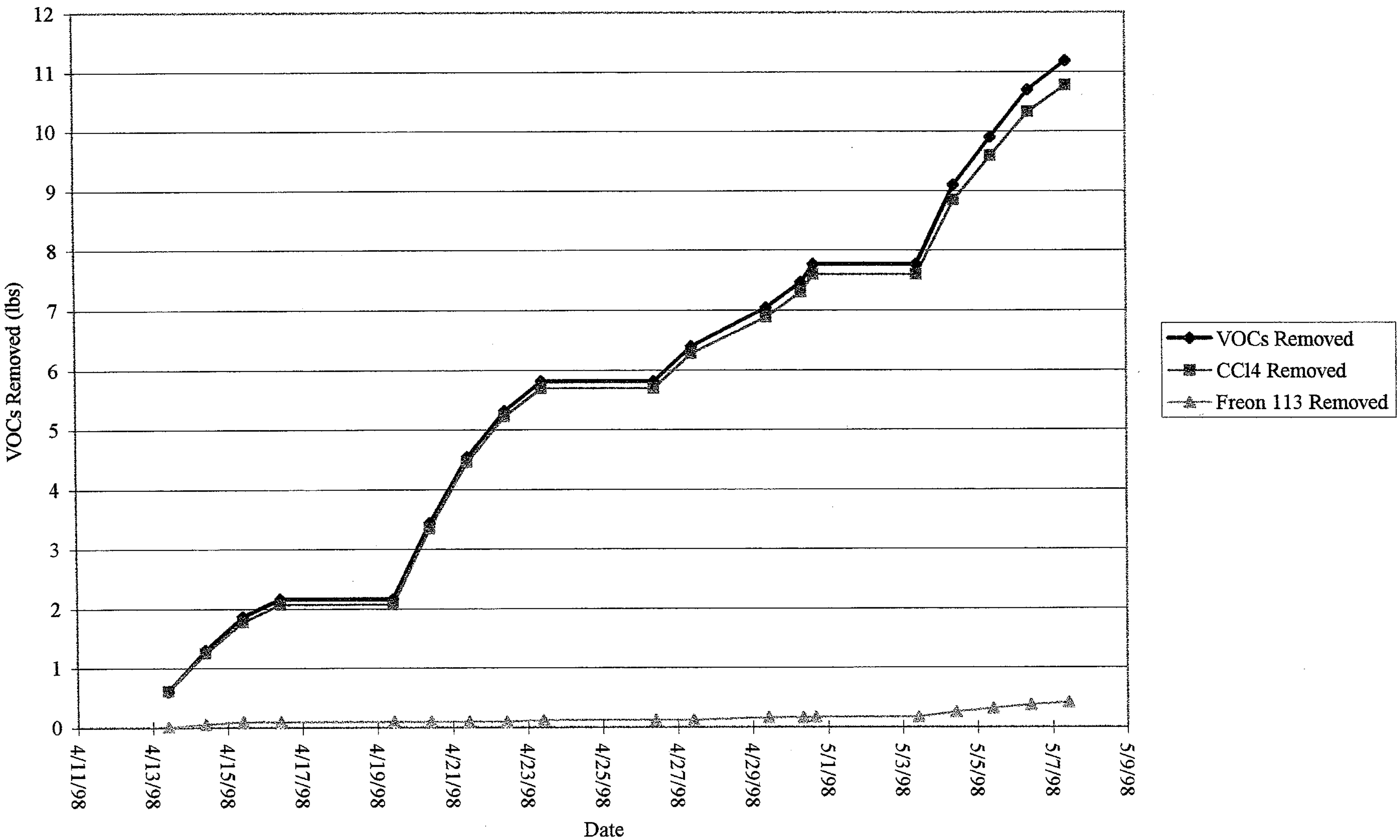


FIGURE A.4-8
TEST 1: CCl_4 CONCENTRATION VS VACUUM

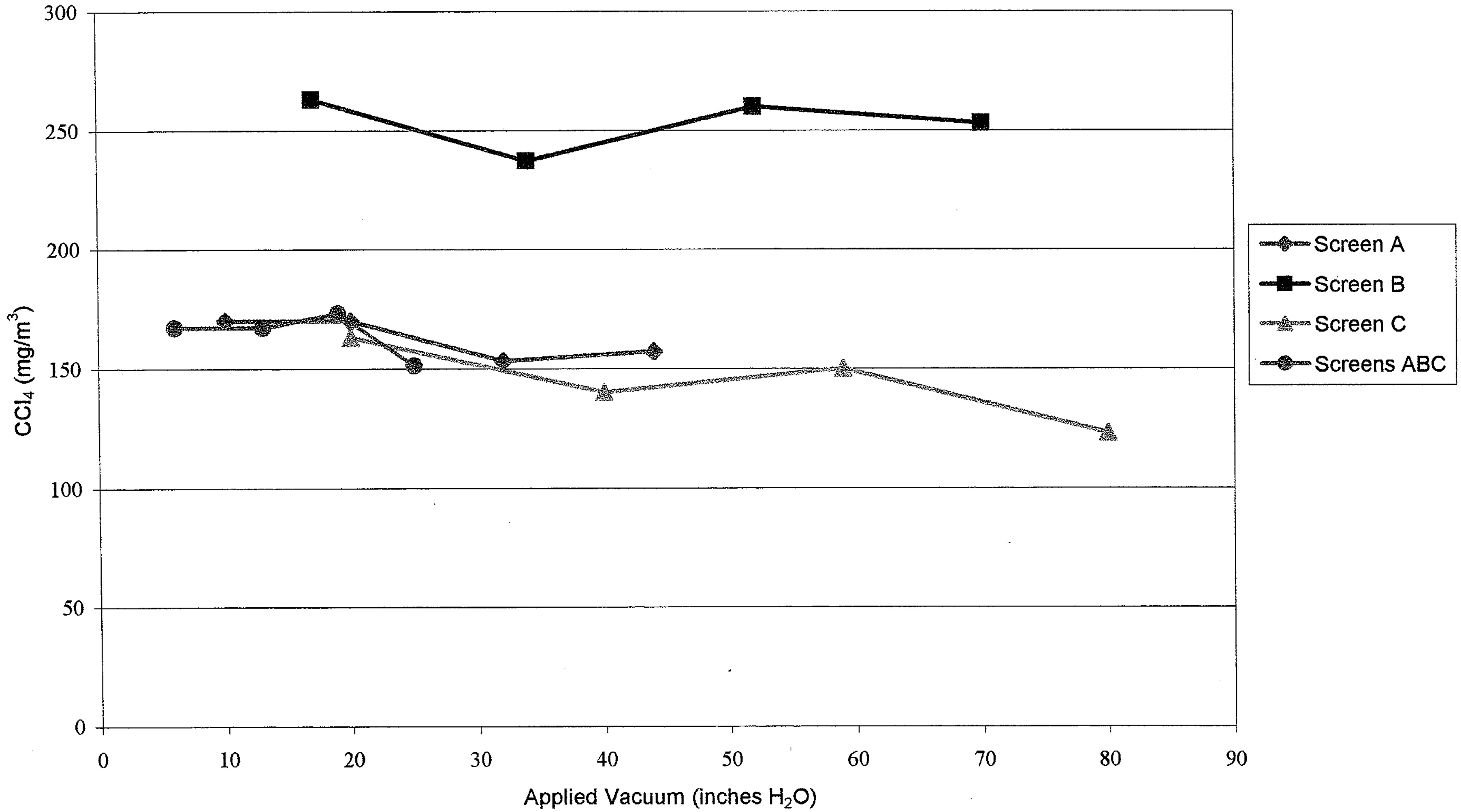
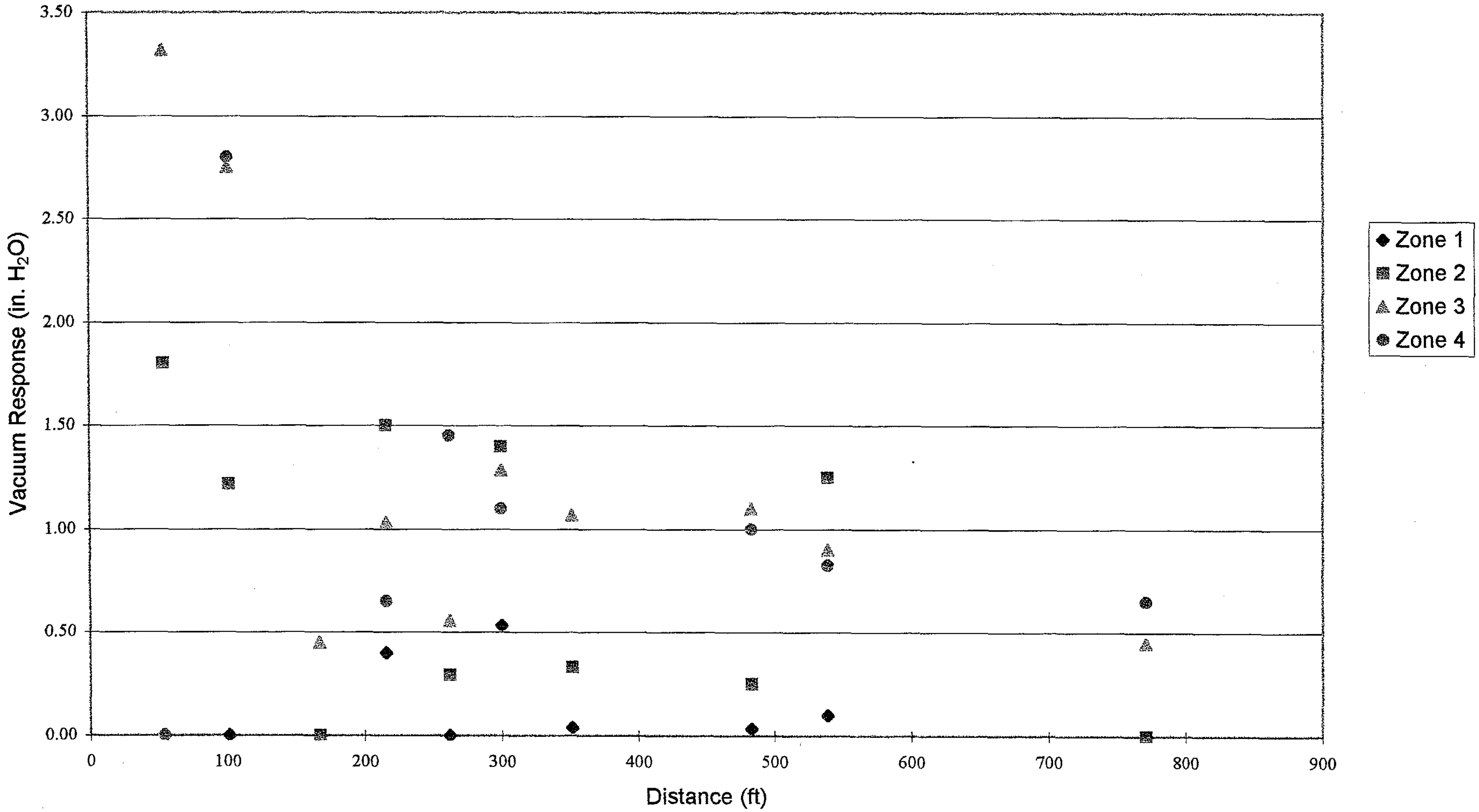
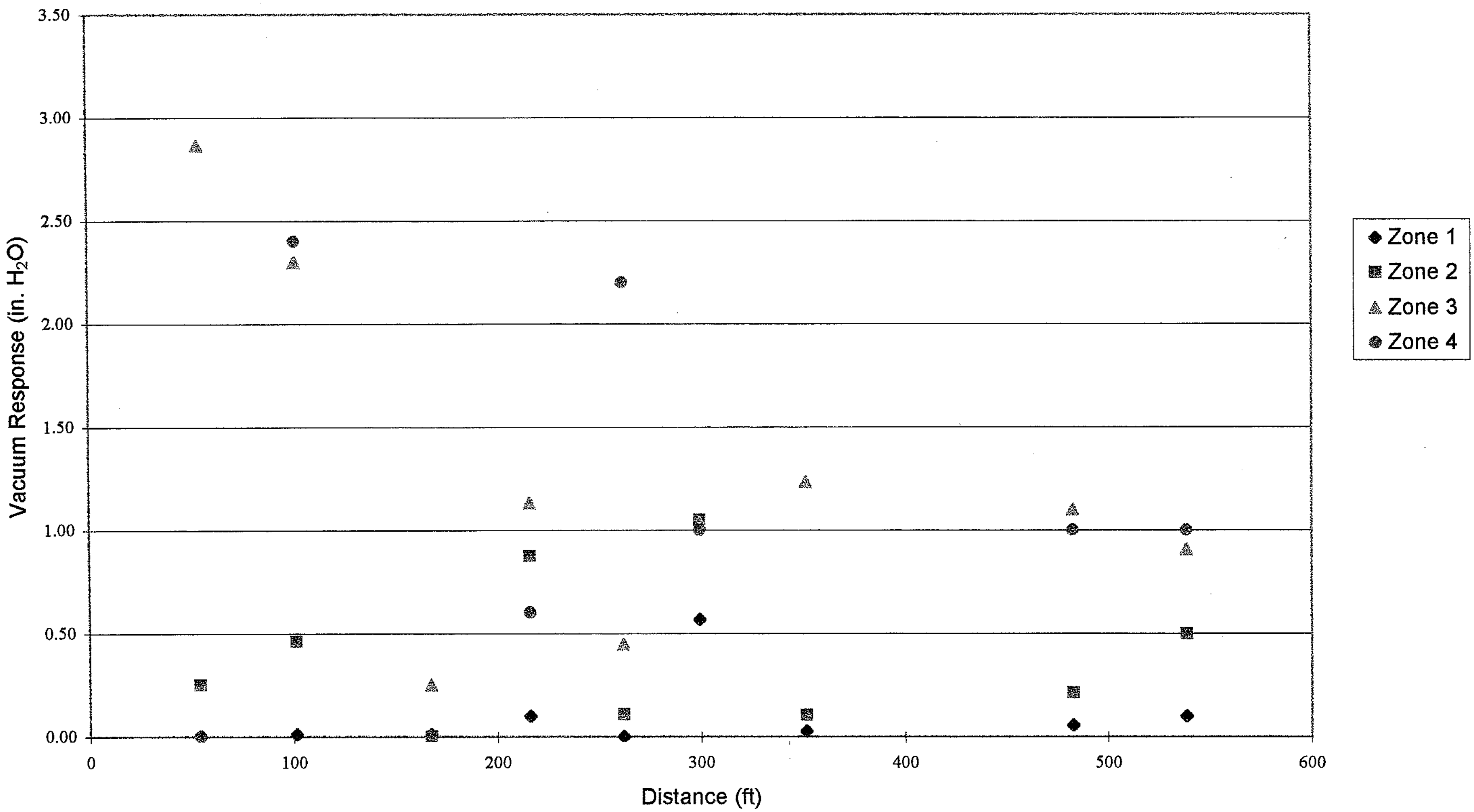


FIGURE A.4-9
TEST 2: ZONE VACUUM RESPONSE
Screens ABC Extracting (100% Vacuum)



Mwdata/Figure A.4-9

FIGURE A.4-10
TEST 2: ZONE VACUUM RESPONSE
Screens BC Extracting (100% Vacuum)



Mwdata/Figure A.4-10

FIGURE A.4-11
TEST 2: SVW-25 VACUUM RESPONSES

FIGURE A.4-11a:
TEST 2 - VACUUM RESPONSES SVW-25 (ZONE 1)

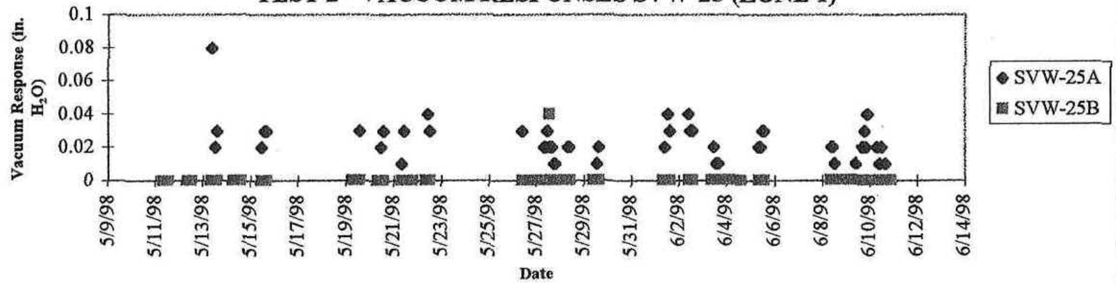


FIGURE A.4-11b:
TEST 2 - VACUUM RESPONSES SVW-25 (ZONE 2)

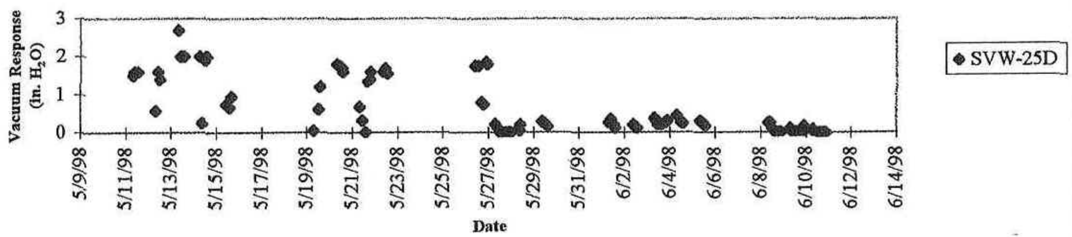


FIGURE A.4-11c:
TEST 2 - VACUUM RESPONSES SVW-25 (ZONE 3)

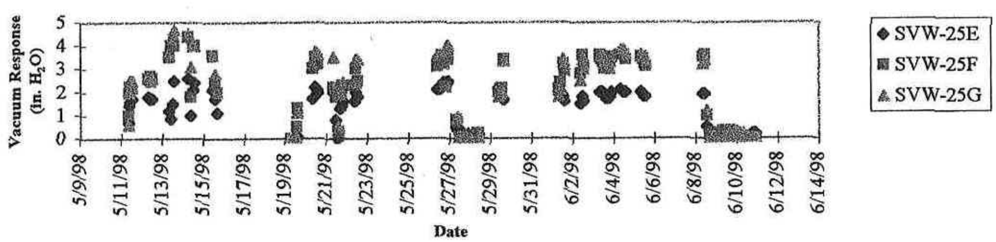


FIGURE A.4-11d:
TEST 2 - VACUUM RESPONSES SVW-25 (ZONE 4)

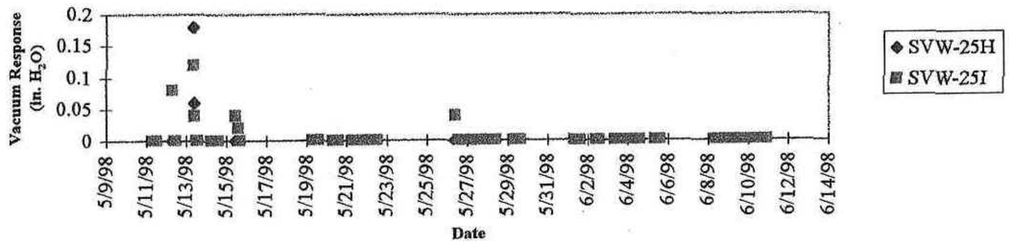
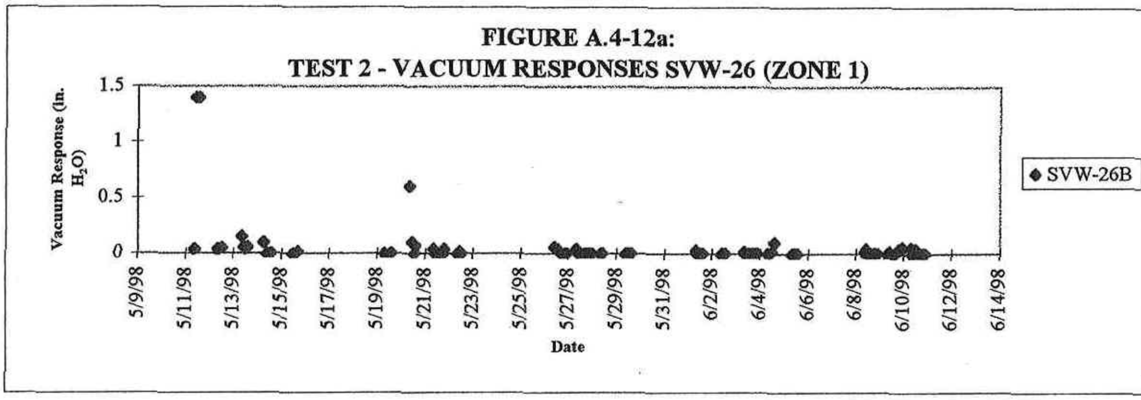
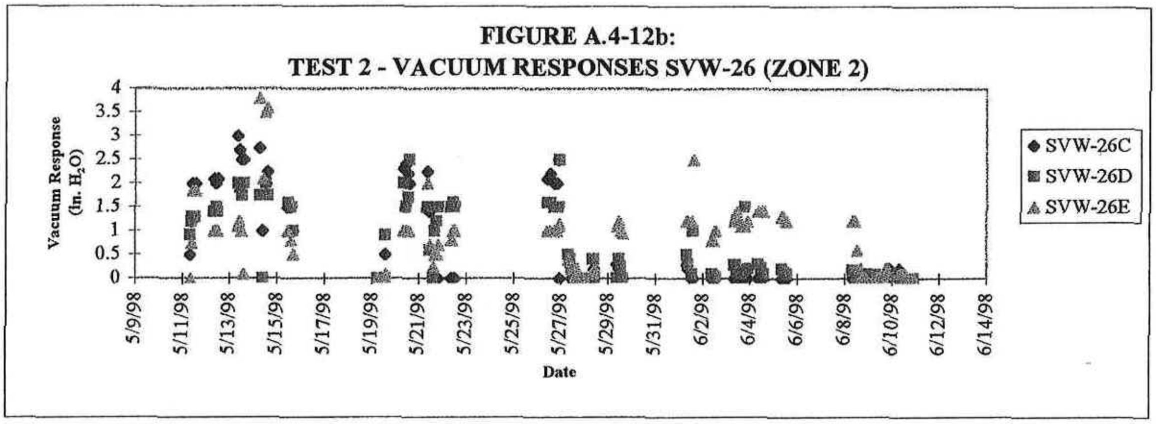
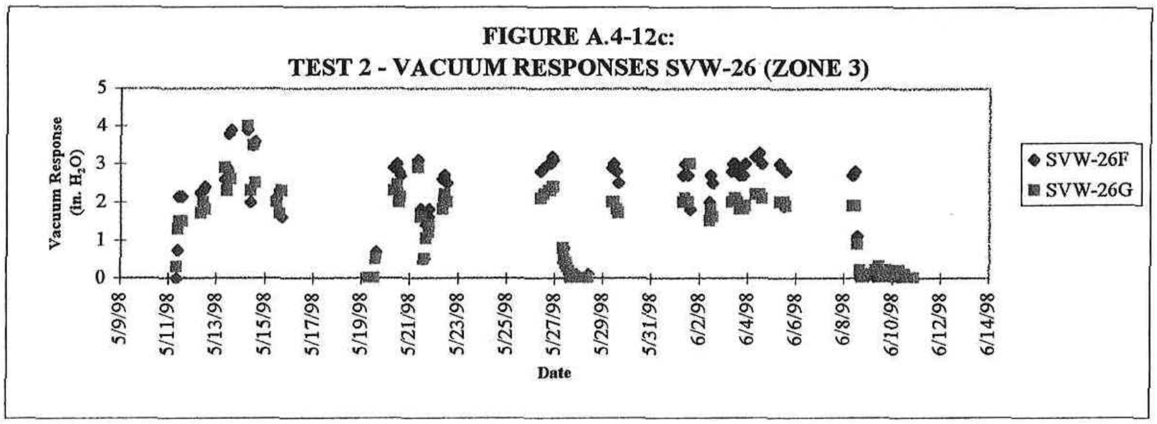


FIGURE A.4-12
TEST 2: SVW-26 VACUUM RESPONSES







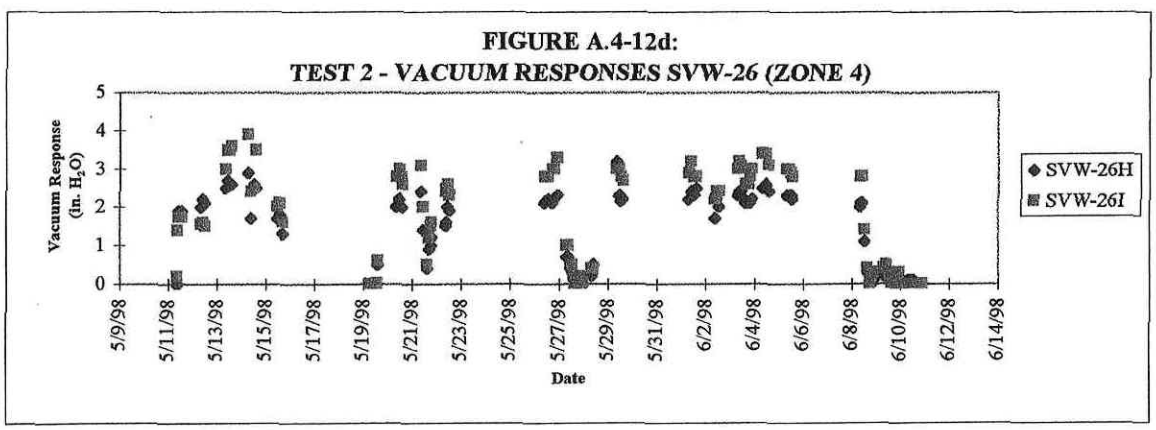
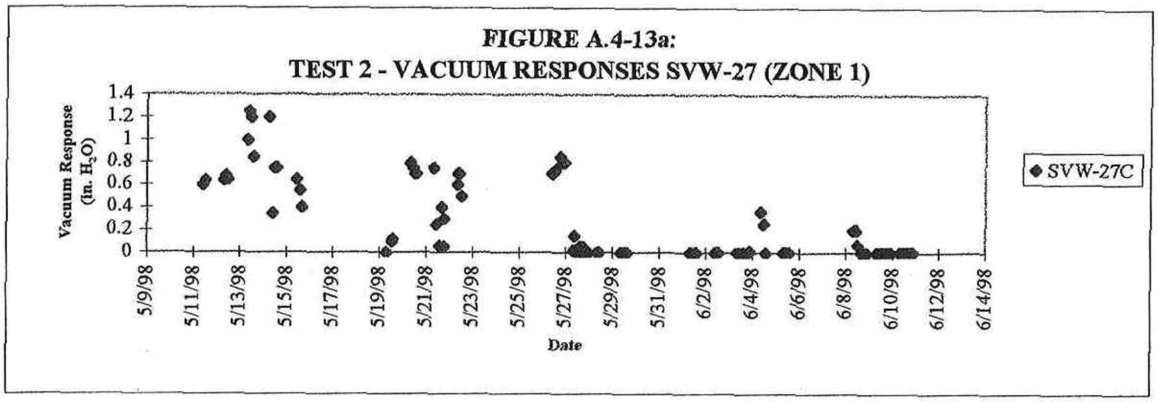
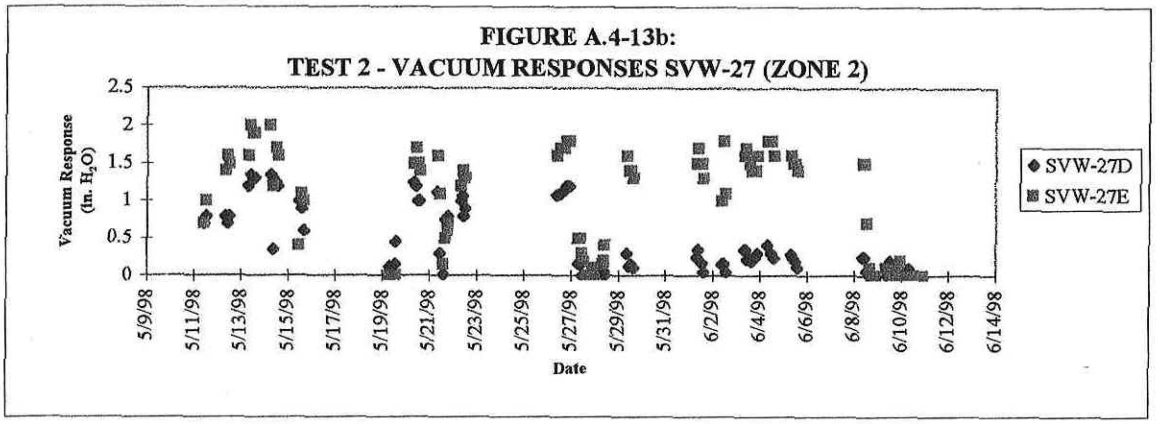
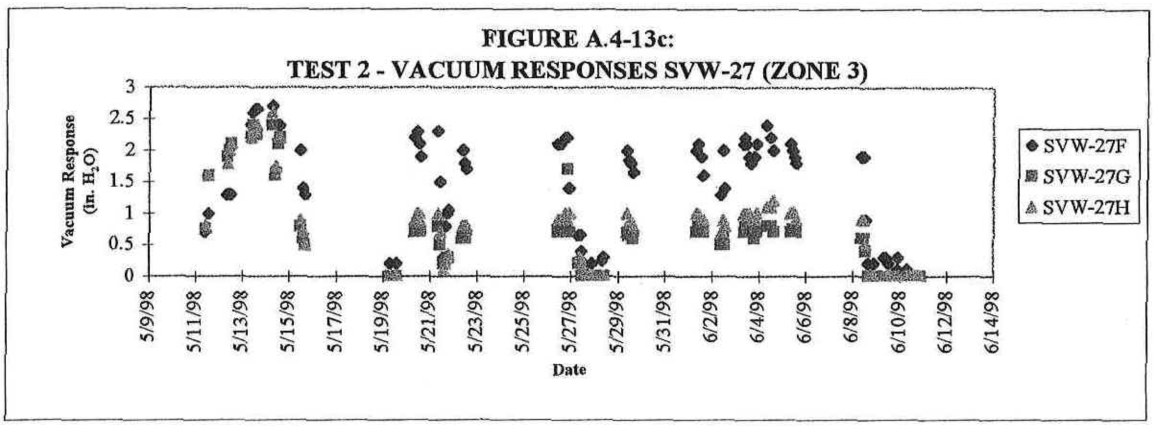
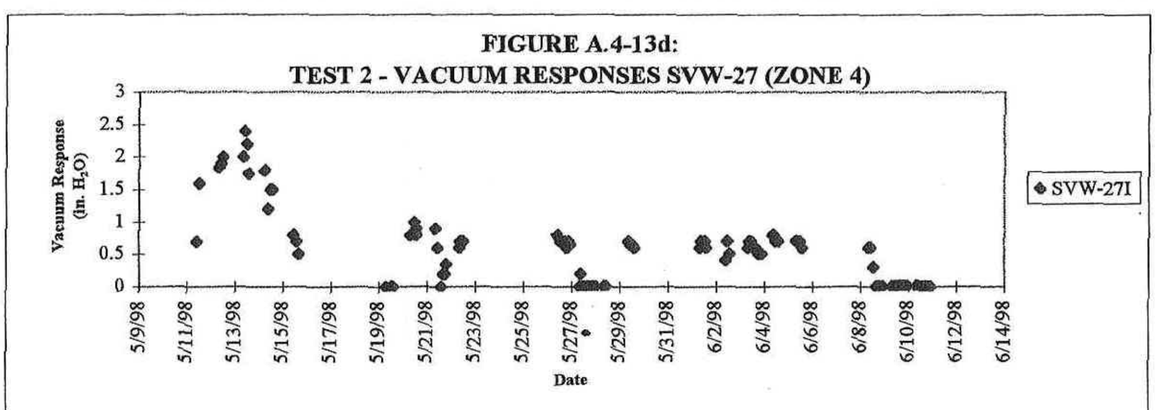


FIGURE A.4-13
TEST 2: SVW-27 VACUUM RESPONSES



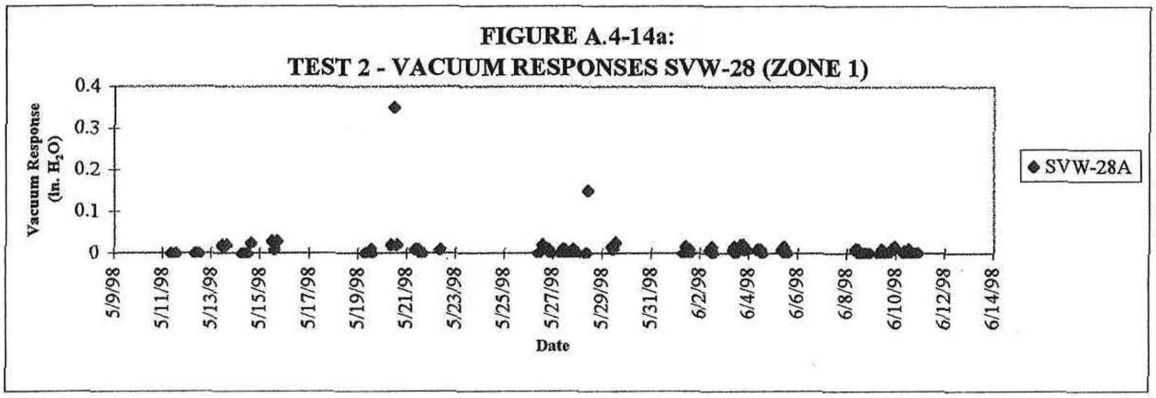


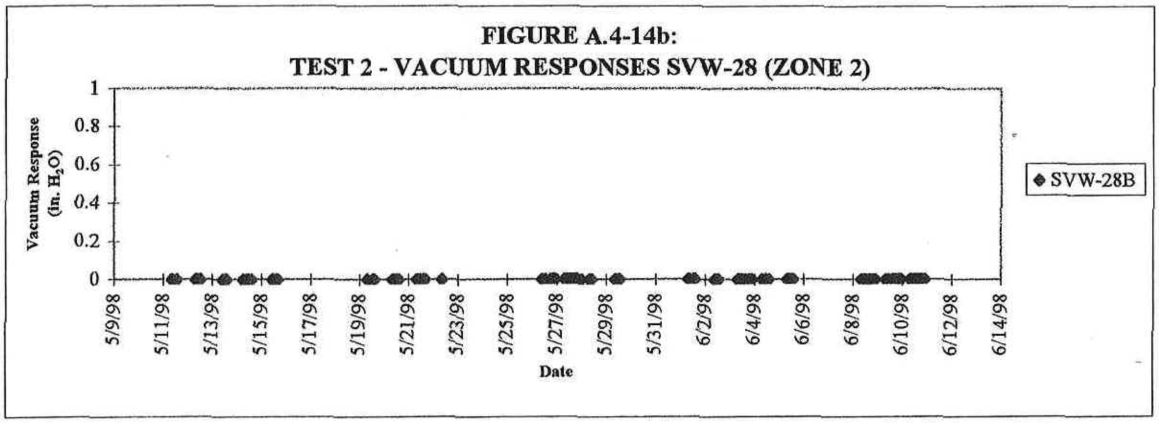


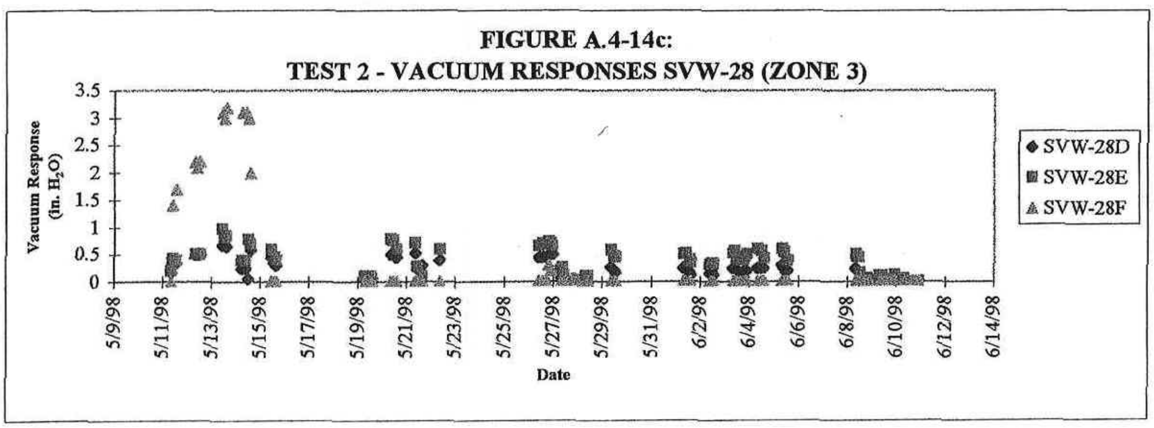


Mwdata.xls/SVW-27 VACUUM RESPONSES

FIGURE A.4-14
TEST 2: SVW-28 VACUUM RESPONSES







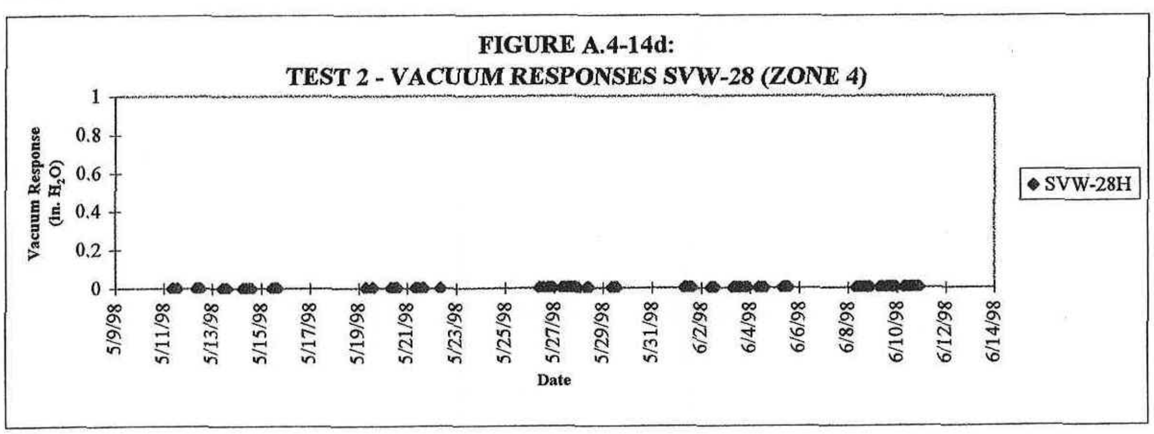
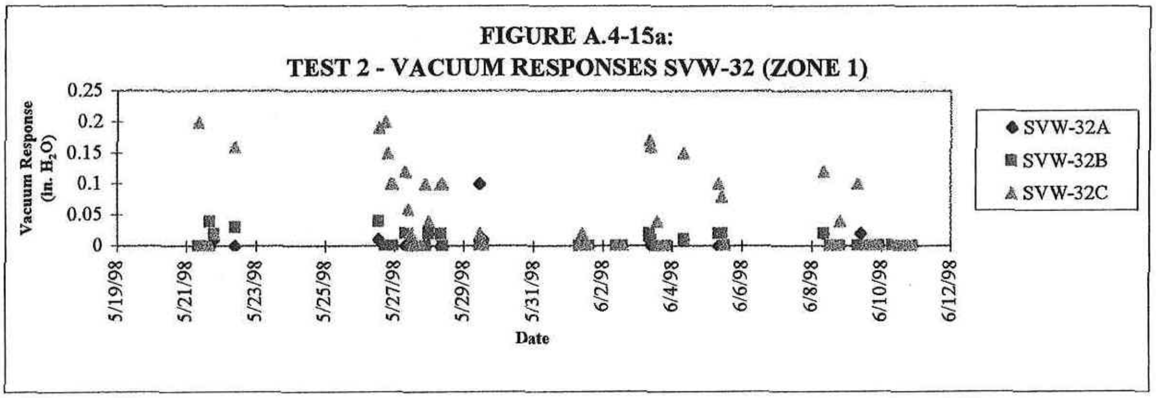
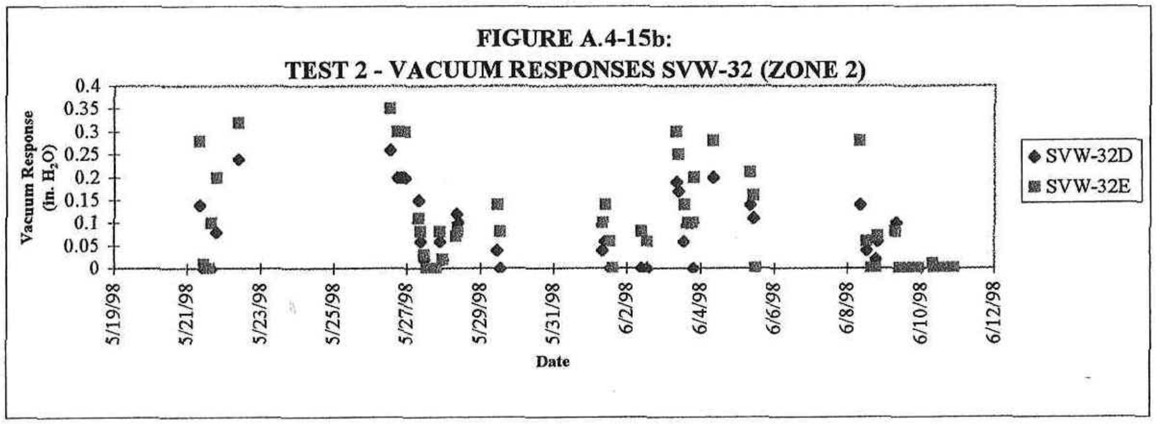
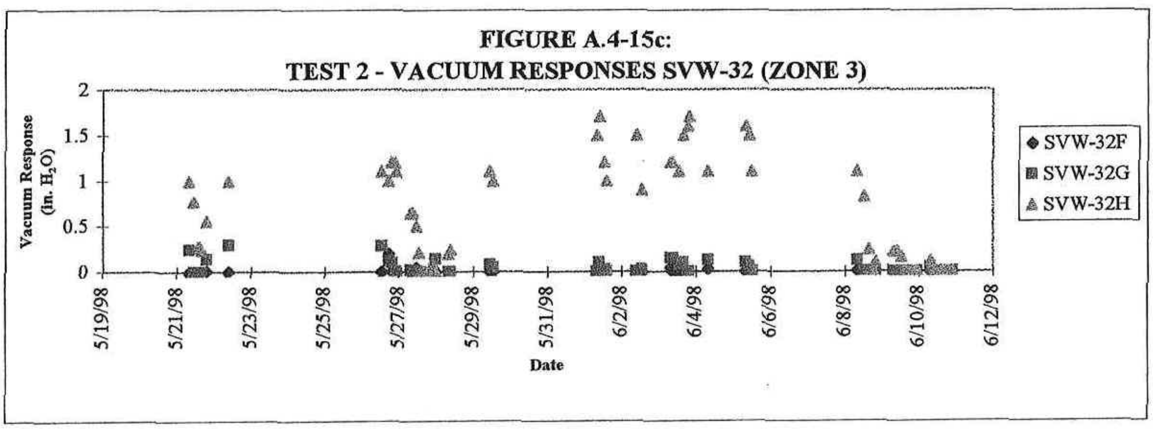


FIGURE A.4-15
TEST 2: SVW-32 VACUUM RESPONSES







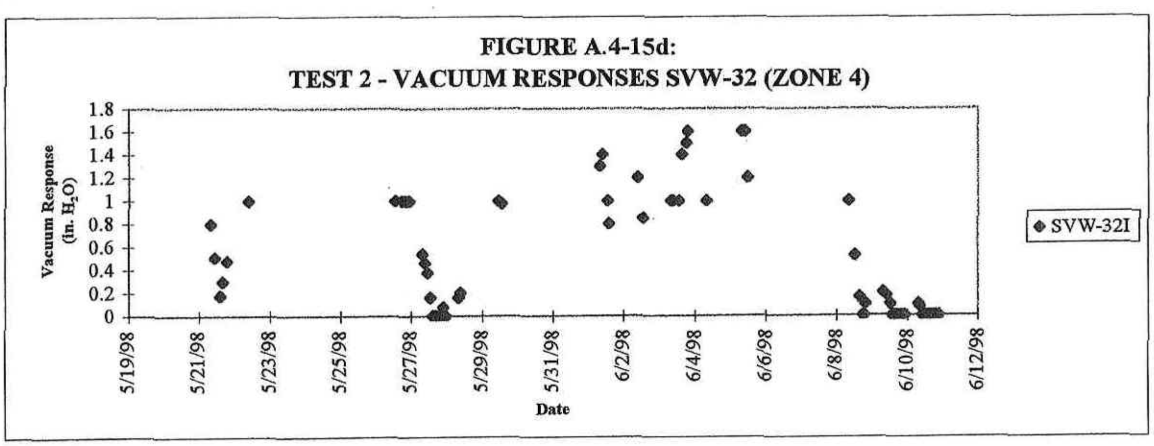
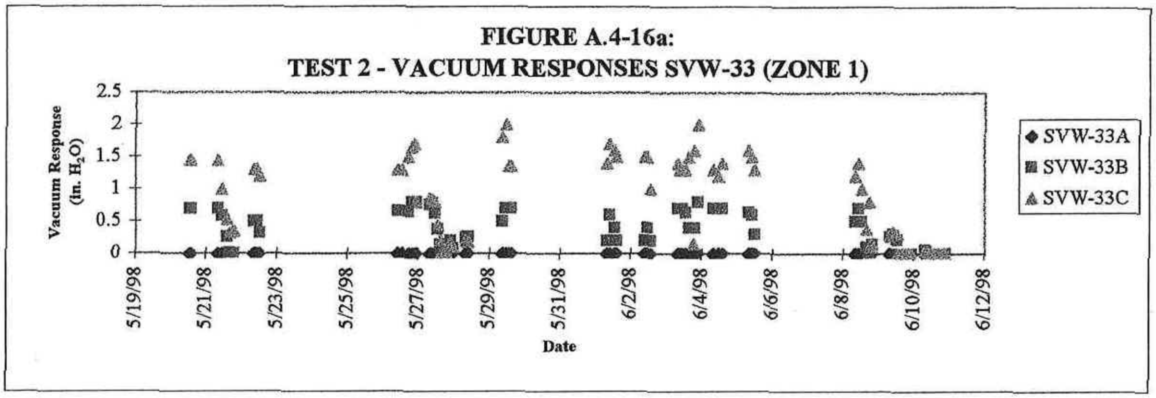
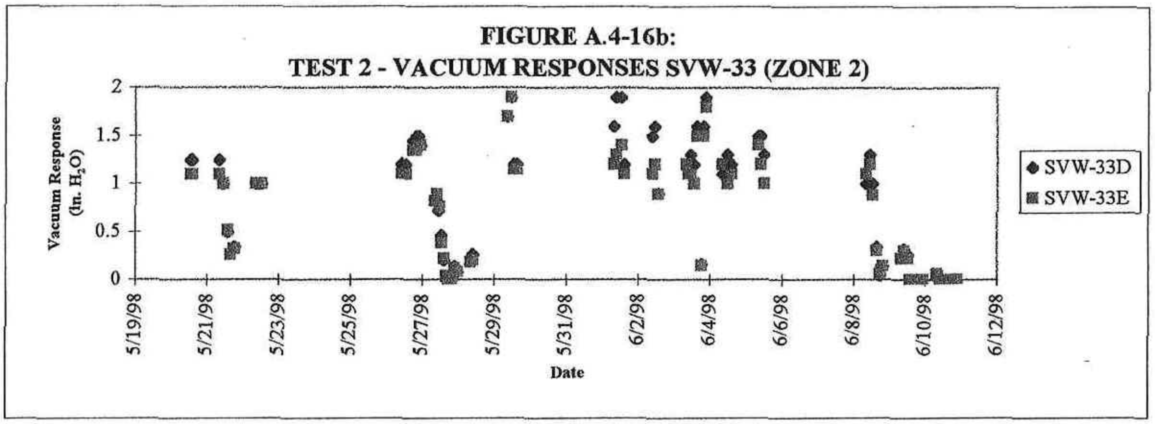
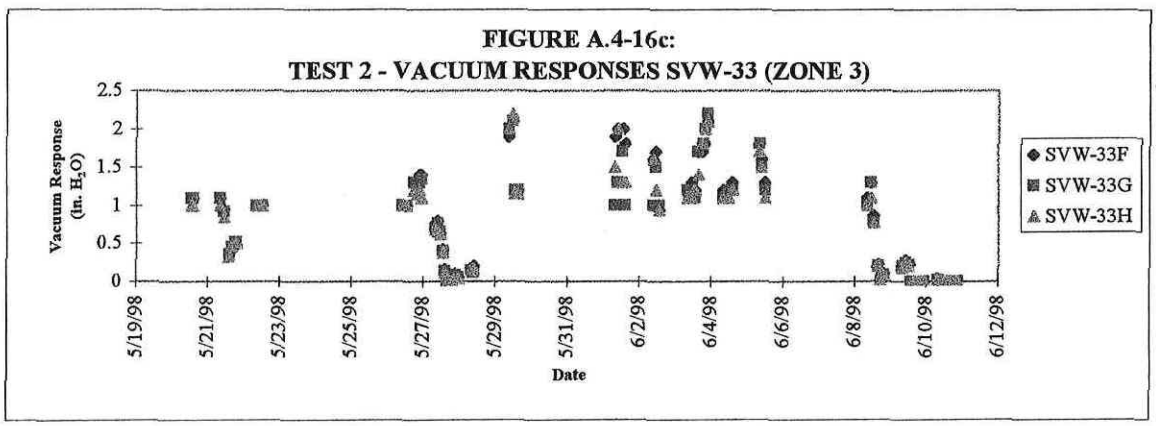


FIGURE A.4-16
TEST 2: SVW-33 VACUUM RESPONSES







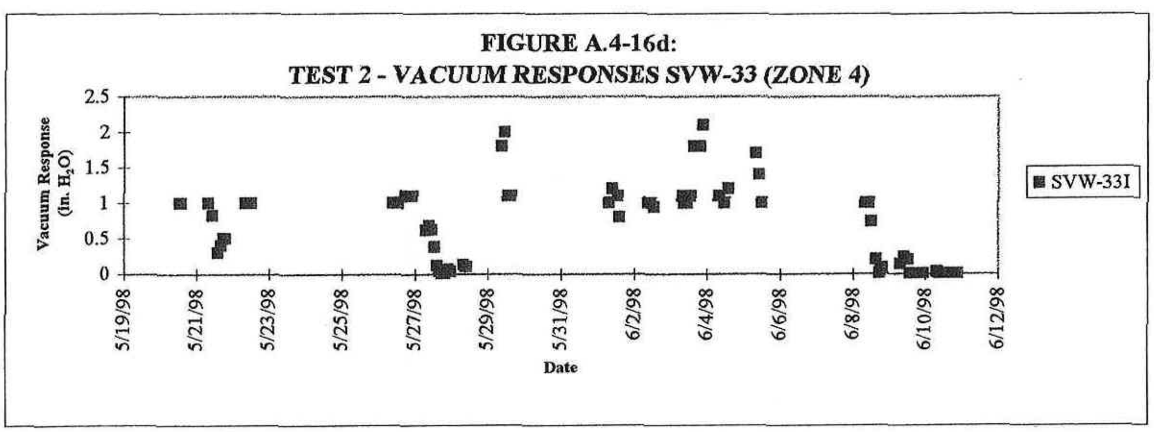
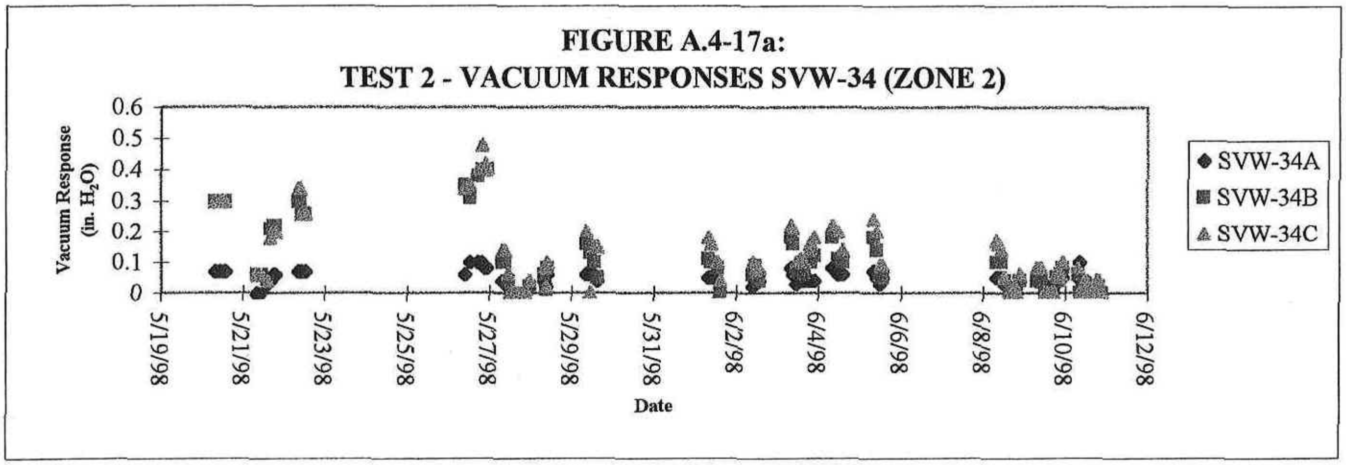
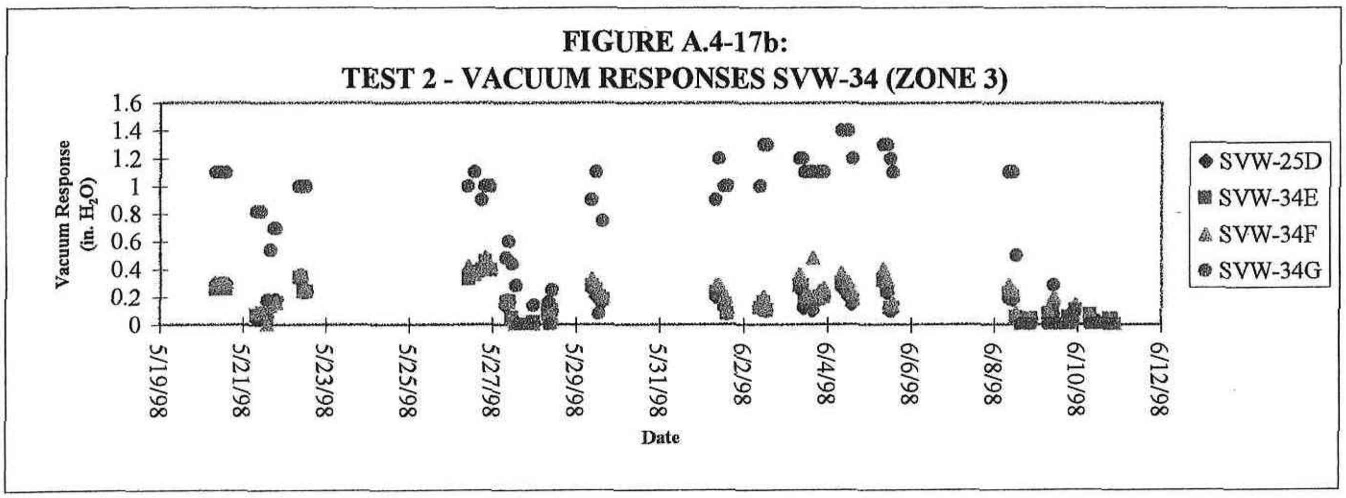
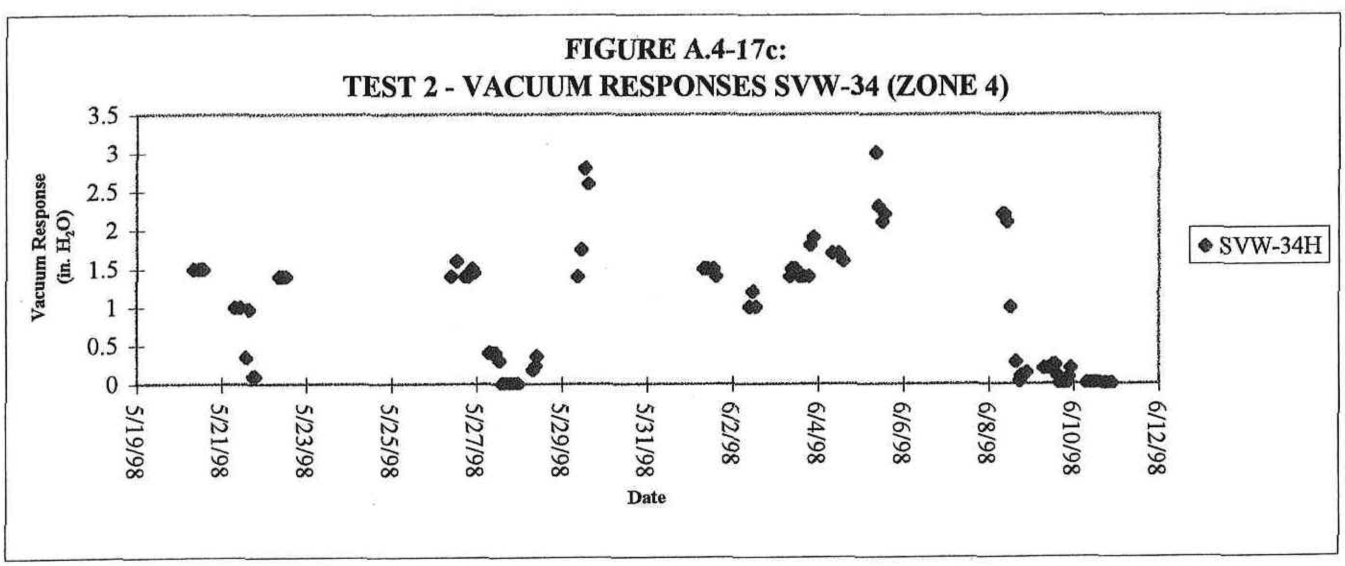


FIGURE A.4-17
TEST 2: SVW-34 VACUUM RESPONSES

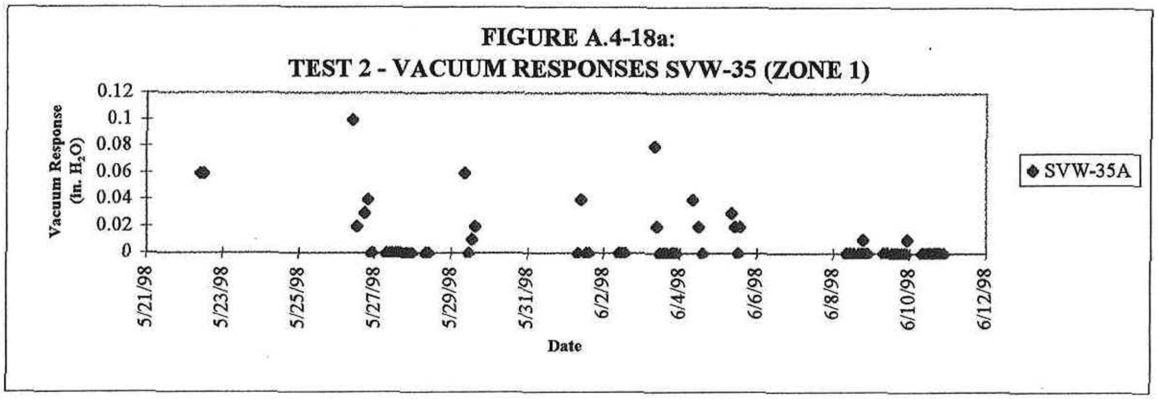


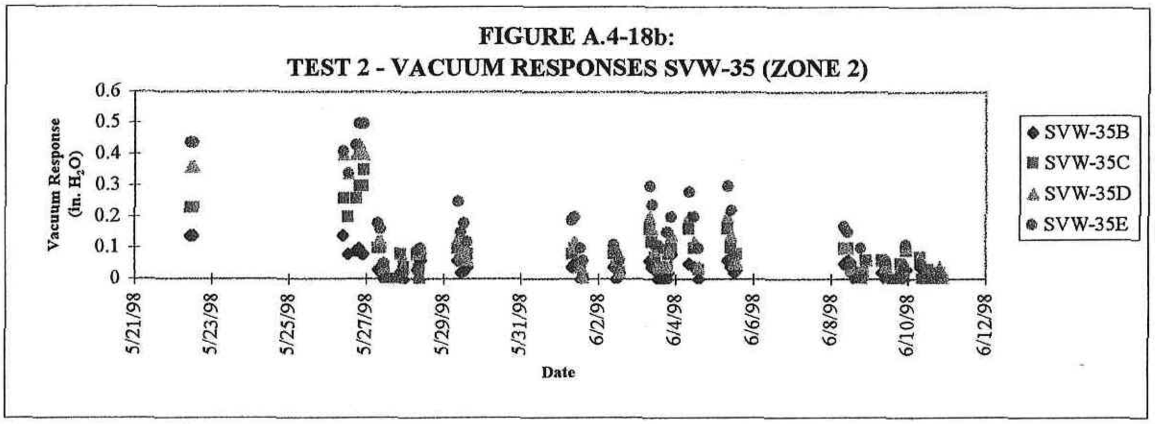


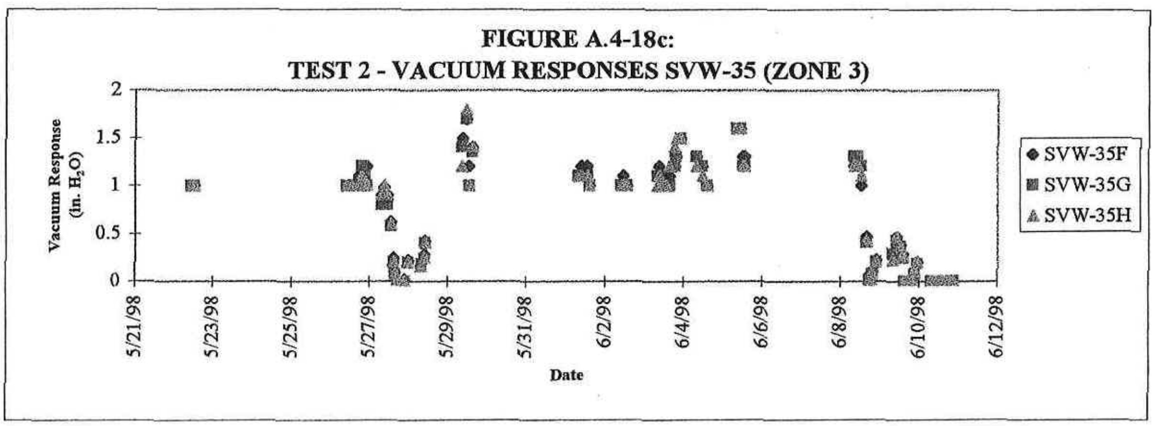


Mwdata.xls/SVW-34 VACUUM RESPONSES

FIGURE A.4-18
TEST 2: SVW-35 VACUUM RESPONSES







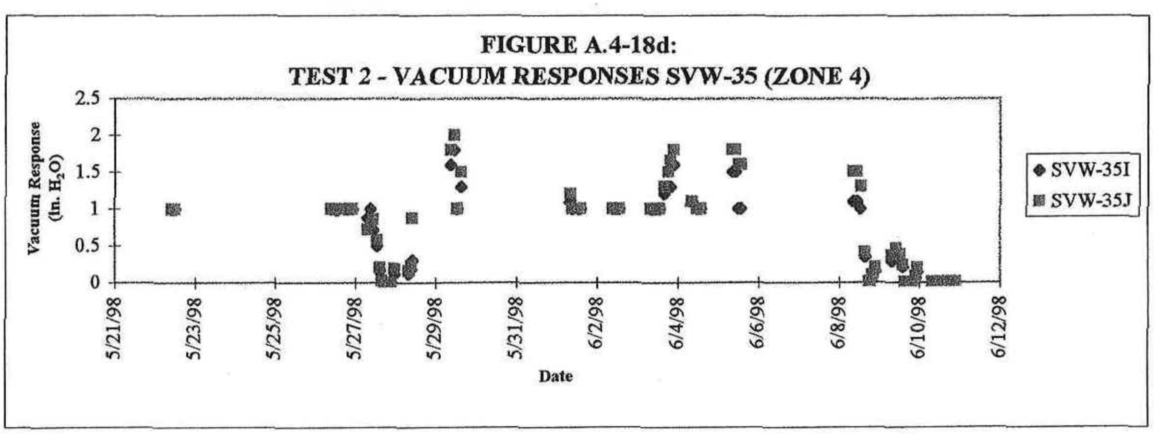


FIGURE A.4-19
TEST 2: SVW-37 VACUUM RESPONSES

FIGURE A.4-19a:
TEST 2 - VACUUM RESPONSES SVW-37 (ZONE 1)

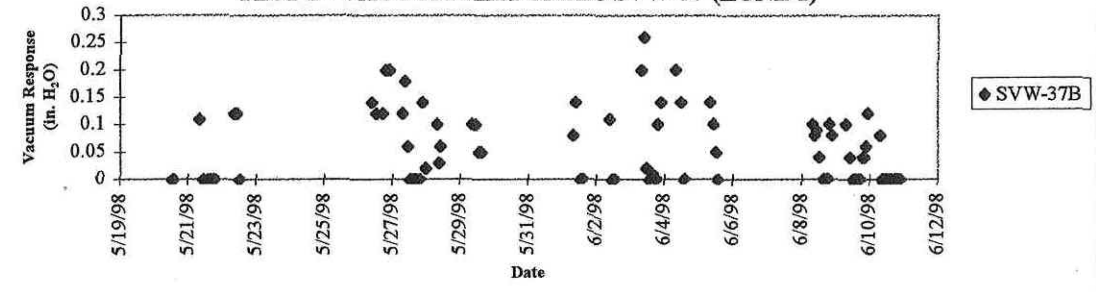


FIGURE A.4-19b:
TEST 2 - VACUUM RESPONSES SVW-37 (ZONE 2)

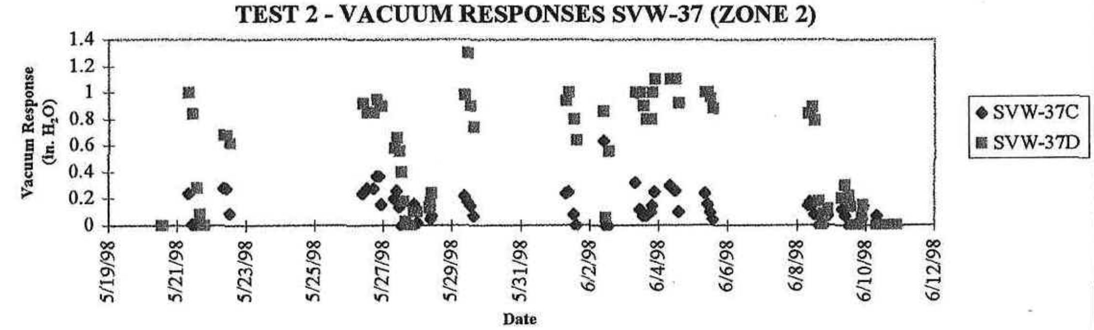


FIGURE A.4-19c:
TEST 2 - VACUUM RESPONSES SVW-37 (ZONE 3)

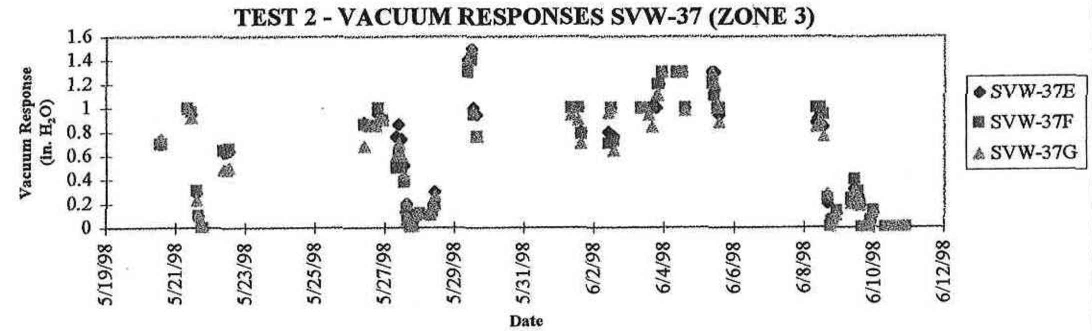
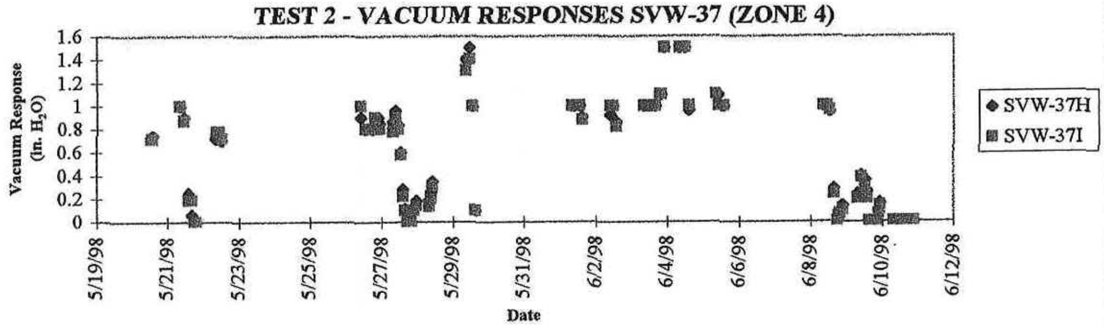
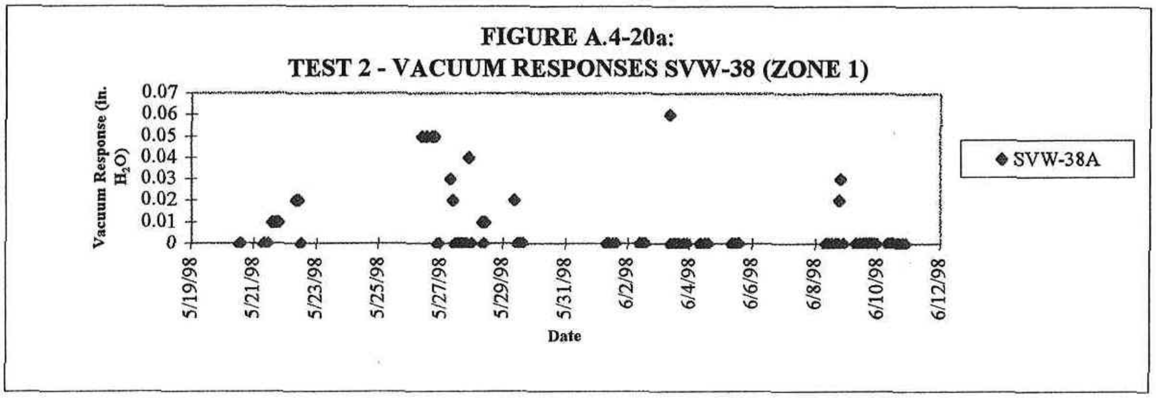


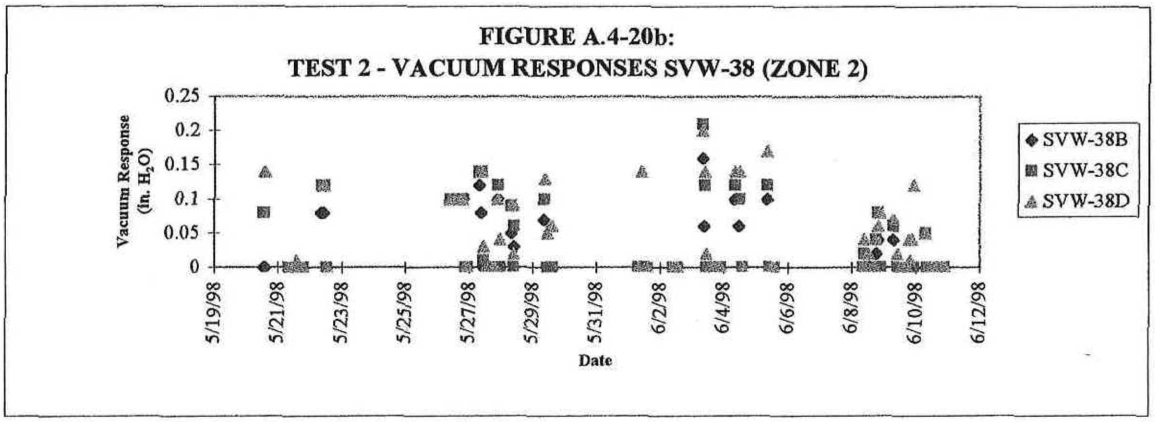
FIGURE A.4-19d:
TEST 2 - VACUUM RESPONSES SVW-37 (ZONE 4)

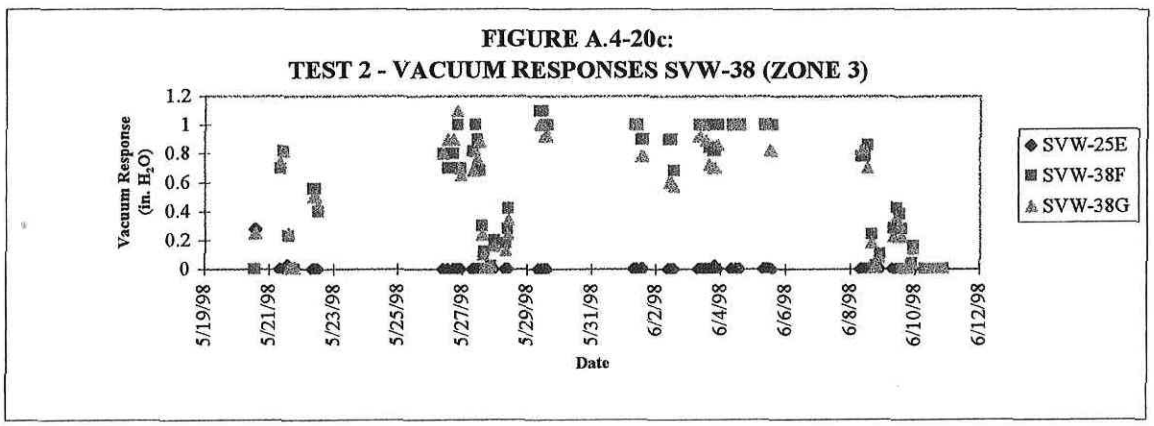


Mwdata.xls/SVW-37 VACUUM RESPONSES

FIGURE A.4-20
TEST 2: SVW-38 VACUUM RESPONSES







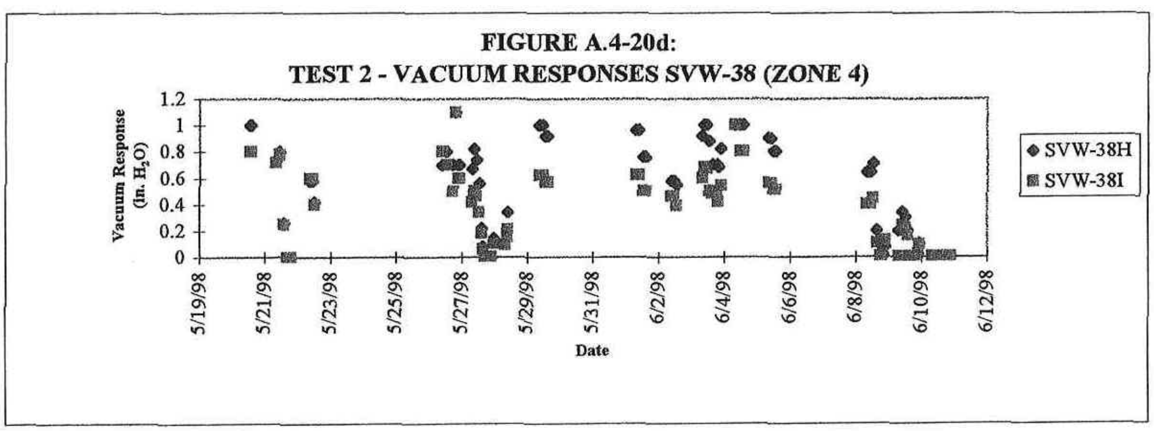
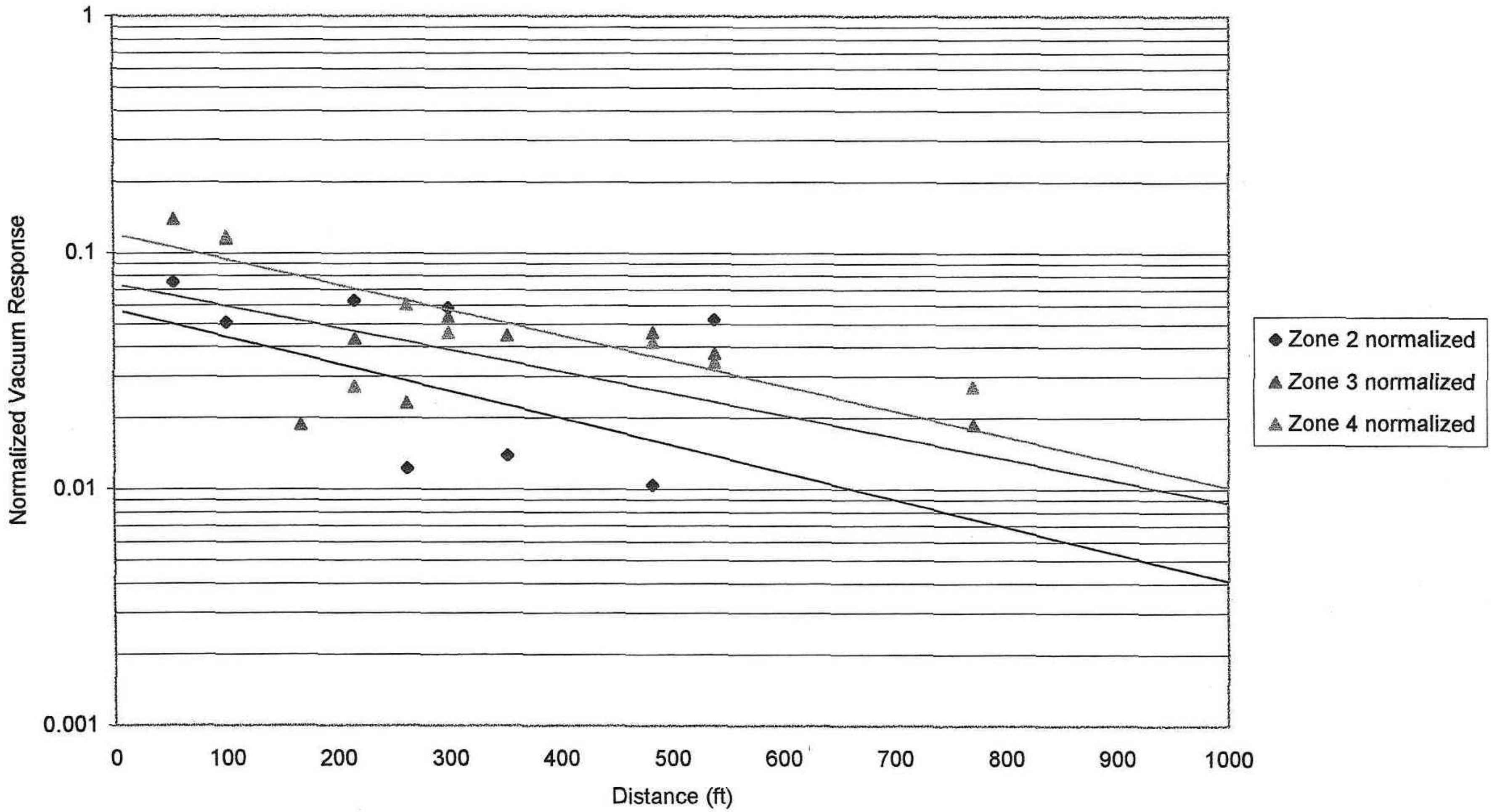
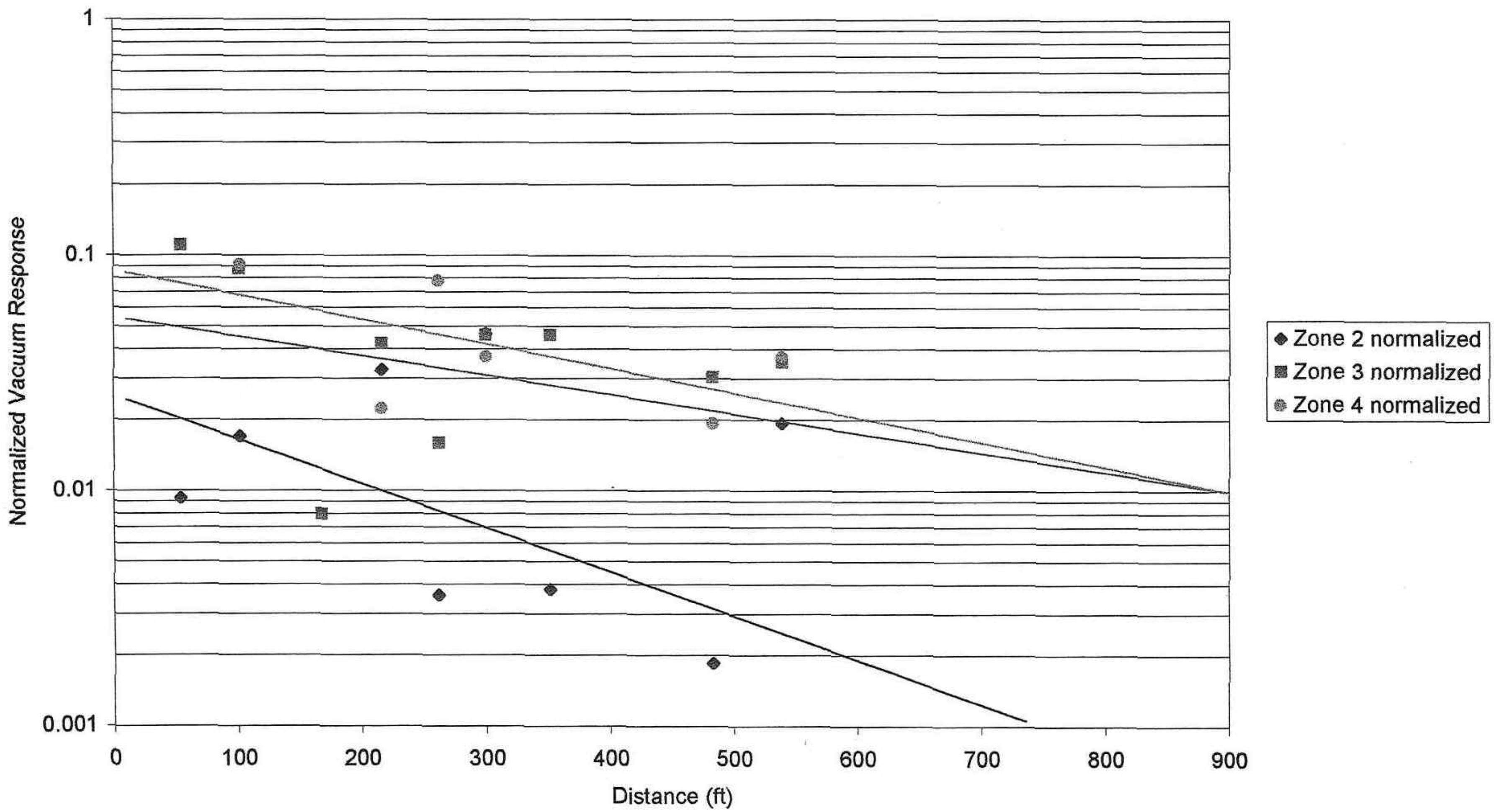


FIGURE A.4-21
TEST 2: NORMALIZED VACUUM RESPONSE
SCREENS ABC EXTRACTING (5/22/98)



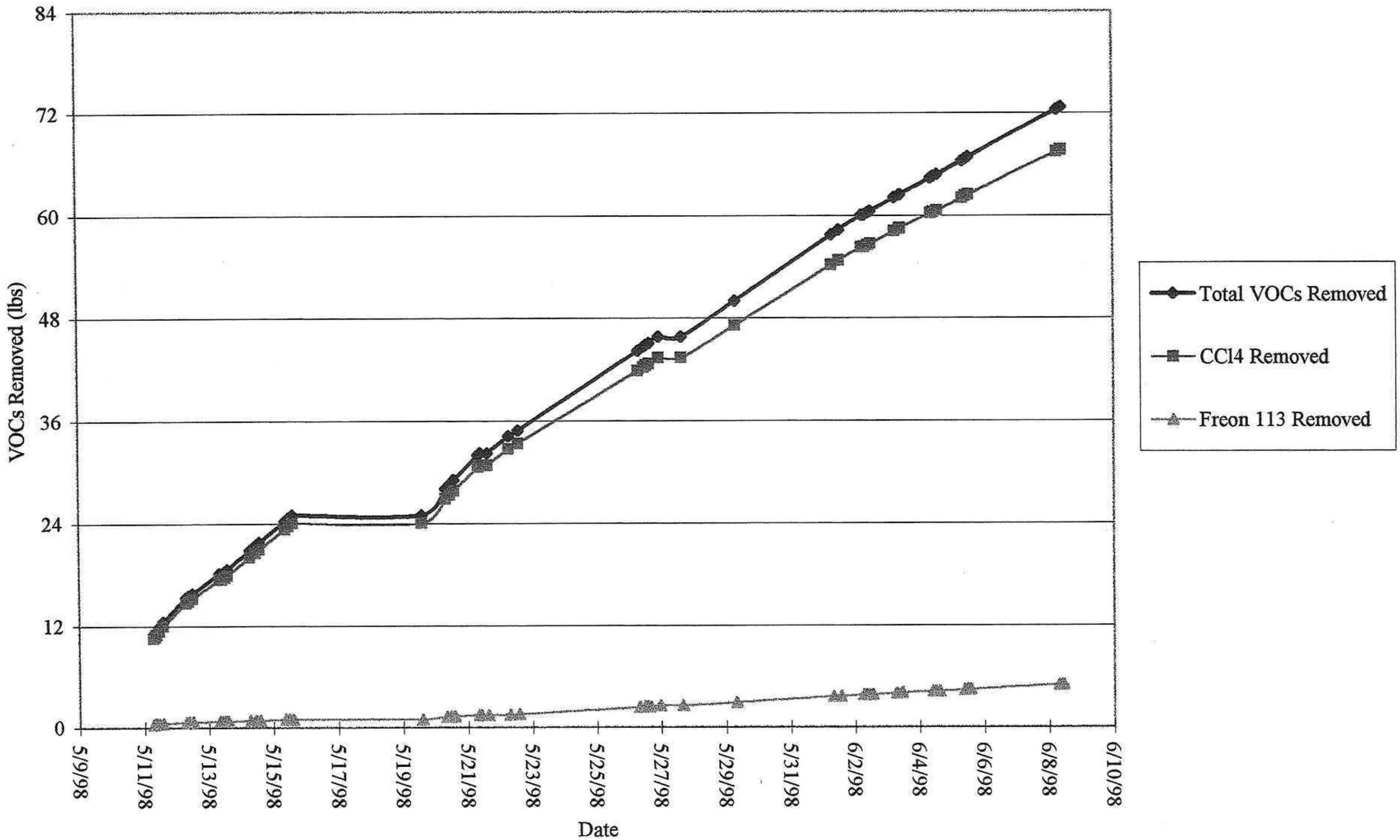
Mwdata / Figure A.4-21

FIGURE A.4-22
TEST 2: NORMALIZED VACUUM RESPONSE
SCREENS BC EXTRACTING (6/8/98)



Mwdata / Figure A.4-22

FIGURE A.4-23
TEST 2: DAILY AVERAGE CUMULATIVE VOCs REMOVED



Continue

FIGURE A.4-24
TEST 2: VOC REMOVAL RATE