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Control of Volatile Organic Contaminants in Groundwater by In-Well Aeration

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CONTROL OF VOLATILE ORGANIC CONTAMINANTS IN GROUNDWATER BY IN-WELL AERATION

by

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16. ABSTRACT

At a 0.1 mgd well contaminated with several volatile organic compounds (VOCs), principally trichloroethylene (TCE), several in-well aeration schemes were evaluated as control technologies. The well was logged by the USGS to define possible zones of VOC entry. A straddle packer and pump apparatus were utilized to isolate those zones and define their yield and level of VOC concentration. The technical literature together with this knowledge of the well were used to design an air lift pump. Operation of the air lift pump confirmed literature prediction of its low wire-to-water efficiency. Removal of TCE did not exceed 65 percent. Mass transfer occurred in the pump's eductor. Air lift pumping coupled with in-well diffused aeration increased TCE removal to 78 percent. When in-well diffused aeration was used with an electric submersible pump, TCE removal averaged 83 percent. In the latter two schemes, mass transfer occurred utilizing the well as a countercurrent stripper. These technologies are limited by the volume of air that can be transferred to the well (air-to-water ratios below 12:1) and the cost of compressing air under high head. Thus, these technologies are not cost-effective compared to packed tower aeration. They are, however, quickly put on-line, easy to operate, and can serve as good short-term remedies while above-ground technologies are under design and construction.

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxics Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing municipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

Under the Safe Drinking Water Act, the EPA will regulate trichloroethylene, vinyl chloride, cis-1,2-dichloroethylene and other volatile organic contaminants found in the nation's groundwater. While the EPA has stipulated that granular activated carbon adsoprtion and packed tower aerators are "best available technologies" for control of these contaminants in drinking water, other technologies may be used. This publication reports on an evaluation of in-well aeration technologies. Air lift pumping with and without in-well diffused aeration, and in-well diffused aeration coupled with electric submersible pumping were evaluated. These technologies were not as cost-effective as packed tower aeration for long-term control of these contaminants. They will, however, provide short-term control at low capital cost while above ground, long-term technologies are under design and construction.

Francis T. Mayo, Director
Water Engineering Research Laboratory

ABSTRACT

Several in-well aeration schemes were evaluated as control technologies at a 0.1 mgd well contaminated with several organic chemicals (VOCs), principally trichloroethylene (TCE). The well was logged by the U.S.G.S. to define possible zones of VOC entry. A straddle packer and pump apparatus were utilized to isolate those zones and define their yield and level of VOC concentration. The technical literature together with this knowledge of the well were used to design an air lift pump. Operation of the air lift pump confirmed the literature prediction of its low wire-to-water efficiency. Removal of TCE did not exceed 65 percent. Mass transfer occurred in the pump's eductor. Air lift pumping coupled with in-well diffused aeration increased TCE removal to 78 percent. When in-well diffused aeration was used with an electric submersible pump, TCE removal averaged 83 percent. In the latter two schemes, mass transfer occurred utilizing the well as a countercurrent stripper.

Off-gases of the in-well aeration process were tested and it was determined that, depending on the raw water chemical concentration, air pollution discharge permits may be required to operate an in-well aeration treatment system. Dissolved oxygen and pH both increased with in-well aeration which may have distribution system corrosion implications. Bacteriological testing was inconclusive.

These technologies are limited by the volume of air that can be transferred to the well (air-to-water ratios below 12:1) and the cost of compressing air under high head. Thus, these technologies are not cost-effective compared to packed tower aeration. They are, however, quickly put on-line, easy to operate, and can serve as good short-term remedies while above-ground technologies are under design and construction.

This report was submitted in fulfillment of cooperative agreement number CR-809758 by the North Penn Water Authority under the partial sponsorship of the U.S. Environmental Protection Agency. This report covers a period from February 1982 to February 1986. Field work was completed as of March 1985.

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ABBREVIATIONS

1,1-DCE	-	1,1-dichloroethylene
1,1,1-TCA	-	1,1,1-trichloroethane
c-1,2-DCE	-	cis-1,2-dichloroethylene
CCL4	-	carbon tetrachloride
cfpm	-	cubic feet per minute
CHCL3	-	chloroform
DO	-	dissolved oxygen
ft	-	foot
GC	-	gas chromatograph(y)
GC/MS	-	gas chromatography/mass spectroscopy
gpd	-	gallons per day
HP	-	horsepower
HPC	-	Heterotrophic Plate Count
in	-	inch
n	-	number of samples tested
NPWA	-	North Penn Water Authority
PCE	-	tetrachloroethylene
%RSD	-	% relative standard deviation
psi	-	pounds per square inch
PVC	-	polyvinyl chloride
SD	-	standard deviation
SP	-	spontaneous potential
TCE	-	trichloroethylene
ug/L	-	micrograms per liter
U.S.G.S.	-	United States Geological Survey
VC	-	vinyl chloride
VOA	-	volatile organic analysis
VOC	-	volatile organic chemical

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We wish to acknowledge the following people who have contributed their efforts to this project: Tucker Moorshead, Earth Data, Inc., St. Michaels, MD., for his role in developing the original idea for this in-well aeration study and for conducting and interpreting the well characterization tests; Dr. I.H. Suffet, Drexel University, Philadelphia, PA., for helping with experimental design and technical editing; Terry Gable, Clarence Godshall, and William Smith, NPWA, for field work; Charles Hertz, Beth Green Hertz, James Towson, and Yifen Tsai, NPWA, for analytical work; Ralph Walter and Dale Reichenbach, NPWA, for drafting; Johanna Brown, NPWA, for word processing and editing; and the NPWA Board of Directors for their support of our research endeavors.

SECTION 1

INTRODUCTION

OVERVIEW

Contamination of groundwater with volatile organic compounds (VOCs) has become common throughout the United States. (1,2,3) Southeastern Pennsylvania and the North Penn Water Authority (NPWA) have not escaped this problem. In 1979 a large amount of trichloroethylene (TCE) was spilled in nearby Collegeville, PA. The Authority sampled all 34 of their operating wells and found eight to be contaminated with TCE and other VOCs. These wells were shut down, resulting in a loss of approximately one-third of the system's total pumping capacity.

Since that time NPWA has been actively pursuing various methods of dealing with the VOC problem. Surface water was purchased from a neighboring water supplier, a granular activated carbon treatment plant was installed at one well, packed tower aeration devices were designed and this study was carried out to investigate in-well aeration techniques.

This report covers the design and operation of various in-well aeration configurations examined by NPWA during the time period of January 1982 to May 1985. The configurations included air-lift pumping with and without in-well diffused aeration (sparging), as well as electric submersible pumping with in-well diffused aeration.

The well selected for this study was Lansdale number 8 (well L-8). This well was heavily contaminated with VOCs and was being pumped to waste in an attempt to control the contamination plume. A description of the well is given in Table 1. It is in a mixed residential/commercial area, with homes in close proximity to the well house.

When a well is found to be contaminated it is common practice to pump it to waste, in order to prevent the contamination plume from spreading throughout the aquifer. In-well aeration, by air-lift pumping, can treat the water as it is being pumped. This can reduce the amount of pollutants being discharged into the sewer system (as at well L-8) or, in some cases, may treat the water to potability. Treating the water while pumping eliminates the need for construction of above-ground treatment devices. In cases where above-ground treatment systems are necessary, in-well aeration may provide a good interim treatment technique while the permanent system is being designed and installed. The in-well aeration equipment used in this study was easily constructed from materials already in NPWA stock.

Shortly after the discovery of VOC pollution at NPWA in 1979, a series of preliminary tests were performed using an air lift pump or an electric submersible pump with a sparger. No attempt was made to record air to water ratios or operating conditions; however, even under these uncontrolled conditions, good removal efficiencies were seen for TCE (above 80%). This provided the incentive for further study of in-well aeration.

TABLE 1. DESCRIPTION OF NPWA WELL L-8

Location: West Third Street, Lansdale, PA.

Depth of Well: 292 feet (original), 286 feet (present)

Depth of Casing: 20 feet (8 inch diameter)

Date Drilled: 1923

Pumping Capacity: 50-70 gpm

VOC PRESENT	HENRY'S LAW CONSTANT (atm - m^3/m^3)(4)
vinyl chloride	8.8
1,1-dichloroethylene	0.40
cis-1,2-dichloroethylene	0.070
1,1,1-trichloroethane	0.31
carbon tetrachloride	1.0
trichloroethylene	0.30
perchloroethylene	0.83

The air lift pump used for this study was similar in design to pumps used by the Lansdale Municipal Authority (predecessor to NPWA) in the 1920's. Compressed air was introduced into an open-ended eductor pipe in the well. The aerated water in the eductor was less dense than the surrounding water in the well and was therefore forced up the eductor and out of the well, because of this density gradient. The three test modes of in-well aeration for this study involved pumping by an air lift pump, air lift pumping in combination with sparging and electric submersible pumping with a sparger. The sparger was simply an open-ended 3/4 in polyvinyl chloride (PVC) pipe that was lowered into the well. Compressed air was introduced through the sparger pipe.

WORK PERFORMED

This study assessed in-well aeration in terms of volatile organic removal efficiency as well as pumping efficiency. In wire-to-water terms, air lift pumps are less efficient than electric pumps. For this reason air lift pumps were replaced with electric pumps at NPWA many years ago. This study attempted to establish whether or not the volatile organic removal capability of an in-well aeration system made it a cost-effective alternative to pumping the water to the surface with an electric pump and then treating it by aeration.

Certain secondary effects of in-well aeration treatment techniques were also examined. Off-gases in the well house were tested to determine whether hazardous conditions were present. The air outside the well house, in the adjacent residential area, was also tested for VOCs. Bacteriological changes as well as corrosion related factors (changes in pH or dissolved oxygen with aeration) were examined.

The first stage of in-well aeration system design in this study was characterization of well L-8. This was done by the U.S. Geological Survey (U.S.G.S.) with a series of well loggings. These tests included caliper, conductivity, temperature, radiological and brine trace logs among others. The U.S.G.S. study determined possible water zones of entry.

Straddle packers were placed in the well to isolate the water zones of entry determined by the U.S.G.S. Each of these zones were analyzed for VOCs and specific capacity. This knowledge of where pollution was entering the well was used to determine the depth to locate the aeration equipment. (For example, if all the pollution was entering the well above 50 feet, locating the equipment at a depth of 200 ft, attempting to maximize counter-current operation, may not be cost effective given the cost of compressing air under that head).

Three different depths for in-well aeration equipment were evaluated at well L-8, based on the findings of the straddle packer testing and air lift pump theory. The air lift pump and sparger were operated at each of these three depths. This provided several types of water and air bubble movement in the well, including both counter-current and co-current stripping.

An electric submersible pump was fixed at one depth in the well while the sparger was tested at each of the three depths used in air lift pump tests. The decision of where to place the equipment during electric pump testing was based on the results of the air lift pump testing.

Parameters measured in the field during in-well aeration testing included air pressure, air temperature, air flow rate, water flow rate and water level in the well. These parameters allowed calculations of pumping efficiencies and air-to-water ratios. The in-well aeration systems tested were evaluated based on these findings, as well as VOC removal and cost.

SECTION 2

CONCLUSIONS

GENERAL

In-well aeration can be a useful treatment technique for VOC removal on a short-term emergency basis. Pumping with an electric submersible pump while using a sparger was particularly well suited to this application. Many drinking water wells are already equipped with a submersible pump and the addition of the air sparger was completed for this study in a matter of a few hours with readily available materials. For an operating cost of 12¢ to 15¢ per thousand gallons, VOC removals of 70% to 95% were achieved (depending on the volatility of the compound). This method of aeration could be used to keep an indispensable contaminated well in service while a permanent treatment system was designed and installed.

In-well aeration by air lift pumping (with or without a sparger) gave somewhat better VOC removal than the electric submersible pump and sparger for a correspondingly higher cost. It was more complicated to install and was, therefore, not as well suited for emergency use (any existing pump would have to be removed). Its operating cost and limited VOC removal capabilities do not make it an acceptable long-term treatment technique.

WELL CHARACTERIZATION

The U.S.G.S. well logging identified two major and 5 minor potential water zones of entry into the well. This data was used to determine where to place straddle packers for isolated zone testing. The packer testing accounted for 80% of the well's specific capacity, therefore, the remaining 20% of the specific capacity was contributed by zones not isolated by packer testing. Differences in VOC concentrations were seen for the isolated water entry zones. The two most heavily contaminated zones were also the largest water producing zones. The open borehole pumping test showed that VOC concentration changed considerably with time. Over short-term tests, such as the in-well aeration tests performed here, large concentration variations could be expected.

FOOTPIECE TESTING

The air lift pump and sparger footpieces were tested using large bubble and small bubble configurations. The small bubble footpiece caused greater operating pressures for the air lift pump. The pressure difference was greatest at high air-to-water ratios (5:1 to 12:1). The most efficient operation of an air lift pump was found to be at a much lower air-to-water ratio (1.5:1) where the pressure differences between the footpieces were very small. If the air lift pump were operated at its maximum pumping efficiency, there would be little difference in operating pressure between the two footpieces tested. If, however, the pump were operated at a higher air-to-water ratio in order to obtain better VOC removal, the small bubble footpiece would have a greater operating pressure and a greater operating cost.

The two air lift pump footpieces tested showed no significant difference in air lift pump efficiency. The maximum efficiency was found to be 30-35%, which confirmed the literature. There was no difference in VOC removal brought about by changing from a large bubble to small bubble air lift pump footpiece. Since there was no difference in VOC removal between the two air lift pump footpieces, and since the small bubble footpiece would be potentially more expensive to operate, the small bubble configuration was abandoned, and the large bubble air lift pump footpiece was used for the rest of the in-well aeration testing.

Sparging air into the well decreased the pumping efficiency of the air lift pump. The small bubble sparger footpiece had a higher operating pressure, and therefore, a higher operating cost than the large bubble sparger footpiece. There was no difference in VOC removal between the large and small bubble sparger footpieces. As with the air lift pump, the small bubble sparger footpiece was not used for any further testing because of higher operating pressure with no improvement of VOC removals.

In the footpiece testing, VOC removals were similar for similar air-to-water ratios, regardless of whether air was introduced by air lift pump or by the air lift pump and sparger combination. Vinyl chloride was the exception to this as it was better removed by the air lift pump and sparger combination than by the air lift pump alone. VOCs were removed in an order which would be expected, based on Henry's Law Constant.

AIR LIFT PUMP TESTING WITH AND WITHOUT A SPARGER

The air lift pump operated most efficiently at 65% submergence. The efficiency decreased as submergence increased, confirming the predictions of the literature. VOC removal was poorer at the 280 ft setting of the air lift pump than it was at 130 ft or 200 ft. VOC removal percentages for the air lift pump alone ranged from 90.4% for vinyl chloride (VC) (best removed according to Henry's Law) to 47.4% for c-1,2-dichloroethylene (c-1,2-DCE) (poorest removal). TCE was 65% removed by air lift pumping without sparging.

A particular air flow rate setting produced different water flow rates (and difference air-to-water ratios) on different days. This was mainly due to water level changes in the well which caused air lift pump submergence to change which, in turn, changed pumping efficiency. Raw water concentrations of VOCs varied widely from one test to the next, as well as varying within a particular test. This confirmed the findings of the pumping test conducted during well characterization.

As shown in the footpiece testing, the sparger caused the air lift pump efficiency to decrease. Even though the sparger caused the air lift pump efficiency to decrease, the pump efficiency with a sparger was higher than if all of the air had been delivered to the air lift pump alone; therefore, in terms of pump efficiency (and cost) it was better to operate an air lift pump and sparger combination, than the air lift pump alone. No VOC removal differences could be seen when the sparger was operated at different depths with the air lift pump. This was mainly because of poor reproducibility of the sparger tests over long periods of time. All measurement systems were checked and the most likely cause of variation was determined to be changing well conditions with time.

The air lift pump and sparger combination yielded VOC removal percentages ranging from 98.6% for VC to 65.0% for c-1,2-DCE, with TCE having 78.3% removal. A higher air-to-water ratio was obtained by using the air lift pump and sparger combination, which accounted for the higher VOC removal capabilities. The highest air-to-water ratios obtained were 10.6:1 for the air lift pump and 17:1 for the air lift pump and sparger combination. Air-to-water ratio was limited when sparging to the point at which water actually bubbled out of the well head because the entire well had been turned into an air lift pump. In a well with a wider borehole the air-to-water ratio might be higher because water would not be forced out of the well as readily. Also, at well L-8 some of the borehole diameter was taken up by test equipment which would not be in the well during regular operational conditions.

Costs of air lift pumping and sparging make this method expensive for long-term use; however, it may be useful as an emergency short-term treatment system. The electric pump and sparger experiments were designed with this in mind.

ELECTRIC PUMP AND SPARGER TESTING

An electric submersible pump was operated at 200 ft, with sparger testing being conducted at 130 ft, 200 ft and 280 ft. The best VOC removal was obtained with the sparger at 130 ft. The 280 ft sparger depth setting was next best, with the 200 ft depth giving the poorest removal. VOC removal findings were consistent with what was expected from well characterization experiments. Sparging at 130 ft caused counter-current stripping as water from the most contaminated zone was pulled past the sparger on its way to the pump. A co-current stripper would have been created by the 280 ft sparger, with at least some of the air being pulled into the pump before it reached the most heavily contaminated zone. With the sparger directly adjacent to the pump, most or all of the air could have been pulled into the pump before any stripping occurred in the well.

Electric pump and sparger testing showed the same variation over long periods as did the air lift pump and sparger testing. With no other part of the experimental system changing, this helped confirm that well conditions changing with time (VOC or water zones of entry, not VOC concentration) could affect in-well aeration.

The VOC removals obtained during electric pump and sparger tests were an average of 82.6% for TCE, 79.9% for c-1,2-DCE and 92.9% for VC. These removals were better than those achieved by air lift pumping with or without a sparger. The air-to-water ratio used to achieve this better removal was 8.2:1, which is lower by half than the maximum air-to-water ratio used in air lift pump and sparger combination tests. For the electric pump and sparger combination, a lower air-to-water ratio achieved better removal than the air lift pump with or without a sparger.

Electric pumping with a sparger is a good emergency treatment technique if the limited VOC removal capabilities will meet your water quality goals. It can be installed very quickly with readily available materials. It can be used to keep a well in service while the permanent treatment system is being designed and installed.

While well characterization was useful during this project, both for experimental design and data interpretation, it would not be necessary in an emergency situation. The sparger should not be set directly adjacent to the pump to avoid having all of the air pulled into the pump before any stripping can occur in the well.

SECONDARY EFFECTS OF IN-WELL AERATION

All methods of in-well aeration tested increased the pH by an average of 0.4 pH units. Dissolved oxygen (DO) was raised to saturation by all of the in-well aeration methods tested. Water entering the weir box (air and water separator) was bubbly in appearance (actually milky white when sparging), but all of the bubbles were gone by the time the water left the weir box.

Bacteriological testing of raw and treated water was inconclusive, with large variations in bacterial counts masking any trends. The R2A method provided consistently higher recovery of organisms than the heterotrophic plate count.

Air sampling showed that in-well aeration would probably not cause air quality problems of industrial hygiene concern, however, it may be considered an air pollution source, and would require the appropriate permits for such a source. This would depend on the raw water concentrations of the contaminants.

SECTION 3

RECOMMENDATIONS

It is recommended that electric pumping with a sparger should be used as an emergency treatment technique. The sparger should not be placed directly adjacent to the pump intake, as this will cause the bubbles to enter the pump immediately and any VOC stripping effect in the well borehole will be lost. Air should be added in slowly increasing amounts until the foaming water is just visible below the well head. This will produce the greatest possible air-to-water ratio. An air and water separator is necessary.

Further air quality testing should be performed to determine the possible need for air discharge permits. The necessity to treat off-gases from in-well aeration to remove VOCs could negate its advantages as a quickly installed emergency treatment system.

Possible corrosion implications need to be further considered. The elevated dissolved oxygen concentration in the treated water could be a problem over the long-term but it is not known whether any additional treatment would be necessary on a short-term basis.

SECTION 4

IN-WELL AERATION

HISTORY OF AIR LIFT PUMPING

The idea of pumping with the air lift method was first tested by Carl Emanual Loscher, a German, in 1797. It's first practical use was 50 years later by Cockford, an American. (5) The application was to pump petroleum from a series of wells in Pennsylvania. It was first patented in the U.S. in 1865. During the early 1900's it was widely used in the water works industry. The Lansdale Water Company, predecessor of North Penn Water Authority, used a steam powered air compressor for air lift pumping during the 1920's and 1930's. After that, the air lift pump was replaced by more efficient turbine or submersible electric pumps.

THE AIR LIFT PUMP

The air lift pump functions by bubbling air into an open-ended discharge pipe in the well. The water in the discharge pipe (called the eductor) then has a reduced specific gravity. The lighter water in the eductor is forced upward and out of the well by the heavier surrounding water. See Figure 1.

Early researchers (5) showed that when the air lift pump was operating at its maximum efficiency (approximately 35%), the air-to-water ratio was low (2 or 3 to 1). It was possible to increase air-to-water ratios to nearly 16 to 1, however, the pumping efficiency was reduced to 7%. It was surmised from this early work that compromises of either pumping efficiency or organic removal efficiency would have to be made in order to successfully use the air lift pump as a volatile organic chemical treatment device.

Another consideration when using an air lift pump was that it required a high percent submergence (% of eductor below pumping water level) in order to work efficiently. The pump was simple to operate with very few moving parts, therefore, the maintenance cost may end up being less than that of an electric pump.

IN-WELL DIFFUSED AERATION

Another form of in-well aeration that was examined in this study was diffused aeration, or sparging. This method has proven useful for aerating drinking water and waste water. The method is usually employed in treatment plant situations. In this study, a plastic sparge line was dropped into the well and air was introduced through this line. The

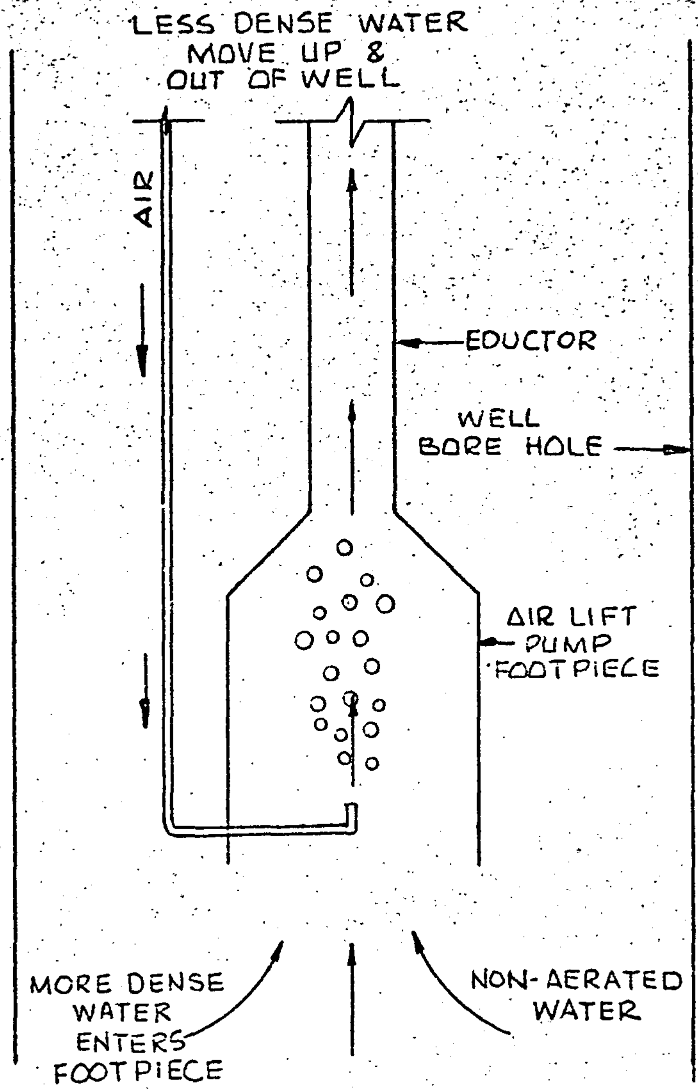

Figure 1. Diagram of air lift pump operation.

sparging was used both with the air lift pump and with the electric pump.

The sparge line was easily moved to various depths in the well. It could be placed directly near pollution entry zones. Operating costs could be adjusted by changing sparger depth, as it was more expensive to operate deeper in the well.

The sparger could be set at a variety of depths with relation to the pump. The actual bubble path would be extremely difficult to determine. Bubbles could go up to the well head or be pulled directly into the pump, depending on the relative positions of the pump and sparger.

WATER QUALITY EFFECTS OF IN-WELL AERATION

The primary water quality effect to be examined in this study was volatile organic contaminant removal. Aeration in other forms is a proven treatment technique for these types of contaminants.

Studies using air lift pumps as sampling devices have shown that a number of secondary water quality effects were also likely with an in-well aeration system (6,7,8). Air lift pumps used in monitoring walls could raise the pH as much as 1.0 pH unit as compared to a peristaltic pump or a bailer (8). This was because of bubbles of air in the eductor stripping dissolved CO_2. The same study also showed effects on various metal concentrations. Iron concentrations were reduced by 32% when pumped by the air lift pump as opposed to the peristalic pump. The zinc concentration was reduced by 17%. Calcium, potassium, magnesium, manganese and sodium concentrations were not affected (8). Formation of iron oxides was probably the reason for the loss of iron. Zinc adsorption onto the iron precipitates was cited as the reason for the drop in zinc concentration.

Dissolved oxygen increase during in-well aeration was of concern because of possible corrosion implications. The air was introduced into the water at depth, and therefore was under pressure. This pressure may have caused more oxygen to be dissolved into the water than would normally occur with conventional above-ground aeration systems (9).

SECTION 5

WELL CHARACTERIZATION

PURPOSE OF CHARACTERIZING THE WELL

Well characterization is helpful when designing a treatment system for a contaminated well. Knowing where and how contaminants enter the well can be used in a variety of ways. In some cases a section of a well may be sealed off to prevent pollutant entry while still permitting the use of the well without treatment. Knowledge of pollutant entry zones can help to interpret sampling results, especially when a small sample pump is used which may not be collecting water representative of the entire well. This could lead to over- or under-estimation of the contaminant levels. Well characterization can determine the geologic materials adjacent to the well. A knowledge of contaminant zones of entry, together with an understanding of the geology near the well, can aid in contaminant source location (10).

In the case of in-well aeration, effectiveness of the treatment method could depend on the placement of equipment in relation to contaminant zones of entry (11,12). Knowing the water and contaminant entry zones enabled the design of test configurations which would examine both counter-current and co-current stripping. The well characterization enabled the interpretation of test results in relation to the equipment's proximity to contaminant entry zones.

The well characterization performed at well L-8 was designed to answer specific questions relating to the design of the in-well aeration equipment and the interpretation of test results. This was accomplished through the following:

1. Determined as-built configuration of the well (i.e., total depth, diameter(s), casing length)
2. Determined location of water zones of entry.
3. Determined location of VOC zones of entry.
4. Determined specific capacity of entire well and individual water zones of entry.
5. Determined static water level.
6. Determined how the quality of the water entering the well varied with time.
7. Determined the depths at which to place the in-well aeration equipment.

The characterization of well L-8 was done in four parts. Historical data was compiled and reviewed. A series of well loggings were performed to determine possible water zones of entry. Straddle packers were used to isolate, pump and sample the water zones of entry. A pumping test was performed to gather further hydrological data. Each of these will be discussed in detail in the following pages.

REVIEW OF HISTORICAL DATA

Records of the North Penn Water Authority were reviewed to compile as much information concerning well L-8 as possible. Since the well had been inventoried by the Pennsylvania Geological Survey during earlier studies in the area, reports published by the Survey were also reviewed (13,14). The driller who constructed the well was contacted and prior pumpage and water quality data were reviewed (15).

Unfortunately, when the well was drilled in 1923 the contractor did not record changes in the lithology of the rock penetrated or any increases in the yield of the well that occurred at various depths. It was assumed that, like most other wells in the NPWA system, well L-8 penetrated layered consolidated rocks of the Brunswick formation and water entered the open borehole below the casing at various depths. The actual quantities of water and related qualities were not known and that was the focus of the well characterization.

Well L-8 was in continuous operation from 1923 until it was taken out of service in 1979 because of VOC contamination. The well was pumped continuously to waste (to contain the VOC contamination plume) until this field work began in February 1983. Table 2 shows VOC concentrations in well L-8 during the time it was being pumped to waste. The 1979 samples were analyzed by gas chromatography (GC) at a local contract laboratory. The March 1981 sample was analyzed by the U.S. EPA at Annapolis, Maryland, using gas chromatography/mass spectroscopy (GC/MS). The December 1981 sample was analyzed by the U.S. EPA at Cincinnati, Ohio, using GC.

As Table 2 shows, well L-8 was heavily contaminated with a variety of halogenated volatile organic chemicals. TCE was found in the highest concentrations, with c-1,2-DCE and PCE also present as major contaminants. Also found at lower concentrations were VC (a human carcinogen) and carbon tetrachloride (CCL4) (an animal carcinogen). Also present were chloroform (CHCL3), 1,1-dichloroethylene (1,1-DCE), 1,2-dichloroethane (1,2-DCA), and 1,1,1-trichloroethane (1,1,1-TCA), all of which are suspected carcinogens (16).

Well L-8 is located in a heavily populated, mixed residential and commercial area of Lansdale, PA. Possible sources of the VOC contamination were numerous. The most likely source, however, was a commercial facility directly across the street from the well. VOC degreasing agents were known to have been used at the facility in the past, and in the early 1970's, the building was destroyed by a fire which caused several explosions. Hundreds of thousands of gallons of water were flushed over ruptured storage drums, which is suspected to have contaminated the groundwater in the area.

Natural groundwater quality is controlled by the chemical nature of the rocks in the aquifer and the residence time of water in the aquifer. The natural quality of ground water in the Brunswick formation is represented in Table 3. The table condenses data from 28 wells in the

Brunswick formation which are not felt to be influenced by cultural phenomenon and would represent natural water quality in the Brunswick. NPWA records of natural water quality at Well 8 are also shown.

TABLE 2. HISTORICAL VOC DATA FROM WELL L-8

PARAMETERS	DEC 1981 (GC)	MAR 1981 (GC/MS)	AUG 1979 (GC)	SEP 1979 (GC)
CHLOROFORM	8.9	0.5	NA	NA
BROMODICHLOROMETHANE	LT 0.2	ND	NA	NA
DIBROMOCHLOROMETHANE	LT 0.5	0.4	NA	NA
BROMOFORM	LT 1.0	ND	NA	NA
DICHLOROIODOMETHANE	LT 1.0	ND	NA	NA
VINYL CHLORIDE	35.	23.	NA	NA
1,1-DICHLOROETHYLENE	6.7	8.3	NA	NA
1,1-DICHLOROETHANE	LT 0.2	ND	NA	NA
CIS-1,2-DICHLOROETHYLENE	400.	240.	NA	NA
1,2-DICHLOROETHANE	0.43	ND	NA	NA
1,1,1-TRICHLOROETHANE	7.0	7.9	NA	NA
CARBON TETRACHLORIDE	0.58	ND	NA	NA
1,2-DICHLOROPROPANE	LT 0.2	ND	NA	NA
TRICHLOROETHYLENE	650.	290.	410.	702.
1,1,2-TRICHLOROETHANE	LT 0.5	ND	NA	NA
1,1,1,2-TETRACHLOROETHANE	LT 0.2	ND	NA	NA
TETRACHLOROETHYLENE	230.	120.	NA	NA
1,1,2,2-TETRACHLOROETHANE	LT 0.5	ND	NA	NA
CHLOROBENZENE	LT 0.5	ND	NA	NA
1,2-DIBROMO-3-CHLOROPROPANE	LT 5.0	ND	NA	NA
BENZENE	LT 0.5	ND	NA	NA
TOLUENE	LT 0.5	ND	NA	NA
ETHYLBENZENE	LT 0.5	ND	NA	NA
BROMOBENZENE	LT 0.5	ND	NA	NA
ISOPROPYLBENZENE	LT 0.5	ND	NA	NA
M-XYLENE	LT 0.2	ND	NA	NA
STYRENE	LT 0.5	ND	NA	NA
O- + P-XYLENE	LT 0.2	ND	NA	NA
N-PROPYLBENZENE	LT 0.5	ND	NA	NA
O-CHLOROTOLUENE	LT 0.5	ND	NA	NA
P-CHLOROTOLUENE	LT 0.5	ND	NA	NA
M-DICHLOROBENZENE	LT 0.5	ND	NA	NA
O-DICHLOROBENZENE	LT 0.5	ND	NA	NA
P-DICHLOROBENZENE	LT 0.5	ND	NA	NA

ALL VALUES ARE IN ug/L
NA - NOT ANALYZED
LT - LESS THAN
ND - NONE DETECTED, LOWER DETECTION LIMIT UNKNOWN

TABLE 3. BASELINE GROUNDWATER QUALITY OF THE BRUNSWICK FORMATION, PENNSYLVANIA AFTER R.E. WRIGHT (17)

CONSTITUENT	NUMBER OF WELL SAMPLES	RANGE	MEDIAN	UNITS	NPWA RECORDS* OF L-8
pH	27	5.2 - 8.1	7.2	Standard Units	7.7
Specific Conductance	25	172. - 959	384.	Micro mho/cm	-
Nitrate (as NO_3)	27	0.10- 42.	6.5	mg/l	5.4
Chloride	27	1.0 - 31.	8.5	mg/l	39.
Sulfate	27	6.3 - 370.	31.	mg/l	38.
Sodium	22	3.2 - 22.0	13.	mg/l	18.
Iron	28	0.01 - 1.6	0.15	mg/l	0.05
Manganese	19	0.01 - 0.38	0.01	mg/l	0.01
Hardness(as $CaCO_3$)	29	32. - 500.	100.	mg/l	155.
Bicarbonate	29	37. - 298.	163.	mg/l	-
Total Dissolved Solids	25	66. - 732	263.	mg/l	375.

* Average concentrations of samples collected at well L-8 from 1970 to 1979

Generally, groundwater quality in the formation is hard to very hard, slightly alkaline and moderately mineralized. Groundwater at well L-8 is similar but has somewhat higher than average concentrations of chlorides, hardness and total dissolved solids.

GEOPHYSICAL WELL LOGGING

Subsurface lithologies, well bore features and borehole fluid characteristics can be determined using borehole geophysical logging. Borehole geophysics can measure the electrical, physical, chemical and acoustical properties of adjacent geologic materials and fluids both in the borehole and adjacent formations (10,18,19).

Borehole geophysical surveys were undertaken in well L-8 with the following objectives:

1. To locate potential water-bearing fracture zones.
2. To locate relatively smooth borehole segments for the placement of inflatable packers in order to isolate the water-bearing fractures zones.
3. To identify lithologic changes (siltstones, sandstones, etc.)
4. To determine well depth, changes in well diameter and casing length.

The geophysical logs employed in this study included; caliper, gamma, spontaneous potential (SP), resistivity, fluid conductivity, temperature, and brine tracing. In each instance a sensing probe was lowered to the bottom of the well on a cable, then the probe was slowly retracted as data was collected at the surface (see Figure 2). Continuous readings were recorded on an analog strip chart recorder. The logging at well L-8 was performed by the U.S.G.S. Information concerning borehole geophysical logging procedures can be found in the literature (10,18).

Borehole diameter and roughness were measured using caliper logging equipment. The hole diameter was measured by four caliper arms which were held against the borehole by springs. The arms opened and closed as they moved up the borehole, drawing a picture of the physical dimensions of the well.

Resistivity logs were employed to aid in the location of bed boundaries and general changes in lithology, which were associated with water-bearing fracture zones. Resistivity logs measured the resistance of the flow of an electric current from one point on the probe to another. Generally consolidated rock had a high resistance because of its low porosity. When the rock became more porous and contained a more conductive fluid the borehole log showed a lower resistivity.

Spontaneous potential logs recorded the natural voltage developed in the borehole due to dissimilar fluids contained in the pore spaces of the formation and in the borehole itself. SP logs aided in delineating formation boundaries and certain lithologies (such as shale and sandstone). SP and resistivity logs were run simultaneously using the same probe and the resultant log was called an electric log.

The measurement of natural gamma rays emitted from the formation was used in conjunction with electric logging to differentiate strata. Sedimentary rock, clays and shales all had a unique gamma signature. Places where different strata intersect were possible water producing zones.

Conductivity logs measured the relative conductivity (inverse of resistance) of the borehole fluid. This logging technique did not measure the specific conductance of the fluid because temperature compensation was not provided. Conductivity logs were used to identify differences in water quality due to fracture openings or breaks in the casing. Conductivity logs could also locate stagnant water in the borehole and water that was moving from one zone to another because of differences in head.

Temperature logs were used to measure the temperature of the water

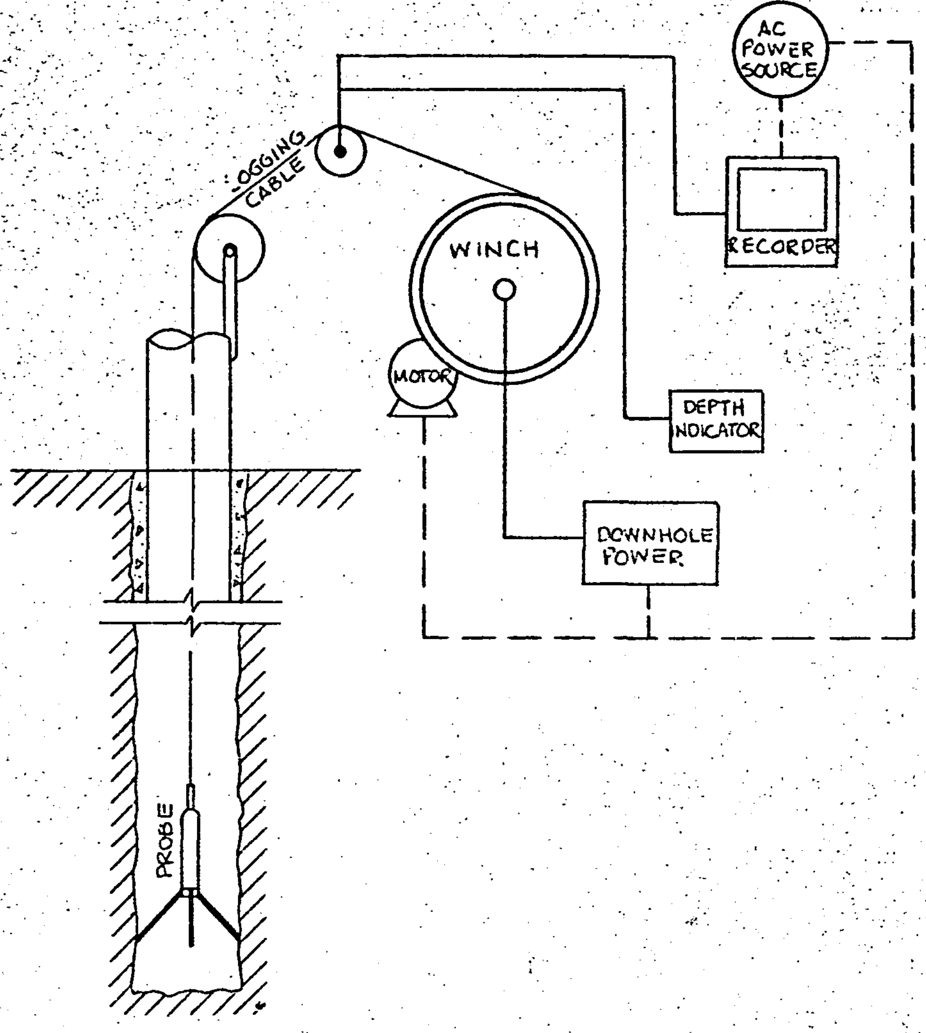

Figure 2. Diagram of well logging system used during characterization of well L-8.

immediately adjacent to the sensor. Thermal gradients in the borehole were examined to locate potential fracture zones. Temperature logs can also be used to identify water that has recently entered the aquifer as natural or artificial recharge.

Brine tracing was used to measure the direction and velocity of the borehole fluid at selected depths in the well. A slug of a saline solution was released in the borehole at a particular depth, then it was tracked with the fluid conductivity probe as it moved up and down the well. (20)

Well L-8 was logged on February 17, 1982 by the U.S. Geological Survey's Pennsylvania District Office. Reduced profiles of the caliper, natural gamma, resistivity and SP logs are shown in Figure 3. Potential water producing fracture zones are marked on the figure along with the positions of the straddle packer system when it was subsequently employed.

The well logging data was compiled and plotted by hydrogeological consultants to North Penn Water Authority. (21) The consultant's report indicated that no one single well log was sufficient to characterize the well. Instead, the log plots were compared by depth and when fracture indications were present on several of the logs at a given depth, that depth was chosen as a possible water zone of entry.

The logs indicated that the casing in well L-8 extended from the pump motor base to approximately 20 feet below the ground surface. The caliper log detected major borehole enlargements associated with zones 3 and 6. Other enlargements were encountered at zones 1,2,4,5, and 7.

The major enlargement at zone 3 was associated with a peak in gamma activity indicating a probable change from a sandy lithology to a low permeability siltstone or mudstone. The resistivity log indicated a relatively low resistance at this zone which may have been related to an increased volume of water in a water producing fracture zone. Zone 6 was associated with a marked decrease in natural gamma radiation, possibly because of an increase in the sand content of the associated bed. Zones 4, 5, and 7 also appeared to be associated with relatively lower gamma signatures.

The overall lithology of the sedimentary rock sequence penetrated by L-8 was fairly uniform with low permeability siltstone and mudstone apparently dominant. Beds with increases in sand content appeared to occur between 73 and 92 ft, 151 and 170 ft, 182 and 195 ft, and 254 and 263 ft.

The fluid conductivity log (not shown due to difficulty in transcription from the original plot) indicated a major change in fluid characteristics at 50 to 60 ft and minor changes at 172 ft, 188 ft, and 264 ft. The temperature log (also not shown) indicated a major change in fluid temperature at 56 ft, a minor change at 186 ft, and a very subtle change at 244 ft. The brine tracing logs showed a major discontinuity at approximately 70 ft and again at 136 ft. A minor deflection was indicated at 180 ft.

Based on the results of the geophysical logs, seven potential water zones of entry and intervals for straddle packer testing were identified. These intervals are shown on Figure 3 and in Table 4.

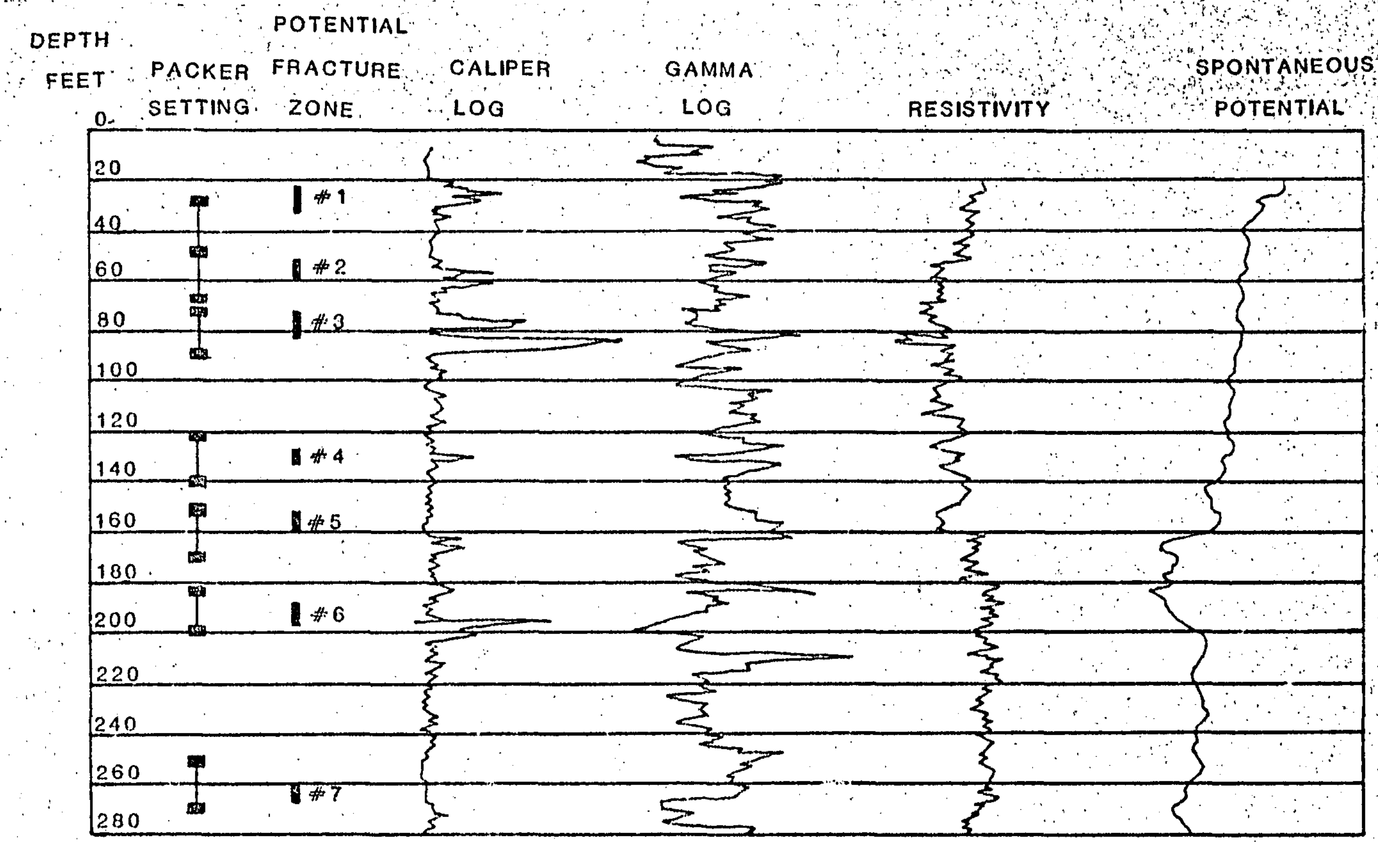

Figure 3. Profiles produced by U.S.G.S. well logging of well L-8.

TABLE 4. POTENTIAL WATER BEARING FRACTURE ZONES AND STRADDLE PACKER POSITIONS FOR WELL L-8 (FEET BELOW CASING TOP)

		Straddle Packer Position	
Potential Fracture Zone	Fracture Zone Location	Center of Upper Packer	Center of Lower Packer
1	22 - 32 ft	28 ft	47 ft
2	53 - 61 ft	47 ft	66 ft
3	72 - 86 ft	70 ft	89 ft
4	126 - 130 ft	121 ft	140 ft
5	156 - 161 ft	152 ft	171 ft
6	188 - 196 ft	182 ft	201 ft
7	260 - 261 ft	252 ft	271 ft

STRADDLE PACKER TESTS

Discrete zone borehole testing utilizing packer equipment has been developed and used by petroleum engineers, engineering geologists and hydrogeologists for many years. By far the greatest application of packers for borehole testing has been by the petroleum industry and engineering geologists for fracture permeability evaluation at dam and foundation sites. The use of packer technology in hydrogeologic studies at North Penn Water Authority has been reported by Suffet, et al (11). Shuter and Pemberton (22) described early U.S. Geological Survey systems along with a system which they developed for borehole testing and sampling. Cherry (23) describes a portable system developed for sampling discrete zones in wells and Koopman, et al (24) describes a system of inflatable packers used in multiple-zone testing of water wells.

Straddle packer tests can provide a variety of information in wells having multiple screen or water entry points. Because discrete sections of the borehole can be isolated when straddle packers are inflated, the tests can be used to determine the following:

1. Head difference and relative elevations of the isolated zone and zones above and below the packer system.
2. The quality of water pumped from the isolated zone.
3. The specific capacity and drawdown characteristics of the isolated zones.

The equipment used in this study was fabricated by Earth Data, Inc., St. Michaels, MD. A diagram of the in-well portion of the system appears in Figure 4 and the surface support system is shown in Figure 5.

The procedure for straddle packer testing in well L-8 was as follows:

1. Measured lengths of lift pipe and added sections to reach the desired depths.
2. Lowered sample tubing and wire into well with lift pipe.

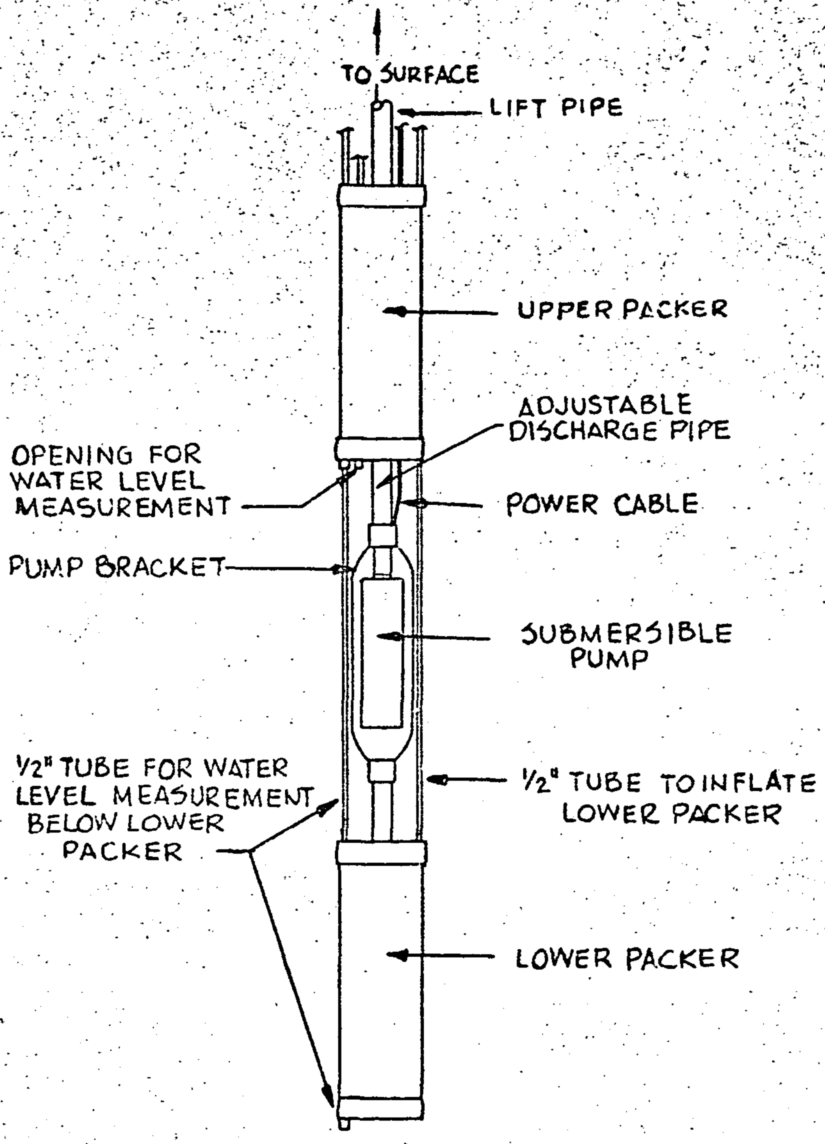

Figure 4. Straddle Packer System used during characterization of well L-8 to pump isolated zones.

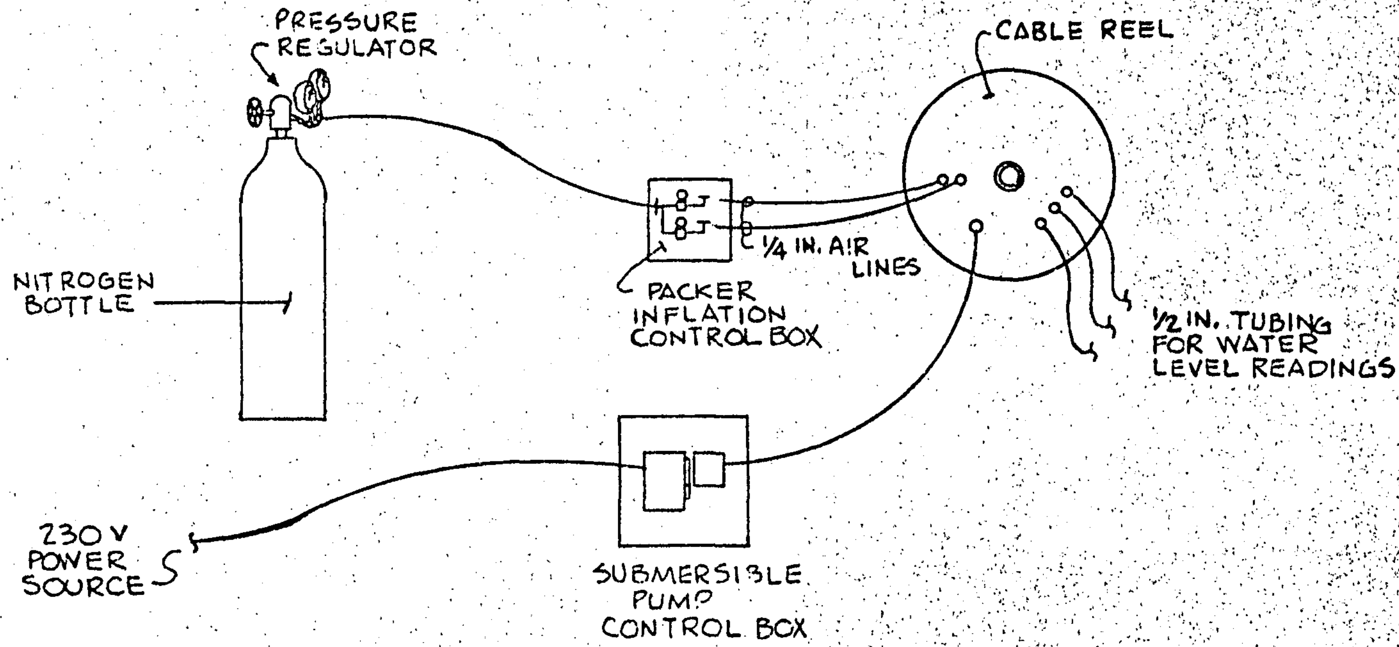

Figure 5. Surface support system for straddle packer apparatus.

3. Cut 1/2 in tubing; measured water levels in the lower, middle and upper zones with packer deflated.
4. Determined hydrostatic pressure because of submergence of each packer.
5. Determined the necessary packer inflation pressure by adding 18 psi to the calculated hydrostatic pressure.
6. Started pump with packers deflated trying to maintain a constant rate of discharge.
7. Measured water levels and pumping rate. Collected samples for volatile organic analysis (VOA) just prior to the end of the step.
8. Inflated upper packer (the resulting interval was referred to as the lower composite test).
9. Measured water level changes and pumping rate.
10. Collected VOA sample just prior to the end of the step.
11. Deflated upper packer and inflated lower packer (referred to as upper composite test).
12. Measured water levels and pumping rate. Collected VOA samples just prior to the end of the step.
13. Inflated upper packer and left the lower packer inflated (referred to as the isolated test).
14. Measured water levels and pumping rate. Collected water samples for VOA.
15. Stopped pumping, deflated packers, spliced 1/2 in tubing and moved the packers to the next position.

Zones 1 and 7 dewatered rapidly during the testing, therefore only limited measurements were made and no samples were collected at these two depths. Drawdown in the other zones ranged from 1.49 to 38.34 ft, indicating a wide range of response to pumping. The head differences between particular zones under non-pumping conditions ranged between 0.12 and 38.24 ft. This indicated the general effectiveness of the hydraulic seal created by the packers and the small potential for movement between portions of the borehole.

The specific capacity of the composite segments and the isolated fracture zones were calculated and compared with an open borehole specific capacity (see Table 5). The specific capacity data shows that zone 3 contributed the majority of the well's yield at 37%. Zones 4, 2, 6, and 5 contributed 22%, 15%, 6%, and 3% to the yield of well L-8, respectively.

The average open hole specific capacity was 4.75 gpm/ft. The sum of the specific capacities of each isolated zone totals 3.82 gpm/ft. Therefore approximately 19% of the total specific capacity of the well was contributed by portions of the borehole not isolated during straddle packer testing.

Figure 6 and Table 6 show results for each VOC individually. A bar graph showing the sum of the various VOC concentrations for each interval tested appears in Figure 7. Vinyl chloride data was not obtained during packer testing. The figures graphically demonstrate the general distribution of contamination in the well borehole.

TABLE 5. WELL L-8 SPECIFIC CAPACITY DATA SUMMARY

SPECIFIC CAPACITY (gpm/ft of drawdown)						% OF OPEN HOLE SPECIFIC CAPACITY		
ZONE	PACKER LOCATIONS	UPPER COMPOSITE	LOWER COMPOSITE	ISOLATED	OPEN HOLE	UPPER	LOWER	ISOLATED
1	28 - 47	0	-	0	-	-	-	-
2	47 - 66	0.91	4.78	0.79	5.16	17.6	92.6	15.3
3	70 - 89	2.31	2.73	1.58	4.29	54.0	64.0	37.0
4	121 - 140	3.24	2.86	1.03	4.62	70.0	62.0	22.0
5	152 - 171	3.63	1.03	0.15	4.91	74.0	21.0	3.0
6	182 - 201	4.62	0.22	0.27	4.75*	97.0	5.0	6.0
7	252 - 271	-	-	0	-	-	-	-

* Average of previous four values

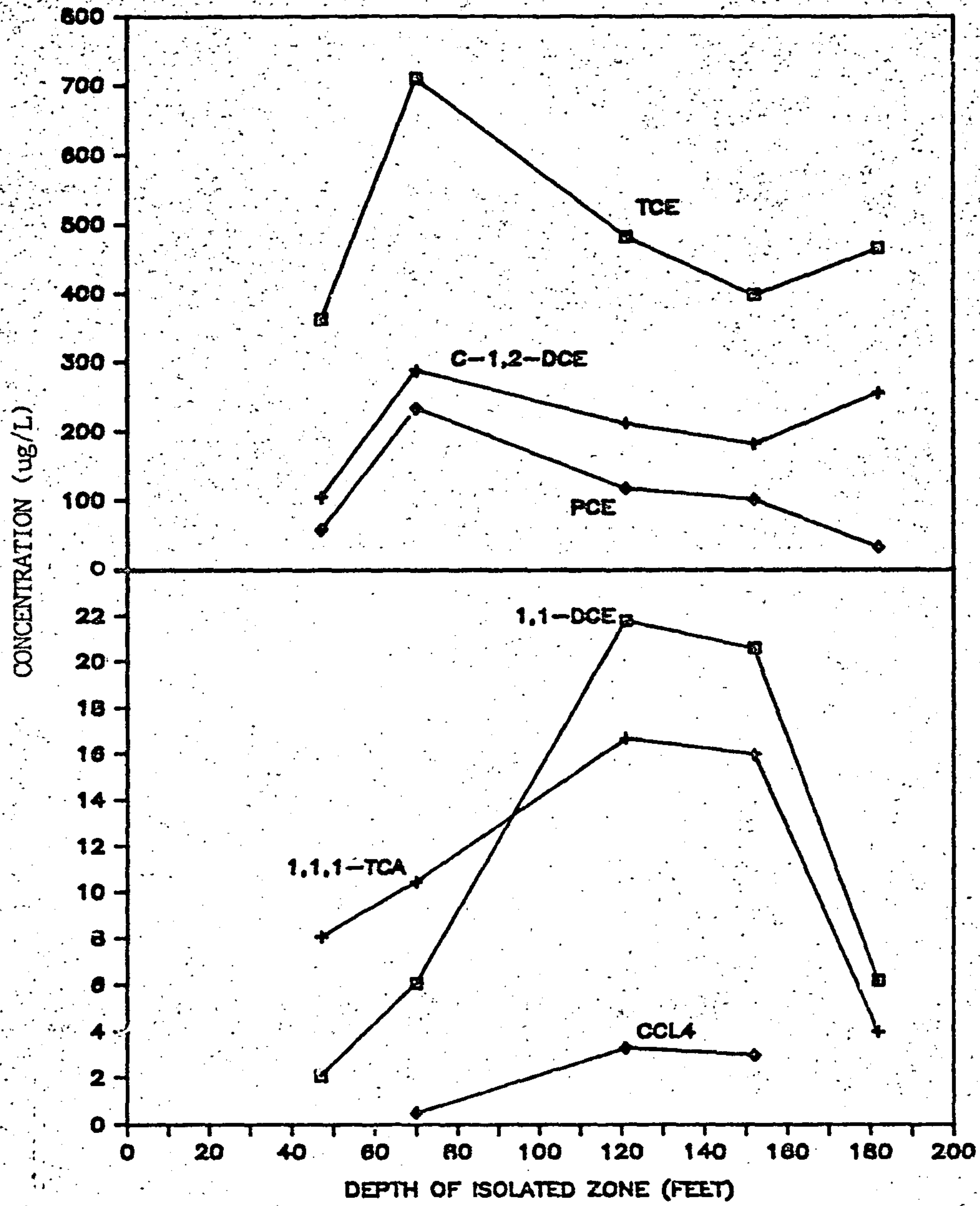

Figure 6. VOC concentrations for isolated zones during packer testing of well L-8.

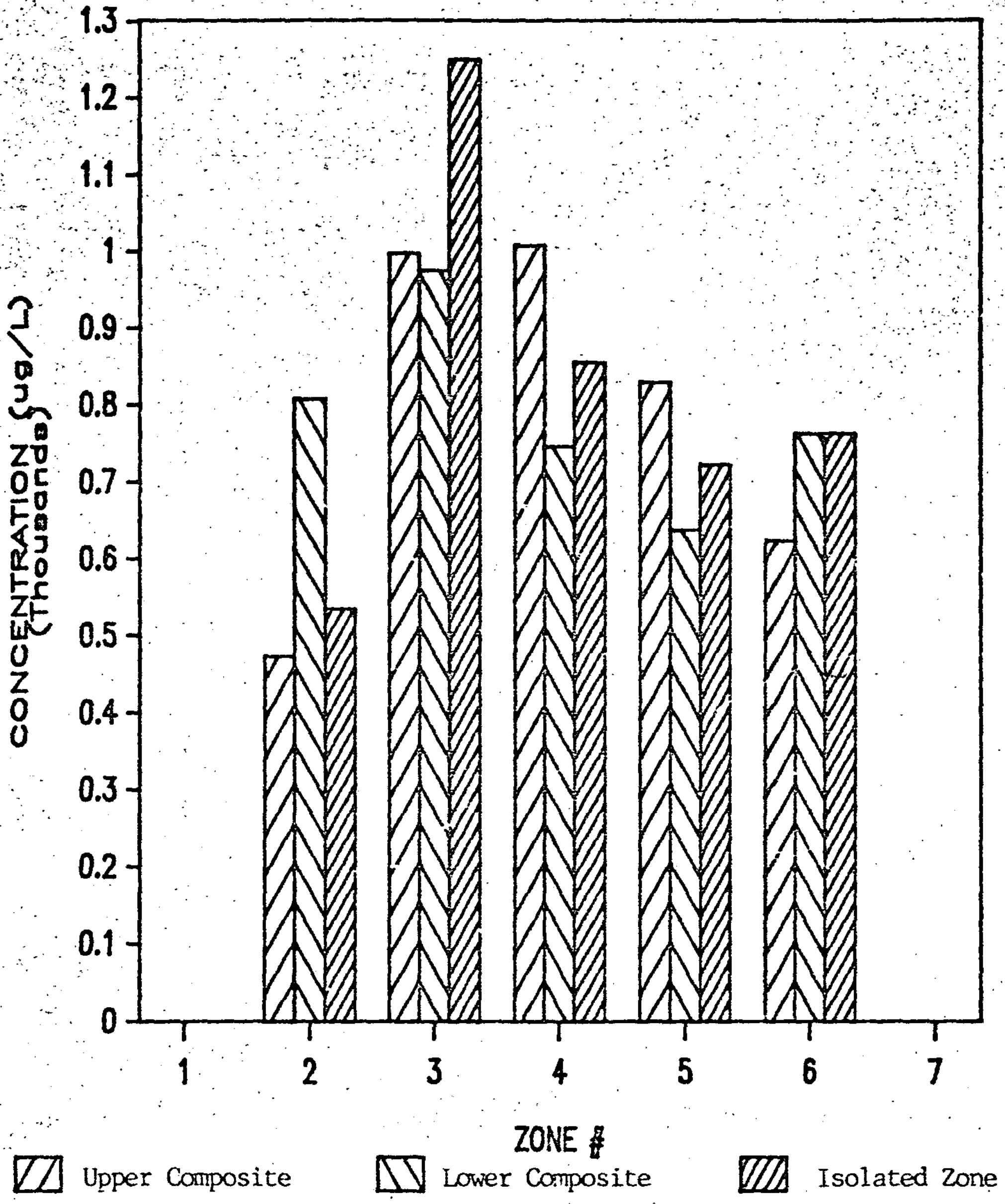

Figure 7. Distribution of total VOCs in well L-8 as determined by straddle packer testing.

TABLE 6. WELL L-8 VOC CONCENTRATIONS FOR ISOLATED ZONE

	CONCENTRATION, ug/L				
ZONE #	2	3	4	5	6
DEPTH (ft)	47-66	70-87	121-140	152-171	182-201
1,1-DCA	2.1	6.1	21.8	20.6	6.2
c-1,2-DCE	105	289	212	182	256
1,1,1-TCA	8.1	10.5	16.7	16	4.0
CCL4	0.5	0.5	3.3	3.0	0.5
TCE	363	710	483	398	466
PCE	58	234	118	102	33
TOTAL VOC	536	1250	857	724	765
% OF WELLS YIELD	15%	37%	22%	3%	6%

The isolated sample of zone 2 showed that this was the least contaminated of the zones identified in the well logging. (see Figure 7). The upper composite sample was less contaminated than the isolated sample, indicating that cleaner water must be entering the well above zone 2. Since zone 1 did not produce any water, there must be a water production zone between zones 1 and 2 which was missed by the well logging. The lower composite sample was considerably higher in VOCs than the isolated zone sample, showing that the water below zone 2 was more heavily contaminated than that at or above zone 2.

Zone 3 results showed a dramatic contrast with zone 2. The isolated sample at this zone showed it to be the most heavily contaminated water producing zone in the well. This zone also produced the most water of the zones tested, at over one-third of the well's total capacity. The major contaminants (TCE, c-1,2-DCE and PCE) were all found in the highest concentration in zone 3. It was interesting to note that the minor contaminants did not reach their highest concentration until zone 4. (see Figure 6). The upper and lower composite samples at this zone confirmed that the water coming from above and below was of lesser VOC concentration than the water produced at zone 3.

Zone 4 was the zone of highest concentration for 1,1-DCE, 1,1,1-TCA and CCL4. The upper composite sample confirmed the presence of the more heavily contaminated water from zone 3, and the lower composite showed the presence of less contaminated water below zone 4.

The zone 5 upper composite sample confirmed the presence of the more highly contaminated water coming from zone 4. The lower composite, however, showed less contaminated water coming from below zone 5. Since the isolated sample from zone 6 was actually higher in VOC concentration than the isolated sample from zone 5, it can be concluded that more water (at a lower concentration than zone 5) must have entered the well between zone 5 and zone 6. This may account for some of the missing well capacity discussed earlier.

The zone 6 upper composite sample confirmed the presence of lower concentration water above the zone. The lower composite sample was equal in concentration to the isolated sample. This, together with very similar specific capacity data for the isolated and lower zone (0.27 and 0.22), indicated that there were no more water producing zones below zone 6.

The well characterization of well L-8 has indicated that casing, grouting or packing off a portion of the well would not be an effective means of improving the quality of the well, because the contamination was entering at many different points. A well of this type would require treatment other than isolation of the contaminant entry zone.

The information gathered by this well characterization was used in designing the in-well aeration experiments to be performed. Further explanation of how this information was used can be found in Section 4.

PUMPING TEST

Traditional methods of well characterization often include pumping tests. Pumping tests can be used to determine well efficiency and long-term expected yield. Water quality samples taken during pumping tests can be used to establish long-term trends in quality as well as provide a representative sample of nearby aquifer conditions.

A pumping test was performed at well L-8 to further characterize the well and provide information about the nature of VOC contamination in the vicinity of the well. It was desirable to know how the VOC concentration would change with time, because each in-well aeration test took one full day and was, therefore, performed from a resting (non-pumping) condition of the well.

The test was conducted over a period of 5 days beginning on September 20, 1982. The pumping rate was held constant at 50 gpm and standard pumping test procedures were followed (25,26,27). Data from the test are found in Figures 8 and 9. Results of the test indicated that the aquifer surrounding the well was not uniform. The average permeabilities of the aquifer appeared to increase, then decrease away from the well. This could be seen by the changes in slope of the drawdown curve (Figure 8). The starting water level was 21.5 ft below the top of the casing. This dropped 15.1 ft, to 36.6 ft after 94 hours of pumping at 50 gpm.

During the pumping test, samples were collected periodically for volatile organic analysis (see Figure 9). The major contaminants showed similar trends of decreasing within the first 0.2 hours of pumping then gradually increasing for the remainder of the test. TCE showed the greatest change, dropping from 720 ug/L to 410 ug/L after 0.2 hours, then steadily rising to 1,190 ug/L by the end of the test.

The nature of the change in the VOC concentration suggested that the sources of contamination were relatively near the well. The decline in concentration during the early period of drawdown indicated that the cone of influence spread initially to areas that were not severely contaminated, thus causing a dilution of the contaminants that enter L-8 under natural or non-pumping flow conditions. After 0.2 hours the contaminant concentration began to rise due to the spread of the cone of influence into the contaminated areas. After approximately 30 hours of pumping, the area contributing contamination was completely engulfed by the cone of influence and the rate of increase in contaminant

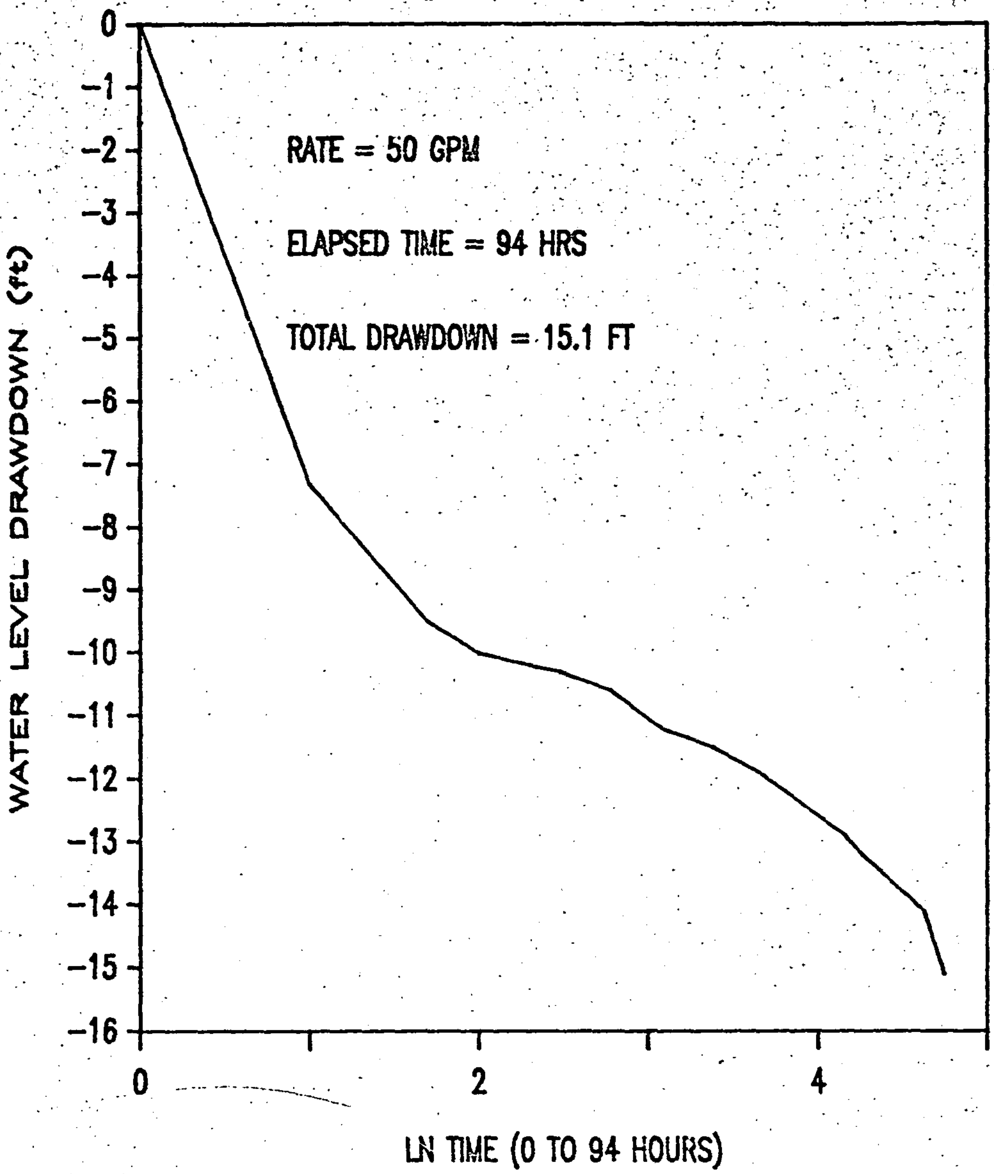

Figure 8. Well L-8 water level drawdown during pumping test phase of well characterization.

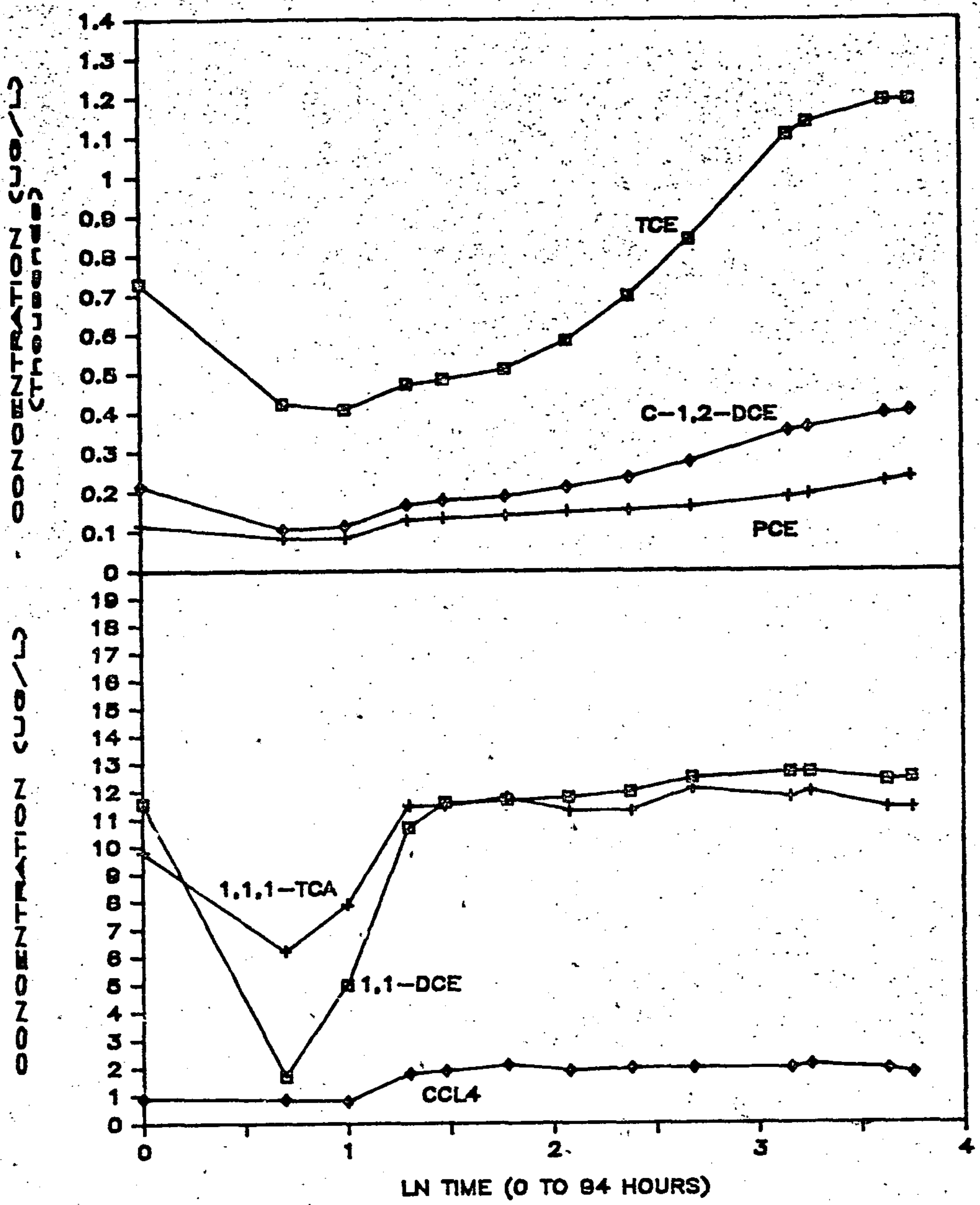

Figure 9. VOC concentration changes with time during pumping test of well L-8.

concentration began to lessen.

This pumping test indicated that large variations in raw water concentrations could be expected over any single day of in-well aeration testing. Because of this, it was necessary to monitor raw water concentration carefully during all phases of the testing.

CONCLUSIONS FOR WELL CHARACTERIZATION

A review of historical data for North Penn Water Authority's well L-8 showed it to be contaminated with a variety of VOCs, six of which were found at high enough concentrations to be used for this study. These compounds of interest were TCE, PCE, VC, c-1,2-DCE, 1,1,1-TCA and CCL4. When the contamination was discovered the total VOC concentration was approximately 1,000 ug/L.

The inorganic quality of well L-8 was typical of the Brunswick formation. It was hard and slightly alkaline, with higher than average chloride levels.

Well logging, performed by the U.S.G.S., identified seven potential water zones of entry into the well. This information was used to determine where to place straddle packers used to collect VOC and water quality data for each zone.

The straddle packer testing of the seven zones identified by the U.S.G.S. accounted for approximately 81% of the well's total specific capacity; therefore, the remaining 19% of the specific capacity was contributed by zones not identified during the well logging. In addition, two zones identified as potential water producing zones dewatered almost immediately during packer testing.

VOC concentrations were different for each of the zones tested. The two most heavily contaminated zones were also the two largest water producing zones. These zones were located at 70 to 89 ft (zone 3) and at 121 to 140 ft (zone 4). Zone 3 contained the highest concentrations of the major contaminants (TCE, c-1,2-DCE and PCE) and zone 4 showed the highest concentrations of the minor contaminants (1,1-DCE, 1,1,1-TCA and CCL4). The information gained during the packer testing was used to determine the depths at which to place the in-well aeration equipment.

The open borehole pumping test showed that VOC concentrations at well L-8 changed considerably with time, and that the changes were especially significant, because the in-well aeration testing would all be performed during this early part of the pump curve. Because of this, very frequent raw water sampling was designed into the in-well aeration testing.

SECTION 6

EXPERIMENTAL DESIGN

The experimental design for this project was developed based on independent and dependent variables. The independent variables were experimental variables that were set in the field. The dependent variables were data which were obtained by setting the independent variables. The dependent variables were, in some cases, calculated (e.g. horsepower) and in other cases were measures of quality changes (water or air) which occurred as a result of varying the independent parameters. Table 7 lists these independent and dependent variables.

Air flow rate was an independent variable. The air delivery system used to control and measure air flow rates throughout the in-well aeration experiments is shown schematically in Figure 10. The system was mounted on a 4 ft x 6 ft plywood board and was located on the well house wall approximately 4 ft from the well head.

As can be seen in Figure 10, the air delivery system was divided into two air flow pathways. Side A was used for the air lift pump and Side B was for the sparger.

The source of compressed air was a gasoline powered Schram Air Compressor capable of delivering 100 psi of air to the in-well aeration system. This was sufficient for the depths at which work was performed at well L-8, but wells of greater depth would require a more powerful compressor.

A pressure gauge (G1) measured the delivery air pressure from the compressor. Each pressure gauge was mounted with a test tee to accept a calibrated gauge by way of a quick-connect fitting. All gauges were checked against the calibrated test gauge at the start of each testing day, as well as periodically during testing. Following gauge G1 was a thermometer (T1) used to measure the temperature of the incoming compressed air. Next there were two filters in series (F1 & F2) to remove oil and water vapor and particulates. F1 was a Deltech 810 series filter and F2 was a Fine Aire glass fiber coalescing filter. Another pressure gauge (G2) followed the filters. G1 and G2 were used to monitor pressure drop over the filters to observe any possible filter clogging. After gauge G2 the air delivery system split into side A (for the air lift pump) and side B (for the air sparger). Ball valves (BV-A and BV-B) were used to turn either side on and off. The ball valves were followed by pressure reducing valves (P-A and P-B) to control the amount of air pressure at the rotometers. Three Brooks rotometers were used. R1-A and R1-B were both calibrated from zero to sixty cubic feet per minute (cfpm). Rotometer R2-A was calibrated from zero to six cfpm, and was used only during the lower flow rate portions of air lift pump efficiency

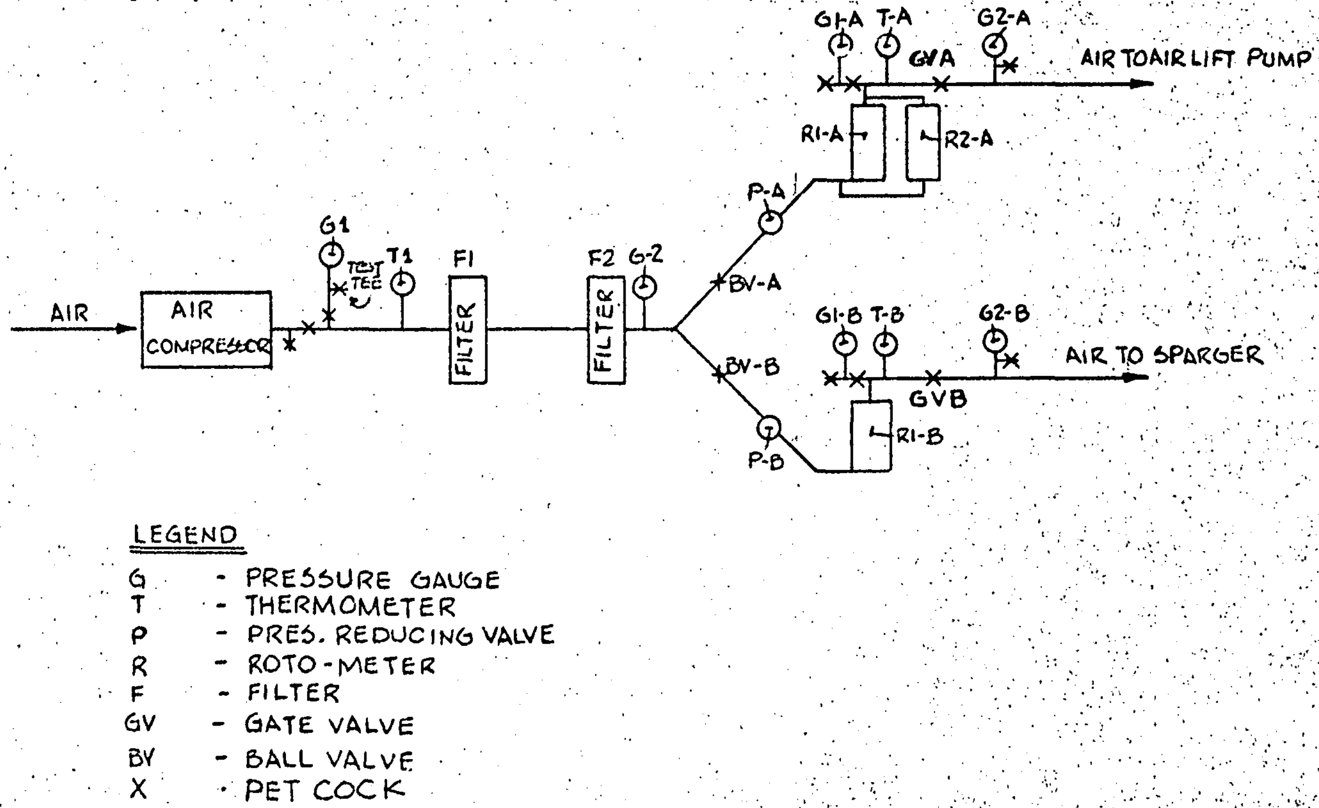

Figure 10. Schematic drawing of air delivery control system for in-well aeration testing.

TABLE 7. GENERAL EXPERIMENTAL DESIGN

INDEPENDENT VARIABLES		DEPENDENT VARIABLES	
VARIABLE	RANGE	VARIABLE	RANGE
Air flow rate	0-116 cfpm	Water flow rate	20-100cfpm
		Submergence	50-75%
Footpiece Configuration	large/small bubble	Water Horsepower	0.5-1.7HP
Depth of Sparger	130 ft,200 ft, 280 ft	Air Horsepower (adiabatic)	0-10HP
Depth of Air Lift Pump	130 ft, 200 ft 280 ft	Required Compressor HP	0-15HP
Depth of Electric Pump	200 ft	Estimated wire-to-water efficiency	0.2-40%
Pumping Water Level	40 ft - 70 ft	Cost to Compress Air	
		Raw Water Quality (primary)	organic removal
		Treated Wtr Quality (primary)	organic removal
		Raw Water Quality (secondary)	pH/DO bact
		Treated Wtr Quality (secondary)	pH/DO bact
		Air Quality	Organics in air at well head, weir box & 20 ft from weir box

testing. Another pressure gauge followed the rotometer on each side (G1-A and G1-B) to determine air pressure at the rotometers. These gauges were followed bv thermometers (T-A and T-B) to measure air temperatures at the rotometers. R1-A, R2-A, R1-B, G1-A, G1-B, T-A and T-B were used to measure the independent variable of air flow rate. Air pressure and temperature at the rotometers were necessary to correct air flow rate for deviations from the rotometer calibration temperature and pressure (see Appendix A). Next, there were gate valves to precisely control the air flow rate through the rotometers (GV-A and GV-B). Finally pressure gauges G2-A and G2-B were used to measure the actual air delivery pressure to the well. After these gauges, flexible rubber compressor hoses were used to connect the air delivery system to the equipment in the well by way of quick-connect fittings.

One independent variable was the footpiece configuration for the air lift pump and the air sparger. Early research (5) had shown that the footpiece configuration of the air lift pump could be varied considerably without altering the pumping efficiency. The experimental design described here was derived to test whether altering the footpiece of the air lift pump could change VOC removal efficiency. Varying bubble size in diffused aeration affects the organic chemical removal efficiency (28) and bubble size is important in modeling aeration treatment systems. In fact, the need to know (or at least predict) bubble size made it difficult to model an in-well aeration system. The bubbles could not be measured, and the flow of the water within the well was unknown. Bubbles may have coalesced, been pulled into the pump or even have left the borehole through fractures before reaching the pump. Because of this, the data gathered during in-well aeration testing is site-specific, and is not useful to predict specific behavior in another system.

The two air lift pump footpieces chosen for this study provided two different bubble sizes. It was hypothesized that smaller bubbles would provide a greater air-to-water surface interface area which could, therefore, increase organic removal efficiency. It was known that the device to reduce bubble size would also increase head loss and be more expensive to operate. One design introduced air into the footpiece through a simple open pipe configuration (see Figure 11). This open pipe footpiece was to produce large bubbles as compared to the second footpiece, which introduced air through a diffusing device. The device used was a Pearlcomb air diffuser, manufactured by FMC Corporation for use in aeration basins. It resembled an aquarium stone, producing very small bubbles. The air sparger footpiece was also tested. The first sparger configuration was a simple, open PVC pipe to produce large bubbles (see Figure 11). The second configuration tested had a Pearlcomb aerator attached at the base of the sparger.

The next independent variables were the depths at which the air lift pump and sparger were set in the well. Three depths were chosen, based on the VOC and water zones of entry determined during the well characterization procedures (discussed in the previous section). The first depth chosen was 130 feet. All depths were measured from the 90° bend in the eductor pipe at the well head, to the top of the air lift pump, electric pump or sparger footpiece. The 130 foot depth was selected because, based on the historic pumping water level at well L-8, it was likely to provide 65% submergence for the air lift pump, which was reported in the literature (5, 29) as the most efficient submergence for operating an air lift pump. This depth was also slightly below the most heavily contaminated zone of water entry into the well. The second depth chosen was 200 feet. This setting was below all of the major VOC and water zones of entry. The third depth setting was 280 feet, which was 10 feet above the bottom of the well. The 280 ft depth was chosen to maximize aeration contact time in the eductor when air lift pumping, and to maximize countercurrent stripping by the sparger in the well borehole. The 200 ft depth would do the same to a lesser extent, and because the cost to compress air increased with depth, the 200 ft setting would be less expensive than 280 ft. Operating the air lift pump at depths greater than 130 ft would increase costs due to submergence greater than the optimum of 65%. Testing would show whether the increased costs would pay off in increased VOC removal.

A 12-member matrix of equipment configurations was devised for the three chosen depth settings (see Figure 12). The entire matrix was examined for the air lift pump combinations. After examining air lift

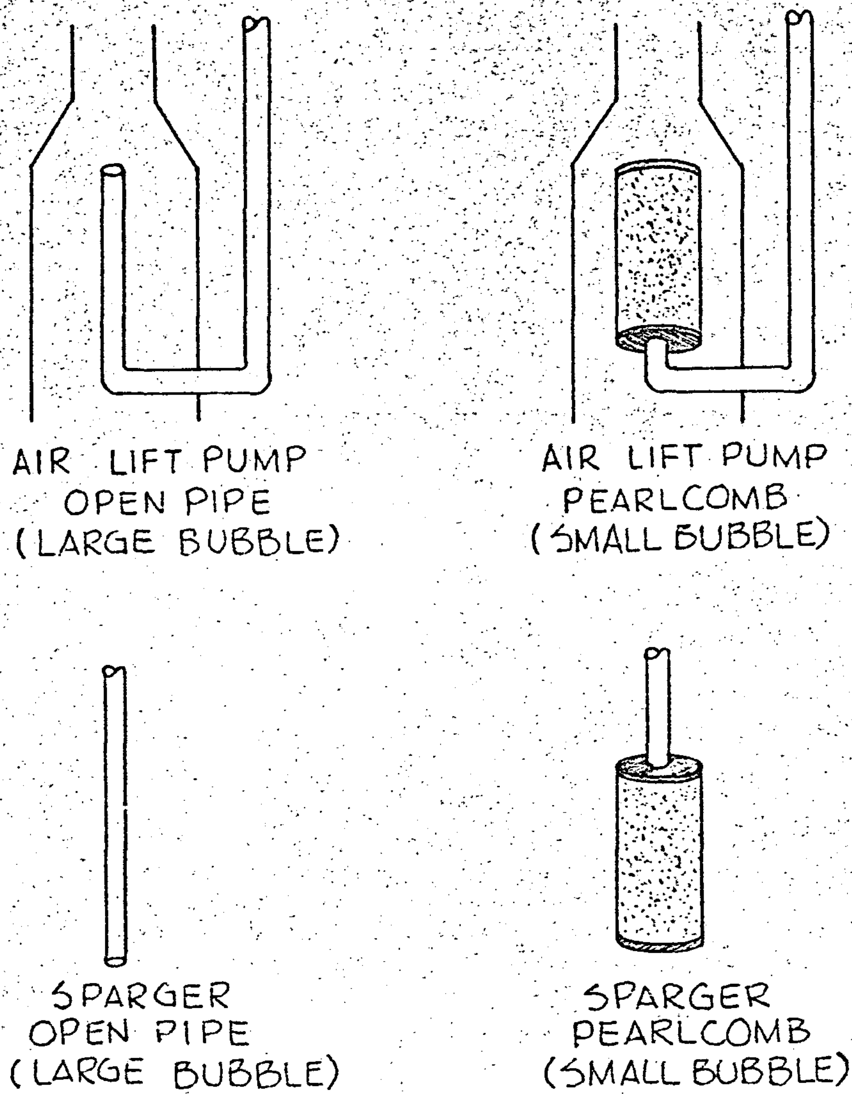

Figure 11. Diagram of air lift pump and sparger configurations for footpiece testing.

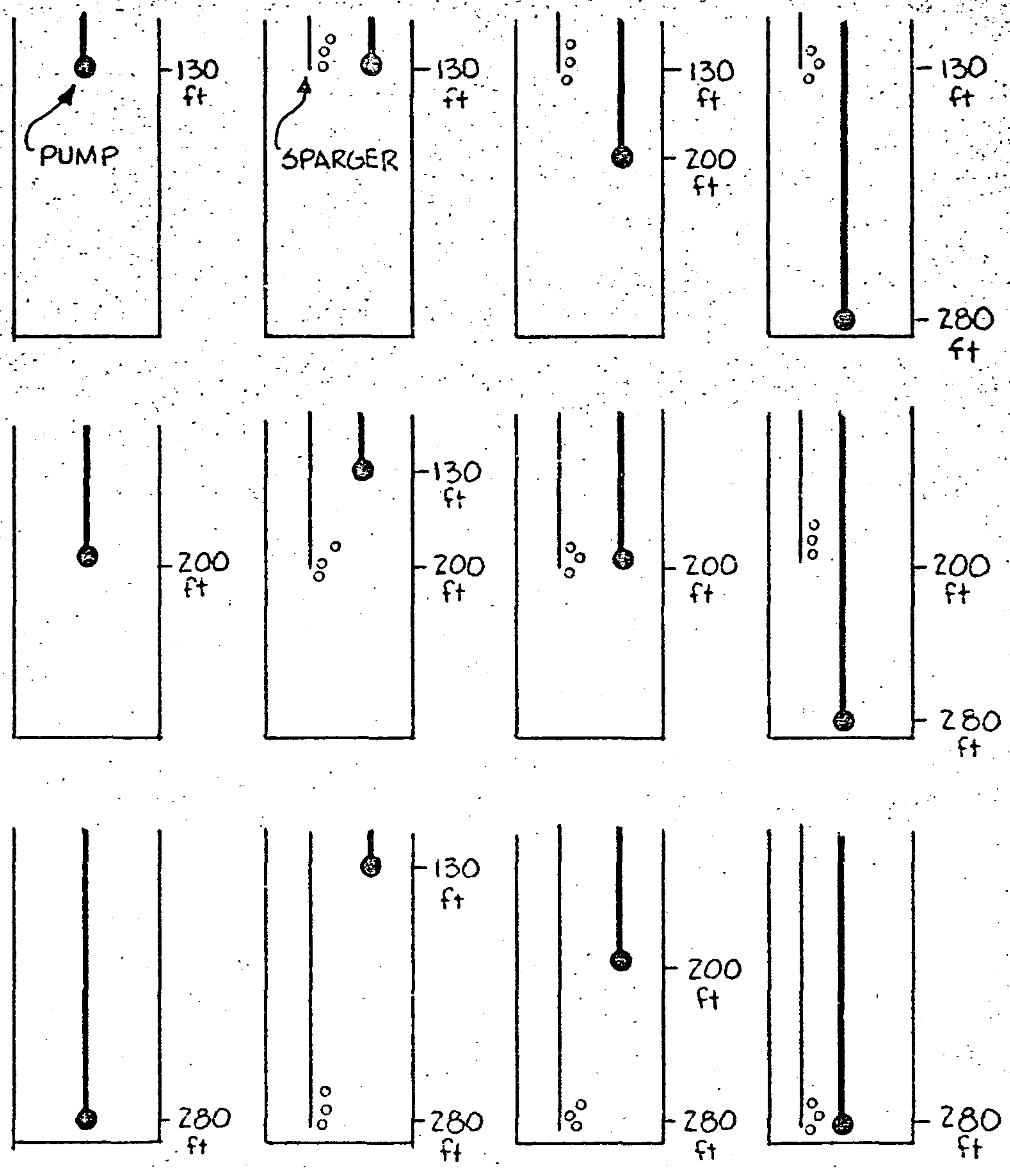

Figure 12. Matrix of depth settings for air lift pump and sparger during in-well aeration testing at well L-8.

pump results the electric pump testing matrix was extracted as a subset of the air lift pump matrix.

Another independent variable was the pumping water level. Under set conditions, the water level while pumping will vary tremendously during the course of the year. This is caused by seasonal rainfall conditions giving the aquifer differing static water levels (the water level in the well when not pumping). On a small scale, when the pump is first turned on, the water level will drop from the static level to the pumping level. At well L-8 this takes at least 90 hours (see results of pumping test at L-8, Section 5). Because of resources the aeration tests were not run this long in each configuration, so the pumping water level was changing with drawdown during the testing.

In earlier tests the water level was measured by dropping an electrical conductance probe down a 1/2 in plastic pipe in the well. When the probe encountered water, a circuit was completed and a deflection was observed on a conductivity scale at the surface. The water level was measured directly from the length of line in the well at the point where the deflection occurred. This method was found to be faulty when air was being introduced into the well through the sparger. In certain configurations (sparger adjacent to or below the probe line pipe), the plastic probe line itself acted like an air lift pump eductor and water was air lifted up through the probe line pipe. To correct this error in later tests, a 3/8 in plastic line was dropped down the well to a known depth (275 ft). A small air compressor was used to introduce just enough air into this plastic line to displace the water in the line. This air was carefully controlled so as to be negligible in comparison with the amount of air flowing during aeration testing. The water level was then calculated from the amount of pressure required to just displace the water in the plastic line (see Appendix A).

The independent variables thus were all direct measurements made in the field. An example of the data collection log may be seen in Figure 13.

The first dependent variable was water flow rate. This was measured by passing the well discharge from the eductor through a v-notch weir box. The box is shown in Figure 14. It was made of stainless steel and was located outside of the well house. The v-notch was 90 degrees. An observation well was attached to the side of the weir box. The well was an 8 in pipe set up vertically with a metal plate welded to the bottom. A smaller pipe allowed water to flow from the box to the well. In this way, the water level in the observation well was the same as the level at the v-notch. A water level recorder was set up on the observation well to provide a continuous record of water level at the v-notch weir. A transparent Tygon tube was attached to the observation well with an adjacent measuring tape to obtain direct readings of water level at the v-notch. Water flow rate calculations from a 90° v-notch are given in Appendix A.

The weir box served a second purpose, aside from water flow rate measurement. It was also the gas and water separator during aeration experiments. The water discharged was milky white with bubbles during experimentation when the air sparger was being used. The open weir box provided a place for the bubbles, as well as the VOCs to be released to the atmosphere. The water was clear of bubbles before it reached the

Date: 10-18-84 TEST # 23 Weather: cloudy-cool

Time	Air Press. at Rotometer 2a	Temp. of Air 1a	Rotometer a	Air Press. down well 3a	Air Press. at Rotometer 2b	Temp. of Air 1b	Rotometer b	Air Press. down well 3b	H_2O Discharge (Weir)	H_2O Level Well (Gray)	Gauge before Filter #4	Temp. before Filter #5	Gauge after Filter #6	
8:47 A.M.										99 / 23.93				STATIC 23.59
1:25 P.M.										96 / 23.84				STATIC 23.84
1:30 P.M.														START AIR
1:40 P.M.	75	69°	35	35	75	68°	35	34	.525	81 / 63.1 ft.	115	85°	114	
1:56 P.M.	75	91°	35	34	75	90°	35	33	.525	81	115	106°	114	SIDEWALK AIR TEST
2:13 P.M.	75	94°	35	34	75	92°	35	33	.525	81	115	106°	114	
2:24 P.M.	75	94°	35	34	75	92°	35	33	.525	80	115	106°	114	
2:35 P.M.	75	94°	35	34	75	93°	35	33	.525	80	115	107°	114	WEIR AIR TEST
2:50 P.M.	75	95°	35	34	75	93°	35	33	.525	79 / 67.8 ft.	115	107°	114	
3:00 P.M.	75	95°	35	34	75	94°	35	33	.525	79	115	108°	114	
3:15 P.M.	75	96°	35	34	75	94°	35	33	.525	79	115	109°	114	WELL-HEAD AIR TEST
3:27 P.M.	75	96°	35	34	75	94°	35	33	.525	79	115	109°	114	

Figure 13. Field data collection sheet for in-well aeration testing at well L-8.

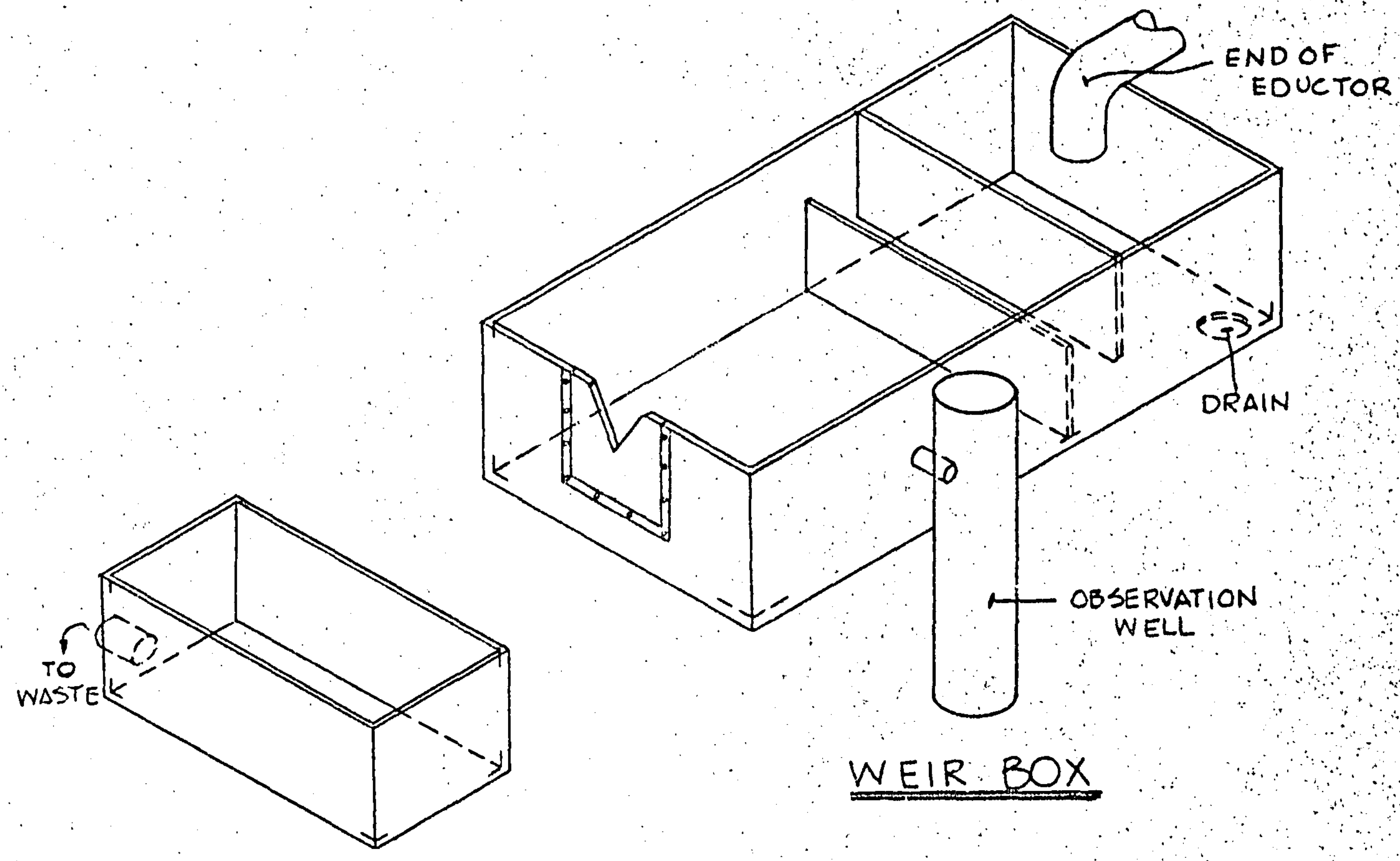

Figure 14. V-notch weir box used as air-water separator and to measure water flow rate. Treated samples were collected at the v-notch, water spilled into the lower box, then went to waste.

v-notch (VOC sample collection point).

The dependent variables of submergence, horsepower, efficiency and cost were calculated from the independent variables. See Appendix A.

Primary and secondary water quality parameters were determined by sampling and analyses. During air lift pump testing the raw water sample was collected from a small (1 HP) submersible pump which was located at the entrance to the air lift pump footpiece. When the air sparger was not being used, raw water could be collected from this point at any time. When the air sparger was being used, the raw water sample had to be taken before the sparger was turned on, or the sample collected at this point would be aerated and not representative of the raw water. Each time the sparger air flow rate was changed, the sparger was first turned off to allow the air to clear from the well. The well was declared free of air from the sparger when the raw water dissolved oxygen concentration returned to background conditions defined at the start of testing, before any air had been introduced to the sparger. It typically took 45 minutes to one hour to clear the well between sparger air flow rate changes.

The primary water quality parameters examined were the six volatile organic compounds found in well L-8 in high enough concentrations to be statistically compared in raw and aerated samples. The samples were collected and analyzed according to EPA method 502.1 (30), which is a purge and trap gas chromatographic procedure using the halogen specificity of the Hall Electrolytic Conductivity Detector (HECD). The gas chromatograph used was a Varian 4600 with a Vista 401 data system. The purge and trap apparatus was a Tekmar LSC-2 with the Tekmar ALS autosampler. The quality control program was developed based on Method 502.1 and the literature (31). Gas chromatographic conditions and quality control procedures are given in Appendix B.

The secondary water quality parameters were pH, dissolved oxygen (DO) and bacteriological quality. The pH and DO measurements were made in the field, immediately after the sample was collected. The pH was measured using a Corning portable pH meter, Model 4. Dissolved oxygen was measured with an Orion DO probe, model 97-08-00. The bacteriological samples were analyzed by both the heterotrophic plate count and the R2A agar plate count methods (32).

The treated water quality, both for primary and secondary parameters, showed water quality after in-well aeration treatment under the conditions represented by the independent variables. The treated water samples were collected from the v-notch of the weir box. The analytical methodology was the same as discussed above for the raw water samples.

The final dependent variable was air quality. Air samples were taken in the well house, over the weir box and 20 ft from the weir box. Two methods were used for examining the air. The first was to pull a known amount of air through a tenax/silica gel/charcoal trap using an industrial hygiene sampling pump. The trap was capped and returned to the laboratory where it was desorbed by the purge and trap device into the gas chromatograph for analysis. Two traps were used in series to monitor for sample breakthrough from the first trap. The second method used to monitor the air was by the on-site analysis using an HNU portable photoionization detector. Both of these methods are described in more detail in Section 12.

SECTION 7

PRELIMINARY FOOTPIECE INVESTIGATIONS

AIR LIFT PUMP FOOTPIECE TESTS - PROCEDURES

Footpiece configurations for both the air lift pump and the in-well diffused aerator (sparger) were independent variables as discussed in Section 6. The preliminary investigations tested two types of footpieces for the air lift pump and two types of footpieces for the sparger. These experiments were also used to develop operating techniques and gain experience in using the air lift pump, both with and without a sparger. Although air lift pumping had been used at North Penn Water Authority in the past, personnel who were familiar with air lift pump operation had retired.

The tests run on the air lift pump, without the sparger, were also used to develop air lift pumping efficiency curves. The air lift pump and sparger were both set at a 130 ft depth in the well. All equipment depths were measured from the top of the air lift pump or sparger footpiece to the center of the 90° bend of the eductor (water discharge pipe) at the well head.

The air lift pump footpiece used for preliminary testing was a combination of the two footpieces to be tested. This design was used so that the air lift pump would not have to be removed from the well to change footpieces. Installing and removing an air lift pump was comparable to performing similar operations for an electric submersible pump in terms of labor and time required. Figure 15 illustrates the air lift pump design used for the preliminary footpiece testing. The air lift pump footpiece was made of 4 in diameter steel pipe. The steel pipe was tapped to accept 3/4 in fittings for the electric submersible sample pump, the air feed line ending with an air diffuser, and the air feed line which ended as a simple open pipe. The air lift footpiece was attached to the 2-1/2 in steel eductor pipe with reducing fittings. The air lift pump was then lowered into the well by attaching 10 ft lengths of 2-1/2 in steel pipe for the eductor and 10 ft lengths of 3/4 in PVC pipe for the sample pump discharge, diffuser air line (small bubble footpiece) and the open pipe air line (large bubble footpiece).

A 1/2 in PVC pipe was lowered into the well to allow a water level measuring probe to be used. This pipe prevented the water level probe wire from becoming entangled with the rest of the equipment in the well.

Each of the PVC pipes were color coded and labelled at the well head so they could be distinguished. A color code diagram was drawn and kept at the well head for reference. The color coding is shown in Figure 15.

The footpieces were chosen to provide different bubble sizes for

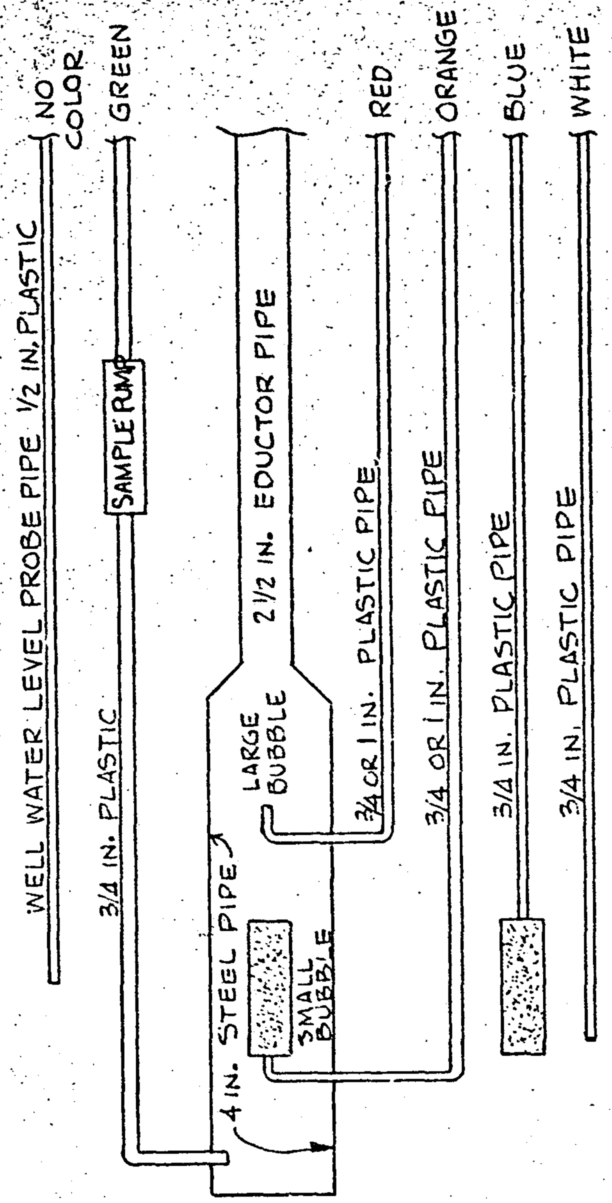

Figure 15. Diagram of in-well aeration equipment used during air lift pump and sparger footpiece testing.

aeration. The tests were to determine whether changing bubble size would significantly affect VOC removal or the cost to compress air because of increased head loss provided by the diffused aerator. Based on the literature, changes in air lift pumping efficiency (amount of water pumped for amount of air added) were not expected with changing air lift pump footpieces.

It is important to make a semantic distinction between a "test" and a "run". Four tests were performed during preliminary footpiece studies. A test was a series of runs, with one depth configuration of in-well aeration equipment per test. For each run, air flow rates were altered. For example, for a particular test the air lift pump and sparger were set at 130 ft in the well. These depth settings were not changed during the test. For each run during the test, a different amount of air was delivered to the air lift pump and/or sparger. Also, during certain of these preliminary tests the footpiece configurations were different for different runs within a test.

Preliminary Test #1 will be described in detail, as it is descriptive of the procedure used in other tests. The air lift pump was operated without the sparger. Air was first delivered to the large bubble air lift pump footpiece. The range of air delivery rotometer settings were from 5 to 116 cfpm. The same air flow rates were then used with the small bubble footpiece.

The portable air compressor was started and the output was connected to the air delivery system (described in Section 6, see Figure 10). The first air flow rate used was 6 cfpm. The rotometer was adjusted to 6 cfpm and the air lift pump was allowed to run for 5 minutes. After 5 minutes, a series of readings were taken of the water level, water flow rate, and the various gauges and thermometers. If the rotometer setting was drifting, it was adjusted at the 5 minute reading. The air lift pump then ran for 10 more minutes to give a total run time of 15 minutes. At the end of the 15 minute run the readings were taken again and VOA samples were collected. This 15 minute run procedure was repeated for 26,40,58,78,96 and 116 cfpm rotometer settings. The entire test consisted of 14 runs; seven with the large bubble air lift pump footpiece and seven with the small bubble air lift pump footpiece. The basic procedure of using 15 minute run times with readings at 5 and 15 minutes and sampling at 15 minutes was used throughout the rest of the in-well aeration testing at well L-8.

During the first air lift pump footpiece test it was discovered that the water level at the v-notch of the weir box was difficult to determine directly. Also, the original rotometers for measuring air delivery were difficult to adjust at low flow rates. Because of these difficulties, the air lift pump efficiency data for the first test were questionable. The weir box was modified to include a direct reading tube and water level recorder (see Section 6 for details). A new rotometer, calibrated from 0 to 6 cfpm, was installed for use for the very low air delivery rates. Preliminary Test #1 was then repeated, using these modifications. The modifications were adopted for use during the rest of the in-well aeration tests at well L-8.

After examining the air lift pump operating data, it was decided that the cost to operate the air lift pump could be reduced by enlarging the size of the air delivery line from 3/4 in to 1 in. A third air lift pump preliminary test was run using the new, larger air delivery line. The large bubble footpiece was used for this test.

AIR LIFT PUMP FOOTPIECE TESTS - RESULTS AND DISCUSSION

In terms of pump operating parameters, the air lift pump footpiece tests confirmed what had been predicted from the literature. Figure 16 illustrates changes in air lift pump operating air pressure and cost to compress air for the three preliminary air lift pump tests. Higher operating pressures resulted in higher operating costs. Costs shown here were only the costs to compress air. They do not include costs of disinfection, repumping after a clear well, operation and maintenance, etc. (see Appendix A). As expected, the operating pressure of the air lift pump equipped with the restricted opening, small bubble footpiece had the highest operating pressure and therefore the highest operating cost. The maximum air pressure for this configuration was 83 psi with a maximum cost of 29.5¢ per thousand gallons. The maximum operating pressure for the large bubble air lift pump footpiece with a 3/4 in air line was 68 psi, which produced a cost of 25.7¢ per thousand gallons. The large bubble air lift pump footpiece, with the 1 in air line, had a maximum operating pressure of 54 psi with a cost of 20.4¢ per thousand gallons to compress air. Pressure differences were most apparent at the higher air delivery rates where friction loss was greater. Since the most efficient operation of the air lift pump was at a lower air flow rate where operating pressure differences were smaller, the choice of footpiece configuration was not found to be critical in terms of cost when designing an air lift pump.

Figure 17 illustrates the results of the preliminary air lift pump tests in terms of pumping efficiency (wire-to-water efficiency). The shape of the pumping efficiency curve followed that predicted from the literature (5,29). The curve sharply rose to a maximum pumping efficiency of 30-35%, then gradually fell as more air was added. The maximum efficiency coincided with an air-to-water ratio range of 1.1:1 through 1.4:1. The shape of the curve was because of slippage in the eductor at higher air-to-water ratios. (At higher than optimum air-to-water ratios, the excess air moves faster up the eductor than the air/water mixture itself. This phenomenon is defined as slippage.) The depth setting of 130 ft for these preliminary tests was designed to provide 65% submergence for the air lift pump, which was the theoretical optimum submergence in terms of air lift pumping efficiency (5,29). Because of this, the pumping efficiency maximum shown in Figure 17 was the best efficiency which could be expected for the air lift pump used in these studies. The 30-35% efficiency was consistant with observed air lift pump efficiencies in the literature.

The data from the air lift pump footpiece test also confirmed the literature wherein the two footpiece configurations examined showed very little difference in air lift pump efficiency (see Figure 17). Changing from the 3/4 in to 1 in air delivery line did cause a slight improvement in air lift pump efficiency.

The VOC removal results for the air lift pump footpiece tests are shown in Table 8 and Figures 18 and 19. The figures represent data from both repeats of the air lift pump footpiece tests using the 3/4 in air

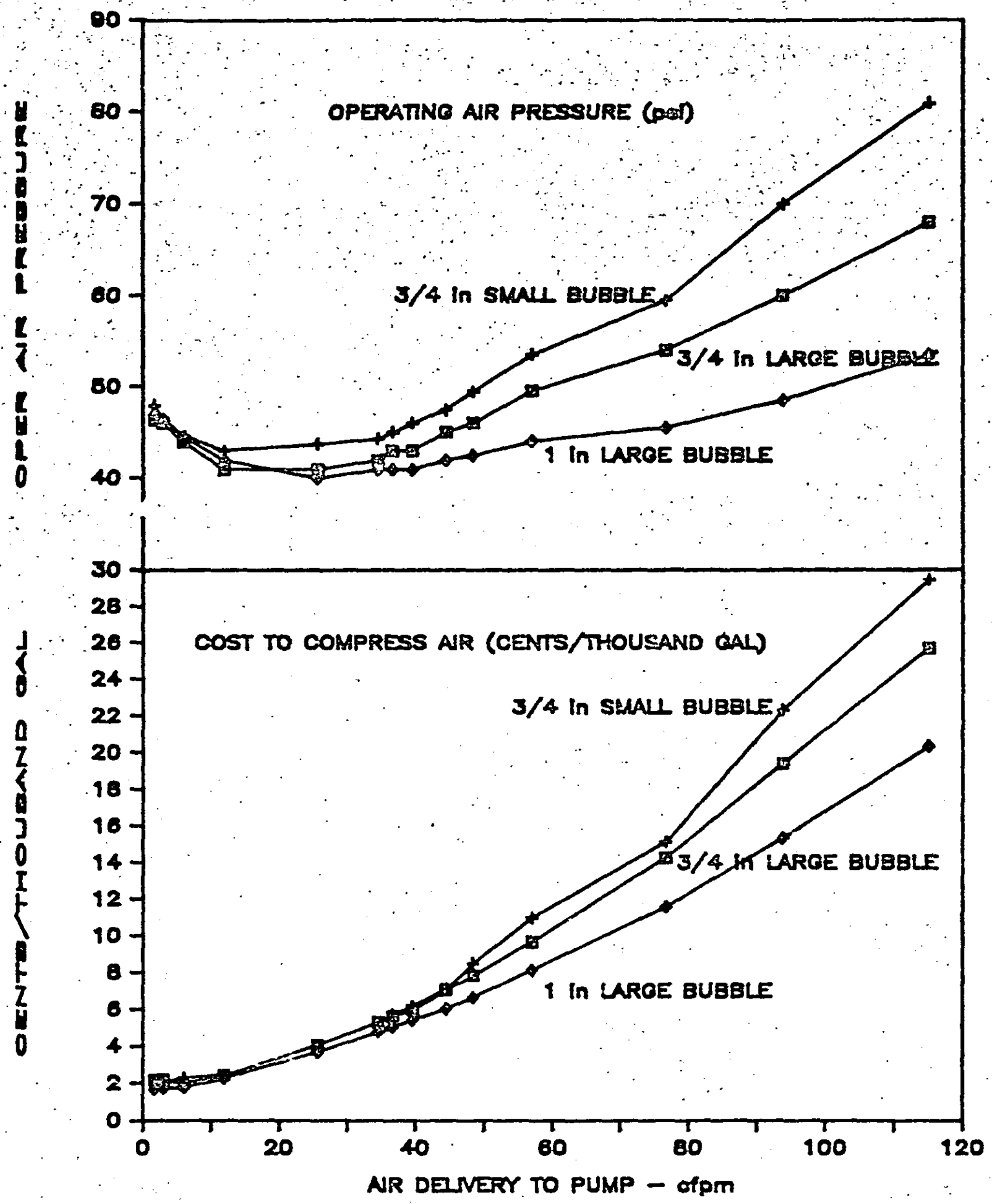

Figure 16. Operating air pressure and cost to compress air for air lift pump footpiece tests during preliminary investigations.

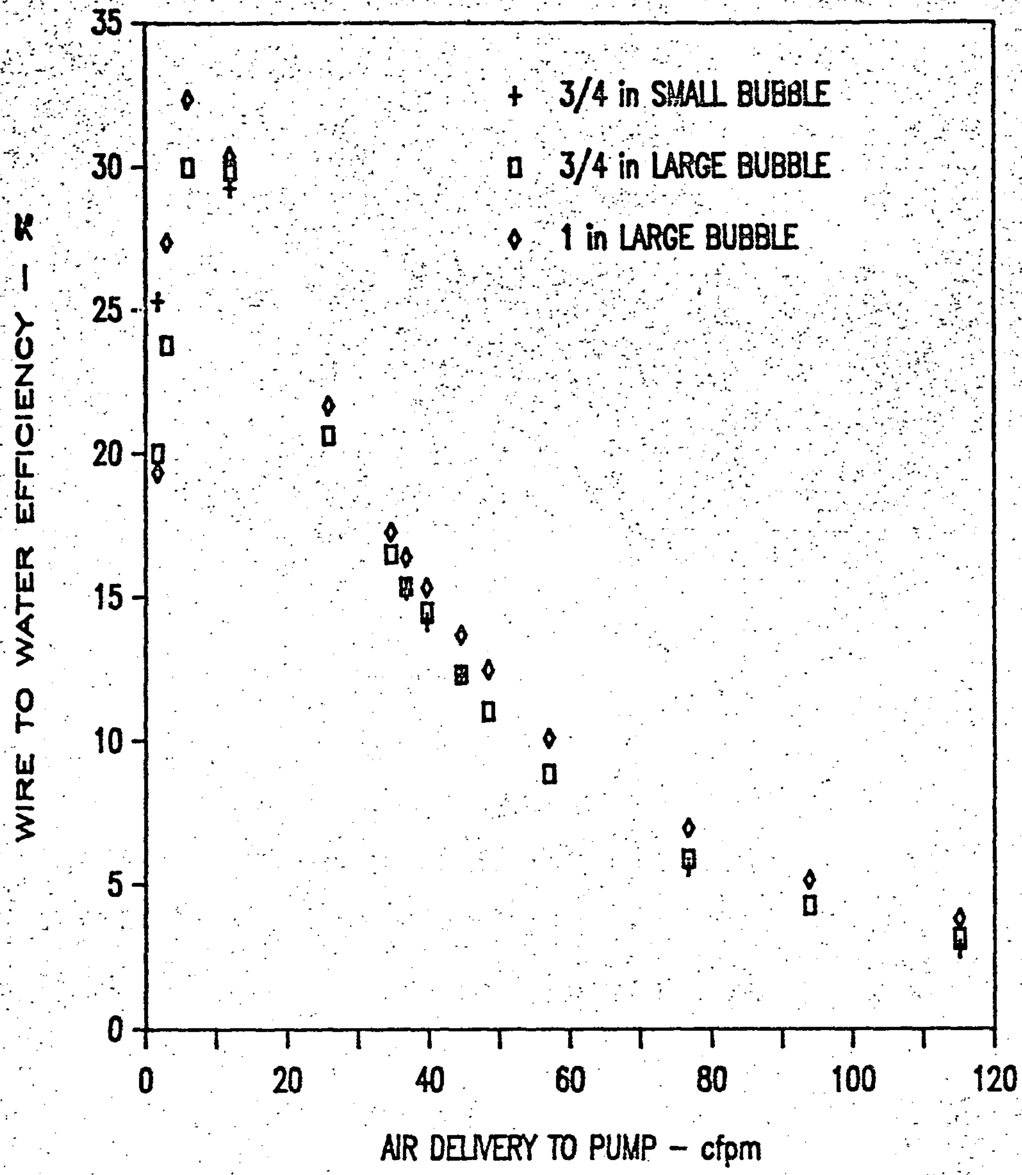

Figure 17. Air lift pump wire to water efficiency for footpiece testing.

TABLE 8. VOC REMOVAL DATA FOR AIR LIFT PUMP FOOTPIECE TESTING (AVERAGE OF ALL LARGE AND SMALL BUBBLE AIR LIFT PUMP FOOTPIECE TESTS)

AIR-TO-WATER RATIO			% REMOVALS FOR VOCs TCE		PCE		c-1,2-DCE		1,1,1-TCA		1,1-DCE		VC	
AVE	%RSD	N	AVE	%RSD	AVE	%RSD	AVE	%RSD	AVE	%RSD	AVE	%RSD	AVE	%RSD
1.2	9.3	5	33.1	19	40.4	14	26.5	33	48.3	19	57.6	11	54.8	22
2.4	6.3	4	40.4	3.7	52.2	4.1	26.7	2.1	56.7	2.1	67.7	2.1	72.1	0.81
3.5	5.1	5	48.5	5.8	62.0	4.7	35.5	7.3	64.9	9.9	74.7	5.2	76.6	4.6
4.9	0.0	2	52.6	4.7	66.2	1.6	37.2	16	73.8	1.4	80.8	0.5	82.6	3.3
7.0	1.4	2	58.2	6.9	71.4	5.7	43.3	9.5	78.9	5.9	85.5	0.1	86.8	2.0
8.7	1.1	2	65.1	0.65	76.7	0.74	48.7	0.60	82.0	1.0	87.0	2.4	89.3	0.80
11.1	5.1	5	70.8	3.3	81.1	2.8	55.2	7.5	85.3	2.4	89.9	1.2	93.6	3.8

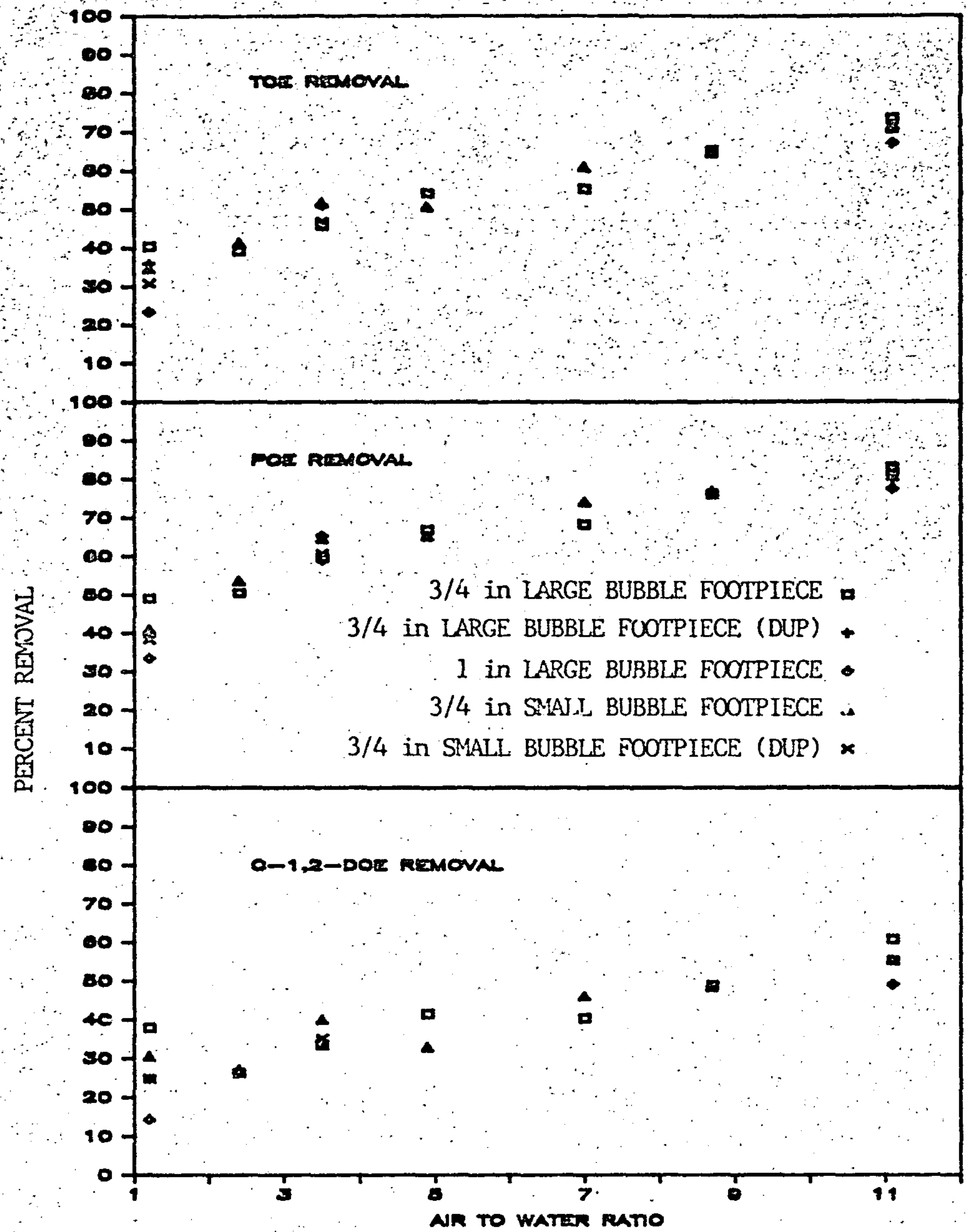

Figure 18. Removal of major contaminants from well L-8 during air lift pump footpiece tests.

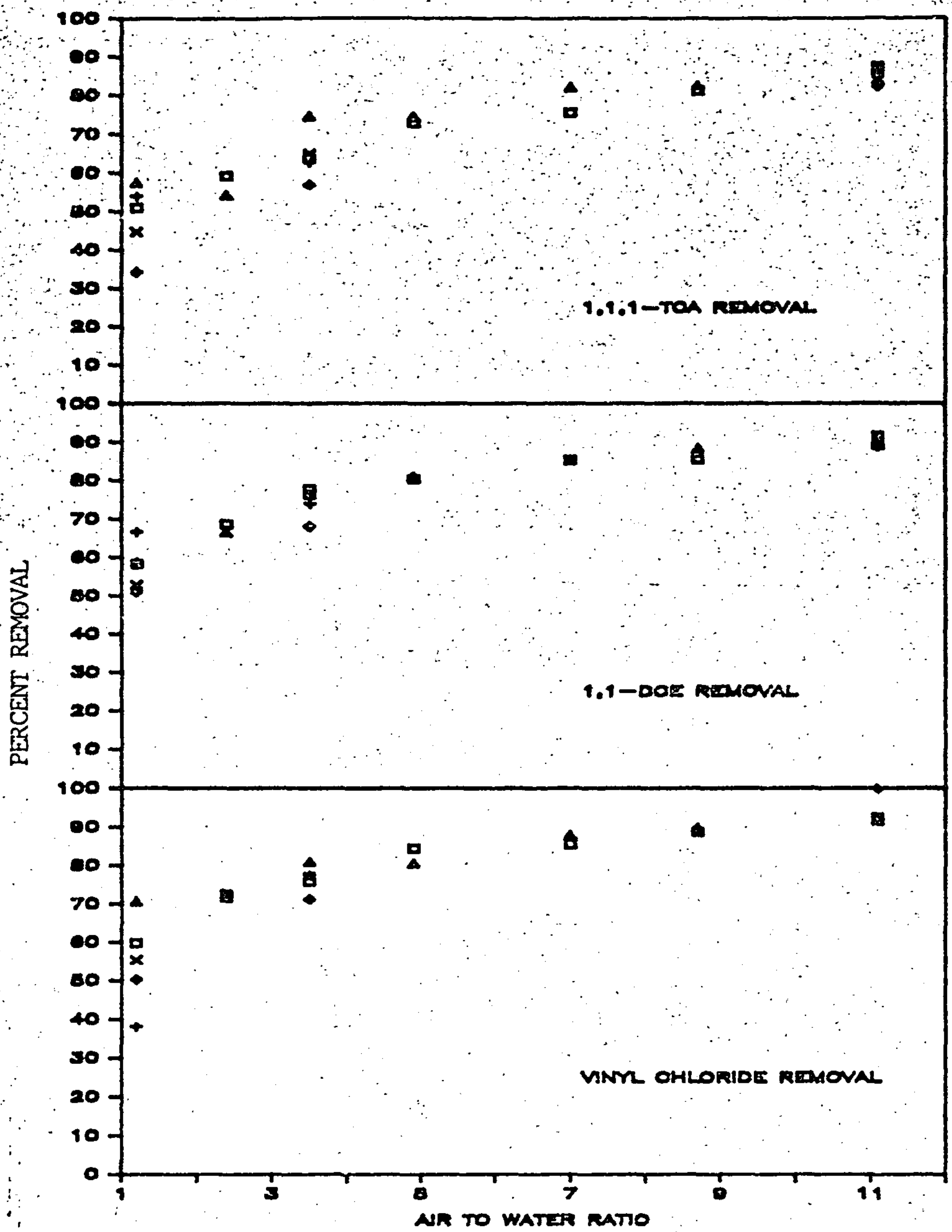

Figure 19. Removal of minor contaminants from well L-8 during air lift pump footpiece tests. For legend, see Figure 18.

line as well as data from the test using the 1 in air line. Visual examination of the results indicated that none of the configurations tested were significantly better or worse in terms of volatile organic chemical removal efficiencies with a ±10% experimental error. It also demonstrated good reproducibility where duplicate tests were conducted and lent confidence to the procedures.

The air-to-water ratios plotted on the x-axes of these figures are averages of ratios obtained during the tests for the same air rotometer setting. A problem with air lift pump field work was that the same rotometer setting yielded different water flow rates at different times. This could be caused by a number of factors, but the principal cause was the air lift pump submergence changed constantly as the water level was drawn down during pumping. Since well water level could not be controlled, it was decided to keep the rotometer settings constant for each run from test to test.

The air-to-water ratio column of Table 8 shows the deviations which occurred for rotometer settings during the preliminary air lift pump tests. The percent relative standard deviation was the highest for the lowest air-to-water ratio. At these very low air deliveries the air/water mixture surged from the eductor at 5 to 10 second intervals causing an uneven water flow. The uneven flow made it difficult to accurately measure water flow rate, which would account for the greater variability in air-to-water ratio at low air delivery rates. These low air delivery rates produced air-to-water ratios below 2 to 3 which is the theoretical optimum for air lift pump operation.

If the air-to-water ratio was the only factor affecting organic removal efficiencies (and not air lift pump footpiece configurations), the percent relative standard deviations for the removal efficiencies should be similar to those for the air-to-water ratios. In most cases in Table 8, this seems to be true, but for several ratios the data were derived from only two data points, which diminished confidence in these conclusions. The data for the lowest air-to-water ratio was consistently higher in percent relative standard deviation for the VOC removals than for the air-to-water ratio, i.e. the VOC removal varied more than the air-to-water ratio at a particular rotometer setting. For this data, air-to-water ratio was probably not the only factor affecting organic removal. Because of the surging water flow at the lowest air-to-water ratio, VOC removals may have been affected by a different, inconsistent type of air/water interface in the eductor and the weir box.

Both the volatile organic chemical removal data and the air lift pump efficiency data indicated that there was no reason to attempt to create smaller bubbles with the air lift pump footpiece. It was not possible to see what was happening in the well during testing, but it can be assumed that, at that depth in the well, in the relatively small eductor pipe, the bubbles rapidly coalesced. Davis and Weidner (5) observed coalescing of small bubbles in their laboratory tests employing glass eductors. For most of the distance the air traveled in the eductor pipe, there likely was no difference between bubbles introduced by the large bubble or small bubble air lift pump footpiece. Because of this, and the higher operating cost of the small bubble footpiece, the large bubble open pipe air lift pump footpiece configuration was used for the rest of the in-well aeration tests. The 1 in air feed line remained in use because of its lower operating pressure.

SPARGER FOOTPIECE TESTS - PROCEDURES

Two 3/4 in air sparge lines were lowered into the well to a depth of 130 ft. The air lift pump remained in the well at a depth of 130 ft. In contrast to installing the air lift pump, installing an air lift sparger was a simple task. The spargers were lowered into the well by attaching 10 ft lengths of 3/4 in PVC pipe at the surface. One sparger ended in a diffussion device to produce small bubbles, while the other was left as an open pipe to produce larger bubbles.

Preliminary Test #1 will be described. It was typical of the other tests performed. The air lift pump was operated at a rotometer setting of 25 cfpm. This air delivery rate was found to be the most efficient in the air lift pump footpiece tests, producing the highest water flow rate per unit of air introduced into the air lift pump.

The first run of each of the sparger footpiece tests was done with the air lift pump alone; no air was being added by the sparger. Next, several runs were performed with increasing amounts of air added through the sparger. Finally the air lift pump and sparger were both turned up to their maximum air delivery rates for one run. This final step was done in order to try to get the highest possible air-to-water ratio without regard to air lift pumping efficiency.

During air sparging it was not possible to collect a raw water sample, because the sample pump would have collected water which was aerated by the sparger (see Figure 15 for sample pump location). In order to collect raw water samples between runs, the sparger had to be shut down, then the well was allowed to clear of bubbles while the air lift pump was still running. The effluent of the sample pump was watched until it was clear to the eye, then the raw water was sampled and the next 15 minute sparging run was started. A dissolved oxygen probe was used to verify the clearing of the well (see Section 6) The clearing process took approximately 45 minutes. During the 15 minute runs, readings of the various gauges and thermometers, as well as water flow rates and well water levels, were taken at 5 and 15 minutes into the run. As with the air lift pump footpiece tests, any necessary adjustments to air delivery rates were made at the 5 minute reading. Treated VOA samples were collected at the v-notch weir at 15 minutes.

SPARGER FOOTPIECE TESTS - RESULTS AND DISCUSSION

Sparging air into the well borehole had an effect on air lift pumping which can be seen in Figure 20. As air was added through the sparger, the amount of water pumped gradually declined. This could be easily explained by re-examining the operating principle of the air lift pump. Introducing air into the eductor of the air lift pump created a density difference between the water inside and outside the eductor. This density difference was the driving force which lifted the water up and out of the well. When the sparger was in use, air was being added both inside and outside the eductor. The density differential was reduced, which reduced the driving force of the air lift pump. In Figure 20, the air lift pump was operated at a constant air delivery rate of 25

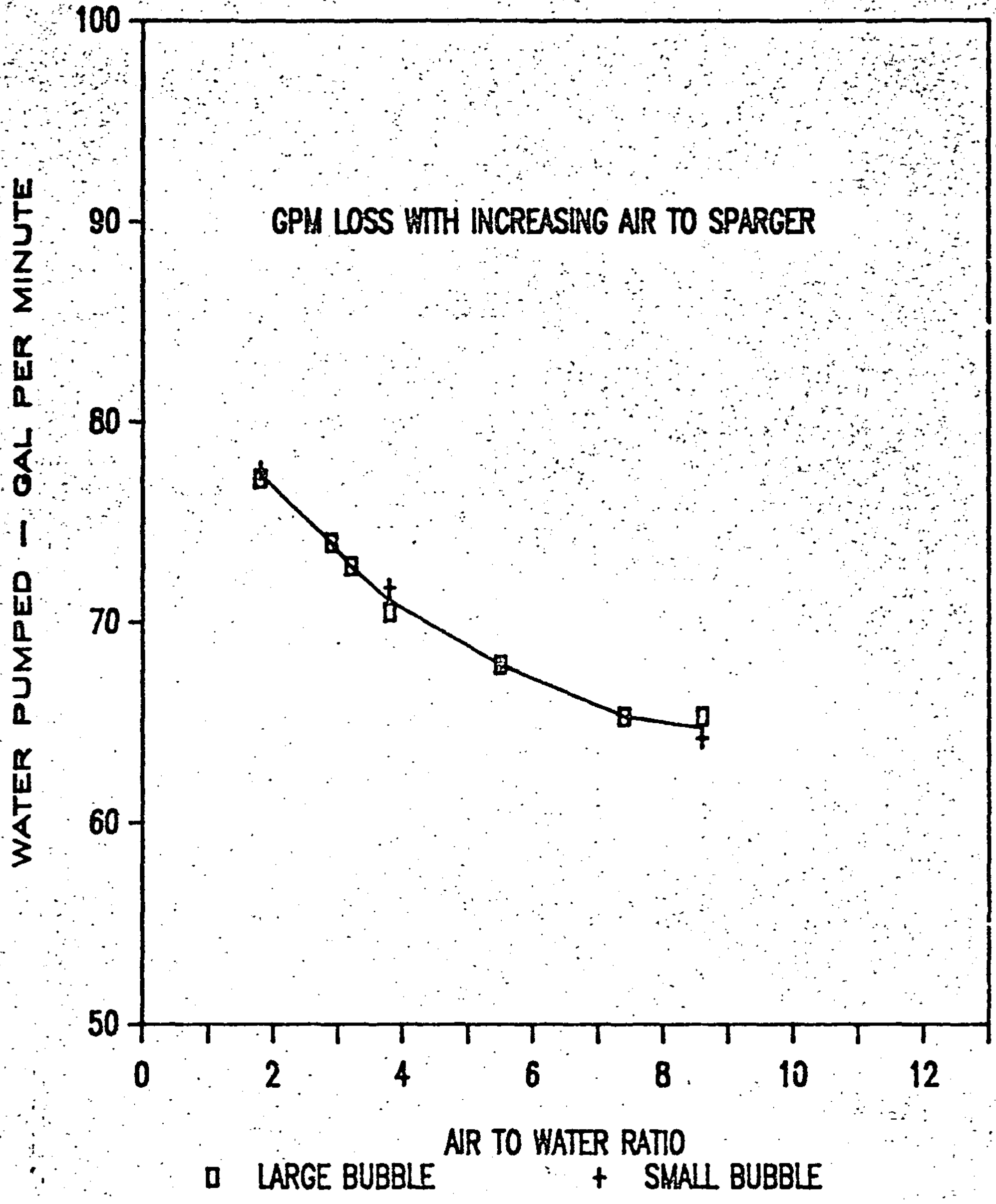

Figure 20. The amount of water pumped by the air lift pump decreased as air was added through the sparger.

cfpm and the amount of water pumped dropped (from 78 to 68 gpm) as the air lift pump driving force was reduced with addition of air through the sparger.

The effect of sparging on air lift pump efficiency could not be determined during the early tests because of inaccurate water level measurements. Water level was needed to calculate the pump horsepower (see Appendix A). When the sparger was operating, the plastic pipe used for the water level probe was filled with aerated water which operated like an air lift pump itself, causing artificially high water level readings. This was not discovered until later testing when water was actually pumped out of the well through the water level probe pipe. The problem was corrected in later tests and the air pressure method of obtaining water levels was used. A description of this procedure can be found in Section 6.

Figure 21 shows the cost to compress air for the sparger footpiece testing. The costs for the air lift pump in combination with the large bubble or small bubble spargers were nearly identical, ranging from 4¢ to 13¢ per thousand gallons at air delivery rates of 28 to 75 cfpm. The operating pressures were only slightly different for the two sparger footpieces. The small bubble sparger footpiece ranged from 34 to 43 psig while the large bubble sparger footpiece required 33.5 to 41 psig operating pressure. These small pressure differences between sparger footpieces translated into very little difference between cost to compress air for the two types of spargers.

The cost to compress air was similar for the air lift pump alone versus the air lift pump and sparger combination. The 3/4 in air line air lift pump with a large bubble footpiece cost 4¢ to 14¢ per thousand gallons (air delivery of 26 to 77 cfpm). This compared with 4¢ to 13¢ per thousand gallons for the air lift pump and sparger combination at similar air delivery rates (28 to 75 cfpm). Cost differences for the air lift pump footpieces became more apparent at air deliveries above 75 cfpm. The sparger was not operated at these higher air delivery rates because, at rates above 75 cfpm, water was blown out of the well borehole. This occurred because the sparger was delivering enough air to turn the entire well into an air lift pump, with the borehole acting as an eductor.

The VOC removal results for sparger footpiece testing are shown in Figures 22 and 23. The figures compare removals for small bubble and large bubble spargers, as well as the earlier results for small bubble and large bubble air lift pump footpieces.

Apparently, there was no significant difference in organic removal efficiencies between the two types of spargers tested. The same conclusion was made earlier for the air lift pump footpieces. The figures also show not only were the small and large bubble sparger VOC removals similar to each other, but VOC removal by the air lift pump-sparger combination was similar to VOC removal by the air lift pump alone. In addition, the VOC removal at the highest air-to-water ratios, representing the runs where the air delivery to the air lift pump was raised to its maximum, agree with removal obtained by keeping the air lift pump at a constant air delivery rate (25 cfpm) and adding increased air to the sparger. In short, the preliminary footpiece tests indicated that for a given air-to-water ratio at a given depth in the well it did

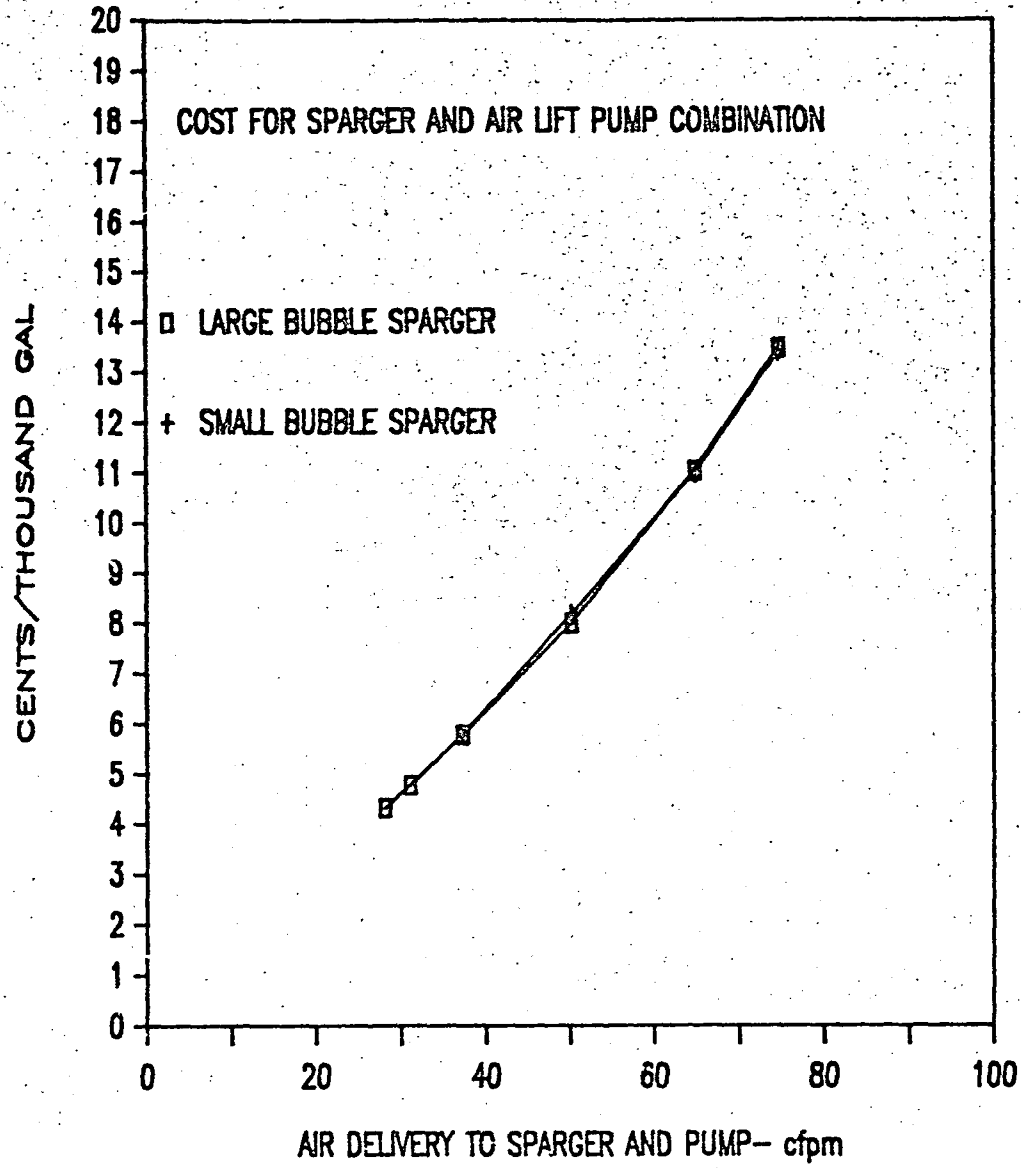

Figure 21. Cost to compress air for air lift pump and sparger combination during footpiece testing.

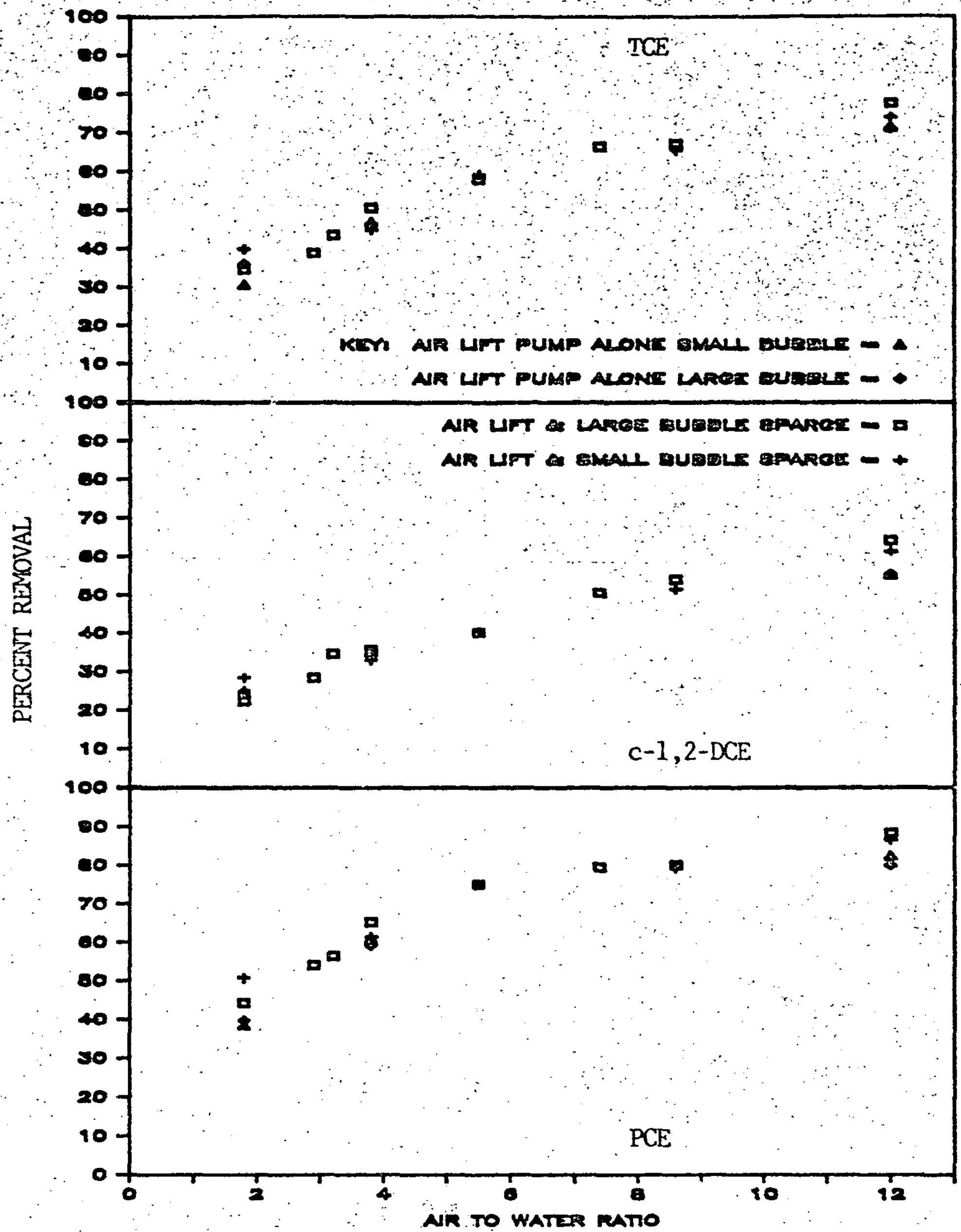

Figure 22. Removal of major contaminants during sparger and air lift pump footpiece testing.

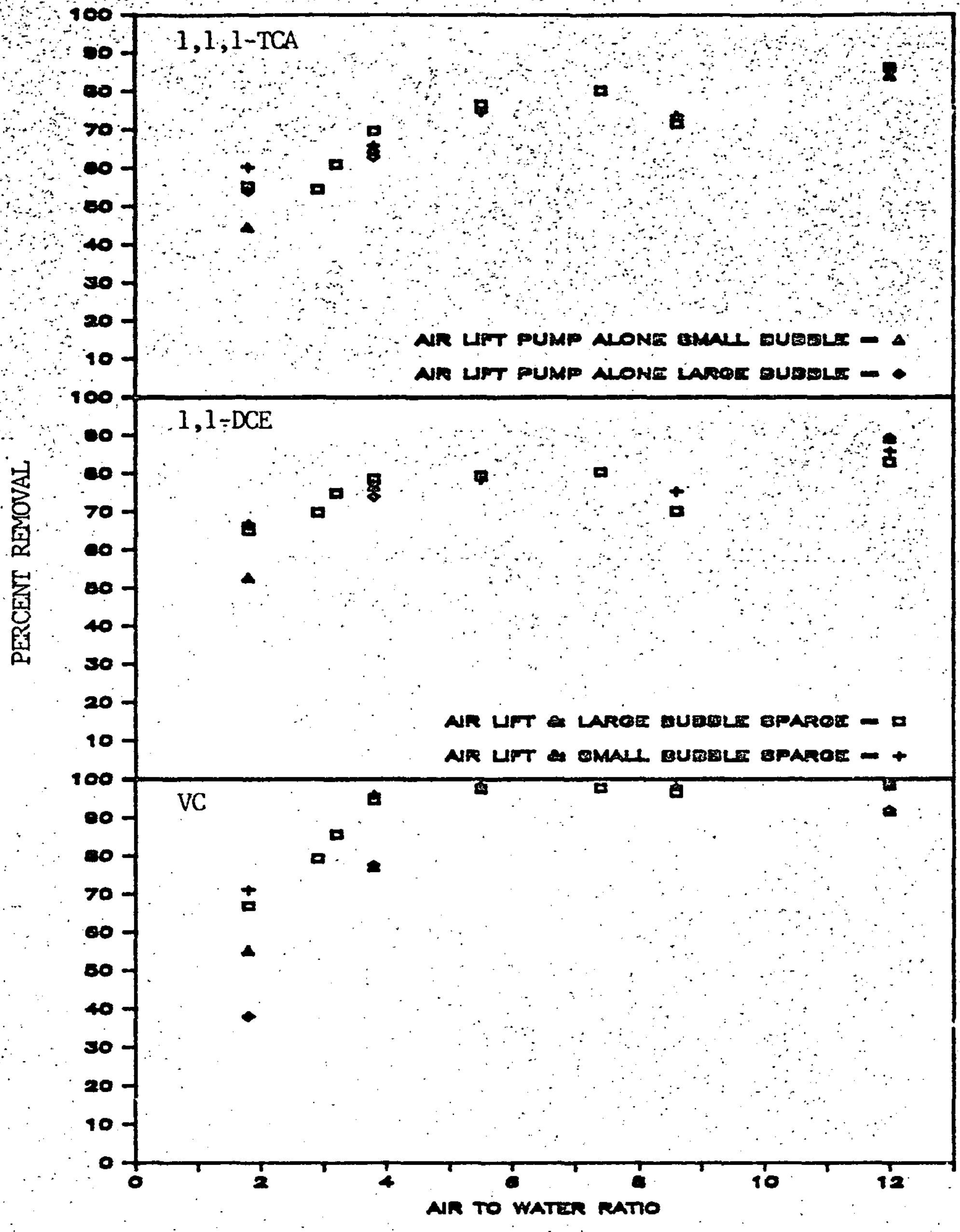

Figure 23. Removal of minor contaminants during sparger and air lift pump footpiece testing.

not matter what configuration of in-well aeration equipment was used, the VOC removals were the same. This held true for all of the compounds except vinyl chloride. For vinyl chloride, although the sparger footpieces both produced the same curves, and the air lift pump footpieces both produced the same curves, the air lift pump by itself did not seem to remove the vinyl chloride as well as the air lift pump and sparger combination. Vinyl chloride has the highest Henry's Law partition constant of all of the compounds found in well L-8, and therefore, was the most easily removed. Perhaps because of this it was more sensitive to in-well aeration configuration changes.

Table 9 is a summary of the air lift pump and sparger footpiece testing removal data, in terms of percent relative standard deviation (%RSD). A similar interpretation was presented for the air lift pump footpiece tests without the sparger in Table 8. As was mentioned in the air lift pump footpiece testing discussion, a given air lift pump rotometer setting did not always give the same water flow rate each time. This was because of changes such as static and pumping water level of the well, which affected the operation of the air lift pump. The air-to-water ratio column of Table 9 showed this variation. The VOC removal percentages showed how removal varied at these different air-to-water ratios. The removals could be expected to vary at least the same amount as the air-to-water ratios (as seen by the percent relative standard deviation). If the in-well aeration configuration affected removal, a much higher %RSD for VOC removals would be expected than that observed for the air-to-water ratio. Table 9 did not show major differences between the %RSD for air-to-water ratios and the %RSDs for removals. The exception was in several of the vinyl chloride points, where the graph in Figure 23 indicated a difference in removal between the air lift pump alone and the air lift pump with a sparger. Table 9 showed a greater variability in air-to-water ratio and VOC removal for lower air delivery rates (also seen in Table 8 for the air lift pump without a sparger). This could be caused by variable flow patterns when less air was being introduced into the well borehole.

CONCLUSIONS FOR FOOTPIECE TESTING

Results of the footpiece testing for the air lift pump indicated that the small bubble footpiece caused greater operating pressure than the large bubble footpiece, as expected. The operating pressure difference was greatest at the highest air-to-water ratios (5:1 to 12:1). In terms of pumping efficiency, the most efficient operation of the air lift pump was found to be at a lower air-to-water ratio (1.5:1), where the operating pressure difference between the pump footpieces was small. There was very little difference in maximum pump efficiency between the large and small bubble air lift pump. The maximum efficiency was found to be 30-35%, which confirmed the literature.

There was no difference in VOC removal between the two air lift pump footpieces. At the maximum obtainable air-to-water ratio of 11.1 to 1, VOC removals ranged from 55.2% for c-1,2-DCE (lowest Henry's Law constant) to 93.6% for vinyl chloride (highest Henry's Law constant).

The cost to compress air ranged from 2¢/1,000 gallons at an air-to-water ratio of 1.2:1, to 29.5¢, 25.7¢, and 20.4¢ per 1,000 gallons for

TABLE 9. VOC REMOVAL DATA FOR SPARGER FOOTPIECE TESTING (AVERAGE OF ALL LARGE & SMALL BUBBLE SPARGER FOOTPIECE TESTS)

AIR TO WATER RATIO			% REMOVALS FOR VOC											
			TCE		PCE		c-1,2-DCE		1,1,-TCA		1,1-DCE		VC	
AVE	%RSD	N	AVE	%RSD	AVE	%RSD	AVE	%RSD	AVE	%RSD	AVE	%RSD	AVE	%RSD
1.8	39	4	35.3	9.2	43.3	11.1	25.2	8.5	53.6	10.5	63.0	9.3	57.9	22.1
2.9	-	1	39.0	-	54.1	-	28.6	-	54.5	-	70.0	-	79.3	-
3.2	-	1	43.5	-	56.5	-	34.8	-	61.1	-	75.0	-	85.6	-
3.8	5.3	4	47.3	4.5	61.7	3.6	34.6	2.8	66.0	3.7	76.9	2.3	86.4	10.5
5.5	0.0	2	58.6	1.1	75.1	0.10	40.6	0.40	75.6	1.3	79.1	0.60	98.2	0.53
7.4	-	1	66.4	-	79.5	-	50.7	-	80.2	-	80.5	-	97.9	-
8.6	1.2	2	66.4	1.1	79.7	0.52	53.0	2.3	72.8	1.5	72.8	3.6	97.5	0.79
12	2.5	4	73.6	3.5	84.4	3.9	59.2	6.5	85.5	1.0	87.0	2.9	95.3	3.5

the small bubble - 3/4 in air line, large bubble - 3/4 in air line and large bubble - 1 in air line air lift pump footpieces, respectively. The cost differences were greatest at the highest air-to-water ratios, where the operating pressure differences were the greatest.

VOC removal efficiency was greatest at the highest air-to-water ratios and the air lift pump efficiency was best at a low air-to-water ratio; therefore, an air lift pump would have to be operated in an inefficient way in order to use the pump for VOC treatment. Operation at the highest air-to-water ratios caused the small bubble air lift pump footpiece to be considerably more expensive than the large bubble footpiece. Since there was no difference in VOC removal between the two air lift pump footpieces, and the small bubble footpiece was more expensive to operate, the large bubble air lift footpiece with a 1 in air delivery line was chosen for use during the rest of the in-well aeration testing.

Sparging air into the well decreased the efficiency of the air lift pump. This was consistent with air lift pump operating theory. There was very little difference in operating pressure and cost to compress air between the large bubble and small bubble sparger footpiece. The cost to compress air for the air lift pump and sparger combination ranged from 4¢ to 14¢ per 1,000 gal for air-to-water ratios of 2:1 to 9:1. These costs were similar to the air lift pump without the sparger at the same air-to-water ratios.

There was no observable difference in VOC removal between the large and small bubble sparger. The large bubble sparger was chosen for use throughout the rest of the in-well aeration testing.

It was found that adding air to the well through the sparger could turn the entire well into an air lift pump and cause water to be lifted up and out of the well borehole and onto the pumphouse floor. The air-to-water ratios were limited when sparging to the point at which the most air could be added without blowing water out of the well borehole.

In the footpiece testing, VOC removals were similar for similar air-to-water ratios, regardless of whether air was introduced by the air lift pump alone or by the air lift pump and sparger combination. Vinyl chloride, with the highest Henry's Law constant, was the exception to this. It was better removed by the air lift pump and sparger combination than the air lift pump alone.

SECTION 8

AIR LIFT PUMP TESTING WITHOUT SPARGING

AIR LIFT PUMP TESTS WITHOUT SPARGING - PROCEDURES

The air lift pump was tested without the sparger (in-well diffused aerator) at each of the three depths chosen for study. The depths (130 ft, 200 ft, and 280 ft) were chosen based on water and VOC zones of entry as determined during the well characterization stage of this study. The 130 ft and 280 ft tests were run in duplicate. The air lift pump testing, without a sparger, is represented in the first column of the experimental matrix in Figure 12. The large bubble footpiece and 1 in air line were used as a result of preliminary testing (see Section 7 for details). One of the tests at 130 ft was performed with the 3/4 in air line.

As with the preliminary footpiece experiments, each air lift pump test consisted of a series of 15 minute runs using various air flow rates. The air flow rates ranged from the maximum air delivery rate possible to the lowest air delivery rate which would pump water. The maximum air delivery was obtained by attaching both the air lift pump and sparger air lines (side A and B of the air delivery system shown in Figure 10) to the air lift pump. The lowest air flow rates were measured by the small air rotometer (0 to 6 cfpm instead of 0 to 60 cfpm), which was placed on the A side of the air delivery system for this purpose.

The actual procedure followed for each run within the air lift pump tests was the same as that used during the air lift pump footpiece testing. At the beginning of a testing day, the static water level (water level before any pumping occurred) was obtained. The air lift pump was turned on at the maximum air delivery rate. The pump was allowed to operate until the weir box was full. When the weir box was full, the timer was started to measure the first 15 minute run. After five minutes, readings were taken of all the valves, gauges, and thermometers, as well as the water flow rate and pumping water level in the well. Any necessary adjustments to rotometers or pressure valves were made at the five minute reading. It was very rare that the rotometers or pressure reducing valves required adjustment during a run. At the end of the 15 minute run time the readings were taken again and VOC samples were collected from the raw water sample tap and the v-notch of the weir box. Once all of the readings and samples were obtained the next air flow rate was selected at the rotometer and the 15 minute run clock was started again. This procedure was repeated until all desired air flow rates had been tested. Note that when using the air lift pump without a sparger it was possible to move directly from one run to the next. When a sparger was used it was necessary to provide a 45-minute waiting time between runs to allow the well to clear of bubbles so that an air-free raw water sample could be collected.

AIR LIFT PUMP TESTS WITHOUT SPARGING - RESULTS AND DISCUSSION

Air lift pump operational results are show in Figure 24. The graphs show air lift pump operating pressure, submergence and wire-to-water efficiency for tests run at each of the three selected depths in the well.

The submergence of the air lift pump determines the required operating pressure. If the air lift pump submergence is too low, operating air pressure will be low, but there will be greater loss because of air slippage so larger volumes of air will be required. If the submergence is very large, air slippage losses and the volume of air required will be smaller, but operating pressure will be very high. Air slippage losses and high operating pressures cause loss in pumping efficiency.

At well L-8, the greatest air lift pump efficiency was predicted to occur at 65% submergence. Figure 24 shows that did occur. The submergence obtained at the 130 ft depth setting was the closest to 65%, and the wire-to-water efficiency was the highest at this depth setting. The wire-to-water efficiency decreased with increasing percent submergence which agrees with the literature (5,29). Figure 25 is a theoretical pumping efficiency curve adapted from Ivens (29). The submergence obtained for the three air lift pump testing depths at well L-8 have been plotted as points on this curve. The data from this testing closely matches the theoretical curve, showing that the 130 ft depth provided the most efficient air lift pump. Operation of the air lift pump at 280 ft (far below the point of optimum submergence) was difficult. Debris and oily sludge-like material were pumped up from the bottom of the well.

Figure 24 shows the results of duplicate testing at the 130 ft and 280 ft depths. The squares, plus signs and diamonds show the results of the air lift pump with a 3/4 in air delivery line. All of the other tests were performed with a 1 in air delivery line. The smaller air line caused a noticeably higher operating pressure at 130 ft, but this difference was not apparent at 280 ft. This figure also shows that even with a different size air line, reproducibility of the air lift pump operational parameters was very good.

The cost to compress air for the air lift pump tests is shown in Figure 26. The air-to-water ratios tested ranged from 1.3 through 10.6 to 1. As expected, the maximum costs were seen at the highest air-to-water ratios, where operating pressures were highest. With the air lift pump at 280 ft, the maximum cost to compress air was 28.4¢ per thousand gallons. With the pump at 200 ft the maximum cost as 25¢ per thousand gallons and at 130 ft the maximum cost was 20.4¢ per thousand gallons. In comparison, it was estimated that the total cost for packed tower aeration would be similar to these in-well aeration costs, but the packed tower costs included amortization of capital, operation, maintenance and repumping to the distribution system (33). Since packed tower aeration also achieves better VOC removal than air lift pumping, these tests

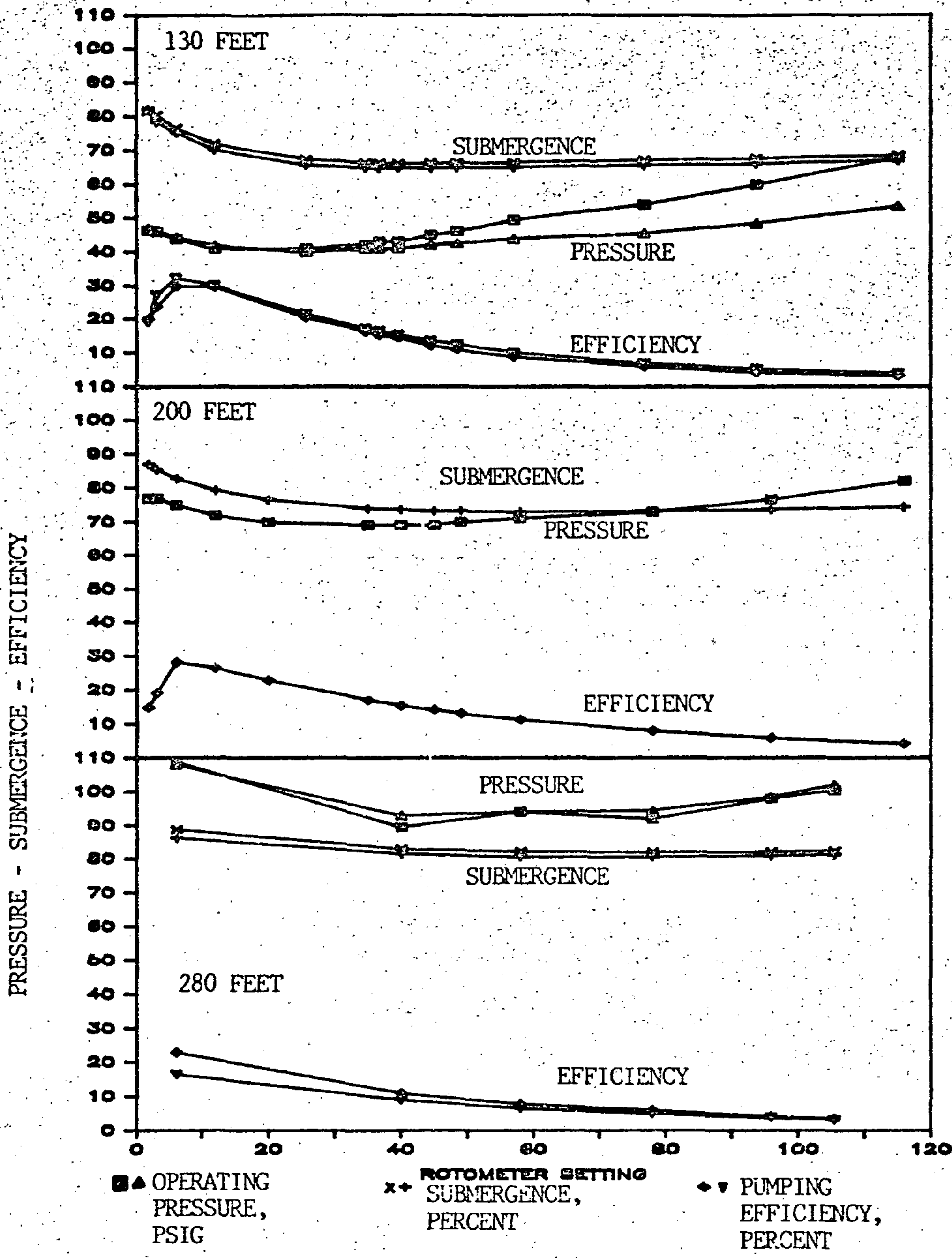

Figure 24. Submergence, operating pressure and pumping efficiency for air lift pump tests at 3 depths in well L-8.

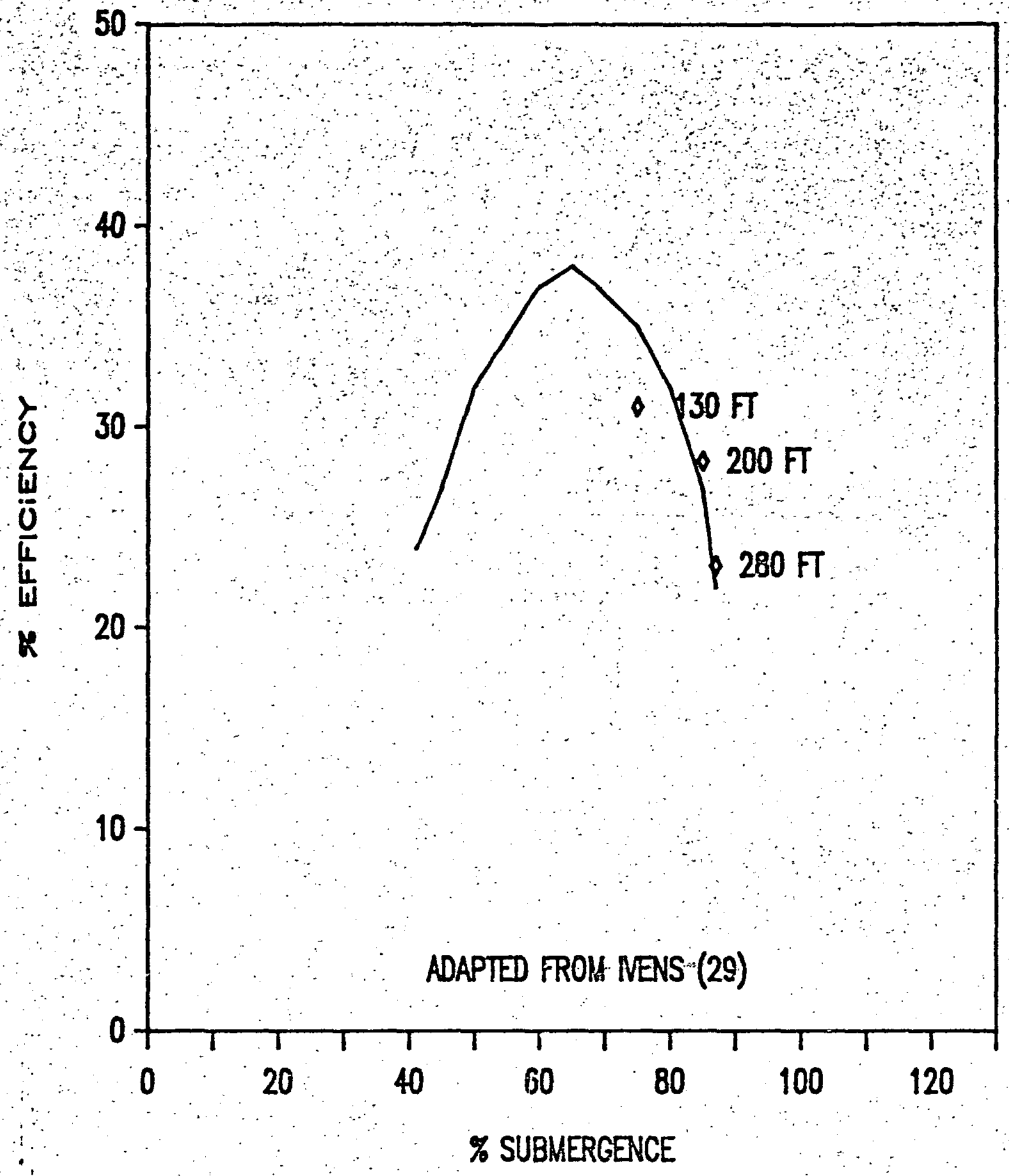

Figure 25. Theoretical air lift pump efficiency curve with points showing a comparison to NPWA test data.

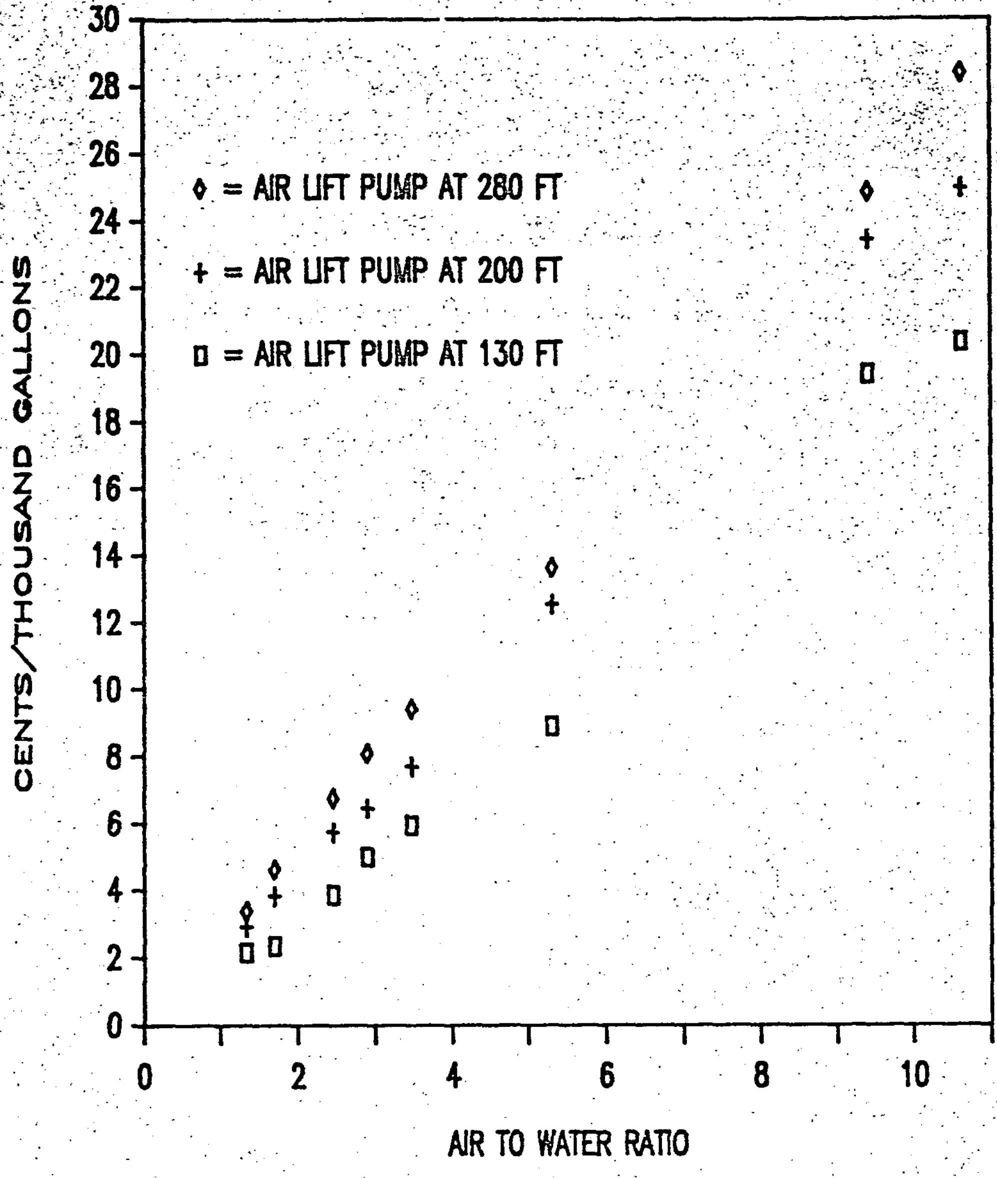

Figure 26. Cost to compress air for air lift pump testing at three depths in well L-8.

showed that packed tower aeration would be the preferred aeration process for VOC treatment over air lift pumping.

The VOC removal results for air lift pumping without a sparger are shown in Table 10 and Figure 27. Three VOCs were graphed to evaluate the removal capabilities of the air lift pump. These compounds were TCE, c-1,2-DCE and VC. The air lift pump footpiece testing indicated that the VOCs found in well L-8 were removed in an order which could be predicted by Henry's Law constants. Rather than evaluate each compound found in the well, these three compounds were chosen because they represent the major contaminant (TCE) as well as vinyl chloride (highest Henry's Law constant) and c-1,2-DCE (lowest Henry's Law constant).

The results of air lift pump testing have been analyzed similarly to the results of the air lift pump and sparger preliminary footpiece testing. VOC removal percentages could be expected to vary from test to test by at least as much as the air-to-water ratio. If some other factor were affecting VOC removal, the VOC removal percentages would vary more than the variation of the air-to-water ratios. Table 10 shows the variation, %RSD, of the air-to-water ratios and VOC removal percentages for each compound studied in well L-8. The %RSDs for the air-to-water ratios are, in most cases, lower than the %RSDs for VOC removal percentages. This would indicate that some factor, other than the variation in air-to-water ratios, was causing the variation in VOC removal percentages. Since the air lift pump was operated at different depths for these tests, depth of the pump in the well was one possible cause of the VOC removal variations.

Figure 27 shows the removal curves for TCE, c-1,2-DCE, and VC. In each case, it was difficult to visually distinguish a difference in VOC removal at the various depths. It might have been expected that the 280 ft depth would have provided the best removal, because the air and water contact time was the longest. Since no VOC removal advantage was obtained by operating the air lift pump at greater depths, and the greater depths were more expensive in terms of operation, an air lift pump treatment system should be designed to operate at the maximum pumping efficiency depth setting.

Raw water concentrations for the three VOCs discussed above are shown in Figure 28. Because of the nature of Henry's Law, it is generally accepted that in aeration, removal efficiency is not related to raw water concentration. This figure shows that the raw water concentration varied widely from one test to the next. Notice also, that the raw water concentrations change a great deal from run to run within a single test. This is why a raw water sample was taken for every treated water sample.

The raw water variation from test to test may also indicate that other conditions within the well were changing. If the concentrations varied, perhaps the zones of VOC entry into the well also changed. This could be a factor, other than depth of the air lift pump, which affected VOC removal. This possible effect of well conditions changing with time will be discussed further when sparger results are shown.

Variation in the analytical method for VOCs was 10% or less. Some of the %RSDs for VOC removal were less than 10% which could be from the analytical method. At several air-to-water ratios, however, the variation was greater than 10% which could not be explained by variation

TABLE 10. VOC REMOVAL BY AIR LIFT PUMP WITHOUT SPARGING (AVERAGE OF ALL THREE PUMP DEPTHS)

AIR TO WATER RATIO			% REMOVAL OF VOCs											
			TCE		PCE		c-1,2-DCE		1,1,1-TCA		1,1-DCE		VC	
AVE	%RSD	N	AVE	%RSD	AVE	%RSD	AVE	%RSD	AVE	%RSD	AVE	%RSD	AVE	%RSD
1.3	3.5	3	27.7	21.1	35.3	8.76	18.1	26.8	41.4	21.6	55.0	15.3	43.8	11.5
1.7	-	1	41.9	-	41.8	-	24.5	-	44.6	-	52.6	-	-	-
2.5	6.1	2	33.7	-	35.6	-	18.6	-	49.2	-	54.7	-	52.1	-
2.9	-	1	50.0	-	56.5	-	34.9	-	60.9	-	72.8	-	60.0	-
3.5	2.7	3	46.2	9.20	60.5	6.06	33.3	4.68	59.9	4.09	71.9	3.69	73.2	4.23
5.3	-	1	48.8	-	59.4	-	30.7	-	70.3	-	72.9	-	74.8	-
9.4	-	1	59.5	-	75.2	-	46.4	-	75.3	-	84.6	-	100.	-
10.6	5.66	4	64.7	7.15	76.7	3.04	47.4	11.8	81.8	3.57	83.8	8.90	90.4	7.45

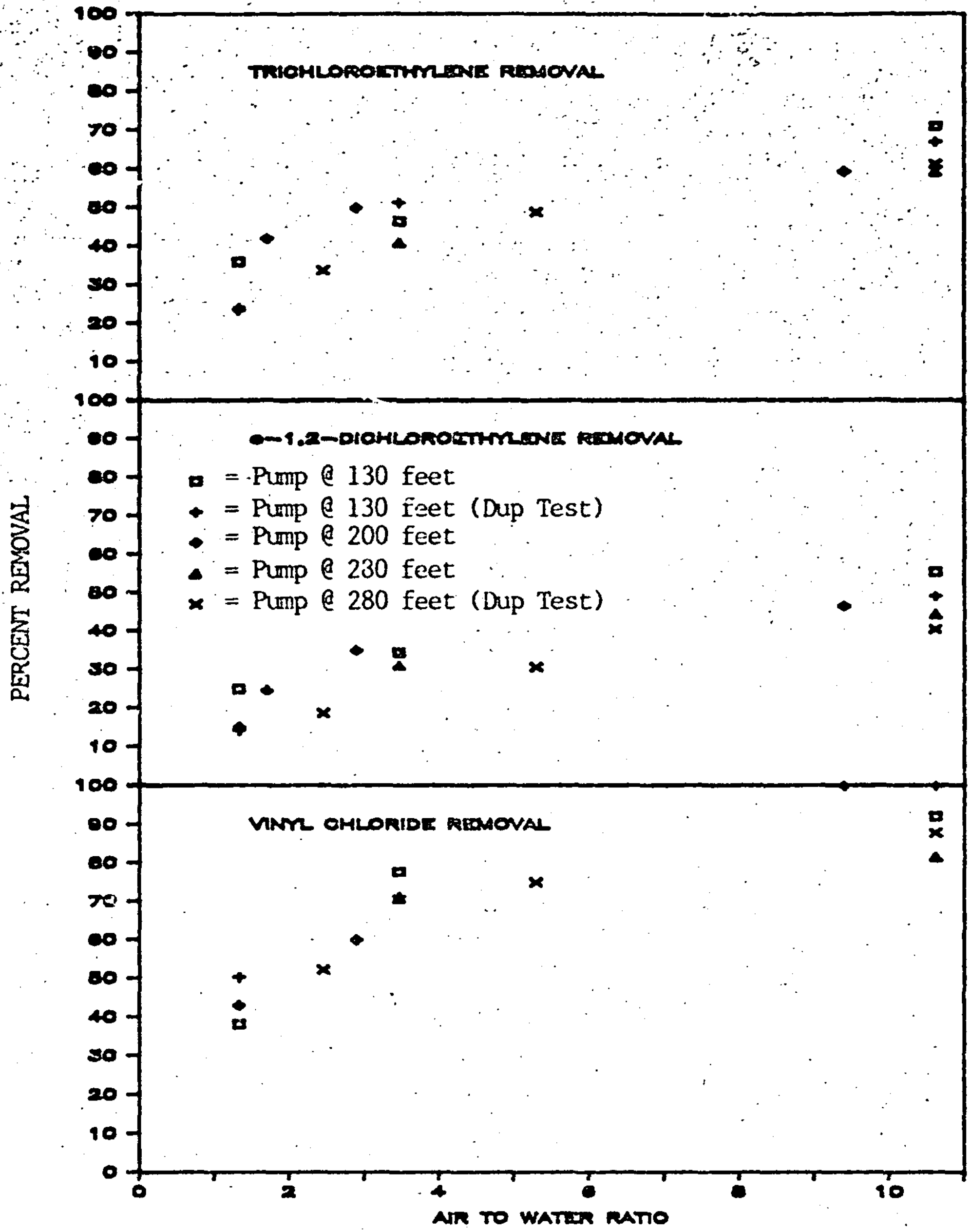

Figure 27. Percent removal of major contaminants by the air lift pump at three different depth settings in well L-8.

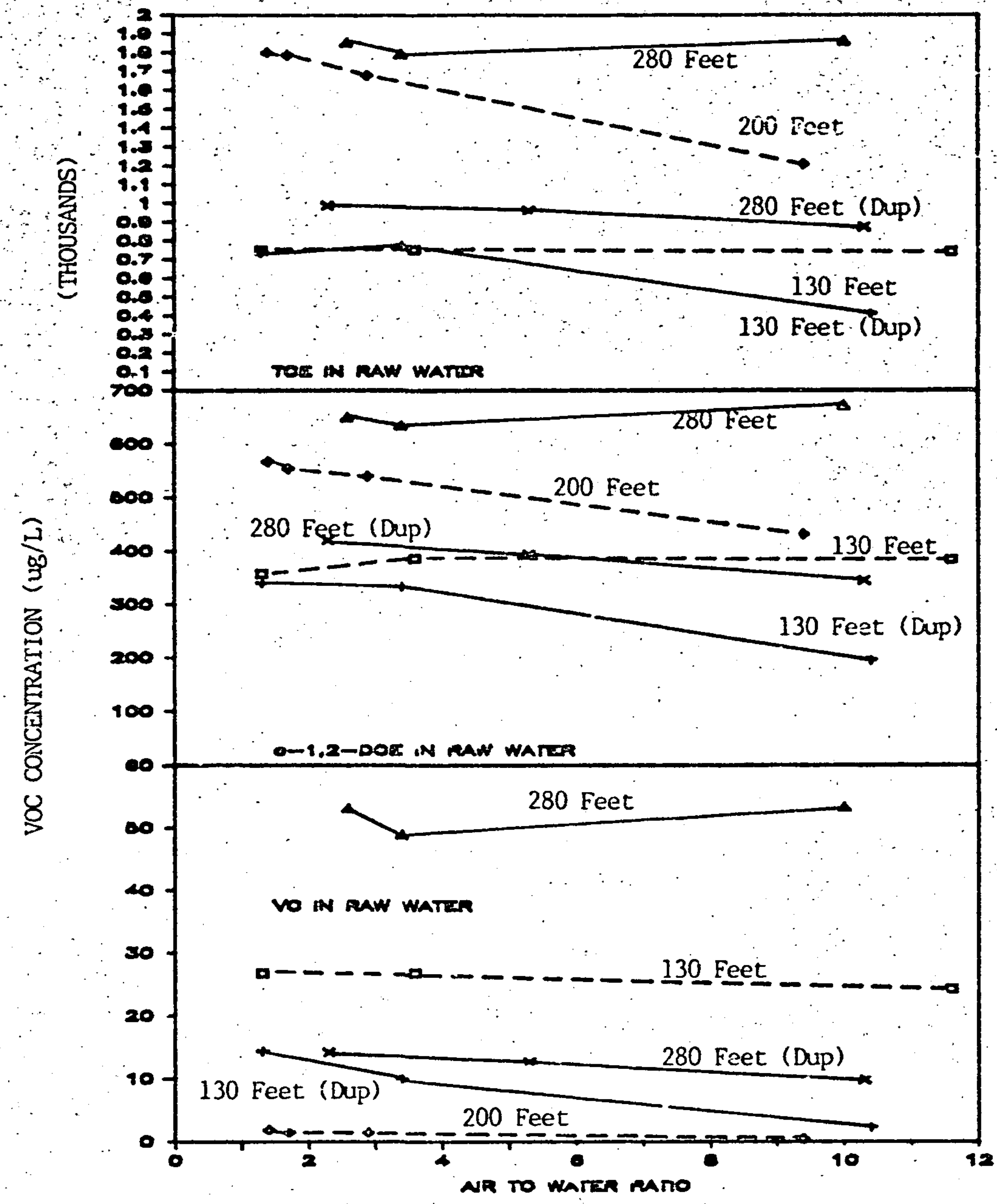

Figure 28. Well L-8 raw water VOC concentration during air lift pump testing at three depths.

during analysis.

AIR LIFT PUMP TESTING AT GLEN COVE, NY

Air lift pumping was also evaluated for VOC control at Glen Cove, New York in another U.S. EPA funded project (34). The air lift pump evaluation was only a minor portion of that project; adjacent wells were used for evaluation of other control technologies.

In the Glen Cove project, a shallow well was selected for installation of an air lift pump. The design was based on 70% submergence and water delivery of 50 gpm. The footpiece configuration was an open-ended pipe; the air line was located concentrically within the eductor. Air and water flow rates were measured by similar procedures to those employed at NPWA. A blower was used rather than an air compressor.

There were several factors, however, that interfered with proper evaluation of air lift pumping. Although designed for 70% submergence, those conditions were rarely realized. Seventy percent assumed no drawdown resulting from operation of nearby wells, however nearby wells were in frequent operation. Pumping water level was measured only once. It revealed 58% submergence as a result of adjacent well operation. Although designed for an air-to-water ratio near 3.3 to give optimum efficiency, it was operated at ratios of 11 or greater. Finally, optimum design conditions suggest an eductor size of 2 to 3 in inside diameter. Allowing for the concentric air line, the 4 in eductor that was used resulted in an equivalent inside diameter of approximately 3.8 in. A larger diameter in combination with larger air flow would promote slippage. Slippage and reduced submergence would promote decreased efficiency. The operating conditions for the one day when pumping water level was measured, are given in Table 11.

TABLE 11. GLEN COVE AIR LIFT PUMP OPERATING CONDITIONS (34)

Water flow, gpm	LT or = 44
Air-to-Water Ratio	GT or = 11
Lift, ft	12.7
Submergence, ft	17.75
Percent submergence	58
Wire-to-Water Efficiency (a)	3.7
Eductor diameter, inch (b)	3.8
Cost to Compress Air ¢/1000 gal (c)	4.2

Data given in:
- a Assuming air compressor of type utilized by NPWA
- b 4-inch I.D. less nominal 1-inch concentric air line
- c Assuming 6¢/kw-hr

LT: Less Than
GT: Greater Than

The very low efficiency at higher than optimum air-to-water ratio is consistent with NPWA air lift performance. The relatively low cost to compress air at that air-to-water ratio results from operating in a shallow well; the compression ratio at Glen Cove was small relative to compressing air under 130 ft or more head at NPWA.

TCE, PCE, c-1,2-DCE and 1,1,1-TCA were measured in the well outside the eductor and effluent from the weir box/separator. Results for the principal VOCs are given in Table 12. The data are consistent with those developed at NPWA in that air lift pumping never achieved removals that would make the technology comparable to packed tower aeration.

TABLE 12. VOC REMOVAL BY AIR LIFT PUMPING AT GLEN COVE (34)

NUMBER TESTS	AIR TO WATER RATIO	RANGE PERCENT REMOVAL TCE	c-1,2-DCE	WATER FLOW GPM a	CONTACT TIME, SEC
2	11	58 ± 2	38 ± 2	44	24
13	15-20	54 ± 10	33 ± 14		
8	21-27	54 ± 3	27 ± 6		
6	34-51	52 ± 3	31 ± 13		

a Data only reported for selected air-to-water ratios

CONCLUSIONS FOR AIR LIFT PUMP TESTING WITHOUT SPARGING

The operating efficiency of the air lift pump was greatest when the pump submergence was near 65% (at the 130 ft depth setting). This was the submergence which the literature predicted would produce the greatest pumping efficiency. The air lift pump efficiency decreased as the submergence increased, which was also described in the literature.

VOC removals for the air lift pump without a sparger ranged from maximums of 90.4% for VC (best removed according to Henry's Law Constant) to 47.4% for c-1,2-DCE (lowest Henry's Law Constant). The best TCE removal obtained was 65%.

VOC removal was poorer at the 280 ft setting of the air lift pump than it was for the 130 ft or 200 ft settings, which were similar to each other in terms of VOC removal. Pump operation was difficult at the deepest setting.

Raw water VOC concentrations varied widely from one test day to the next, as well as varying within a particular test. This confirmed the predictions derived from the pump test conducted during well characterization and emphasized the need for frequent raw water sampling.

The cost to compress air for the air lift pump was found to be similar to the total costs (air, operation and maintenance) of a packed tower aeration system. It was concluded that in-well aeration by air lift pumping alone would not be an adequate substitute technology for packed tower aeration. Air lift pump testing performed at Glen Cove, NY, under a separate U.S. EPA funded project, confirmed this observation.

SECTION 9

AIR LIFT PUMP TESTING WITH A SPARGER

AIR LIFT PUMP TESTS WITH SPARGING - PROCEDURES

The air lift pump was tested with the sparger in various combinations of depths, as shown by the experimental matrix in Figure 12. The air lift pump was the same one used in air lift pump testing without a sparger. The sparger was made of 10 ft sections of 3/4 in plastic pipe, connected with fittings to reach the desired depth. The sparger did not have any type of attachment at the footpiece, as was determined in the Preliminary Footpiece Testing (Section 7).

The testing procedure established during the preliminary footpiece testing and air lift pump testing was used for all of the air lift pump and sparger combination testing. The static water level was recorded, then the air lift pump was operated at a constant air delivery rate of 20 cfpm. This rate was chosen because it produced an efficient air lift pump in terms of pumping (even though it was not the most efficient in terms of VOC removal). The weir box was allowed to fill, so that water flow rate measurements could begin. Next, the sparger was turned on to the first selected flow rate. The tests were conducted as a series of fifteen minute runs. For these tests, the A side of the control board was used for the air lift pump, and the B side of the control board was used for the sparger. (See Figure 10 for a diagram of the air control board). After each run using a sparger, air delivery to the sparger was stopped, and the well was allowed to clear of air. During the well clearing time, the raw water tap was sampled and monitored for DO concentration. When the DO value reached what it had been before sparging was started, a raw water sample was collected, and the next sparger flow rate was started to begin the next 15 minute run. An average time to clear the well of air between runs was 45 minutes. This clearing was an important procedural difference between running tests of the air lift pump with the sparger as opposed to without the sparger. When a sparger was not used, the only air being introduced into the well was being injected directly into the air lift pump, and therefore the air would not affect the integrity of a raw water sample. While the sparger was operating the raw water sample pump was surrounded by aerated water. Collecting the raw water while sparging would result in a sample full of bubbles, which is unacceptable for VOA sampling. It was important to collect raw water VOC samples for each run, because preliminary tests had shown that raw water VOC concentrations varied a great deal, especially when the well was first turned on. The air lift pump could not be turned on and left on for the number of days that it might take to allow VOC concentrations to level off (see pumping test results, Figure 9), because the portable air compressor which we used was too loud to leave operating overnight in a residential area.

The operation of the sparger caused problems with the method originally chosen to measure the water level. A 1/2 in plastic pipe had been lowered into the well where an electrical resistance water level probe was used to measure the water level in the plastic pipe. This design worked well as long as the sparger was not operating. When the sparger was operating in some configurations, the air from the sparger entered the plastic pipe for the water level probe and actually turned the probe pipe into an air lift pump eductor. This water level measurement problem made it impossible to determine air lift pumping efficiency while the sparger was operating and several tests were repeated in order to obtain pumping efficiency data. The water level measurement procedure had to be changed to an air pressure method, which is described in full in Section 6, Experimental Design.

Air lift pump operational problems occurred at the 280 ft depth setting, so these tests were not repeated. Operating the air lift pump this close to the bottom of the well caused an oily sludge to be pumped out at the beginning of each testing cycle. Water flow rates were inconsistent. No pumping efficiency data was obtained at this depth.

AIR LIFT PUMP TESTING WITH SPARGING - RESULTS AND DISCUSSION

Figure 29 shows the wire-to-water efficiency of the air lift pump with and without sparging. It is important, when looking at this figure, to realize that the curves for air lift pump efficiency with and without a sparger are shaped for fundamentally different reasons. The curves for the air lift pump without a sparger were created by adding increasing amounts of air directly to the air lift pump footpiece, thus increasing the air-to-water ratio for in-well aeration. As discussed earlier, an air lift pump has a point of maximum efficiency, at which the minimum amount of slippage will occur in the eductor pipe. Operation with air-to-water ratios greater than the maximum efficiency will cause a drop in the efficiency curve.

The curves showing the effect of the sparger on air lift pump efficiency were obtained by operating the air lift pump at a constant air delivery rate (20 cfpm) while increasing air to the sparger. The efficiency of the air lift pump was observed to have dropped as the sparger air delivery rate was increased (which increased the total air-to-water ratio of the in-well aeration system). This drop in efficiency of the pump was caused by decreasing the water density differential across the pump footpiece, which provided the driving force for operation of the pump. Even though the wire-to-water efficiency of the pump decreased while sparging, it still remained higher than when the air lift pump was operated at increasing air delivery rates without a sparger (as examined in terms of total air-to-water ratio).

Figure 30 shows amounts of water pumped with and without sparging, with the air lift pump set at 130 ft and 200 ft, respectively. The air lift pump without a sparger pumped more water than the air lift pump with a sparger at a given total air-to-water ratio.

Even though less water was pumped when the air lift pump was

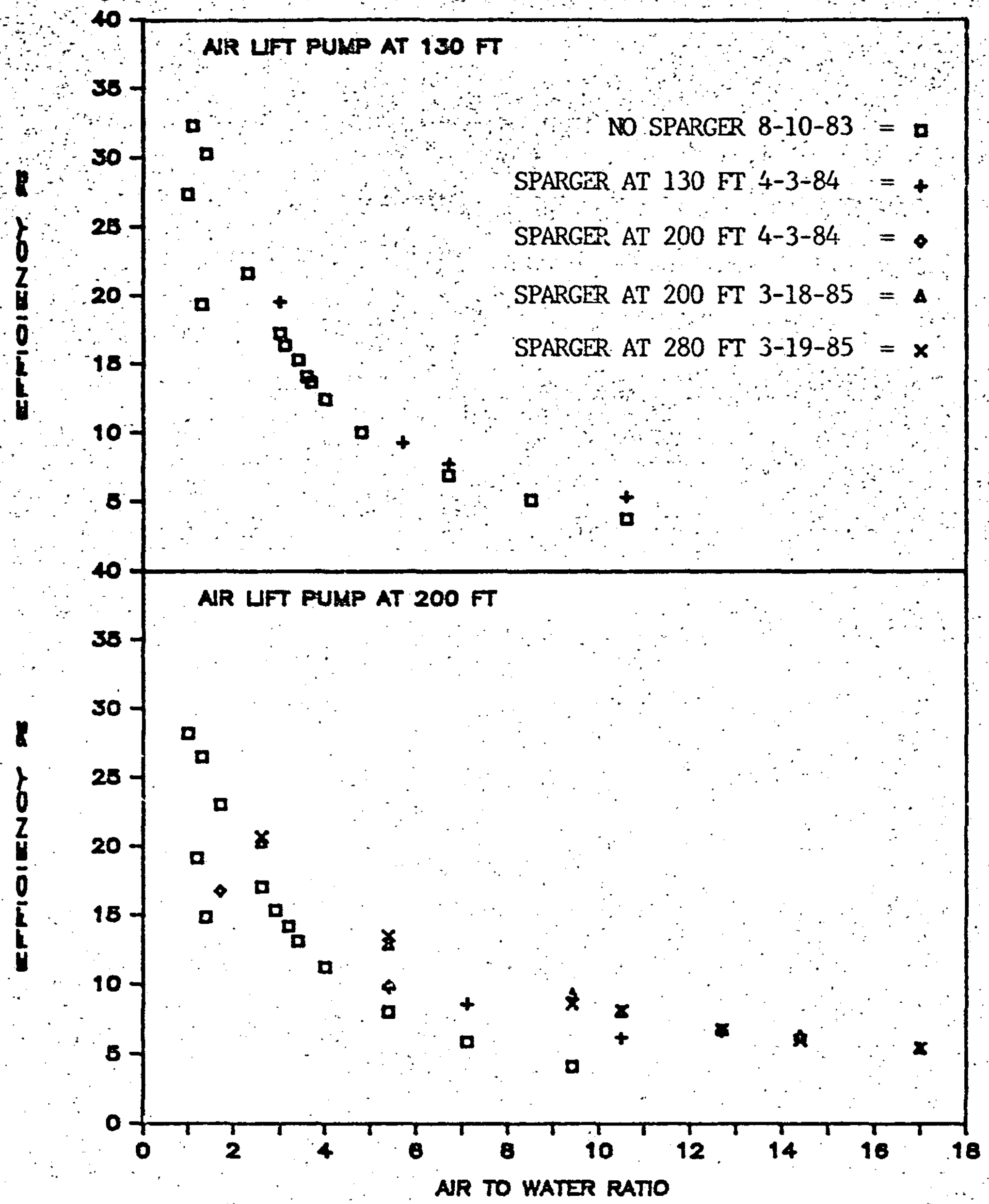

Figure 29. Air lift pump efficiency curves showing the effect of operating the air lift pump while sparging.

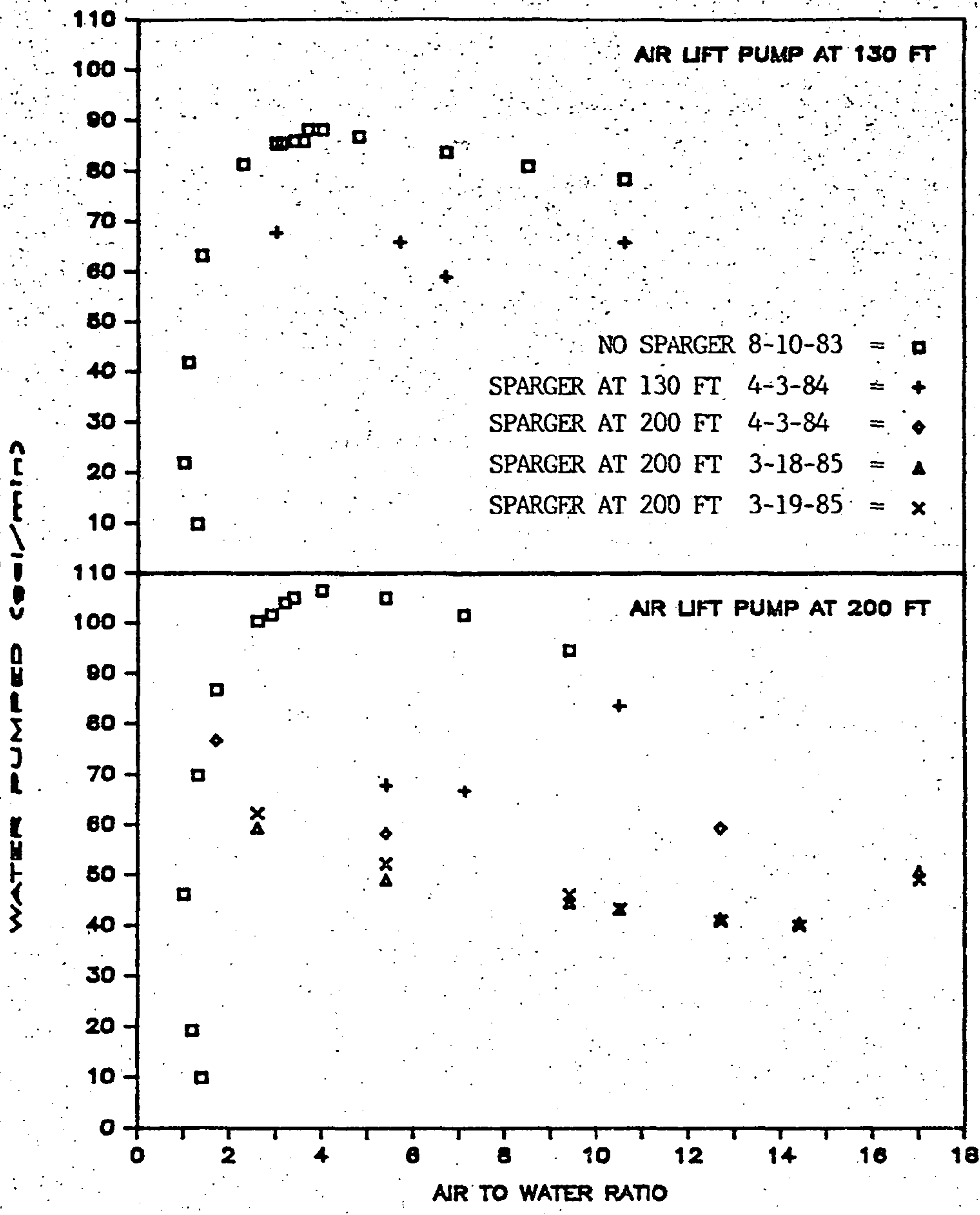

Figure 30. Rate of water pumped by the air lift pump with and without a sparger.

operated with a sparger, the air lift pump efficiency was greater with the sparger than without. This was because, for any air-to-water ratio, only a portion of the total air being delivered was used by the air lift pump to move water, so only a portion of the total air delivered was used in the air lift pump efficiency calculations. In terms of pumping efficiency, for a given amount of air to be delivered, it was better to use the air lift pump and sparger combination than the air lift pump alone.

Even though less water was pumped for the same air-to-water ratio while air lifting and sparging, as opposed to air lift pumping alone, the cost to compress air for the combined operation was less than for putting all of the air into the air lift pump. See Figure 31 for the costs to compress air for the various air lift pump and sparger configurations and compare this with Figure 26 which showed the costs of air lift pumping without a sparger. At the same air-to-water ratios it was less expensive to operate the air lift pump-sparger combination than the air lift pump alone; however, the combination system allowed a larger amount of air to be delivered. At these high air delivery rates, the costs exceeded 30¢ per 1,000 gal. Since this was only the cost to compress air, that makes this method cost more than a packed tower aeration system (34), which achieves better VOC removal.

Table 13 shows the results for testing the sparger with the air lift pump at 130 ft. The % removals shown are averages for all three sparger depths combined (130 ft, 200 ft, and 280 ft). These removals are shown next to their respective air-to-water ratios.

TABLE 13. VOC REMOVAL WITH AIR LIFT PUMP AT 130 FT (AVERAGE OF ALL 3 SPARGER DEPTHS)

AIR TO WATER			TCE % REMOVAL		c-1,2-DCE % REMOVAL		VINYL CHLORIDE % REMOVAL	
AVE	%RSD	N	AVE	%RSD	AVE	%RSD	AVE	%RSD
2.2	9.4	5	33.0	19.6	24.6	11.1	62.3	9.93
3.0	1.7	2	42.6	8.45	28.7	0.35	79.0	0.38
3.2	0	2	39.6	9.71	29.2	19.2	77.8	10.0
4.2	6.3	4	49.3	5.83	34.6	2.70	91.2	4.87
5.7	3.3	5	55.1	11.0	39.8	14.8	96.0	2.97
7.3	3.8	4	61.4	18.2	45.2	21.6	97.6	0.79
8.6	1.2	2	66.4	1.05	53.0	2.26	97.5	0.82
12.	4.8	5	78.3	7.98	65.0	13.1	98.6	0.40

As with the previous testing, air-to-water ratio varies, even at the same

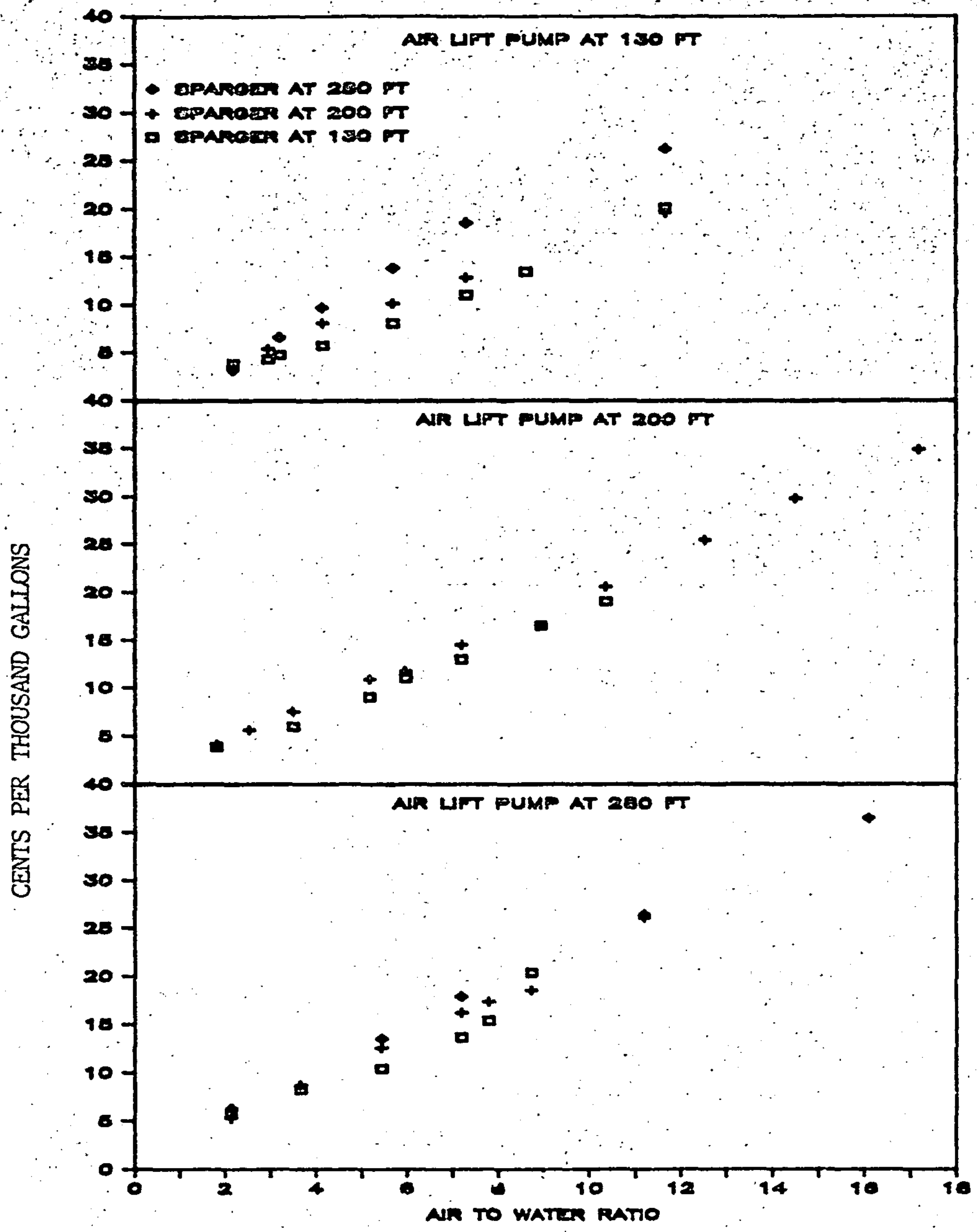

Figure 31. Cost to compress air for air lift pump and sparger testing at well L-8.

rotometer setting, because of changes in pump efficiency caused by varying well water level. The air-to-water ratio variation and the VOC removal variations are shown as % RSD. If nothing but the air to water ratio was changing, the %RSDs for the VOC removals should be similar to the %RSDs for the air-to-water ratios. In Table 13 the %RSDs for the VOC removals are greater for the removal of TCE and c-1,2-DCE than are the %RSDs for the air-to-water ratio. This indicates that for these compounds, there was some other cause of variation besides the variation in air-to-water ratio. Since these results are compiled from testing with the sparger at three different depths, the sparger depths might have been assumed to be the cause of the variation. An examination of VOC removal data (see Figure 32) shows there was no pattern associated with depth of the sparger. The variation appeared to be caused by poor duplicate testing when there was long period of time between tests. The footpiece testing had shown very good reproducibility of repeat tests when they were run within a few days of each other. All air and water flow rate measurement equipment was checked for proper calibration and the VOC analytical quality control data was evaluated, yet no changes had occurred in any of these over time. It was known that raw water concentration and well water levels were changing. These could be indications that VOC or water zones of entry might also have changed. While it is generally accepted that VOC removal is independent of raw water concentration, water entry zone changes might affect the reproducibility of in-well aeration over time.

Figure 32 illustrates that the vinyl chloride data did not show as large a variation as the TCE or c-1,2-DCE. Table 13 shows the %RSDs for vinyl chloride removal to be similar to or less than the %RSDs for air-to-water ratios. This indicated that nothing other than air-to-water ratio was causing variation in VC removal (unlike TCE and c-1,2-DCE). Vinyl chloride had the highest Henry's Law constant of the compounds tested and was very rapidly removed to greater than 90%. The variation decreased as percent removal increased.

Tables 14 and 15 show the VOC removal data for tests with the air lift pump at 200 ft and 280 ft respectively. These results show the same variations in %RSDs as the results for the air lift pump at 130 ft. The tests at 200 ft were conducted over the longest period of time and they show the greatest variation. Figure 33 illustrates testing with the air lift pump at 200 ft and Figure 34 shows the 280 ft air lift pump tests. No pattern existed which would suggest a difference in VOC removals caused by the depth of the sparger. Instead, changing geological well conditions over time were the most likely sources of the variation.

The maximum air-to-water ratios which could be achieved varied from 12:1 with the air lift pump at 130 ft, to 17:1 with the air lift at 200 ft, to 16:1 at 280 ft. The air-to-water ratio was limited by the point at which water was lifted out of the well bore hole by the foaming caused by the sparger. This maximum air delivery point was influenced mainly by the static water level of the well. When the water level was closer to the surface, the water blew out of the borehole more quickly.

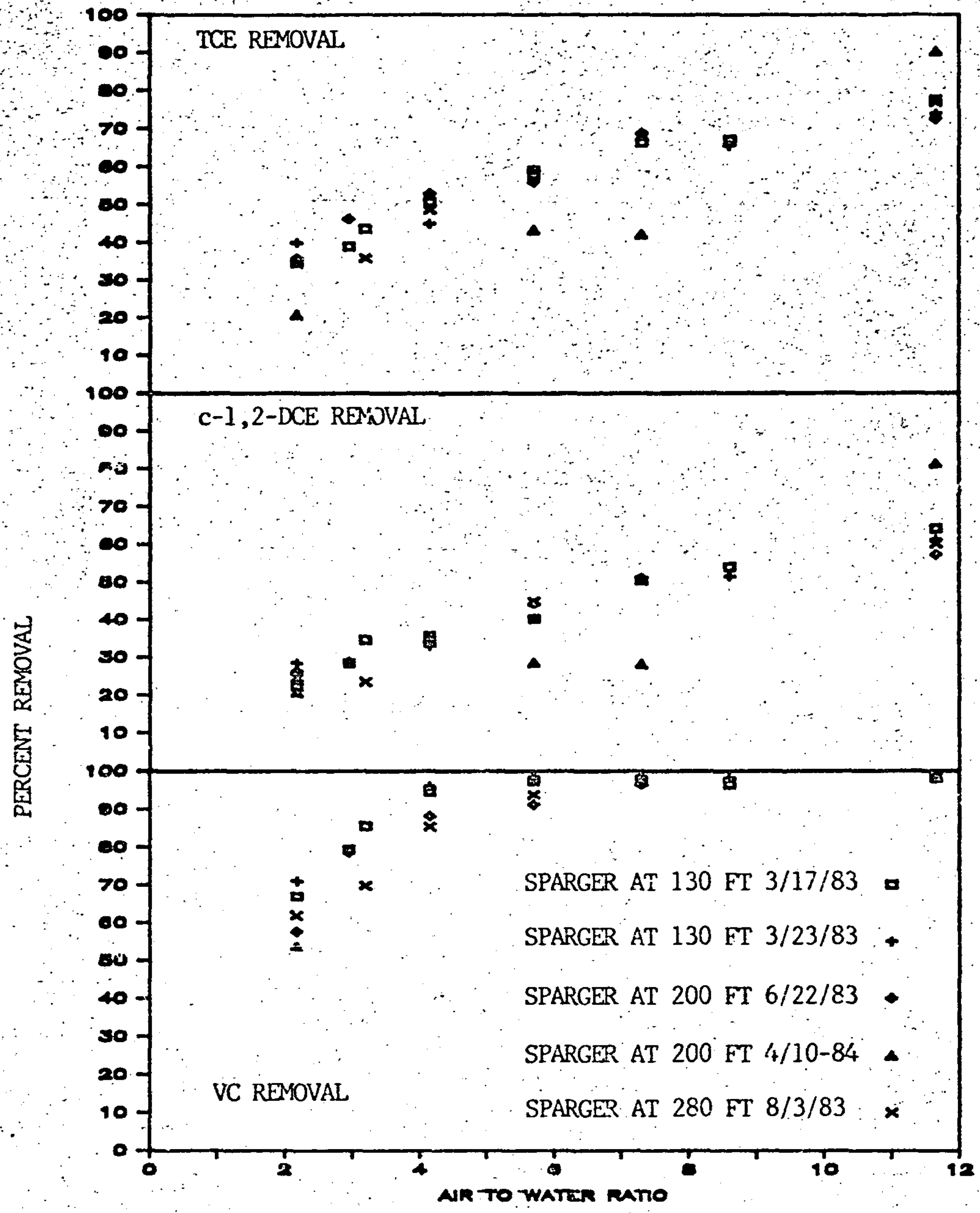

Figure 32. VOC removal data for air lift pumping at 130 feet while sparging at three depths.

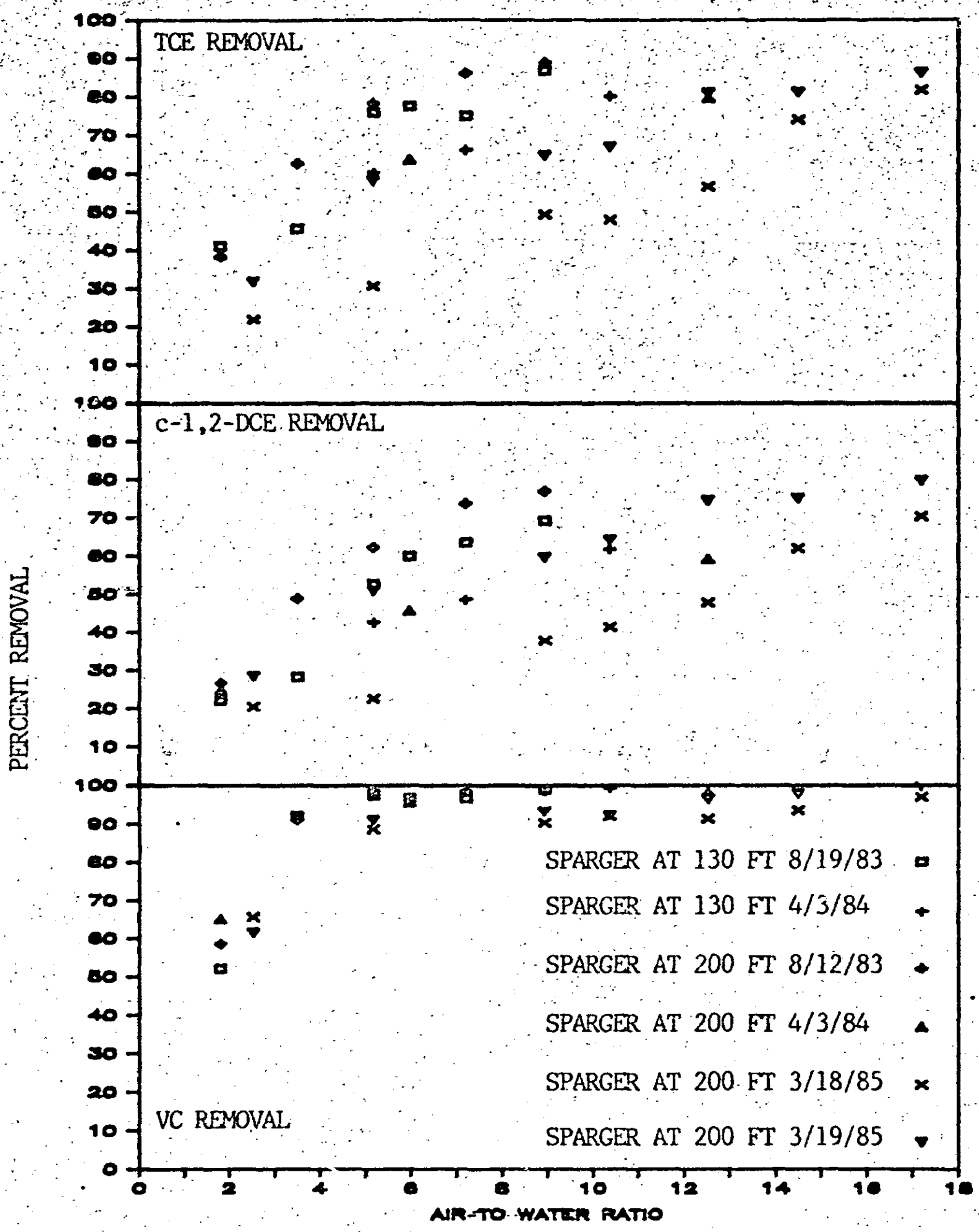

Figure 33. VOC removal data for air lift pumping at 200 feet while sparging at three depths.

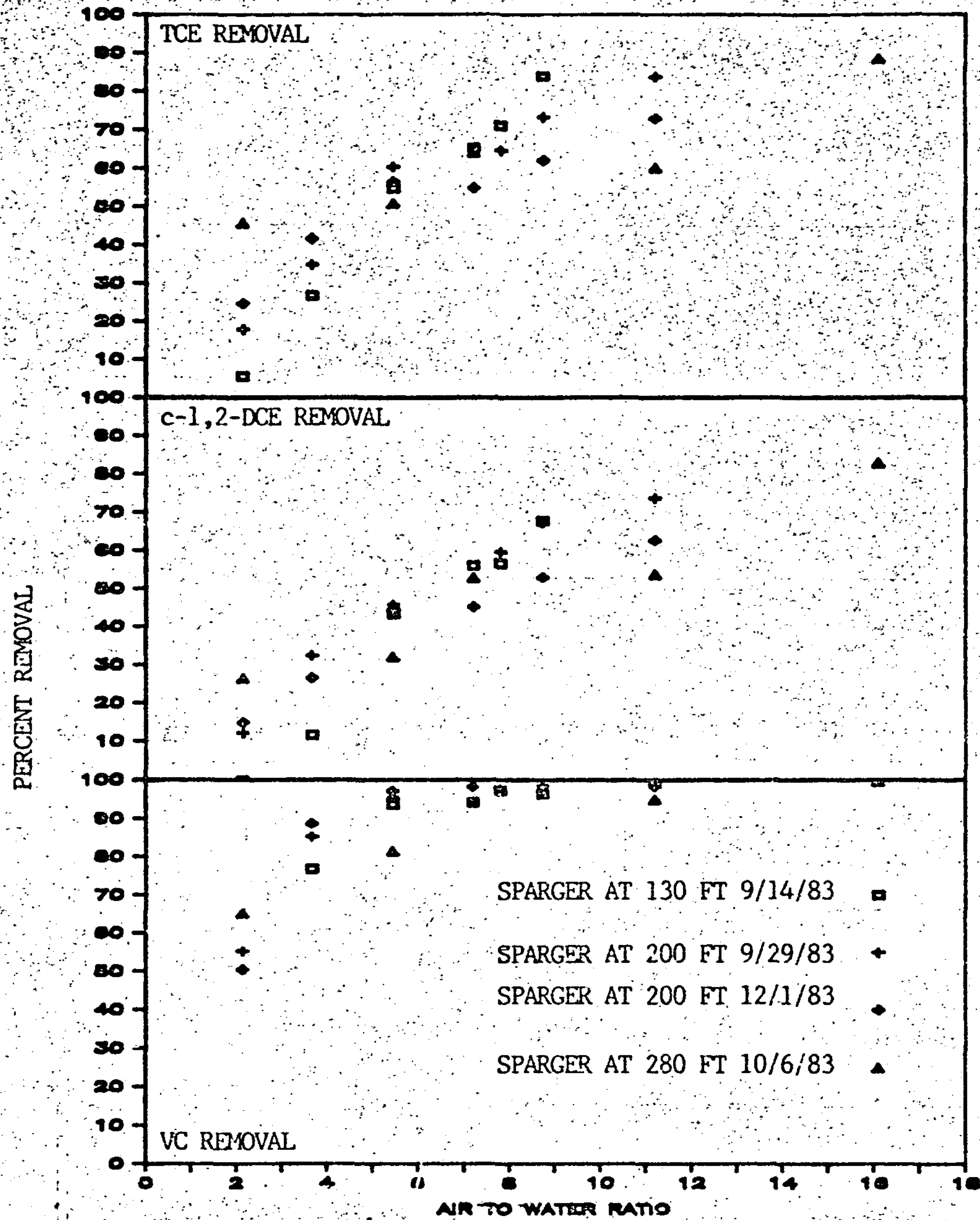

Figure 34. VOC removal data for air lift pumping at 280 feet while sparging at three depths.

TABLE 14. VOC REMOVAL WITH AIR LIFT PUMP AT 200 FT
(AVERAGE OF ALL 3 SPARGER DEPTHS)

AIR TO WATER			TCE % REMOVAL		c-1,2-DCE % REMOVAL		VINYL CHLORIDE % REMOVAL	
AVE	%RSD	N	AVE	%RSD	AVE	%RSD	AVE	%RSD
1.8	7.9	3	39.6	3.04	24.7	7.49	58.7	9.11
2.5	3.7	3	29.7	19.1	26.9	17.5	66.0	5.58
3.5	6.2	3	50.0	18.4	37.0	23.6	86.6	8.28
5.2	6.3	6	59.4	26.7	45.7	26.9	93.1	6.01
6.0	3.4	3	66.5	12.4	50.8	13.0	92.8	5.48
7.2	2.3	3	75.8	10.7	62.1	16.7	98.0	0.87
8.9	7.7	5	71.5	20.6	59.0	23.5	94.1	4.43
10.	1.2	3	65.2	20.3	56.1	18.3	94.7	3.59
12.	1.9	3	72.5	15.4	60.8	18.0	95.5	3.07
15.	0.69	2	77.8	4.57	68.8	9.45	96.0	2.24
17.	1.2	2	84.2	2.67	75.2	6.18	98.6	1.37

TABLE 15. VOC REMOVAL WITH AIR LIFT PUMP AT 280 FT
(AVERAGE OF ALL 3 SPARGER DEPTHS)

AIR TO WATER			TCE % REMOVAL		c-1,2-DCE % REMOVAL		VINYL CHLORIDE % REMOVAL	
AVE	%RSD	N	AVE	%RSD	AVE	%RSD	AVE	%RSD
2.1	8.4	4	23.4	62.1	13.4	70.3	42.7	59.1
3.7	1.3	3	34.5	17.7	23.7	36.9	83.6	6.00
5.4	3.3	4	55.7	6.19	41.6	13.2	92.0	6.75
7.2	2.0	3	61.4	7.64	51.5	8.82	95.7	1.95
7.8	0.0	2	67.9	4.71	58.2	2.66	97.6	0.36
8.7	6.4	3	73.1	12.2	62.8	11.0	97.4	0.90
11.	3.3	3	72.3	13.4	63.5	12.9	97.6	1.87
16.	–	1	88.4	–	83.0	–	99.7	–

CONCLUSIONS FOR AIR LIFT PUMP TESTING WITH A SPARGER

Operation of the sparger while air lift pumping caused the air lift pump efficiency to decrease. This was predicted by air lift pump operational theory, because the density difference across the air lift pump eductor (the pump's driving force) was reduced by sparging. Even though the sparger caused the air lift pump efficiency to decrease, the pump efficiency with a sparger was higher than if all of the air had been delivered to the air lift pump alone; therefore, in terms of pump efficiency (and cost), it was better to operate an air lift pump and sparger combination than to operate an air lift pump alone.

The maximum VOC removal percentages for the air lift pump and sparger combination were 98.6% for VC, 65.0% for c-1,2-DCE and 78.3% for TCE. The air lift pump and sparger combination was able to produce a higher air-to-water ratio (17:1) than the air lift pump alone (11:1).

This accounted for the higher VOC removal capabilities of the combined system. When sparging, the air-to-water ratio was limited to the point at which adding more air caused water to foam out of the top of the well head. In a well with a wider borehole the air to water ratio (and VOC removal) might be higher because water would not be forced out of the well so readily. At well L-8 some of the borehole diameter was taken up by test equipment which would not be in the well during regular operational conditions.

No VOC removal differences were observed when the sparger was operated at different depths with the air lift pump. Any possible differences were obscured by poor reproducibility of sparger tests over long periods of time. All measurement systems were checked and the most likely cause of variation was assumed to be changing hydrological well conditions over time.

This cost to compress air for the air lift pump and sparger combination exceeded 30¢ per thousand gallons, not including any capital or maintenance expenses. This, together with the relatively low VOC removal percentages, indicates that the air lift pump and sparger in-well aeration system would not be a suitable long-term treatment option to replace packed tower aeration. It was, however, simple to assemble and operate, which would make it suitable for an emergency treatment technique. The following experiments using an electric submersible pump and air sparger were designed with the goal of investigating a short-term, emergency VOC treatment technology.

SECTION 10

ELECTRIC PUMP TESTING WITH A SPARGER

ELECTRIC PUMP TESTING WITH SPARGER - PROCEDURES

For this portion of in-well aeration testing, an electric submersible pump was used in combination with a sparger. Since the air lift pump testing with a sparger did not indicate that in-well aeration would be an effective long-term treatment option for VOCs, this portion of the study was designed with a short-term emergency treatment method as a goal. In many cases, electric submersible pumps are already in place in drinking water wells. The sparger which was used for this experiment was of the simple, open-pipe, large bubble design used in air-lift pump/sparger combination testing. One inch plastic pipe was used instead of 3/4 in, to reduce air delivery costs caused by higher pressures in the smaller pipe. The electric pump was operated at one fixed depth (200 ft) which was below the zones of significant water yield (see Section 5). The sparger was tested at three depths (130 ft, 200 ft, and 280 ft). Figure 35 shows the electric submersible pump and sparger combinations used. These were the same equipment depths examined in the air lift testing portion of this study. The depths were chosen on the basis of well characterizations discussed in Section 5. Installing and moving the sparger was a very easy task and could be performed in a matter of minutes, which was consistent with the goal of developing an emergency treatment procedure.

As with the air lift pump testing, the electric pump experiments were broken into tests which consisted of several fifteen minute runs. Each test was conducted with a single equipment configuration (i.e., electric pump at 200 ft with the sparger at 130 ft). Each air flow rate within a test was called a run. Runs were fifteen minutes long. The static water level was recorded before the start of each test. Next, the electric submersible pump was turned on and the weir box was allowed to fill. (See Section 6 for a discussion of the weir box and its role in water flow rate measurements). A raw water sample was collected from the electric submersible pump at the well head. As noted in Figure 35, no small electric sample pump was used, as was necessary for air lift pump testing. In the electric pump testing (as well as the air lift pump testing) raw water samples could not be collected while the sparger was in operation. Because of this, the well had to be cleared of air between each sample run so that a raw water sample could be obtained for each air flow rate tested. To clear the well, air delivery to the sparger was stopped, and the submersible pump continued to operate. The pump effluent was monitored for dissolved oxygen at the raw sample location.

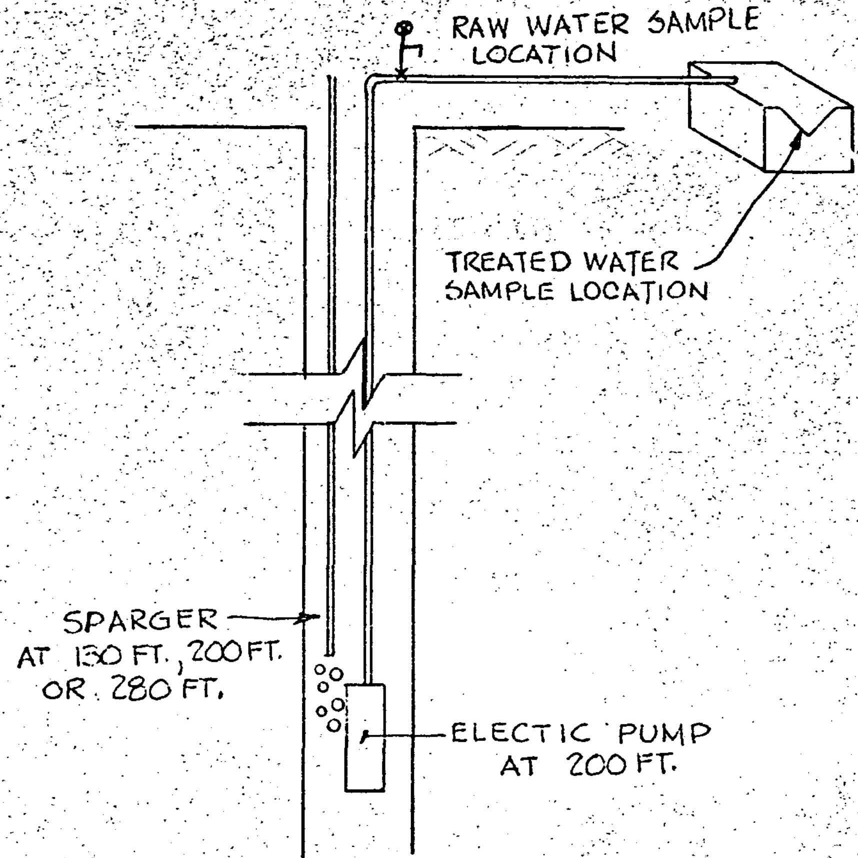

Figure 35. Electric pump and sparger configuration used for testing at well L-8.

When the dissolved oxygen of the water being discharged returned to the concentration at which it was before aeration, the well was declared clear of air. The raw water sample was collected, the next air flow rate for the sparger was started and the fifteen minute run began. Readings of all of the air delivery equipment, water flow rate, and well water level were obtained at five and fifteen minutes into each run. The treated sampled was collected at the fifteen minute point from the water discharging at the v-notch of the weir box. The water flow rate used for most of the electric pump testing was 100 gpm. As with the air lift pump testing, the limiting factor for the amount of air which could be added through the sparger was water blowing out of the borehole at the well surface. The water flow rate was lowered for later testing, to achieve a higher air-to-water ratio. This effort was only partly successful because the pumping water level was closer to the surface when less water was pumped, so less air could be added before the water came out of the borehole.

ELECTRIC PUMP TESTING WITH SPARGER - RESULTS AND DISCUSSION

The VOC removal results for the electric pump testing with a sparger are shown in Table 16. Three contaminants (TCE, c-1,2-DCE, and VC) were used to evaluate these tests. The maximum air-to-water ratio which could be achieved before water blew out of the borehole was 8.2. Maximum VOC removals were 82.6%, 79.9%, and 92.9% for TCE, c-1,2-DCE and VC, respectively. These removals were better than those achieved by the air lift pump systems at the same air-to-water ratio. The variabilities of VOC removal were generally greater than air-to-water ratios at the same rotometer settings, indicating that varying the depth of the sparger did affect VOC removals.

TABLE 16. VOC % REMOVALS BY ELECTRIC PUMP WITH SPARGER (AVERAGE OF ALL 3 SPARGER DEPTHS)

AIR TO WATER RATIO			% REMOVALS OF VOCs TCE		c-1,2-DCE		VINYL CHLORIDE	
AVE	%RSD	N	AVE	%RSD	AVE	%RSD	AVE	%RSD
0.00	0.00	6	14.7	68.3	8.57	97.0	17.5	60.3
0.80	0.00	3	18.5	44.2	10.4	33.6	48.9	8.13
1.5	0.00	2	32.9	42.9	21.2	65.6	78.3	9.45
2.2	9.2	5	49.8	27.8	30.3	55.9	85.8	6.00
3.0	0.0	2	53.7	15.3	30.0	43.7	92.7	1.29
3.7	0.0	2	62.0	10.7	38.2	26.2	91.0	4.23
4.5	4.4	6	68.4	15.3	51.6	26.4	91.5	5.00
5.2	3.6	5	72.9	13.8	59.1	19.7	92.7	1.92
5.9	0.0	4	70.5	11.7	52.2	18.5	92.2	3.38
6.4	1.9	3	77.3	7.57	66.5	15.1	92.2	1.85
7.4	0.67	2	79.4	5.10	74.3	3.90	94.5	0.00
8.2	0.61	2	82.6	0.420	79.9	0.500	92.9	0.650

Figure 36 shows VOC removal results with theelectric pump at 200 ft and the sparger set at 130 ft, 200 ft or 280 ft. The results indicated that the best removal was obtained with the sparger set at 130 ft. These findings were consistent with what could be expected in terms of the well characterization discussed in Section 5. It was determined that most of the VOC contamination was entering the well in the two zones between 106 ft and 140 ft. These zones also produced nearly 60% of the water entering the well. Very little water (less than 10% of the well's yield) was entering below 200 ft, therefore, most of the water movement in the well was down from 106-140 ft toward the pump at 200 ft. With the sparger at 130 ft, a counter-current stripper could have been created with the air being delivered just at the bottom of the most contaminated zone. This would be an efficient way to strip the VOCs, and Figure 36 shows the best TCE removal with the sparger at 130 ft. When the sparger was set at 280 ft, this created a co-current stripper through a very small portion of the total yield of the well. A good deal of the air could have been pulled into the pump before it reached the more contaminated water entry zones. When the sparger was adjacent to the pump at 200 ft perhaps a portion of the air was pulled into the pump before any stripping could occur in the well. In an emergency situation a well characterization would not need to be done. The sparger should be placed above the pump or below the pump but these tests indicated that the sparger should not be placed directly next to the pump.

In order to look at the reproducibility of electric pump and sparger treatment, the test of the sparger at 130 ft was repeated in October, 1984, five months after the original test at 130 ft. The results were vastly different, as can be seen in Figure 37. The weir box and air delivery systems were all recalibrated to determine if any air or water flow rates were incorrect. No inconsistencies were found during the recalibration. The quality control program for sampling and analysis was still in place and gave no indication of any analytical problem. It was decided to do two more tests with the sparger at 130 ft, two days in a row. These results for TCE are shown as the January 23 and 24, 1985 curves in Figure 37. As can be seen in the graph, the results of tests run two days in a row closely matched each other, they also matched the second test of the sparger at 130 ft, conducted in October, 1984. Because no cause for these variations could be found in the measuring procedures, it was determined that variations in VOC removals for the same in-well aeration configurations could have been caused by well changes over long periods of time. Conclusions based on the curves in Figure 36 are considered to be valid because those three tests were performed within one month of each other. It would have been impossible to determine exactly what was changing in the well without repeating the well characterization (logging and packer testing) described in Section 5. It was known that the raw water VOC concentration and static water level of the well changed with time. Perhaps water entry zones or VOC entry zones also changed with time. Whatever caused the changes, it was clear that in-well aeration, both with the air lift pump and electric pump with a sparger, provided variable results over a long period of time at NPWA. The same may be the case in other locations, depending on the hydrogeology.

It was difficult to see any difference in vinyl chloride removal for

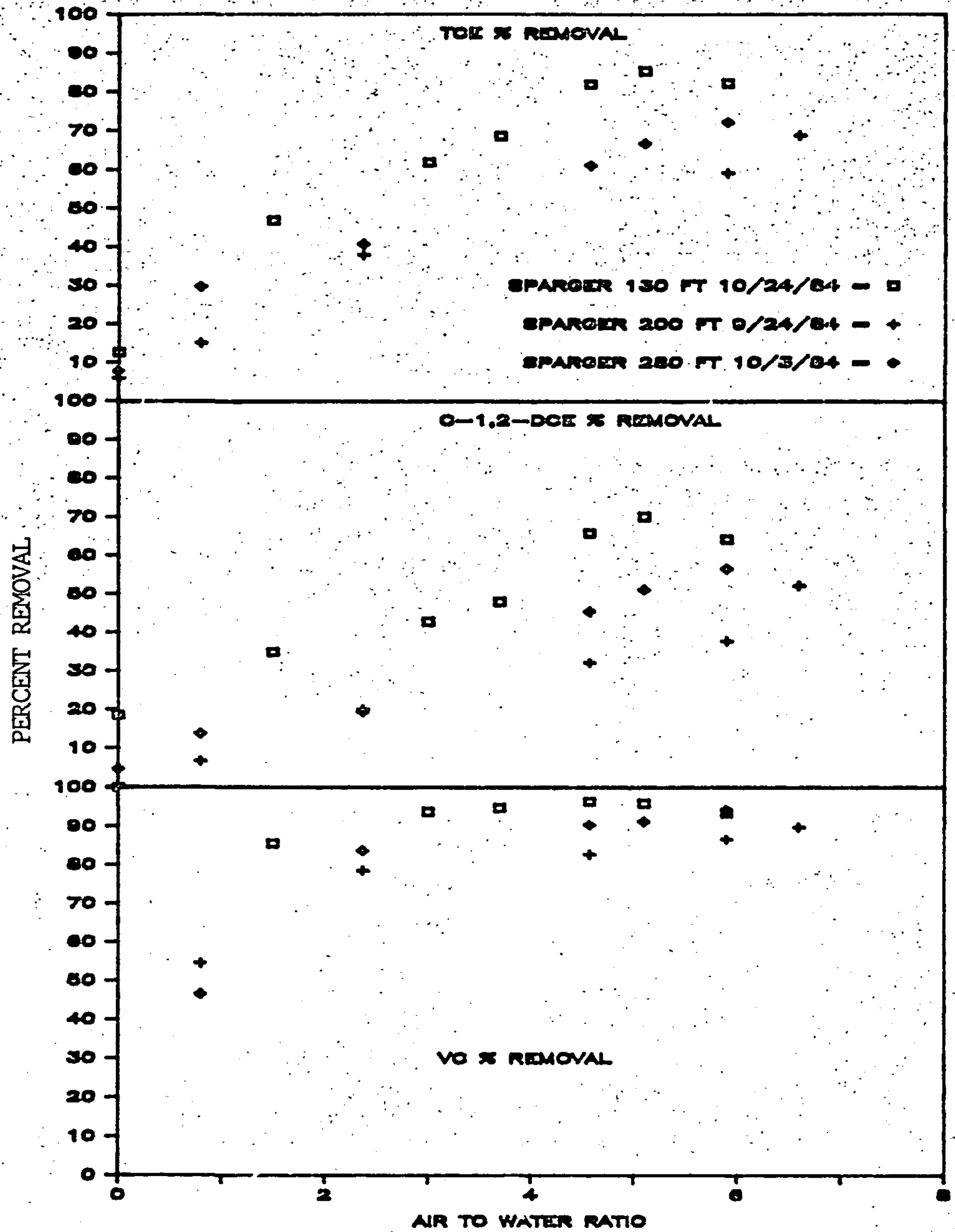

Figure 36. VOC removal by electric submersible pump and sparger combination, with sparger set at three different depths. Electric pump at 200 ft.

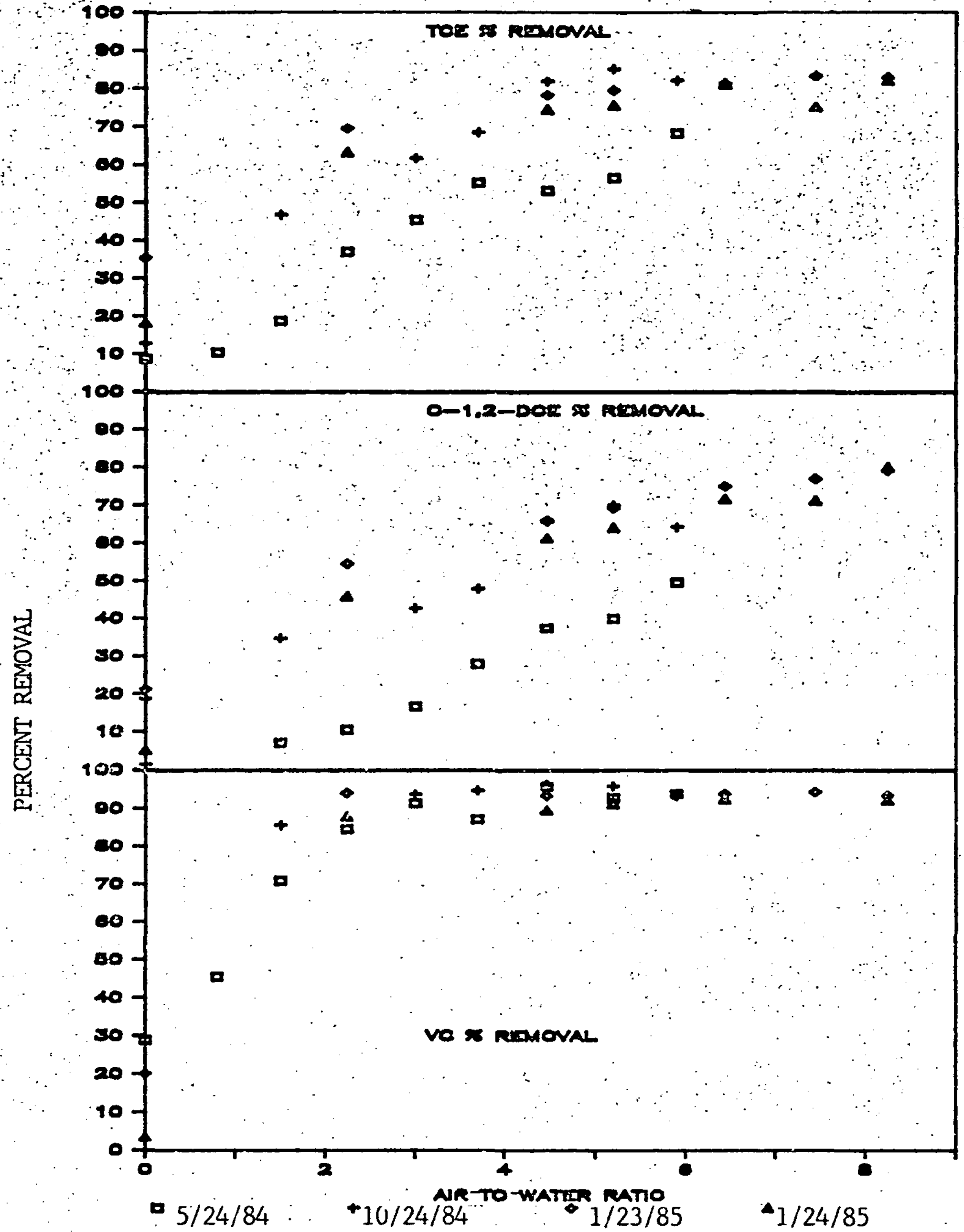

Figure 37. Results of duplicate testing with electric submersible pump and sparger showing variation over five months time. Electric pump at 200 ft and sparger at 130 ft.

the four repeat tests performed with the sparger at 130 ft (see Figure 37). As with the rest of the in-well aeration tests, vinyl chloride was the most easily treated, with the removal curve rising very sharply, then leveling out into a plateau.

In Figure 37, the tests conducted in January, 1985 were performed at 60 gpm, while the two earlier tests use a flow rate of 100 gpm. While it was possible to increase the maximum air to water ratio from 5.9 to 8.3, the amount of air which could be added was still limited by water coming out of the borehole at the surface of the well. For all compounds, with the exception of c-1,2-DCE, it did not appear that raising the air-to-water ratio beyond that achieved in this testing would cause any further removal. This is said because the removal curves have reached the plateau, which is normally seen in aeration curves, where adding much larger amounts of air produces very little further removal. In Figure 37, it can be seen that c-1,2-DCE did not reach that plateau. This compound has the lowest Henry's Law constant of all the compounds examined. If some way could be found to increase the air-to-water ratio, more removal could be expected for this compound.

Costs for the electric pump and sparger combination are shown in Figure 38. The cost to compress air was calculated and 3¢ per thousand gallons was added as an estimated cost for electricity to operate the pump. As with previous cost discussions, these numbers do not include operation and maintenance or amortization of capital expenses.

The most costly electric pump and sparger combination tested was with the pump at 200 ft and the sparger at 280 ft. The cost approached 15¢ per thousand gallons with an air to water ratio of 6 to 1. Very little difference in cost could be seen between the 130 ft and 200 ft sparger depths. The maximum cost for these depths was around 12¢ per thousand gallons. The cost of this method, together with the ease and rapidity of installation, showed that electric pumping with sparging was a viable emergency treatment technique for VOC removal, providing the limited removal capabilities would meet the necessary effluent concentration requirements.

CONCLUSIONS FOR ELECTRIC PUMP AND SPARGER TESTING

VOC removal differences were seen when the sparger was operated at different depths relative to the electric submersible pump which was set at a depth of 200 ft. The VOC removal findings were consistent with the well characterization findings. Sparging at 130 ft provided the best VOC removal. This depth would have produced a counter-current stripping effect as water from the most contaminated zone in the well was pulled down past the sparger on its way to the pump. With the sparger at 280 ft, a co-current stripper was produced as both bubbles and water travelled up toward the pump with some or all of the air being pulled into the pump before it reached the most contaminated zone. When the sparger was adjacent to the pump, at 200 ft, most of the air was likely to have been pulled directly into the pump, before any stripping could occur in the well.

The maximum VOC removals obtained by electric pumping with a sparger were 82.6% for TCE, 79.9% for c-1,2-DCE and 92.9% for VC, at a maximum air-to-water ratio of 8.2:1. These removals were better than for the air

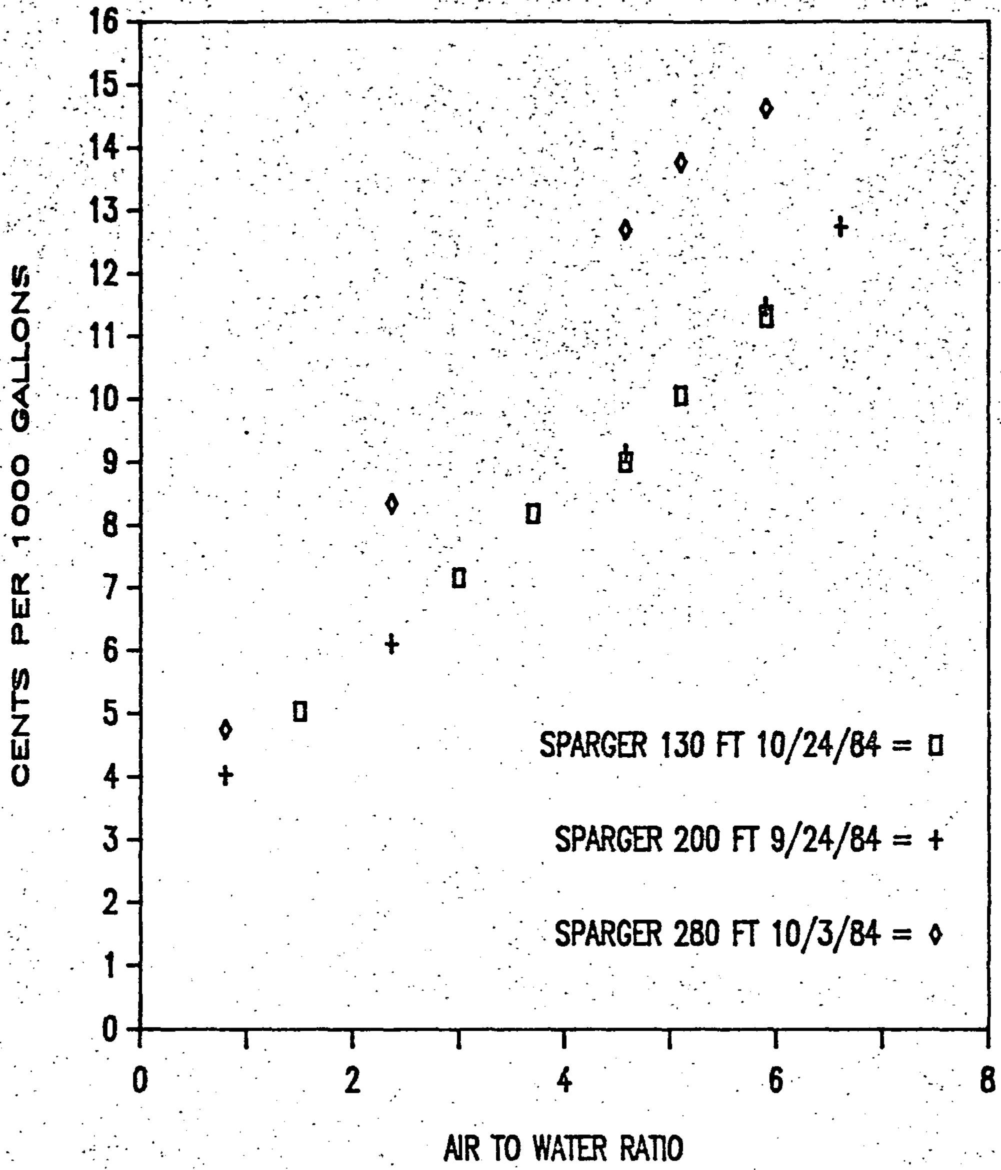

Figure 38. Costs to operate electric pump and sparger for in-well aeration at well L-8. Electric pump at 200 ft.

lift pump systems at the same air-to-water ratio; however, a higher air-to-water ratio was obtained with the air lift pump (with or without a sparger).

The electric pump with a sparger would be a good emergency treatment technique if its limited VOC removal capabilities will meet the necessary water quality goals. It was easy to install and inexpensive to operate (up to 15¢ per thousand gallons for air and electricity). While well characterization was helpful for experimental design and data interpretation, it would not be necessary in an emergency situation. The sparger should not be set directly adjacent to the pump. In-well aeration by the electric submersible pump and sparger combination can be used to keep a contaminated well in service while permanent treatment systems are being designed and installed.

SECTION 11

SECONDARY EFFECTS OF IN-WELL AERATION

GENERAL

Part of the scope of this project was to examine secondary effects of in-well aeration. Dissolved oxygen, pH and temperature were determined in order to discuss corrosion implications. Bacteriological tests were conducted using both the heterotrophic plate count (HPC) and the R2A plate count procedures. In addition, air samples were analyzed at the well head, at the weir box, and at the sidewalk in front of the well house. These studies were not the major emphasis of this project and they will be presented in a brief fashion.

DISSOLVED OXYGEN, pH AND TEMPERATURE

Dissolved oxygen concentration and pH of drinking water in the distribution system may have an effect on corrosion of water mains. High DO and/or low pH can cause water to become aggressive, thus shortening the useful life of various piping materials.

Dissolved oxygen and pH samples were collected in BOD bottles at the raw water sample tap and at the v-notch of the weir box. The samples were analyzed immediately in the field for DO, pH and temperature. DO was measured using an Orion Research Model 97-08 oxygen electrode. The pH and temperature were obtained with a Corning Model 4 portable pH/temperature meter.

The results of the pH, DO and temperature testing are shown in Table 17. The mean values for all of the samples collected at the raw tap and weir box (treated) have been calculated. The table also shows the standard deviation (SD), number of samples tested (n), and the %RSD. The range of values obtained throughout the testing is also shown.

In over sixty runs, the value of pH was found to increase with in-well aeration 100% of the time. The average raw water pH was 7.2 and the average treated water pH was 7.6, yielding an average increase of 0.4 pH units. The variation in pH was higher for the treated water (%RSD = 2.75) than for the raw water (%RSD = 1.62). This increased variation in treated water was due to the fact that these numbers represented pH values from the entire range of air-to-water ratios used during in-well aeration testing. The raw water could be expected to show less variability. In very general terms, an increase in pH, as seen here, could help prevent corrosion in the distribution system by pushing the Langelier Index to a more positive value.

The average dissolved oxygen concentration for the raw water was

TABLE 17. SECONDARY WATER QUALITY EFFECTS OF IN-WELL AERATION

	Method	Ave		SD	n	%RSD	Range	Ave % Saturation
pH								
		Ave		SD	n	%RSD	Range	
Raw		7.2	±	0.12	63	1.62	7.0-7.5	
Treated		7.2	±	0.21	65	2.75	7.1-8.0	
Dissolved Oxygen-mg/L								Ave % Saturation
Raw		2.17	±	1.15	78	53.0	0.9-7.5	22%
Treated		10.8	±	0.52	78	4.78	9.9-13.0	100%
Temperature - °C								
Raw		15.8	±	1.28	69	8.08	13.0-18.4	
Treated		15.1	±	1.27	72	8.40	12.7-17.3	
Bacteriological-counts/ml								
	Method	Ave		SD	n	%RSD	Range	
Raw	HPC	73	±	61	21	84	2-243	
Treated	HPC	71	±	79	21	110	1-282	
Raw	R2A	638	±	540	12	85	130-2100	
Treated	R2A	647	±	430	12	66	70-1370	

2.17 ppm over 78 runs. The average dissolved oxygen concentration at the v-notch of the weir box was 10.78 ppm. With average water temperatures of 15.8 and 15.1 at the raw and weir sample collection points, the dissolved oxygen concentrations obtained represent an increase in dissolved oxygen saturation from 22% to 100%. This increase in DO to 100% saturation occurred for the entire range of air-to-water ratios tested. No bubbles were present in the weir box by the time the water reached the v-notch. Water that is saturated with dissolved oxygen has the potential to be more aggressive than a lower DO water. This could be especially harmful in systems with unlined, iron pipe. Since the conclusions of this study show the best use for in-well aeration is on a short-term basis for emergencies, no treatment to reduce oxygen levels should be necessary.

The bacteriological testing during in-well aeration experiments was inconclusive. The results in Table 17 showed that both the heterotrophic plate count and the R2A agar plate count methods revealed no difference in bacteriological quality of the water before and after in-well aeration. This was to be expected, because the samples were collected immediately after treatment, and any bacteria present would not have had time to be affected by the changes in conditions. This should be investigated further if the water enters a distribution system where the bacteria have more time to contact the water with higher pH and dissolved oxygen at saturation.

The bacteriological testing did show a significant difference in recovery of bacteria between the two methods used. The counts of bacteria per milliliter were approximately 9 times higher with the R2A method than for the HPC.

Further study is needed to determine the effects of in-well aeration on corrosion and bacteria in a water distribution system. Dissolved oxygen and pH, both factors which can influence corrosion and bacteriological growth, are clearly affected by in-well aeration.

AIR SAMPLING

Air samples were collected during four in-well aeration tests to determine possible exposure hazards in the area around the well house. One method used was an adaptation of GC purge and trap techniques (35,36). A second survey was done using a portable photoionization detector. The air tests were intended to be a preliminary estimate of air concentrations to determine whether further consideration of air exposure would be necessary.

Trap and Desorb Method - Results and Discussion

Volatile organic chemical traps from the GC purge and trap sample concentrator were used to collect air samples. The traps were packed with Tenax, silica gel and charcoal. To clean the traps in preparation for testing, they were baked for one hour in the purge and trap apparatus. After the bake cycle they were desorbed into the GC for analysis to confirm that no organics were remaining on the trap. Once cooled, the traps were removed from the purge and trap device and the ends were immediately sealed with parafin film. One sealed trap was carried into the field and returned to the lab without breaking the seal, to act as a field blank.

The configuration of the air sampling system is shown in Figure 39. Two of the laboratory prepared traps were hooked together with fittings. This assembly was performed in the field immediately before the sample was collected. Two traps were used in series in order to provide a primary analytical trap and back-up trap to test for breakthrough of the primary trap.

The traps were connected to an industrial hygiene sampling pump. The outlet of the pump was directed into a bubble flow meter to measure the air flow. This was necessary because earlier laboratory tests showed that each combination of traps produced a slightly different flow rate for one particular setting on the sample pump.

The system was calibrated by purging an aqueous standard onto the Tenax/silica gel/charcoal trap and desorbing as for a regular GC analysis of water, however, instead of calculating as ug/L of compound in the aqueous sample, the GC was calibrated to the actual nanograms of material adsorbed by the trap. When the traps from the field were desorbed, the results were reported in nanograms. The field measured air flow rates of sample collection were then used to calculate air concentrations. An example calculation to determine volatile organic chemical concentration in air is shown below:

1. Determine cubic meters of air collected from field flow data which is measured in liters/minute.

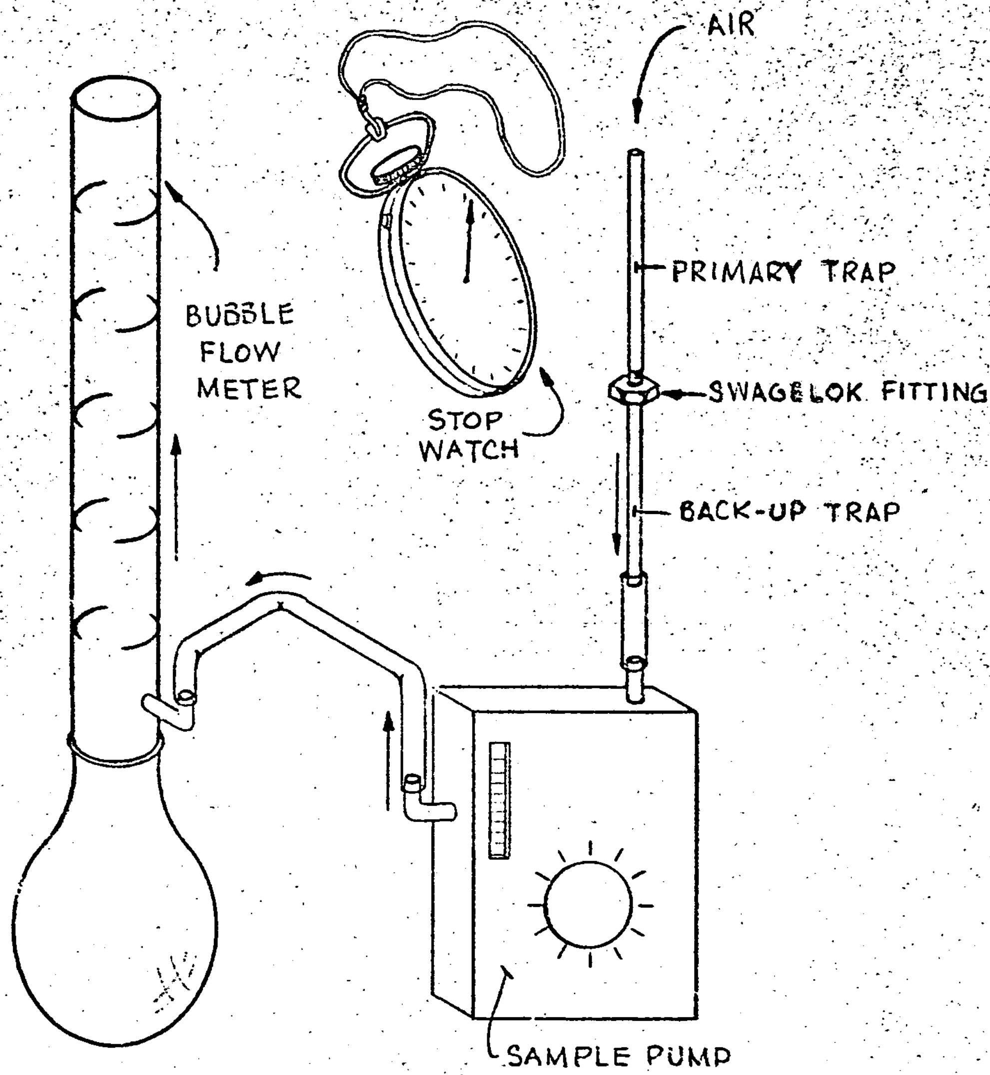

Figure 39. Drawing of air sampling system used to test off-gases of in-well aeration.

collection time (min) x flow rate (L/min) = Liters air sampled

$$\frac{\text{Liters air sampled}}{1{,}000\ L/m^3} = \text{cubic meters of air sampled}$$

2. Determine microgram/cubic meter concentration in air.

$$\frac{\text{ng VOC collected / cubic meters of air sampled}}{1{,}000\ \text{ng/microgram}} = \text{micrograms VOC/cubic meter air}$$

3. Convert to parts per billion VOC in air

$$\text{ppm} = (0.02445\ \text{cubic meters air/mole air}) \times \frac{(x\ \text{ug/cubic meter VOC in air})}{\text{molecule weight of VOC, g/mole}}$$

$$\text{ppb} = \text{ppm} \times 1{,}000$$

Sampling locations are diagramed in Figure 40. For this method, samples were collected directly at the well head, above the treated water sample location of the weir box and at the sidewalk in front of the pumphouse. The samples were collected while operating the electric pump at 200 ft in the well and with the sparger delivering the maximum possible air at 130 ft.

The results of the air sampling by trap and desorb method are shown in Table 18. In both samplings, concentrations were very high at the well head, lower at the weir box and nearly zero at the sidewalk in front of the pumphouse. There were several problems with the method. Each of the back-up traps showed some contamination (1% to 5% of the main trap concentrations) by the major compounds. In the second sampling, the field blank was contaminated (see Table 18). Even with these problems, it can be seen that the VOC concentrations in air may be reason for concern, and would require further study by a standard method for air analysis. The Pennsylvania Interim Air Standards (37) for TCE and PCE are 1200 ppb. The well head sampling exceeds or nears these limits in both cases. The VC interim limit is 2.4 ppb, 1,1-DCE is 37 ppb and CCL4 is 12 ppb. All of these are exceeded at the well head by this method of

TABLE 18. RESULTS OF AIR SAMPLING BY TRAP AND DESORB METHOD

FIRST SAMPLE COLLECTION	Well Head	Weir Box	Sidewalk	Blank
Air Flow	21.70 mL/min	15.06 mL/min	19.40 mL/min	no air
Collection Time	30 min	30 min	30 min	sampled
VC (ppb air)	810	0	0	0
1,1-DCE "	200	5.3	0	0
c-1,2-DCE "	GT3,600	55	0	0
CHCL3 "	0	0	0	0
1,1,1-TCA "	120	5.3	0	0
CCL4 "	14	0	0	0
TCE "	GT4,200	130	1.0	0
PCE "	GT1,900	13	0	0

(continued)

TABLE 18. (continued)

SECOND SAMPLE COLLECTION

	Well Head	Weir Box	Sidewalk	Blank
Air Flow	20.02 mL/min	15.62 mL/min	19.36 mL/min	no air
Collection Time	15 min	15 min	15 min	sampled
VC (ppb air)	21	2.7	0	0
1,1-DCE "	460	0	0	0
c-1,2-DCE "	1,900	11	3.3	10
CHCL3 "	0	0	0	0
1,1,1-TCA "	160	7.5	0	1.5
CCL4 "	35	0	0	0
TCE "	GT5,700	57	8.2	12
PCE "	700	7.4	1.0	0

GT = Greater Than
0 = Less than 1.0 ppb in air

sampling and analysis. Air discharge permits and/or air VOC control measures might be needed for wells as heavily contaminated as this one.

Photoionization Detector Method - Results and Discussion

Another type of air survey was completed using an HNU Model P1101 Photoionization Analyzer. This is a portable instrument which samples air and instantaneously reads total VOC concentration in parts per million as benzene. The air was tested at the well head, above the weir box and at the sidewalk in front of the well house, just as with the trap and desorb method. In addition, the air was tested two feet directly above the well head and at a workbench in the well house approximately 8 ft from the well head. The latter two locations were selected to see if workers who were in the well house would be exposed to dangerous levels of VOCs in the air.

The HNU analyzer survey was done while operating the air lift pump at 200 ft with the sparger at 200 ft. Air was tested with the sparger off, then with the sparger blowing the maximum amount of air (50 cfpm). The results show no response on the analyzer at any of the sample locations when the sparger was not operating. The lower detection limit of the instrument is 0.2 ppm as benzene. With the sparger operating, there was no response at the work bench, weir box or the sidewalk sample sites. The well head gave a response of 6.2 ppm and the sample two feet directly above the well showed a response of 1.8 ppm. Since workers would generally not be in the immediate vicinity of the well head for long periods of time, the operation of this in-well aeration system would not pose a hazard to workers. In spite of these results, however, it is recommended that the well house be well ventilated when using an in-well diffused aerator to avoid build-up of the VOCs in the air. These samples were collected with well house windows and doors closed to try to simulate a "worst-case" situation.

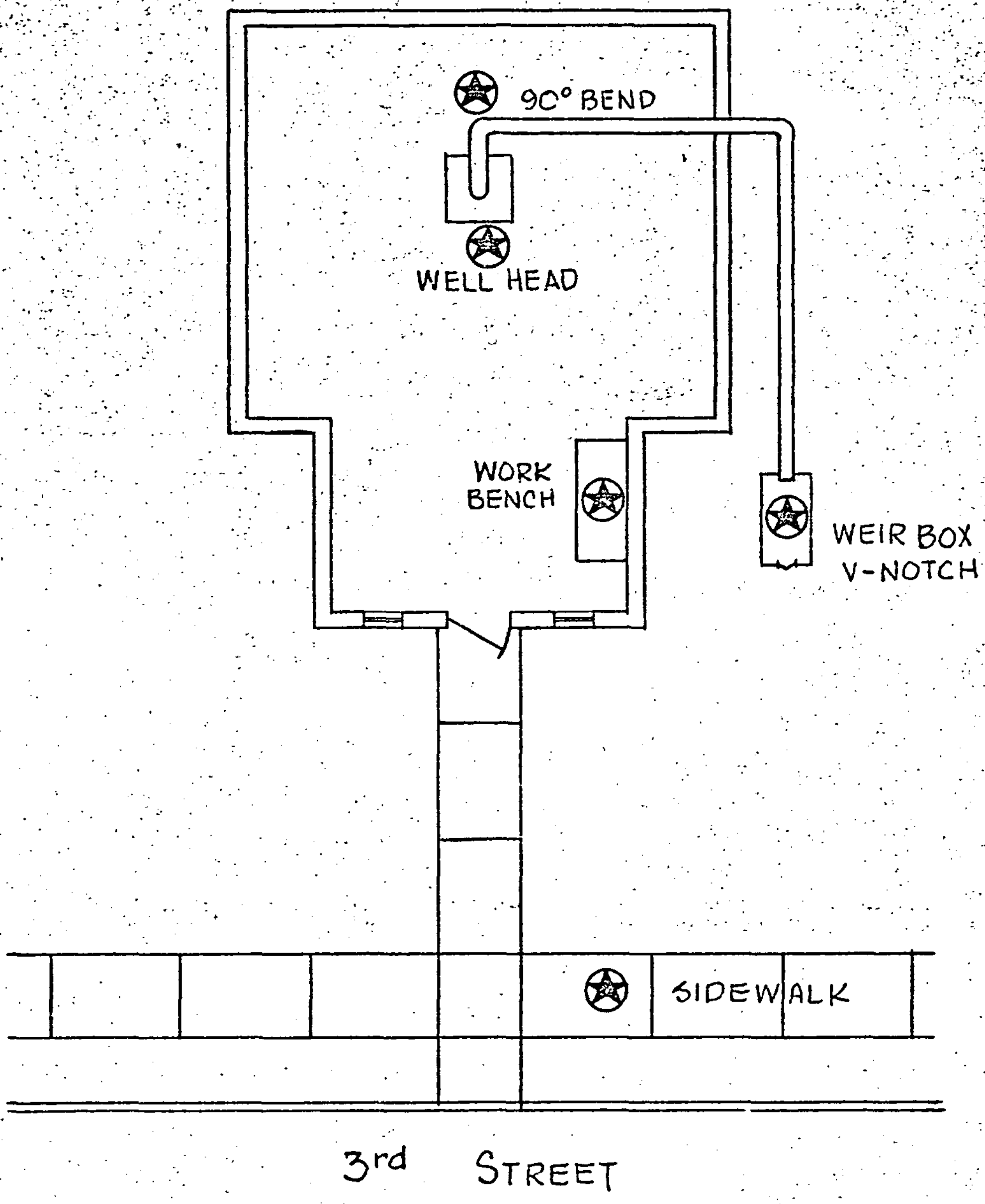

Figure 40. Air sampling locations for in-well aeration off-gas testing at well L-8.

CONCLUSIONS FOR SECONDARY EFFECTS OF IN-WELL AERATION

All methods of in-well aeration tested increase the pH of the well water by an average of 0.4 pH units. Dissolved oxygen was raised to saturation by all of the in-well aeration methods tested. The oxygen increase could cause water treated by this method to become more corrosive. This should not be a problem for short-term use in an emergency situation.

Water entering the weir box after sparging was milky white in appearance. By the time it left the separator it was clear, causing no problems with aesthetics.

The bacteriological testing of raw and treated water was inconclusive, with large variations in bacterial counts masking any trends. The R2A method provided consistently higher recovery of organisms than the heterotrophic plate count.

Air sampling showed that in-well aeration would probably not cause air quality problems of industrial hygiene concern, however, the well may be considered an air pollution source, and would require any appropriate permits for such a source. This would depend on the raw water concentrations of the contaminants and on air flow rates used. It would be prudent to ventilate a well house with an in-well diffused aerator in operation.

SECTION 12

COST ESTIMATES

FIRST SCENARIO

In this case, costs have been computed for an in-well aeration system to be used at a well with an electric submersible pump in place. The well is 500 ft deep with a static water level of 25 ft and a pumping water level of 100 ft. The water flow rate is 70 gpm. A sparger will be added to the well for use with the existing submersible pump. The sparger will be set at 175 ft. The pump will remain at 200 ft. The system will be in service for approximately three months.

The VOC concentrations are 10 ug/L of TCE and 250 ug/L of 1,1,1-TCA. It would require 50% removal for TCE and 20% removal for 1,1,1-TCA to bring the VOC concentrations below the limits. In-well aeration would produce the necessary removals.

Cost to rent air compressor (3 months)	$ 4,092
1 in PVC pipe/fittings/valves	200
Fuel tank (250 gals)	500
Air filter	175
Well vent	300
Installation labor	2,000
	$ 7,267
Operating Costs -	
Oil and Filters	$ 500
Gasoline (2 gal/hr)	4,368
Labor	5,460
Electricity (3¢/1000 gal/wtr pumped)	281
	$10,609
Electric Pump and Sparger	
Total Cost-3 months operation	$17,876
Cost per 1,000 gallons of water treated	$ 1.91

SECOND SCENARIO

In this case we desire to bring an old well back into service. There is no pump presently in the well. The well is 300 ft deep with a static water level of 45 ft and a pumping water level of 70 ft. The water flow rate is 70 gpm. An air lift pump and sparger will be installed. The air lift pump footpiece will be at 200 ft to yield 65% submergence. The sparger will be at 250 ft. The system will be in operation for three months.

The well has a TCE concentration of 20 ug/L (need 75% removal), a PCE concentration of 5 ug/L and a VC concentration of 5 ug/L (need 80% removal). The air lift pump and sparger combination should provide the necessary VOC removals.

Cost to rent air compressor	$ 4,092
2½ in steel pipe (eductor)	390
Pump footpiece (material & fabrication)	200
Air line (1 in) for pump	150
1 in sparger pipe	250
Fuel tank (250 gal)	500
Air filters	175
Well vent	300
Crane rental (to install pump eductor)	500
Installation labor	3,000
	$ 9,557
Operating Costs -	
Oil and filters	$ 500
Gasoline (2 gal/hr)	4,368
Labor	5,460
	$10,328
Air Lift and Sparger -	
Total cost - 3 months operation	$19,885
Cost per 1,000 gallons of water treated	$ 2.12

GAS AND WATER SEPARATOR

If the well being treated does not have a previously existing chlorine retention tank, one will have to be installed to serve as the gas and water separator. Costs shown here do not reflect the costs of additional chlorine, which might be necessary because of stripping as the bubbles are released.

Concrete tank (1,500 gal)	$ 2,000
Pump (to system)	1,000
Electrical control equipment	1,500
Installation	2,000
	$ 6,500

DISCUSSION

The total cost of an electric submersible pump with a sparger was less than an air lift pump and sparger, as long as the electric submersible pump was previously in the well. These costs did not show purchase or rental of an electric submersible pump.

In-well aeration may not be a good treatment option if a gas-water separator is not already present. A chlorine retention tank would probably be included in the construction of the permanent VOC treatment facility. The time involved in installing the tank would probably negate its usefulness as an emergency treatment measure.

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APPENDIX A

SUMMARY OF EQUATIONS USED

1. AIR DELIVERY - Equation used to adjust for differences from calibration temperature and pressure for air rotometers (supplied by Brooks Instrument Company):

$$Qact = Q_{rotometers} \times \sqrt{\frac{Pread}{Pcal}} \times \sqrt{\frac{Tcal}{Tread}}$$

Where - Qact = Air Discharge, SCFM
Qroto = Rotometer Reading
Pread = Pressure at Rotometer + 14.7 psi (absolute)
Pcal = 75 psi + 14.7 psi = 89.7 psi
Tread = °F Air at Rotometer + 460°F
Tcal = 70°F + 460°F = 530°F

2. SUBMERGENCE - percent of air lift pump eductor which was below the pumping water level (reference 29):

$$S = \frac{L - h}{L} \times 100$$

Where - S = % Submergence
L = Distance from footpiece to discharge pipe
h = Distance from pumping water level to discharge pipe

3. WIRE-TO-WATER EFFICIENCY - derived from water horsepower and required compressor horsepower (reference 38):

$$HP_w = \frac{Q_w \times h \times 8.345 \text{ lb/gal}}{33{,}000} = \frac{Q_w \cdot h}{3945}$$

Where - HP_w = Water Horsepower
Q_w = Water Flow Rate (gpm)
h = Distance from pumping water level to discharge pipe

$$HP_A = Q_A \times 0.01511 \times P_1 \left[\left(\frac{P2}{P_1}\right)^{0.29} - 1\right]$$

Where - HP_A = Adiabatic Air Horsepower
P_1 = Absolute Pressure of Free Air
P_2 = Absolute Pressure of Air Supplied to Pump
Q_A = SCFM Air Supplied to Pump

$$HP_E = \frac{HP_A}{E_c \times E_m}$$

Where – HP_E = Required Compressor Horsepower for Electric Motor
E_c = Compressor Efficiency
E_m = Motor Efficiency

$$E = \frac{HP_w}{HP_E}$$

Where – E = Estimated Wire-to-Water Efficiency
HP_w = Water Horsepower
HP_E = Required Compressor Horsepower

4. AIR-TO-WATER RATIO:

$$\frac{V_A}{V_w} = \frac{ft^3/min \times 7.48\ gal/ft^3}{gal/min}$$

Where – V_A = Volume of Air
V_w = Volume of Water

5. WATER LEVEL MEASUREMENT USING AN AIR LINE – feet of water in the air line is calculated from the pressure required to remove the water from the line, then substracted from the length of the air line:

$$L_w = \frac{P_w}{0.4335}$$

$$WL = L_{AL} - L_w$$

Where – L_w = Feet of water in air line
P_w = Pressure required to move water out of air line
WL = Water Level
L_{AL} = Length of Air Line

6. WATER FLOW RATE – as calculated from a 90° triangular v-notch weir (reference 39):

$$Q = cH^{5/2}$$

Where – Q = Water Flow Rate (ft^3/sec)
H = Height of Water Above Weir (ft)
c = 486.2 for weir box used

7. % REMOVAL OF VOC =

$$\frac{C_R - C_T}{C_R} \times 100\%$$

Where – C_R = Raw water concentration
C_T = Treated water concentration

8. COST TO COMPRESS AIR – calculated at 6¢ per kilowatt hour

$$\text{Cost ¢/1000 gal} = \frac{6¢/KWHr \times 0.746\ KW/HP \times HP_w \times 1{,}000\ gal}{Q_w \times 60\ min/hr}$$

Where – HP_w = water horsepower
Q_w = water flow rate (gal/min)

APPENDIX B

GAS CHROMATOGRAPHIC CONDITIONS AND QUALITY CONTROL PROGRAM

All volatile organic analyses were performed using EPA Method 502.1 for the gas chromatograph (GC). The analyses were done at the North Penn Water Authority Laboratory using a Varian 4600 GC with a Varian Vista 401 Chromatography Data System. The samples were concentrated and introduced into the GC by way of a Tekmar LSC-2 Purge and Trap equipped with a Tekmar ALS Autosampler. The trap was packed with Tenax, silica gel and charcoal.

The GC column used was 8-foot, glass, 1% SP-1000 on Carbopack-B (60/80 mesh). The purge and carrier gases were helium. The detector was a Hall Electrolytic Conductivity Detector (HECD). The temperature program sequence was 45°C isothermal for three minutes, program at 8°C per minute to 220°C, then hold at 220°C for five minutes.

The NPWA Laboratory is certified by the Commonwealth of Pennsylvania to perform trihalomethane analyses under the Safe Drinking Water Act. Method 502.1 is used for the THM as well as the VOC analyses. The quality control program used with this method is approved by the Commonwealth and has undergone in-house inspection of record keeping, equipment, analysts and procedures.

In addition to the Safe Drinking Water Act requirements, several quality control procedures were developed specifically for this study. Once every three months, quality control samples were obtained from U.S. EPA-EMSL for volatile organic chemicals. The samples were provided at two levels of concentrations, and had nine compounds in each sample. Every day one of these samples was analyzed, with high or low range concentrations being examined on alternate days. The results for each day were compared to the true values provided by U.S. EPA-EMSL before any samples were analyzed. If error was less than 10%, samples were analyzed. If the error was greater than 10%, the cause of error was determined and corrected before samples were analyzed.

All VOC samples were collected in duplicate in the field. At least 10% of these field duplicates were analyzed. The percent difference for each compound was determined by dividing the difference between the duplicates by the average of the duplicates, then multiplying by 100. The percent differences were well within 20% for the compounds found in well L-8 at high concentrations, and within 25% to 30% for the minor contaminants.

In order to determine the GC retention time stability, and thus be more confident in the VOC identifications, the retention times for each compound in the daily calibration standard were recorded. These data were compiled on a monthly basis and the average, standard deviation, percent relative standard deviation and retention time relative to chloroform were calculated for each compound in the method. Percent relative standard deviations were generally less than 0.5%. If the average retention time changed from the previous month, the new retention time was inserted into the GC method in the data system.

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