In Situ Instrumentation for Evaluating Air Injection Remediation Technologies

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ABSTRACT An instrumentation system consisting of driven well-points, instrumentation bundles, and discrete sampling has been developed for monitoring subsurface conditions during the operation of air injection remediation systems. The driven well points provide intimate contact reducing the impact on the remediation process. The instrumentation bundles afford continuous monitoring of subsurface conditions. The saturated zone bundle provides information on dissolved oxygen, temperature, and ground water displacement for use in defining the volume of influence of air injection systems in the saturated zone. The vadose zone bundle provides data on changes in oxygen concentrations and temperature. Both bundles allow discrete sampling for laboratory analysis. Criteria for sensor evaluation and laboratory testing protocols used for sensor evaluation are discussed. Also included are a description of the bundle housing and well-point layout at a field site.

KEYWORDS: air sparging, monitoring, remediation, in-well aeration, dissolved oxygen

Introduction

Leaking underground storage tanks are responsible for contaminating many ground water aquifers throughout the U.S. Air injection technologies, such as *in situ* air sparging (IAS) and in-well aeration (IWA), have been used to remediate contaminated soil and ground water [1, 2]. An IAS system, shown in Figure 1, delivers air directly to the subsurface and displaces water out of the formation. IWA, shown in Figure 2, vapor strips the water in the remediation well and circulates aerated water through the subsurface by density driven convection. These methods have apparently been used successfully at a number of field sites based on general observations [1, 2], but basic quantitative information on the processes controlling their performance is lacking. The main focus of these technologies has been physical stripping with secondary consideration for the biological aspect. IAS and IWA also encourage microbial degradation by aerating the ground water and volatilizing the contaminant out of the ground water, making it available for degradation by the soil microbial population in the vadose zone. The biological component of air injection remediation has not yet been studied in detail.

The instrumentation bundles were developed to provide some of the missing operational and performance data necessary to adequately monitor a field scale air injection system. The bundles are placed in small, 2 in. (51 mm), driven well-points at appropriate locations and depths in order to contribute descriptive data. A smaller well-point would have less impact on the subsurface, but would not have accommodated the desired instrumentation. Discrete samples will be taken for laboratory analysis to confirm and supplement the results of the instrumentation bundles.

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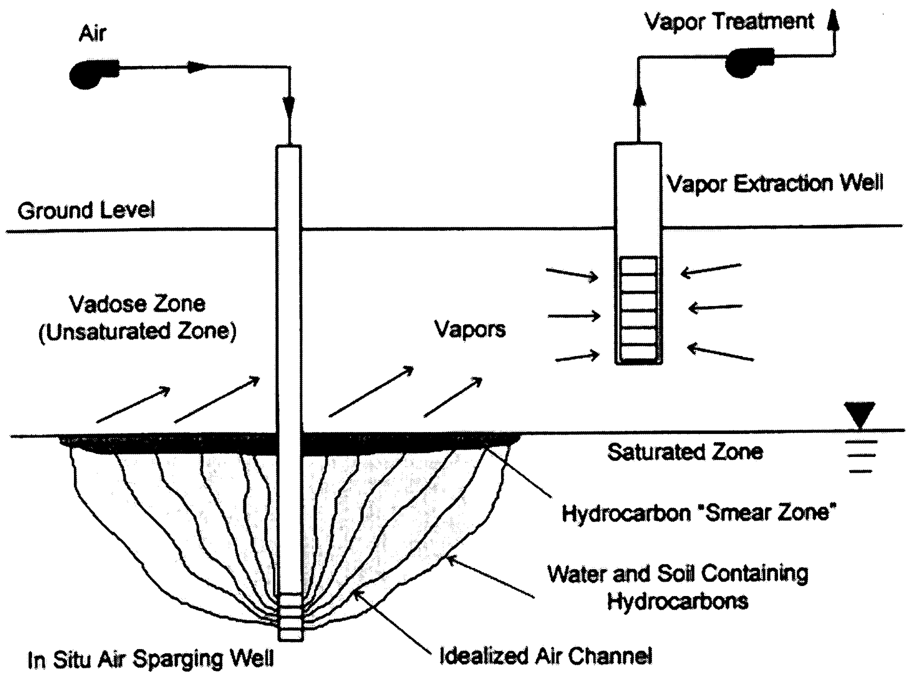

FIGURE 1. SCHEMATIC OF IAS SYSTEM [1].

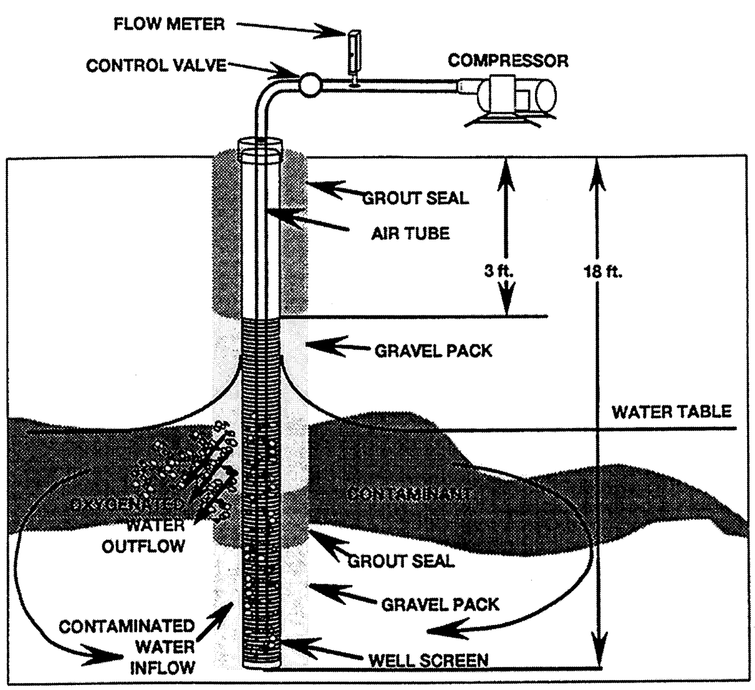

FIGURE 2. SCHEMATIC OF IWA SYSTEM [2].

This paper describes preliminary criteria and sensor evaluation results that led to the final selection of the sensors in the instrumentation bundle. The results of laboratory testing of the completed saturated zone bundle within an actual screened well-

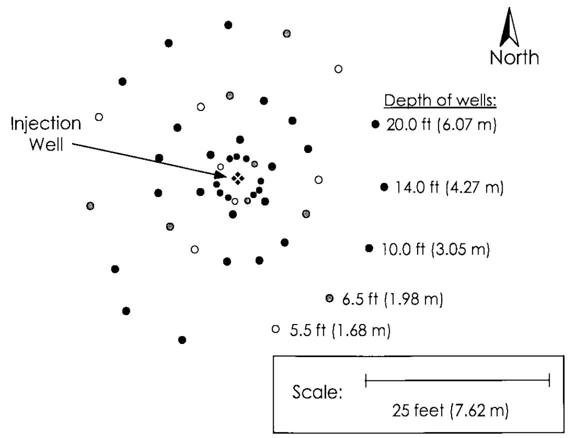

FIGURE 3a. PLAN VIEW OF MONITORING WELL LOCATIONS AT FIELD SITE.

point are discussed. The monitoring well layout at the field site and a general description of the driven well-point are also included.

PROBLEM STATEMENT

Monitoring at many remediation sites consists of a limited number of monitoring locations used to collect discrete water samples for laboratory analysis or that are used for *in situ* analysis of ground water conditions. This is perhaps adequate for monitoring plume migration but not for quantitative evaluation of the operation and performance of IAS and IWA systems. Enough monitoring wells must be placed within the expected zone of influence in order to accurately detect how operational changes affect key parameters in the subsurface. The monitoring well layout of the site to be studied is shown in Figures 3a and 3b. This monitoring grid density was selected to allow a detailed evaluation of the air injection technologies under study and consists of 49 monitoring locations arranged in concentric circles around the remediation well. Each circle consists of three monitoring locations at each of five depths ranging from the 4 to 20 feet (1.2 to 6.1 m) below grade.

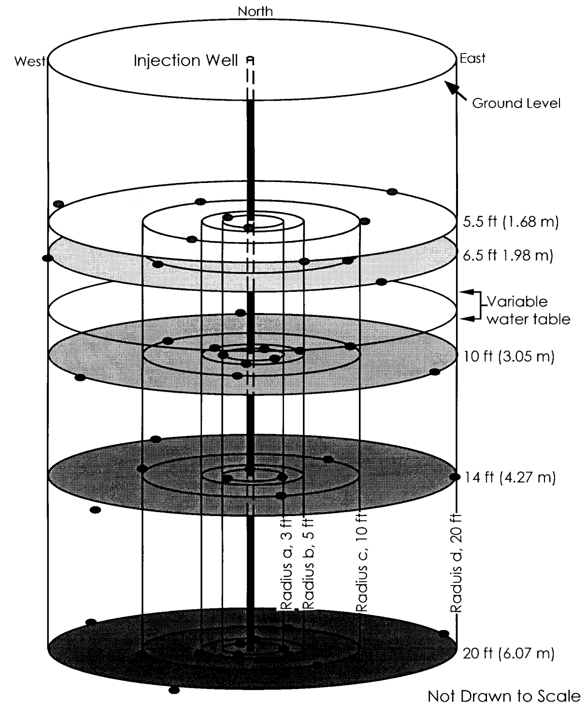

FIGURE 3b. THREE-DIMENSIONAL VIEW OF MONITORING WELL LOCATIONS AT FIELD SITE.

Parameters that are ideally measured in real-time during active remediation in the saturated and unsaturated zones include oxygen and contaminant concentrations, pressure gradients, and temperature. These parameters have been used in previous studies to describe the effectiveness of remediation strategies and have important physical interpretations. Oxygen concentration changes over time allow quantification of the oxygen transfer and oxygen uptake rates taking place during remediation. Contaminant concentrations help define removal rates. Pressure gradients are a response to flow characteristics and allow the determination of both flow rate and direction in the subsurface. Temperature affects the rate of microbial metabolism and the solubility of oxygen in the ground water [1, 2].

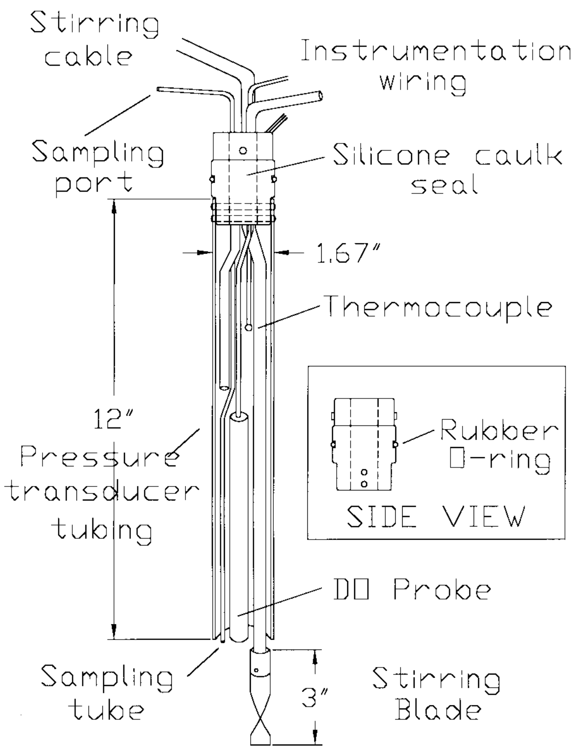

FIGURE 4. HOUSING DESIGN AND SENSORS INCLUDED IN SATURATED ZONE BUNDLE.

Multi-parameter probes are available, but they are expensive and difficult to seal in the subsurface, limiting their accuracy in providing *in situ* measurements. An economical sensor bundle to monitor most of the operational parameters described above has been designed and constructed. The sensors are contained in a housing that has been designed to seal inside a permanent screened well-point. Some of the parameters cannot be measured with *in situ* sensors, however, so limited discrete sampling has also been provided for in the final bundle design.

The approximate cost of the instrumentation bundle is $690 for the saturated zone bundle and $140 for the vadose zone bundle distributed as seen in Table 1.

The price of a multi-parameter probe commercially available, not including a data collection device, is approximately $5,000 [3]. The multi-parameter probes are economically feasible in some monitoring situations where only a limited number of wells are to be used or when the probe can be moved among wells. However, these multi-parameter probes are not appropriate for more extensive real-time data collection of changes in subsurface conditions. The cost associated with available multi-parameter probes prompted the development of the more economic instrumentation bundle.

TABLE 1. APPROXIMATE COST DISTRIBUTION OF THE INSTRUMENTATION BUNDLE.

	Saturated Zone Bundle	Vadose Zone Bundle
Instrumentation	$640	$90
Housing/Stirring	$25	$25
Cable	$25	$25
Total per Bundle	$690	$140

DESCRIPTION OF INSTRUMENTATION BUNDLE

The saturated zone instrumentation bundles developed consist of a DO sensor, stirring blade, pressure transducer, thermocouple, and sampling tube for the saturated zone and an oxygen sensor, thermocouple, and sampling tube for the vadose zone as seen in Figures 4 and 5. The housing is machined from 6061 T-6 aluminum and fitted with a rubber o-ring that seals against the machined PVC wall of a screened well point (Figure 6). To provide access to the desired sampling location at a field site, the well points are hydraulically driven into a soil formation to ensure intimate contact between the well point and the formation. Once the well points are installed, the completed bundles are placed inside the well points, lowered to

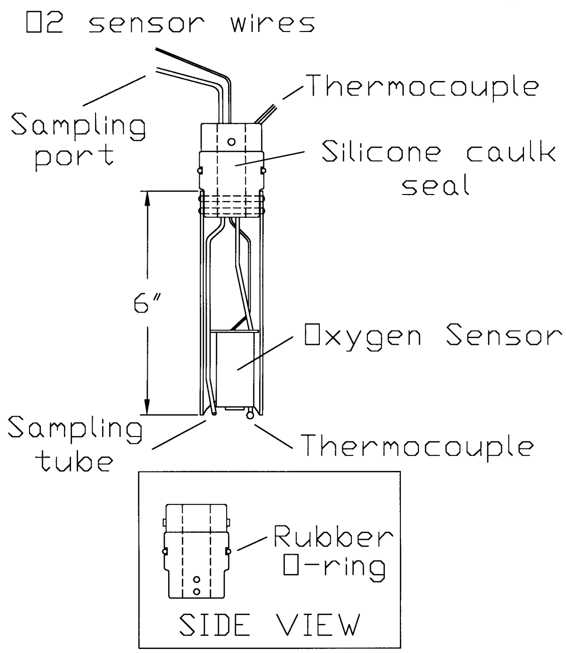

FIGURE 5. HOUSING DESIGN AND SENSORS INCLUDED IN VADOSE ZONE BUNDLE.

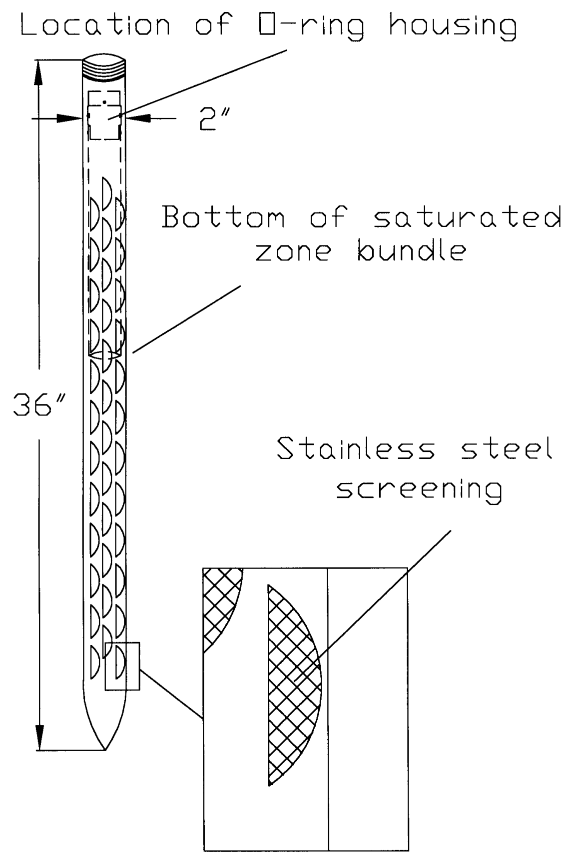

FIGURE 6. WELL POINT WITH HOUSING INSERTED.

the appropriate depths, and are seated to the PVC wall with the application of a slight downward force. The hole for sensor wires at the top of the housing is sealed with a submersible sealant (Figures 4 and 5). This design reduces the risk of preferential pathways by providing intimate contact between the formation and the driven well-point and subsequently sealing the instrumentation bundle in the well-point.

The data are collected at a specified time interval by a 21X Micrologger, an analog data recorder manufactured by Campbell Scientific, Inc. (CSI, Logan, UT). Belden shielded wire was used in the field to prevent unwanted background interference in the signals from the sensors.

PRELIMINARY SENSOR SELECTION

The first step in designing the instrumentation bundle was to identify sensors available that met the primary criteria listed below:

- Cost-effectiveness
- Size
- Ease of use
- Compatibility with the 21x datalogger

The sensors which met these primary criteria were tested comparatively in the laboratory. In addition to these primary criteria, there were other sensor-specific performance criteria that will be discussed in later sections. The sensors tested are listed with manufacturer name, part number, and price in Table 2.

The SenSym SCX Series Pressure Transducers were recommended by CSI as an inexpensive sensor that would work well with the 21X. The T-type thermocouple was also recommended and manufactured by CSI. Through a collaborative effort with CSI, four DO probes, representing a wide price range, were compared. In addition three oxygen gas sensors were identified and tested in the laboratory, as was one hydrocarbon sensor, the only one of its type commercially available.

LABORATORY EVALUATION

Pressure transducers

The sensor-specific criteria for the pressure transducer were accuracy and barometric pressure compensation. Barometric pressure varies over time and needs to be compensated for to yield accurate pressure results. The SenSym SCX series solid-state pressure transducers measure the pressure difference between a port exposed to the atmosphere, Port A, and a port exposed to the environment of interest, Port B. Since the output is linearly proportional to the differential pressure, barometric pressure has no effect on the response. Since the pressure transducers met the primary criteria and one of the sensor-specific criteria, they were calibrated to determine their accuracy.

Calibration procedure

The pressure transducers were calibrated by connecting one end of a Nalgene tube, 0.187 inches (4.8 mm) inside diameter (Nalgene P/N 0918-100), to Port B, and the other at a known depth in a column of water. Port A was left open to the atmosphere. Six measurements within the range of each pressure transducer were taken. The SCX-15DN measures pressure differences from 1 to 15 psi (6.9 to 103.4 kPa). It was calibrated at the depths and corresponding pressures shown in Table 3.

Thermocouples

The T-type thermocouple was recommended by CSI because it is accurate and available as 24 gauge wire with stiff casing. The large gauge size makes them easier to handle; however, the large gauge wire can create problems when there is a large temperature differential between the environment of interest and the surface. Heat transfer through the thermocouple wire can influence

TABLE 2. SENSORS EVALUATED FOR USE IN INSTRUMENTATION BUNDLE.

Type[a]	Manufacturer	Part No.	Approximate Cost
PT	SenSym	SCX Series	$50
TC	CSI	105T	$40 (60 foot length)
DO	Technalithics Inc. (Amp)	535-0112	$200
	Technalithics Inc. (Probe)	190-0100	$250
DO/MP	Yellow Springs Instr. (YSI)	Model 600	$3,000
DO	OxyGuard	Md 2385 B	$490
DO/MP	Hydrolab	H20	$5,000
Oxy	Figaro	KE-25	$50
Oxy	Jensen	P5	$120
Oxy	Datawrite	XT252	$225
HC	Figaro	TGS-822	$16

[a]PT—pressure transducer, TC—thermocouple, DO—dissolved oxygen, MP—multi-parameter, Oxy—oxygen, HC—hydrocarbon

the junction temperature and cause large errors in temperature measurement. This is avoided by using 30 gauge thermocouple wire from the top of the well to the environment of interest and placing a 2 foot (0.61 m) loop of thermocouple wire inside the well casing. The smaller gauge wire and loop in the well casing increase the thermal impedance from the surface to the junction, greatly reducing potential measurement errors. The accuracy of the T-type thermocouples in general has been tested and established by the manufacturer and was not repeated in this study [4].

Dissolved oxygen probes

Two of the primary criteria that heavily influenced the DO probe selection were size and cost. Some DO probes are only available as large, expensive multi-parameter probes, as seen in Table 4.

None of these probes fit inside the 2 in (51 mm) well point and all are cost prohibitive. A temperature-compensating polarographic probe that was cost-effective and small enough to fit in the housing was identified. It had been designed to be used with a DO meter and was not suitable for use with the 21X datalogger due to the high impedance of the probe. Technalithics, Inc., (Waco, TX) modified the probe and designed and manufactured an impedance-matching signal amplifier so the probe would interface with the 21X datalogger. This probe was chosen for use in the final instrumentation bundle, provided that it met certain specific performance criteria.

The sensor-specific performance criteria required for the selected DO probe were accuracy, temperature compensation, low DO consumption rate, and maintenance of *in situ* accuracy for up to two weeks. Temperature compensation is required because of seasonal and daily temperature fluctuations in the zone of interest. A high DO consumption rate is undesirable as this results in inaccurate readings due to oxygen depletion around the probe. A stirring blade, powered from the surface by a motor through a speedometer cable, is included in the saturated zone bundle to induce flow past the DO probe to reduce this measurement error. The polarographic type probes consume less oxygen than galvanic types, so only temperature-compensated polarographic type probes were tested [5]. The environment of interest is contaminated with gasoline hydrocarbons that may cause adverse changes in the probes' accuracy and response time.

Tests were performed to compare the accuracy and temperature compensation of a prototype of the chosen probe to the more

TABLE 3. TEST DEPTHS AND CORRESPONDING PRESSURES FOR SATURATED ZONE PRESSURE TRANSDUCERS.

Depth of water (feet) (m)	Pressure (psig) (kPa)
0.0 (0.0)	0.0 (0.0)
3.75 (1.14)	1.62 (11.17)
7.50 (2.29)	3.25 (22.41)
11.25 (3.43)	4.87 (33.58)
15.00 (4.57)	6.50 (44.82)
18.75 (5.72)	8.12 (55.98)
22.50 (6.86)	9.74 (67.15)

TABLE 4. COST AND SIZE DATA FOR COMMERCIALLY-AVAILABLE MULTI-PARAMETER PROBES.

Label	Outside Diameter	Cost
X	3.5 in (89 mm)	$3,000
Y	3.5 in (89 mm)	$5,000
Z	3 in (76 mm)	$4,000

expensive multi-parameter probes shown in Table 4. A sample of the production probes were tested to confirm that they met the other two specific performance criteria, minimal DO depletion and maintenance of *in situ* accuracy. The comparison procedures for accuracy and temperature compensation (described below) were developed jointly by CSI and Utah State University (USU). The DO depletion and *in situ* accuracy procedures were developed by USU.

Accuracy comparison procedure

All probes were calibrated according to the manufacturers' instructions and placed in a 20 gallon (76 liter) aquarium filled approximately one-third full with water. The water temperature was brought to 20°C and allowed to equilibrate for 5 minutes. The water was bubbled with air to reach DO saturation. The probes' outputs were recorded, and three samples were removed from the aquarium for analysis by Winkler titration, Standard Method 4500-O [6]. The DO level was lowered to approximately 6.5 mg/l by bubbling the water with an air/nitrogen mix. The probes' outputs were recorded compared to titrated samples. The process was repeated for 4.0 mg/l and 1.5 mg/l. A replicate run was performed, using the same procedure [7].

Temperature compensation comparison procedure

All probes were calibrated according to the manufacturers' instructions and placed in a 20 gallon (76 liter) aquarium filled approximately one-third full with water. The water was bubbled with air continuously for all tests. The water temperature was brought to 25°C by the addition of warm water and allowed to equilibrate for five minutes. The probes' outputs were recorded, and three samples were removed from the aquarium for analysis by Winkler titration, Standard Method 4500-O [6]. The temperature was lowered to 15°C by adding cool water and allowed to equilibrate for 5 minutes. The probes' outputs were recorded compared to titrated samples. The process was repeated for 10°C and 5°C. A replicate run was performed using the same procedure [7].

Depletion procedure

Three probes were calibrated according to the manufacturers' instructions and were sealed in individual 1 liter Erlenmeyer flasks filled with oxygen-saturated water. Three Winkler titration samples of the saturated water were taken and recorded to obtain an initial DO level. The probes' outputs were recorded for 10 days without stirring. Three Winkler titration samples were taken from each flask at the end of the 10-day test period to compare with the initial and determine the amount consumed by the probes [8].

In situ accuracy procedure

Three probes were calibrated according to the manufacturers' instructions and were placed in 1 liter of clean, oxygen-saturated water. The probes' outputs were recorded for 5 minutes, and three Winkler titration samples were taken to compare with the probes' responses. The procedure was repeated in 1 liter of oxygen-saturated water containing 80 ppm unleaded gasoline (HC solution). The influence of long-term exposure to the HC solution on the accuracy and response of the probes was checked by repeating this procedure after soaking for 3, 6, 10, and 14 days after the initial test [8].

Oxygen sensors

The specific criteria for the oxygen sensors were oxygen consumption and temperature compensation. The consumption of oxygen immediately around the probe/environment interface yields inaccurate readings of the oxygen concentration in the surrounding environment. Temperature should have a minimal affect on the probe of choice since seasonal and daily temperature fluctuations will be present in the vadose zone. Therefore, three oxygen sensors were tested for oxygen consumption and temperature compensation: Jensen, Datawrite, and Figaro.

The oxygen sensors identified and tested, listed in Table 2, met most of the primary criteria. The one exception is the Datawrite sensor which is too large and requires modification to connect to the datalogger. The Figaro sensor is notably less expensive than the other probes, as seen in Table 2. The sensor chosen based on the preliminary and specific criteria, the Figaro KE-25, was then calibrated to verify that the response curve was linear.

Comparison procedure

To test for oxygen consumption and temperature compensation, the sensors were calibrated according to the manufacturers' directions and sealed individually in 250 ml Erlenmeyer flasks. The sealed flasks were left in the laboratory for 4 days. The laboratory experienced daily temperature fluctuations ranging from approximately 26°C in mid-afternoon to 17°C early in the morning.

Calibration procedure

The Figaro KE-25 oxygen sensor had the lowest oxygen consumption rate and best temperature compensation of the sensors tested. A number of the same type of sensor were calibrated to verify their accuracy. Before calibration, the sensors were attached to the wires to be used in the field. This was done to prevent systematic error produced by the voltage drop due to the resistance of the wire, since the voltage output from the Figaro oxygen sensor is small, from 5 to 30 millivolts. The sensors were placed in a glove bag (Instruments for Research and Industry, Cheltenham, PA. Part no. X-17-17H) which was completely purged five times with compressed nitrogen. The sensors were allowed to equilibrate for 5 minutes while the output was recorded at 1 second intervals. This was repeated using house compressed air (assumed to be 21% oxygen) and a mixture of 10% oxygen and 90% nitrogen by volume.

Hydrocarbon sensors

The Figaro TGS-822 was the only hydrocarbon sensor identified that reportedly detects long-chained and aromatic hydrocarbons. The hydrocarbon sensor, as obtained from Figaro, is a raw component designed to be incorporated into application-specific circuits. A circuit was designed to measure and amplify the sensor output as it was exposed to hydrocarbon vapors. The test targeted the sensor's sensitivity and accuracy at varying concentrations. N-hexane was used as the hydrocarbon source representative of gasoline vapor.

Calibration procedure

According to Figaro USA, Inc., the range of the hydrocarbon sensor is between 100 and 5,000 parts per million by volume (ppmv) [9]. The linear range of the sensor, on a log/log plot, is 100 to 2,000 ppmv due to the amplification configuration. Therefore, three sensors were tested at five concentrations between 100 and 2,000 ppm as shown in Table 5.

Following 7 days of conditioning according to the manufacturers specifications, the sensors were sealed in a 4 liter glass Erlenmeyer flask by threading the wires through a hole in a rubber stopper sealed with silicone caulk. A known volume of liquid hexane, calculated to yield the desired concentration, was injected into the jar. The sensor was allowed to equilibrate for 45 minutes before the output was recorded. The jar was purged for 20 minutes with humidified, compressed air, and the procedure was repeated at the next concentration.

The last injection of 138 ppmv was left in the flask overnight to observe the long-term reaction of the sensor to hydrocarbon vapors and to determine if the sensor output varied with time. The 138 ppmv injection was replicated to confirm the results of the sensor reaction test.

LABORATORY EVALUATION RESULTS

The sensors were tested to verify both preliminary and specific criteria. The highest accuracy possible is desired, but cost effectiveness and ease-of-use are equally important when many instrumentation bundles are to be used in the field.

TABLE 5. TEST CONCENTRATIONS AND INJECTION VOLUMES FOR HYDROCARBON SENSOR CALIBRATION.

Concentration (ppmv)	Injection Volume in 4.098 liter Container (µl)
2018	44
963	21
459	10
229	5
138	3

Pressure transducers

The pressure transducers were tested in a column of water at the depths shown in Table 3. The calibration curves for three representative sensors (not shown) were linear as indicated by an average coefficient of determination of 0.993.

Based on the calibration curves, the pressure transducers will give accurate results in the field. They are also easy to use and relatively inexpensive ($50 each) and were selected for inclusion in the final instrumentation bundle.

Dissolved oxygen sensors

The price of the probes tested varied greatly as seen in Table 2. It was important to obtain the most accurate probe for the least cost. The test procedures were designed to test the accuracy and temperature compensation of the probes. The data were analyzed using the difference between the sensor reading and the average of the three Winkler titration values at each data point. This difference normalizes the data across the slight variations in temperature and DO at each sampling event so they can be compared directly. The mean difference and 95% confidence interval for the constant temperature test are shown in Figure 7; those for the temperature compensation test are shown in Figure 8.

The Technalithics probe performed nearly as well as the more expensive probes at a constant temperature and varying DO level as seen in Figure 7. The 95% confidence interval of the difference in response from the Winkler value overlap the other sensors, making it not statistically different from the more expensive probes based on these testing procedures.

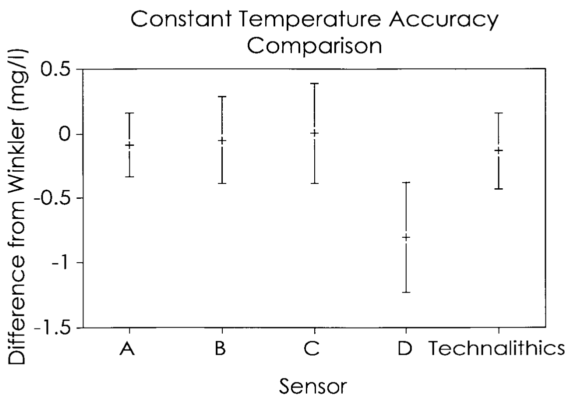

FIGURE 7. CONSTANT TEMPERATURE ACCURACY COMPARISON TEST RESULTS FOR DO PROBES. MEAN DIFFERENCE AND 95% CONFIDENCE INTERVAL SHOWN.

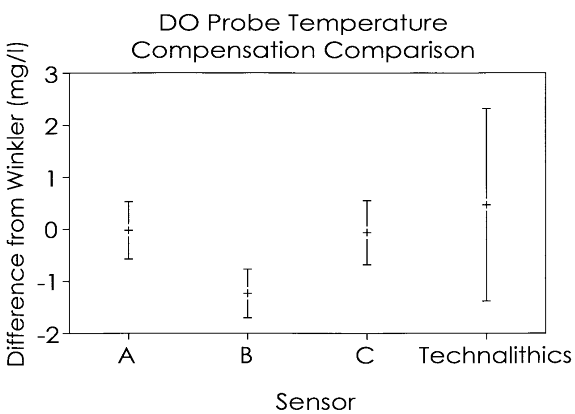

FIGURE 8. TEMPERATURE COMPENSATION COMPARISON TEST RESULTS FOR DO PROBES. MEAN DIFFERENCE AND 95% CONFIDENCE INTERVAL SHOWN.

The temperature compensation test, as shown in Figure 8, shows that the mean difference for the expensive multi-parameter

TABLE 6. DO DEPLETION RATE FOR THREE TECHNALITHICS PROBES WITHOUT STIRRING.

Sensor	DO Depletion Rate (mg/day)
P1	0.22
P2	0.29
P3	0.45

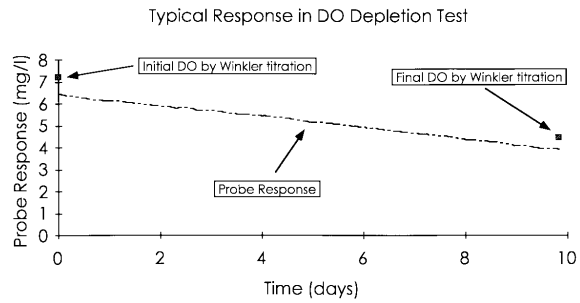

FIGURE 9. TYPICAL RESPONSE OF TECHNALITHICS DO PROBE IN DO DEPLETION TEST WITHOUT MIXING.

probes A and C were very close to zero, with the 95% confidence interval one-third smaller than the Technalithics sensor. The Technalithics probe performed reasonably well, with a mean difference of 0.47 mg/l and a 95% confidence interval that brackets all of the other probes and includes zero. This difference is greater than expected; however, the probe tested is a prototype. The production model has been slightly modified to improve its performance, but these tests have not been retested due to time constraints. Therefore, the Technalithics probe was selected for use in the instrumentation bundle. It meets the stated criteria of ease of use, compatibility with the 21X, size, and cost of $549.

Three Technalithics production model DO probes were evaluated for DO depletion rate and *in situ* accuracy. A typical response is seen in Figure 9. The difference between the probe output and the ending Winkler DO value may be due to localized depletion around the membrane, since the test was performed without stirring. The depletion rates calculated from the DO depletion rate test are listed in Table 6. The depletion rate was assumed to be zero order and was calculated by taking the difference in DO, as calculated from the Winkler titration

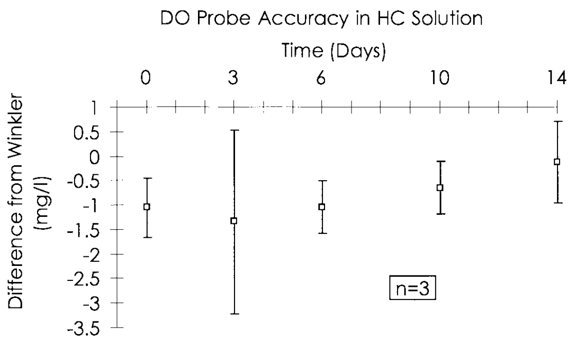

FIGURE 10. ACCURACY OF CHOSEN DO PROBE IN HC SOLUTION OVER 14 DAYS.

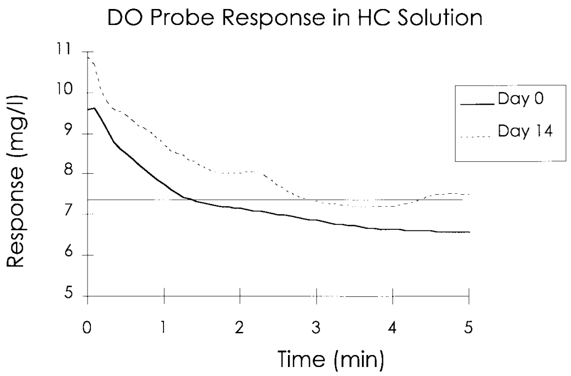

FIGURE 11. CHANGE IN RESPONSE OF DO PROBE AFTER 14 DAYS IN HC SOLUTION.

samples, and dividing by the length of the test.

These data average 0.32 mg/day producing a 4.5 mg oxygen depletion over a two week sampling period (0.32mg/day * 14 days) without mixing, yielding a lower detection limit for oxygen uptake measurements of approximately 0.32 mg/day. The saturated zone bundle includes a stirring blade that will be operated 5 minutes before sampling to reduce the error due to DO depletion around the probe.

The difference between the initial and final accuracy and response when the probes are exposed to the HC solution gives an idea of how they will perform *in situ*. The mean change in accuracy and 95% confidence

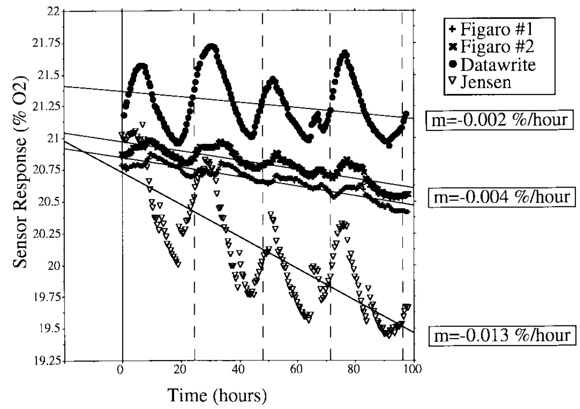

FIGURE 12. OXYGEN SENSOR RESPONSE TO VARIABLE TEMPERATURE IN A SEALED ENVIRONMENT.

intervals for three probes are shown in Figure 10. The initial and final response over the 14-day period is shown in Figure 11. Both the response time and accuracy are affected, but not significantly. The probes are expected to perform well *in situ*.

Oxygen sensor

Oxygen consumption and the effect of temperature on the response were of concern in the initial stages of choosing an oxygen sensor. The response of the sensors tested at variable temperature in a sealed container is shown in Figure 12.

The Figaro sensors had the smallest variation as a function of temperature, as seen by the low amplitude variations, and very low oxygen consumption rate (0.004% O_2/hour). These factors and the low cost ($50) led to the selection of the Figaro KE-25 oxygen sensor for use in the final instrumentation bundle.

The next step was to calibrate the sensors to verify that the response curve was linear. Calibration curves for three oxygen sensors yielded an average coefficient of determination of 0.9997, indicating a linear

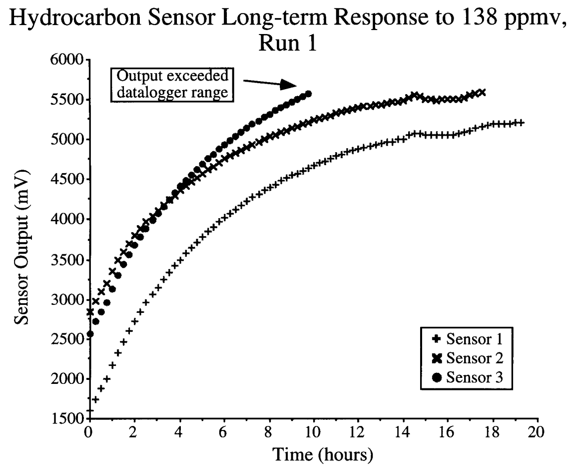

FIGURE 13. LONG-TERM RESPONSE OF HC SENSOR TO 138 PPMV N-HEXANE.

relationship of sensor response as a function of oxygen concentration.

Hydrocarbon sensors

The hydrocarbon sensor was tested at the concentration levels shown in Table 5. The relation between concentration and voltage output is log/log. The linear regression of the log/log relationship (not shown) yielded an average coefficient of determination of 0.996, indicating a linear relationship of sensor response as a function of hydrocarbon concentration.

The last injection of 138 ppmv was left in the flask for 20 hours. At that time, the sensor output increased to above the output value observed for 2,018 ppmv during previous testing, Figure 13.

This same response was observed when the test was repeated and indicates that the sensor signal is not stable with the current electronic configuration. Many different electrical amplification circuits have been tried to obtain a reliable signal. It has been determined that the sensor will not be useful for our application due to response instability.

Instrumentation bundle and well point

When the instrumentation bundle is inserted into the screened well point, the sensors are sealed from the atmosphere. The design, as seen in Figure 5, was tested in the laboratory. Critical components of the sealing system targeted by this test include the o-ring and the seal around the wires. This test also measured the performance of the saturated zone bundle sensors—thermocouple, pressure transducer and DO probe—in a realistic setting inside a well point. The vadose zone bundle was not tested individually.

Procedure

The screened well point was attached to a 4 foot (1.2 m) length of steel pipe and placed upright in a glass column. The saturated zone instrumentation bundle was inserted into the well point. The column was filled with tap water to just below the coupling at the top of the well point. Two hundred and fifty ml of dilute food coloring solution were put into the top of the well point using a tremmie tube. The water around the well point was observed for leakage for 30 minutes. Appearance of dye at this point would have indicated that the seal was ineffective. Five liters of ice water were then poured into the water around the well point using the tremmie tube. Sensor output was recorded for 15 minutes. The water was siphoned out to 6 inches below the top of the well point and the water in the water column was bubbled with nitrogen. Sensor output was recorded for an additional 5 minute period. Finally, 6 liters of hot water were poured into the water around the well point. Sensor output was recorded for 15 minutes to complete the instrumentation/well point test.

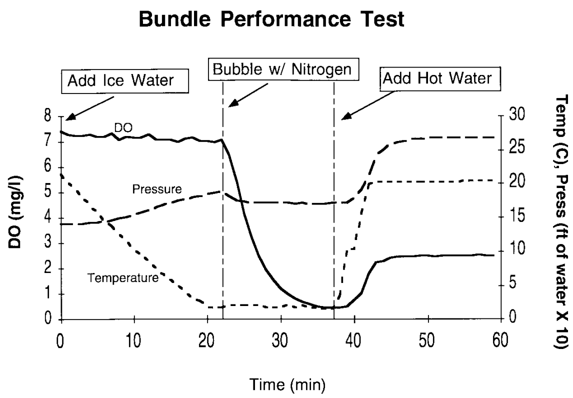

FIGURE 14. INSTRUMENTATION BUNDLE RESULTS IN LABORATORY-SIMULATED SUBSURFACE ENVIRONMENT.

Results

The red dye used to test the o-ring and wire seals was not seen in the water around the well point. The housing sealed against the well point, and the submersible sealant prevented leaks around the wires. Figure 14 illustrates sensor response during the bundle/well point testing. A change in pressure was observed as the water level fell and rose again. The thermocouple registered a change in temperature as the cold and hot water was poured in. The DO probe measured a difference in DO as the water around the well point was bubbled with nitrogen gas. These data indicate that the final instrumentation bundle developed will provide information on the changes in the subsurface during the operation of remediation strategies.

DISCUSSION

The sensors selected for use in the saturated zone instrumentation bundle are the SenSym pressure transducer, Technalithics DO probe, and CSI T-type thermocouple. Also included is a stirring blade to provide flow past the DO probe to reduce measurement error caused by oxygen depletion at the membrane. These sensors met both the primary and sensor-specific performance criteria. The SenSym pressure transducer is inexpensive ($50), easy to use, interfaces well with the 21X datalogger, is accurate, and it automatically compensates for changes in barometric pressure. The Technalithics DO probe is inexpensive ($549) when compared to other DO probes, is easy to use, interfaces well with the 21X datalogger, is sufficiently accurate for field test purposes, has a low DO consumption rate, is temperature compensated, and maintains sufficient accuracy *in situ*. The CSI T-type thermocouple, although not tested in the laboratory, is known to be cost effective, easy to use, and accurate. The approximate total cost for the saturated zone bundle, including cable, housing, and stirring mechanism is $690.

The sensors selected for use in the vadose zone instrumentation bundle are the Figaro oxygen sensor and CSI T-type thermocouple. These sensors met both the preliminary and sensor-specific performance criteria. The Figaro oxygen sensor is inexpensive ($50), easy to use, interfaces well with the 21X datalogger, is accurate, has a low oxygen consumption rate at the probe/environment interface, and is temperature compensated. The Figaro hydrocarbon sensor is cost-effective, but inadequate for field purposes due to variability in its response over time. The approximate total cost for the vadose zone bundle, without the hydrocarbon sensor, including cable and the housing is $140.

The housing and screened well-point sealed very well and the final instrumentation bundle measured changes in temperature, pressure, and DO accurately in a laboratory-simulated subsurface environment.

CONCLUSIONS

The instrumentation bundle developed detects changes in DO, pressure, and temperature in the saturated zone, and oxygen and temperature in the vadose zone. Both bundles allow discrete sampling in addition to real-time data collection. The relatively low cost of the bundles, $690 for the saturated zone and $140 for the vadose zone, allows a large number of them to be used in the field evaluation of air injection remediation technologies. The intimate contact of the formation and driven well-point and the instrumentation bundle/well-point seal reduce the risk of preferential pathways while providing continuous, representative subsurface-condition data. The result of real-time monitoring will provide more detailed operational and performance data about IAS and IWA systems than have been previously available and will elucidate biological removal mechanisms taking place during air injection site remediation.

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