CHAPTER 4

Pilot Tests

4-1. Introduction

Pilot tests have their greatest potential value in proving that technologies can be demonstrated to work properly at a specific site. Even if IAS processes were perfectly understood (which is not the case), pilot tests would still be needed because the site conditions are not perfectly known. Pilot tests are essential to ensure that the design variables that must be determined empirically are properly measured. They also permit the designer to try variations on the basic design to optimize the application to a particular site geology.

4-2. Pilot Testing Strategy

a. The primary objective of a pilot-scale IAS test is to evaluate the subsurface response to air injection and extraction. Sufficient time may not be available to evaluate contaminant fate and removal rates. The primary objectives of the pilot test include the following.

(1) Determine if injected air can reach the vadose zone in the vicinity of the IAS well.

(2) Determine the pressure and flow characteristics at the location of the IAS well.

(3) Determine the duration of groundwater transients during start-up and shut-down.

b. During continuous IAS pilot tests, data can be collected about the approximate extent of the ZOI, optimal injection rates and pressures, and off-gas handling considerations. The duration of the expansion and contraction transient phases is also of interest for pulsed IAS systems. The selected strategy will determine the preferred monitoring techniques and IAS mode of operation.

c. The results of pilot-scale testing may represent the physical conditions (e.g., IAS air-entry pressure, pressure distribution, air-filled porosity) that will occur during full-scale operation, but they may not predict the long-term chemical behavior (e.g., contaminant concentrations, dissolved oxygen [DO] levels) during full-scale IAS. Different pilot-scale testing approaches often yield different predictions of full-scale remedial success.

d. Variables that are particularly important to consider when designing an IAS pilot test include the soil stratigraphy, local or temporary hydrogeological conditions (e.g., water level, the presence of subsurface structures), and the presence of NAPL.

(1) Stratigraphy may be the single most important factor to understanding whether IAS can potentially be successful at a site. Therefore, particular attention must be paid to the relationship among the location of the sparge well screen, the target soil and groundwater contamination, and the nature of the soil strata at and above the well screen. If air cannot flow through the strata that are contaminated, then IAS will not be successful.

(2) The depth of the water table relative to the depth of the contamination, and relative to "normal" water table depths, will significantly affect both the perceived success of the pilot test and the applicability of the pilot test data to future system operation. The ZOI predicted by a pilot test may be quite different from the ZOI observed during future system operations if the water table elevation changes at a later date. Lower water tables (relative to the pilot test level) reduce the amount of time that air spends in the saturated subsurface and thereby can result in less lateral air flow or less contaminant removal.

(3) Subsurface structures can reduce a ZOI or produce an asymmetric ZOI by inducing local short-circuiting.

(4) Assessing the presence of NAPL should include more than monitoring wells for free product. As even residual NAPL (i.e., below the water table) can limit the effectiveness of IAS, it is important to carefully assess whether NAPL is present by a variety of means, such as visual inspection, laser induced-fluorescence, or dye testing of intact soil cores. If NAPL is detected it should be removed to the extent practicable prior to doing IAS pilot testing (NFESC 2001).

e. Pilot-scale tests typically are focused on determining the ZOI (paragraph 2-8a). If sufficient time is available, the ZOI may be determined by measuring changes in groundwater DO and contaminant concentrations. If testing must be done in a relatively short time, geophysical measurements of saturation (neutron probe, time-domain reflectometry, or resistivity tomography) can be very useful. It should be noted that establishing the ZOI based on DO data requires a significant number of monitoring points, which are not readily available at most sites. It will require additional time to install wells prior to system operation.

f. Tracer gases, including sulfur hexafluoride and helium, can be injected and traced to rapidly estimate the ZOI, subsurface travel times, and the efficiency of capture of volatile emissions (USEPA 1996). Groundwater analytical results obtained from samples collected while sparging is active or the aquifer has not stabilized may not represent stabilized conditions. In-well aeration of monitoring wells (paragraph 3-3d(2)) is a particular concern during pilot testing and operation of full-scale IAS systems; therefore, groundwater concentrations are best measured in monitoring points having short screen intervals (e.g., less than 60 cm) that do not promote in-well aeration. In cases of standard monitoring wells having long screen intervals that may preferentially conduct air, measurements are best made either prior to IAS startup, or a while (at least several weeks) after IAS shutdown. Another option during IAS pilot testing is to actively extract groundwater while sampling so that analytical results are more representative of the aquifer. If an inappropriate pump is used, however, this approach may inadvertently alter the groundwater DO and VOC concentrations. To minimize the influence of pumping during sampling on groundwater flow patterns, low-flow sampling protocols should be utilized (Puls and Barcelona 1996).

g. At sites that may require a large IAS implementation (i.e., more than 5 to 10 sparge wells), it may be desirable to implement the system in phases, rather than all at once. A pilot test can be considered the initial phase of the IAS remediation. Pilot tests generally provide operational data for one or two wells in one or two relatively small areas of the site. However, given the large degree of heterogeneity and imperfect understanding of the extent of contamination at many sites, it may be premature to design and implement a large, multi-well IAS or IAS/SVE system based on a limited pilot test. Often the very execution of a remediation design (e.g., installation of remediation wells) dramatically increases our site understanding and confidence in the conceptual model. A prudent approach, if the pilot test results are encouraging, would be to continue operating the pilot test wells, and incrementally add additional injection and extraction wells. If the resulting system is installed in phases, then full-scale operational data can be developed and then used for modifying the design of subsequent system components.

4-3. Pilot Testing Guidance

Detailed guidance on conducting pilot IAS tests is provided in Marley and Bruell (1995) and Wisconsin DNR (1993), to which the reader is referred for specific component details. Following is a discussion of pilot test operating philosophy, and current trends in IAS evaluation methods. Figure 4-1 presents a flow diagram for conducting a pilot-scale IAS test. The first step is selecting the test strategy, as indicated in paragraph 4-2. Second, select and install the injection and monitoring components. Note that there is often contamination in both the vadose and saturated zones at IAS sites. If the pilot test includes an SVE system, consult EM 1110-1-4001 for detailed guidance. Finally, injection tests are conducted at selected flow rates, with preliminary, transient, and steady state monitoring for each iteration. If sparging is to be conducted in a well field or with pulsed injection, tests should be conducted under varying pulsing intervals. Figure 4-1 incorporates provisions for conducting both short-term pre-qualification tests, as well as longer term pilot tests used to develop a design basis for the full-scale IAS system. For example, depending upon budgetary and scheduling constraints, IAS monitoring alternatives may include only injection pressure/air flow rate, water level, and DO measurements from existing monitoring wells. In the event the results are favorable, a subsequent, longer-term test could be done to refine the IAS design parameters. Table 6-1 should also be consulted, as it provides an overview of the equipment and steps involved in setting up and starting up an IAS system.

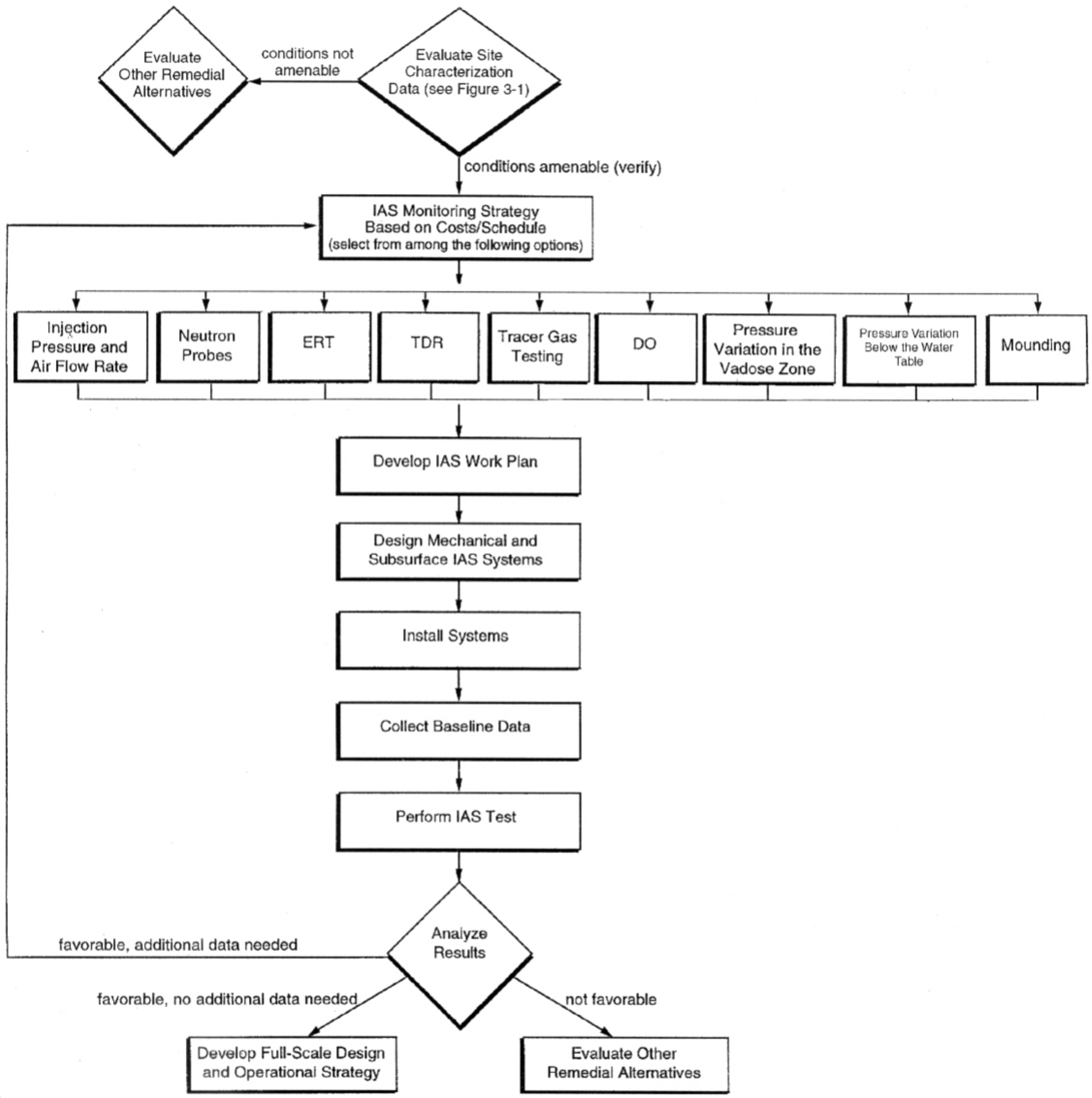


Figure 4-1. Pilot testing process.

a. Equipment Guidance.

(1) *Mechanical System*. The air injection system consists primarily of an injection well, injection blower or pump, and ancillary equipment to include a pressure relief valve, inlet filter,

and flow control valve to meter injection rates. Provisions should be made for measuring pressure, temperature, and flow at the wellhead. Figure 4-2 illustrates a typical installation. Details on selecting and installing the mechanical system are provided in Chapter 5. Blowers should be capable of injecting a minimum airflow of 0.08 m^3/min (3 standard cubic feet/minute [scfm]) at the selected depth and pressure. Evidence exists (Wisconsin DNR 1993) that the optimal flow rate is as high as the formation can withstand without fracturing the aquifer. An additional danger of overpressurization is that it can induce annular seal leakage in the injection well. Maximum flow rates are limited by the overburden pressure, which includes the soil weight and water column weight. Paragraph 5-3d presents a method of calculating overburden pressure for a given sparge depth. The ultimate fate of pilot test components should be considered during the selection process, including whether the components may be incorporated into a full-scale IAS system. Temporary aboveground plumbing and electrical connections are acceptable for pilot tests; however, care should be taken to ensure that the blower power supplies are adequate to prevent thermal overload, and that the air supply piping is compatible with the blower outlet temperatures; furthermore, provisions may be included for heat dissipation (e.g., air-to-air heat exchanger) between blower and sparge well. The surface mechanical system should be tested prior to injecting subsurface air to verify that the components work as designed.

(2) *Injection Wells*.

(*a*) With respect to pilot tests, the primary considerations for injection well construction are the depth to the top of the screened interval and preventing annular space short-circuiting. Practitioners have installed a variety of screen lengths and depths to the top of the screen. Screen length appears not to be a primary design consideration, as research indicates that air generally escapes within a very short interval near the top of the screen. Screen type also does not appear to be a significant design consideration, as pore size distribution in the formation controls airflow. A 0.6-m (2-ft) length of continuous wrap well screen is generally acceptable (paragraph 5-3c(1)). Typical top-of-screen depths for pilot tests associated with shallow LNAPL contamination are 1.5 to 6.0 m (5 to 20 ft) below the water table. (Additional guidance on screen depth relative to stratigraphy, water table fluctuation, and contaminant distribution is provided in paragraph 5-3c(2)). Injection wells can be installed using hollow-stem auger drilling and standard environmental completion techniques or using steel pipe and direct push installation, though direct-push wells are not recommended because of the risk of air leakage around the pushed point (paragraph 5-4a(6)). Injection pipes can be connected to the riser using threaded connections, fittings, or no-hub connectors, but care should be taken to prevent air leakage at joints. It frequently is advantageous to finish the well-head with a tee, with air injection from the side and a threaded plug on the top to allow ready access to the well for sampling or gauging. A check valve may be necessary for pulsed injection to prevent backflow up the well following shutdown. Guidelines regarding well design and construction are discussed in more detail in paragraphs 5-3 and 5-4.

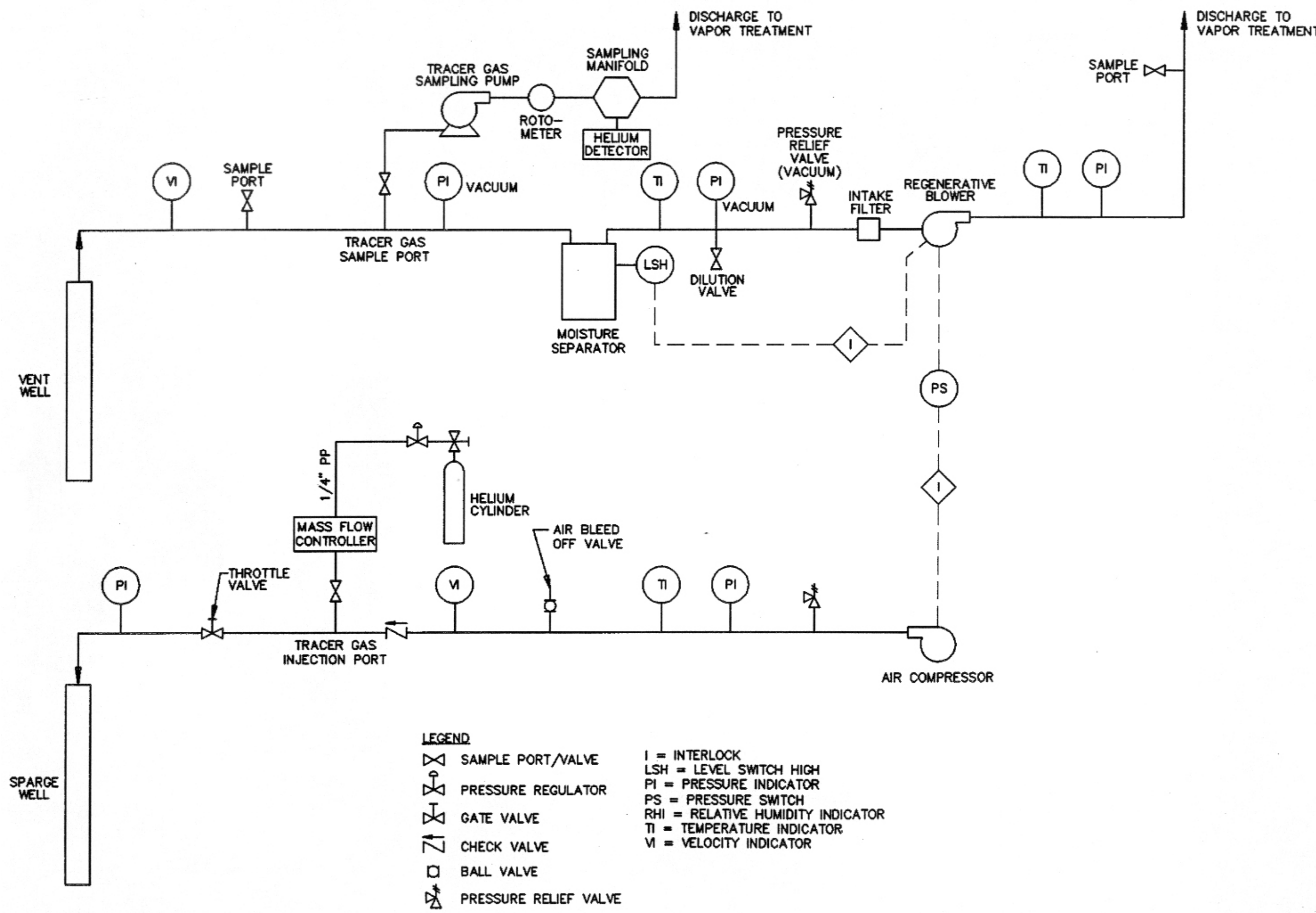


Figure 4-2. Pilot-scale piping and instrumentation diagram.

(*b*) There are few available guidelines regarding the location of monitoring probes associated with a given injection well. However, injection well spacings ranging from 3.7 to 15 m (12 to 50 ft) have been reported in the literature (Wisconsin DNR 1993). Therefore, given a ZOI of 1.8 to 7.6 m (6 to 25 ft), monitoring probes should be located at distances less than 1.8 to 7.6 m to provide useful design data. Positioning monitoring points in various directions and at various distances from IAS points, as well as at various depths of interest, will enhance the data quality obtainable from the pilot test. As a minimum, there should be at least three monitoring points in the saturated zone, spaced from 1.5 m from the injection well, out to a distance equal to two times the depth of the sparge point screen below the water table.

b. Pilot Test Monitoring Methods. Table 4-1 summarizes data acquisition methods for pilot tests, not all of which will apply to a given test.

(1) *Injection Pressure and Airflow*.

(*a*) Injection pressure and airflow should be monitored at the IAS wellhead using an appropriately precise pressure gauge and flow monitoring device (e.g., anemometer, annubar, pitot tube). Be sure to develop the IAS wells first so that an accurate indication of the air-entry pressure of the formation can be obtained during this procedure. If the injection pressure, P_i, is increased gradually in small increments, and the corresponding injected airflow, Q, is precisely monitored, one of three general scenarios is likely (Figure 4-3) (Baker et al. 1996, Baker and McKay 1997). In each of the first two scenarios, Q will initially remain at zero until at least the hydrostatic pressure, P_h, is overcome (paragraph 2-5) (unless there is leakage in the delivery system between the point of measurement and the sparge screen).

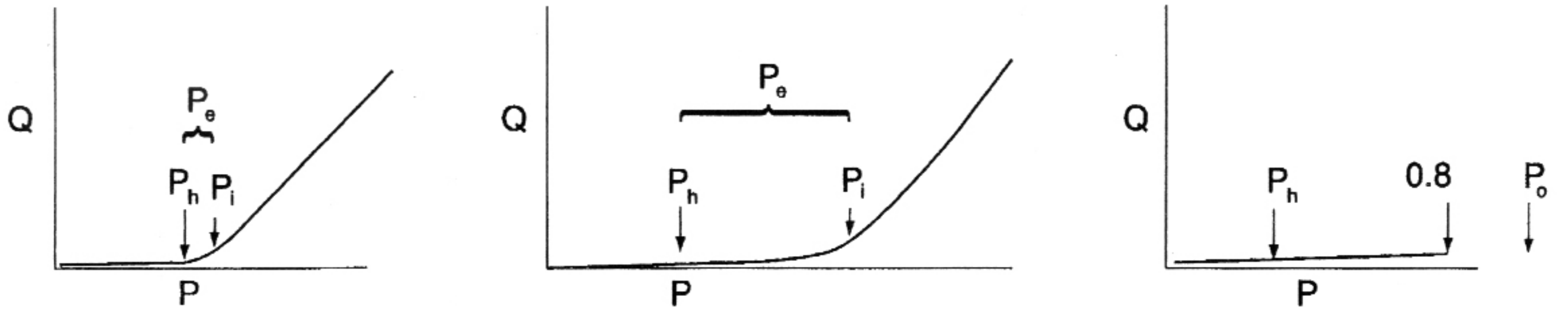
- If airflow commences at, or very close to, P_h (Figure 4-3a), this is an indication that the observed air-entry pressure, P_e, is very small, and that airflow is occurring predominantly within the largest pores. Airflow may potentially be well-distributed in this case if the soils consist of uniform sands, but if the soils are non-uniform, preferential flow via the most permeable pathways is likely.

- If airflow does not become significant until a pressure well above P_h (Figure 4-3b), the sparge screen probably did not intersect macropores or high permeability lenses. Airflow may be well-distributed in this case if the formation consists of uniform fine sands or silts.

- Finally, if no significant airflow is measured, even when 0.6 to 0.8 times the overburden pressure (paragraph 5-3*d*) is applied (Figure 4-3c), then the sparge well should be depressurized. The sparge screen is probably installed in a low permeability, high air-entry pressure formation, and there is a risk of pneumatically fracturing the formation. If possible, it is recommended that sparging be relocated above such a layer, in a more permeable unconfined aquifer, if one is present.

Table 4-1
Pilot Test Monitoring Methods

Method	Applicable installations	Analytical equipment	Results
Injection Pressure and Airflow	Ports in wellhead or manifold	Pressure gauge, anemometer or pitot tube, datalogger	Apparent IAS air-entry pressure, well capacity, system requirements
Neutron Thermalization	Access tube consisting of bottom-capped 5 cm (2 in.) Sch. 40 carbon steel pipe	Neutron probe with source, and counter/ detector	Vertical profile of saturation, ZOI
Electrical Resistance Tomography (ERT)	Electrode array attached to parallel PVC pipes, 1.5–7.5 m (5 to 25 ft) apart	Power supply, Current/volt meters, Analyzer	Saturation within plane of electrodes, ZOI
Time-Domain Reflectometry (TDR)	Steel waveguide pushed into bottom of soil boring	Electrical pulse generator/detector	Saturation in proximity of waveguide
Tracer Gas	Monitoring wells, Soil gas monitoring points, SVE wellhead	Tracer gas detector	ZOI, Air flow velocities, Percent capture
DO	Galvanic "Implants," Monitoring wells	DO meter, Flow cell, Data logger, in situ ampoules	Dissolved gas ZOI
Pressure (unsaturated zone)	Monitoring wells, Soil gas monitoring points	Differential pressure gauge	Air flow ZOI within unsaturated zone
Pressure (below water table)	Monitoring wells, Soil gas monitoring points	Differential pressure gauge	Steady state air flow ZOI
Hydrocarbon Offgas Concentrations	SVE wellhead, Soil gas monitoring points	FID, PID; vapor sampling equipment	Evidence that IAS is or is not causing significant increases in volatilization
Groundwater Elevation	Monitoring wells	Pressure transducer/ datalogger	Groundwater mounding; optimal pulse interval



a. Low observed value of air-entry pressure indicates that flow is predominantly occurring within macropores

b. Substantial value of air-entry pressure indicates that flow is predominantly occurring within matrix porosity— an indication of well-distributed airflow.

c. Lack of air-entry up until 80% of overburden pressure indicates that sparge screen is installed in a low permeability formation. Caution: there is a risk of pneumatic fracturing!

P_h = Hydrostatic Pressure
P_e = Air-Entry Pressure
P_i = Injection Pressure
P_o = Overburden Pressure

Figure 4-3. Interpretations of air-entry pressure from flow vs. pressure data.

(*b*) The interpretations of air-entry pressure as summarized above and in Figure 4-3 are based on the special case in which hydrostatic pressure, P_h, is defined (see paragraph 2-6*a*) as being the elevation difference between the pre-IAS water table and the top of the IAS well screen. More generality is gained if P_h is viewed as being a function of the elevation at which air enters the formation. For example, consider the case in which the entire 1 m-long filter pack is in contact with a fine sandy soil having a moderate air-entry pressure, except for two identical coarse sand lenses, one at the top of the well screen, and a second 50 cm below the first, each having a relatively low air-entry pressure. Air will enter the upper coarse sand lens first, when the injection pressure, P_i attains the ($P_h + P_e$) value of that lens. For air to enter the lower sand lens, however, P_i would need to attain the ($P_h + P_e$) value of that lens, a pressure head 50 cm greater than the P_i required for air entry into the upper lens. Even though the two sand lenses are identical and both in contact with the filter pack, a greater pressure is required to overcome the greater hydrostatic head existing at the deeper layer (i.e., greater depth below the pre-IAS water table). Baker and McKay (1997) provide examples of how this more general analysis has been applied.

(*c*) Note that in the event that the filter pack extends a considerable distance above the well screen, the P_h value for this analysis must remain that of the top of the well screen, because water must be displaced at least to the top of the well screen for air to enter the filter pack. One cannot discern what layers have been invaded during IAS from monitoring of injection pressures alone. Stratigraphic information is also required, as is knowledge of the capillary pressure–saturation curves (and corresponding P_{infl} values) of, at a minimum, the least and most resistive layers between the IAS filter pack and the water table (paragraph 3-3a(2)).

(*d*) Stepped-rate testing of airflow and pressure can also be conducted in combination with other monitoring techniques, such as pressure measurement below the water table, neutron probes, or ERT, to determine the pressure and flow that produces optimal air saturation (McCray and Falta 1996, Morton et al. 1996, Acomb et al. 1995, Schima et al. 1996, Baker and McKay 1997).

(*e*) It is recommended that the pilot test include more than one on-and off-cycle. Although the ZOI was not observed to change from one injection cycle to the next, the expansion phase is seen to reoccur during each pulse, during which the ZOI is somewhat larger than during continuous operation (McKay and Acomb 1996). Incorporation of pulsed IAS into the pilot test confirms the repeatability of the data, as well as facilitating selection of the pulse interval for design (paragraph 6-6b).

(2) *Neutron Probes*. One of the best available ways to determine actual airflow pathways during IAS is the use of neutron probes. Neutron probes measure the thermalization of emitted neutrons, which, being proportional primarily to the density of hydrogen, yields a precise measure of liquid saturation. Subsurface hydrogen is primarily contained in water, although hydrogen

in contaminants is counted as well. The typical probe emits fast neutrons from an Americium-Beryllium source and counts slowed neutrons using a thermal neutron detector (Gardner 1986). The probe is suspended from a cable and sequential measurements are taken throughout the length of an access tube. The spherical zone of measurement extends 15 cm in radius from the probe in saturated soils, and as much as 40 cm in unsaturated soils. Neutron probe operation conducted during IAS pilot tests should conform to ASTM standard D5220-92; however, in lieu of full calibration (which is not needed because precision rather than accuracy is required), counts of thermalized neutrons during IAS can simply be compared with baseline (0% air saturation) counts collected prior to IAS. Figure 4-4 depicts a typical pilot test layout showing four neutron probe access tubes arrayed along a radial extending outward from the IAS injection well, and Figure 4-5 presents results from one such test conducted in uniform sands (Acomb et al. 1995, McKay and Acomb 1996). Figure 4-6, by contrast, shows results from a test conducted in a stratified formation, in which only slight changes of saturation are evident during IAS (Baker et al. 1996). Such results were also obtained during an IAS pilot test at the U.S. Army Engineer Research and Development Center's Cold Regions Research and Engineering Laboratory (CRREL), Hanover, NH (Baker and McKay 1997).

(3) *Time-Domain Reflectometry*. Time Domain Reflectometry (TDR) measures soil moisture content by propagation of electromagnetic pulses along a pair of transmission waveguides in direct contact with the soil. TDR offers a precise measurement of soil moisture content because the dielectric constant of dry soil particles (approximately 3 to 5) differs so much from that of water (approximately 80) (Topp et al. 1994). TDR systems have been deployed for IAS monitoring (Clayton et al. 1995) by pushing a pair of waveguides (a probe) into the bottom of a soil boring to a known depth, and backfilling the portion of the soil boring above the waveguide with grout. Each pair of buried waveguides typically consists of twin parallel steel rods approx. 0.7 cm in diameter and 6 cm apart, with the length of the waveguide selected on the basis of the depth over which one is interested in measuring an average moisture content. An electromagnetic pulse is generated that travels down the two parallel waveguides and the velocity of propagation of the reflected wave is calculated. The zone of measurement extends only approximately 1–2 cm from the waveguide. TDR is a well-established technology, provides real time moisture and time-series measurements, and can be procured commercially, although probes suitable for deep installations usually must be custom-fabricated.

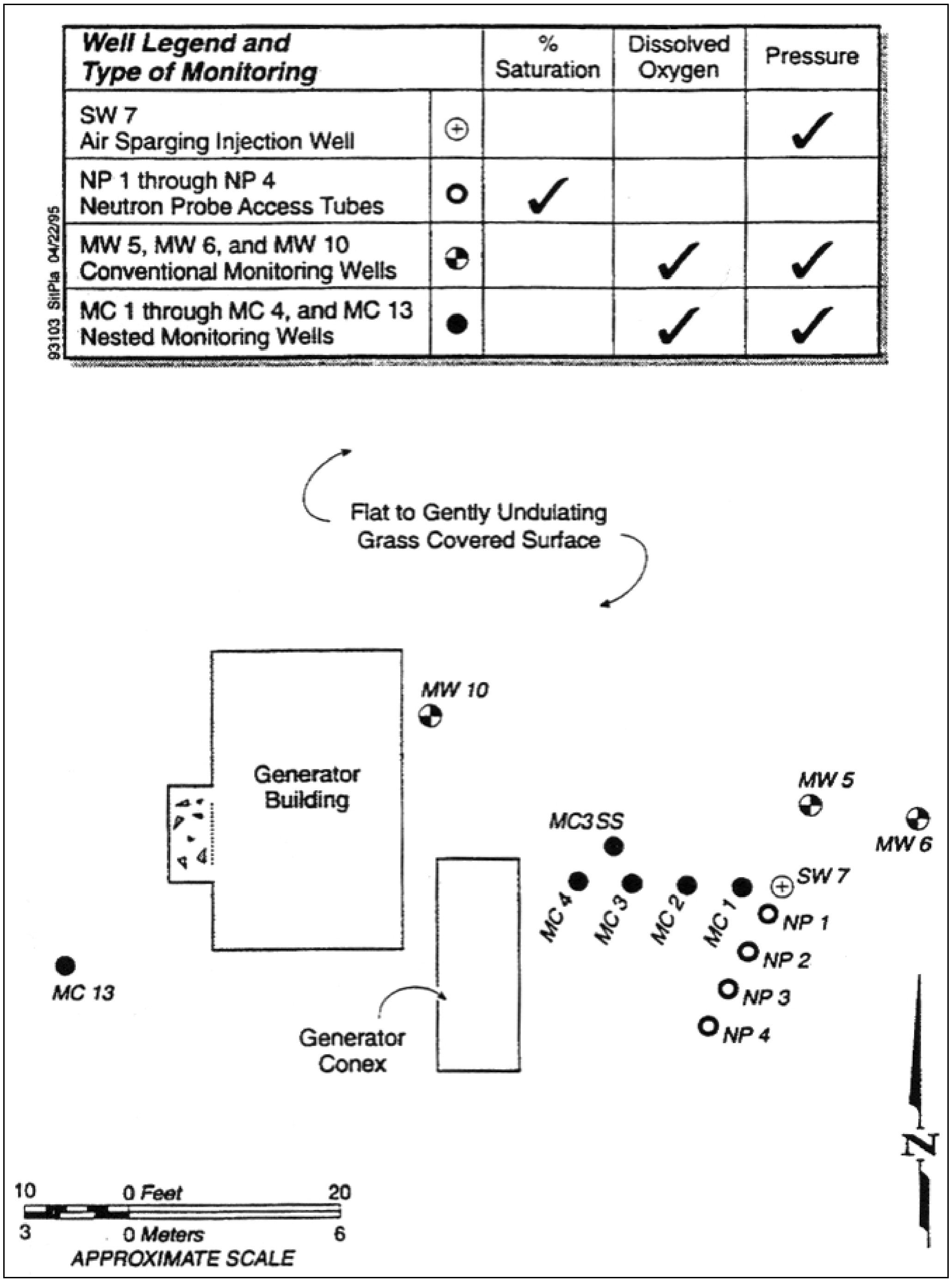


Figure 4-4. Site plan showing air sparging injection well, neutron probe access tubes, and monitoring wells used in the study. Water levels were also measured at the monitoring wells (after Acomb et al. 1995).

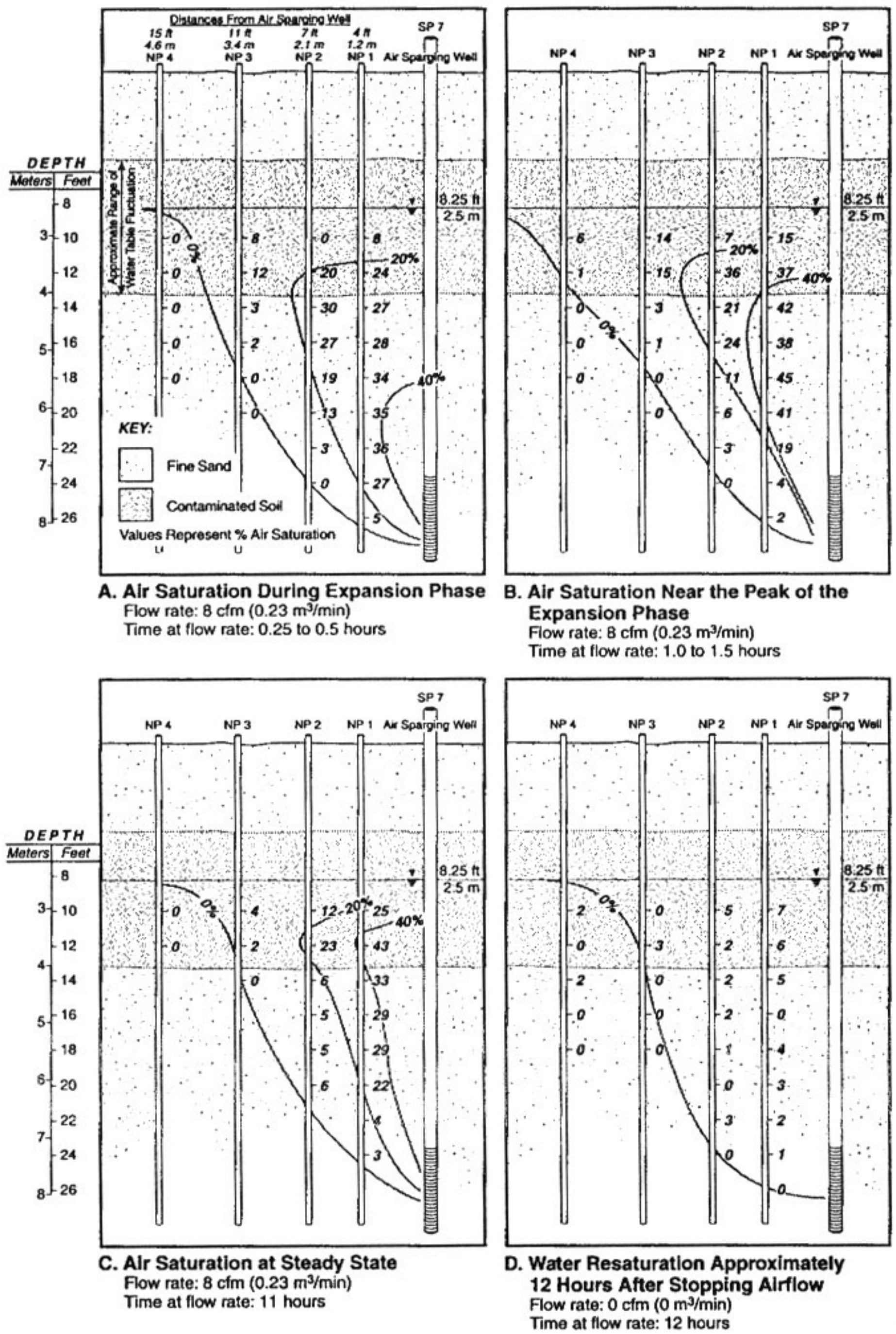


Figure 4-5. Cross section through the air sparging well and neutron probe pipes showing changes in air saturation through time (after Acomb et al. 1995).

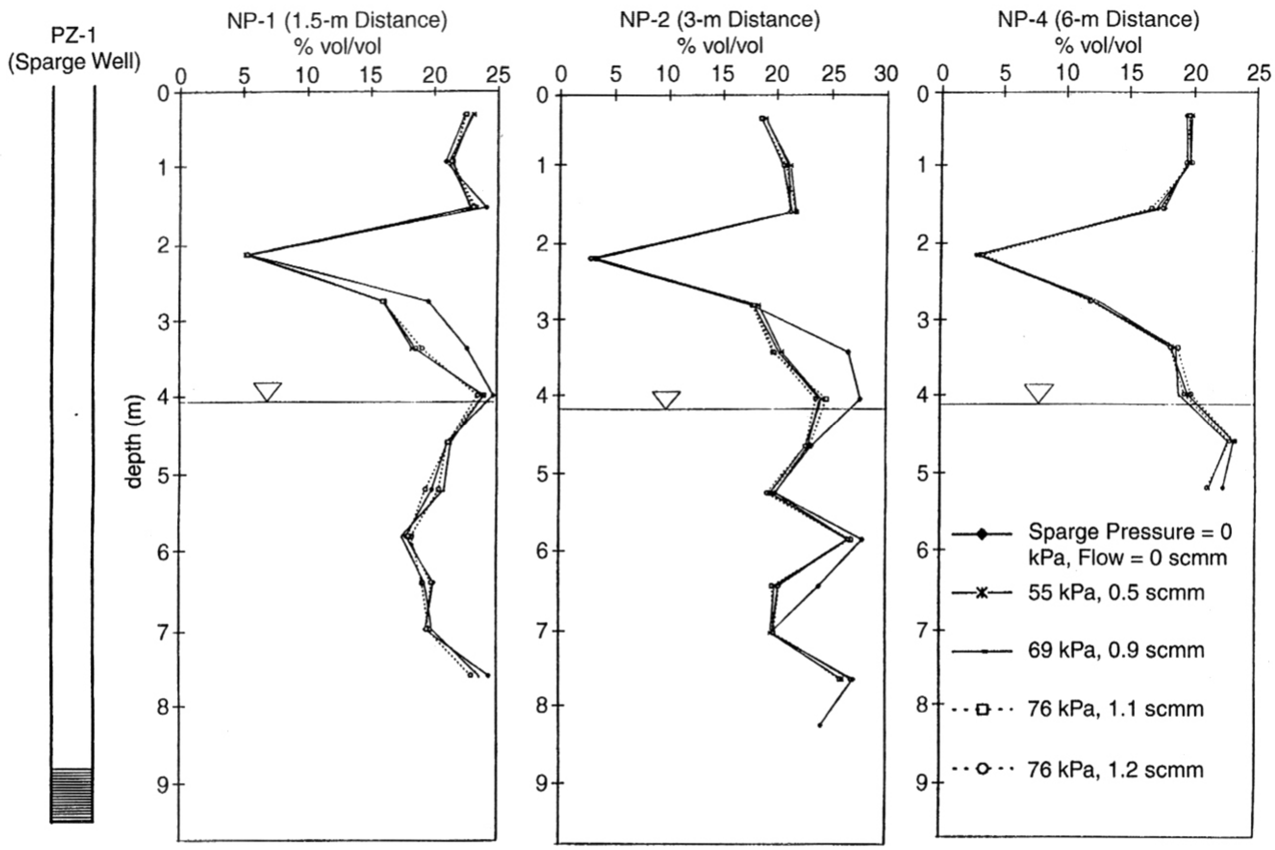


Figure 4-6. Moisture profiles obtained by neutron logging at 1.5, 3, and 6 m from the IAS well during various stages of the IAS test, showing the pre-test water table elevation for reference. Differences between the baseline measurement (sparge pressure = 0, flow = 0) and all subsequent measurements indicated the minimal air saturation due to IAS at this highly stratified site (after Baker et al. 1996).

(4) *Electrical Resistivity Tomography*. Electrical Resistivity Tomography (ERT) is a technique that can be very effective in monitoring the distribution of air associated with IAS programs. The technology provides two-dimensional images of the resistivity distribution between two boreholes. The resistivity distribution is a function of water saturation, porosity, clay content, and electrical conductivity of the pore fluid. As a result, areas within the subsurface characterized by a low water saturation (i.e., that created by air injection during IAS), will have a relatively high resistivity in the resistivity distribution image (Schima et al. 1996). Consequently, ERT may be used to determine the air saturation adjacent to an IAS well. An example electrode layout is shown in Figure 4-7, while results from a sandy site are presented in Figure 4-8. Investigators such as Schima et al. (1996) utilized well spacings of approximately 1.5 to 7.5

m to develop resistivity profiles. Their findings, as well as those in Lundegard and LaBrecque (1996) suggest that ERT provides a robust mechanism for monitoring sparge performance and the distribution of air within the saturated zone during IAS. This method has been employed in IAS research, and shows considerable promise for IAS pilot scale test monitoring. Although the setup and instrumentation may be more costly than other monitoring methods, the data interpretation costs are not anticipated to be particularly high. Algorithms for analysis of tomographic data are common. Given the potentially high resolution of subsurface conditions in three dimensions, there may be air sparging applications that make the benefits of ERT worth the costs.

(5) *Dissolved Oxygen*. Dissolved oxygen concentrations within the saturated zone are used alone or in concert with dissolved tracer concentrations to estimate the extent of potential contaminant removal through biodegradation and an approximation of ZOI. DO distribution is controlled by advective and diffusive mechanisms. DO concentrations are measured within monitoring points by devices such as galvanic oxygen probes connected to dataloggers, or by collecting representative groundwater samples from monitoring wells for analysis by standard surface DO analytical techniques. It is imperative that groundwater collection locations be isolated from the atmosphere during air injection to preclude in-well aeration, and that measurements be made directly in the wells where possible to prevent biodegradation from reducing the DO in the sample to below the level in the well. It is also advisable to employ monitoring points screened entirely below the water table within zones of interest. The use of low-flow sampling devices for purging and sampling minimizes variations in groundwater flow patterns adjacent to conventional well screens and the potential for mobilizing suspended, fine grained material, which may bias groundwater chemistry data. Procedures for low-flow (minimal drawdown) groundwater sampling have been described by Puls and Barcelona (1996). Alternatively, comparisons of pre-IAS and post-IAS DO can conveniently be made in-situ by lowering prepared vacuum ampoules (e.g., ChemEts®) containing reagent into a sampling well and using a trigger mechanism to break the ampoule's tip, allowing groundwater to enter the ampoule and react with the reagent. The ampoule is then lifted to the surface and compared with colorimetric standards. This method is fast, inexpensive, accurate, and minimizes the aeration that can occur while pumping groundwater to the surface (Pannell and Levy 1993).

(6) *Pressure within the Vadose Zone*. Pressure within the vadose zone can be monitored using soil gas probes connected to differential pressure gauges. These values have been used to approximate the ZOI surrounding an IAS injection well. However, research has indicated that this method may overestimate the actual ZOI by up to an order of magnitude, depending on the definition of ZOI, because the pressure influence propagates beyond the air exit points (Figure 4-9) (Lundegard 1994). Changes in soil gas pressure in the vadose zone can indicate sparge air migration from the saturated to the unsaturated zones; however, they also can result from barometric pressure changes, and can be difficult to attribute to IAS airflow owing to the piston effect of rainfall events, as well as pressure changes caused by SVE systems, if concurrently operating. Although vadose zone pressure measurements are not a clear indication of where airflow is occurring, it may be possible to predict the ZOI at the water table by adopting certain flux as-

sumptions and factoring in measured soil gas pressure gradients (Wilson et al. 1992). Measurements of pressure within the vadose zone at multiple points can also be used to demonstrate continuity, or lack thereof, within strata.

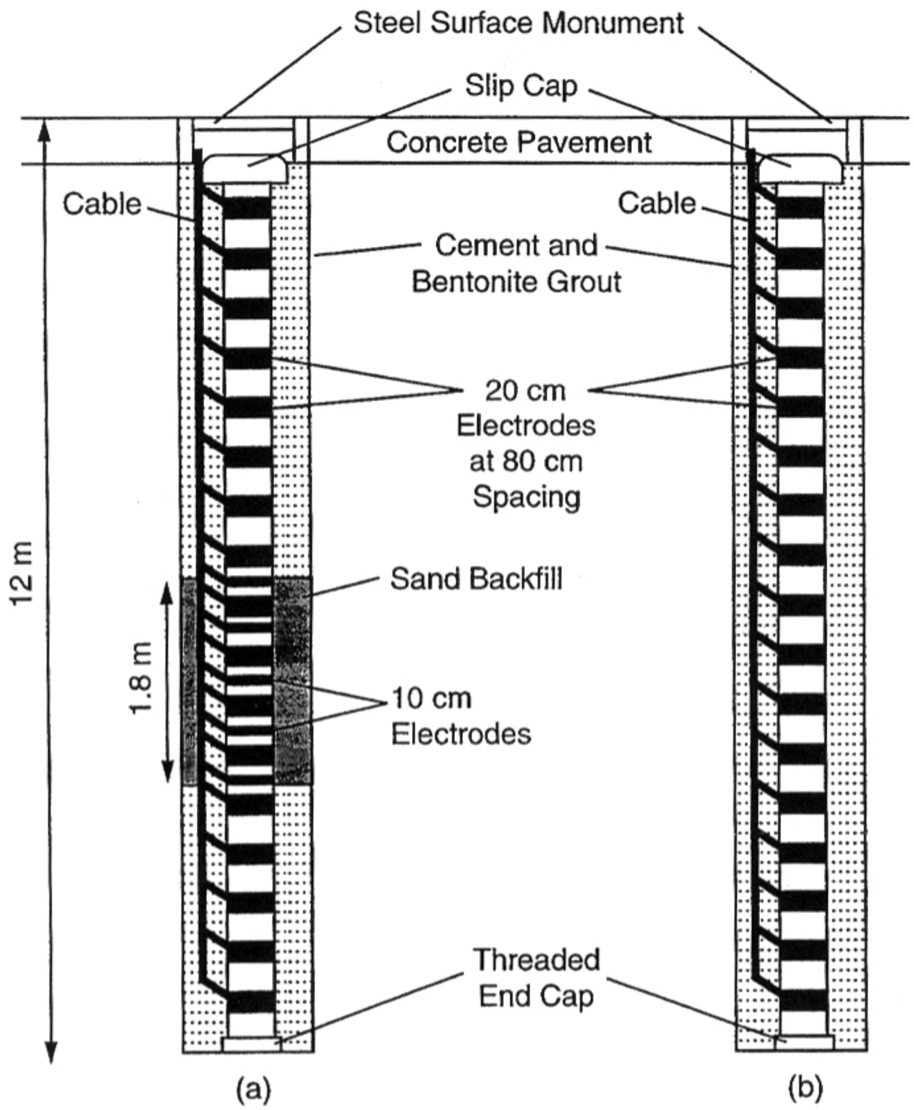


Figure 4-7. (a) ERT electrode layout in sparge well and monitoring well; (b) electrode layout in additional monitoring points. Neither are drawn to scale (from Schima et al. 1996; reprinted by permission of Ground Water Monitoring & Remediation, copyright 1996, All rights reserved).

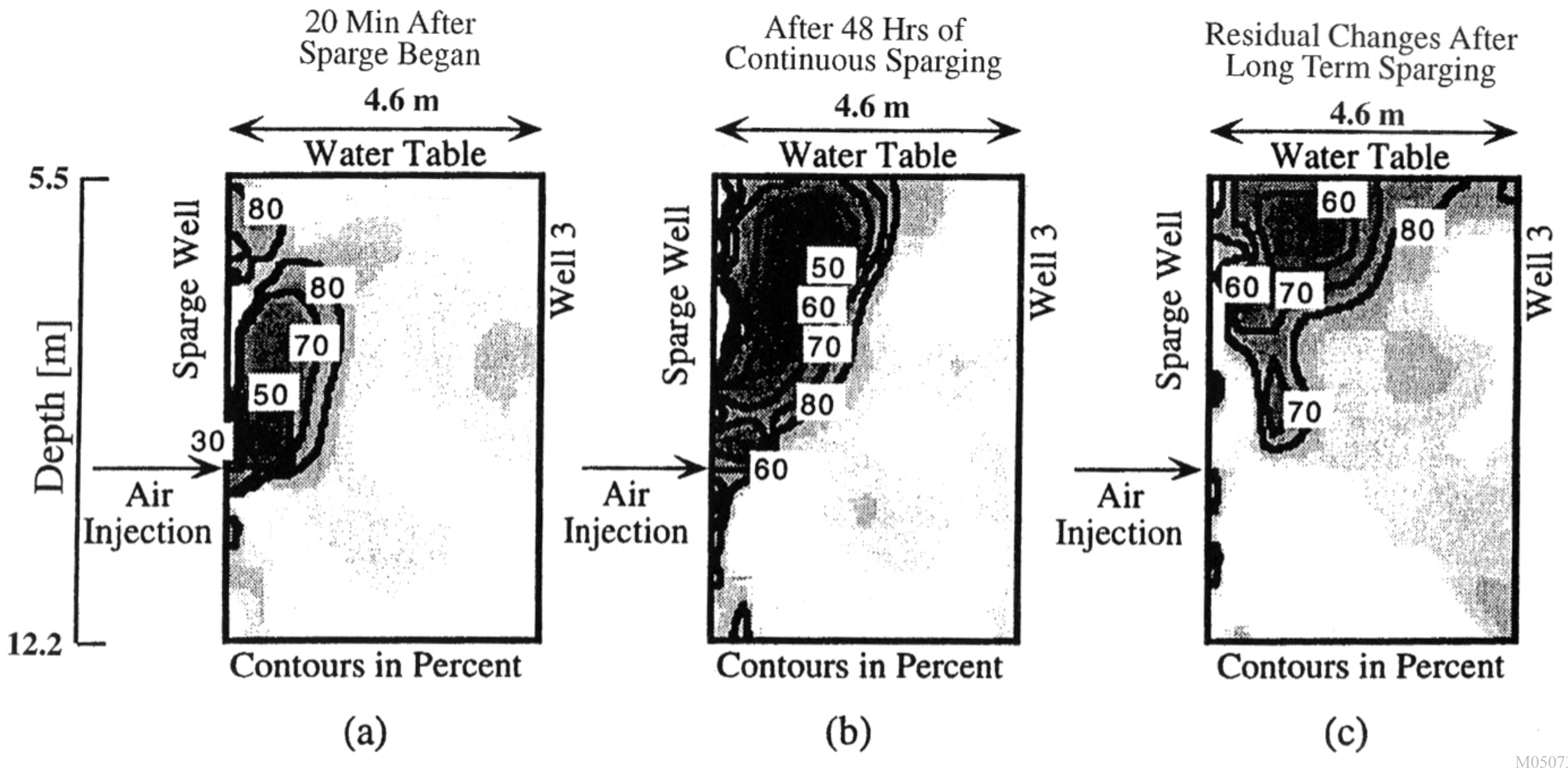


Figure 4-8. ERT image showing percent water saturation in the saturated zone between the sparge well and a monitoring well. Contours are as labeled. (a) Twenty minutes of continuous sparging; (b) near steady-state conditions, after 48 hours of continuous sparging; and (c) residual changes after all sparge events have stopped (from Schima et al. 1996, reprinted by permission of Ground Water Monitoring & Remediation; copyright 1996; all rights reserved).

(7) *Pressure Measurements in Probes Installed below the Water Table*. Pressure changes during IAS can be measured at the wellheads of monitoring probes (soil vapor probes, piezometers or wells) screened entirely below the water table. The observed results will differ, depending on whether or not air channels intersect the probes. If sparged air does intersect such a monitoring point, it will readily enter the probe, which has a negligible entry pressure. A gauge or transducer connected to the capped top of the probe will then show a pressure increase equal to the pressure in the air channel that impinges upon it. If still evident upon achievement of steady state conditions (i.e., after decay of the transient groundwater mound), such a pressure increase can be viewed as equal to the capillary pressure head within the partially desaturated portion of the formation through which the sparged air is flowing (McCray and Falta 1996, Morton et al. 1996). That capillary pressure head, in turn, can be related directly to the air saturation using the soil's moisture retention curve (paragraph 3-3a(2)). Given a sufficient number of monitoring probes, the spatial distribution of air saturation and thus the air sparging ZOI can be accurately delineated (McCray and Falta 1996, Morton et al. 1996, Larson and Falta 1996).

(*a*) If air channels do not intersect the probes, pressure increases will still be evident, but only during the transient phases that follow IAS start-up or shut-down. Such readings indicate how a pressure pulse propagates away from a sparge point during the expansion and collapse phases of IAS, and are thus related to groundwater mounding (paragraph 4-3b(8)). Transient pressure increases following IAS start-up should not be construed as meaning that airflow is occurring at such monitoring points. Thus, the ZOI need to be interpreted with caution on the basis of transient pressure changes at monitoring points (Lundegard 1994, Acomb et al. 1995).

(*b*) It is important to note that air trapped in the saturated zone can sometimes take a prolonged period of time to dissipate following air injection. Lundegard and LaBrecque (1996) observed that 19 hours after IAS ceased, air was exhaling from a piezometer screened below the water table at the rate of 0.014 m^3/min (0.5 scfm) and with a shut-in gauge pressure of 20.7 kPa (3 psi), behavior consistent with the gradual deflation of trapped air that they imaged by ERT.

(8) *Groundwater Elevation Changes*. Groundwater elevation changes can be monitored via water elevation probes in water table monitoring wells, or via pressure transducers installed at selected depths and locations in such wells and connected to dataloggers. Although a pressure transducer is capable of measuring the hydrostatic pressure associated with a change in the water table surface (i.e., that related to mounding), the head, measured in centimeters of water, is calculated by assuming a specific gravity of 1.0. In cases where the fluid column in the aquifer consists of a mixture of water and air (e.g., during effective IAS), a correction to the fluid density is needed to calculate the change in head (centimeters of water) attributable to mounding. Therefore, it may be more appropriate to report the mound buildup and decay as a pressure in kilopascals rather than in centimeters of water.

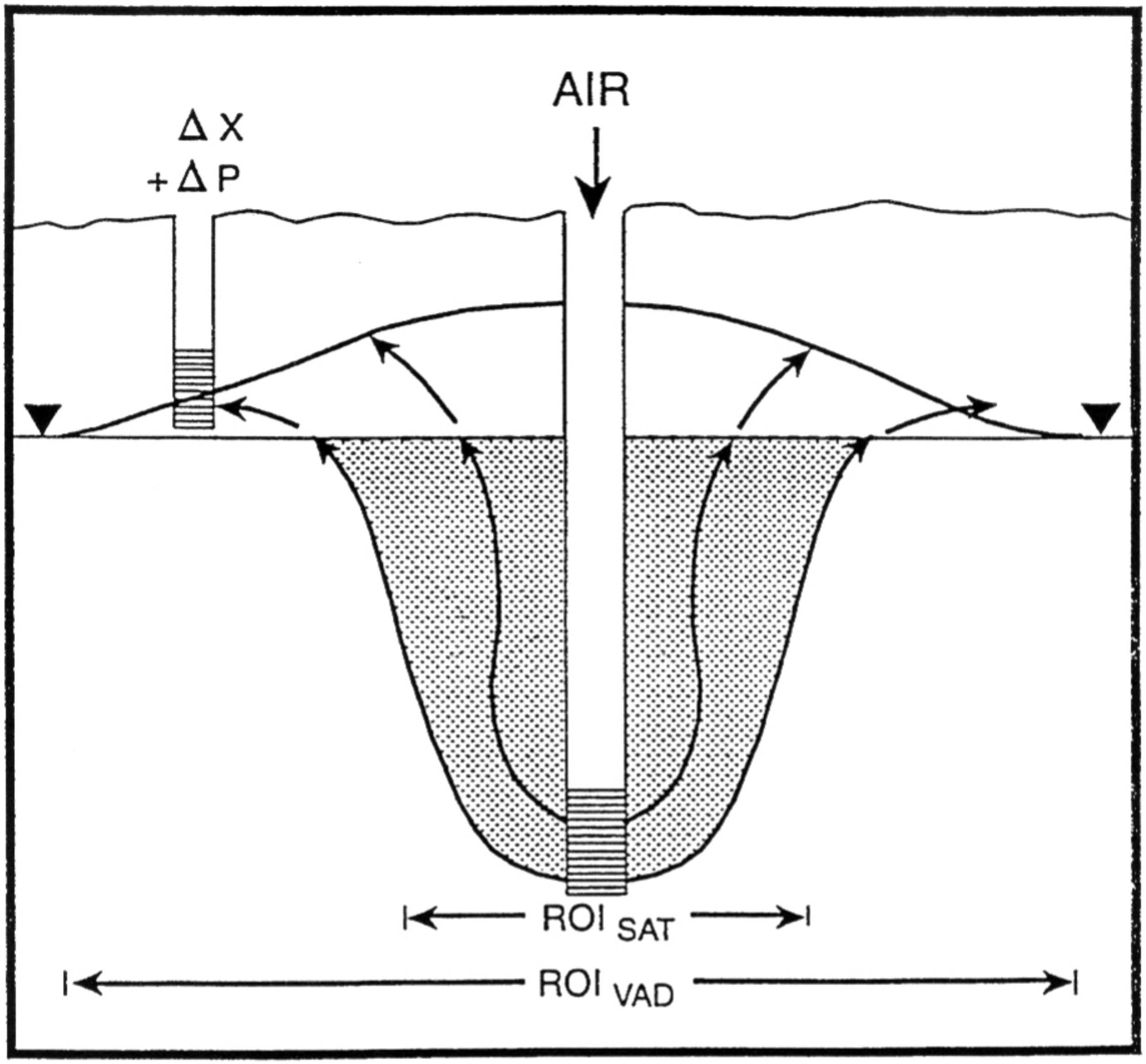


Figure 4-9. Schematic representation of the difference between the air sparging region of influence in the saturated zone (*ROI_{SAT}*) and in the vadose zone (*ROI_{VAD}*). The Region of influence will generally be less in the saturated zone than in the vadose zone. Discrete Measurements of vadose zone properties, such as pressure (ΔX), will lead to estimated *ROI_{SAT}* values that tend to be too large (from Lundegard 1994; reprinted by permission of National Ground Water Association; copyright 1994; all rights reserved).

(*a*) Groundwater elevation changes have also been used to approximate the ZOI around IAS injection wells, but research has shown that changes in hydrostatic head radiate outward from the center of the transient groundwater mound far beyond the locations of air channels (Figure 2-7) (Lundegard 1994, 1995). Therefore, such results are not indicative of regions subject either to groundwater mixing or to air-filled channels.

(*b*) The magnitude of mounding depends on site conditions and the location of the observation well relative to the sparge well. Groundwater mounds of as much as 0.5 to 1 m have been reported in the literature (Brown et al. 1993, Boersma et al. 1993, Lundegard 1995) although in coarse sands and gravels, the mounding may be almost nondetectable. Lundegard (1995) reports mound buildup at distances of 1.5 to 19 m (5 to 63 ft) in a relatively homogeneous sand aquifer under an injection pressure of 41 kPa (6 psig) and an air flow rate of 0.5 scmm (18 scfm). The mounds dissipated within 3 to 4 hours after continuous air injection. In contrast, mounding associated with a heterogeneous sand unit with interbedded gravel and silt was observed in monitoring wells located at distances of 33 m (108 ft) from the injection well. The mound dissipated to within 85% of the initial water surface elevation after approximately 5.3 hours of continuous injection. Maximum mounding was reported in a well located approximately 1.8 m (6 ft) from the injection well and was approximately 0.4 m (1.3 ft) in height (Lundegard 1995). The amount of time it takes for the groundwater mound to dissipate is the recommended basis for determining pulsing on-off cycles. The desired objective is for the groundwater to remain mounded during the entire time air is supplied to a given well (paragraph 6-6b).

(*c*) It should be noted that changes in the barometric pressure should be recorded from monitoring wells during the sparge test. These wells should be located beyond the ZOI to account for temporal variations in the water table surface during the test.

c. Monitoring Frequency.

(1) Monitoring should be started immediately before commencing injection (to establish baseline conditions), and as continuously as practicable for each parameter during the initial transient conditions. As discussed in paragraph 2-5f, in uniform fine sands, initial conditions have been observed to include an expansion of the air-saturated zone, followed by a collapse phase (Figures 2-6 and 4-5) (Acomb et al. 1995). The ultimate "steady state" conditions also are dynamic to varying degrees for different parameters, although at a different time scale than the initial transient mounding conditions. It is imperative that all the necessary background parameters discussed in Chapter 3 be measured and evaluated before injecting or extracting subsurface air, as perturbations can take extended periods of time to return to the original conditions, if ever. As an alternative to monitoring barometric pressure, water level fluctuations can be monitored in a background well prior to, during, and following IAS. Vertical and horizontal positions should be surveyed for all monitoring locations for modeling and evaluation.

(2) Most pilot tests have been conducted for relatively short times, often less than one day (Marley and Bruell 1995). It is recommended, however, that sufficient time (e.g., a minimum of 8 hours, and in some instances, weeks) be set aside to ensure attainment of Data Quality Objectives (EM 200-1-2). The most modest of pilot test objectives would be simply to prequalify a site as potentially suitable for IAS, by measuring injection pressure and airflow during the onset of IAS (paragraph 4-3b(1), Figure 4-3). Such a test can be conducted and repeated in a day (Baker and McKay 1997, McKay and Baker 1997). A more common approach would be to maintain the test to the point of re-equilibration of water levels (stable air paths) during IAS. If the goal is only to determine ZOI during steady-state IAS (based on observed air saturation using pressure measurements below the water table, neutron probe testing, TDR or ERT), a short test of 8 hours to 2 days should be sufficient. If the goal is to observe oxygen uptake, then 2 to 4 days for the air injection portion of the test, followed by 2 to 4 weeks for the oxygen uptake portion of the test, may be advisable, especially if DO or tracer gases are being used as indicators of ZOI. Extending the pilot test by several days can be far less expensive than the cost of remobilization. Finally, if the goal is to observe contaminant concentration decreases in groundwater, or indications of fouling, several months may be required, depending on site-specific conditions. Note that care must be exercised when relying on monitoring wells for VOC and DO measurements during and following IAS, as discussed in paragraph 7-2.

d. Tracer Gas Tests.

(1) Tracer gas tests employ gases not naturally occurring in unconsolidated sediment, such as sulfur hexafluoride or helium, to indicate rates of subsurface gas flow. Ideally, the selected tracer gas closely approximates the physical and chemical characteristics of diatomic oxygen, such as solubility and density (molecular weight). During the IAS test, the tracer gas is injected at the well directly into the injection airstream. Equipment required (Figure 4-10) includes the gas source (gas cylinder), pressure regulator, flow meter, piping to the injection point, a sampling pump, a tracer gas detector, and cylinders of tracer gas at a range of known concentrations for calibration of the detector. Soil gas samples are typically collected from discrete soil gas sampling points in the unsaturated zone. These points must be sealed from the atmosphere when not being sampled to prevent short-circuiting. It may be necessary to purge sampling points after each sample collection. The soil gas sample results are interpreted to show the spatial distribution and velocity of the vapor flows, and to indicate preferential airflow pathways (Baker et al. 1995). It is also possible to inject a known mass of tracer gas and, by monitoring the tracer gas concentration in an overlying SVE system flow, determine the percentage of the injected gas that will be able to be captured (Johnson et al. 1996a). This technique should be employed whenever there are significant concerns about uncontrolled emissions to exposure points.

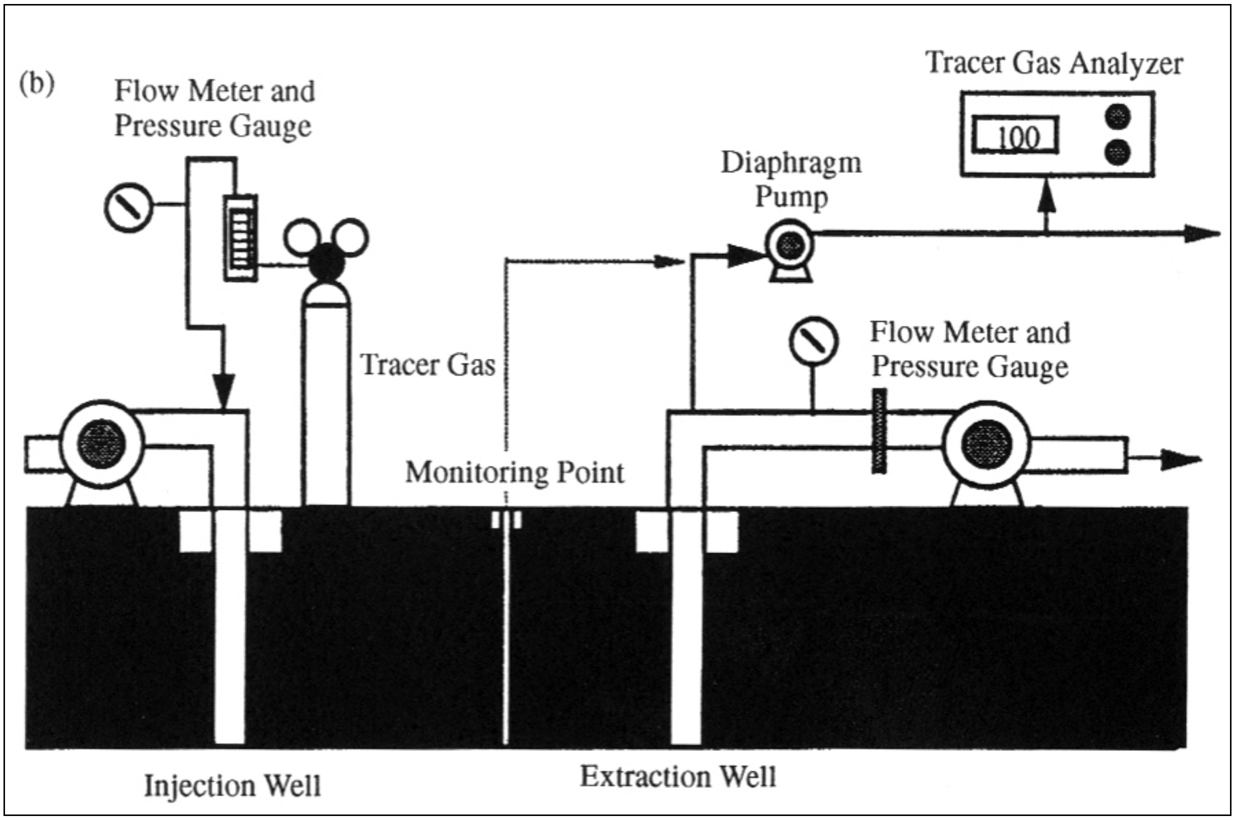


Figure 4-10. Tracer gas measurements and helium recovery test (after Johnson et al. 1995).

(2) Helium tracer testing involves injecting helium at a concentration of approximately 5% in air to limit the potential for differential density-driven flows. Helium is monitored in the deep vadose zone to identify the general area where sparge air is penetrating the water table and, by inference, the zone of influence of a sparge system. Major advantages of helium testing include the ease of implementation and the low cost of helium, the helium detector, and associated equipment. The contrasting disadvantage is that helium testing does not indicate the actual three-dimensional zone of influence in the saturated zone, merely a two-dimensional representation of the uppermost portion of this zone.

(3) Sulfur hexafluoride has a similar solubility to oxygen in groundwater and is used as a tracer for monitoring the saturated zone of influence of a sparge system. Unlike oxygen, sulfur hexafluoride is not affected by microbial activity and thus is a more conservative tracer than dissolved oxygen. Therefore, sulfur hexafluoride tracer testing is appropriate for pilot test sites where conditions are such that oxygen introduced into the subsurface may be rapidly utilized, thereby rendering it less useful as an indicator of zone of influence.

(*a*) Sulfur hexafluoride can be metered into the sparge air at a low concentration. Groundwater samples are collected from monitoring well piezometers and are analyzed by gas chromatograph and electron capture detector. Because sulfur hexafluoride is a gas at ambient temperatures, great care must be taken to collect groundwater samples without loss of volatiles. It is also imperative that groundwater collection locations be isolated from the atmosphere during air injection to preclude in-well aeration. Monitoring points with short screen intervals located entirely below the water table within zones of interest are most appropriate for this.

(*b*) An advantage of sulfur hexafluoride tracer testing is that it can directly indicate the three-dimensional zone of influence around a sparge point. However, the extent to which this three-dimensional zone is defined is a function of monitoring point and sampling density, and therefore, rigorous testing can add to pilot test complexity and expense.

e. Respirometry Testing. Saturated zone in-situ respirometry methods have recently been tested at an IAS site at Fort Wainwright, Alaska (Gould and Sexton 1996). Microbial uptake of DO in the saturated zone was measured quarterly, and the decrease in DO concentration was attributed to biodegradation of hydrocarbons based on certain assumptions, including soil porosity and ZOI. Accounting for advective and dispersive fluxes of DO away from the ZOI following IAS shutdown, as well as the effects of non-target inorganics such as ferrous iron on oxygen uptake, are limitations of such methods.

f. Potential for Vapor Intrusion into Buildings. In situations where the pilot test is conducted near occupied buildings, some monitoring of the potential for vapor migration toward occupied buildings may be appropriate. Monitoring of vapor concentrations in vapor probes set outside these buildings would be most effective at providing early warning of vapor migration. Vapor probes should be monitored first to screen for acute toxic hazards followed by monitoring to determine the presence of chronic toxic hazards. Montoring for acute toxic VOC hazards can be performed by use of a PID or FID. Monitoring for chronic VOC hazards can be conducted by use of Method TO 15 or equivalent. Indoor air monitoring should generally be avoided due to complications from background chemicals typically found in the buildings as well as the likelihood of logistical difficulties in obtaining access for sampling during the operation. The likelihood of air migration into the building given the relatively short duration of the typical pilot test should be considered in making decisions regarding such monitoring, particularly if one goal is evaluating the likelihood of vapor intrusion during full-scale IAS application.

Page intentionally left blank