CHAPTER 5

Design Considerations for Air Sparging Systems

5-1. Introduction

Prior to developing a design strategy, it is important to understand the processes responsible for removing the hydrocarbons and how they may be optimized. As mentioned previously, there are two primary processes: i) volatilization and ii) biodegradation. The success of an air sparging system depends on the ability of hydrocarbons to transfer from the water phase into the air phase, and oxygen (or other gas) from the air phase into the water phase.

5-2. Design Strategy

a. *Introduction*. Given the conceptual background presented in foregoing chapters, it is evident that by increasing the rate of VOC and oxygen transfer across the vapor–liquid interface, the rate of contaminant removal can be enhanced. The rate of mass transfer across the vapor–liquid interface will largely be a function of vapor–liquid surface area (as well as the Henry's constant of the contaminant). Therefore, the strategy behind designing an IAS–biosparging system must be focused on maximizing the vapor–liquid contact and, consequently, the mass transfer rates across the vapor–liquid interface.

(1) The primary strategic issues that the design team must consider when designing an IAS–biosparging system include the following.

(*a*) Is it more feasible or desirable to strip contaminants from the groundwater or to promote in-situ biodegradation? Should other groundwater amendments be considered to promote in-situ biodegradation?

(*b*) Is sparging being conducted to effect groundwater geochemical changes (e.g., for immobilizing reduced metals)?

(*c*) Is collection of vapors by SVE required to avoid fugitive emissions or unwanted vapor migration or escape?

(*d*) What subsurface well configuration will be necessary to cost-effectively deliver air to the zone of interest (e.g., horizontal or vertical injection wells)?

(*e*) Will pulsed flow or continuous flow maximize mass transfer rates across the vapor/liquid interface?

(*f*) Will the IAS system be large enough to benefit from a phased installation? Will data collected from operation of a first phase of the IAS system assist in the correct placement of future IAS wells or optimizing the use of aboveground equipment including the sparge compressor and off-gas treatment equipment? Can the pilot system be utilized as the initial IAS system phase, and the future system design be tailored based on operational experience?

(2) The answers to these questions will drive the configuration of both the below-ground and above-ground components of the IAS system. The data and approach that should be used to answer these questions are described conceptually in Chapters 2 and 3. These data are in turn used as the design basis for the IAS system.

b. Delivery of Air. To optimize the mass transfer rate, it is important to understand the mechanisms that control channel formation and propagation, which were presented in paragraphs 2-5 and 2-6. Air (or another gas) is injected into a sparge well under pressure. As the air pressure is increased, standing water within the well is displaced. For the air to enter the formation, the air pressure must be greater than the sum of the water pressure (i.e., hydrostatic pressure) and the air entry pressure (equations 2-1, 2-2, and 2-3).

(1) Once air has entered the formation, its movement is dictated by the pressure differential between the air and water, as long as the air remains directly connected by continuous channels to the sparge well. In the event the channel "snaps off," the resulting air bubble may travel through the formation, driven by the density difference between the air and water phases (buoyancy), but only in very coarse-grained sediments (grain sizes less than 2 mm, see paragraph 2-7b). Otherwise, flow occurs in the form of finger-like channels that remain in place as long as the air pressure is maintained. Qualitative observations indicate that an increase in air pressure causes an increase in channel size and the formation of additional channels (Ahlfeld et al. 1994). This is an important consideration for design. Recall that Mohr's (1995) conceptual model suggests that channel location and density (i.e., number of channels per unit cross section) have a profound effect on both hydrocarbon removal and oxygen transfer rates.

(2) The stratigraphy governs the air channel distribution. Channel densities tend to be lower for stratified sediments, owing primarily to the lateral dispersion of air confined by overlying low permeability zones. An extreme example is the formation of air pockets or "air ponding" that may extend in lateral directions indefinitely beneath a confining layer unless an exit point such as a well screen is encountered (Figure 5-1) (Johnson et al. 1993, Baker et al. 1995). Based on the discussion above, micro- scale (i.e., pore-scale) and macro-scale (i.e., stratigraphic) heterogeneities have a profound influence on air channel location and density. During the conceptual design, it is important to reconsider these issues. For example, air channels that are spaced at significant distances from one another are not expected to provide adequate mass transfer and removal. In other words, for air sparging to be successful, it must produce enough air saturation with a small enough channel size so that there is sufficient interfacial area for mass transfer to occur (Figure 2-5) (Mohr 1995). Given low air saturation in small radius channels,

there is very little interfacial area, and mass transfer will be very low. With high air saturation and large radius channels, the interfacial area is also very small, and diffusion still must occur over long distances. Only under high air saturation and small channel radius are the interfacial area sufficient and the diffusion path lengths short enough for moderate mass transfer rates to occur. Nomagraphs provided by Mohr (1995) suggest that channel spacings of 0.1 to 1.0 cm may be necessary to achieve reasonable rates of mass transfer. An increase in the channel density (i.e., an even smaller spacing between adjacent channels), will further enhance remediation rates. At some point, however, increased airflow will tend to produce diminishing returns with respect to increased air saturation and channel density. This optimum might be determined through neutron probe or ERT measurements, or pressure measurements below the water table at various stages during a stepped-flow test (paragraph 4-3b(1)).

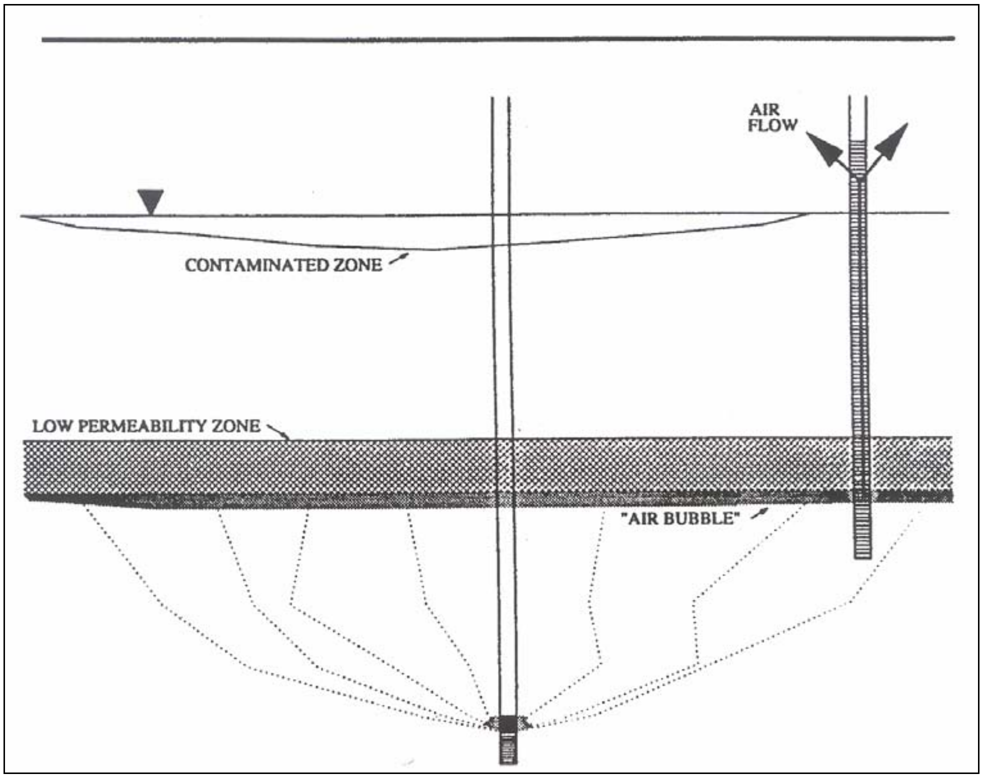

Figure 5-1. Schematic drawing showing sparged air forming an "air bubble" below a low permeability zone, and "short-circuiting" through a monitoring well, thus bypassing the zone of contamination (from Johnson et al. 1993; reprinted by permission of *Ground Water Monitoring & Remediation*; copyright 1995; All rights reserved.)

c. Biodegradation.

(1) There have been a number of discussions in the literature about whether air sparging operates primarily through volatilization or biodegradation. However, given the conceptual model described in Chapter 2, it is apparent that air sparging operates in both modes. Paragraphs 2-8b and 3-3e discuss many of the considerations that underlie biosparging design. In some instances, such as those sites affected by chlorinated solvents, the introduction of oxygen in air may not be sufficient to stimulate biodegradation of the target compounds if they are not readily degradable under aerobic conditions. Some form of conditioned air may be needed to promote in-situ biodegradation, or vapor-phase transport may be the only functioning removal mechanism.

(2) VOCs such as TCE, chloroform, cis- and trans-1,2-dichloroethene, and methylene chloride can be biologically co-oxidized during growth on a variety of substrates, including methane, propane, butane, and toluene (Norris 1994). Therefore, if the injected air can be conditioned with one or more of these of gases, chlorinated VOCs may be destroyed through both volatilization and biodegradation (Lombard et al. 1994).

5-3. Design Guidance—Subsurface

The mechanisms identified above provide a "general" basis for advancing the design. This chapter will provide more specific guidance for the subsurface design of IAS systems. There are many subsurface features that must be addressed during system design that are critical components of an effective IAS system. Systems should be designed to optimize volatilization and biodegradation processes and minimize adverse effects, such as uncontrolled migration of vapors or groundwater. Key features for design, along with typical ranges of values, are listed in Table 5-1. Each parameter has either been previously quantified or will be discussed in this chapter.

Table 5-1
Design Parameters for IAS Systems

Parameter	Typical Range[1]
Well diameter	2.5 to 10 cm (1 to 4 inches)
Well screen length	15 to 300 cm (0.5 to 10 ft)
Depth of top of well screen below water table	1.5 to 6 m (5 to 20 ft)
Air sparging flow rate	0.04 to 1.1 m^3/min (1.3 to 40 scfm)
Air sparging injection overpressure[2]	2 to 120 kPa (0.3 to 18 psig)
IAS ZOI	1.5 to 7.5 m (5 to 25 ft)

[1]Modified from Marley and Bruell (1995).
[2]Overpressure is injection pressure in excess of hydrostatic pressure, P_h.

a. Airflow Rates.

(1) The airflow rate should be as high as needed to achieve an adequate air channel density, but the injection pressure should not be excessive because of the risk of causing lateral mobilization of contaminants off-site or fugitive emissions to basements, buried utilities, or the surface (Brown 1994). There is debate over what range of airflow rates is appropriate to consider during IAS system design. Wisconsin DNR (1993) recommends airflow rates of 0.08 to 0.4 m^3/min (3 to 15 scfm) per IAS well, while the USEPA (1995a) recommends airflow rates from 0.08 to 0.67 m^3/min (3 to 25 scfm). An API-sponsored survey of 39 IAS systems (Marley and Bruell 1995), however, report airflow rates ranging from 0.04 to 1.1 m^3/min (1.3 to 40 scfm) per well, while another survey of 32 IAS systems (Bass and Brown 1996) reports airflow rates from 0.11 to 1.0 m^3/min (4 to 35 scfm) per well. The Air Sparging Design Paradigm developed by the ESTCP (Leeson et al. 2002) recommends that the "Standard" IAS design use 20 cfm per well, but "Site-Specific" designs can vary. The Navy's Air Sparging Design Guidance (Navy 2001) recommends IAS design flow rates from 6 to 20 scfm. Marley and Bruell (1995) say that higher flow rates result in increased air channel density and therefore more effective mass transfer. It is possible that more effective and rapid remediation is possible with higher per-well airflow rates than have historically been used or recommended, provided that injection pressures are not high enough to cause soil fracturing.

(2) If capture of VOCs is required, SVE airflow rates must be sufficient to establish capture zones for the injected air. Marley and Bruell (1995) report that most practitioners ensure that the SVE airflow rate is at least twice the IAS airflow rate. Wisconsin DNR (1993) requires a minimum SVE airflow rate of four times the IAS airflow rate; however, at sites somewhat removed from buildings or subsurface structures, such criteria may be neglected.

b. Well Spacing. Well spacing should be based on the ZOI, as discussed in paragraph 2-8a. As previously explained, the effectiveness of air sparging for either volatilization or bioremediation depends on the transfer of mass to or from the air channels. Diffusion of contaminants or oxygen within groundwater controls the rate of mass transfer and requires channel separations measured on the order of centimeters to decimeters to be effective. As such, good air saturation is an indicator that air channel spacing is reasonably close. It is suggested that well spacing be based on maintaining a minimum 3% three-dimensional air saturation within the target contaminated zone. Measurement of relative changes in water saturation by neutron probe or electrical resistivity tomography would support the evaluation of sparging adequacy and realistic ZOI. The "radius of influence" has commonly been used to describe the effect a sparge well has on the groundwater system. Reported IAS radius of influence values are displayed in Figure 5-2. This definition has often been ambiguous in the context of air sparging, however, as it is a two-dimensional parameter applied to a three-dimensional problem (Ahlfeld et al. 1994, Johnson et al. 1995).

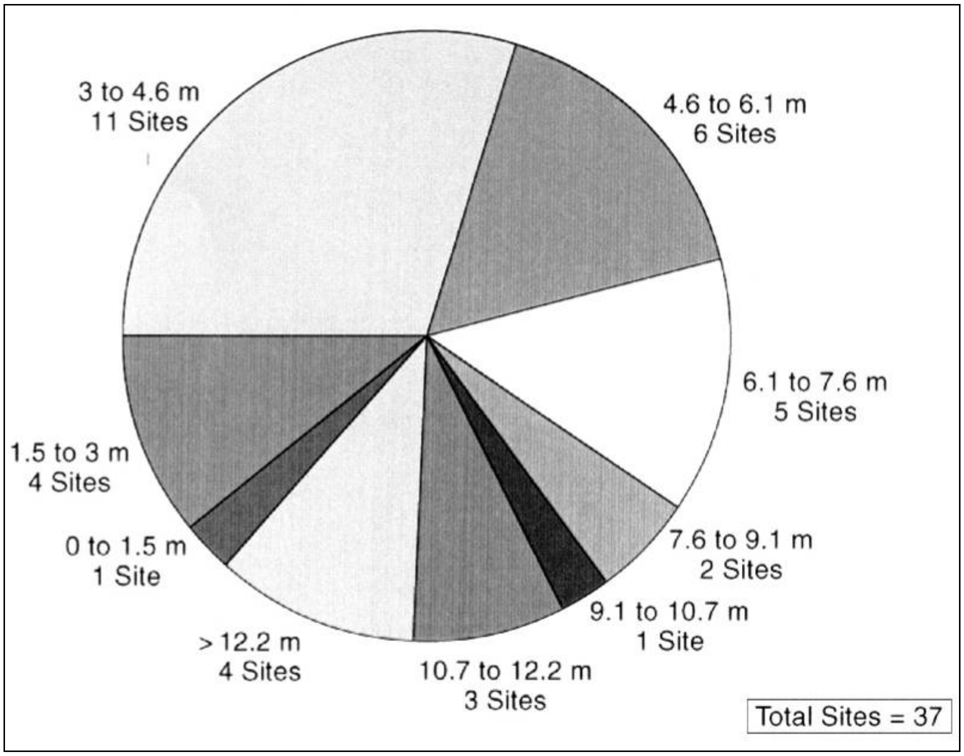

Figure 5-2. Reported in-situ air sparging radius of influence vs. number of sites (after Marley and Bruell 1995).

c. Well Screen Length and Depth.

(1) *Well Screen Length*. Although current research indicates that air often escapes within a very short interval near the top of the well screen, screen length may require some consideration. In the unlikely event that air-entry pressures diminish with depth along the length of well screen to a greater degree than hydrostatic pressures increase over the same depth, some fraction of the air may take deeper exits than would be expected. The result may be an increase in the ZOI, unless air is confined within a few strata.

(2) *Well Screen Depth*.

(*a*) Well screen depth for IAS is defined as the distance between the phreatic surface and the top of well screen. IAS optimal injection depths have not been evaluated rigorously. Typical top of screen depths used are between 1.5 and 4.6 m (5 and 15 ft) below the phreatic surface. Lundegard and Anderson (1996) determined through numerical modeling that, other factors being equal (e.g., no change in anisotropy), the depth of injection does not significantly change the size of the ZOI of the air plume under steady state conditions. Increased injection depth may increase the ZOI under transient conditions. The shallowest injection depth evaluated by Lundegard and Anderson was 3 m below the phreatic surface.

(*b*) When considering the depth of the IAS injection point, it should be noted that with increasing depth there is a trade off between the potential size of the ZOI and the possibility of flow diversion attributable to the stratigraphy. Slight changes in the depth of injection could cause a drastic change in the orientation and geometry of the air pathways and a related change in the ZOI.

(*c*) The primary consideration for well screen depth and placement is to match the three-dimensional contaminant distribution within the saturated zone with the three-dimensional air distribution. In cases where dissolved concentrations occur at significant depths below the water table surface, consideration should be given to focusing air injection deeper within the saturated zone. As a result, typical top of screen depths for pilot tests may in certain cases extend as deep as 15 m (50 ft) below the seasonal low water table (Marley and Bruell 1995). Bear in mind that wells screened at greater depths below the water table will have commensurately higher pressure requirements, which will affect aboveground equipment costs.

(*d*) Where LNAPL exists, consider applying IAS at shallower depths below the water table surface. This depth should ideally be selected based on knowledge of the location of NAPL-filled pores beneath the water table. As described in Chapter 2, LNAPL may be distributed well below the water table, depending on a variety of factors, including historical (since the LNAPL release) water table fluctuations and the pressure-head pushing the LNAPL downward during the release. Field observations of LNAPL saturation beneath the water table should be used to determine the bottom of the LNAPL zone. IAS well screens should be set based on this depth. Without this knowledge, typical top of screen depths for pilot tests are 1.5 to 6 m (5 to 20 ft) below the seasonal low water table. Note the reference made to the seasonal low water table; otherwise, the IAS well may be only seasonally useful. One strategy for setting well depths is to "customize" the screen location for each well based on field observations of LNAPL saturations in core samples when the IAS well is installed. By using knowledge from each IAS well, the IAS well network can be made appropriately specific to the site. Note that air contact with residual LNAPL is sometimes difficult to achieve, in which case the LNAPL may represent a long-term source of low concentrations of dissolved contaminants.

d. Injection and Overburden Pressures.

(1) An overpressure is an injection pressure in excess of what is needed to overcome the hydrostatic pressure imposed by the column of standing water within the sparge well (Marley and Bruell 1995). Some overpressure is required to overcome the air-entry pressure needed to displace water from within the well screen and adjacent soils (paragraph 2-6). It is important that excessive over-pressurization be avoided, however, so that the aquifer does not fracture and the system does not fail. As a general guideline, maximum injection pressures should consider

the weight of the soil and fluid columns above the sparge zone, as well as a design safety factor. The following equations may be used to estimate the pressure exerted by the weight of the soil and water column overlying an IAS well screen at a given depth, with φ being the soil porosity and *s.g.* being specific gravity:

$$pressure_{\text{soil column}} = (depth_{\text{top well screen}})\ (s.g._{\text{soil}})\ (1 - \varphi)\ (9.8\ \text{kN/m}^3) \quad (5\text{-}1)$$

$$pressure_{\text{water column}} = (depth_{\text{top well screen}} - depth_{\text{water table}})\ (s.g._{\text{water}})\ (\varphi)\ (9.8\ \text{kN/m}^3) \quad (5\text{-}2)$$

$$total\ overburden\ pressure = pressure_{\text{soil column}} + pressure_{\text{water column}} \quad (5\text{-}3)$$

$$max.\ injection\ pressure = (0.6\ \text{to}\ 0.8)\ (total\ overburden\ pressure) \quad (5\text{-}4)$$

(with a minimum safety factor of 35 kPa or 5 psig)

(2) If porosity has not been measured, it is strongly recommended that a conservative porosity of 40 to 50% be used in the above calculations (Wisconsin DNR 1993, 1995). It should be noted that although fracturing attributable to over-pressurization may cause additional macro-channels to develop and airflow rates to increase, the air–hydrocarbon mass transfer rates may actually decrease because of smaller interfacial (air–water) surface area.

(3) The following simplistic example is provided to illustrate estimation of the overburden pressure and maximum injection pressure (Wisconsin DNR 1993, Marley and Bruell 1995):

(*a*) Assumptions are as follows.

- Soil specific gravity of 2.7, and groundwater specific gravity of 1.0.
- Water table depth of 5.5 m below ground surface (bgs).
- IAS well screened from 9.1 to 10.7 m bgs.
- Porosity of 40% (0.40).
- Soils are homogeneous, isotropic and unconsolidated.

(*b*) Employing equations 5-1, 5-2, and 5-3, we estimate the overlying pressure exerted by the weight of the soil column as follows:

$$Pressure_{\text{soil column}} = Weight\ of\ soil/\text{m}^2 = (9.1\ \text{m})(2.7)(1 - 0.4)(9.8\ \text{kN/m}^3) = 144\text{kN/m}^2$$

$$Pressure_{\text{water column}} = Weight\ of\ water/\text{m}^2 = (9.1\ \text{m} - 5.5\ \text{m})(0.4)(9.8\ \text{kN/m}^3) = 14\ \text{kN/m}^2$$

Total weight of soil and water/m^2 = 144 + 14 =158 kN/m^2

Total overburden pressure = (158 kN/m^2) 1 (kPa/[kN/m^2]) = 158 kPa at 9.1 m bgs (23 psig at 30 ft).

(*c*) In this example, injection pressures greater than 158 kPa (23 psig) could cause system problems and secondary permeability channels to develop. Therefore, using a maximum injection pressure of 60% of the overlying pressure (i.e., a conservative safety factor of 40%), we arrive at a maximum injection pressure of 95 kPa or 14 psig for this example. Designers must remember that each site has specific conditions and requirements, should use all available information when doing these calculations (such as water table fluctuation data), and should evaluate additional geotechnical information if available.

(4) Taking both the calculated pressure data and the pilot test data into consideration, the designer can calculate the pressure necessary to deliver the desired airflow rate under all seasonal operating conditions. Professional judgment is required to determine design pressures and flow rates for each IAS well, and to balance flows among wells in a well field. In the final analysis, balancing flows will depend on factoring in system monitoring data obtained during operation (see Chapter 6). If an airflow rate of approximately 0.01 m^3/min (0.4 scfm) per well cannot be maintained, the soil permeability may be too low and IAS may not be appropriate for the site.

e. Depth to Groundwater and Seasonal Variations. The depth to water and temporal variations in the piezometric surface should be evaluated prior to design. This information is necessary to assure proper screen placement and compressor selection, as the size of the compressor is largely dependent on the hydrostatic pressure associated with the standing water column. It may be necessary to complete borings with vertically discrete well screen clusters (i.e., with two screen depths) for sites with significant fluctuations in seasonal groundwater elevation.

f. Well Field Design.

(1) *General*. The number and placement of air injection wells should be chosen to maximize the air–water interfacial area within the zone of contamination. Well placement is derived from the anticipated ZOI determined from a site-specific pilot test. Techniques for evaluating a ZOI have been described in Table 4-1. Well placement is also a function of water table depth and soil conditions (i.e., heterogeneity, classification, etc.). A typical site plan is shown as Figure 5-3.

(2) *System Configurations*. IAS systems may be used for both source area treatment and contaminant plume control. The distribution and configuration of wells used for these purposes varies according to site constraints.

(*a*) Examples of IAS system configurations include:

- A linear orientation of wells perpendicular to groundwater flow direction (e.g., a sparging curtain).

- Nested wells (IAS and SVE at different depths of the same borehole) distributed throughout a plume or source area.

- Encapsulation of the contaminant plume (i.e., surrounding the plume with IAS wells).

- Horizontal IAS wells.

(*b*) When using sparge curtains, care must be taken in both the design and operation to ensure that sufficient contact is achieved between the sparged air and the contaminated groundwater plume passing through the curtain. To the extent that air channels cause a decrease in hydraulic conductivity and an increase in upgradient head, a sparge curtain may result in contaminated groundwater migration around the curtain. The IAS well network configuration and mode of operation should account for this possibility (see discussion of pulsing, paragraph 6-6b). Similarly, encapsulation systems must be designated and operated to account for transient groundwater mounding that will occur with the injection of sparged air.

(*c*) For some applications, horizontal wells can be extremely useful. Horizontal wells or sparging trenches have been used at sites with shallow aquifers, long, thin contaminant plumes, and limited-access plume areas such as under buildings or roads. Typically, fewer horizontal wells are needed but the installation costs per well are significantly higher. Furthermore, it may not be possible to prevent all the airflow from occurring at one portion of the horizontal well screen, although some notable efforts have been made (Wade 1996). Installing a series of shorter, segmented well screens, each with its own air delivery tube and separated by grouted sections, may be necessary, but is apt to be expensive. Construction of horizontal IAS wells is addressed in paragraph 5-4c, as well as in USEPA (1994) and Larson (1996).

(*d*) If the well configuration selected only addresses a portion of the plume, groundwater extraction may be required to control lateral migration. Conversely, if IAS wells extend to the perimeter of the contaminant plume and therefore contain contaminant migration, groundwater extraction wells may not be necessary. The system designer should completely understand site conditions and choose a configuration that will effectively accomplish site-specific treatment goals.

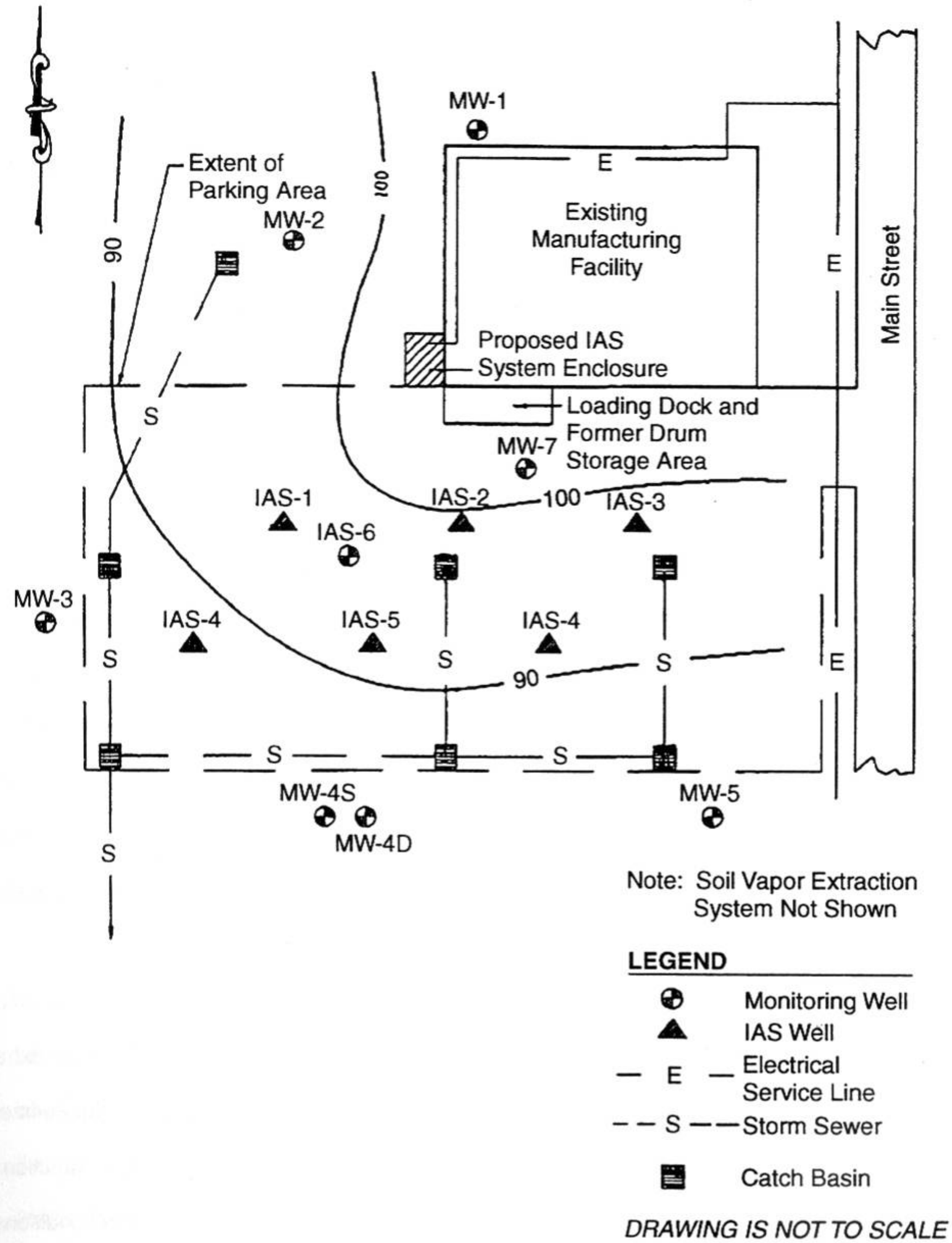

Figure 5-3. Typical IAS site plan.

5-4. Subsurface Construction

During IAS system operation, lateral distribution of dissolved contaminants in the saturated zone may increase because of horizontal vapor movement (Brown and Fraxedas 1991) and induction of new groundwater flow patterns (Marley and Bruell 1995). To account for this potential, monitoring wells and air sparging wells should be placed near the perimeter of the contaminated zones. Alternatively, the well system design and piping layout should be prepared for the possibility of future expansion should evidence of plume spreading arise, with capped tees to provide the capability of adding peripheral wells, if necessary. Prior to finalizing the well layout, care should be taken to locate existing utilities. IAS wells, utilities, and appurtenances should be relocated as necessary. Site access, including considerations for support facilities, storage areas and parking, should also be identified to prevent the potential release or migration of contaminants by installation equipment during construction (e.g., air-rotary drilling might push vapors into a nearby basement).

a. Vertical Sparging Wells.

(1) *Casing*. New polyvinyl chloride (PVC), 50 mm (2 in.) in diameter, is normally used for sparging well casing (Figure 5-4). Larger diameters may be needed to increase flow capacity, but require larger boreholes. Assess pressure drop inside well casing and screen diameters based on the pneumatic analysis procedures used for piping. Other materials may be specified if air amendments or site contaminants, at expected concentrations, are likely to be damaging to PVC. Materials with appropriate physical properties and chemical resistance may be used in place of PVC where economical. Use heat-resistant materials if thermal enhancements may be applied at the site. The casing must be strong enough to resist the expected air and grout pressures.

(2) *Screen*. Well screen is usually PVC with slotted or continuous wrap openings. Continuous-wrap screen is strongly preferred because the increased open area reduces the pressure drop across the screen and therefore reduces energy costs for the blower. Special “diffuser” tips that are promoted for use in lieu of conventional screens may result in a higher pressure drop for a given flow of air than conventional screens. Such diffuser tips neither result in bubble migration in the formation nor alter the flow of air through discrete channels in the formation.

(3) *Filter Pack*. Choose filter pack material according to methods outlined in a text such as Driscoll (1986).

(4) *Seal and Grout*. A well seal is necessary to prevent entry of grout into the filter pack and well screen. Unamended sodium bentonite, as pellets, granules, or a high-solids bentonite grout, is normally specified for the seal material. A cement grout is preferred to fill the annulus above the seal to the ground surface because it resists desiccation cracking. The mixture of the grout should be specified and is normally one 42.6-kg (94-lb) bag of cement (optionally with up

to 2.25 kg [5 lb] of bentonite powder to further resist cracking), with less than 18 L (5 gal.) of clean water. Reference ASTM C 150 in the specification as appropriate.

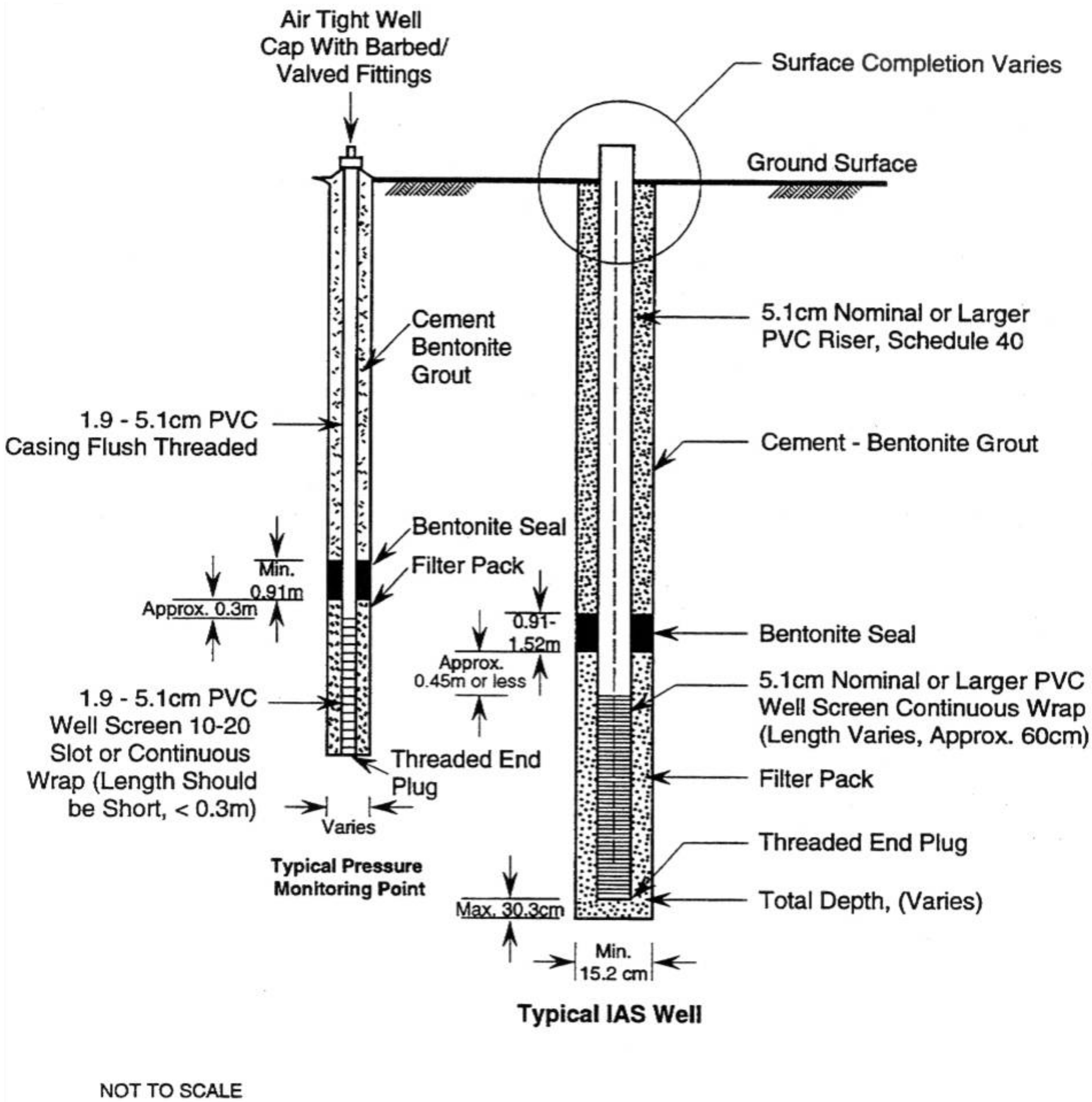

Figure 5-4. IAS well/monitoring point construction details.

(5) *End Caps/Centralizers*. Flush-threaded end caps, consistent with the casing and screen in size and material, should be specified. Centralizers center the well in the borehole and must be a size appropriate for the casing and borehole.

(6) *Drilling Methods and Borehole Dimensions*. There are many methods for drilling air sparging wells. Avoid methods that result in significant formation damage that may be difficult to overcome by well development. For example, some drilling methods potentially smear clay on the borehole wall. This may ultimately require elevated air injection pressures to push air into the formation or may actually alter air paths into the formation. It may be useful to sample soils at regular intervals (a frequency of 1.5 m [5 feet] is common) to evaluate stratigraphy above the water table. It is critical, however, to continuously sample soil below the water table at the depth of contamination to determine whether there are confining strata that will inhibit airflow through the contaminated soil. Materials encountered should be described according to a standard such as ASTM D 2488. Normally, the diameter of the borehole is at least 150 mm (6 in.) greater than the diameter of the casing and screen to allow placement of the filter pack. The depth of the borehole should be based on the planned screen depth. Although direct-push techniques have been used to place air sparging injection points, this method is not recommended. In some cases such placement appears to be successful; however, there is an increased risk of air leakage around the pushed point. This is especially true where significant force was required to drive the casing such that the borehole was enlarged around the casing owing to excessive deflection during placement. In addition, damage can be inflicted on the sparge points during direct-push placement (e.g., sparge point blockage with soils, screen damage). Figure 5-5 shows examples of such damage for direct-push points in glacial tills. Lastly, direct-push points are more difficult to successfully develop than traditional wells. This may result in an increase in required injection pressures and, at best, higher energy costs or, at worst, unequal injection pressure, causing preferential flow into a single or a few sparge points and no flow into others. The screens in the direct-push points shown in Figure 5-5 were sufficiently compromised to limit airflow, even at very high pressures, causing preferential flow into other undamaged sparge points.

(7) *Well Placement and Wellhead Completion*. Wells should be constructed as any other water well. Refer to EM 1110-1-4000 for typical installation techniques and requirements. The completion of the wellhead will depend on the other features of the design, such as the piping and instrumentation requirements. If there is any standing water in the well above the bentonite seal, grout needs to be tremied into place to displace that water. Fit each wellhead with both a pressure gauge and a shutoff valve, and possibly a flow-measuring device. Each well requires proper development, as described in Driscoll (1986) or USEPA (1975). Establish the horizontal coordinates of the well by survey. Survey the elevation of the top of the casing. The accuracy of the surveys depends on the project needs, but generally is to the nearest 0.3 m (1 ft) for the horizontal coordinates and the nearest 0.003 m (0.01 ft) for elevation.

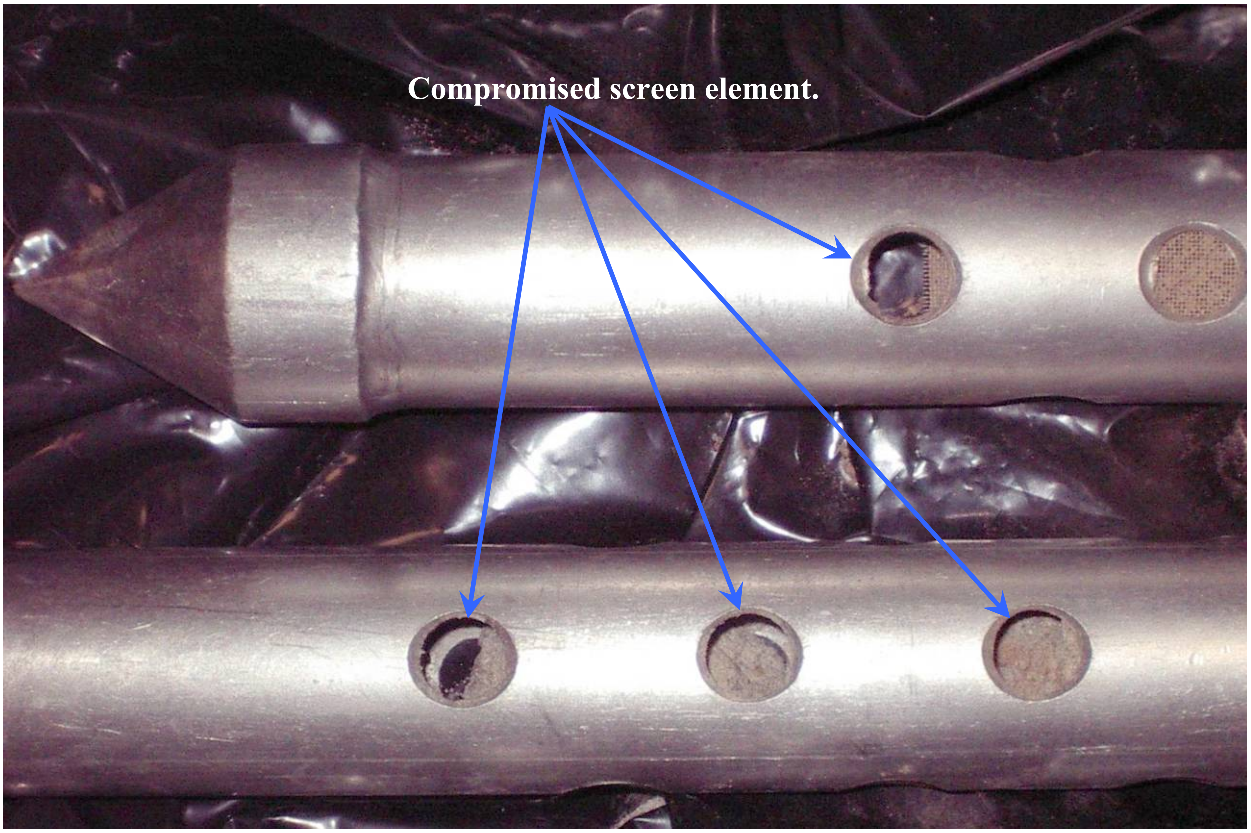

Figure 5-5. Example of "failed" direct push sparge point.

b. Soil Gas/Pressure Monitoring Points.

(1) *Well Materials*. Generally, the same materials can be used for the monitoring points as for the extraction wells; however, there may be a difference in size. Generally, 20- to 50-mm (3/4- to 2-in.) diameter PVC pipe is used. Flush-threaded pipe is preferred, but for smaller diameters, couplings may be needed. Either slotted or continuous-wrap screen can be specified. Slotted pipe is adequate for monitoring points. Other screen types can be used. Options include slotted drive points and porous points. Keep screen length to a minimum to avoid air short-circuiting long vertical distances through the screened interval. Filter pack material, if required, should be appropriately sized for the screen slot width.

(2) *Installation*. Although a hollow-stem auger is still the primary means of installing monitoring points, direct-push methods can also be used to place slotted drive points or other pressure or soil gas probes at specific depths. Sample the materials encountered for logging and physical and chemical testing. The borehole diameter should be approximately 101 mm (4 in.) larger than the screen and casing to allow placement of the filter pack. This obviously would not apply to points placed by direct-push methods. Monitoring point depth selection is entirely site

dependent, but monitoring of multiple depths within the zone to be monitored is recommended. Casing, screen, and annular material are normally placed by methods similar to those used to install sparging wells; however, direct-push techniques are rapid alternatives for placing monitoring points to the desired depths. Actual means of placement depends on the system, materials used, and site geology.

(3) *Surface Completion*. Complete the monitoring points with a suitable barbed or valved sampling port or septum attached by threaded connection to an appropriate end cap. Attach the cap to the top of the casing by an airtight connection. The points can be set above grade with suitable protection or below grade, typically in a flush-mount valve box. Survey each monitoring point to same accuracy as the air sparging wells.

c. Horizontal Wells.

(1) Horizontal wells can be used for sparging provided adequate steps are taken to assure uniform air delivery. Pay careful attention to the vertical well alignment to avoid preferential air injection at high spots (which have lower hydrostatic pressures) in the screen. Avoid using drain pipe wrapped with geotextile or other filter-like materials because of the potential for fine material to plug the openings. Perforated piping is more difficult to develop and rehabilitate than continuous slot screen. Prepacked. continuous-slot screens have been successfully used in sparging applications. There are porous materials, including porous sintered polyethylene, that have also been used very successfully as screen and filter pack in horizontal wells. Refer to USEPA (1994) for additional design guidance.

(2) Successful use of horizontal wells has been documented at a number of site locations, including the Department of Energy's Savannah River site (USDOE 1995), a formerly used Defense site near Hastings, Nebraska, as documented by the U.S. Army Engineer District, Kansas City (Siegwald et al. 1996), and the Guadalupe Oil Field in central California. At the Savannah River and Hastings sites, the horizontal wells involved sparging sections over 60 m (200 ft) long. Air distribution was good in both cases. In the Hastings project, special tubing runs were terminated within different sections of the horizontal run to verify full displacement of water by air within the well. The chlorinated organic plume being treated at the Hastings site apparently began to migrate around the ends of the sparging curtain. Groundwater flow models calibrated to water levels observed during sparging suggested that formation transmissivity was reduced by over 50% because of the creation of air-filled porosity. At both the Savannah River and Hastings site, a horizontal well was used for injection of air, methane, nitrous oxide, and triethyl phosphate into the saturated zone to enhance co-metabolic bioremediation of chlorinated organics. At the Guadalupe site, the horizontal well was 58 m (190 ft) long with a 15 m (50 ft) long screen. This well was installed in relatively uniform eolian dune sand, and carefully monitored during a 6-day pilot test. Electrical resistance tomography (ERT) results showed that there was uniform airflow from the entire screen into the formation. However, the ERT data indicated that

the airflow was confined to within 1.5 m (5 ft) of the well. Dissolved oxygen data indicated that the influence of the well was limited to a 2.3 m (7.5 ft) region on either side of the well axis.

d. Sparge Trenches. Sparging trenches can be used effectively at sites with shallow contaminated groundwater or as the treatment gate in a funnel and gate system. The placement of a sparging trench can be accomplished by several methods including normal excavation or trenching machines (which excavate and place pipe and filter pack in one pass). Figure 5-6 illustrates a typical sparging trench.

(1) *Construction Materials*. Although PVC casing is commonly used, flexible or rigid polyethylene pipe may be more efficient for certain excavation methods, such as trenching machines. The pipe must resist the crushing pressures of the backfill and compaction equipment. Screen can consist of slotted pipe, continuous slot screen, or porous material. The guidance for specifying filter pack in vertical sparging wells may be applied for trenches, but somewhat coarser material may be needed for a secure bedding and cover for the pipe and screen. For treatment gates, use uniform coarse material which has typical pore sizes larger than 2 mm. This results in bubble flow, rather than channel flow, and higher mass transfer efficiency. Coarse material (uniform coarse sand or gravel) also provides a high hydraulic conductivity during sparging and assures adequate flow capacity for a treatment gate. Native material may be used as backfill above the filter pack in an excavated sparging trench. Coarse filter pack material may extend into the unsaturated zone especially if there is an overlying SVE system.

(2) *Excavation and Placement Methods*. Methods used to install sparging trenches include many standard earth-excavating equipment (e.g., backhoe) and trenching machines. Given this wide variety, it may be desirable to specify only the pipe, screen, pack materials, and an ultimate pipe alignment and depth. The trenching technique used by the contractor must provide an adequate filter placement around the collector pipe. Dewatering or shoring will be required in most cases. Compliance with Occupation Safety and Health Administration and USACE safety requirements is mandatory. Piping and screen placement is very similar to placement of piping for underground utilities and leach fields. Refer to ASTM F481.

5-5. Manifold and Instrumentation Design

a. General.

(1) Figure 5-7 is a schematic diagram that includes a typical IAS piping and instrumentation diagram (P&ID).

(*a*) IAS manifold components commonly include the following.

- Pressure, flow, and temperature gauges.

- Pressure relief valve or bypass line.
- Excess air bleed valves.
- Throttle valves.
- Manifold piping or hose.
- Check valves.
- Optionally, solenoid valves and sample ports (to enable groundwater sampling to check for rebound at later times).

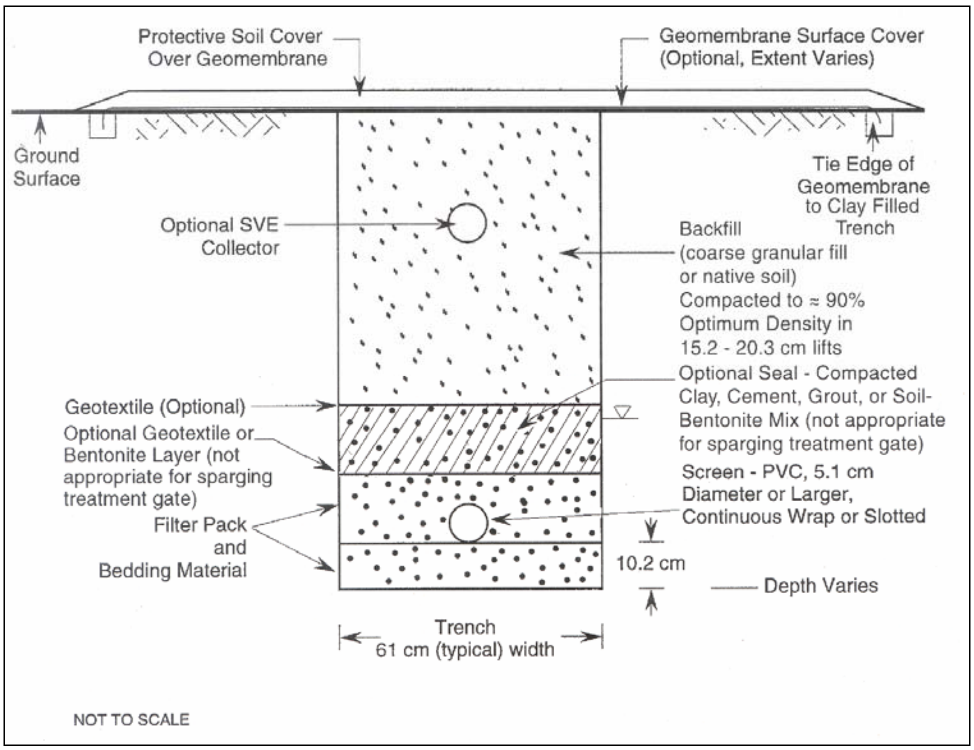

Figure 5-6. Typical horizontal IAS well design.

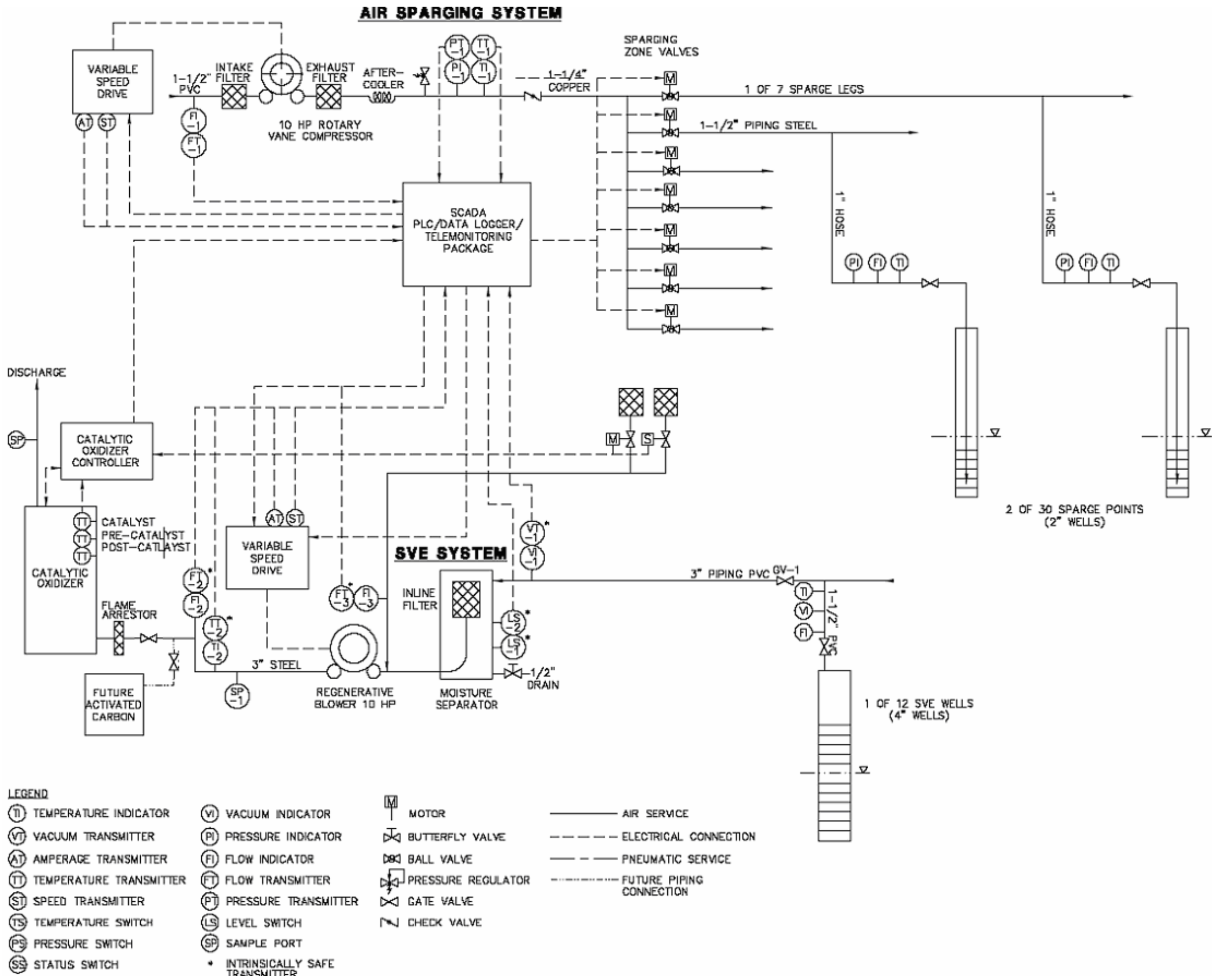

Figure 5-7. Example IAS and SVE piping and instrumentation diagram for an IAS system with 30 IAS wells on 7 "headers" or "legs" and 12 SVE wells.

(*b*) Each of these components is discussed below. The piping system can be designed for installation either above or below the ground surface, depending on the traffic requirements of the area and the need for adequate protection against frost.

(2) Table 5-2 provides an example of the control logic that might be used with the system shown in Figure 5-7. When designing an IAS system, site specific factors dictate the types of control features and the degree of system automation. Systems that have a full-time operator are monitored and controlled differently than are remote systems that only get infrequent O&M visits. Table 5-2 references a system controller with autodialer that is used to relay system data to

the operator, such as abnormally high pressure in the sparge manifold indicating blockage in the piping. Development of control logic, as shown in this table, is required to complete an IAS design.

b. Design and Installation of the IAS Manifold. Beginning at the outlet of the air supply source (typically a compressor, blower or gas cylinder), compatible materials are connected to supply headers for the IAS wells. Typical manifold construction materials include metal piping, rubber hose, or ABS pipe. PVC pipe, although in common use, is not recommended by manufacturers for above-ground air pressure service. PVC pipe is acceptable for below ground installation as long as it is strong enough to resist maximum air pressures. Pipe sizes are flow and pressure dependent; see EM 1110-1-4001 for pipe sizing. Design for installation of plastic pipe above grade should have provisions for movement ascribable to thermal expansion and contraction in accordance with Plastics Pipe Institute (PPI) TR-21(2001).

(1) Prior to routing to individual IAS well supply, permanent pressure and temperature gauges and switches, along with an air flow meter, are installed for quick visual measurements during routine system checks. They are also installed potentially for interlock connection to the electrical supply in case the system does not conform to specified operating conditions. These permanent measurement devices should be installed in accordance with the manufacturer's recommendations for length of unobstructed flow, etc. A pressure relief valve (manual or automatic) or system bypass line should be installed to exhaust excess pressure from the manifold. This will prevent excessive pressure that could cause damage to the manifold or aquifer. Exhaust air can be directed to the atmosphere or to the air source intake. A silencer for the blower or compressor exhaust should be considered, based on site conditions and air velocities.

(2) A header from the manifold to each well must be designed (Figures 5-8 and 5-9). The designer must evaluate all reasonable construction options for piping materials and the associated costs to determine the most effective air delivery system to each IAS well. Once the piping materials are selected, each well should have a throttle valve, check valve, temporary ports for flow, pressure and temperature measurements, groundwater sampling port and, optionally, a solenoid valve. The throttle valve is used to adjust airflow or to isolate a well from the manifold system. Typical throttle valves used are gate, globe, butterfly, or ball valves. Check valves are installed on each well to prevent temporary back-pressure in the screened interval of the aquifer from forcing air and water up into the manifold system when airflow to a well ceases (Marley and Bruell 1995). Check valves are also very important for minimizing the mobilization of silt towards the IAS well from backpressure when airflow ceases, particularly during pulsed operation. If the system is not pulsed, but rather operates continuously, and a check valve is not installed on each well, then a single check valve should be located on the manifold line between the permanent instrumentation and the gas pressure source.

Table 5-2
Instrumentation and Control Logic for Example IAS and SVE System

Motor, Valve or Switch	Control Logic	Signal to Autodialer
SVE vacuum blower motor	If vacuum blower motor ceases operating, de-energize IAS compressor motor and catalytic oxidizer (unless catalytic oxidizer has an internal flow sensor to perform identical function)	If vacuum blower motor stops operating, notify operator via autodialer
Catalytic oxidizer thermal safety switch	If catalytic oxidizers units stop, de-energize SVE blower	If catalytic oxidizer stops operating, notify operator via autodialer
IAS compressor motor	none	If IAS compressor motor stops operating, notify operator via autodialer
Low pressure switch on IAS compressor outlet	If pressure is too low (indicating a piping leak or that the pressure relief valve has released), de-energize IAS compressor motor	If pressure is low (indicating no or low flow), notify operator via autodialer
High water level switch in water knock-out tank	If high water level switch makes contact, de-energize SVE blower motor	If water level is high, notify operator via autodialer
Low vacuum (high pressure) switch prior to SVE blower	If vacuum is low (indicating leak in SVE piping), de-energize SVE blower motor	If low vacuum (high pressure) switch is triggered, notify operator via autodialer
Low pressure switch after SVE blower	If pressure is low (indicating leak in piping to catalytic oxidizer), de-energize SVE blower motor	If low pressure switch is triggered, notify operator via autodialer
Vacuum relief valve prior to SVE blower	Allows ambient air to be drawn in if clogging in SVE occurs	None
Pressure relief valve on outlet of IAS compressor	Releases compressed air if IAS lines become clogged	None

(3) One or more ports that can be used for temporary measurements of airflow, pressure, and temperature are recommended for system-optimizing adjustments during operations. Solenoid valves are optional features and their use is dictated by the system operating and control strategy. If pulsed operation of the system is anticipated for more effective remediation or reduced energy consumption (discussed in more detail in paragraph 6-6b), solenoid valves should be installed for individual well activation and deactivation. Timers, either analog or programmable logic control (PLC), can be employed to control solenoid valves as desired. It should be noted that check and solenoid valves may significantly restrict air flow or generate significant line pressure drops. The pressure drop across these appurtenances, if they are used, must be accounted for when sizing manifold piping. Also, all manifold instruments should be constructed with quick-connect couplings for ease of maintenance and removal.

(4) The manifold that supplies air to each IAS well is often installed underground, below the site's frost line. Above-ground installation designs should be reviewed for items such as shock load and potential vehicular damage. All construction, including excavation, trench bottom preparation, and backfilling and compaction should be done in accordance with industry accepted standards. The manifold sizing is site specific and depends on factors such as airflow rates, pressure losses, material costs, and line distribution patterns. As stated above, although often considered convenient for short-term tests, PVC is neither intended nor recommended for above-ground air pressure service. All piping should be installed in accordance with the manufacturer's recommendations. If rubber hose or ABS pipe is used, tracing tape or other appropriate material that can be detected by a metal detector should be included after the installation is completed for future location. Once the manifold has been completed to each well, high pressure air hose or hard pipe, accompanied with couplings and plugs, can be used to secure the manifold to the well header (Marley and Bruell 1995). Care must be taken to ensure that the pressure drop through this connection is accounted for by using manufacturer recommended friction loss factors when calculating the minimum pipe diameter.

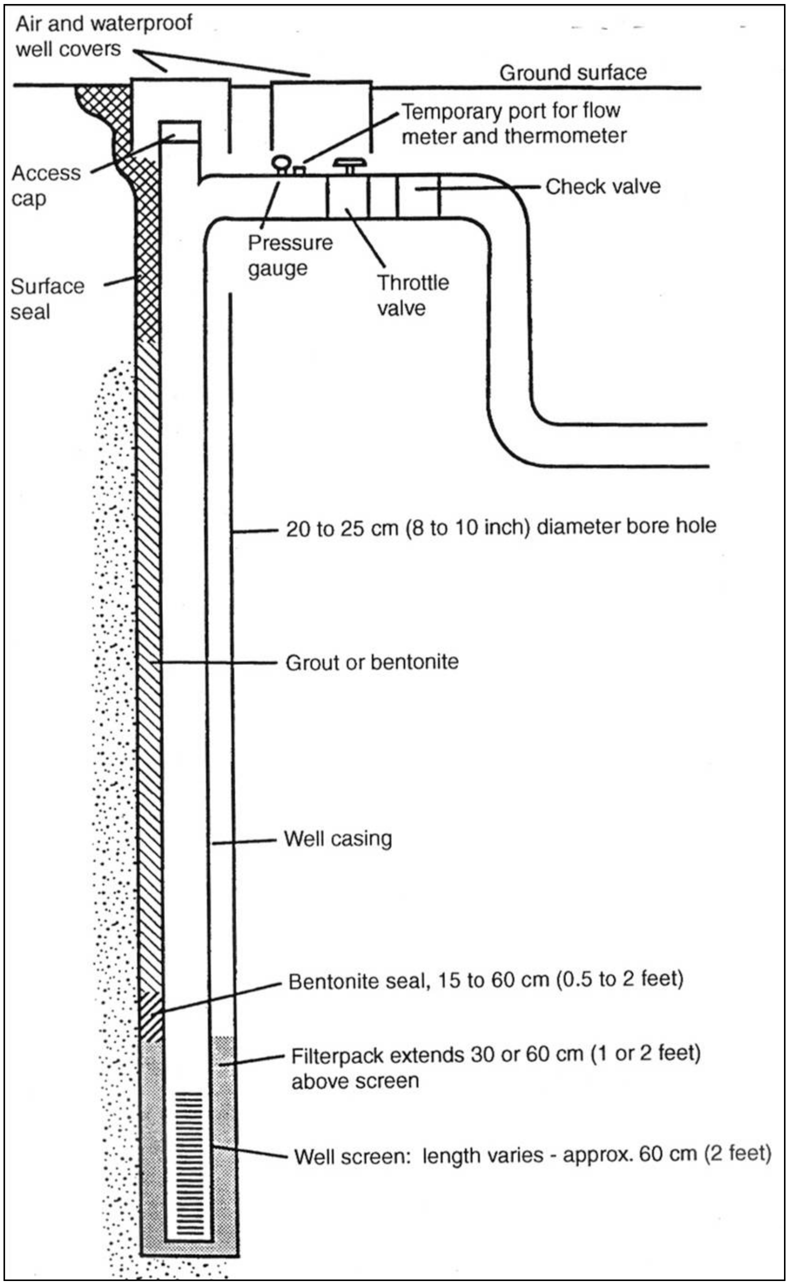

Figure 5-8. Typical air sparging well design and wellhead completion (after Wisconsin DNR 1993).

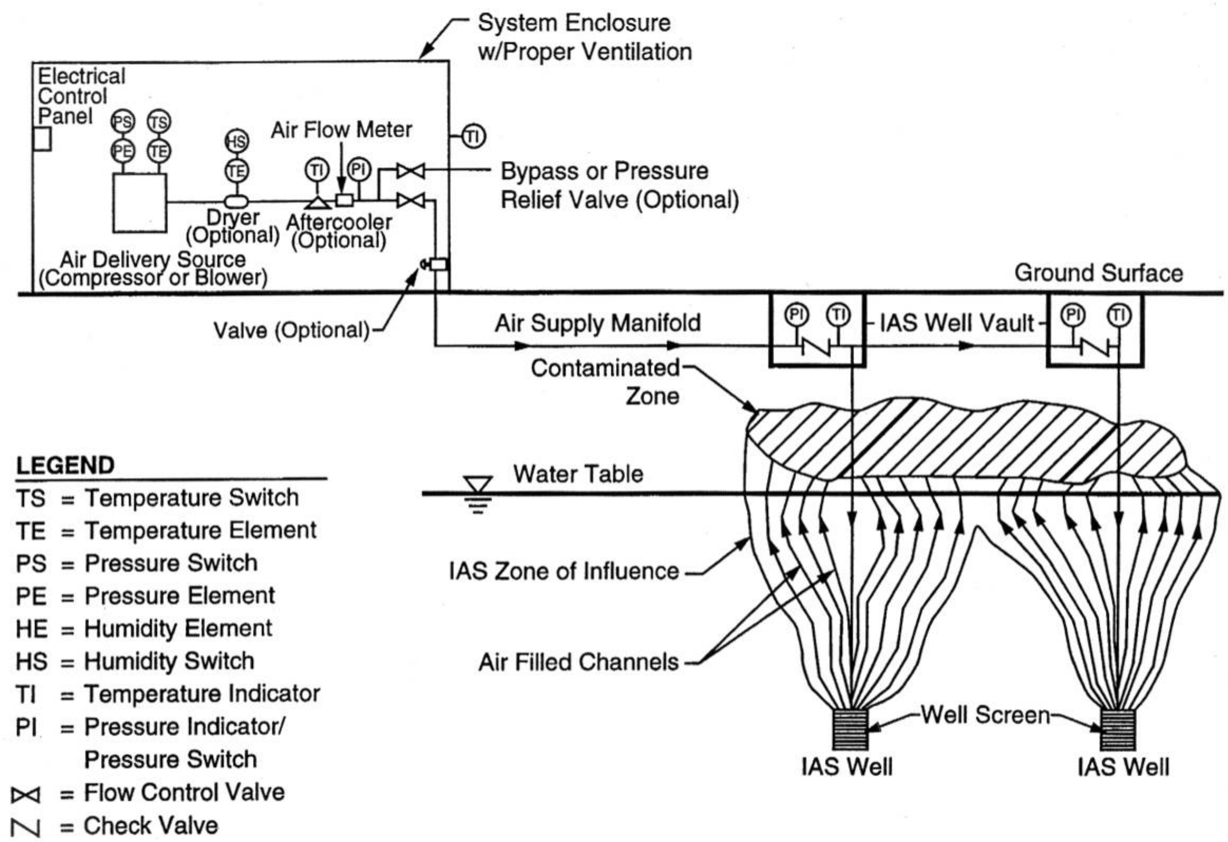

Figure 5-9. Typical IAS preliminary system diagram. At this site the contamination resides largely within the capillary fringe.

5-6. Air Delivery Equipment Design

a. General. Air delivery sources are designed based on system requirements developed from pilot tests, and based on design calculations of required minimum pressures attributable to hydrostatic head, air-entry pressure head, and manifold losses. When the total system design calculations are completed and pilot test data are reviewed, the optimum pressure and flow for each well is determined for the site-specific geological and physical domain. The air supply is typically delivered by either an air compressor or blower.

b. Unit Selection.

(1) The first consideration when beginning calculations for operating pressures is to avoid excessive pressures that could cause system to malfunction or create secondary permeability in the aquifer. To begin to estimate minimum and maximum air pressures required for operation,

the designer should assume that the pressure must at least equal the hydrostatic pressure at the top of the well screen plus the air-entry pressure required to overcome capillary forces. Calculating the hydrostatic pressure further down on the well screen will be necessary if the designer wants to take advantage of more of the screen, air entry pressures notwithstanding. For calculating the minimum required system operating pressure, the designer should use the common conversion (equation 2-2) that each foot below the water table equals 0.43 psig of hydrostatic pressure (or equivalently, that each meter equals 9.74 kPa), and add the estimated air-entry pressure, yielding the minimum operational pressure required. The designer should be careful to consider water table fluctuations when estimating the top of screen depth below the water table.

(2) Table 5-3 summarizes the features of various types of air delivery equipment. When selecting air delivery equipment, the unit must be capable of producing pressures sufficient to depress the water table in all IAS wells below the top of the screen and deliver the required air flow to each well. Additional considerations, such as explosion-proof equipment, silencers, dryers, filters, and air coolers, are discussed below. Common air delivery sources, along with a brief explanation of mechanical and operational considerations and the interrelationship with the design variables, are listed below. The designer should select air delivery equipment whose pump curves indicate that the unit will operate efficiently within the design pressure and flow ranges. As with any equipment selection, the designer should contact the vendors or manufacturers and review performance curves (i.e., blower curves) prior to specification. All units should be rated for continuous duty.

(*a*) *Reciprocating Piston Air Compressors*. These units are used when the application calls for high pressures (e.g., for an IAS well screened at considerable depth below the water table); however, they generally deliver a relatively low flow rate. Only oil-less units should be specified to ensure that lubrication oils are not injected into the subsurface if there is a mechanical failure. These units are capable of producing substantial pressures that could cause manifold problems. Therefore, the designer should install an automatic pressure relief valve on the air compressor outlet if this type of unit is specified. Please note that reciprocating compressors can be expensive.

(*b*) *Rotary Screw Air Compressor*. While providing a wider range of capability (up to 1100 kPa [160 psig] at moderate flow rates) for IAS service, these units typically contain oil, which could accidentally be discharged into the subsurface. Therefore, a filter should be employed to ensure removal of any oil in the air compressor outlet. These units are acceptable for IAS service but may be more expensive and require more maintenance than reciprocating compressor units.

Table 5-3
Typical IAS Air Delivery Equipment

Compressor/blower type	Maximum pressure range	Typical capacity per motor size	Features
Reciprocating piston air compressor	100–125 psi	2 hp, same unit: 10 cfm @ 16 psi 7 cfm @ 100 psi	-useful for deep sparging or with tight soils -relatively constant flow through a wide pressure range -long service-free life -relatively high air pulsations -loud -low flow -high pressure
Rotary screw air compressor	100–175 psi	7.5 hp, same unit: 32 cfm @ 100 psi 23 cfm @ 150 psi	-useful for deep sparging or with tight soils -moderate flow at high pressures -oil lubricated - potential for oil discharge -very high flow units available -quieter than other types
Regenerative blower	5–10 psi	5 hp, same unit: 60 cfm @ 5 psi 40 cfm @ 8 psi	-more often used for SVE than IAS -relatively less expensive -flow decreases as higher pressures needed -no preventive maintenance required -no air pulsations -very high flow rates possible -relatively inexpensive
Rotary Lobe blowers	10–15 psi	5 hp, by changing rotational speed: 130 cfm @ 6 psi 60 cfm @ 10 psi	-more often used for SVE -flow can only be changed by changing motors, chassis, or belt drive -relatively constant flow and pressure with fixed speed motor
Rotary vane compressors	15–20 psi	5 hp, same unit: 30 cfm @ 10 psi 35 cfm @ 5 psi	-most common unit for IAS -quieter than other types -oil lubricated models need oil filtration -oil less models may need filtration of carbon dust -rather flat pressure/flow curve (i.e., similar flow @ a range of pressures) -10K–20K hr service-free operation

(*c*) *Regenerative Blowers*. Regenerative blowers are used for typical low pressure applications of up to 70 kPa (10 psig) (i.e., sites conducive to air flow at low pressures). They are more often used for creating high flows at low vacuums for SVE applications than for IAS injection. There are several advantages associated with using these units, including low capital cost, low maintenance, and oil-free air delivery. If higher pressures are required, a multi-stage blower system may be used.

(*d*) *Rotary Lobe Blowers*. These units are typically capable of producing up to 100 kPa (15 psig) service. The units may have an oil-filled gear case and should use a filter for oil removal as necessary. If higher pressures are required, a multi-stage blower system may be used. Advantages of this type of equipment include low maintenance and flexibility of operating pressure range by adjustment of belt drives to modify the blower speed.

(*e*) *Rotary Vane Compressors*. These compressors are very often used for IAS applications and are available in oil-less or lubricated models. They develop pressure by having sliding flat vanes in an eccentric-mounted rotor that are flung outward against the bore of the pump. Typical maximum air pressures are in a medium range of 100–135 kPa (15–20 psig). While different size compressors are available for a range of flows, the flow generated by a specific unit does not vary greatly against varying pressure heads.

(*f*) *Considerations Common to all Blowers*. Air is usually supplied to the specified compressor or blower unit from an ambient air intake. It may be necessary to install an inlet filter to remove particulate matter based on the location of the intake. If possible, the unit should be located away from possible contaminant sources (including soil venting systems). Non-explosion proof equipment may be used if the unit and appurtenances are located in a safe environment. Local electrical and building inspectors may require the use of explosion proof equipment for a particular site.

(3) Compression of air can generate a significant amount of noise and heat. A silencer or appropriate noise controls should be considered for all applications, especially in noise sensitive conditions. Excess noise can typically be reduced to acceptable levels through the proper application of standard noise reduction materials in equipment housing areas. Refer to EM 1110-1-4001 for further guidance. Additionally, as part of the system design, anticipated system exhaust temperatures should be calculated to ensure that discharge piping is able to withstand the compression discharge temperature and pressures. All discharge piping should be properly anchored to overcome pressure forces generated from the unit. The air injection discharge should have temperature and pressure elements and switches that are interlocked into the electrical control panel for automatic shutdown when the pressure or temperature exceeds safe operating criteria. An aftercooler can be used to reduce the discharge temperature to acceptable levels before it enters into manifold systems.

5-7. Power Distribution and Controls

a. Electrical Service and Single-Line Diagram. Electrical service needs for the IAS system should be planned at the beginning of the design phase. The design philosophy must emphasize technical requirements, safety, flexibility, and accessibility for operation and maintenance. All electrical work must be done by licensed contractors and in accordance with all applicable codes and standards, including the National Electric Code and local requirements. If there is a potential for vapors to accumulate, show NFPA 70 hazardous area classification on the drawings. It is necessary to identify the existing service voltage to project the loads for motors and equipment. The loads are then noted with the use of a single-line diagram. Planning should include anticipating future power needs that might be required (e.g., if the system might be expanded). The single-line diagram is an excellent tool to communicate the power needs to the electrical utility company, or in the case of an industrial setting, to communicate with the plant electricians. The single-line diagram, also called one-line diagram, graphically depicts the power requirements of each load device of the system. If a separate or new electric service is necessary, the electrical utility will have to determine if capacity exists on their existing transformer or whether a new transformer is required. The requirements and cost for a new transformer are a function of project electrical power to be consumed over the duration of the project. Consulting a local electrician and the electrical utility during the beginning of the design phase will ensure that equipment selected is suited to the available power. Figure 5-10 is an example of a preliminary single-line diagram for the example P&ID (Figure 5-7).

b. Control Systems. An integral aspect of the system design is considering operational controls and contingencies. System controls are site specific and may include items such as automatic shutdown devices if operational design exceedances are encountered (e.g., temperature or pressure), programmable logic control (PLC) operation of solenoid valves during system cycling, and system shutdown owing to high water levels in SVE knockout pots. Exterior warning lights, alarms and telemonitoring may be part of the system controls. It is useful to develop the system control logic during the early stages of design to ensure that the system P&ID includes all of the relevant controls and monitoring devices.

c. SCADA. Supervisory Control and Data Acquisition (SCADA) is the combination of the controls of a PLC, telemonitoring, and data logging. SCADA systems may increase the capital costs for IAS systems over more conventional control systems. However, these costs are typically recovered during system O&M through reduced downtime and increased maintenance efficiency. In the event of system failures, the SCADA package will notify of the failure, and personnel can remotely (e.g., from the office) communicate with the site to download data collected prior to the failure. The data can be analyzed to find the events that led up to the failure. The problem can sometimes be remedied remotely by modifying system operating or control parameters. If not, then a better-informed technician can visit the site to remedy the failure with appropriate equipment and replacement parts. Other benefits of the SCADA package include data collection used to help prepare reports on system operation and performance. The data can also provide insight for optimizing system performance.

d. Low-Voltage Control Strategy. Remote remediation systems are typically visited by a technician on a weekly to monthly schedule. The technician visiting and maintaining the site will have a multidiscipline background. Often, the technician's first order of expertise will not be electrical controls; therefore, a useful strategy for IAS systems is to implement a low-voltage SCADA control center. A low-voltage (e.g., 24-V) panel will minimize the technician's exposure to dangerous voltages, and yet allow for a qualified technician to open the SCADA panel to troubleshoot. This low voltage SCADA panel can interface to high voltage control panels, motor starter, or variable frequency drives. The specification and strategy for a SCADA panel electrically isolated from voltages above 30 V must be conveyed to the equipment manufacturer or fabricator during the bid process. Not all equipment manufacturers will have built IAS systems with a strategy of panel isolation of low control voltage and power voltage. This strategy of safety is even more important with the use of 480-V power.

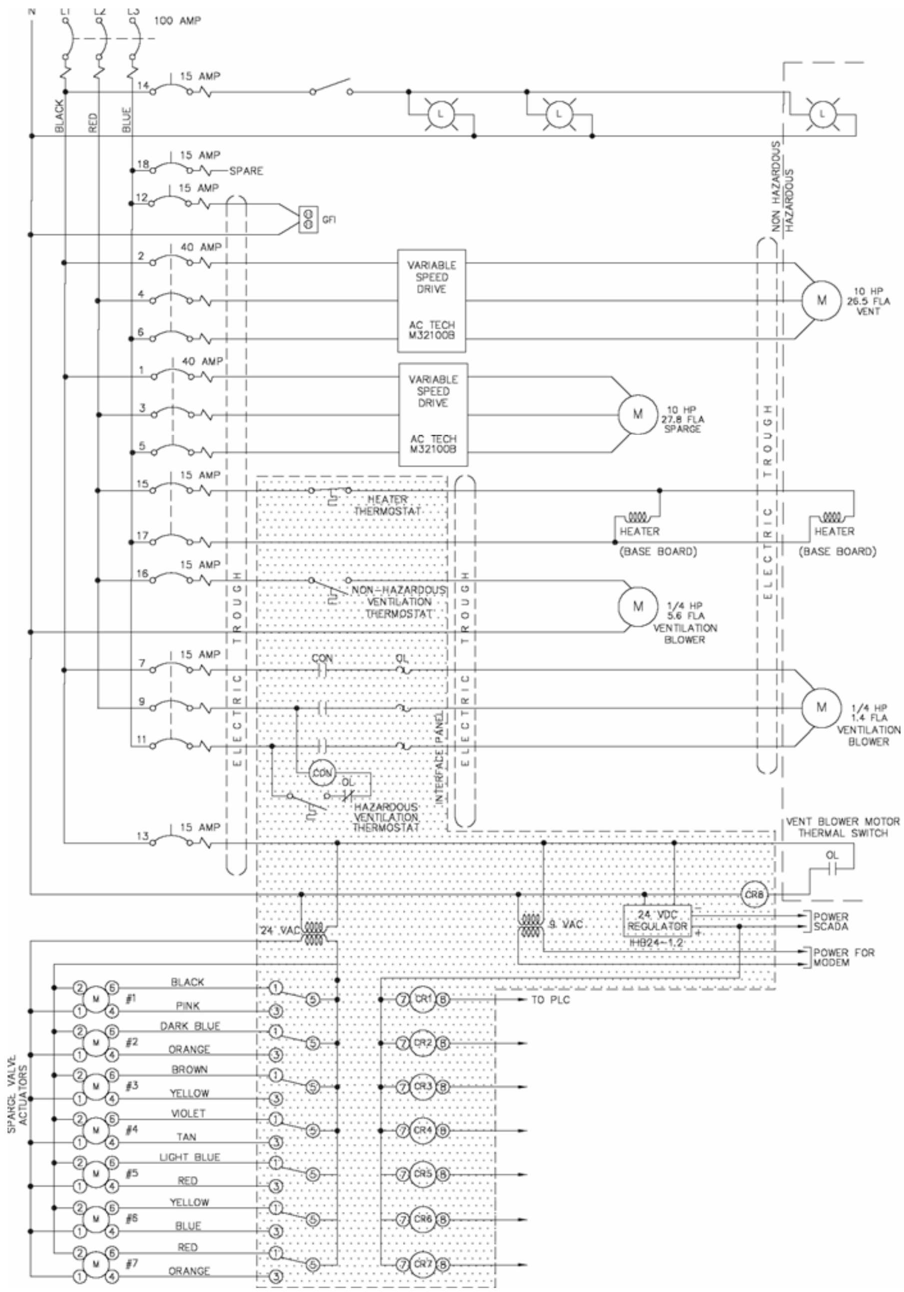

Figure 5-10. Example preliminary single-line diagram for the IAS/SVE system depicted in Figure 5-7.

e. Variable Frequency Drives. A typical IAS blower or compressor is driven by an AC motor that operates at a fixed frequency (the North American standard is 60 Hz), and consequently the blower or compressor motor rotates at a fixed frequency. Therefore, a typical blower or compressor has a simple pressure to flow relationship (the "blower curve") where the blower or compressor can only produce a single pressure for a desired flow rate. A variable frequency drive (VFD) can provide AC electrical output to a three-phase inductive electrical motor over a range of frequencies, thus allowing for different motor speeds and different flow/pressure relationships for a given sparge blower or compressor. Thus, a single blower/compressor driven by a VFD can satisfy varying requirements for air sparging flow rates and pressures. The VFD provides code-required motor thermal protection, local control on motor operation and motor speed, and can allow for phase conversion from single-phase power input to three-phase motor operation (if three-phase power is unavailable). Advances in technology and increased production over the past decade have lowered costs for VFDs to levels that make them worth considering for many air sparging applications, including use on pilot test skids; use at sites with sparge wells that have significantly varying air entry pressures owing to differences in soil types or well screen depths; and use on sites expected to shrink in size as remediation progresses. Another advantage of VFDs applied to sparge blowers or compressors is an energy savings over fixed-rpm delivery equipment that relies on energy-wasting flow and pressure control by throttling or "dumping air" (regularly releasing pressure to the atmosphere). VFDs also eliminate high amperage motor startups.

f. Zone Valve Controls. As presented in paragraph 6-6, air injection to sparge wells continuously is not recommended for achieving even air dispersion and good surface area contact of sparged air to the aquifer. It is best if sparge wells are "pulsed" or cycled from receiving pressure and flow to a period of resting. Rather than cycling the air delivery system on and off, it is more desirable to use zone valves on a timer to cycle the flow to the individual wells. With multiple zones, the air delivery system can be sized to the demands of wells on each individual zone, rather than to all of the IAS wells at one time. If the number of sparge valves is limited to two zones, then a single asymmetrical timer relay can be used to turn one valve on while the other is turned off. For more than two sparge zones, either the programmable logic controller (or SCADA), if used, requires internal programming or else separate sequencer timers have to be used. Lawn sprinkler sequencer timers can be used to inexpensively provide the cycling logic from zone to zone. Sprinkler timers are intended to start a process of beginning a cycle on the first zone for a programmed period, then switching to a subsequent zone for their programmed period. The lawn sprinkler sequencers are easily understood and programmed, but typically do not perform the function of beginning the cycle anew after the end of the sequence. The sequencer will require an external module to initiate it after the end of the sequence. Additional relays may be required in a zone valve control to allow for some "open-valve" overlap of two sequential zone valves. With both zone valves open (i.e., open-valve overlap), the opening and closing valves may result in a high restriction in the pipe, resulting in a higher pressure than allowed with the air delivery equipment.

5-8. System Appurtenances

a. *Heaters*. Heaters may be used to warm injected air delivered to the IAS wells (Wisconsin DNR 1993). The heat added during compression should be sufficient to maintain the injection air temperature above the natural groundwater temperature. Additional heat may be required for low pressure systems during the winter or in cases where significant manifold piping is exposed to subfreezing conditions. The designer should determine whether direct-fired heaters that inject air that is reduced in oxygen content will have a negative effect on remediation by biodegradation. Electric heater elements may be used to add heat to the injected air. An advantage of electric heat over direct-fired heaters is ease of installation and elimination of the use of a gas fuel or liquid fuel and the related infrastructure. A disadvantage of electric heat is that energy costs are typically two to three times that of gas or liquid fuels.

b. *Injection of Gases Other Than Air*. There are a variety of gases other than air that can be introduced into the subsurface through the use of an IAS system. These other gases include enriched oxygen or ozone streams instead of air to attempt to achieve higher dissolved oxygen concentrations. (Note: The solubility of oxygen in groundwater in equilibrium with atmospheric air is approximately 10.1 mg/L at 15°C, while the theoretical solubility of oxygen in groundwater in equilibrium with pure oxygen is 48 mg/L at the same temperature. However, once the sum of the partial pressures of all of the dissolved gases in groundwater exceeds the groundwater pressure, gases tend to come out of solution and form bubbles. Thus, it is uncommon to achieve groundwater DO concentrations significantly greater than 10 mg/L.) At sites containing high concentrations of dissolved iron, the designer should consider the possibility that when delivering more concentrated forms of oxidant, such as pure oxygen, faster precipitation or plugging of the soil may occur. Also, as pure oxygen and ozone are highly reactive substances, the design team must ensure that all mechanical equipment and piping in direct contact with the oxygen or ozone is specifically rated for use in this environment.

(1) In addition to alternate electron acceptors, gases that promote co-metabolic bioremediation can be delivered by an in-situ sparging system. As described previously, some aerobic bacteria can biodegrade chlorinated solvents such as TCE, DCE, and vinyl chloride if supplied with methane or propane and oxygen. Hazen et al. (1994) have demonstrated that biosparging with a mixture of methane in air can promote in-situ biodegradation of these compounds in aquifers that contain methanotrophic bacteria. When designing such a system, it is critical that the designer ensure that the concentration of methane in air be less than the lower explosive limit for methane (i.e., less than 5%). Other gases that have been used to promote co-metabolism include propane and butane.

(2) Delivery of gaseous nitrous oxide or triethyl phosphate into groundwater are examples of using of gases other than air with in-situ sparging technology. Nitrous oxide and triethyl phosphate may be added to the air supply of an IAS system to provide nitrogen and phosphate,

respectively, to promote biodegradation in saturated soils in which biological activity is naturally limited by the amount of available nitrogen and phosphate (Hazen et al. 1994).

c. Buildings or Enclosures. All air supply equipment should be installed in an enclosure to protect the system from the weather. It could be a roof or shed, provided NEMA 4 enclosures are specified for controls and motors. Judgment must be used to account for the climate of the site. As previously discussed, significant heat is generated from the compression of air, and proper building design should include ventilation that allows for cooling during the warmer months and heat containment during the colder months. This proper ventilation may eliminate the need for additional winterization measures inside the enclosure.

5-9. Design Documents

a. Specifications. If a typical package of specifications and plans are to be prepared, a number of guide specifications are available for use. Content of the packages depends on the acquisition strategy, customer requirements, and regulator requirements. USACE-CEGS Guide Specifications for Military Construction, which are typically included or can be modified for SVE/BV design, are listed beneath each design component. A potential specification section shown ending in "XXX" is one for which a CEGS does not currently exist but which is under development or should be developed based on the project requirements. The designer should always check the Unified Facilities Guide Specifications (UFGS) web site* for the most recent versions of all guide specifications and the addition of new ones. For a traditional detailed design, the following sections may be appropriate:

(1) *General Clauses and Performance Requirements*.

01240 Cost and Performance Report.
01270 Measurement and Payment.
01320 Project Schedule.
01330 Submittal Procedures.
01351 Safety, Health, and Emergency Response (HTRW/UST).
01355 Environmental Protection.
01450 Chemical Data Quality Control.
01451 Contractor Quality Control.
01780 Closeout Submittals.
01810 Commissioning and Demonstration for In-situ Air Sparging (IAS) Systems (Similar spec for SVE systems can be modified as appropriate).
01830 Operation, Maintenance, and Process Monitoring for IAS Systems (Similar spec for SVE systems can be modified as appropriate).

* http://www.ccb.org/docs/ufgshome/UFGSToc.htm

(2) *Site Work*.

02111 Excavation and Handling of Contaminated Material.
02120 Transportation and Disposal of Hazardous Materials 02150 Piping; Off-Gas.
02210 Subsurface Drilling, Sampling and Testing.
02300 Earthwork (includes Excavation, Trenching and Backfilling).
02522 Ground Water and Vapor Monitoring Wells (Ground Water Monitoring Wells Specification can be modified).
02521 Vapor Extraction Wells (Water Well Specification can be modified for SVE/BV wells).

(3) *Treatment Web Site Specifications*.

11215 Fans/Blowers/Pumps; Off-Gas.
11XXX Instrumentation and Controls (may be included in blower specification).
13405 Process Control.
15080 Thermal Insulation for Mechanical Systems (if applicable).
15200A Pipelines, Liquid Process Piping.
16370 Electrical Distribution System, Aerial.
16375 Electrical Distribution System, Underground.
16415 Electrical Work, Interior.
16475 Coordinated Power System Protection.

b. Drawings. The following drawings would typically be made available for a design package for IAS:

(1) Site location.

(2) Project plan with well locations.

(3) Piping profiles.

(4) Well construction details.

(5) Process and Instrumentation Diagram.

(6) Piping and equipment layout.

(7) Piping sections.

(8) Power plan.

(9) Power/control plans.

(10) Electrical details.

(11) Lighting, power, and one-line electrical diagrams. Areas with NFPA hazard classifications that require upgraded or special electrical components should be shown on the drawings.

c. Performance Specifications. If performance-based contracting is chosen for acquiring IAS services, the performance specification may simply require achieving remediation goals within some period, or may require that the IAS system be designed and implemented so as to achieve the following.

(1) A certain air saturation for a certain period of time in a certain treatment volume, including specific means to measure attainment of this.

(2) No adverse migration of contaminant vapors to the surface, utility corridors, including specific locations and concentration or flux limits.

(3) No unanticipated plume migration because of IAS implementation, including specific monitoring locations and limits on changes in concentrations at these locations.

(4) Appropriate associated SVE system operation and treatment of vapors, including required vacuum conditions or flow rates and treatment requirements for off-gas.