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Combined Air Sparge and Bioremediation of an Underground Coal Gasification Site

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# **COMBINED AIR SPARGE AND BIOREMEDIATION OF AN UNDERGROUND COAL GASIFICATION SITE**

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## **ABSTRACT**

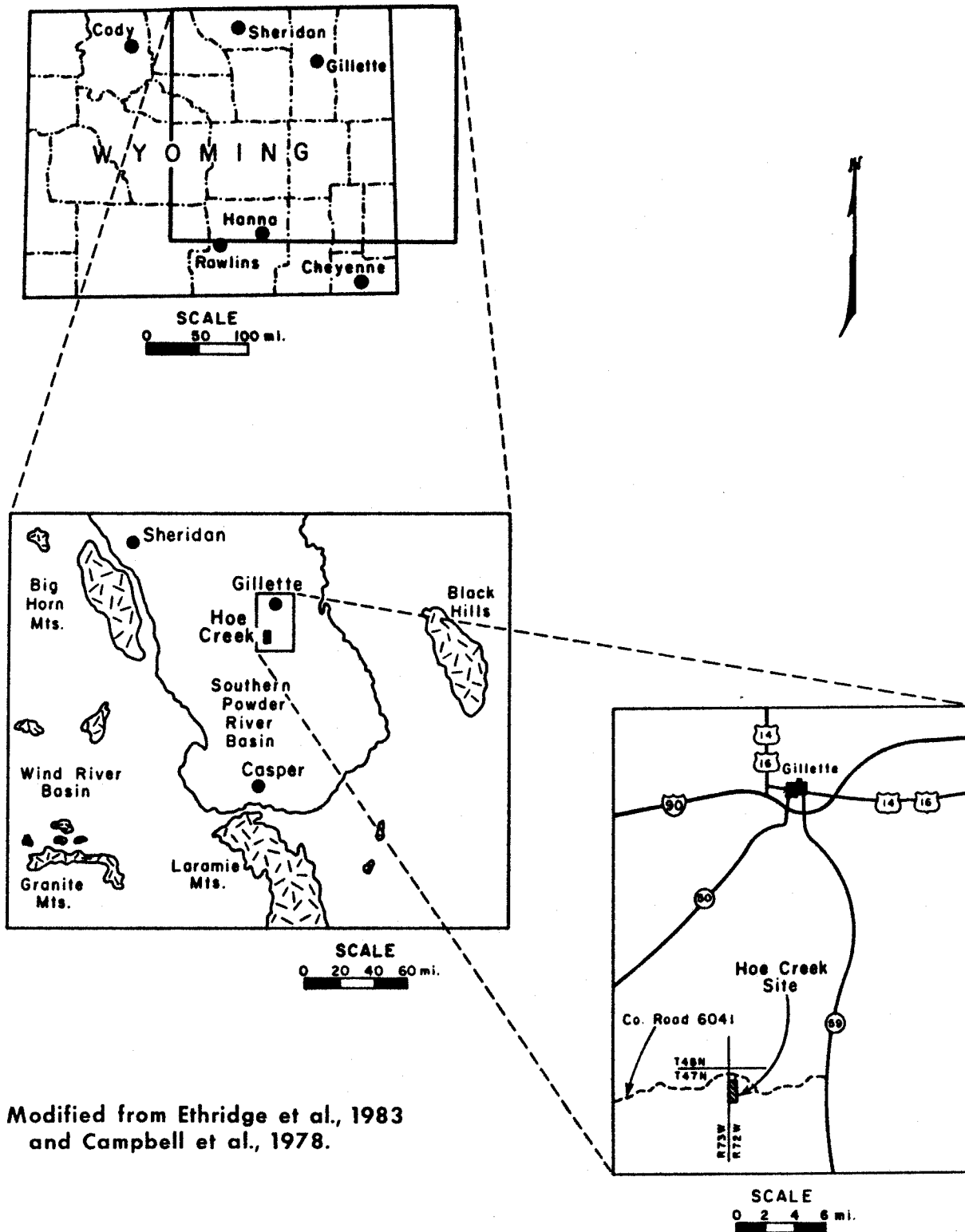
EG&G Technical Services of West Virginia (TSWV) Inc. is successfully remediating a former underground coal gasification (UCG) test site in northeastern Wyoming. EG&G is demonstrating the effectiveness of combined air sparge and biostimulation technology. This project is being conducted for the U.S. Department of Energy (DOE) - Morgantown Energy Technology Center (METC), the lease holder of the site. UCG testing from 1976 through 1979 contaminated three water-bearing units at the site with benzene. Previous pump and treat operations at the site showed the presence of a persistent non-dissolved benzene source material. The Felix 1 coal seam is the most contaminated unit at the site and was the target unit for the initial demonstration.

Air sparging was selected to strip dissolved benzene, volatilize the non-dissolved benzene source material, and to provide oxygen for increasing aerobic bacteria populations. Indigenous bacteria populations were stimulated with ammonium phosphate addition. EG&G designed the remediation system to take advantage of the hydrogeologic environment to produce a cost-effective approach to the groundwater remediation. Groundwater pumping was used to manipulate subsurface air flow, nutrient transport, and biomass management. Demonstration operations began on September 29, 1995, and were suspended on April 30, 1996 to begin demonstration expansion. Initial results of the demonstration show substantial reduction in benzene concentrations across the demonstration area. Benzene concentration reductions greater than 80% were observed two months after demonstration operations were suspended.

## **INTRODUCTION**

The Morgantown Energy Technology Center (METC) of the U.S. Department of Energy requested EG&G Technical Services of West Virginia (TSWV) Inc. to perform a remediation demonstration at the Hoe Creek underground coal gasification (UCG) site in northeastern Wyoming. UCG testing conducted from 1976 through 1979 introduced contaminants into the groundwater at the site. Principal contaminants were volatile and semi-volatile organics. Groundwater monitoring at the site showed that benzene was the contaminant of highest concentration and persistence. Several types of phenols continue to be detected at the site; however, their concentrations have decreased significantly with time.

The Hoe Creek underground coal gasification (UCG) test site is located in Campbell County, Wyoming, about 20 miles southwest of Gillette, Wyoming (Figure 1). Lawrence Livermore National Laboratory (LLNL) under contract to the U.S. Department of Energy (DOE) selected the site to develop UCG technology to exploit coal deposits not suitable for conventional mining. UCG extracts the energy of the coal through in situ coal gasification. The apparent reasons that the site was



Modified from Ethridge et al., 1983  
and Campbell et al., 1978.

Figure 1. Hoe Creek Site Location [2].

selected for UCG testing were relatively shallow coal deposits on Federal property (U.S. Bureau of Land Management). The shallow coal deposits reduced costs of testing and the Federal property reduced lease complications.

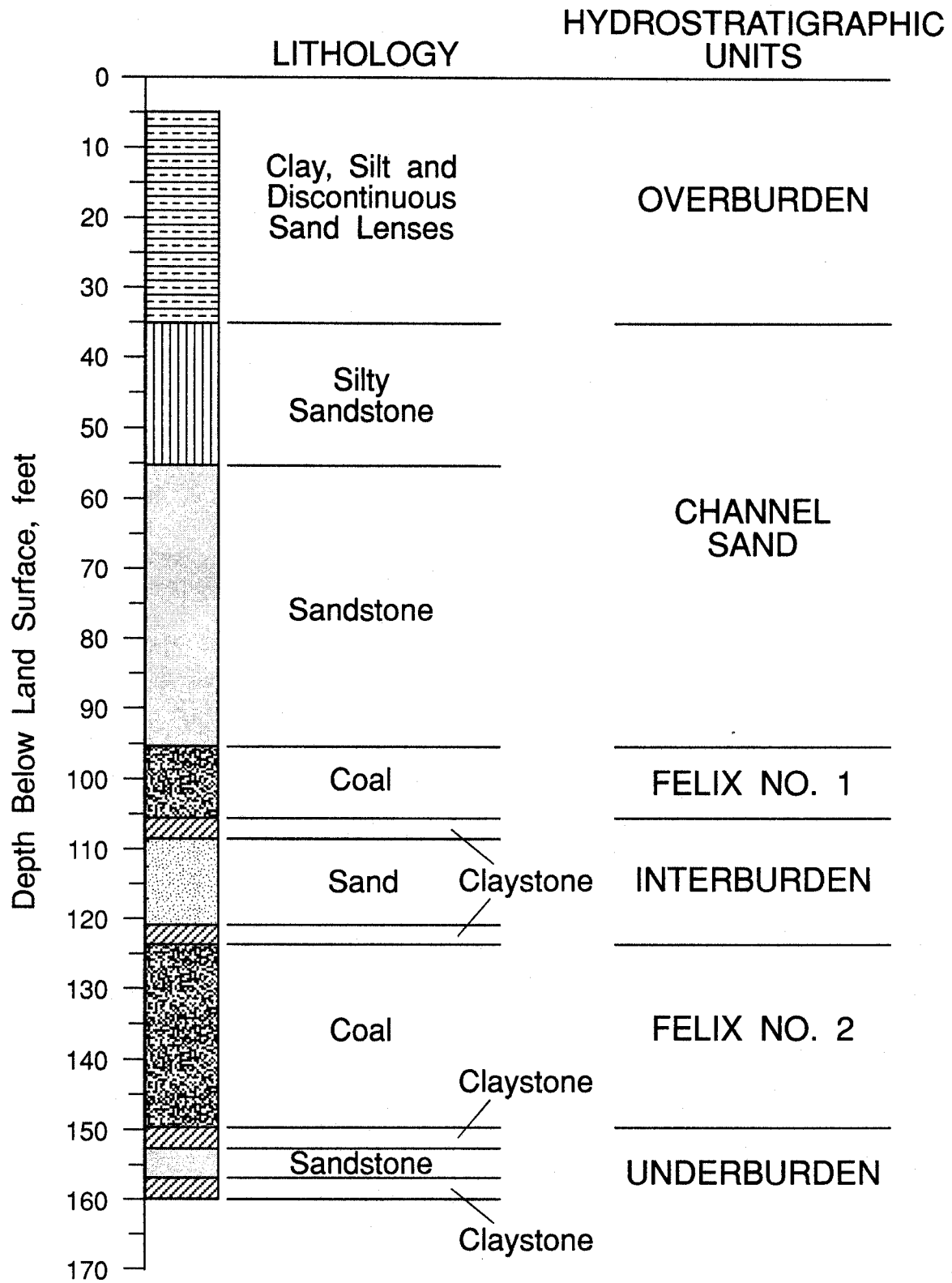
## **Site Features**

Figure 2 shows the geohydrologic sequences of interest at the site. There are three water-bearing units (aquifers) within 200 feet of the surface at the site and they reside in the Wasatch Formation. These are the channel sand (CS), Felix 1 (F1) coal seam, and the Felix 2 (F2) coal seam. Loosely consolidated sandstone type materials comprise the Channel Sand unit. Depths to the CS in the testing area range from 30 to 100 ft. Unit thickness is approximately 50 ft. The F1 coal ranges in depth from 80 to 130 ft and is approximately 10 feet thick. The F2 coal seam ranges in depth from 110 to 160 ft and is approximately 25 ft thick. The F1 coal is separated from the F2 by 10 to 30 ft of sandstone and claystone interburden. The F2 coal was the target resource of the UCG tests.

Hydrology tests have been performed at the site. Barrash et al. [1] reported on the most recent hydrology tests. In the tests, leakage between aquifers occurred to some degree throughout the site. This leakage between water bearing zones likely results from natural fractures propagated through two or more of the water bearing zones, well intrusions, and subsidence caused by collapse of the gasification cavities.

In the two coal seams, hydraulic conductivities were greater in the vertical component than the horizontal component (Table 1) and they were nearly equal in the Channel Sand. Hydraulic conductivities relate to the ease with which a fluid will flow in a particular media (permeability). Storage coefficients relate to the amount of fluid an aquifer will release during pumping. The F1 and F2 values are typical for confined aquifers and the Channel Sand value is more typical of an unconfined aquifer [4].

Transmissivities relate to the amount of flow through a vertical section of an aquifer in response to a hydraulic gradient (pressure drop). Transmissivities less than 1,000 gallon per day per foot (gpd/ft) are considered low-yield aquifers [4]. It is important to note that fluid flow in coal seams is through natural fractures. Most coal seams contain intrinsic fracture networks called cleats that serve as flow conduits. The channel sand aquifer is a more typical aquifer media where flow is described by porous flow models. The geohydrologic characteristics of the site influenced the test operation and contributed to the groundwater contamination at the site.



Modified from Gilbert/Commonwealth Inc., 1991.

Figure 2. Hoe Creek Hydrogeologic Sequence [3].

## 1. Hoe Creek Average Hydraulic Parameters

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<u>Aquifer</u>	Hydraulic Conductivity	Storage	Transmissivity
	<u>Horizontal/Vertical</u> <u>ft/Day</u>	<u>Coefficient</u>	<u>gpd/ft</u>
Channel Sand	2.6/1.7	0.08	583
Felix 1 Coal	5.1/10.0	0.000003	381
Felix 2 Coal	5.2/20.0	0.0053	972

From Barrash et al., 1988.

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### UCG Testing History

Three UCG tests were conducted at the test site from 1976 through 1979. These tests are designated as the Hoe Creek I, II, and III tests. Test locations within the site are shown in Figure 3. The target coal seam for all three tests was the Felix 2. UCG technology requires the natural horizontal permeability to be enhanced between injection and production wells before UCG can begin. These three tests used different permeability enhancement techniques.

Hoe Creek I tested explosive fracturing as a permeability enhancement technique. After explosive fracturing, the Felix 2 coal seam was ignited on October 15, 1976 and gasified for 11 days. Air was used to react with the coal. The gasification sequence produced generally low-quality gas, gas heating value less than 100 btu/scf. The gasification test consumed only about 10 percent of the coal rubble available to the process. The Hoe Creek I UCG test affected an area 16 ft wide by 35 ft long [5]. Gasification was mostly restricted to the upper 10 ft of the 25 ft coal seam. Approximately 7 percent of the produced gas was not accounted for at the surface and was assumed to be lost to the subsurface units.

The Hoe Creek II test was conducted to test reverse combustion linking to enhance the permeability between injection and production wells. In reverse combustion linking, a fire is ignited at the base of the production well and high pressure air is injected into the injection well. The air permeates through the coal and intersects the combustion zone at the base of the production well. The combustion zone traces the oxygen source back to the injection well, creating a highly-permeable char zone.

Gasification was initiated on October 28, 1977 and was completed 59 days later on December 25, 1977 [5]. Air was used as the oxygen supply except for a two-day test when steam and oxygen were used. Steam and oxygen injection improves the gas heating value of the produced gases because it eliminates nitrogen dilution when using air. Low product gas heating values, high particulate production, and high water production generally characterized the gasification test [6]. Hill et al. [6] indicated that system pressures were increased in an attempt to control water influx into the gasification cavity; however, substantial gas losses resulted from these attempts and the practice

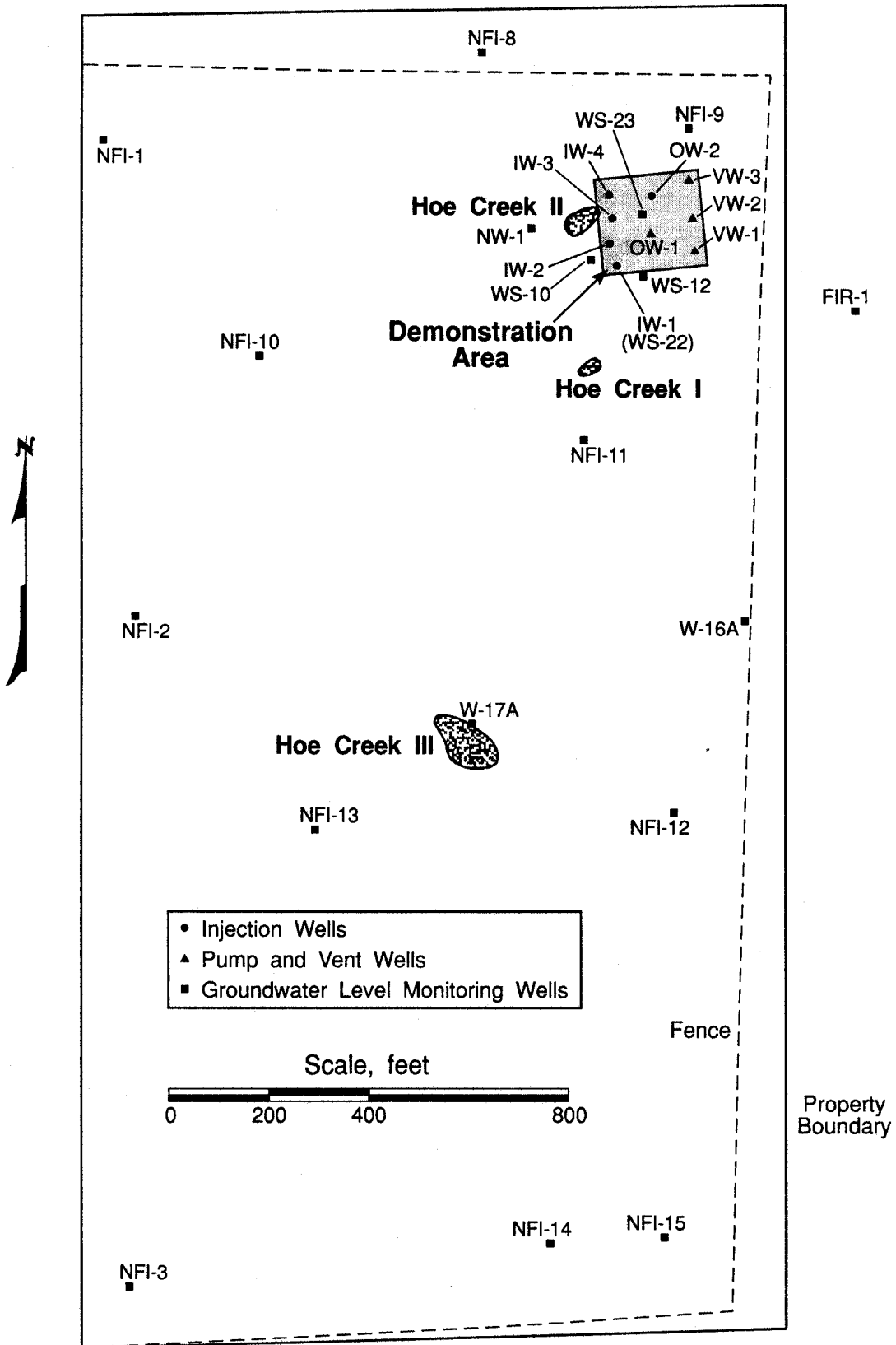


Figure 3. Hoe Creek Test Site and Remediation Demonstration Area.



was abandoned. Throughout most of the test, system pressures were maintained above hydrostatic pressure for the Felix 2 coal seam (approximately 25 psig) and the Felix 1 coal seam (approximately 20 psig). Postburn evaluation of the test revealed that the gasification zone moved into the Felix coal seam where a significant amount of coal was consumed [5]. Hoe Creek II operations resulted in gas losses of approximately 20 percent.

The Hoe Creek III test was conducted from August 17, 1979 through October 10, 1979. The test used a horizontally-drilled well combined with reverse combustion to establish permeability between injection and production points. Approximately 4,200 tons of coal were consumed in the test. Similar to Hoe Creek II, the gasification moved into the Felix 1 coal seam and, during the latter stages of gasification, most of the coal consumed was in the Felix 1 [7]. Gas losses averaged 17 percent for the test; however, data reported by Stephens [7] indicated that most of the losses occurred after the gasification zone moved into the Felix 1 coal seam. The lower hydrostatic pressure in the Felix 1 may have contributed to gas losses. Within a month of test completion, subsidence propagated to the surface of the test area and resulted in an approximate 20 ft by 10 ft by 10 ft deep depression at the surface. The area extent of the subsurface rubble-filled cavity was estimated at 170 ft long by 56 ft wide.

## **Environmental Impacts**

Subsidence and groundwater contamination resulted from the UCG testing at the Hoe Creek site. Subsidence propagated to the surface at the Hoe Creek II and III sites. The subsidence resulted from the void created from the coal consumed during gasification and propagated to the surface through the weakly consolidated overburden material. The Hoe Creek II subsidence resulted in a cylindrical-shaped hole approximately 15 feet in diameter and 40 feet deep and the Hoe Creek III subsidence resulted in a 20 ft by 10 ft by 10 ft deep surface depression. Not enough coal was consumed during the Hoe Creek I test to cause significant subsidence. The major environmental consequence of the subsidence was the interconnection of the hydrostratigraphic zones during gasification that resulted in multiple aquifer contamination. Groundwater Contamination

**Groundwater Contamination.** UCG test operations introduced organic and inorganic contaminants into the local groundwater at the Hoe Creek site. Inorganic contaminants introduced from the testing did not significantly elevate natural concentrations to the exclusion of original use category (livestock watering) to warrant major concern. The organic contamination, however, did pose regulatory concern because of the concentrations and the corresponding potential health risks. Of particular concern was benzene for its concentrations occurring at the site and its designation as a human carcinogen.

The Felix 1 coal seam at the Hoe Creek II and III sites exhibited the highest benzene concentrations at the site (Figure 3). Benzene concentrations as high as 3,000 µg/L have been measured. The benzene contamination is generally confined to within 300 feet of the gasification cavities in the affected aquifers.

A number of pump and treat operations have been conducted at the site since 1986 [8]. Approximately 20 million gallons have been pumped from the affected aquifers to contain the contaminated groundwater. Benzene concentrations remained largely unaffected by the pumping.

The persistence of the benzene in the groundwater suggest a non-dissolved source that is continuing to leach benzene into the groundwater.

**UCG Contamination Mechanics.** Most subsurface contamination results from the migration of a substance from the surface or leakage from subsurface storage enclosure. The form of the contamination does not undergo phase changes in deposition or transport. The contamination also is usually associated with shallow geologic settings.

The contamination associated with the Hoe Creek site was generated in a relatively deep formation as a gas. Constituents in the gas were transported out into unaffected portions of the formations. Some high-boiling point constituents condensed in the subsurface units when cooled and produced the contamination source. Figure 4 shows a simple schematic of the underground coal gasification process. Oxygen reacts with the coal and UCG gases to produce heat and product gases (mostly noncondensable gases at atmospheric conditions). The heat generated from the process (temperatures can exceed 3000 °F) dries and pyrolyzes the surrounding coal. Some of the gases evolving out of the pyrolysis will condense when cooled to ambient conditions. These coal liquids are generally high boiling point, viscous tars. However, less viscous, lower boiling point liquids are also produced.

When the combination of the UCG cavity pressure and the gas buoyant forces exceed the hydraulic pressure surrounding the UCG cavity, the gases can move into unaffected areas of the coal seam and exposed overburden [9]. Constituents of the gases with boiling points between the cavity temperatures and ambient (approximately 55 °F) will condense in the coal or exposed overburden. Normally these gases condense close to the cavity walls. Most natural geologic materials have low thermal conductivities. This is particularly true with coal where the temperature gradient can exceed 3000 °F/ft. Much of the liquids are subsequently consumed in the process as coal continues to be consumed. The escaping gases usually will flow at the interface of the coal seam and the overburden confining unit because of the lower hydraulic pressure at the top of the coal and the buoyancy of the gases. These gases will generally expand along and move in the structural up dip direction.

Normally the condensable materials will continue to condense near the cavity walls even after substantial cavity gases have expanded into sections of adjacent geologic units. One possible mechanism where coal liquids may have been deposited or transported away from the gasification cavity is under sustained gas flow out of the cavity. Under sustained gas flow, transport channels would be heated by the gases allowing the condensable gases to move farther out into the geologic unit. Sustained gas flow could result from a breaching of the water-saturated area of a geologic unit or through a surface protrusion such as a monitoring well.

A recent coring study performed at the Hoe Creek site [10] indicated that two fractions of coal liquids may exist in the subsurface of the Hoe Creek site: a viscous tar phase and a lighter fraction, the lighter phase being the non-dissolved benzene source. Results from their recent coring program indicate that high benzene concentrations are not associated with the deposit of the viscous coal tars. This suggests that the non-dissolved benzene source was deposited away from the more viscous liquids.

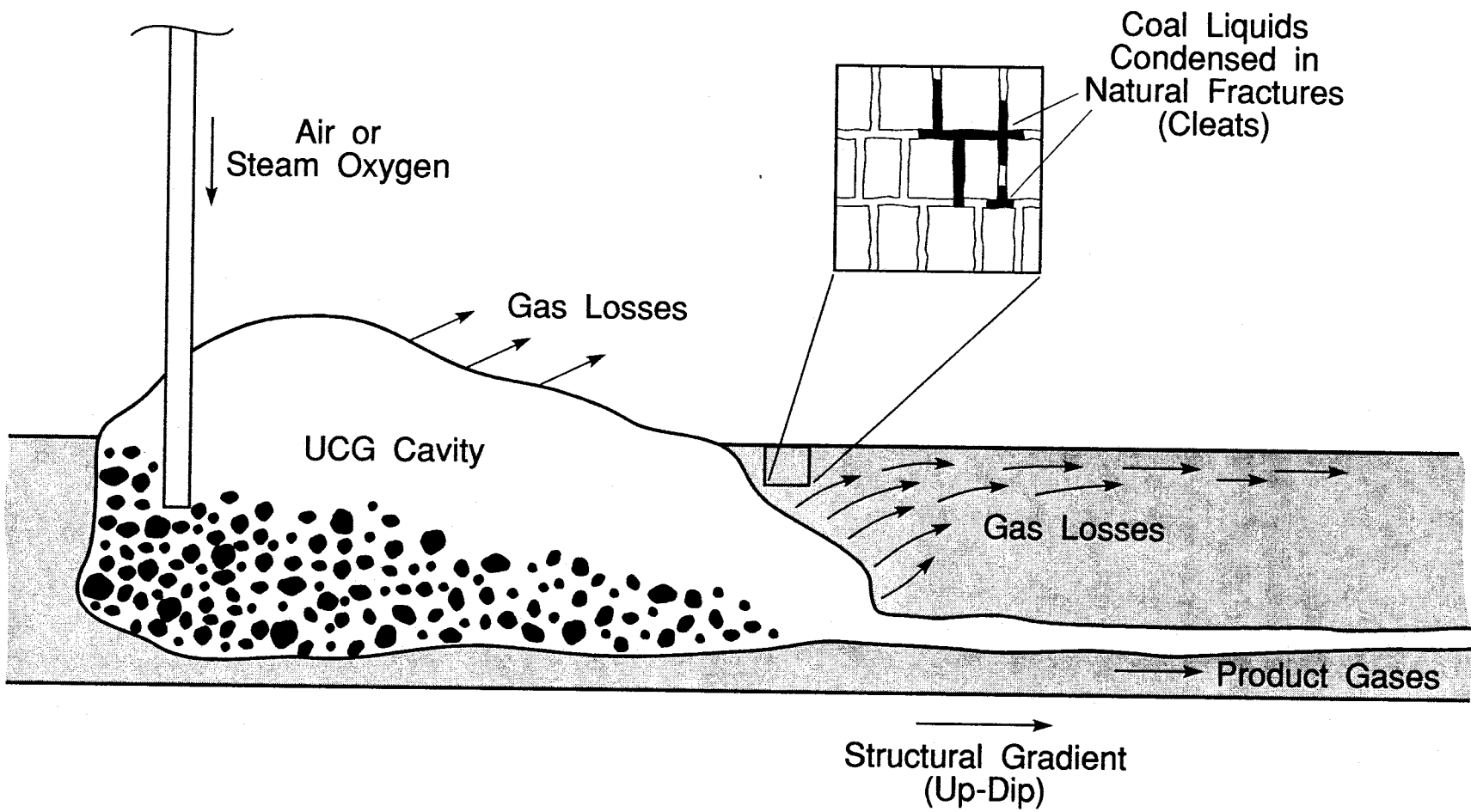


Figure 4. Underground Coal Gasification Process.

## **AIR SPARGE AND BIOREMEDIATION DEMONSTRATION**

The Morgantown Energy Technology Center, U.S. Department of Energy, requested EG&G TSWV Inc. to perform a groundwater remediation demonstration at the Hoe Creek site. The demonstration was to apply “best practical technology” based on available current technologies and site studies.

### **Technology Selection and Approach**

A combination of air sparging, bioremediation, and groundwater pumping was selected for the demonstration. These processes were selected based on the following considerations:

1. Transport and deposition of the contaminant source.
2. Characteristics of the non-dissolved benzene source and secondary contamination.
3. Contamination containment.
4. Hydrogeologic characteristics of the contaminated matrix.
5. Probability of success.
6. Environmental disruptions and impacts.
7. Regulatory Acceptance.
8. Low capital and operating costs.

The combination of these remediation technologies offers the most efficient and cost-effective approach for final groundwater remediation at the site. Benzene removal from groundwater is readily accomplished with the combination of air sparging and bioremediation [11]. Air sparging is expected to be the prime remediation mechanism with bioremediation being a secondary mechanism. Air sparging can directly impact a non-dissolved source material more readily than bioremediation. With direct air and non-dissolved source contact, mass can transfer directly from the source liquid to the gaseous phase (air). Bioremediation is mostly limited to degrading dissolved organics and can only impact non-dissolved organic source materials indirectly. Air can permeate less permeable sections of contaminated matrix materials to provide efficient contaminant transfer from the affected matrix material and groundwater to the air. Air sparging can also be applied to follow the actual transport flow paths that deposited the contamination source to provide effective air and contaminant contact. Injected air introduces dissolved oxygen into the groundwater to stimulate native heterotrophic bacteria populations.

Stimulating the natural biological degradation of organic contaminants has been demonstrated to be cost-effective and an efficient remediation process. Bioremediation requires much longer treatment duration than air sparging and is not as effective in contaminant mass removal [12]. For this reason, bioremediation was selected as the secondary process. The process usually consists of enhancing dissolved oxygen concentrations and other nutrients in the groundwater to promote native microbe populations that can process organic contamination. Numerous studies, demonstrations, and successful site remediations have occurred. Some laboratory studies have been performed on actual Hoe Creek groundwater [13].

Groundwater pumping can be applied to control air and biological nutrient flow and can be used to contain contaminated groundwater. By reducing the hydraulic head near a pumping well, air will tend to flow toward the area of lower hydraulic head. Biological nutrients also can be dispersed

across an area by pumping. Because air injection will displace groundwater, air injection can force movement of contaminated groundwater. Groundwater pumping can control the transport of contaminated groundwater.

## **Design**

EG&G selected the Felix 1 coal seam east of the Hoe Creek II test area for the demonstration project (Figure 5). This area historically has shown high benzene concentrations. The F1 coal also has shown the highest contaminant concentrations of the three affected units. The contaminated units are closer to the surface here than near the Hoe Creek III area. Shallower wells save on drilling and materials costs. The selection of this area also permits air to be injected at points that would cause the subsurface flow of air to follow similar flow paths that transported the original contaminant source material. This would maximize contact between injected air and hydrocarbon contaminants.

Figure 5 shows the demonstration well network. The well pattern consists of five air injection wells and four pump, vent, and observation wells. The orientation of the injection wells and the vent and pump wells was selected to use the structural and hydraulic properties of the area to control fluid transport across the demonstration area. The general structural gradient (increasing elevation) of the F1 coal seam trends toward the east-northeast. Due to the natural buoyancy of gases to expand and travel toward regions of lower pressure, injected air was expected to move along the top of the F1 coal seam toward the vent and pump wells. Pumping the vent and pump wells also lowers the hydraulic pressure around these wells and stimulates pneumatic flow toward them.

In addition to the air injection, ammonium phosphate (AP) is added in the injection wells to stimulate indigenous heterotrophic (native hydrocarbon degrading) bacteria. AP is a common fertilizer and is easy to handle. During warm month operation, dispersion of the AP across the demonstration area is enhanced through groundwater pumping. During cold weather operation (November - April), natural groundwater convective transport disperses the nutrient, but to a much slower degree.

## **Operations**

Air injection was initiated into the four injection wells (IW-1, IW-2, IW-3, and IW-4) on September 29, 1995. There were two periods of operation. The first period was initiated on September 29, 1995 and lasted until February 6, 1996, when operations were suspended to monitor benzene rebound in the groundwater. The second period started on February 7, 1996 and ended on April 30, 1996, when the second benzene rebound monitoring period started. Dibasic ammonium phosphate (AP) was also injected into the four injection wells on a slow continuous basis. AP was added as a 0.1-0.2 % solution at total rates of 0-60 gpd. AP injection was suspended during the air pulsing test (described latter in this section). Air also was injected into OW-2 from October 30, 1995 to January 10, 1996. Air injection rates were varied into the individual wells during the initial phases of operations to determine the best flow rate combination for air sweep across the demonstration area. Air was supplied from one or two 15-hp compressors. Each compressor was capable of producing 60 scfm at 15 psig. The majority of the operations were conducted using continuous one compressor operation with flow rates ranging from 50-60 scfm. Groundwater pumping was initiated from the pump/vent/ observation wells (VW-1, VW-2, VW-3, OW-1, and OW-2) on September 16, 1996 and ended on October 29, 1996.

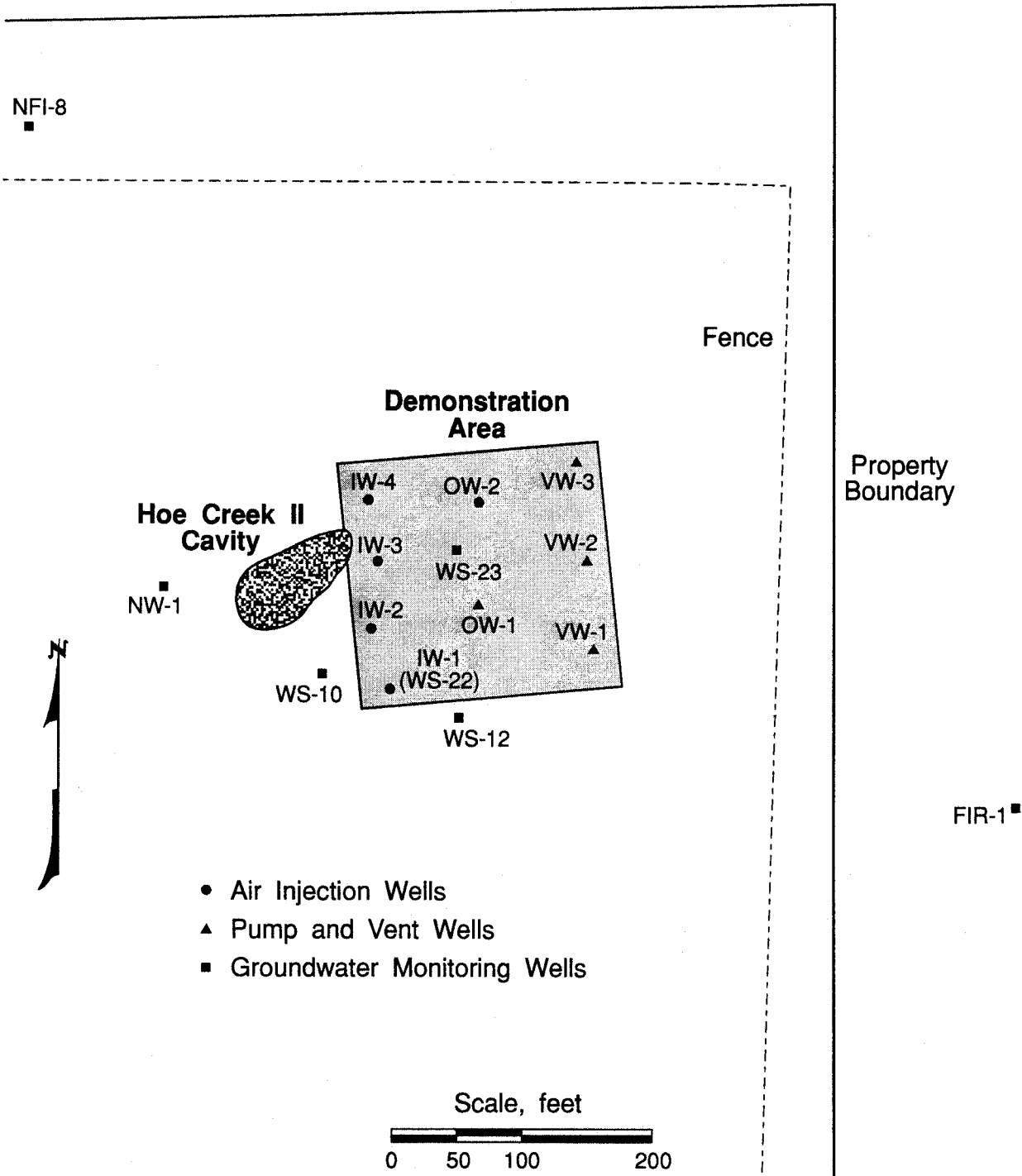


Figure 5. Demonstration Area and Felix 1 Well Network.

A pulsing air sparge test was conducted using both compressors from December 12, 1995 through January 10, 1996. Twenty-four hour periods of air injection were alternated with 24 hour periods of no air injection. AP injection was suspended during this testing phase. Total air injection rates ranged from 100-120 scfm during this operating period.

Air flow patterns across the demonstration area changed with time during the initial period of air injection. After the start of air injection, the air appeared to move radially away from the injection points. Vent gas production and audible gas bubbling began almost immediately from well WS-10 (Figure 5). This phenomenon lasted less than four hours before gas production ceased in this well. WS-12 then began to vent gas and to bubble audibly. The air appeared to change from a radial flow pattern to a linear pattern across the demonstration area. EG&G believes that the air moves in a radial pattern until the air begins to contact vent channels in the area of least resistance in the structural up-dip directions.

Subsurface air flow patterns also change during periods of prolonged continuous air injection. The observed changes did not follow a pattern or frequency. This behavior was observed across the demonstration area. Changing vent gas production rates were observed in wells WS-12, VW-1, VW-2, and OW-1 during uninterrupted periods of air injection.

## **Groundwater Quality Results**

Groundwater quality impacts are discussed in two sections: Groundwater Quality Impacts During Demonstration Operations and Benzene Rebound. The first section discusses changes to the groundwater quality during air sparging operations. The second section discusses groundwater quality changes during two periods of benzene rebound monitoring.

**Groundwater Quality Impacts During Demonstration Operations.** Figure 6 shows pre-demonstration benzene contamination contours in and around the demonstration area. The highest benzene concentrations observed at the Hoe Creek II site are centered inside the demonstration area. Figure 7 shows the benzene contamination contours on October 24, 1995, twenty-five days after startup of the demonstration. Dissolved benzene has been effectively stripped from the groundwater across the demonstration area.

These results support the original hypothesis that the injected air would travel toward the structural up-dip direction because of the buoyancy forces of the air and the lower hydraulic head. The air was confined in the upper part of the Felix 1 coal seam during transport. Dames and Moore [10] has indicated that this region is the probable location of the benzene contaminant source material and is supported by UCG gas transport theory.

Table 2 shows the benzene concentration for the demonstration through April 30, 1996. Operations were suspended on this date for the second benzene rebound monitoring period. There were two benzene rebound monitoring periods. The first period lasted from January 10, 1996 through February 6, 1996 and the second period lasted from April 30, 1996 through June 19, 1996. Results of the rebound monitoring are discussed in the next section "Benzene Rebound."

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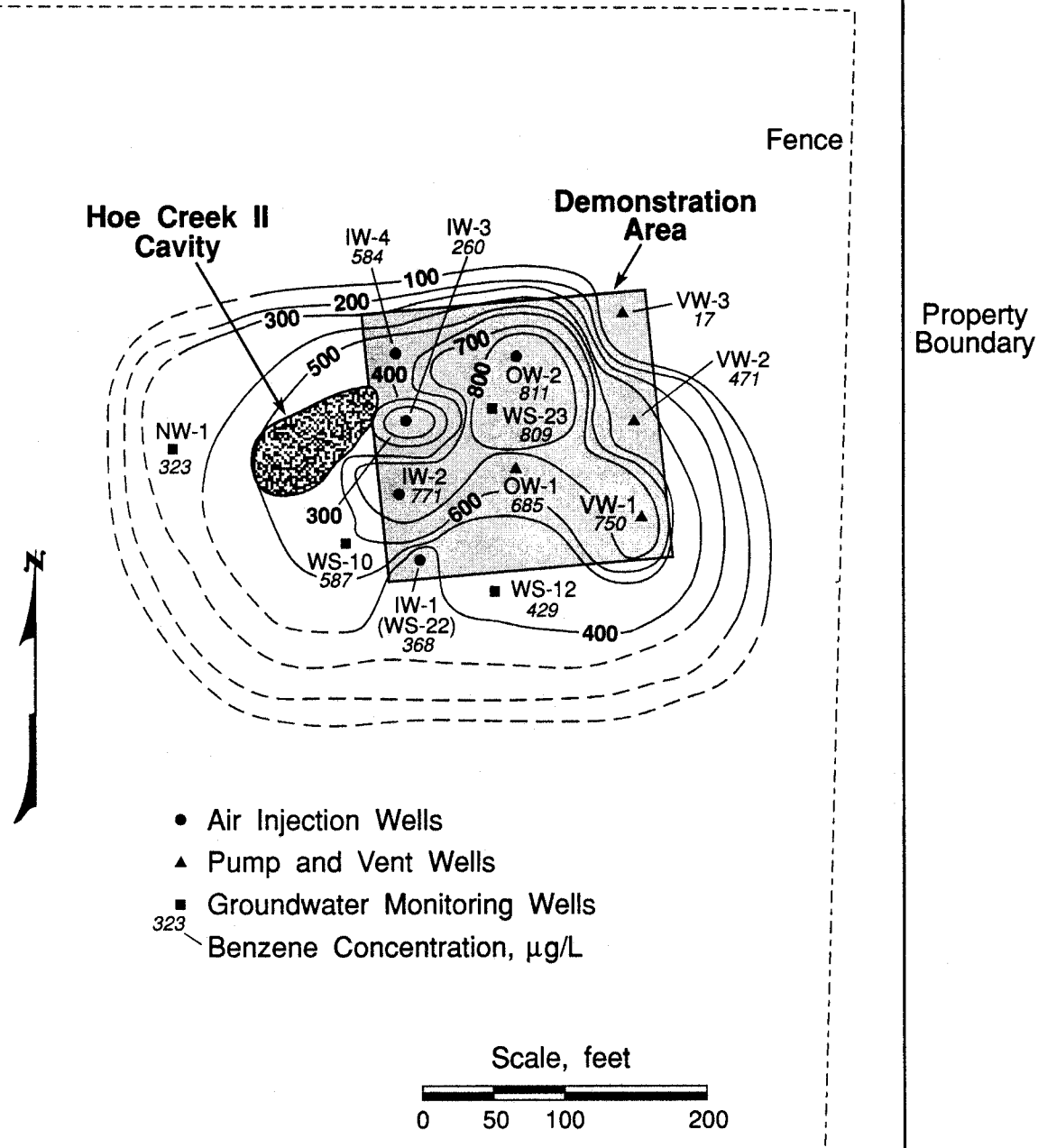


Figure 6. Pre-Demonstration Benzene Concentrations in Felix 1 Coal Seam, Hoe Creek II Area.



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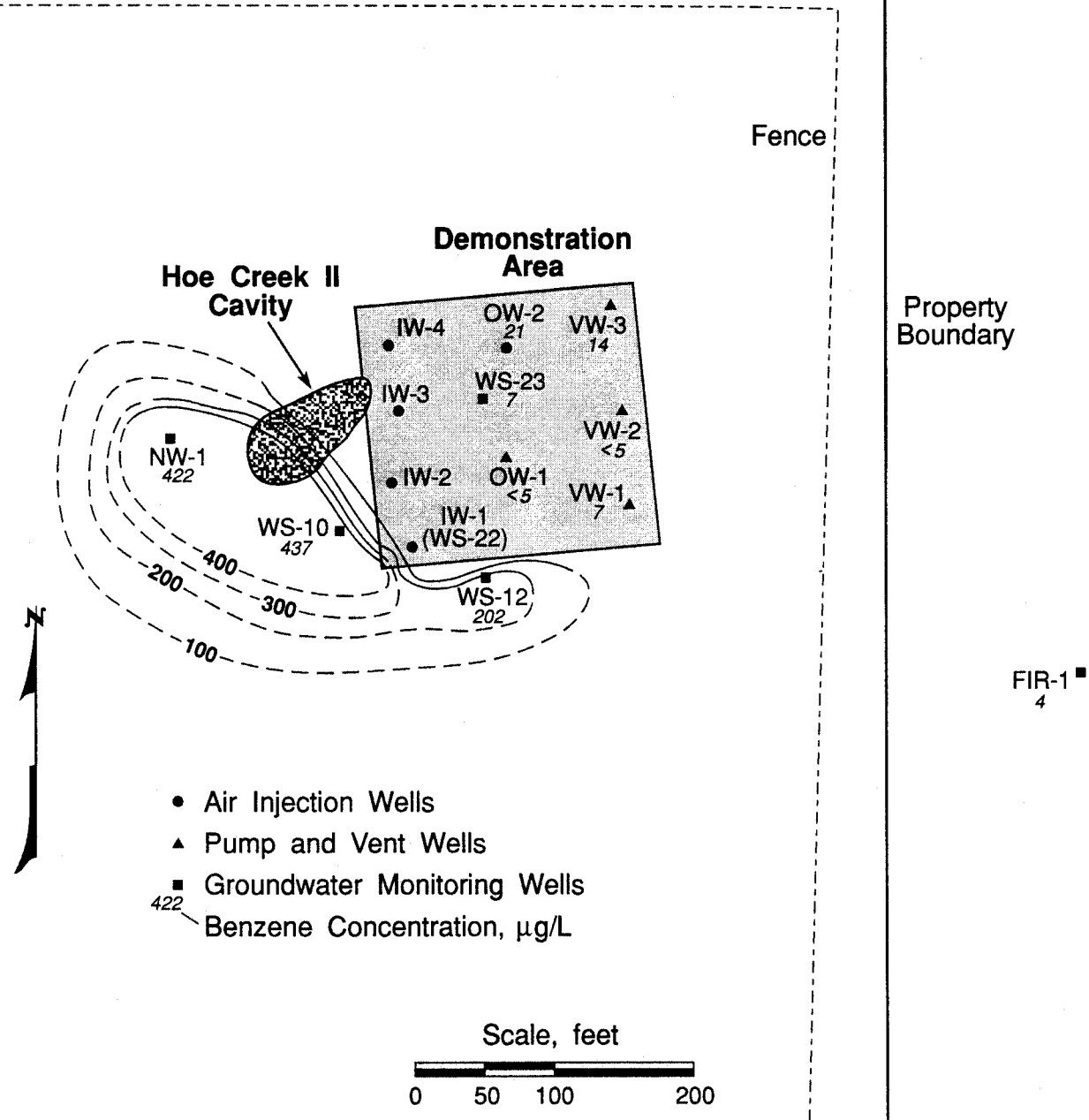


Figure 7. October 24, 1995 Benzene Concentrations in the Felix 1 Coal Seam, Hoe Creek II Area.

Table 2. Benzene Concentrations in Felix 1 Coal Seam During Remediation Demonstration, µg/L.

<u>Well</u>	<u>6-Sep-95<sup>1</sup></u>	<u>24-Oct-95</u>	<u>28-Nov-95</u>	<u>10-Jan-96</u>	<u>6-Feb-96</u>	<u>5-Mar-96</u>	<u>11-Apr-96</u>	<u>30-Apr-96</u>
OW-1	685	<5	<5	<5	248	7	<5	89
OW-2	811	21	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>	<5	<5
VW-1	750	7	37	51	215	36	125	323
VW-2	471	<5	<5	<5	93	<5	<5	<5
VW-3	17	14	36	43	25	36	35	19
IW-1	368	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>
IW-2	771	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>	30	NS <sup>2</sup>	NS <sup>2</sup>	7/8.64
IW-3	260	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>
IW-4	584	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>	NS <sup>2</sup>
WS-23	809	7	8	19	201	20	<5	<5
WS-12	429	202	23	5	72	9	8	22
WS-10	587	437	502	235	296	345	368	408
FIR-1	6.4	4	<5	20	6	18	12	8
NW-1	323	422	467	378	345	425	387	412
NF1-8	<5	<5	<5	<5	<5	<5	<5	<5
NW-2	151	166	193	144	190	169	180	184

<sup>1</sup> Pre-demonstration

<sup>2</sup> Not Sampled

Air sparging effectively reduced dissolved benzene in the groundwater across the demonstration area. Pre-demonstration benzene concentrations ranged from 17 to 811 µg/L in the demonstration area. On October 24, 1996, concentrations ranged from <5 to 21 µg/L. This rapid stripping of benzene showed excellent air/contaminant contact and supported the original theory used to select air sparging as a viable remediation technology for the Hoe Creek site. Benzene reductions were also observed in several wells outside the demonstration area. WS-12 showed substantial reductions in benzene concentrations during air sparging. Well WS-10 also showed reductions in benzene concentrations as a result of the air pulsing tests (December 12, 1995 - January 10, 1996). The initial radial flow produced every two days during the air pulse test reduced benzene concentration greater than 50 % in WS-10.

Groundwater benzene concentrations and vent gas production in well VW-1 indicated that groundwater pumping could improve air flow and improve benzene removal to a degree in the demonstration area. Benzene concentrations increased in this well after groundwater pumping was suspended on October 29, 1995. Groundwater pumping was suspended because of the on-set of cold weather. Vent gas production also was reduced out of the well after pumping was suspended.

Benzene concentrations remained low across the demonstration area during air injection periods indicating continued excellent air/contaminant contact throughout most of the operation period. An exception was at the end of the second operation period. VW-1 showed increasing benzene concentrations on the last two sampling periods and OW-1 showed a substantial increase on the last sampling period (April 30, 1996). Vent gas production ceased in wells VW-1 and OW-1 prior to the April 11 sampling period. The reason for the change in air flow is not known.

**Benzene Rebound.** The principal objective of the remediation demonstration was to determine the ability of the selected technologies to reduce the non-dissolved and immobile benzene source material. Air sparging was selected as the principle technology because it can evaporate non-dissolved volatile and semi-volatile organic material directly. Previous pump and treat operations at the site showed that the source material was immobile and that remediation using pump and treat methods would be slow. Because the source material is immobile, pump and treat technology is limited to a slow degradation of the source material through the dissolution of the source material into the groundwater by leaching. Likewise, bioremediation can only process dissolved organics and therefore degradation of the non-dissolved source also would be slow.

In order to determine the effectiveness of air sparging to remove non-dissolved benzene source material, benzene rebound concentrations in the groundwater need to be evaluated with time. Pump and treat operations at the site showed that rebound should be relatively fast because benzene concentrations do not substantially decrease during excessive pumping. Monitoring rebound during excessive periods of time in a small area of the contaminated site poses problems in differentiating between influx of contaminated groundwater and leaching from the non-dissolved source. For this reason two rebound periods were evaluated so that they could be compared to determine impacts on source reduction.

The two periods of benzene rebound monitoring were from January 10, 1996 through February 6, 1996 (27 days) and April 30, 1996 through June 19, 1996 (50 days). All demonstration operations were suspended during the monitoring period. Table 3 shows the results of the two benzene rebound monitoring periods. The pre-demonstration analysis (September 6, 1995) results are presented in the table for comparison.

Table 3. Benzene Rebound Analyses, µg/L.

Well#	6-Sep-95	10-Jan-96	6-Feb-96	30-Apr-96	2-May-96	5-May-96	7-May-96	14-May-96	21-May-96	28-May-96	19-Jun-96
IW-1	368					8.7	7.4	10.9	13.3	12	19.9
IW-2	771		30	8.64	12	10.6	10.3		18.3	23	21.4
OW-1	685	<5	248	83.6	97.3	125	128	174	163	194	232
OW-2	811			<5			14.7		31.3	34	21.3
VW-1	750	51	215	223	187.2		236	288	249	277	303
VW-2	471	<5	93	<5			69.8		81.6	94	124
WS-12	429	5	72	22							73.6
WS-23	809	19	201	<5							139

The February 6, 1996, results represent the sampling after 27 days of operation suspension. Operations were suspended on January 10, 1996 after groundwater samples were taken and were resumed on February 7, 1996. Benzene rebound in the wells normally affected by the air sparging ranged from 4% for IW-2 to 36% for OW-1. The small rebound observed in IW-2 (4%) and WS-12 (17%) resulted from being at or near the points of air injection. Significant degradation of source material likely occurred in this area. Source material degradation likely occurred throughout the demonstration area but not to the same extent as near the injection wells. Figure 8 shows the benzene concentration contours on February 6, 1996. Based on the wells sampled in the demonstration area and well WS-12, benzene reductions of 78% were observed at the end of this monitoring period.

The second benzene monitoring period began April 30, 1996 and ended June 19, 1996. A more extensive monitoring program was conducted. The rebound results are very promising particularly for the injection wells (IW-1, IW-2, and OW-2). After 50 days of rebound, benzene reductions of 94-97% were observed for these wells. The benzene concentrations in these wells appeared to have stabilized. Although injection wells IW-3 and IW-4 were not sampled, similar reductions are likely in these wells. Figure 9 shows the benzene concentration contours on June 19, 1996. Benzene contamination is concentrated in the southeast quarter of the demonstration area.

Of particular importance is the reduction observed in well OW-2. Air injection into this well lasted approximately 70 days versus 180 days for the other injection wells and was terminated on February 6, 1996. The end of the second monitoring period was approximately 130 days after termination of air injection in OW-2. This well also recorded the highest benzene concentration (811  $\mu\text{g/L}$ ) in pre-demonstration sampling. Another aspect that will be discussed in the "Microbial Stimulation" is that no bacterial nutrients other than air were injected into this well and heterotrophic bacteria counts were less than the other injection wells. The degradation of the non-dissolved source had to result from air sparging.

Although much less pronounced, substantial reductions were observed in the other demonstration wells and monitoring wells WS-23 and WS-12. Figure 10 shows the concentrations for the monitored wells during this monitoring period. VW-1, OW-1, and VW-2 show a gradual increasing trend indicating influence from leaching of the non-dissolved source material or groundwater influx or both. To further evaluate the impact to the non-dissolved source material in the vicinity of the vent and pump wells (OW-1, VW-1, and VW-2) and monitoring wells WS-10 and WS-12, the second rebound analytical results were compared with the first rebound monitoring period.

Figure 11 shows a histogram of the process wells IW-1, IW-2, OW-1, OW-2, VW-1, and VW-2 and monitoring wells WS-10 and WS-23 for pre-demonstration, February 6, 1996, May 28, 1996, and June 19, 1996. The May 28 analyses were included because they represent a similar duration for monitoring (28 days) as the first monitoring period (27 days). The benzene rebound in the injection wells were discussed previously and are included in the figure for further reference. Only VW-1 had higher benzene concentrations for both sampling events of the second monitoring period than the first monitoring period; however, the concentration of this well began at a much higher concentration (223  $\mu\text{g/L}$ , 4/30/96) during the second round as the first round (51  $\mu\text{g/L}$ , 1/10/96). Even the previous sampling event (April 11, 1996, Table 2) showed a benzene concentration of 118  $\mu\text{g/L}$ . This indicates that the air sparging was not affecting the dissolved benzene as much, and

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■  
<5

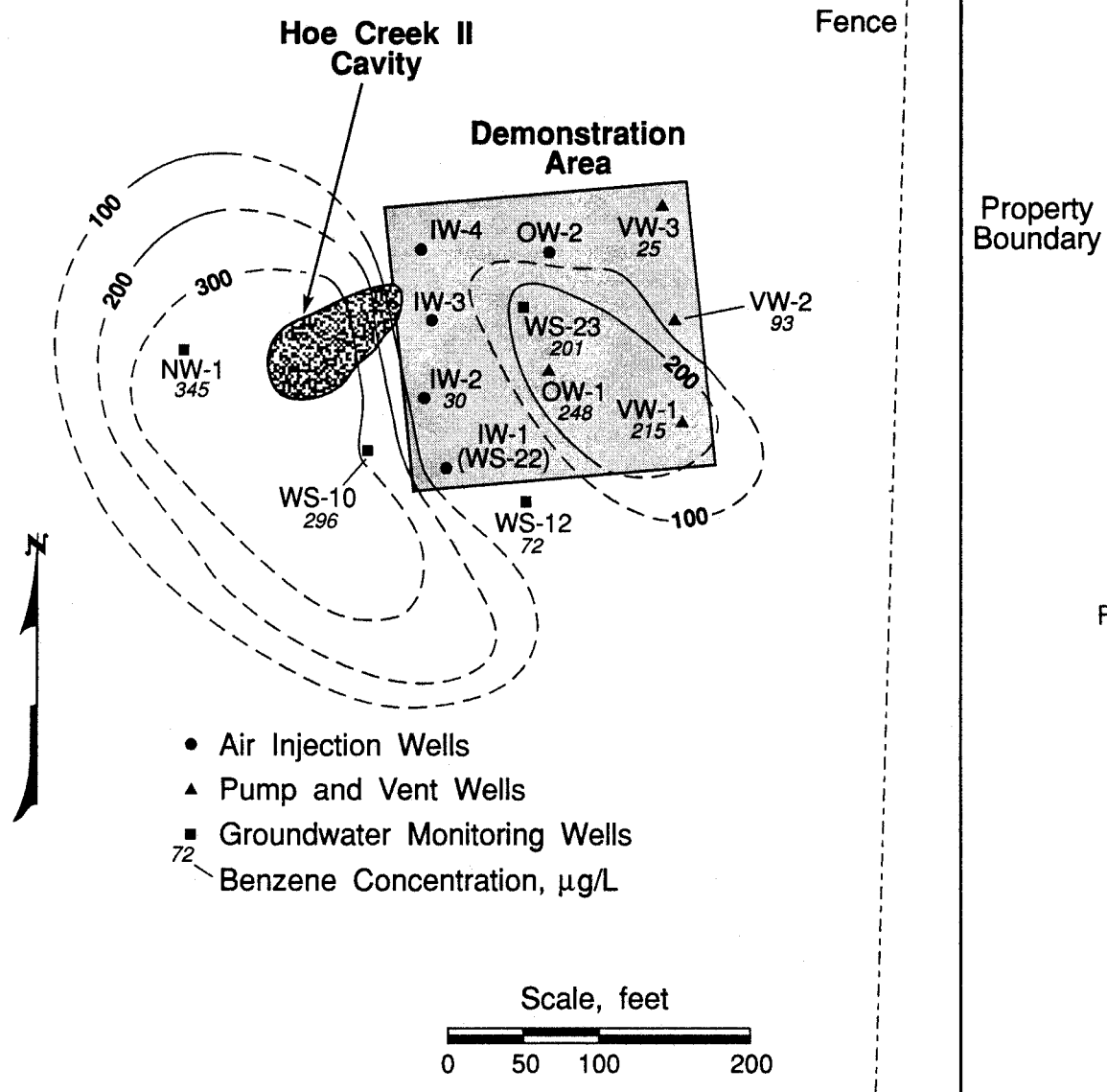


Figure 8. Benzene Concentration Contours on February 6, 1996, µg/L.

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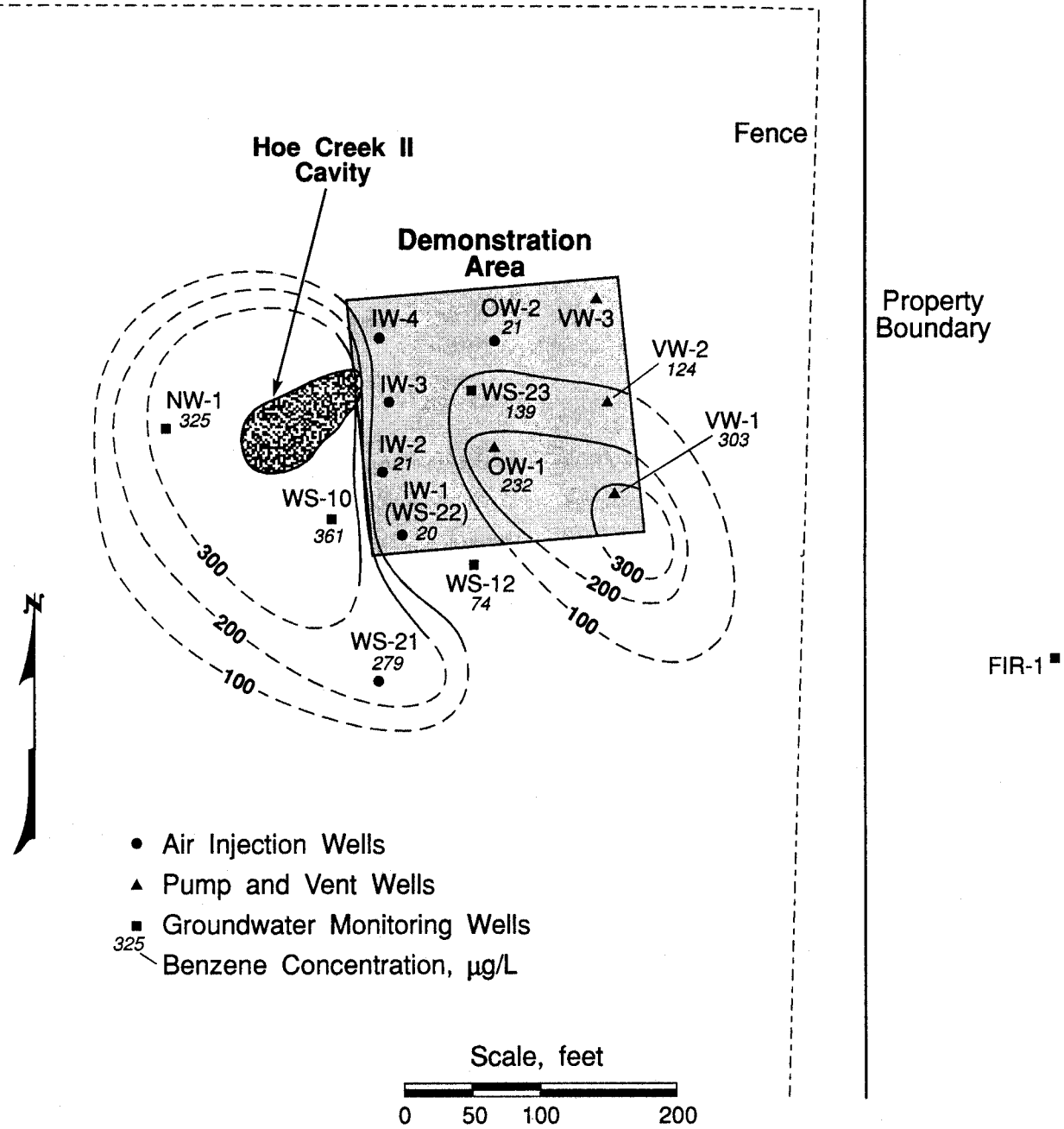


Figure 9. Benzene Concentration Contours on June 19, 1996, µg/L.

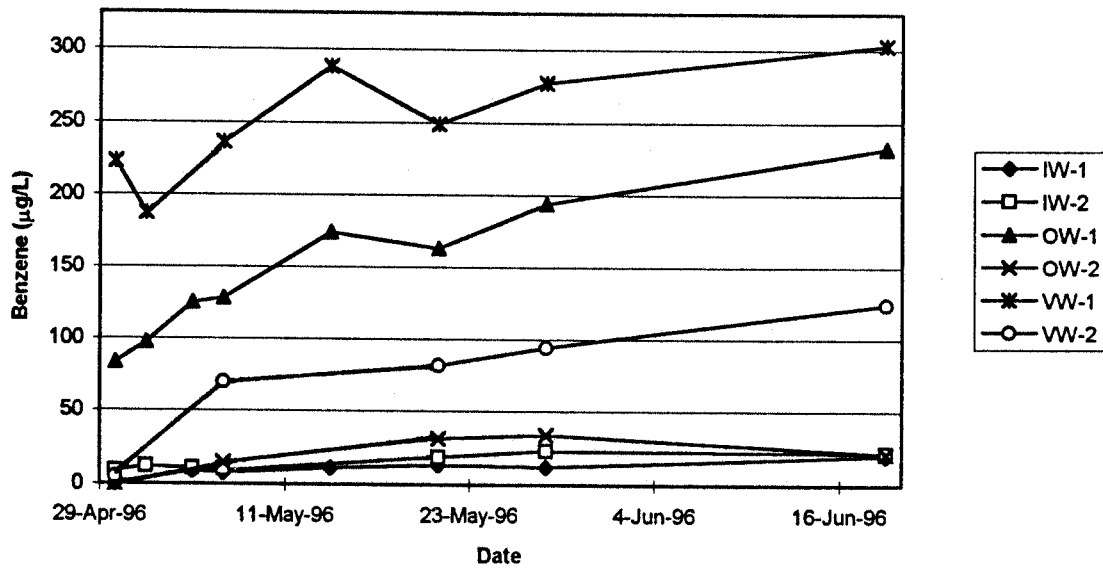


Figure 10. Benzene Concentrations during the Second Rebound Monitoring Period, April 30, 1996 - June 19, 1996.

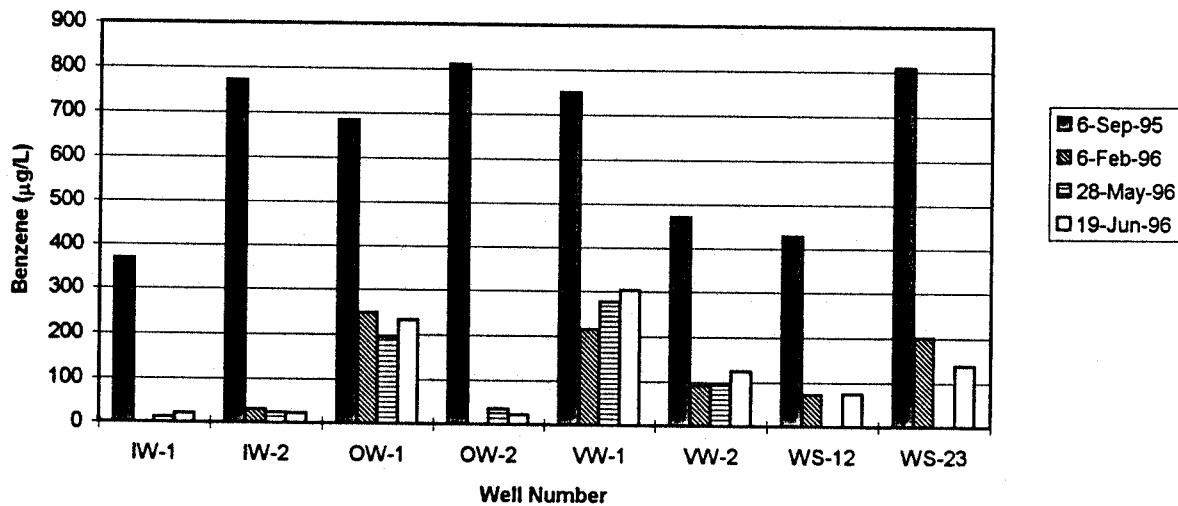


Figure 11. Benzene Concentrations: Pre-Demonstration (September 6, 1995), February 6, 1996, May 28, 1996, and June 19, 1996.

benzene rebound was already occurring before the start of the second round of monitoring. Results of the April 30, 1996 sampling also showed that well OW-1 had already begun to rebound before the second monitoring period began.

Even though OW-1 benzene concentrations began to rebound prior to the start of the second monitoring period, this well and wells WS-12 and WS-23 showed less rebound during the second period. OW-1 had benzene concentrations of 194 µg/L after 28 days and 232 µg/L after 50 days of rebound during the second monitoring period. This compares to 248 during the first period (27 days). WS-23 had substantially less rebound after 50 days (139 µg/L) than the first rebound period (201 µg/L) after 27 days. WS-12 showed the same rebound for the second period (73.6 µg/L after 50 days) as the first period (72 µg/L after 27 days). These results show that the non-dissolved source material is being degraded away from the injection wells.

### **Microbial Stimulation**

Tables 4 and 5 present heterotrophic bacteria (organic degrading) concentrations during the demonstration. Several observations can be made regarding these data. Bacteria concentrations remained below 100,000 except for injection wells IW-1 and IW-2. Well OW-2 was also used as an injection well; however, unlike IW-1 and IW-2, ammonia phosphate was not injected into this well. Nolan and Suthersan [13] reported that the Felix 1 groundwater lacked sufficient phosphorus to maintain viable heterotrophic bacteria concentrations. In their laboratory study using Hoe Creek groundwater from the Felix 1 coal, they showed that adding phosphorus to the groundwater substantially improved biodegradation of phenols. King et al. [14] reported that aerobic bacteria require nitrogen and phosphorus in addition to oxygen for sustaining viable bacteria population.

Heterotrophic bacteria concentrations showed a significant decline during the first rebound monitoring period. This results from the lack of dissolved oxygen during the suspension of air injection. The populations rebounded after air injection was resumed.

Bacteria analyses during the second rebound monitoring period showed some interesting trends. Bacteria concentrations showed relatively high concentrations during the first two weeks of operation suspension (April 30, 1995 - May 14, 1996), followed by substantial declines during the next two weeks (May 14, 1996 - May 28, 1996), followed by a substantial resurgence during the last part of the monitoring period (May 28, 1996 - June 19, 1996). The reason for the initial increase was that the organics were no longer being stripped from the groundwater and became available as nourishment for the bacteria. There was sufficient dissolved oxygen to support this increased activity. The following decline was caused by a depletion of the dissolved oxygen to sustain the bacteria. The final resurgence in bacteria concentrations may indicate that the bacteria were facultative. Facultative bacteria can use other material to oxidize carbon when free oxygen is not available [14]. King, Long, and Sheldon [14] cite an example of the bacteria using the oxygen bound to nitrogen as nitrate. The bacteria could acclimate to another electron acceptor. It may take some time for the acclimation.

Bioremediation in this demonstration is being used as a secondary process. Bioremediation is limited to degrading dissolved organics and would take much longer than air sparging to degrade the non-dissolved source. In the context of the current demonstration, biodegradation is probably occurring in the peripheral areas where sufficient organics exist and dissolved oxygen from air injection is present in the groundwater.



Table 4. Heterotrophic Bacteria Concentrations, April 12, 1995 - April 11, 1996, Colony Forming Units per Milliliter (cfu/mL).

<u>Well #</u>	<u>12-Apr-95</u>	<u>19-Sep-95</u>	<u>28-Nov-95</u>	<u>10-Jan-96</u>	<u>6-Feb-96</u>	<u>5-Mar-96</u>	<u>11-Apr-96</u>
OW-1		20,000		72,000	1,400	8,700	5,900
OW-2							4,900
VW-1		600		14,000	400	21,000	63,000
VW-2				15,000	2,600	14,000	16,000
VW-3		20,000		15,000	2,800	49,000	7,800
IW-2					84,000		
WS-10			4,200	35,000	1,700		75,000
WS-12			310	ND	1,400	8,300	12,000
WS-23	310				700		55,000

Table 5. Heterotrophic Bacteria Concentrations, April 30, 1996 - June 19, 1996, Colony Forming Units per Milliliter (cfu/mL).

<u>Well #</u>	<u>30-Apr-96</u>	<u>7-May-96</u>	<u>14-May-96</u>	<u>21-May-96</u>	<u>28-May-96</u>	<u>19-Jun-96</u>
OW-1	<10	47,000	35,000	11,000	2,700	85,000
OW-2	14,000	49,000		9,400	8,000	40,000
VW-1	19,000	8,200	12,000	6,200	210	15,000
VW-2	4,500	35,000		5,600	2,100	58,000
VW-3	25,000					
IW-1		340,000	430,000	66,000	30,000	300,000
IW-2	>57,000	1,500,000		650,000	60,000	900,000
WS-10						24,000
WS-23						2,100
NW-1	160					2,200

Microbial stimulation across the demonstration area is inhibited because of the reliance on natural groundwater convection to transport the ammonium phosphate nutrient. With the resumption of groundwater pumping, the transport of the ammonium phosphate should significantly improve bacterial population stimulation.

## CONCLUSIONS

Air sparging effectively removed dissolved benzene across the demonstration area and significantly degraded the non-dissolved benzene source material near the air injection wells. The depletion of the benzene shows that in this geologic setting, the designed remediation system offers excellent contaminant-air contact. In general, benzene reductions greater than 80% were experienced across the demonstration area after a 50-day benzene rebound period. Benzene reductions greater than 90% were observed near the air injection wells and showed little benzene rebound in a 50 day period.

These demonstration results seem to verify the hypothesis that because of the buoyancy forces of the gas and the geologic setting, air flowed to the top of the Felix 1 coal and moved along the top of the coal seam in the structural up-dip direction across the demonstration area. This basically mimics the contaminant transport paths that deposited the source material during UCG testing. Groundwater pumping can help control subsurface pneumatic transport by reducing the hydraulic pressure near a pumping well.

Heterotrophic bacteria stimulation occurred with air injection and ammonium phosphate addition. The ammonium phosphate provides required phosphorus and nitrogen nutrients essential to bacteria. There was an indication that the heterotrophic bacteria at the site are facultative and are capable of using other electron acceptors when free oxygen is not available.

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