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REVIEW OF INFORMATION AND DATA RELEVANT TO THE HOE CREEK UNDERGROUND COAL GASIFICATION SITE RESTORATION

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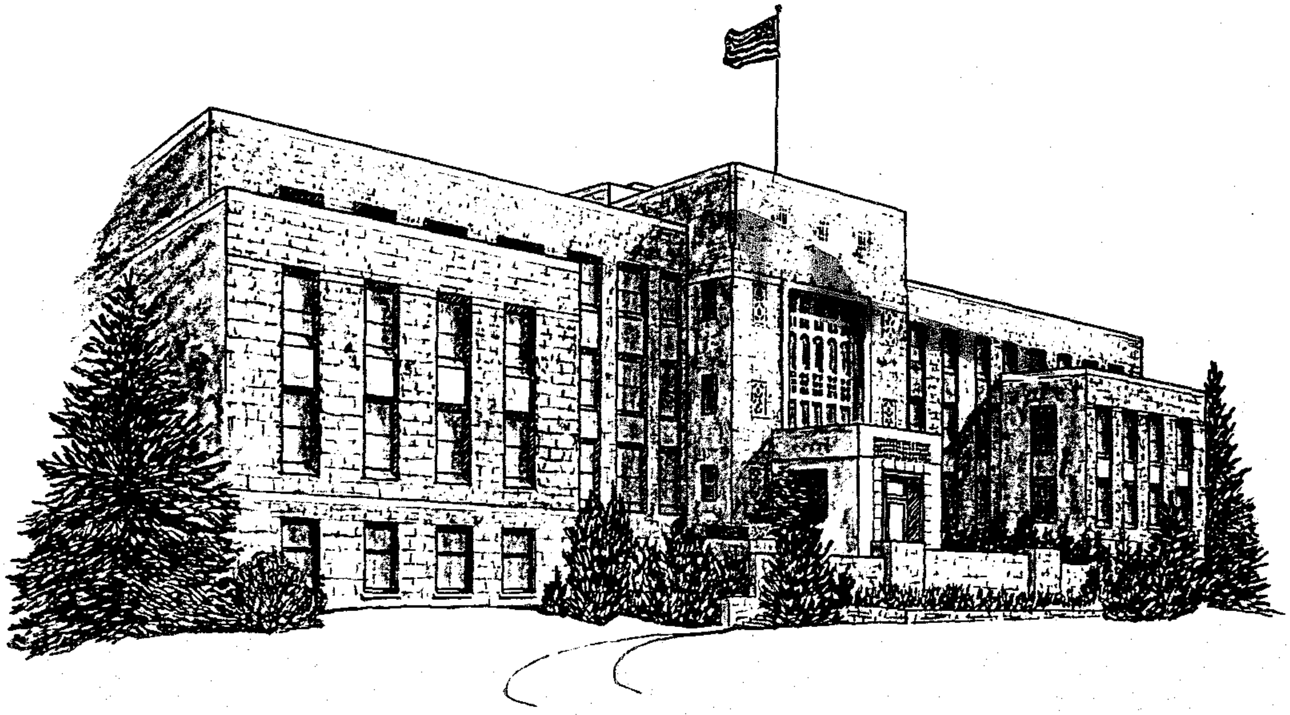

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REVIEW OF INFORMATION AND DATA RELEVANT TO THE HOE CREEK UNDERGROUND COAL GASIFICATION SITE RESTORATION

By
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By
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SUMMARY

Available information on underground coal gasification (UCG) activities and groundwater quality at the Hoe Creek site, south of Gillette, Wyoming, has been reviewed. The original UCG tests were conducted in 1976, 1977, and 1979 by Lawrence Livermore Laboratories under U.S. Department of Energy (DOE) contract. Experimental in situ tests were performed under excessive pressure conditions. This eventually caused coal tars and other gasification products to be pushed out from the burn cavities. The monitoring results to this day (1992) indicate that residual groundwater contamination exists because of the tests. Final decisions are pending between the U.S. Department of Energy (DOE) and the Wyoming Department of Environmental Quality--Land Quality Division (WDEQ) on how the site should be remediated, with WDEQ favoring excavation (i.e., treating the site as a coal mine).

A review of groundwater monitoring data in published information revealed that there are many analyses of inorganic parameters and very few complete organic analyses for species other than phenol. The organic contaminants in groundwater are of concern. Groundwater sampling in 1985, seven years after the gasification burns, showed that the most predominant organic compounds remaining in the groundwater were xylenol isomers, ethylphenol isomers, and relatively low-molecular-weight aromatic hydrocarbons such as naphthalene, alkylbenzenes, and benzene.

Phenolics reported as the compound phenol have been consistently tracked, but the results are different depending upon the analytical method used (gas chromatograph-mass spectrometry (GC-MS) or U.S. Environmental Protection Agency (EPA) colorimetric Methods EPA 420.1 and 420.2). Even the two colorimetric methods produce different results because the reagents used in the colorimetric methods react differently with different phenolic isomers. Consequently, results of different laboratories using different methods over different sampling periods cannot be easily compared.

Establishing baseline organic analysis concentrations is important because it will affect the methods used in site restoration. The WDEQ requires that DOE restore groundwater quality using the best practicable technology. Background groundwater quality data for organic parameters are very limited. Available information shows that some organic compounds were present in the coal seam prior to the first burn, but at low levels (3 to 8.5 mg/L dissolved organic carbon and 0 to 2 μg/L phenols). Extensive organic analyses were also done on a well (designated PERM-1) located 800 ft west of the Hoe Creek I burn zone after the burn was initiated. The results of these analyses were reported as background concentrations by Lawrence Livermore Laboratories.

This report summarizes the information on existing wells, groundwater phenol concentrations (EPA Method 420.2), and benzene concentrations (GC-MS method) for the various wells completed in the Felix 1, Felix 2, and channel sand units at the Hoe Creek site.

INTRODUCTION

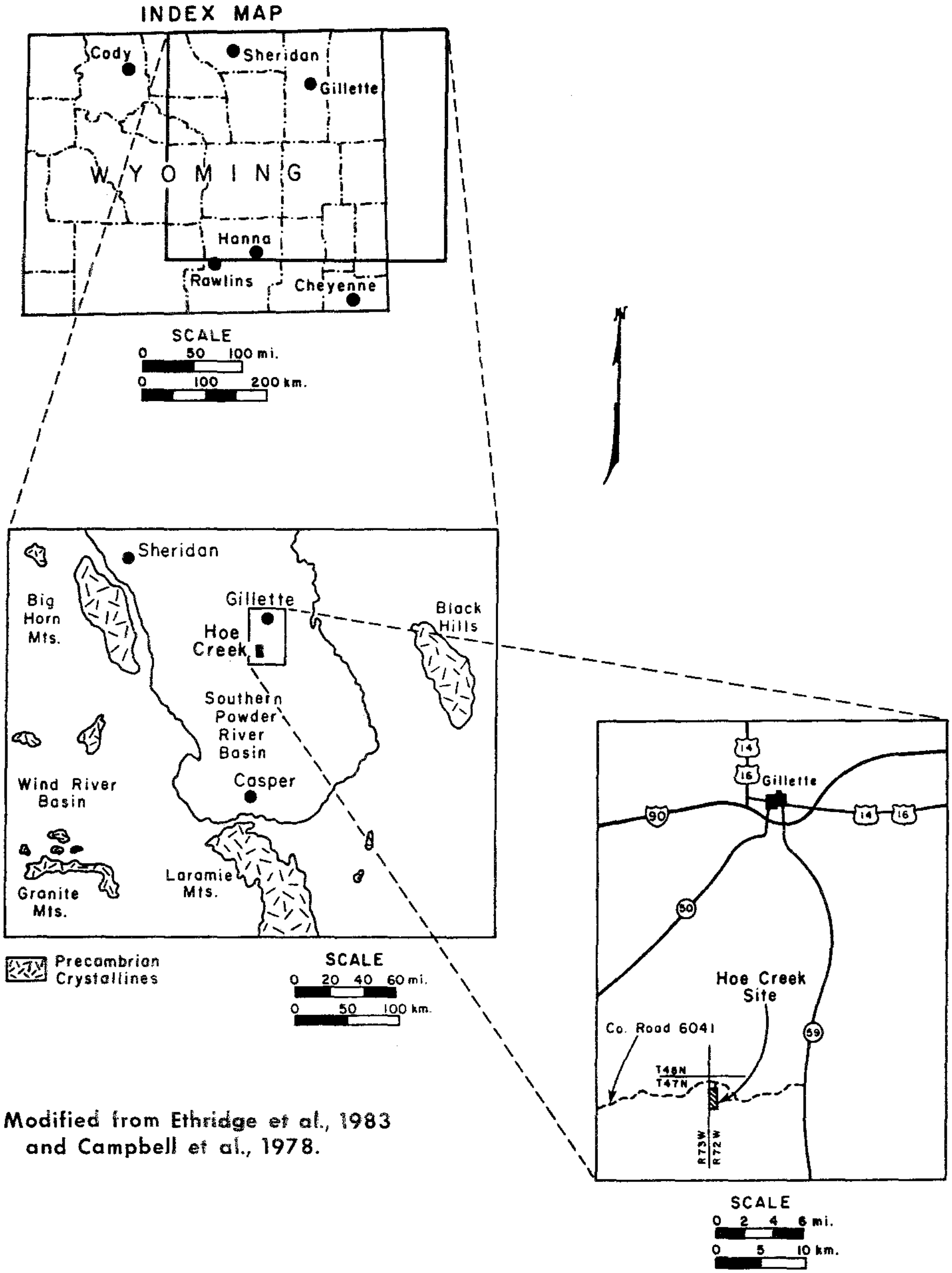
The purpose of this document is to review all reports concerning Hoe Creek activities that were generated prior to June 1991. A list of these reports and brief summaries of each are in the Appendix A. From these documents, Western Research Institute (WRI) evaluated selected information on groundwater quality and the condition of groundwater monitoring wells. This information should be considered in any risk assessment and in establishing cleanup criteria for groundwater quality in the Hoe Creek area of Campbell County, Wyoming.

Three underground coal gasification (UCG) tests were performed during the late 1970s by Lawrence Livermore National Laboratory (LLL) under contract with DOE at the Hoe Creek UCG site approximately 18 miles south of Gillette, Wyoming (Figure 1). The Felix 2 coal seam was the target of the three burns. This coal seam, at the burn location, is 24 ft thick and approximately 150 ft below the surface. The groundwater table varies between 35 and 83 ft below the surface. Contamination of groundwater following the UCG tests is a concern. All facilities originally used to conduct the UCG tests have been removed, except for groundwater monitoring wells at the 80-acre site.

The first UCG burn (Hoe Creek I) began October 15, 1976; lasted 11 days; and gasified 129 tons of coal, of which at least 9 tons of gasified material was not recovered. The Hoe Creek II burn was conducted in 1977 for 58 days and gasified 2480 tons of coal, of which 496 tons of gasified material was not recovered. The Hoe Creek III burn was conducted in 1979 for 47 days and gasified 3950 tons of coal, of which 750 tons was not recovered (Hill et al. 1980). Hill et al. (1980) cite evidence that the Felix 2 coal burn for Hoe Creek II and III penetrated the overlying claystone-sandstone interburden material (13 to 17 ft thick) and extended into the Felix 1 coal seam (10 to 12 ft thick), above the interburden material. The surface has subsided at Hoe Creek III, producing a crater at the burn site.

Lawrence Livermore National Laboratory (Hill et al. 1980) reported that because the UCG tests were conducted under pressure, 1255 tons of unrecovered gasified coal from the three burns pushed outward and upward from the burn cavities. This gasified coal penetrated the Felix 1 and Felix 2 coal seams as well as interburden and upper lithologic units. WRI estimates that ~ 5% (64 tons) of the gasified coal condensed as coal tars (Nordin et al. 1990). Roof collapse occurred in the Hoe Creek II and III cavities. As the gases were pushed out from the cavities, subsurface matrix materials became contaminated with coal tars and organic materials.

The groundwater contamination at the Hoe Creek site has been monitored with different combinations of sampled parameters from site wells because the Wyoming Department of Environmental Quality--Land Quality Division (WDEQ) and the U.S. Department of Energy (DOE), which sponsored the UCG tests, want to arrive at a final decision for restoration. The WDEQ position is that the groundwater quality must be restored to its original condition before DOE can be released from any further obligations to the site. DOE has implemented several



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

Figure 1. Hoe Creek UCG Site

groundwater pump-and-treat remediation efforts since 1986. The groundwater pump-and-treat efforts have been only partly successful. WDEQ has suggested excavation of the site. Other remediation methods are being considered.

The DOE has contracted with a number of parties for quarterly groundwater sampling and analysis, and for various remediation studies and plume containment. Some of this work has been performed by WRI under DOE-cooperative agreement DE-FC21-86MC11076. A recent study, Remedial Investigation/Feasibility Study, was completed in April 1991 by Gilbert/Commonwealth Inc. and James M. Montgomery Consulting Engineers Inc. In November 1991, DOE awarded a contract to EG&G WASC Inc. for groundwater contamination plume containment. As of December 1991, EG&G WASC Inc. has written a management plan with the plume containment scheduled to begin in 1992.

DOE has requested that the Hoe Creek site be given a preliminary assessment for Superfund status. This is a subject of controversy with WDEQ because a risk assessment based on a no-action alternative is part of the Superfund consideration and the no-action alternative is not acceptable to WDEQ.

In a groundwater quality study, Campbell et al. (1978) report that during and after the Hoe Creek I burn, the groundwater became contaminated with organic materials. The sampling data suggested that during gasification the contaminants moved more easily in the direction of highest permeability (North 59° East). Several important organic contaminants in groundwater showed a large decrease in concentration with time (up to 280 days after Hoe Creek I gasification studies), but phenolic compounds were more persistent. Campbell et al. (1978) reported that the groundwater contamination was temporary and DOE went ahead with Hoe Creek II and III UCG burn tests.

Fifteen months after the last gasification burn (Hoe Creek III), LLL sampled the groundwater from three wells (designated WS-6, WS-10, W-1a) and analyzed the groundwater for dissolved organic contaminants (Stuermer et al. 1982). This study identified approximately 135 organic contaminants that had persisted in the groundwater. These compounds included aromatic acidic, neutral, and basic compounds of low molecular weight that represent the water-soluble component of a more complex organic mixture deposited in the aquifer. When the analytical results of groundwater sampled 15 months after the burn (Stuermer et al. 1982) are compared with analyses made during and right after the burn (Campbell et al. 1978), contaminants that remained after 15 months were the phenols, aromatic carboxylic acids, aromatic hydrocarbons, ketones, aldehydes, pyridines, quinolines, isoquinolines, and aromatic amines. Stuermer et al. recommended naphthalene, o-xylene, 2-methylpyridine, and o-cresol as useful indicator compounds of organic contamination for monitoring purposes because these compounds were present in relatively high concentrations. Contaminants that essentially disappeared were the low-molecular-weight, straight-chain hydrocarbons and high-molecular-weight hydrocarbons that are water insoluble. The water-insoluble tars were believed to be sorbed onto the coal matrix but leached out phenols and other contaminants into the groundwater source.

Stuermer et al. (1982) determined that the suite of organic compounds contaminating the groundwater was not simple. Identified phenolic compounds included phenol; o-, m-, and p-cresol; 2-ethylphenol; three dimethylphenol isomers including 3,4-dimethylphenol; 3-ethylphenol; seven C_3-phenol isomers; two methylethylphenol isomers; and others. The total concentration of phenolic compounds in groundwater sampled at well WS-10 was 44.1 mg/L, of which phenol was 10.2 mg/L. Similarly, 20 pyridine-type compounds were measured. The total reported basic organic compound concentration in groundwater sampled at well WS-10 was 0.24 mg/L. Of this, pyridine was 0.053 mg/L, and 2-methylpyridine was 0.061 mg/L.

WYOMING DEPARTMENT OF ENVIRONMENTAL QUALITY

Wyoming Department of Environmental Quality Files

The first two UCG burns were conducted with no notification of record to WDEQ. The WDEQ files contain a permit application dated December 1978 for the Hoe Creek III site, Permit RD1. The permit application lists BLM as the surface and mineral owner. The permit application contained a number of attachments and maps:

Attachment D-1: Archaeological clearance (conclusion: no archaeological sites)

Attachment D-2: Climatological summaries

Attachment D-3: Geology of the Hoe Creek site (incl. Qualheim, 1977, and core boring results)

Attachment D-4: Fullerton-Superficial Geologic Map of Scraper Reservoir

Attachment D-5: Geologic Map of Scraper Reservoir Quadrangle

Attachment D-6: Hydraulic Testing, Felix 2 Coal Seam (results of two vertical test wells at Hoe Creek III site)

Attachment D-7: Groundwater Quality at Hoe Creek I (Campbell et al. 1978)

Attachment D-8: Photographs of vegetation (not useful for identification), list of vegetation (some identified by generic name only), and wildlife information (mammals and raptors only)

Attachment D-9: Mapping units and series description; mine plan for Hoe Creek III

Attachment MP-3: Well completion description and maps for dewatering

Map D-1: Occurrence of groundwater in Gillette area

Map D-2:	Water well locations within three miles of permit area and surface water rights
Map D-3:	Hoe Creek III site water well location map, rev 4, February 13, 1980
Map MP-1:	Plot plan, contour map showing site layout

The WDEQ granted a license (Permit RRD #1, U.S. DOE Hoe Creek Site) to carry out the UCG activities for the third burn.

The WDEQ files contain a number of published reports and some unpublished information on groundwater quality, UCG burn results, and geological characterization following the Hoe Creek III burn. Reports include one by Cyrus W. Rice (NUS Corp) prepared for Lawrence Livermore Laboratories (June 1980) on groundwater treatment in association with UCG projects, another NUS Corp report on costs of groundwater treatment, a report by M. Humenick and S.J. Sierka (September 1982) to DOE on UCG wastewater treatment; and some suggestions by Versar Inc. to DOE that surrounding coal be used as a passive restoration technology. This data package in WDEQ files appeared to be prepared in response to a WDEQ request for information (WDEQ letter dated June 23, 1981).

The WDEQ files contain groundwater quality data from sampling during August 1982 and potentiometric surface maps. A number of inorganic parameters including heavy metals and ammonia were analyzed from various wells. The only organic parameter analyzed was phenol (highest phenol concentration = 5.6 mg/L from well W-22A). There are also considerable earlier data (1976 through November 1981) on inorganic groundwater parameters, some of which were copied from various Lawrence Livermore Laboratory reports.

The WDEQ files contain a Notice of Violation dated August 13, 1984, for the Hoe Creek site. This notice stated that DOE must restore the groundwater to baseline conditions.

The WDEQ files contain a letter dated April 21, 1986, from DOE. This letter contains what DOE regards as baseline water conditions and target parameter levels for cleanup:

phenols	20 ppb (20 μg/L)
chloride	2000 ppm
ammonia-N	10 ppm
sulfate	3000 ppm
TDS	5000 ppm
TOC	200 ppm
calcium	1000 ppm
sodium	1000 ppm
potassium	200 ppm
cyanide	5 ppm

DOE has supplied WDEQ with the results of quarterly groundwater monitoring events, starting with the October 1985 sampling event and continuing to the present (1992). During this time, various laboratories have been contracted to sample and analyze groundwater from selected wells (Brookcliffs Commercial Laboratories, Steamboat Springs, Colorado, 1985; Applied Hydrology Associates, Denver, Colorado, 1985-1987; WRI, Laramie, Wyoming, 1988-1990; James M. Montgomery Consulting Engineers Inc., Laramie, Wyoming, 1991). With the exception of the May 1988 water quality data, and some WRI volatile organic carbon data taken in 1989-1990, their results are limited to various inorganic parameters including metals and ammonia, as well as total organic carbon and chemical oxygen demand. The only organic parameter that was monitored was phenolics reported as phenol, which was measured according to U.S. Environmental Protection Agency (EPA) Method 420.2 (U.S. EPA 1983a). James M. Montgomery Consulting Engineers Inc. used EPA Method 420.1 (U.S. EPA 1983b), which gives different results for mixtures of phenolics.

The May 1988 WRI quarterly report included analyses of groundwater from selected wells for EPA Methods 624 and 625 (U.S. EPA 1984a, b) volatiles and semivolatiles and for radium 226 and radium 228. The organic parameters in this EPA list that could potentially be present in Hoe Creek groundwater were phenol, 2-methylphenol, 4-methylphenol, 2,4-dimethylphenol, 3-methylphenol, naphthalene, benzene, toluene, and ethylbenzene (Mason et al. 1985). This EPA target list does not include all of the organic contaminants that can be present. WDEQ obtained a copy of the WRI sampling and analyses procedures as a result of a meeting on October 5, 1988.

The DOE target levels are higher than what either DOE or LLL considered as baseline concentrations based on limited water analyses.

WDEQ has never approved the April 21, 1986 DOE list. However, in January 1990 WDEQ communicated informally to WRI that levels of inorganic constituents remaining in the groundwater are acceptable, but organic parameters are matters of concern.

The WDEQ file contains reports and correspondence relating to groundwater pump-and-treat activities starting in 1986. Permit No. GPC 86-236 was issued to WRI dated August 19, 1986, for reinjection of groundwater following treatment by carbon filtration. DOE correspondence states that 20 ppb (20 μg/L) is the target cleanup level. The DOE also applied for a Permit to Construct the carbon adsorption units and spray system for the 1989 groundwater restoration activity (application cover letter dated May 25, 1989).

Wyoming Department of Environmental Quality Requirements

WDEQ authority is derived from the Wyoming Environmental Quality Act, the purpose of which is to preserve and enhance the air and water in the state, including reclamation of the land. The WDEQ Land Quality Division enforces the Wyoming Surface Mining Reclamation and Control Act, which covers mining activities (including in situ coal mining). The WDEQ also enforces rules and regulations whose authority is granted by the Environmental Quality Act, sections 35-11-101 through 35-11-1104. Chapter XXI of the WDEQ rules and regulations covers in situ mining operations (WDEQ 1989).

Chapter XXI, Section 3 requires that permit applications for in situ mining include a reclamation plan, which in turn must include [paragraph (d) (i)].

> The information necessary to demonstrate that the operation will return all affected groundwater, including affected groundwater within the production zone, receiving strata, and any other areas, to a condition such that its quality of use is equal to or better than, and consistent with the uses for which the water was suitable prior to the operation by employing the best practicable technology. Such a demonstration shall be made by showing that through the employment of the best practicable technology, as defined in W.S. 35-11-103(f)(i):
>
> (A) The condition and quality of all affected groundwater will be returned to background or better, or:
>
> (B) The requirements of Section 2.d.(1)(a) cannot be achieved. In this event the condition and quality of all affected groundwater will at a minimum be returned to a quality of use, equal to and consistent with uses for which the water was suitable prior to the commencement of the operation.

The definition of best practicable technology and groundwater restoration (W.S. 35-11-103(f)(i) and (iii)) are:

> (f) Specific definitions applying to in situ mining are:
>
> (i) "Best practicable technology" means a technology based process justifiable in terms of existing performance and achievability in relation to health and safety which minimizes, to the extent safe and practicable, disturbances and adverse impacts of the operation on human or animal life, fish, wildlife, plant life, and related environmental values.
>
> (iii) "Groundwater restoration" means the condition achieved when the quality of all groundwater affected by the injection of recovery fluids is returned to a quality of use equal to or better than, and consistent with the uses for which the water was suitable prior to the operation by employing the best practicable technology.

The representatives of WDEQ have stated that the DOE must restore groundwater quality using the best practicable technology before they will release DOE from obligation to the site. If DOE refuses, DOE will forfeit their bond (about $172,000 in 1972 dollars). Only organic contaminants in groundwater are of concern to WDEQ (R. Donovan, WDEQ, personal communication, January 19, 1990), and cleanup levels have not been established. If, after using the best practicable technology, groundwater is still not restored to original or better conditions, WDEQ may then release DOE from obligation to the site at the discretion of the WDEQ director.

BACKGROUND WATER QUALITY

Baseline groundwater quality data are limited, especially on organic constituents. A publication on this subject was written by Lawrence Livermore Laboratories (Campbell et al. 1978), and it summarizes the results of analyses performed by Lawrence Livermore Laboratories, U.S. Geological Survey, and Research Triangle Institute.

Campbell et al. (1978) report that the concentration of phenolic materials present before gasification was in the range of 0 to 2 μg/L, and the dissolved organic carbon was between 3 and 8.5 mg/L. The dissolved organic carbon was composed of approximately 50% hydrophobic and 50% hydrophilic compounds. About 75% of the hydrophobics were organic acids, and 25% were neutral compounds. The hydrophilic material consisted of 80% organic acids, 12% neutral, and 8% organic bases. The individual compounds were not identified. These so called background groundwater samples were collected from several wells identified as EM-1, DW-1, DW-TOT (which was a combination of DW-1, DW-4, and DW-5), and PERM-1. These wells were completed to just below the Felix 2 coal seam. Details of environmental monitoring (designated by prefix EM) and dewatering (designated by prefix DW) well construction and depths are also reported by Campbell et al. (1978).

After the burns took place (Hoe Creek I in 1976, Hoe Creek II in 1977, and Hoe Creek III in 1979), the only background data were from wells upgradient from the burn locations. Applied Hydrology Associates, Denver, Colorado, was contracted by DOE during the mid-1980s to perform quarterly sampling of groundwater at the Hoe Creek site. These analyses were done by ACZ Inc. in Steamboat Springs, Colorado, and other laboratories. The organic analysis work was limited to phenol. The most recent groundwater sampling report in the WDEQ files covers the sampling event that was done in August 1987. Western Research Institute (WRI) was contracted to do the quarterly sampling starting in March 1988 and ending in mid 1990.

Campbell et al. (1978) includes organic analyses of Felix II coal groundwater that was pumped from well PERM-1. This sample was collected 7 days after the start of the Hoe Creek I burn (Table 1). The PERM-1 well was located 800 ft west of the burn zone and was believed to represent baseline conditions. It was used to determine how water quality was affected in other wells nearer and downgradient to the burn as the burn progressed. Campbell et al. determined that the concentrations of organic constituents associated with coal gasification increased significantly during the burn. Phenol was selected as the indicator chemical to assess groundwater cleanup and recovery. Recently, Renk et al. (1990) tracked several other organic parameters at the site including benzene, toluene, ethylbenzene, and naphthalene.

Table 1. Principal Organic Species Identified by GC-MS Analyses of Water Pumped from Well PERM-1 Located 800 ft West of the Burn Zone[a]

Compound	Concentration, ppb or µg/L
n-Pentane	1.10 ± 0.3
2-Methyl pentane	8.68 ± 1.8
3-Methyl pentane	3.64 ± 1.9
n-Hexane	32.42 ± 11.0
Methyl Cyclopentene	5.64 ± 0.3
Benzene	3.72 ± 0.9
Toluene	11.32 ± 1.3
Xylenes	0.64 ± 0.1
p-Ethyl toluene	1.22 ± 0.3
n-Decane	0.44 ± 0.2
Naphthalene	4.70 ± 1.0
C_9H_{20} isomer	0.78 ± 0.3
Styrene	0.62 ± 0.1
o-Xylene	0.64 ± 0.1
C_{10} H_{22} isomer	0.30 ± 0.1
C_{10} H_{22} isomer (different isomer)	0.20 ± 0.1
Benzaldehyde	1.46 ± 0.2
p-Ethyl toluene	1.22 ± 0.3
$C_{11}H_{24}$ isomer	1.92 ± 0.5
Cyanobenzene	0.56 ± 0.2
n-Decane	0.44 ± 0.2
1,2,3-Trimethylbenzene	0.56 ± 0.2
$C_{12}H_{26}$ + C_4-alkylbenzene isomers	0.30 ± 0.1
Acetophenone	1.02 ± 0.3
2-Decane	0.40 ± 0.2
C_5-Alkylbenzene isomer	0.36 ± 0.2
β-Methylnaphthalene	0.36 ± 0.1
n-Tetradecane	0.22 ± 0.1
Ethyl formate[b]	720
Ethyl acetate[b]	810
Dimethyl ether (tent)[b]	135
n-Butanal[b]	3
n-Nonanal[b]	34
n-Decanal (tent)[b]	6.6
Phenol[b]	72
Dimethylphenol isomer[b]	186
Cresol isomer[b]	364
Ethylphenol isomer[b]	9
C_2-Alkyl phenol isomer[b]	69
C_2-Alkyl phenol isomer (different one)[b]	72
C_3-alkyl phenol isomer[b]	9
Ethylphenol isomer[b]	33

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[a] From Campbell et al. (1978, page 9), sampled October 22, 1976, 7 days into Hoe Creek I burn, with statement "The concentrations are thought to represent background levels of these species in the Felix II seam".

[b] From Campbell et al. (1978, Table F25) with statement, "Semivolatile Analyses".

Campbell et al. (1978) report that the wells were pumped 20 to 60 minutes at a flow rate of 3 gpm prior to sampling. The water samples were analyzed by three independent laboratories using gas chromatograph-mass spectrometry (GC-MS), and there was little difference in the results between the laboratories. The individual results from these laboratories are not included in Campbell's report. In addition, their results suggest that after gasification, the ratio of volatile aromatics (e.g., benzene) to aliphatic materials (e.g., hexane and pentane) was much greater than 1, whereas before gasification the ratio was much less than 1. Methane dissolved in the pregasification coal seam water was reported to be 11 ± 4 mg/L. Water from local ranch wells not completed into the coal seam contained undetectable amounts of methane (<0.2 mg/L).

Campbell et al. (1978, Table F25) lists several phenolic compounds measured in groundwater that was sampled from well PERM-1 7 days after start of gasification. They claim these values represent background levels. Phenol was listed as 72 ppb; other phenolic compounds (dimethylphenol, cresol, ethylphenol) were also detected. No explanation is offered for why phenol should be present in a background well that is 800 ft upgradient from the burn. They do state in their report that groundwater was affected at distances 100 ft from the burn zone.

WRI accepted an offer by Marlin E. Lowry to do a computer data base search in U.S. Geological Survey files for any organic analyses (GC-MS) in groundwater that was sampled from wells completed in Wyoming coal seams. This search was not fruitful. Considerable data on inorganic constituents were generated by this search. But, except for a well located in Crook County (T53N R65W Sect 18, 1544 ft deep) that contained 0.3 µg/L of phenol (Lowry 1991, personal communication), organic analyses were lacking. This low value was not confirmed by WRI. Organic analyses (except for total petroleum hydrocarbons) were also lacking in WDEQ Water Quality Division files on coal-bed methane development.

PHENOL ANALYSES

DOE began quarterly sampling of Hoe Creek groundwater in November 1985. The analyses included a suite of inorganic parameters including metals, sulfate, bicarbonate, chloride, bromide, boron, ammonia, nitrate, COD, sulfide, and cyanide. The only organic parameters measured were TOC and phenols. Sampling was done by Applied Hydrology Associates, Denver, Colorado. They used several laboratories (Brookcliffs Commercial Laboratories, Steamboat Springs, Colorado; Intermountain Laboratories, Gillette, Wyoming; Accu-Labs Research Inc., Wheatridge, Colorado). WRI took over the quarterly sampling for the same parameters in May 1988. WRI analyzed phenol using EPA Method 420.2. Starting in 1991, sampling was done by James M. Montgomery Consulting Engineers Inc.; this analysis procedure used EPA Method 420.1 for phenols.

Phenol has been the major indicator compound used to assess efficiency of cleanup activities and groundwater contamination at Hoe Creek. Recently, Renk et al. (1990) added benzene as a groundwater tracking contaminant. However, phenol is the only organic compound in the groundwater for which there is a long historical record (with some data gaps).

A major source of confusion is that there are a number of phenolic compounds (e.g., dimethylphenol, cresol, ethylphenol) other than phenol. Dimethylphenol and other phenolic compounds have different isomers depending on whether the functional groups are in the ortho-, para-, or meta positions of the basic phenol structure. Different procedures can be used to analyze phenol, and these different procedures can produce different values for phenol.

The GC-MS method can distinguish between different phenolic compounds and most of their isomers. Campbell et al. (1978) subcontracted the analytical work to Research Triangle Institute, who used a freon-TF extraction after an initial pH adjustment (Table 2). The current EPA Method 625 base-neutral-acid procedure for GC-MS analyses uses 1 liter of sample that is adjusted to pH 2. Following the EPA procedure, the sample is extracted with 500 mL of methylene chloride. The extract is evaporated to 1 mL in a nitrogen atmosphere at 35°C (95°F), and this concentrate is used for GC-MS analyses. Only four phenolic compounds (excluding those with nitrogen or chlorine in their structure) are analyzed as part of the normal protocol: phenol, 2-methylphenol, 4-methylphenol, and 2,4-dimethylphenol. Other phenolic compounds can be analyzed at additional cost using appropriate standards.

Table 2. Phenolic Compounds Identified by GC-MS Analyses in Groundwater Following Gasification at Hoe Creek I[a], Concentrations in ppb (μg/L).

Well: Days after Gasification:	EM-4 6	EM-4 83	EM-5 6	DW-4 6	DW-4 83
Phenol	138	93	159	120	163
Dimethyl phenol isomers	721	412	570	120	220
Cresol isomers	607	388	96	1650	502
Ethyl phenol isomers	522	420	193	777	486
C_3-alkyl phenol isomers	<1	<1	<1	580	9
C_4-alkyl phenol isomers	<1	<1	<1	15	<1
C_5-alkyl phenol isomers	<1	<1	<1	3	<1
Total phenolic compounds	1988	1312	1018	3265	1380

[a] From Campbell et al. (1978, Appendix Tables F26 through F34); Day 0 was October 15, 1976.

The GC-MS analytical work is expensive. The cost of an EPA Method 625 extraction and semivolatile analysis including the four phenolic compounds is approximately $400. Identification of all the phenolic compounds is a major research project, which can increase analytical costs to over $1500 per sample. In the interest of lower costs and rapid turn-around time, a colorimetric method is typically used (at a cost of about $45 per sample). This method uses phenol as a standard. The problem with this method is that reagents used also react in varying degrees with all phenolic compounds and their isomers. That is, it is a method which provides a measurement of phenolics based on calibration with the compound phenol. For example, 2-methylphenol, 3-methylphenol, and 4-methylphenol all react differently.

EPA published three colorimetric procedures (Methods 420.1, 420.2, and 420.3) for phenol analysis (U.S. EPA 1983b, a, c). The different procedures do not produce the same analytical result when applied to Hoe Creek groundwater because the reagents used are different in both quantity and order of addition. This results in a different response relative to the compound phenol for the mixture of phenolic compounds actually in the groundwater. WRI has used Method 420.2 on all of the Hoe Creek groundwater phenol analyses during its contract period (1988-1990). When different analytical procedures for phenol are used by the different laboratories contracted to analyze Hoe Creek groundwater a comparison of the results can not be made. For comparison over time, only Method 420.2 can be used.

A comparison of sample splits analyzed by WRI using Method 420.2 and by Data-Chem Laboratory using Method 420.1 is listed in Table 3. The Data-Chem Laboratory results are reported in the Gilbert/Commonwealth Inc. and James M. Montgomery Consulting Engineers Inc. (1991) quarterly groundwater monitoring report. Method 420.1 gives a phenol value that is 2.5 to 4 times the Method 420.2 result.

Table 3. Comparison of Phenol Analytical Results Obtained With EPA Method 420.1 and EPA Method 420.2, μg/L

EPA Method: Laboratory:	420.1 Data-Chem	420.2 WRI	420.1 WRI
Well Number[a]			
W-17A	250	100	---
WS-26	260	93	---
W-1A	170	44	---
WS-10	260	74	---
W-8A	70	<20	---
W-4A	70	<20	---
W-22A	250	74	198

[a] Wells sampled February 15, 1991; 16 other wells sampled with groundwater less than 20 μg/L phenols by either method.

Both Methods 420.1 and 420.2 are based on the ability of phenolic materials to react with 4-aminoantipyrene in the presence of potassium ferrocyanide at pH 10 to form a stable, reddish-brown antipyrene dye. The amount of color produced is a function of the concentration of phenolic material.

If the water sample is already colored, both methods employ a preliminary step to distill the phenols; the reagents are added in the distillation step. Both methods use phenol as a standard. The two methods differ in that Method 420.1 is manual and Method 420.2 uses a Technicon Autoanalyzer. WRI has determined that there was no difference in the result whether or not the preliminary distillation was used with Method 402.2.

In Method 420.1, 4-aminoantipyrene reagent is added to an already buffered sample (pH 10) followed by the potassium ferrocyanide addition; the absorbance is measured at 510 nm after 15 minutes. In Method 420.2, the buffer is added to the potassium ferrocyanide solution, and the buffered ferrocyanide solution is then added to the sample. This is followed by addition of 4-aminoantipyrene reagent. The relative amount of 4-aminoantipyrene reagent that is added per unit of sample is much less for Method 420.2 compared with Method 420.1. The red-brown complex is measured using a colorimeter equipped with a 50-nm flow cell and 500- or 520-nm filter (Method 420.2). WRI believes that the procedural differences between Methods 420.1 and 420.2 are enough to cause the phenolic compounds to react differently with the reagents.

POSTBURN ORGANIC CONTAMINANT GROUNDWATER STUDIES

Mason et al. (1985) conducted a sampling and analysis program in 1985 on organic contaminants remaining in the groundwater seven years after the Hoe Creek II burn. Groundwater samples from the Felix 1 and Felix 2 coal seam aquifers and from the Hoe Creek II burn cavity were collected along a line extending east from the Hoe Creek II burn site (Figure 2). Extraction procedures were used to separate each of the water samples into hydrophilic and organophilic fractions. The organophilic fractions were further separated into organophilic acid fractions, organophilic base fractions, and organophilic neutral fractions. Each fraction was then analyzed by gas chromatography.

Eleven water samples (Table 4) were obtained; two were obtained from the Hoe Creek II burn cavity (well A). One of these duplicate well A samples was spiked with standard compounds to establish the percentages of recovery. The compounds were added to yield concentrations of 20 to 40 ppb. Percent recoveries of these standard compounds are listed in Table 5.

Peak response corresponded to a limit of detection of about 0.2 ppm, but the working range for the standard curves was 1 ppb and above. Therefore, peaks that were detected but had concentrations less than 1 ppb were reported as <1.0 ppb.

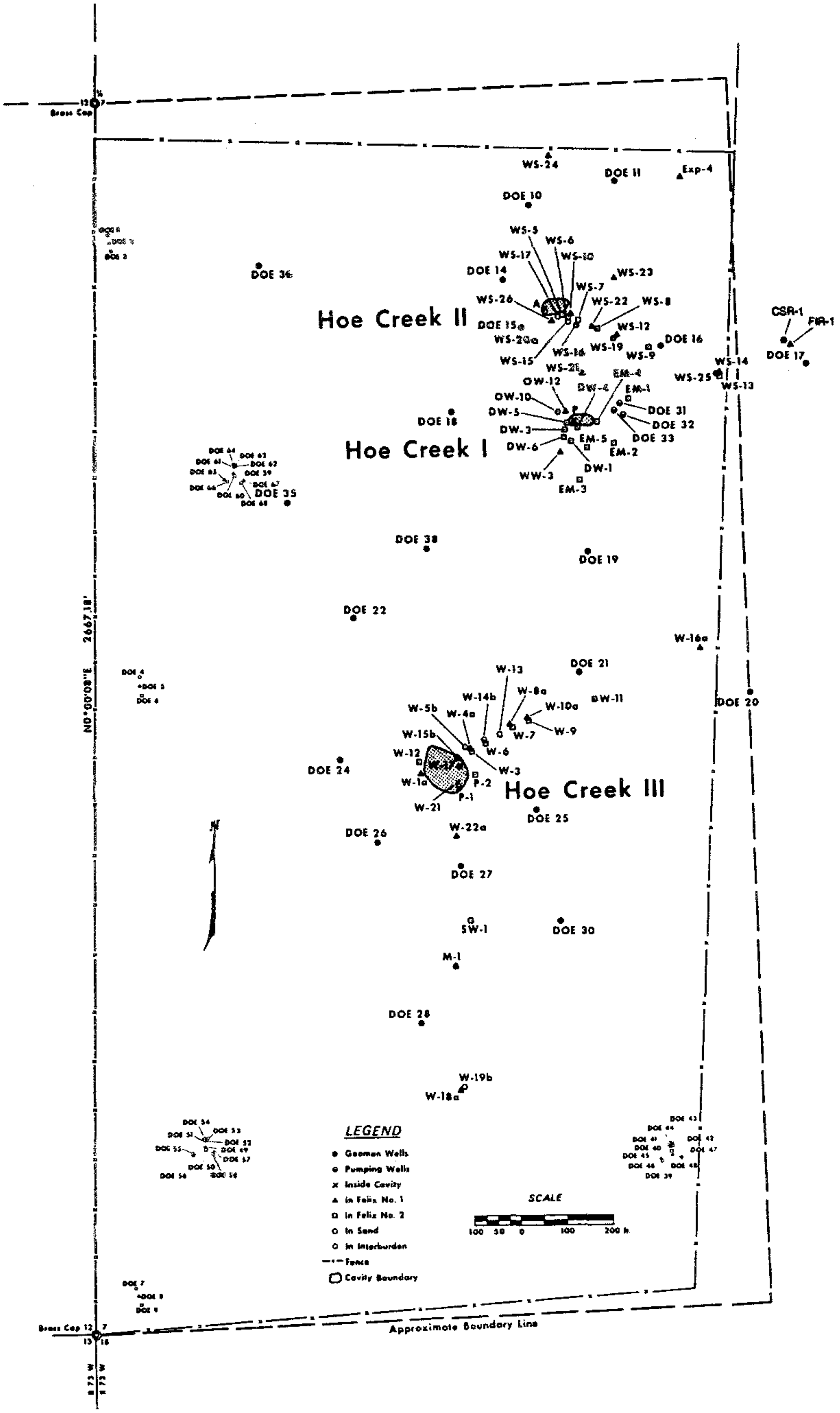

Figure 2. Hoe Creek UCG Site Showing Well Locations

Table 4. Wells Sampled in Study by Mason et al. (1985)

Well Name	Aquifer
Well A	UCG Hoe Creek II Cavity
WS-5	Felix 2
WS-10	Felix 1
WS-9	Felix 2
DOE 16 F-1	Felix 1
DOE 16 F-2	Felix 2
WS-14	Felix 1
WS-13	Felix 2
DOE 17 F-1	Felix 1
DOE 17 F-2	Felix 2

Table 5. Percentage of Compounds Recovered from Hoe Creek II Burn Cavity (Well A) Sampled in 1985 (Mason et al. 1985)

Compound	Fraction	Percentage Recovery
Phenol	organophilic-acid	36.4
o-Cresol	organophilic-acid	68.5
2,4-Xylenol	organophilic-acid	60.2
Toluene	organophilic-neutral	40.4
o-Xylene	organophilic-neutral	46.2
2-Methylpyridine	organophilic-base	0

The concentrations of organics measured in wells DOE 17 F-1 and DOE 17 F-2 were low to undetectable. The analyses of these wells were used as baseline data for the study.

The concentrations of organophilic compounds in groundwaters from the Felix 1 and Felix 2 coal seams are listed in Tables 1 and 6, respectively. Wells WS-5 and WS-10 had the highest amount of organic contamination, although the distribution of organics in these wells was not alike. Contamination in well WS-5 was dominated by hydrocarbon compounds, such as naphthalene and alkylated benzene, whereas in well WS-10 the contamination was dominated by phenols, particularly the xylenols and ethylphenols. Contamination in groundwater collected from the Hoe Creek II burn cavity (well A) and from wells located more than 200 ft from the cavity was much lower.

Table 6. Concentrations of Organophilics in Felix 1 Wells as Reported by Mason et al. (1985), μg/L

	Well A[a] (0 ft)	WS-10 (55 ft)	DOE 16 F-1 (263 ft)	WS-14 (400 ft)	DOE 17 F-1 (578 ft)	DDW Blank[b]
Acids						
Phenol	<1.0	2.7	5.3	4.5	1.4	[c]
o-Cresol	[c]	579.	4.4	<1.0	[c]	[c]
m- and p-Cresol	[c]	791	2.2	<1.0	[c]	[c]
2,6-Xylenol	2.0	210.	3.3	<1.0	[c]	[c]
2-Ethylphenol	<1.0	466.	4.4	<1.0	[c]	[c]
2,4- and 2,5-Xylenol	3.6	1280.	7.9	1.8	[c]	[c]
C_2-Phenol isomer[d]	[c]	1250.	4.4	<1.0	[c]	[c]
2,3-Xylenol	1.7	444.	2.0	[c]	[c]	[c]
3,4-Xylenol	2.7	624.	1.3	[c]	[c]	[c]
Neutrals						
Toluene	<1.0	112.	51.8	2.1	2.1	1.9
Ethylbenzene	[c]	26.3	28.1	6.8	[c]	[c]
o-Xylene	[c]	43.0	31.5	[c]	<1.0	1.0
Indan	<1.0	27.2	30.2	2.4	<1.0	<1.0
Naphthalene	<1.0	220.	161.	1.5	<1.0	[c]
Bases						
2-Methylpyridine	[c]	75.1	[c]	[c]	[c]	[c]
3- and 4-methylpyridine	[c]	39.1	[c]	[c]	[c]	[c]
Aniline	<1.0	60.5	<1.0	[c]	[c]	[c]

[a] All distances were measured from well A, which is located in the Hoe Creek II burn cavity.

[b] Analysis of laboratory-generated, deionized-distilled water (DDW) method blank

[c] not detected

[d] 3- and 4-ethylphenol and 3,5-xylenol

Although phenols (organophilic acids) were detected in the outlying wells, the organophilic neutral compounds such as naphthalene occurred at much higher concentrations. The concentration of organophilic bases is much lower in these groundwater samples. Overall, the most predominant organic compounds in these samples were xylenol isomers, ethylphenol isomers, and low-molecular-weight aromatic hydrocarbons such as naphthalene and alkylated benzenes.

Mason et al. (1985) compared data (an abbreviated list of acid, base, and neutral organics, Table 6) collected seven years after gasification with data reported by Stuermer et al. (1982), taken 15 months after gasification. The most obvious change that occurred during this time is the drop in phenol and cresol concentrations in well WS-10 (Table 7). Concentrations of compounds in the organophilic base and neutral fractions have decreased less dramatically. Mead and Raber (1980) reported a decrease in phenol concentrations in WS-10 about two years after gasification, with a concurrent increase in a well 100 ft to the east. Thus, phenol, which is a highly water-soluble compound, appears to have migrated away from the Hoe Creek II cavity.

Table 7. Concentrations of Organophilics in Felix 2 Wells as Reported by Mason et al. (1985), μg/L

	WS-5 (39 ft)[a]	WS-9 (239 ft)	DOE 16 F-2 (263 ft)	WS-13 (403 ft)	DOE 17 F-2 (578 ft)
Acids					
Phenol	1.0	11.4	<1.0	<1.0	[b]
o-Cresol	6.9	2.9	[b]	3.5	[b]
m- and p-Cresol	<1.0	[b]	[b]	<1.0	[b]
2,6 Xylenol	<1.0	1.3	[b]	2.4	[b]
2-Ethylphenol	6.0	2.4	[b]	3.9	[b]
2,4- and 2,5-Xylenol	8.2	3.7	[b]	5.6	[b]
C_2-Phenol isomer[c]	6.9	2.0	[b]	4.8	[b]
2,3-Xylenol	8.3	1.0	[b]	2.5	[b]
3,4-Xylenol	4.9	0.6	[b]	1.1	[b]
Neutrals					
Toluene	21.5	5.0	2.5	16.6	1.3
Ethylbenzene	94.2	9.5	12.7	8.8	1.7
o-Xylene	100.	7.9	2.9	7.9	---
Indan	164.	[b]	19.9	5.4	<1.0
Naphthalene	730.	21.0	7.5	16.9	<1.0
Bases					
2-Methylpyridine	12.7	[b]	[b]	[b]	[b]
3- and 4-Methylpyridine	2.0	[b]	[b]	[b]	[b]
Aniline	<1.0 [b]	[b]	[b]	1.3	

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[a] All distances were measured from well A, which is located in the Hoe Creek II burn cavity.

[b] not detected

[c] 3- and 4-ethylphenol and 3,5-xylenol

STATUS OF EXISTING WELLS AT THE HOE CREEK SITE

Of the approximately 150 existing wells at the Hoe Creek site, only thirteen have been monitored repeatedly over an extended period of time. Phenol is one of the major contaminants of concern at the site. A relatively large amount of data on phenol has been collected. Figures in Appendix B show the history of phenol contamination in groundwater from the thirteen wells for which the most data exist. Benzene, another contaminant of concern, has been consistently examined for the last three years. Barteaux (1986) summarized much of the water quality data up to 1986.

Groundwater samples from other wells at the Hoe Creek site have shown contamination by phenol and/or benzene; however, these wells have not been sampled frequently. Table 8 lists these wells and the range of contamination concentrations detected in recent years.

Table 8. Contamination Ranges for Infrequently Sampled Wells

	Phenol, μg/L	Benzene, μg/L
Channel		
WS-19	<20 - 64	<5 - 280
WS-16	100 - 370	91 - 1300
CSR-1	<20 - 31	<5
Felix 1		
FIR-1	<20 - 30	<5 - 51
WS-21	20 - 260	<5 - 420
WS-26	68 - 200	160 - 200
W-8a	130 - 340	590 - 800
W-10a	40 - 140	310 - 560
W-17a	60 - 440	67 - 130
Felix 2		
DOE-17	33 - 100	<5 - 200
DW-4	<20 - 25	<5 - 56
WS-7	21 - 45	130 - 490
P-2	<20 - 60	33 - 200
W-6	<20	<5 - 68
W-12	<20 - 21	41 - 54

In addition, a large number of samples from Geomon wells at the site have shown significant contamination. The integrity of these wells is questionable. In a November 1, 1989, letter from Urban Sharum (DOE) to

Roy Spears (WDEQ), Mr. Sharum listed the following Geomon wells as being nonfunctional or marginally operable:

DOE-10
DOE-11
DOE-14
DOE-15
DOE-16
DOE-17
DOE-18
DOE-19
DOE-20
DOE-21
DOE-22
DOE-24
DOE-25
DOE-26
DOE-27
DOE-28
DOE-30
DOE-35
DOE-36
DOE-38

Of these wells, DOE-10, DOE-11, DOE-14, and DOE-17 were recompleted as Felix 2 wells during the spring of 1989. Gilbert/Commonwealth (1991) report that well integrity analyses show a majority of the wells at the site are judged unsuitable for sampling or remediation use. Most were rejected because completion data were lacking. Of the wells illustrated in Appendix B, only the channel sand wells WS-15 and WS-17 were not rejected. Of the fifteen infrequently sampled wells listed in Table 1, channel sands wells WS-16 and WS-19, Felix 1 wells FIR-1 and W-17a, and Felix 2 wells WS-23 and DOE-17 were not rejected.

Very little data exist on the stable yield of wells at the Hoe Creek site. Stable yield is the discharge rate that can be maintained for an extended period of time from a particular well. The most comprehensive well yield data are contained in reports on the 1987 restoration (Nordin et al. 1988) and the 1989 restoration (Renk et al. 1990). In the 1987 restoration, reinjection of treated water may have artificially enhanced yield from the two pumping wells. During the 1989 restoration, pumping of wells in close proximity to each other probably reduced the stable yield from individual wells. Table 9 lists expected stable yields from wells pumped during the 1989 restoration. Yield from individual wells may be higher than the value listed if each well is pumped alone and the surrounding wells are not pumped.

Table 9. Expected Yield from Wells at the Hoe Creek Site

Well Name	Expected Stable Yield, GPM
WS-5	3.5
WS-6	2.4
WS-7	3.2
WS-10	7.4
WS-15	0.3
WS-16	0.2
WS-17	0.1
WS-19	1.0
WS-21	2.0
WS-22	5.0
WS-23	<0.1
WS-26	0.6
DW-4	6.0
WS-24	0.4
W-1a	2.0
W-6	0.5
W-17a	0.3
W-21	4.0
P-2	0.1
W-10a	1.2

CONCLUSIONS

Background water quality data on the Felix 1 and 2 coal seams near the Hoe Creek cavity site, especially for organic parameters, are very limited and are open to question. Although phenol is the parameter that was tracked to assess the aquifer cleanup, it is one of the many organic contaminants at Hoe Creek. Different procedures used by different laboratories to analyze phenol have resulted in different phenol numbers, which has added to the confusion. Many different phenolic compounds are in the groundwater as the result of the gasification, and these react differently with the reagents used in the colorimetric methods (EPA 420.1, 420.2) used to detect phenol.

While attempting to construct baseline conditions from other sources of information, WRI contacted Marlin E. Lowry, a retired hydrologist familiar with the original Hoe Creek burn, who commented to WRI that he questioned the validity of the baseline organic concentrations. His concern was that the groundwater may have been contaminated with petroleum hydrocarbons from the well drilling equipment and that the wells were not adequately pumped during sampling.

RECOMMENDATIONS

Good, definitive organic analyses of the water in the Felix 1 and Felix 2 coal seam aquifers should be done at remote locations (over 2000 ft away upgradient and downgradient) from the burn cavities using EPA Methods 624 and 625 extraction procedures and by GC-MS. This will require completion of at least four wells (Felix 1 and 2, upgradient and downgradient). These wells should provide background water quality data. The analyses should include all of the phenolic compounds including cresol and up to C_3 carbon isomers. Western Research Institute (WRI) recommends that GC-MS methods be used in detailed organic analyses of the groundwater associated with the Felix 1 and 2 coal seams at locations remote from the site in order to establish baseline data.

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DISCLAIMER

Mention of specific brand names or models of equipment is for information only and does not imply endorsement of any particular brand.

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Hill, R.W., C.B. Thorsness, R.J. Cena, W.R. Arman, and D.R. Stephens, 1980, Results from the Third LLL Underground Coal Gasification Experiment at Hoe Creek. Sixth Underground Coal Conversion Symposium Proc., Shangri-La, OK, Conf. No. 800716, 19-29.

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Mead, W., and E. Raber, 1980, Environmental Controls for Underground Coal Gasification: Groundwater Effects and Control Technologies. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-84075.

Nordin, J.S., W. Barrash, and B.T. Nolan, 1988, Groundwater Restoration Field Test at the Hoe Creek Underground Coal Gasification Site. Western Research Institute, Laramie, WY, DOE/MC/11076-2454.

Nordin, J.S., W. Griffin, T. Chatwin, S. Lindblom, and S. Crader, 1990, Remediation Cleanup Operations for the Hoe Creek UCG Site. Western Research Institute, Laramie, WY, DOE/MC/11076-2955.

Qualheim, B.J., 1977, Geological Exploration of Potential Underground Coal Gasification Sites in the Powder River Basin of Wyoming and Montana. Lawrence Livermore Laboratory, Livermore, CA, UCRL-52237.

Renk, R.R., S.E. Crader, S.R. Lindblom, and J.R. Covell, 1990, Hoe Creek Groundwater Restoration. Western Research Institute, Laramie, WY, DOE/MC/11076-2948.

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U.S. EPA, 1983b, Method 420.1, Spectrophotometric, Manual 4-AAP with Distillation, Methods for Chemical Analysis of Water and Wastes. National Technical Information Service, Springfield, VA, PB-84-128677.

U.S. EPA, 1983c, Method 420.3, Spectrophotometric, MBTH with Distillation, Methods for Chemical Analysis of Water and Wastes. National Technical Information Service, Springfield, VA, PB-84-128677.

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APPENDIX A

List of Reports on the
Hoe Creek Underground Coal Gasification Site

Adams, J.C., and D.J. Kocornik, 1986, Phenol Degradation by Indigenous Bacteria in Underground Coal Gasification Wastewaters. Western Research Institute, Laramie, WY, DOE DE-FC21-83FE60177.

Several strains of phenol-metabolizing bacteria were found to be indigenous to UCG-affected waters from Hanna and Hoe Creek, Wyoming. Studies were performed to delineate the limits of phenol concentration, temperature, nutrient supplementation, and dissolved oxygen concentration within which these bacteria actively degraded phenol.

Advani, S.H., J.K. Lee, O.K. Min, and S. Lee, 1982, Status of Technology Associated with Cavity and Subsidence Response Prediction Associated With Underground Coal Conversion. Proceedings of the 8th Underground Coal Conversion Symposium, Keystone, CO.

A brief review of the state-of-the-art pertaining to roof collapse and subsidence modeling applicable to underground coal conversion is given. The role of material properties and their temperature dependent sensitivity is discussed. Numerical evaluations of Hanna II and Hoe Creek experiments are detailed along with selected comparisons.

Aiman, W. R., 1979, Reverse Combustion Along a Borehole in a Shrinking Coal: Preliminary Results. Lawrence Livermore Laboratory, Livermore, CA, UCRL-82541.

Reverse combustion along a borehole (76-mm diameter) was used during LLL's field experiment in underground coal gasification: Hoe Creek III. The enlarged channel produced by reverse combustion will allow high gas velocities for the forward combustion phase of gasification.

Aiman, William R., 1979, Reverse Combustion in a Borehole. Lawrence Livermore Laboratory, Livermore, CA, UCRL-83461.

Reverse combustion along a directionally drilled horizontal channel 76-mm in diameter was used during a field experiment (Hoe Creek III) on in-situ coal gasification. Planning the field work required laboratory experiments, which are reported here.

Aiman, W.R., C.B. Thorsness, R.W. Hill, R.B. Rozsa, R. Cena, D.W. Gregg, and D.R. Stephens, 1978, The Hoe Creek II Field Experiment on Underground Coal Gasification: Preliminary Results. Lawrence Livermore Laboratory, Livermore, CA, UCRL-80592.

The linked vertical wells scheme for in situ coal gasification was used for the second experiment at Hoe Creek. The experiment took 100 days for air flow testing, reverse combustion linking, forward combustion gasification, and postburn steam flow.

Aiman, W.R., C.B. Thorsness, R.W. Hill, and D.R. Stephens, 1980, An Underground Coal Gasification Experiment: Hoe Creek II. Combustion Science and Technology, 21:#97-107.

In this experiment, the scheme of linked vertical wells of forward combustion gasification and post-burn steam flow are reported.

Aiman, W.R., H.C. Ganow, and C.B. Thorsness, 1979, Hoe Creek II Revisited: Boundaries of the Gasification Zone. Lawrence Livermore Laboratory, Livermore, CA, UCRL-83498.

Lawrence Livermore Laboratory completed an exploratory drilling program at the site of Hoe Creek II field experiment on in-situ coal gasification. The results have been used to further define the boundaries of the gasification zone.

Aiman, W.R., R.W. Lyczkowski, C.B. Thorsness, and R.J. Cena, 1979, Reverse Combustion in a Horizontally Bored Channel. Proceedings of the 5th Underground Coal Conversion Symposium, Alexandria, VA.

This paper discusses the experimental and mathematical modeling of reverse combustion along a horizontally bored channel in shrinking coal. The purpose of the modeling effort is to provide information to assist in planning the reverse combustion phase of the Hoe Creek III field experiment.

Applied Hydrology Associates, 1987, Groundwater Monitoring Report, Nov. 1987. Submitted to U.S. DOE, Laramie Project Office, by Applied Hydrology Associates, Denver, CO.

This report documents the sampling methods, field results, and laboratory results from groundwater monitoring wells at the Hoe Creek UCG site.

Chemical and Engineering News, 1980, In-Situ Coal Gasification Data Look Promising, Vol. 58, No. 29, 37-40.

Latest data from Hoe Creek field tests are generally considered a success in demonstrating the feasibility of in-situ coal conversion.

Bader, B.E., and R.E. Glass, 1981, The Role of Site Characteristics in the Control of Underground Coal Gasification. Sandia National Laboratories, Albuquerque, NM, SAND 80-2664.

This paper combines field test and analysis results to identify site-specific parameters of process control. The discussion centers on the flow and mechanical properties of the seam. There are other potentially critical parameters and processes such as the petrographic constituents of the coal, the chemistry of combustion, and the in situ stress distribution, which also can affect the quality of the UCG process.

Barrash, W., J.W. Martin, and U. Sharum, 1988, Status Report of Groundwater Quality at the Hoe Creek Underground Coal Gasification Site, Powder River Basin, Wyoming. Western Research Institute, Laramie, WY, DOE DE-FC21-86MC11076.

This report summarizes activities relating to underground coal gasification experiments, groundwater monitoring, and groundwater restoration at the U.S. DOE Hoe Creek site. The status of groundwater quality at the Hoe Creek site is documented and compared with Wyoming Department of Environmental Quality standards.

Barrash, W., R.S. Schowengerdt, and P. Smith, 1987, Hydrogeology of the Hoe Creek Underground Coal Gasification Site, Powder River Basin, Wyoming. Western Research Institute, Laramie, WY, DOE DE-FC21-86MC11076.

Western Research Institute conducted a series of aquifer tests in 1985 in the southeast, southwest, and northwest corners of the Hoe Creek site to determine the values of hydraulic parameter for and the interaction between all hydrostratigraphic units at undisturbed locations. Six constant rate pumping tests were performed; two tests were performed at each of the three sites.

Barteaux, W.L., 1986, Hoe Creek Underground Coal Gasification Site, in Final Report, Volume I, Research Investigations in Oil Shale, Tar Sand, Underground Coal Gasification, Advanced Process Technology and Asphalt Research, April 1983 to September 1986. Western Research Institute, Laramie, WY, DOE DE-FC21-83FE60177.

The objectives of this research were (1) the characterization of UCG impact on the Hoe Creek groundwater, including identification of contaminant plume location and solute transport mechanisms and (2) the development of land and groundwater quality restoration schemes.

Barteaux, W.L., and G. Berdan, 1986, Status Report for the Hanna and Hoe Creek Underground Coal Gasification Sites. Western Research Institute, Laramie, WY, DOE DE-FC21-83FE60177.

This report is a summary of work performed at the Hanna and Hoe Creek UCG sites from June 1985 to June 1986, including a discussion of upcoming plans.

Barteaux, W.L., G.L. Berdan, and J. Lawrence, 1986, Environmental Evaluation and Restoration Plan of the Hoe Creek Underground Coal Gasification Site, Wyoming. Western Research Institute, Laramie, WY, DOE/MC/11076-2641.

To prepare for developing a plan, WRI compiled background information on the site. The geologic and hydrologic characteristics of the site were determined, and the water quality data were analyzed. Modeling the site was considered, and possible restoration methods were examined. Samples were collected and laboratory tests were conducted. WRI then developed and began implementing a field-scale restoration test.

Berdan, G.L., B.T. Nolan, W.L. Barteaux, and W. Barrash, 1987, Status Report for the Hanna and Hoe Creek Underground Coal Gasification Test Sites. Western Research Institute, Laramie, WY, DOE/MC/11076-2457.

The paper contains a summary of work performed by WRI at the Hanna and Hoe Creek sites from June 1986 to June 1987, including groundwater treatment demonstrations, bench-scale carbon adsorption experiments, design of the scaled-up treatment system, and a well-pumping test.

Burns, L.K., G.N. Craig, W.G. Alexander, F.G. Ethridge, T. Laughter, and A.D. Youngberg, 1982, The Application of Geological and Mineralogical Studies to Underground Coal Gasification Technology. Proceedings of the 8th Underground Coal Conversion Symposium, Keystone, CO.

The main objectives of this paper are: (1) to summarize the geology, lithology, and mineralogy of the overburden of the Hanna and Hoe Creek sites; (2) to evaluate the lithology and mineralogy of the pyrometamorphic rocks formed by the burns; (3) to show the distribution of pyrometamorphic rocks at the two sites; (4) to compare spatial distribution of minerals, textural features, and lithologies of pyrometamorphic rocks at the sites; (5) to compare the temperatures estimated from pyrometamorphic minerals with those measured with thermocouples during the experiments; and (6) to suggest how the results discussed here may be applied to UCG technology.

Campbell, J.H., and V. Dalton, 1978, Effects of Underground Coal Gasification on Groundwater Quality. American Chemical Society Division of Fuel Chemistry Preprints 23(2).

This paper is focused on the results of the water sampling program associated with the Hoe Creek I gasification experiment and results from recent laboratory experiments on ash leaching and pollutant transport.

Campbell, J.H., E. Pellizzari, and S. Santor, 1978, Results of a Groundwater Quality Study Near an Underground Coal Gasification Experiment (Hoe Creek I). Lawrence Livermore Laboratory, Livermore, CA, UCRL-52405.

Water from more than 12 wells in the vicinity of the Hoe Creek I experiment were sampled before, during and up to 10 months following gasification. Water samples were analyzed for a variety of characteristics, including the presence of 70 inorganic compounds and elements, phenolic materials, and volatile and semivolatile organics.

Campbell, J.H., F.T. Wang, S.W. Mead, and J.F. Busby, 1979, Groundwater Quality Near an Underground Coal Gasification Experiment. Journal of Hydrology, 44:#241-266.

Water samples were analyzed for a variety of characteristics, including the presence of 70 inorganic species, phenolic materials, and volatile and semivolatile organics. There was a greatly increased concentration of organic materials, particularly phenols, just outside the burn boundary and a variety of inorganic species issuing from within the residual ash bed. All detectable contaminants rapidly decreased in concentration with distance, although above-background levels of some materials were detected 30 m (100 ft) from the burn zone within 3 days of the gasification.

Cena, R.J., and C.B. Thorsness, 1981, LLL Underground Coal Gasification Data Base. Lawrence Livermore National Laboratory, Livermore, CA, UCID-19169.

The Lawrence Livermore National Laboratory developed a data base containing results from thirteen DOE-sponsored UCG field tests. Included in the data base are process material and energy balance results for each test on a consistent basis. Highlights of the data base and comparison results for each test are discussed.

Cena, R.J., C.B. Thorsness, and L.L. Ott, 1982, Underground Coal Gasification Data Base. Lawrence Livermore Laboratory, Livermore, CA, UCID-19169 Rev. 1.

This report presents process parameters and the results of material and energy balances for each test in a variety of forms. The raw process data used to construct the data base is first discussed along with material and energy balance conventions. Following this, each test is described with the process geometry, and a brief operating chronology is given.

Chang, H.L., D.M. Himmelblau, and T.F. Edgar, 1982, Flow Characteristics in Underground Coal Gasification. In Situ, 6(2): 143-162.

This paper discusses how flow field in in-situ combustion can be interpreted from the residence time distribution of the tracer gas using flow models such as the axial dispersion and parallel tanks-in-series models.

Crader, S.E., and G.S. Huntington, 1991, Hoe Creek 1990 Quarterly Sampling Cumulative Report. Western Research Institute, Laramie, WY, WRI-91-R025.

This report summarizes the results of groundwater sampling in 1990 and compares the results with those obtained in previous years. Possible further options for remediation of the Hoe Creek site are discussed.

Creighton, J.R, 1983, Hydrology of Pollutant Removal at the Hoe Creek Site. In-house report, Lawrence Livermore Laboratory, Livermore, CA.

This report investigates the validity of the assumption that polluted water at the Hoe Creek II experiment can be pumped out and either treated to remove pollutants or placed in a lined evaporation pond with the residue moved to an appropriate dump site after the water has been evaporated.

Dalton, V.A., and J.H. Campbell, 1978, Laboratory Measurements of Groundwater Leaching and Transport of Pollutants Produced During Underground Coal Gasification. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-80834.

Two series of laboratory experiments dealing with release and migration of pollutants produced during underground coal gasification are discussed. In the first series of experiments, coal ash samples prepared by heat treatment to 1000, 1100, and 1200°C have been subjected to water leaching at 23°C. A second set of experiments deals

with the transport of pollutants away from a gasification site by the natural groundwater flow through the coal seam. These results are compared with groundwater measurements taken at the LLL Hoe Creek I coal gasification site.

Division of Site Characterization, 1986, Status Report on the Results of Groundwater Treatment at the Hoe Creek UCG Site. Western Research Institute, Laramie, WY, DOE DE-FC21-83FE60177.

A groundwater treatment system consisting of granular activated carbon adsorption units and ancillary equipment was tested at the Hoe Creek UCG site. The overall goal of the research is to test the feasibility of using the carbon adsorption process for removing phenols and TOC from the Hoe Creek groundwater.

Dockter, L., and E.M. McTernan, 1984, Underground Coal Gasification: Environmental Update. Presented before the UCG session, 1984 annual meeting of the AIChE, San Francisco, CA.

To evaluate the potential for groundwater contamination by underground coal gasification, extensive postburn groundwater monitoring programs were done at two test sites in Wyoming. An overview of the environmental concerns related to UCG and some results to date on the two field sites are presented in this report.

Ethridge, F.G., L.K. Burns, W.G. Alexander, G.N. Craig II, and A.D. Youngberg, 1983, Overburden Characterization and Post-Burn Study of the Hoe Creek, Wyoming Underground Coal Gasification Site and Comparison with the Hanna, Wyoming Site. U.S. Department of Energy Report No. DOE/LC/10705-T1, 185 p.

The primary purpose of the study was to characterize the geology of the overburden and interlayered rock and to determine and evaluate the mineralogical and textural changes that were imposed by the Hoe Creek III experiment.

Ganow, H.C., 1979, In Situ Coal Gasification at the Hoe Creek, Wyoming, Field Site--An Overview. The Wyoming Geological Association, Earth Science Bulletin, 12(3).

In this article, the concept of in situ coal gasification is briefly reviewed. This is followed by a discussion of the Hoe Creek site geology and hydrology and the results of Experiments I and II. Experiment III would be burned almost entirely with steam and oxygen, and should provide urgently needed data on process economics. Last, results from experiments designed to assess two major environmental concerns, cavity subsidence and groundwater pollution, are presented.

Geo-Con Inc., 1989, Hoe Creek UCG Facility Cleanup, Gillette, WY. Proposal to Western Research Institute, 9-H072.

This proposal describes an in situ fixation of previously burned coal seams to reduce or eliminate groundwater contamination. Several different methods are described, along with cost estimates, project control, and statement of qualifications and capabilities.

Gilbert/Commonwealth, Inc., and James M. Montgomery Consulting Engineers, 1991, Remedial Investigation/Feasibility Study for the Hoe Creek Underground Coal Gasification Site. Report prepared for U.S. DOE, Morgantown Energy Technology Center under contract No. DE-AC21-89MC25177.

Detailed procedures by which work will be accomplished are presented in this report, which includes sampling and analysis, quality control, field sampling, and health and safety.

Glass, R.E., 1982, Thermomechanical Cavity Growth Modeling. Proceedings of the 8th Underground Coal Conversion Symposium, Keystone, CO.

A thermomechanical model that uses temperature and bedding plane dependent properties indicates that the cavity shapes seen at both the Hanna and Hoe Creek test sites result from the temperature-dependent properties of the coal, such as the coefficients of thermal expansion and the elastic moduli. The model determines stress levels and uses a simple bedding-plane-dependent stress failure mechanism to determine cavity growth.

Greenlaw, R.C., H.C. Ganow, and R.T. Langland, 1978, Nonlinear Subsidence Modeling at Hoe Creek. Proceedings of the 4th Annual Underground Coal Conversion Symposium, Steamboat Springs, CO.

This paper discusses an approach to including nonlinear effects in the subsidence models that have been developed. In addition, some computer models have been calibrated against both field measurements and elastic theory.

Hill, R.W., 1981, Burn Cavity Growth During the Hoe Creek III Underground Coal Gasification Experiment. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-85173-R-1.

The changing shape of the Hoe Creek III burn cavity with time is inferred from data from three types of instruments installed throughout the experimental zone: (1) thermocouples at various levels in a number of holes to map temperatures, (2) extensometers at various levels in other holes, to detect motions of the overburden material, and (3) high-frequency electromagnetic scans (HFEM) made between various pairs of holes to detect cavities and zones of burning coal. Additional data on the final shape of the underground cavity are derived from the results of a core-drilling program carried out from the surface after the burn had ended.

Hill, R.W., C.B. Thorsness, R.J. Cena, W.R. Aiman, and D.R. Stephens, 1980, Results From the Third LLL Underground Coal Gasification Experiment at Hoe Creek. Proceedings of the 6th Underground Coal Conversion Symposium, Shangri-La, OK.

Results from the Hoe Creek III UCG test are described. The experiment employed a drilled channel between process wells spaced 130 ft apart. The drilled channel was enlarged by reverse combustion prior to forward gasification. The average gas composition during the steam-oxygen phase was 37% hydrogen, 5% methane, 11% carbon monoxide, and 44% carbon dioxide. Gas recovery was approximately 82% during the test, and the average thermochemical efficiency was near 65%.

Hill, R.W., C.B. Thorsness, D.R. Stephens, D.S. Thompson, and W.R. Aiman, 1978, The LLL Underground Coal Gasification Project: 1978 Status. Am. Nucl. Soc. Trans. Vol. 30.

In this paper, results are presented from the LLL UCG experiment, Hoe Creek II. It was a two-process-well experiment, using both air and oxygen/steam injection. Both low- and medium-Btu gas were produced.

Homsy, R.V., 1979, Two-Dimensional Transient Dispersion and Adsorption in Porous Media. Proceedings of the 5th Underground Coal Conversion Symposium, Alexandria, VA.

A case study was conducted, characteristic of actual conditions encountered at the Hoe Creek I gasification site in Gillette, Wyoming, where field experiments were being done.

Huntington, G.S., 1990, Hoe Creek August 1990 Quarterly Groundwater Sampling. Western Research Institute, Laramie, WY, WRI-90-R048.

Of the three burn areas at the Hoe Creek UCG site, the Felix 1 zone exhibits the highest levels of both benzene and phenol. Benzene and phenol were detected in the channel sand zone and the Felix 2 zone, but in concentrations that are an order of magnitude lower than the Felix 1 zone. The trend toward increasing benzene and decreasing phenol concentrations noted in May 1990 was reversed. Benzene decreased from the May values and phenol increased.

Lawrence Livermore National Laboratory, 1976, LLNL In Situ Coal Gasification Program, Quarterly Progress Report, Jan.-March. Livermore, CA, UCRL-50026-76-1.

The Hoe Creek site was winterized following explosive fracturing, preliminary permeability, and air-flow testing. Simple gasification models based upon thermodynamics are described. A high-pressure combustion tube run during the last quarter demonstrated smooth gasification in a packed bed at about 0.5 ft/h. Laboratory electrical conductivity measurements of coal and coal chars showed that there are both prospects and problems in using this technique as a diagnostic tool for underground coal gasification.

Lawrence Livermore National Laboratory, 1977, Environmental Studies of In Situ Coal Gasification: Annual Report, Fiscal Year, 1977. Livermore, CA, UCRL-50032-78.

The investigation is focused on changes in groundwater quality and the effects of ground movement and subsidence, which represent important environmental concerns associated with the in situ coal gasification process. Methods include laboratory measurements, predictive modeling studies, and field measurements carried out in conjunction with LLL coal gasification experiments in northeastern Wyoming. These activities will serve as a basis for the identification of appropriate environmental control technologies.

Lawrence Livermore National Laboratory, 1978, LLNL In Situ Coal Gasification Program, Quarterly Progress Report, April-June. Livermore, CA, UCRL-50026-78-2.

During the quarter, Hoe Creek II and III field gasification programs were reviewed. Progress was made in in situ modeling efforts, and these are reported along with results from in situ laboratory experiments and environmental studies. The preliminary design is discussed for Hoe Creek III, which is a full oxygen/steam field test. Laboratory measurements of pollutant transport and field results from groundwater quality studies at Hoe Creek I are presented.

Lawrence Livermore National Laboratory, 1979, LLNL In Situ Coal Gasification Program, Quarterly Progress Report, July-September. Livermore, CA, UCRL-50026-79-3.

The Hoe Creek III field experiment was the primary activity during this quarter. The experiment lasted 37 days and consisted of three phases: reverse combustion, air burn, and oxygen/steam burn.

Lawrence Livermore National Laboratory, 1979, LLNL In-Situ Coal Gasification Program, Quarterly Progress Report, Oct.-Dec. Livermore, CA, UCRL-50026-79-4.

This contains a discussion of water quality measurements at the Hoe Creek III site, and hydrologic effects resulting from aquifer interconnection at Hoe Creek II and III.

Lawrence Livermore National Laboratory, 1980, LLNL In Situ Coal Gasification Program, Quarterly Progress Report, Jan.-March. Livermore, CA, UCRL-50026-80-1.

This report summarizes laboratory tests that were conducted to determine the cause of lowered redox potential (Eh) of groundwater from the Hoe Creek experiments, which have increased the dissolved iron.

Lawrence Livermore National Laboratory, 1980, LLNL In Situ Coal Gasification Program, Quarterly Progress Report, April-June. Livermore, CA, UCRL-50026-80-2.

Plans for phased reclamation and restoration of the Hoe Creek sites are discussed, including surface-facility dismantling, plugging and sealing of diagnostic and process wells, and long-term water monitoring.

Lawrence Livermore National Laboratory, 1981, LLNL In Situ Coal Gasification Program, Quarterly Progress Report, Jan.-March. Livermore, CA, UCRL-50026-81-1.

The Hoe Creek III experiment, conducted during the fall of 1979, was located 600 ft south of the Hoe Creek I site. It was the largest of the three UCG experiments. On the basis of previous experience, extensive roof collapse, gasification of both coal seams, and interconnection of both coal aquifers and the overlying sand aquifer were expected.

Lawrence Livermore National Laboratory, 1981, LLNL Underground Coal Gasification Project, Quarterly Progress Report, July-September. Livermore, CA, UCRL-50026-81-3.

This report summarizes preliminary interpretations and conclusions derived from the exploratory coring program implemented at the Hoe Creek III site about 10 months after the conclusion of the burn experiment.

Lawrence Livermore National Laboratory, 1982, LLNL Underground Coal Gasification Project, Quarterly Progress Report, April-June. Livermore, CA, UCRL-50026-82-2.

Water samples from the Hoe Creek II site were analyzed for phenols in the field and in the laboratory using both gas chromatography and mass spectrometry. Changes in phenol concentrations as a function of time and distance from the gasification cavity are discussed.

Loop, R.B., 1980, Materials for In Situ Processing Systems. Proceedings of the 5th Conference on Materials for Coal Conversion and Utilization, Gaithersburg, MD, II: 61-63.

Specimens were exposed to product gas streams from two in situ gasification sites: Hanna IV and Hoe Creek III. The erosion/corrosion effects were analyzed and compared with results obtained during a previous exposure at the Hanna IV test site.

Mason, J.M., R.E. Poulson, and L.S. Johnson, 1985, Distribution of Organic Contaminants in Groundwaters Near the Hoe Creek II UCG Site. Western Research Institute, Laramie, WY, DOE/METC-85/6028.

Ten groundwater samples were collected from the Felix 1 and Felix 2 coal seam aquifers along a east-southeast trend extending from the burn cavity to 578 ft away. Organophilic-acid, -base, and -neutral subfractions were analyzed for phenols, low-molecular-weight aromatic hydrocarbons, alkyl-pyridines, and aniline by capillary column gas chromatography.

McKee, C.R., and S.C. Way, 1980, Hydrologic Site Characterization for In Situ Coal Gasification. Proceedings of the 6th Underground Coal Conversion Symposium, Afton, OK.

Practical hydrologic testing methods are outlined for obtaining directional permeability, the ratio of horizontal to vertical permeability, permeability of confining layers along with compressibility, well efficiency, and the in-situ fracture distribution. Field examples are given to illustrate the required instrumentation and derived parameters.

McTernan, E.M., and S.C. Davidson, 1984, Techniques Used in the Determination of the Areal Extent of Organic Contamination at the U.S. DOE Hoe Creek Underground Coal Gasification Site. Proceedings of the 10th Underground Coal Gasification Symposium, Williamsburg, VA.

A field reconnaissance program was developed by Western Research Institute (WRI) for the DOE, based on the following objectives: (1) establish the areal extent of organic contamination in all directions and install monitor wells, (2) determine if organic contamination had moved off-site to the east, and (3) provide monitoring wells to allow assessment of contamination migration rates.

Mead, S.W., 1981, Environmental Control Aspects of In-Situ Coal Gasification: Groundwater Quality Changes and Subsidence Effects. Lawrence Livermore National Laboratory, Livermore, CA, UCID-18931.

The environmental and safety engineering division of Lawrence Livermore Laboratory published this fiscal year 1980 program summary.

Mead, W.S., J.H. Campbell, and D.R. Stephens, 1977, Groundwater Quality Effects of an Underground Coal Gasification Experiment. Proceedings of the 3rd Underground Coal Conversion Symposium, Fallen Leaf Lake, CA.

In an effort to clarify the significance of contamination of local groundwaters following the UCG process, water from more than 12 wells in the vicinity of Hoe Creek test sites were sampled before, during, and up to 6 months following gasification. Water samples were analyzed in the field and in the laboratory for a variety of characteristics, including the presence of 70 inorganic elements and compounds, phenolic materials, dissolved organic carbon, and volatile organics.

Mead, W., and E. Raber, 1980, Environmental Controls for Underground Coal Gasification: Groundwater Effects and Control Technologies. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-84075.

LLL has conducted three UCG experiments at the Hoe Creek site in northeast Wyoming. Environmental studies were conducted in conjunction with UCG experiments, including an investigation of changes in local groundwater quality and subsidence effects. These investigations have led to the development of preliminary plans for a specific method of groundwater quality restoration using activated carbon adsorption, as well as investigating unconventional technologies that may be appropriate. These water treatment technologies are being explored as possible supplements to natural controls and process restrictions.

Mead, S.W., F.T. Wang, and H.C. Ganow, 1978, Environmental Investigations of In Situ Coal Gasification Experiments. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-81395.

Groundwater quality measurements near the site of the Hoe Creek I experiment show a continuing decrease, after more than a year, in the concentration of important contaminants. Data from subsurface geotechnical instruments installed at the Hoe Creek II gasification experiment as well as measurements of groundwater levels show that roof collapse has connected the gasification cavity with overlying aquifers. The implications of this interconnection for the dispersal of underground contaminants were investigated.

Mead, S.W., F.T. Wang, H.C. Ganow, and D.H. Stuermer, 1979, Environmental Studies of LLL's Hoe Creek II Underground Coal Gasification Experiment. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-82409.

During the Hoe Creek II experiment, roof collapse and the inadvertent gasification of an overlying coal seam resulted in the interconnection of three aquifers, including the two gasified coal seams. More than a dozen wells in and near the gasification cavity have been monitored for water quality changes. A limited water quality analysis was carried out in the field, and a detailed analysis was performed in the lab.

Mead, S.W., F.T. Wang, H.C. Ganow, D.H. Stuermer, and R. Stone, 1979, Groundwater Effects of Underground Coal Gasification Experiments in Northeastern Wyoming. Soc. of Petroleum Engr. Paper SPE8449, 54th Annual Fall Technical Conference and Exhibition, Las Vegas, NV.

The Lawrence Livermore Laboratory has carried out two underground coal gasification experiments at the Hoe Creek site in northeast Wyoming. Environmental studies were conducted in conjunction with the UCG experiments, including an investigation of changes in local groundwater quality. Field investigations include groundwater monitoring near the UCG experiments, geotechnical measurements of ground deformations, and postburn coring.

Mead, S.W., F.T. Wang, and D.H. Stuermer, 1982, UCG Environmental Research-Summary and Suggested Projections. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-88015.

Some specific problems at the Hoe Creek site that appear to need attention are considered, and some general recommendations for environmental activities that may help pave the way for commercial UCG technology are discussed.

Mead, S.W., F.W. Wang, D.H. Stuermer, E. Raber, H.C. Ganow, and R. Stone, 1980, Implications of Groundwater Measurements at the Hoe Creek UCG site in Northeastern Wyoming. Proceedings of the 6th Underground Coal Conversion Symposium, Shangri-La, OK.

Groundwater quality measurements extended over four years and were supplemented by laboratory studies of contaminant sorption by coal. Cavity roof collapse and aquifer interconnection were also investigated using surface and subsurface geotechnical instruments, postburn coring, and hydraulic head measurements.

Morgantown Energy Technology Center, 1986, Technology Status Report-Underground Coal Gasification. DOE/METC-87/0244.

This report contains a summary of the DOE's underground coal gasification program, accomplishments of the fiscal 1984-1986 program, and future activities.

Nolan, B.T., 1986, Research Plan for the Hoe Creek Restoration Field Test. Western Research Institute, Laramie, WY, DOE DE-LFC21-86MC11076.

A carbon adsorption treatment system was tested at the Hoe Creek UCG site from August to October 1986. Further research was planned for summer 1987, in which a larger activated-carbon treatment system was to be employed. This report contains a description of the proposed treatment system, test procedures, and a project schedule.

Nolan, B.T., 1987, Results of the Groundwater Treatment Demonstration at the Hoe Creek Underground Coal Gasification site. Western Research Institute, Laramie, WY, DOE DE-FC21-86FE60177.

A groundwater treatment system was tested at the Hoe Creek UCG site from August to October, 1986. The treatment system consisted of filter vessels, granular activated-carbon adsorbers, and ancillary equipment. Hydrological data from step-drawdown pumping tests adequately fit the Hantush-Jacob model for leaky aquifers. Significant amounts of phenols and total organic carbon were removed from the groundwater by the treatment system, although concentrations of phenols in wells generally did not decrease.

Nolan, B.T., H.L. Bergman, and D.J. Kocornik, 1986, Control Technology Research and Environmental Methodologies for the Mitigation of Underground Coal Gasification Impacts: Research Plan for Task 2-Control Technology Evaluation for UCG-Affected Subsurface Waters. Western Research Institute report for Gas Research Institute under contract No. GRI-86/0244 5084-253-1100.

The objective of task 2 is to evaluate the technical feasibility of using various cost-effective control technologies to treat subsurface waters affected by UCG, including test plan development and UCG control technology literature review, sample procurement procedures, sample characterization, bench-scale control technology experiments, and final report preparation.

Nolan, B.T., and S. Suthersan, 1987, Laboratory Studies on Evaluation of In Situ Biodegradation at the Hoe Creek UCG Site. Western Research Institute, Laramie, WY, DOE/MC/11076-2683.

Laboratory experiments were conducted to evaluate the potential for in situ biodegradation in the contaminated groundwater aquifer at the Hoe Creek UCG site. Experiments were performed in electrolytic respirometric cells under simulated environmental conditions.

Nordin, J.S., W. Barrash, W. Barteaux, and T. Nolan, 1987, Groundwater Treatment at the Hoe Creek Underground Coal Gasification Site. Proceedings of the 13th Underground Coal Gasification Symposium, Laramie, WY.

Two million gallons of contaminated groundwater, pumped from wells adjacent to the Hoe Creek II UCG cavity, were treated and then injected into the gasification cavity. Treatment consisted of suspended solids removal and carbon adsorption, which reduced phenol concentration to below detectable limits (<20 ppb).

Nordin, J.S., W. Barrash, and B.T. Nolan, 1988, Groundwater Restoration Field Test at the Hoe Creek Underground Coal Gasification Site. Western Research Institute, Laramie, WY, DOE/MC/11076-2454.

Two million gallons of groundwater was pumped from wells adjacent to the Hoe Creek II underground coal gasification cavity, passed through filters and carbon adsorbers, and then was reinjected into the cavity. Phenol was the target compound of the water treatment system.

Nordin, J.S., W. Griffin, T.J. Chatwin, S. Lindblom, and S. Crader, 1990, Remediation Cleanup Options for the Hoe Creek UCG Site. Western Research Institute, Laramie, WY, DOE/MC/11076-2955.

Six alternative remediation methods are evaluated in this report: (1) excavation, (2) three variations of groundwater plume containment, (3) in situ vacuum extraction, (4) pump and treat using a defined pattern of pumping wells to obtain an effective matrix sweep, (5) in situ flushing using a surfactant, and (6) in situ bioremediation.

Pace Synthetic Fuels Quarterly, 1983, Hoe Creek Water Quality Experiments Completed. 20(2).

LLL identified 135 compounds produced by UCG activities that have persisted in the local groundwater for 15 months after the nearest gasification experiment. These compounds consist of aromatic acidic, neutral, and basic compounds of low molecular weight that probably represent the water-soluble component of a more complex organic mixture deposited in the aquifer.

Quimby, W.F., and W.L. Barteaux, 1985, Preliminary Data Analysis to Evaluate Contaminant Migration in Groundwater at the Hoe Creek, Wyoming Underground Coal Gasification Site. Western Research Institute, Laramie, WY, DOE DE-FC21-83FE60177.

This report presents background information on the Hoe Creek site and the results of applying digital-filtering techniques to the water quality data collected by LLL. The overall objective of this study is to more fully characterize any contaminant migration that has occurred as a result of the UCG process/

Quimby, W.F., and W.L. Barteaux, 1985, Status Report of Events, Results and Plans for the Hanna and Hoe Creek Underground Coal Gasification Sites. Western Research Institute, Laramie, WY, DOE DE-FC21-83FE60177.

The report is a summary of work performed on the Hanna and Hoe Creek sites from April 1984 to March 31, 1985, and of planned work efforts.

Raber, E., and R. Stone, 1980, Groundwater Hydrologic Effects Resulting From Underground Coal Gasification Experiments at the Hoe Creek Site Near Gillette, Wyoming. Lawrence Livermore National Laboratory, Livermore, CA, Interim Report, October 1979-March 1980, UCID-18627.

To evaluate changes in the groundwater flow patterns at Hoe Creek sites II and III, completion of supplementary wells was necessary to define the distance versus head drawdown relationships in each of three aquifers. Changes in groundwater flow patterns have a definite effect on contaminant dispersal and will be taken into consideration.

Ramirez, A.L., H.C. Ganow, and D.G. Wilder, 1981, Postburn Core Drilling Results From Hoe Creek III. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-86766.

This paper presents interpretations derived from the analysis of the postburn drilling results from the Hoe Creek III experiment. The general objectives of this work were to establish the characteristics of the burn cavity and of the materials within and surrounding the cavity.

Renk, R.R., S.E. Crader, G.S. Huntington, and R.L. Oliver, 1989, Hoe Creek Groundwater Restoration Operations and Maintenance Manual. Western Research Institute, Laramie, WY, DOE DE-FC21-86MC11076.

The basic plan was to remove contaminated groundwater to the surface, pass it through activated carbon to remove organics, and dispose of the treated water by spray evaporation.

Renk, R.R., S.E. Crader, S.R. Lindblom, and J.R. Covell, 1990, Hoe Creek Groundwater Restoration, 1989. Western Research Institute, Laramie, WY, DOE/MC/11076-2948.

During the summer of 1989, approximately 6.5 million gallons of contaminated groundwater was pumped from 23 wells at the Hoe Creek UCG site. The organic contaminants were removed using activated carbon before the water was sprayed on 15.4 acres at the site. Approximately 2647 g (5.8 lb) of phenols and 10,714 g (23.6 lb) of benzene were removed from the aquifers.

Sanderson, W.B., 1988, March 1988 Groundwater Monitoring Report for the Hoe Creek UCG Site. Western Research Institute, Laramie, WY, DOE DE-FC21-86MC11076.

This report contains data from the March 1988 sampling of Hoe Creek groundwater.

Sanderson, W.B., S. Crader, and R.A. Wills, 1988, May 1988 Groundwater Monitoring Report for the Hoe Creek UCG Site. Western Research Institute, Laramie, WY, DOE DE-FC21-86MC11076.

This report contains data from the May 1988 sampling of Hoe Creek groundwater.

Saulnier, G., E.M. McTernan, and T.C. Bartke, 1983, An Evaluation of the Magnitude of Groundwater Contamination at the U.S. DOE Hoe Creek UCG Site. Proceedings of the 9th Annual Underground Coal Gasification Symposium, Bloomingdale, IL, 496-511.

This report contains a discussion of the major contaminants present in the Hoe Creek groundwater, the source and movement of contaminants, and methods of detection.

Schowengerdt, R.S., J.J. Mason, and M. Healy, 1985, Preliminary Evaluation of the Hydraulic Characteristics of the Felix 1 and Felix 2 Coal Seam Aquifers, Hoe Creek Site, Campbell County, Wyoming. Western Research Institute, Laramie, WY, DOE DE-FC21-83FE60177.

To define the hydrologic regime at the Hoe Creek site with respect to spatial distribution of hydraulic characteristics and aquifer interconnection, a well installation and aquifer testing program was initiated in November 1984. The following report defines the geologic and hydrologic framework of the site, the testing strategy, well installation technique, aquifer testing procedure, and the data analysis/interpretation.

Snoeberger, D.F., 1977, Field Hydrological Tests of Explosively Fractured Coal. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-78957.

Hydrologic tests were made in the explosively fractured Felix 2 coal seam on part of the Lawrence Livermore Laboratory in situ coal gasification experiment at the Hoe Creek site, 24 km southwest of Gillette, Wyoming. The purposes were to evaluate wells and regions to be gasified and to gain information for the improvement of explosive effects predictions. In this paper, prior work is summarized, and preliminary interpretations of the post-fracturing hydrological tests are given.

Snoeberger, D.F., and R. Stone, 1977, Cleat Orientation and Areal Hydraulic Anisotropy of a Wyoming Coal Aquifer. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-79045.

The anisotropic areal hydraulic conductivity of the Felix 2 coal was defined in a four-well pump test at a site in northeast Wyoming. The direction of maximum hydraulic conductivity approximately corresponds to the trend of the prominent face cleat in the coal, whereas the direction of minimum hydraulic conductivity corresponds to the trend off the butt cleat. The cleat orientation appears related to the alignment of major structural features of the region.

Stephens, D.R., and R.W. Hill, 1978, Underground Coal Gasification of Rocky Mountain Coal. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-81382.

A brief review of UCG technology is given followed by a description of LLL's UCG experiment, Hoe Creek II. Gas of 100-150 Btu/scf was produced using air injection, and gas of 250-300 Btu/scf was produced when injecting steam and oxygen.

Stone, R., 1977, Measurement of the Spatial Variation of Hydraulic Characteristics of an Explosion-Fractured Coal Seam. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52298.

A series of preliminary incremental slug-withdrawal tests were conducted in the Felix 2 coal seam to determine how the hydraulic properties of the coal were affected by the detonation of two, 340-kg explosive charges near its base. For the tests, three wells completed in the seam at various distances from the explosive emplacements were used. The wells were constructed and tested in a manner that allowed estimation of the hydraulic conductivity of the upper, middle, and lower parts of the seam.

Stone, R., and D.F. Snoeberger, 1976, Evaluation of the Native Hydraulic Characteristics of the Felix Coal (Eocene, Wasatch Formation) and Associated Strata, Hoe Creek Site, Campbell County, Wyoming. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-51992.

The native hydraulic characteristics of the shallow Felix coal and adjacent strata have been estimated from the results of comprehensive field tests at the Campbell County, Wyoming site of proposed in situ coal gasification experiments. The field tests involved withdrawal of water from and water injection into wells completed in the Felix coal. Measurement of the effects of these hydraulic perturbations in terms of water-level fluctuations in wells completed in the coal and adjacent strata provided the data used in the analysis.

Stuermer, D.H., D.J. Ng, and C.J. Morris, 1982, Organic Contaminants in Groundwater Near an Underground Coal Gasification Site in Northeastern Wyoming. Environ. Science and Technology, 16: 582-587.

This paper describes in detail the composition of organic constituents that were observed 15 months after the completion of gasification in groundwater samples from two aquifers near two different UCG experiments at the Hoe Creek site.

Stuermer, D.H., D.J. Ng, C.J. Morris, and A. Cotton, 1979, Distribution of Neutral Organic Reaction By-Products in the Groundwater at an Underground Coal Gasification Site. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52847.

Investigations of the composition and distribution of neutral organic compounds in groundwater from a series of wells within and near a UCG site over 15 months suggest that the neutral compounds of concern are a series of low-molecular-weight, water-soluble aromatic hydrocarbons. Evidence for transport of these compounds in the groundwater is presented.

Sullivan, D.A., K.L. Atwood, T.M. Ivory, and P.V. Morgan, 1980, Licensing of the Hoe Creek III Experiment--What is Groundwater Restoration? Proceedings of the 6th Underground Coal Conversion Symposium, Shangri-La, OK.

The environmental licensing of the Hoe Creek III experiment describes current (1980) regulatory constraints in Wyoming. Of all the environmental issues associated with the licensing of this experiment, groundwater restoration remains as the most sensitive issue for future experiments and commercial development. Through judicious site selection and evaluation of the best practicable technology for groundwater restoration, the regulatory framework in Wyoming can allow for development of the in situ coal gasification industry within the state if the regulations are implemented within the form and intent of the Wyoming In-Situ Mining Act.

Sutherland, H.J., P.J. Hommert, L.M. Taylor, and S.E. Benzley, 1984, Subsidence Prediction for Two UCG Projects. In Situ, 8(4): 347-367.

The motion of strata that overlie two UCG projects are calculated using the analyses that have been developed for the prediction of subsidence above coal mines. These techniques are used to analyze the Hoe Creek III burn and the forthcoming TONO UCG project partial seam test.

Timourian, H., J.S. Felton, D.H. Stuermer, S. Healy, P. Berry, M. Tompkins, G. Battaglia, F.T. Hatch, L.H. Thompson, A.V. Carrano, J. Minkler, and E. Salazar, 1982, Mutagenic and Toxic Activity of Environmental Effluents from Underground Coal Gasification Experiments. J. Toxicology and Environ. Health, 9: 975-994.

Using bacterial bioassays, groundwater and tar from product gas from Hoe Creek II and III, test sites were screened for the presence of mutagens and toxins. The Salmonella reversion bioassay was used to determine mutagenicity, and the Microtox Model 2055 bioassay was used to determine toxicity.

Thorsness, C.B., 1980, Steam Tracer Experiment at the Hoe Creek No. 3 Underground Coal Gasification Field Test. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53082.

A steam tracer test was conducted during the later stages of the Hoe Creek III UCG field test, using deuterium oxide as the tracer. This report describes the tracer test and the analysis of the data that were obtained.

Thorsness, C.B., and R.J. Cenal, 1980, A UCG Process Data Base. Proceedings of the 6th Underground Coal Conversion Symposium. Shangri-La, OK.

This paper describes a UCG data base developed to assist in making detailed data from DOE-sponsored field programs easily available. In addition, the data in the current data base are used to summarize the results of the Hoe Creek I, II, and III experiments.

Thorsness, C.B., R.J. Cena, W.R. Aiman, R.W. Hill, and D.R. Stephens, 1978, Hoe Creek No. 2: Underground Coal Gasification Experiment with Air and Oxygen/Steam Injection Periods. 53rd Fall Technical Conference and Exhibition, Soc. of Petroleum Engr. of AIME, Houston, TX, Report SPE-7512.

This paper presents results from LLL's Hoe Creek II experiment. The experiment used an injection well and a production well 18.7 m apart and alternating periods of air and oxygen/steam injection. Fourteen days of reverse combustion linked the injection and production wells. This was followed by 58 days of forward combustion gasification.

Thorsness, C.B., and J.R. Creighton, 1982, Review of Underground Coal Gasification Field Experiments at Hoe Creek. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-87662.

This report contains a comparison of the different linking methods used in the three Hoe Creek tests and the product gas quality obtained from each.

TRW Energy Development Group, 1983, Hydrologic and Contaminant Assessment, Hoe Creek Underground Coal Gasification Site Near Gillette, Wyoming. McLean, VA, report to U.S. DOE., 53.

This report provides a brief synopsis of the problem of groundwater contamination, including a hydrogeologic description of the area, highlights of the baseline data collection program, and description of some significant process characteristics that may have affected the distribution of contaminants. Succeeding sections present TRW's comments on the levels of contamination, potential reactions leading to or controlling the current distribution of dissolved constituents, some potential remedial action measures, and monitoring requirements.

U.S. Department of Energy, 1988, Hoe Creek Groundwater Restoration Plan. Report submitted to Wyoming Department of Environmental Quality.

The status of all facility wells is discussed. This is followed by the subsurface cleanup plan and the plan for surface cleanup of the groundwater.

U.S. Department of Energy, Morgantown Energy Technology Center, Western Research Institute, 1988, Status Report of Groundwater Quality for Abandonment of the Hoe Creek Underground Coal Gasification Site, Powder River Basin, Wyoming. Report to Wyoming Department of Environmental Quality.

This report summarizes activities relating to underground coal gasification experiments and groundwater restoration at the Hoe Creek site. The status of groundwater quality at the site is documented and compared with Wyoming WDEQ standards for site closure.

Wang, F.T., 1979, A Comparison of Analytical Methods for Phenols, Cyanide and Sulfate as Applied to Ground-water Samples From Underground Coal Gasification Sites. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-82702.

Groundwater samples obtained from two UCG experiments have been analyzed for phenols, cyanide, and sulfate. These samples were analyzed in the field; they were also preserved and sent to remote laboratories for analysis. Comparisons of the results show that the agreement between laboratory and field analyses are fairly good. This suggests that the methods of preservation are effective for these types of groundwater samples and that field analysis gives reliable information.

Wang, F.T., and W. Mead, 1985, Changes in Major Organic Contaminants in the Groundwater at the Hoe Creek Underground Coal Gasification Site. Proceedings of the 11th Annual Underground Coal Gasification Symposium, Denver, CO.

A mechanism is described for the deposition of coal pyrolysis products that may help to elucidate the observed behavior of organic contaminants at the Hoe Creek UCG site.

Wang, F.T., S.W. Mead, and D.H. Stuermer, 1981, Groundwater Contamination Near the Hoe Creek UCG Experiments. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-85880.

The Hoe Creek II and III experiments have provided the opportunity to study the contamination of a sand aquifer located above a gasified coal seam in a hydrological recharge area. Preliminary results indicate that the water in the overlying sand aquifer is much less contaminated with organic compounds than the water in the gasified coal aquifer.

Wang, F.T., S.W. Mead, and D.H. Stuermer, 1982, Mechanisms for Groundwater Contamination by UCG-Preliminary Conclusions from the Hoe Creek Study. Proceedings of the 8th Underground Coal Conversion Symposium, Keystone, CO.

This paper investigates the mechanisms responsible for the formation and dispersal of contaminants in groundwater from the UCG process.

Wang, F.T., S.W. Mead, and D.H. Stuermer, 1982, Water Quality Monitoring at the Hoe Creek Test Site: Review and Preliminary Conclusions. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-87650.

In this paper, results of groundwater contamination measurements at the Hoe Creek site are presented. Water samples were collected from two gasified coal seam aquifers and an overlying channel sand aquifer. Also discussed is a possible strategy for monitoring groundwater in the vicinity of a UCG site.

APPENDIX B

History of Phenol Contamination in Groundwater from Frequently Sampled Wells

CONTENTS OF APPENDIX B

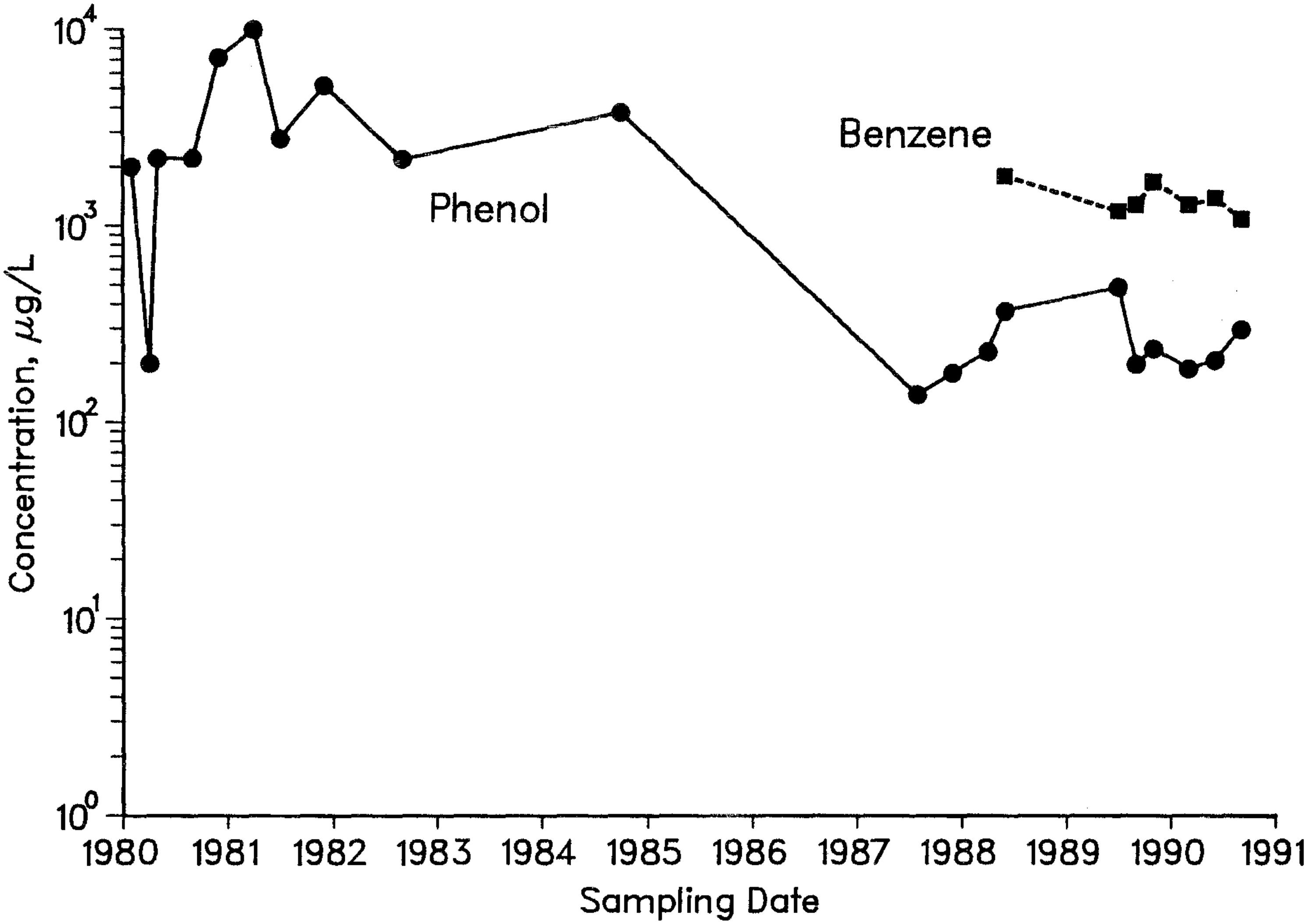


Figure B-1. History of Phenol and Benzene Contamination in Groundwater Sampled From Well W-1a

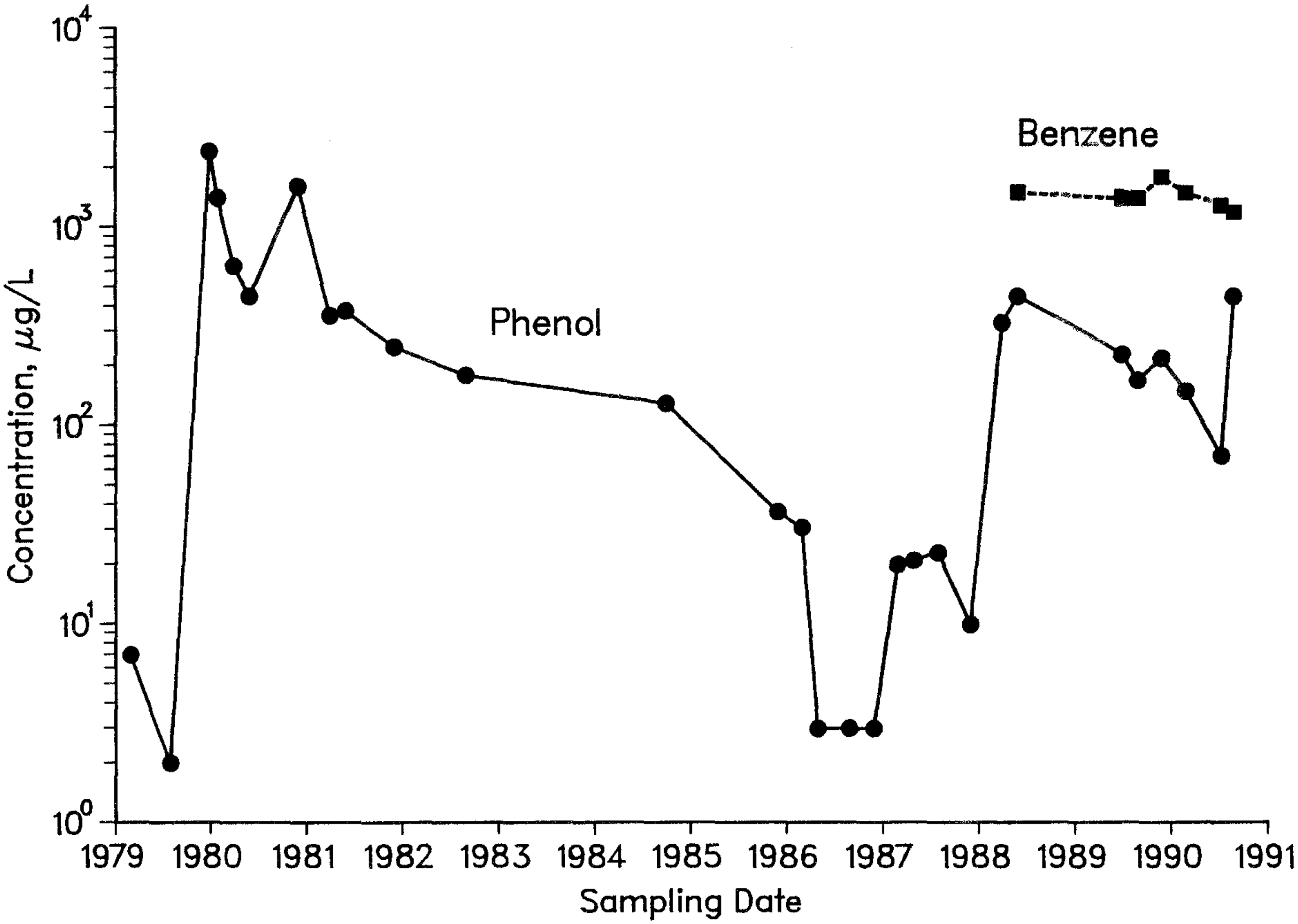
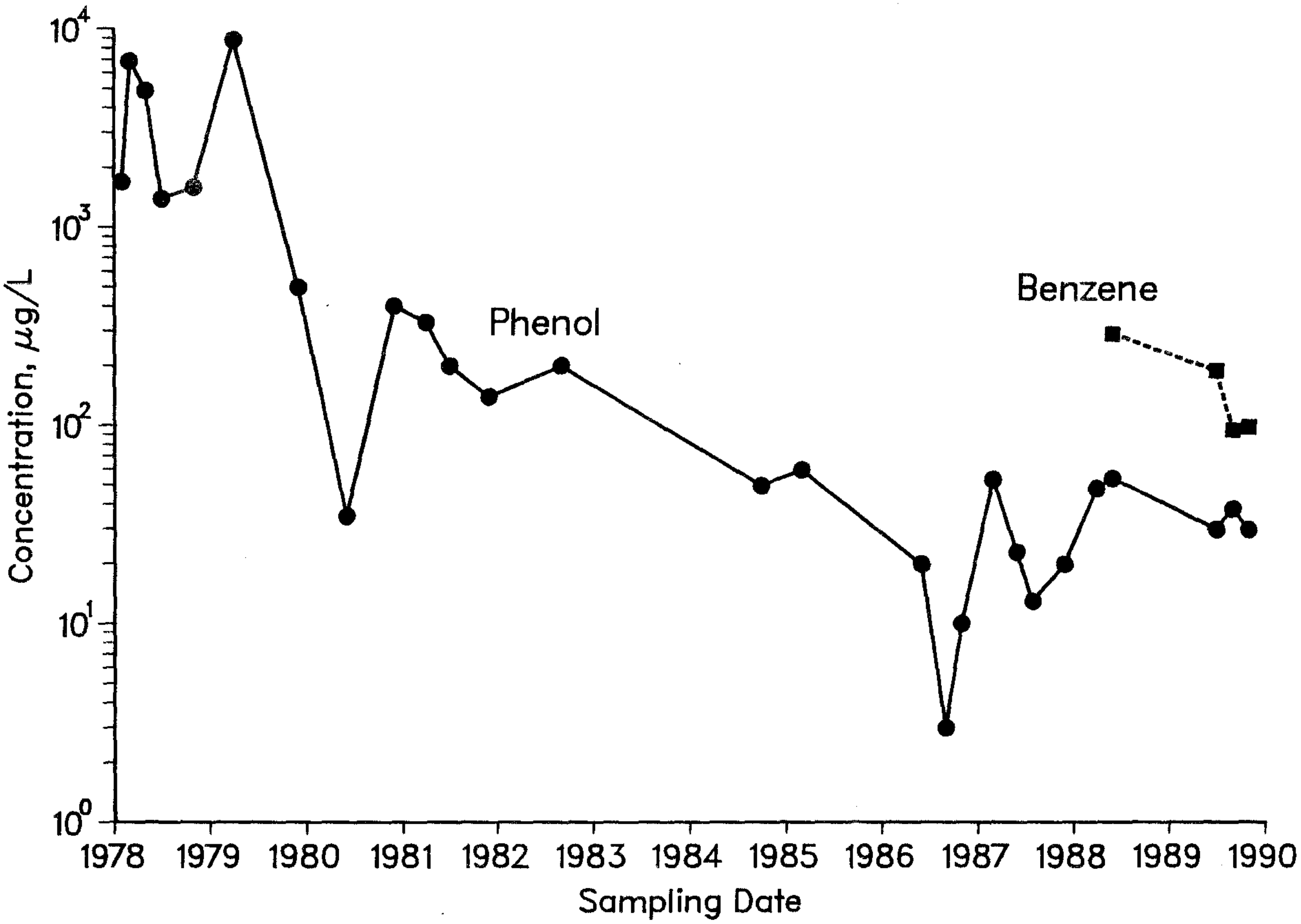


Figure B-2. History of Phenol and Benzene Contamination in Groundwater Sampled From Well W-4a



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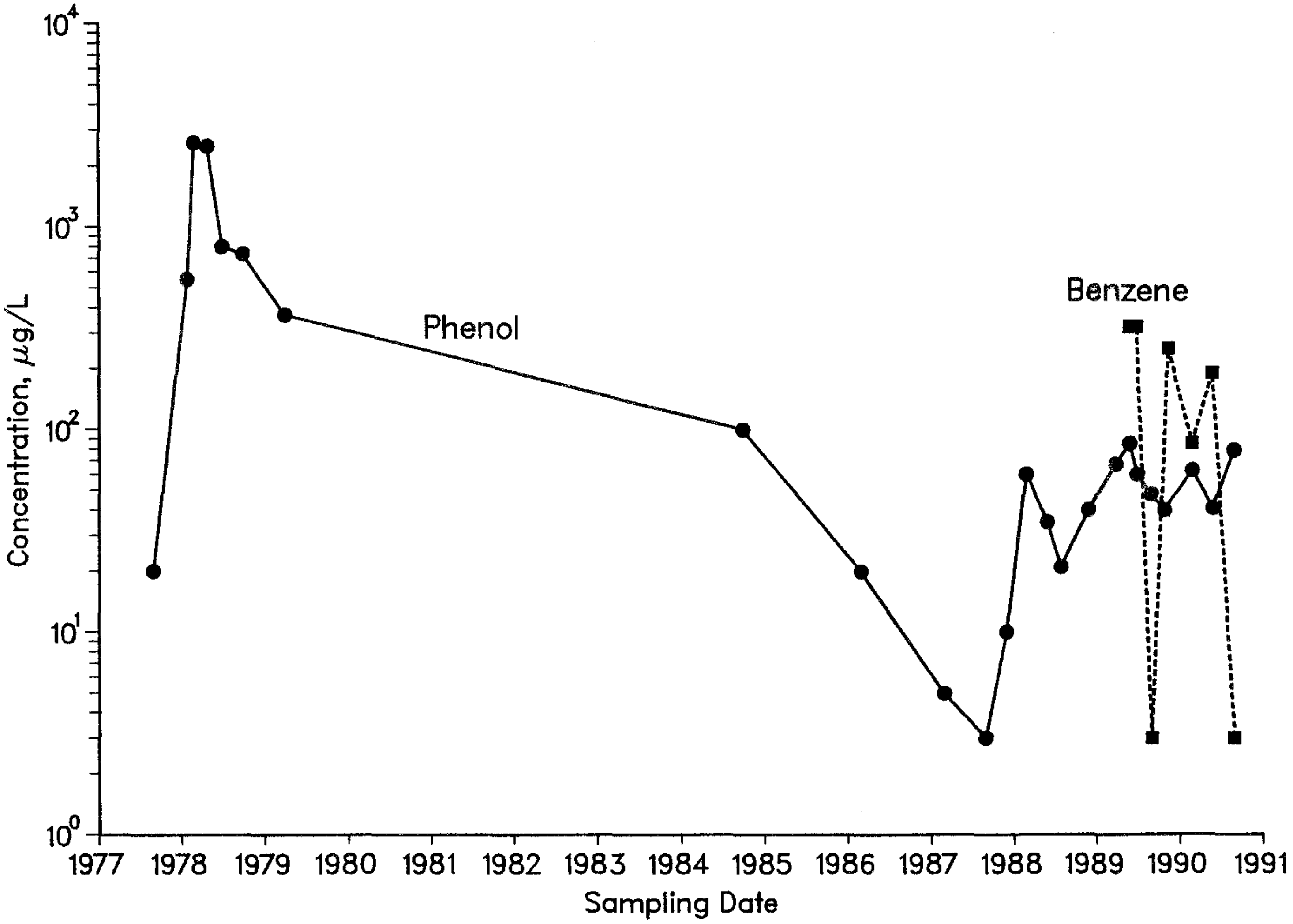

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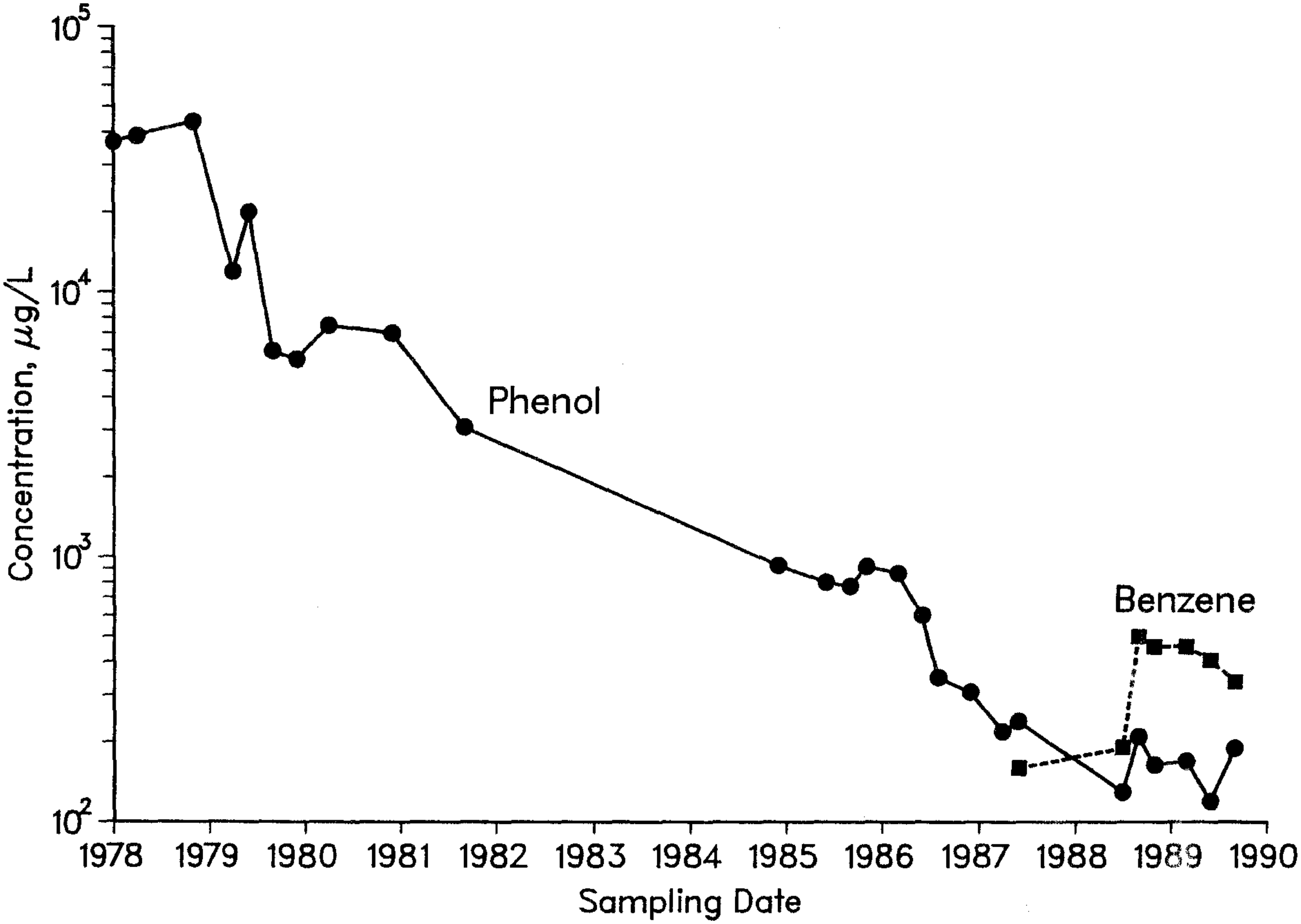


Figure B-5. History of Phenol and Benzene Contamination in Groundwater Sampled From Well WS-10

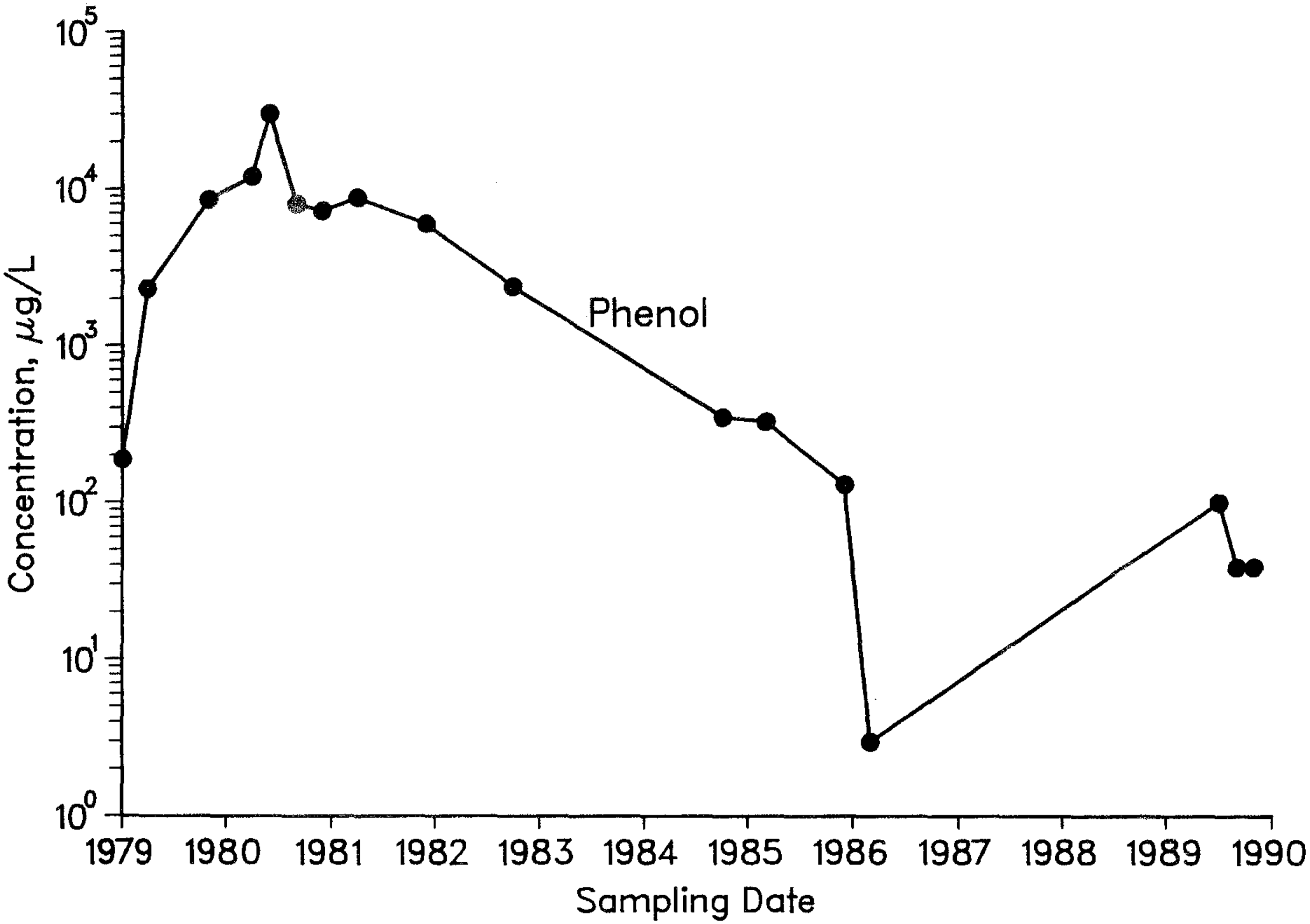
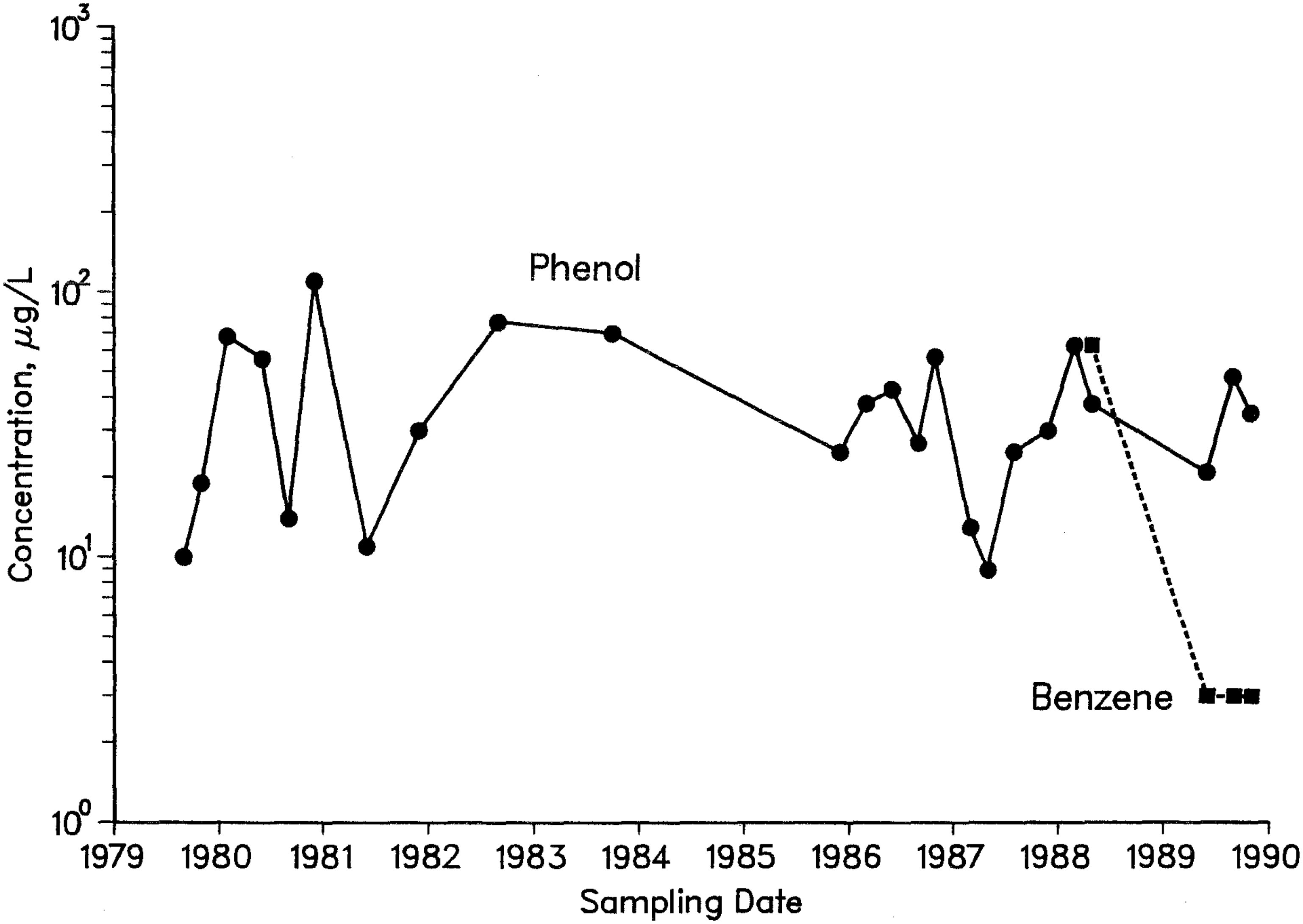


Figure B-6. History of Phenol Contamination in Groundwater Sampled From Well WS-12



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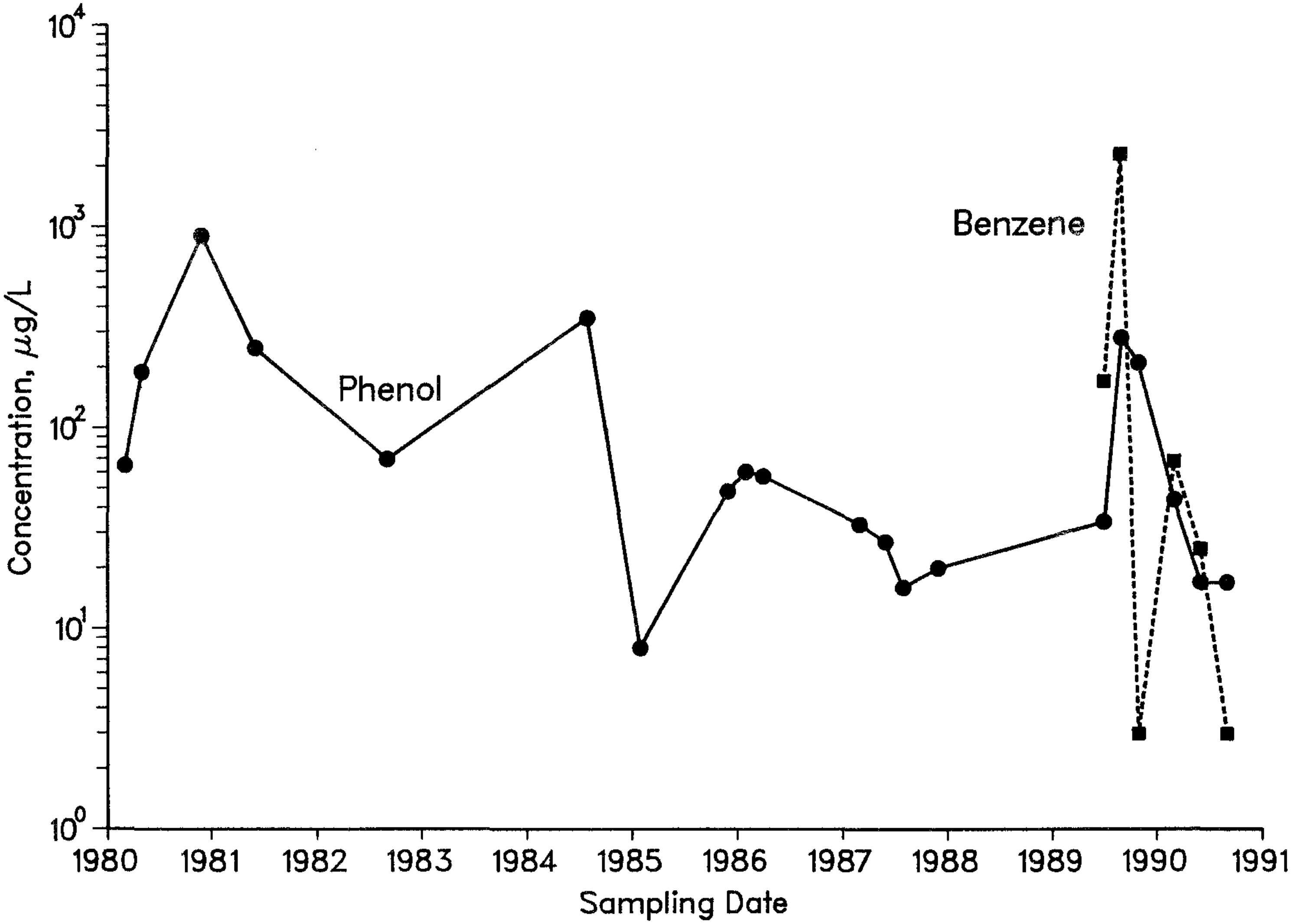

Figure B-8. History of Phenol and Benzene Contamination in Groundwater Sampled From Well WS-15

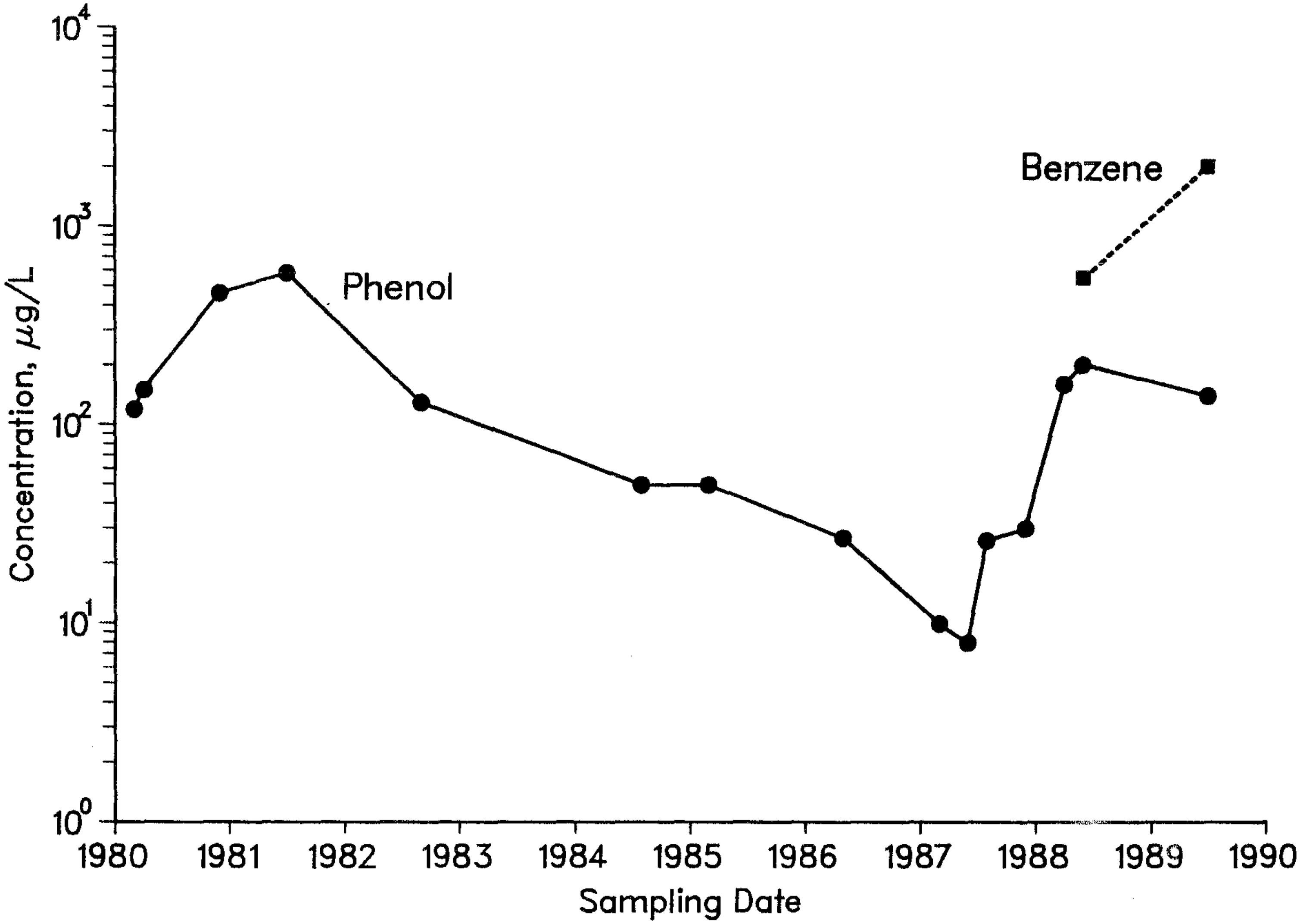

Figure B-9. History of Phenol and Benzene Contamination in Groundwater Sampled From Well WS-17

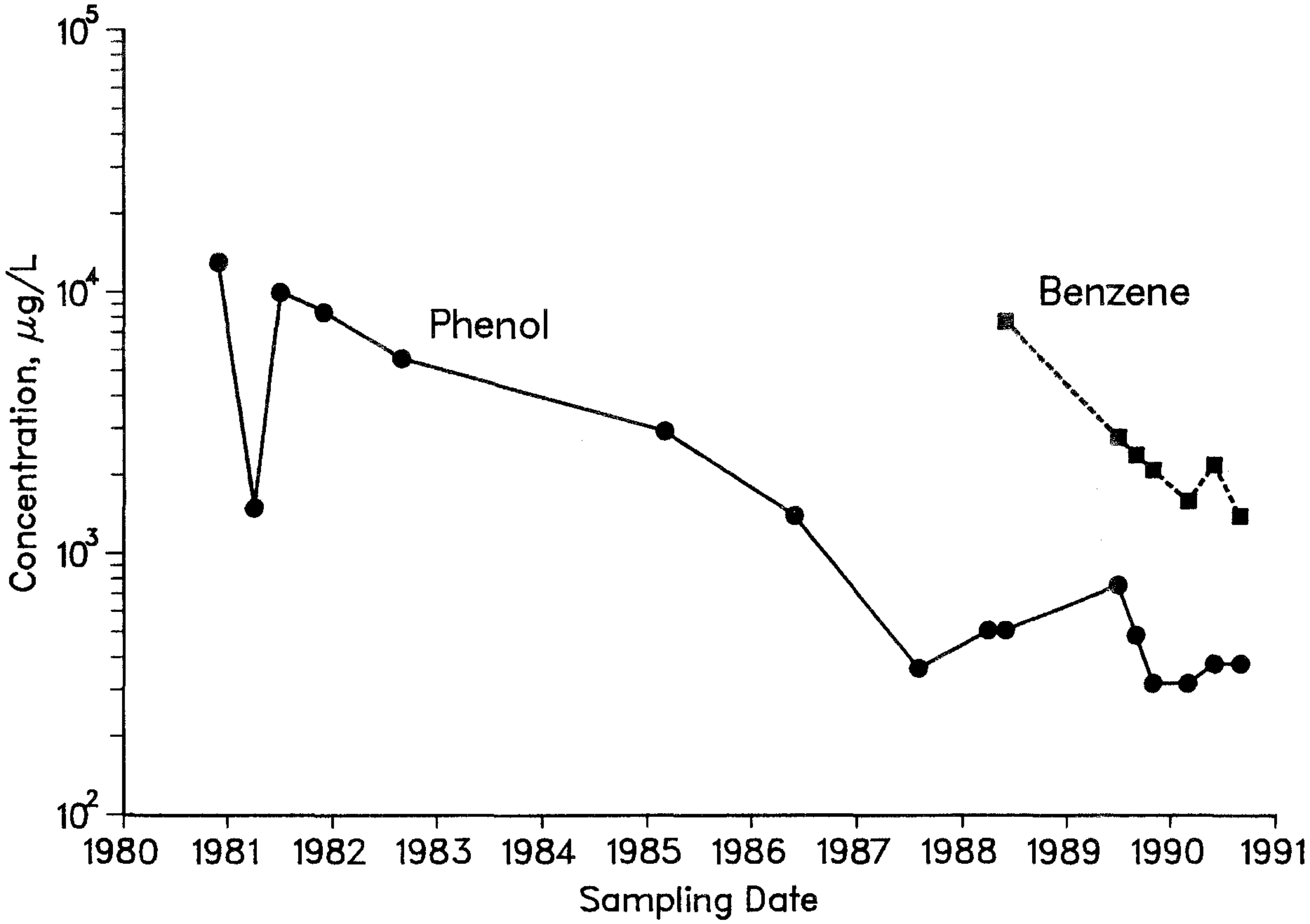

Figure B-10. History of Phenol and Benzene Contamination in Groundwater Sampled From Well W-22a

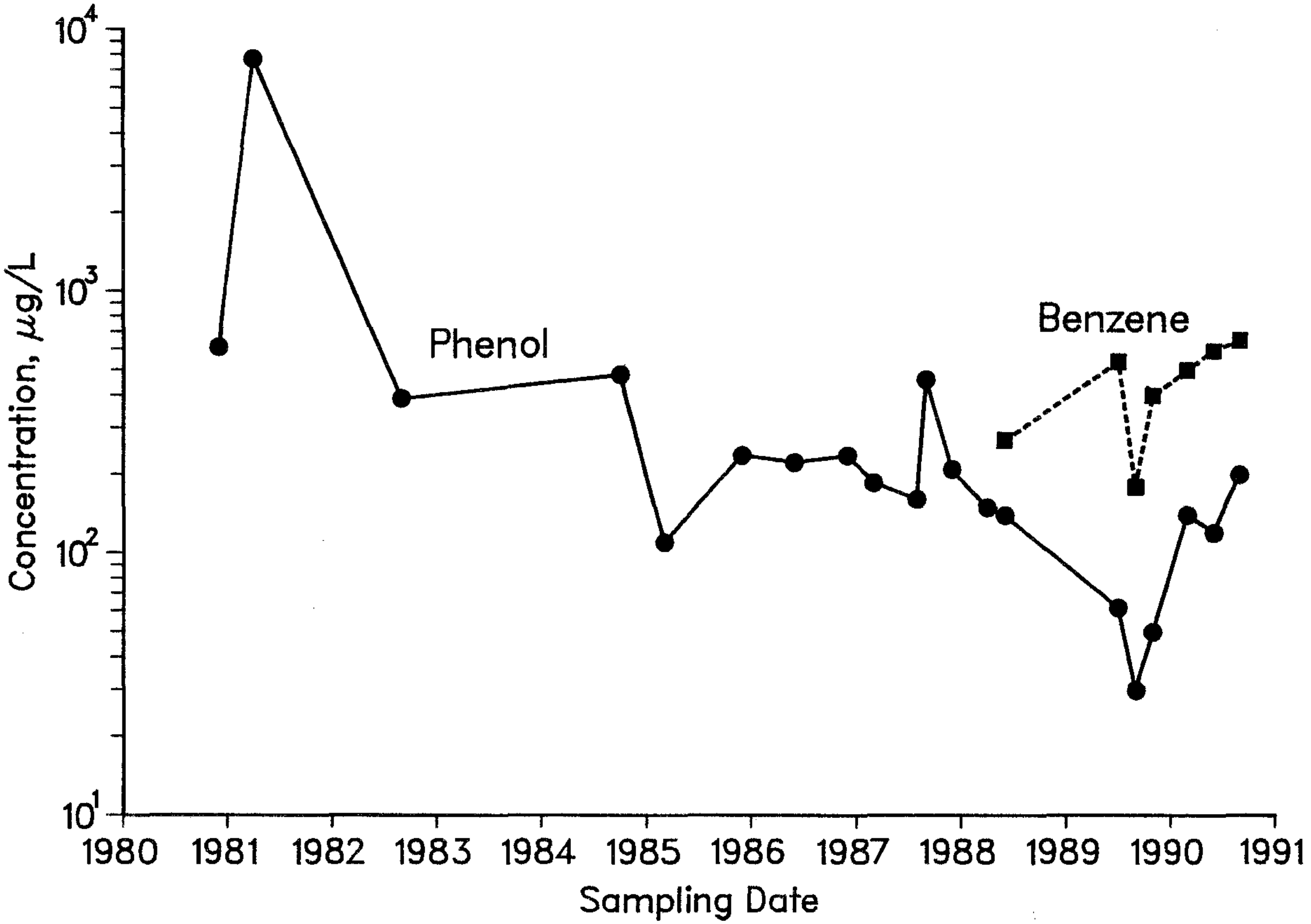

Figure B-11. History of Phenol and Benzene Contamination in Groundwater Sampled From Well WS-22

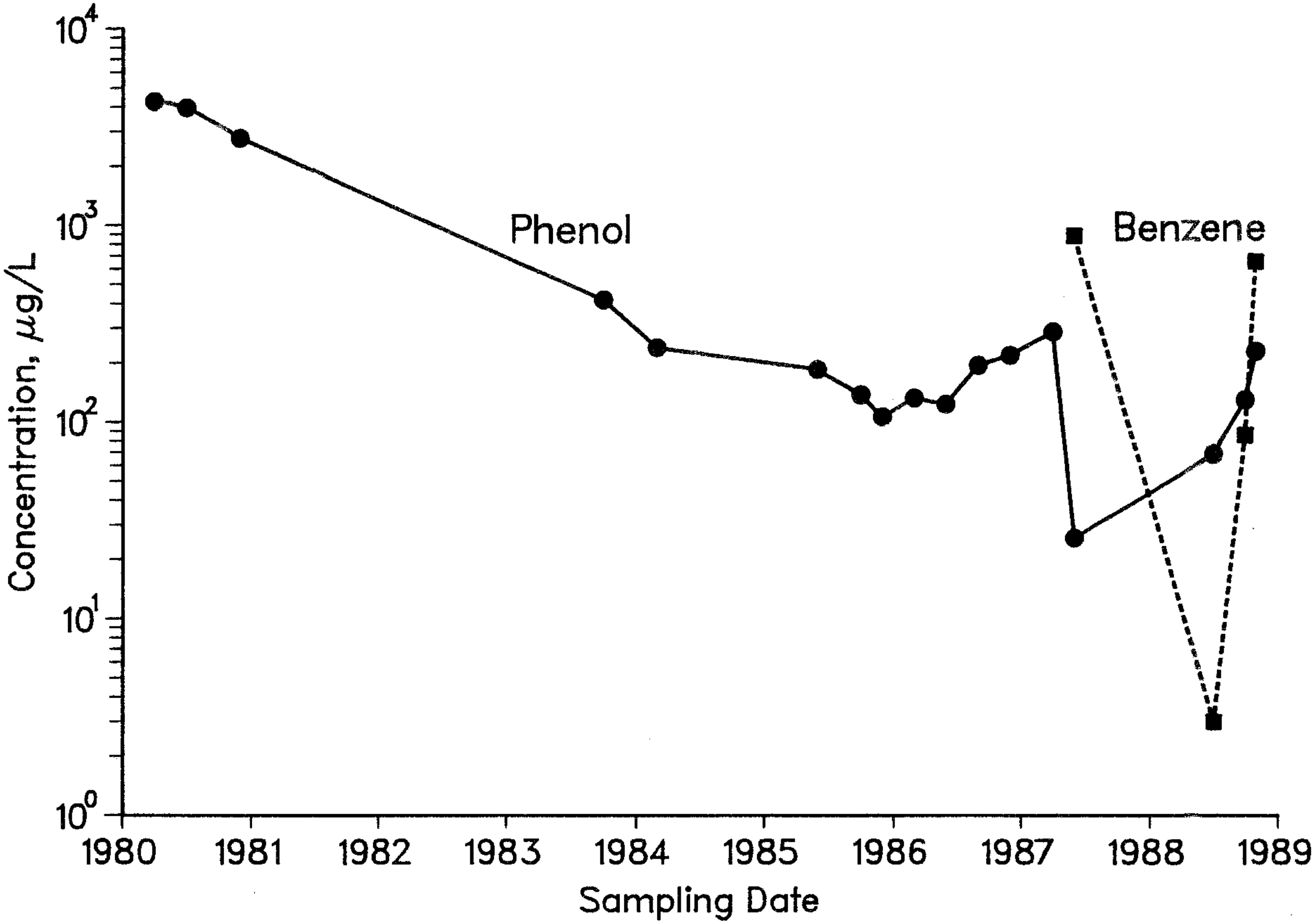

Figure B-12. History of Phenol and Benzene Contamination in Groundwater Sampled From Well WS-23

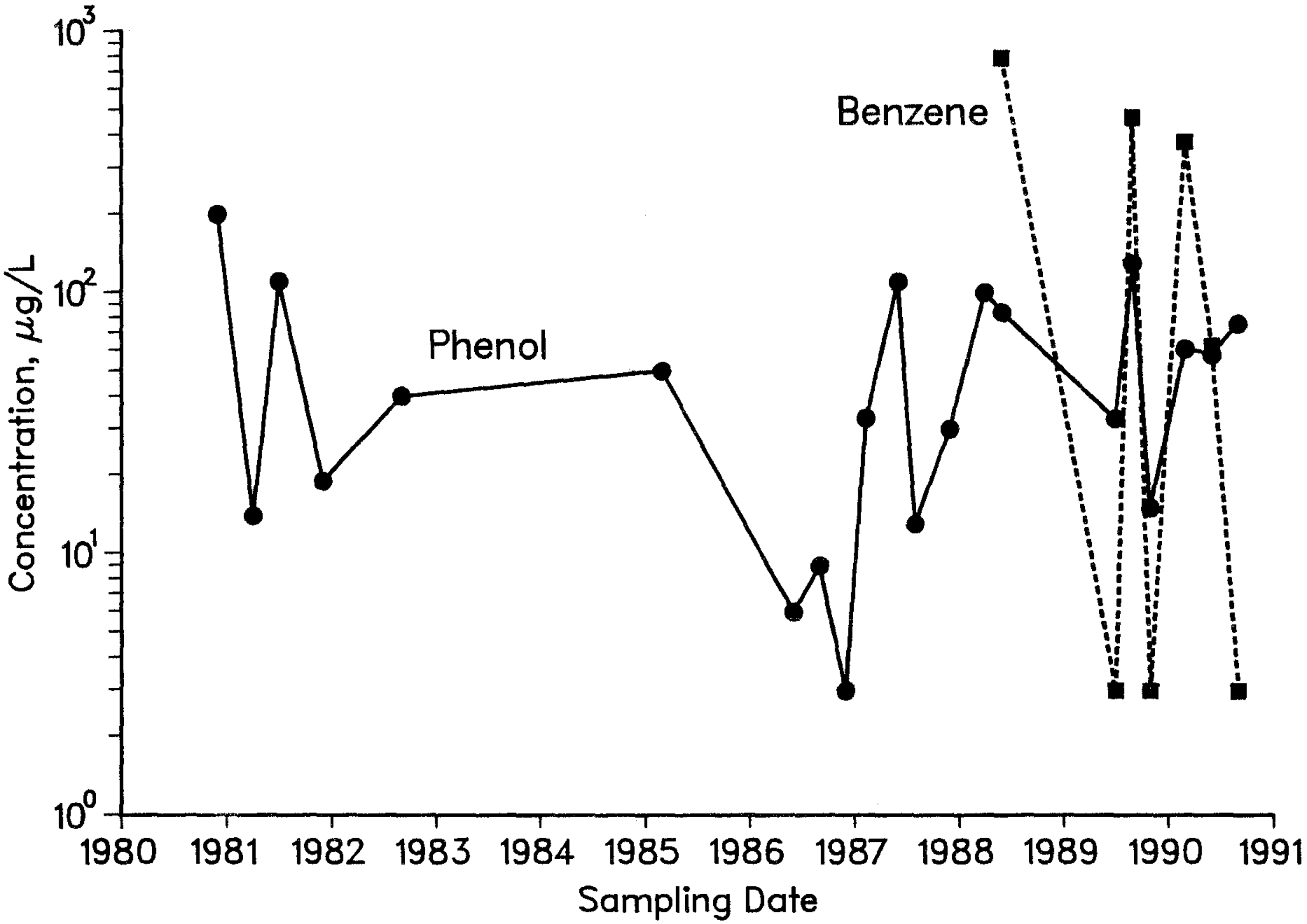

Figure B-13. History of Phenol and Benzene Contamination in Groundwater Sampled From Well WS-24