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Rocky Mountain 1
Underground Coal Gasification Test
Hanna, Wyoming
Groundwater Evaluation

Final Report
June 10, 1988 - June 30, 1993

S. R. Lindblom
V. E. Smith

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Work Performed Under Contract No.: DE-FG21-88MC25038

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Western Research Institute
Laramie, Wyoming

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Laramie, Wyoming 82071

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EXECUTIVE SUMMARY

Title	Rocky Mountain 1 Underground Coal Gasification Test, Hanna, Wyoming, Groundwater Evaluation
Contractor	Western Research Institute (WRI) GRI Contract Number: 5087-253-1619 DOE Grant Number: DE-FG21-88MC25038
Principal Investigators	S.R. Lindblom V.E. Smith
Objectives	The objectives were to describe the baseline hydrology of the Rocky Mountain 1 (RM1) underground coal gasification (UCG) site, to assess the environmental impacts of the UCG test, and to evaluate the effectiveness of postburn measures taken to minimize aquifer contamination through long-term groundwater monitoring.
Technical Perspective	Underground coal gasification is a process that could expand coal reserves by exploiting coal resources that are currently uneconomical to recover. The technical feasibility of UCG has been proven in many tests in the United States and around the world. However, groundwater contamination resulting from the UCG process has been an important element of concern when considering the application of this technology. The evaluation of long-term environmental impacts and the effectiveness of available measures to minimize or eliminate groundwater contamination are key aspects in determining the potential for future commercialization of the process. Two UCG processes were tested in late 1987 and early 1988 near Hanna, Wyoming. The two processes were the extended linked well (ELW) and the controlled retracting injection point (CRIP) processes. Groundwater monitoring was conducted at the site before, during, and after the UCG test to evaluate the environmental impacts and the success of mitigation activities.

Results

Thirty holes were drilled or cored at the site as part of the baseline geohydrologic evaluation. Of these, 22 were completed as monitoring wells and were situated approximately in two rectangles centered around the two process modules. The purpose of the outer ring wells was to monitor hydrologic and groundwater quality changes away from the immediate process area, while the inner ring wells were used to monitor changes in the immediate vicinity of the two process modules. Subsurface changes, such as well blockage and cavity roof collapse, have caused elimination or replacement of some monitoring wells over the course of the project. The drilled holes completed as wells were used not only to collect groundwater samples from the site, but also to determine the hydrologic characteristics of the site. Packer tests, slug tests, and single- and multi-well pump tests were used to determine aquifer parameters and to identify factors influencing the hydrologic system. Results from these aquifer tests, in addition to other field data, were used as input data for two groundwater models: the Random Walk solute transport model and a finite element model.

The baseline water quality sampling program began in August 1986 on a quarterly basis and continued until test operations commenced in November 1987. Groundwater samples were collected from wells completed in the Hanna No. 1 coal seam, the unit C overburden, and the stratum immediately beneath the coal seam. Water levels were measured across the site before each sampling event. Analyses of baseline water samples indicated groundwater of similar composition in the understrata, the Hanna No. 1 coal seam, and the overburden. The dominant ions in the coal seam groundwater were sodium (450 mg/L), bicarbonate (800 mg/L), and sulfate (450 mg/L). These ions in groundwater typically evolve from calcite dissolution, pyrite oxidation, and ion exchange. Concentrations of these ions in the overburden groundwater were slightly less than those in the coal seam groundwater, while concentrations in the understrata groundwater were slightly higher than in the coal seam groundwater. Somewhat higher sulfate concentrations were observed in samples from wells in the southwest portion of the site.

Groundwater monitoring was performed during the UCG experiments, from November 17, 1987 through February 26, 1988. The purposes of collecting groundwater samples on a regular basis during the test were to monitor water quality changes and to detect any excursions of UCG gases into the surrounding strata.

Analyses of samples during the test from the unit C overburden indicated that concentrations of most analytes were similar to baseline. The pH of overburden groundwater in monitoring well EMW-10 decreased slightly from baseline; however, the same magnitude of variation also was seen during baseline sampling. It appears that the unit C overburden was unaffected by the UCG test.

Coal seam wells to the north and east of the test area showed only slight changes in groundwater quality. Samples from wells to the south and west of the test area showed definite effects of the test on coal seam groundwater quality. The pH of samples from wells in the south and west areas of the site decreased from a pretest average of 8.5 to an average during the test of 6.5. Groundwater samples from wells in other areas of the site showed only minor fluctuations in pH without any observable trends. Groundwater samples from the south and west areas, having lower pH values, also showed increased alkalinity. Groundwater samples showing smaller fluctuations in pH, had correspondingly smaller changes in alkalinity.

Changes in concentrations of total organic carbon (TOC), total dissolved solids (TDS), ammonia, and sulfate were similar to those observed for pH and alkalinity. Concentrations of these analytes increased above baseline levels in groundwater samples from wells in the south and west areas of the site. No increase was apparent in most samples from wells in other areas of the site. Concentrations of sulfate, ammonia, TOC and TDS in groundwater samples from inner ring coal seam wells TW-5 and EMW-9 remained relatively constant until groundwater flow patterns changed due to the termination of the ELW UCG test. This caused an increase in the concentrations of these analytes.

Boron concentrations in samples from coal seam wells across the site appeared to randomly fluctuate between a maximum of 0.033 mg/L and a minimum below the analytical detection limit (0.010 mg/L). Because the boron concentrations were so low, the variations were probably due to inconsistencies in the sampling or analytical conditions.

Concentrations of phenol, cyanide, and sulfide in groundwater samples from all monitored hydrostratigraphic units were below the analytical detection limits during baseline sampling and throughout the duration of the test.

Groundwater samples were collected once during the test for analyses by Radian Corporation for the modified Skinner list of organic compounds. Groundwater samples collected on February 3, 1988 showed high concentrations of the volatile organics benzene, ethyl benzene, toluene and xylenes. Analyses for semivolatile organics showed significant concentrations of cresols, phenols, and polyaromatic hydrocarbons in the groundwater samples. No chlorinated organic compounds were detected.

No hydraulic communication between the Hanna No. 1 coal seam and any of the overburden and understrata units was apparent and the UCG test had no observable effect on hydraulic head in units other than the coal seam. Water level measurements in the Hanna No. 1 coal seam over the entire site showed a potentiometric surface with a cone of depression centered in the area of the UCG cavities. This cone of depression was maintained for the entire test. Variations in the orientation and magnitude of the cone of depression were dependent on the groundwater flow boundaries of the coal seam and on removal rates of groundwater from the coal aquifer.

Following the test, groundwater restoration activities took place in two parts. The first restoration occurred in the summer and fall of 1988. Approximately 2,100,000 gallons of water were pumped from the two cavities and treated to remove colloidal and dissolved organics, heavy metals, and ammonia before discharge to

the surface through an atomizing spray system. The treatment system effectively removed dissolved organics and ammonia from the groundwater. Concentrations of selected analytes in the treated water from September 15-20, 1988 include <0.020 mg/L of total phenol, 0.3 mg/L of ammonia, 0.638 mg/L of boron, and 15 mg/L of TOC.

The second restoration occurred in the summer of 1989. Approximately 1,570,000 gallons of groundwater were treated for the removal of dissolved organics. The second treatment system did not use the addition of chemicals because in the first treatment, the chemicals had only a small beneficial effect and resulted in a high TDS level in the treated water. The second treatment system was not effective in removing dissolved organics from the cavity water because of contamination in the carbon adsorbers. Before the second treatment, the quality of cavity water was very similar to baseline and generally improved during pumping. Boron was the only parameter significantly higher than baseline concentrations. Benzene was not detected during the second restoration activity; however, it was detected in groundwater samples from coal seam wells beginning in June 1989.

Evacuation of the cavities during both restoration activities resulted in coal seam water levels at least 250 ft below baseline water level elevations in the vertical process wells. This extremely low water level near the center of the site indicated a cone of depression in the coal seam potentiometric surface centered on or near the two cavities. Water levels in both the unit C overburden and the strata immediately underlying the coal seam were unaffected by either the test or the subsequent restoration activities.

The unit A/B overburden experienced a significant water level decline in response to the UCG test and groundwater restorations. Water levels measured shortly after the last restoration indicated groundwater elevations 100 to 150 ft below baseline elevations.

Long-term monitoring of groundwater at the RM1 site began at the completion of gasification operations (February 26, 1988). Groundwater sampling activities were completed in December 1992. Quarterly sampling was conducted from February, 1988 through December 1990. Semiannual sampling was conducted in 1991 and 1992.

Quarterly and semiannual water level measurements since the second groundwater restoration have shown that water levels in the unit C overburden and the understrata unit have remained relatively constant. Water levels in the unit A/B overburden have gradually recovered to near baseline levels. Water levels in the Hanna No. 1 coal seam had essentially recovered from the effects of the UCG test and groundwater restoration activities by December 1991. Baseline water levels in the Hanna No. 1 coal seam varied between 6880 and 6915 ft above sea level over the year of baseline evaluation. The most recent water level measurements (December 1992) indicate groundwater elevations of approximately 6900 ft. While the coal seam aquifer was the most affected by the test, water levels rebounded quickly and have increased gradually over the past two years.

With few exceptions, groundwater quality during the last sampling event (December 1992) was at or near baseline quality. Some analytes (TOC, TDS, and ammonia) in groundwater samples from wells in the west and southwest areas of the site were consistently higher in concentration than in samples from wells in other areas of the site. This pattern was also observed during the baseline evaluation and test monitoring. These higher concentrations may have resulted from influx of water with higher concentrations of these parameters from off site. The higher transmissivity of the coal seam in this area would facilitate movement of groundwater onto the site in response to hydraulic gradients induced by UCG and restoration operations.

Low concentrations of benzene have persisted in a few wells at the site. Coal seam wells EMW-1 and EMW-3 have most often yielded water containing benzene.

Benzene concentrations in groundwater samples from well EMW-1 varied from <0.010 mg/L to 0.044 mg/L from 1986 to 1992, while EMW-3 benzene concentrations ranged from <0.010 mg/L to 0.019 mg/L. Concentrations have stabilized over the last two years at approximately 0.020 mg/L. Other analyte concentrations in noncavity wells have stabilized at or below baseline levels.

For some parameters, the groundwater quality in the UCG cavities is slightly worse than in the surrounding strata. Sulfate and TDS concentrations are above baseline in the ELW cavity. Boron concentrations remain an order of magnitude above baseline concentrations in both the ELW and CRIP cavities. Other parameters have stabilized at concentrations at or below baseline. However, no migration of these materials into the groundwater outside the cavities has been observed.

Conclusions

The RM1 test had significant ephemeral impacts on the hydrology of the primary aquifer at the site, the Hanna No. 1 coal seam. Lesser impacts were detected in the strata above the coal seam and no impacts were observed below the coal seam.

Water levels, which had decreased over 200 ft near the center of the site during the UCG test and postburn activities, have completely recovered. The groundwater flow patterns observed during the baseline site evaluation have been reestablished. No remaining effect of the RM1 test on groundwater elevations is apparent.

The UCG test did affect groundwater quality at the site on a short-term basis. However, long-term monitoring has shown that procedures undertaken during the test, in addition to postburn restoration measures, were effective in minimizing the spread of contaminants and in removing most contaminants from the subsurface environment. Boron in the two UCG cavities remains an order of magnitude above baseline concentrations. This is not the case over the remainder of the site, as boron in groundwater samples from all other wells has remained below baseline concentrations for the last two years. Low concentrations of benzene have frequently

been detected in a few inner ring coal seam wells. The benzene is probably associated with coal tars in the vicinity of these wells. The majority of wells at the site have shown no evidence of widespread benzene contamination. Total organic carbon and total dissolved solids concentrations have often been detected above baseline levels in peripheral wells along the western edge of the site; however, it is doubtful that these higher concentrations resulted from byproducts of the UCG test. Except for these instances, water quality parameters at the site are now at or below baseline levels.

Technical Approach

Baseline information on the groundwater at the RM1 site was collected over a one-year period prior to the start of the UCG test. Water samples collected during the test, in conjunction with process data, were used to determine the immediate effects of the UCG process on groundwater quality. After UCG operations ceased, water samples were collected across the site on a quarterly basis for two years and on a semiannual basis for two additional years to assess long-term environmental impacts and the effectiveness of groundwater restoration activities. Water levels measured at monitoring wells across the site during all phases of the project were used to determine groundwater flow patterns.

Project Implications

Previous UCG tests had shown that the UCG concept worked, but little effort had gone into environmental considerations. A major objective of the RM1 UCG test was to carry out a large underground coal gasification burn with minimal or no adverse environmental impacts. Groundwater contamination was a major concern. To demonstrate whether or not this goal could be accomplished, it was necessary to fully document any changes that might take place in the site groundwater systems, as well as the operations responsible for such changes. The RM1 groundwater monitoring effort was initiated to serve this purpose. This study fully documents that using proper process measures and postburn mitigation techniques, underground coal gasification can be conducted with very little impact to groundwater quality and subsurface hydrology.

ACKNOWLEDGMENTS

Work performed by Western Research Institute (WRI) on the RM1 project was funded by the U.S. Department of Energy under cooperative agreement DE-FC21-86MC11076 and grant DE-FG21-88MC25038 and by the Gas Research Institute under contract 5087-253-1619. The direction and assistance provided by J. Evans of the Gas Research Institute and U. Sharum of the U.S. Department of Energy is appreciated. The authors would also like to acknowledge the work performed on this multi-disciplined project by M. Vardaman and D.S. Dennis of United Engineers & Constructors, Inc.; J. Covell, J. Boysen, and L.C. Marchant, formerly of WRI; C. Schmidt of the North Dakota Energy and Environmental Research Center; and C. West and R. Vincent of the Wyoming Department of Environmental Quality.

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1.0 INTRODUCTION

1.1 Test Objectives and Processes

The Rocky Mountain 1 (RM1) underground coal gasification (UCG) test was conducted from November 16, 1987 through February 26, 1988, near Hanna, Wyoming (Figure 1). The test was conducted to evaluate two separate UCG process configurations and the environmental concerns associated with UCG operations. The project had three environmental objectives: (1) to evaluate the environmental impacts of underground coal gasification, (2) to minimize the environmental impacts, and (3) to comply with environmental permitting requirements. The project was funded by the U.S. Department of Energy (DOE), the Gas Research Institute (GRI), Amoco Production, Union Pacific Resources, and the Electric Power Research Institute. Western Research Institute (WRI)was contracted by DOE and GRI to participate in several phases of the project, including the environmental monitoring.

The two UCG process configurations tested were the extended linked well (ELW) and the controlled retracting injection point (CRIP) configurations. The ELW configuration consisted of a horizontal production well (PW-1) initially intersecting one vertical injection well (VIW-1) (Figure 2). The coal gasification was initiated at the intersection of the two wells. As the gasification progressed through the coal seam away from the initial injection well, the efficiency of the gasification reaction declined. Gasification efficiency is a measure of the amount of thermal energy used in gasification reactions versus the amount of thermal energy lost to the overburden and as the result of other factors (Covell et al. 1992). When the gasification efficiency declined to a predetermined level, the process was switched to a second injection well (VIW-2), which intersected the horizontal production well and gasification continued. The RM1 ELW module operated for 61 days, consumed 4,430 tons of coal, and recovered 90% of the produced gases (Covell et al. 1992).

The CRIP configuration consisted of a horizontal production well (CPW-1) intersected by a horizontal injection well (CIW-1) (Figure 3). A metal liner was inserted through the casing and open hole of the injection well to the desired initial injection point. A mobile ignitor and burner was inserted through the metal liner. After ignition, air or oxygen was injected through the liner during gasification. As the gasification progressed, gasification efficiency declined as progressively more heat was lost, primarily to the overburden. When efficiency dropped to a predetermined point, the mobile ignitor and burner was placed a distance back from the end of the liner. The burner was ignited and the liner burnt off, exposing fresh coal to the UCG process and increasing the efficiency of gasification. The ignitor and burner unit was then retracted to the next injection point. The CRIP module operated for 97 days and gasified 11,280 tons of coal. Gas recovery for the CRIP module was estimated at 88% (Covell et al. 1992).

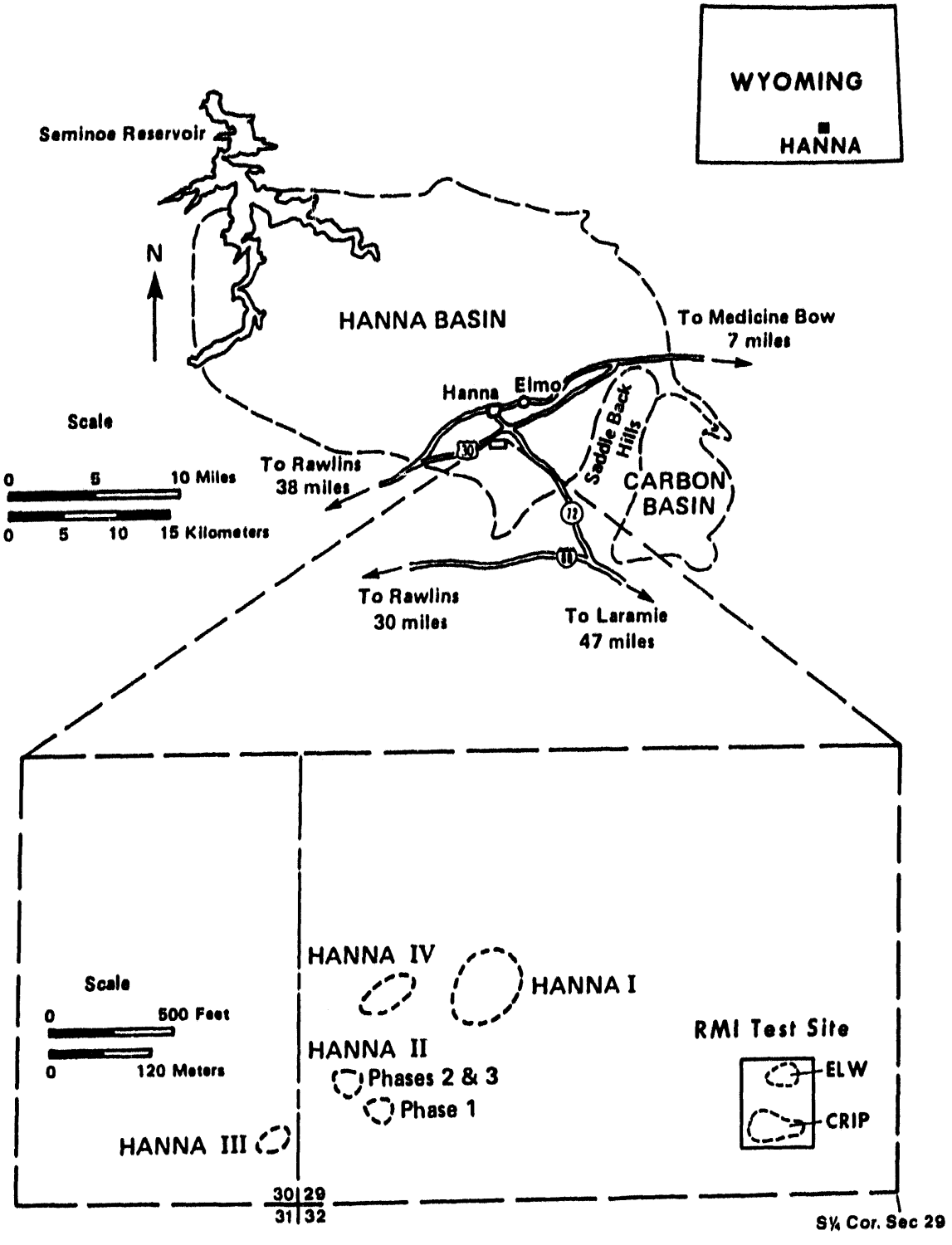


Figure 1. Location Map of the RMI UCG Test Site

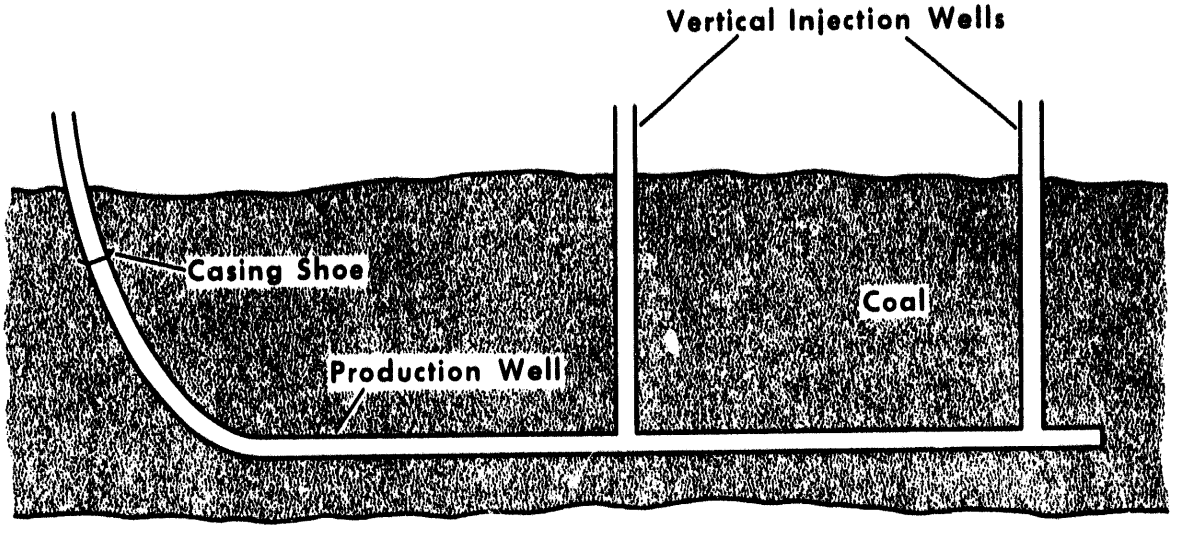


Figure 2. ELW UCG Configurations

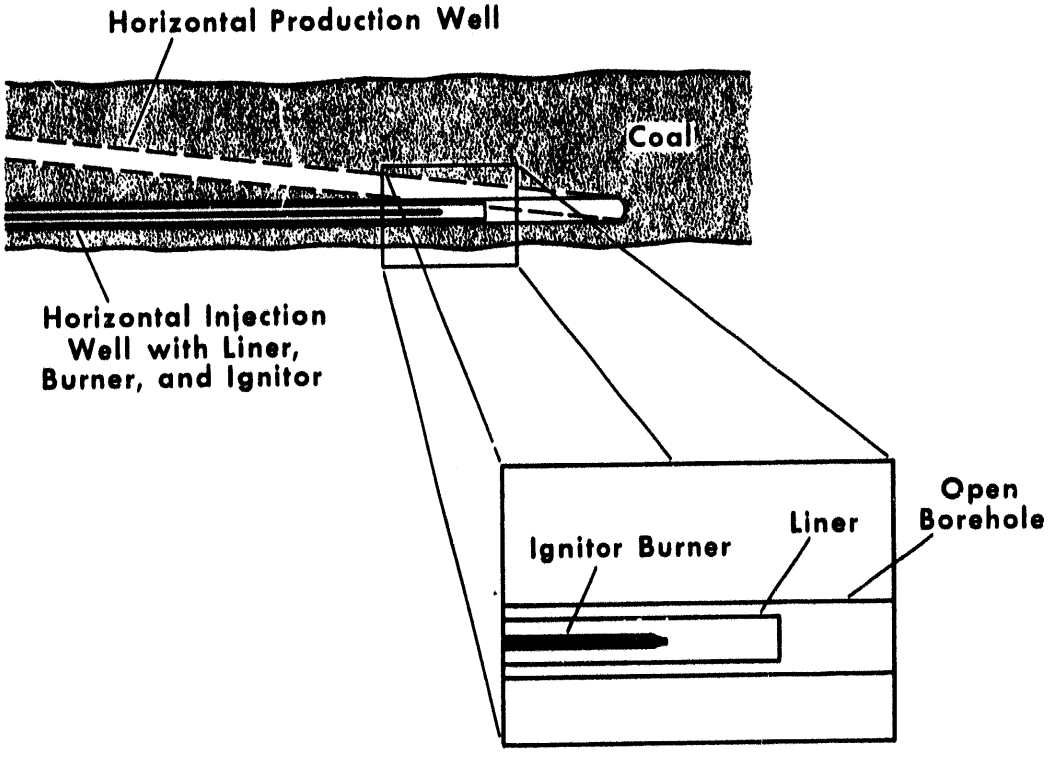


Figure 3. CRIP UCG Configurations

To assess the environmental impacts of the UCG test a network of monitoring wells was established at the site. The network was designed to monitor groundwater quality and subsurface hydrology in the Hanna No. 1 coal seam and surrounding strata.

1.2 Geology and Hydrology

The geology of the RM1 site was described in detail by Oliver (1987). The Hanna No. 1 coal seam is approximately 30 ft thick. The top of the coal seam lies at depths between 350 and 365 ft below the surface in the test area (Figure 4). The coal seam strikes N55°W and uniformly dips N35°E at 7°. The only major structural feature at the site is a normal fault with approximately 30 ft of stratigraphic displacement (Figure 5). The fault trends west-northwest and dips slightly to the southwest. Displacement along the fault has caused the coal seam to be positioned against the understrata on the downthrown (southern) side of the fault and against the overburden on the upthrown (northern) side of the fault.

The internal structure of the Hanna No. 1 coal seam is dominated by two nearly perpendicular, vertical cleats. The two cleat directions correspond to the strike and dip of the coal seam, N55°W and N35°E, respectively. Cleat spacing was determined from cores and surface outcrops to be 1 to 2 inches.

Approximately 260 ft of siltstone, sandstone, claystone, and shale overlies the Hanna No. 1 coal seam. A general stratigraphic section is shown in Figure 6. The overburden is divided into units A, B, C, and D from oldest to youngest. Unit D consists of silts, shales, and a thin coal seam. It is exposed at the surface and ranges from 0 to 105 ft thick. The unit C overburden is made up primarily of sandstone with a few siltstone and shale sequences. The thickness of the unit C overburden unit ranges from 100 to 150 ft. Units A and B are the oldest of the overburden strata and lie immediately above the Hanna No. 1 coal seam. Units A and B are composed predominantly of claystone and siltstone with interbedded sandstones. It is impossible to distinguish between units A and B solely on a lithologic basis, therefore the unit has been designated unit A/B (Oliver 1987).

The Hanna No. 1 coal seam is the primary water-bearing unit at the site. It is essentially confined by the understrata and the A/B overburden unit. Figure 7 shows the location of the RM1 site in relation to the Hanna syncline and topographical features. The RM1 site is located in the south-central portion of the Hanna Basin. Groundwater in the Hanna No. 1 coal seam tends to flow towards the center of the Hanna syncline, although flow is probably disrupted by northwest-trending normal faults. Recharge to the Hanna No. 1 coal seam occurs along outcrops 1/2 mile south and west of the RM1 site along Standpipe Draw (Figure 7). Discharge occurs along Big Ditch Draw, approximately 1/4 mile east of the town of Hanna, in the form of seeps and springs.

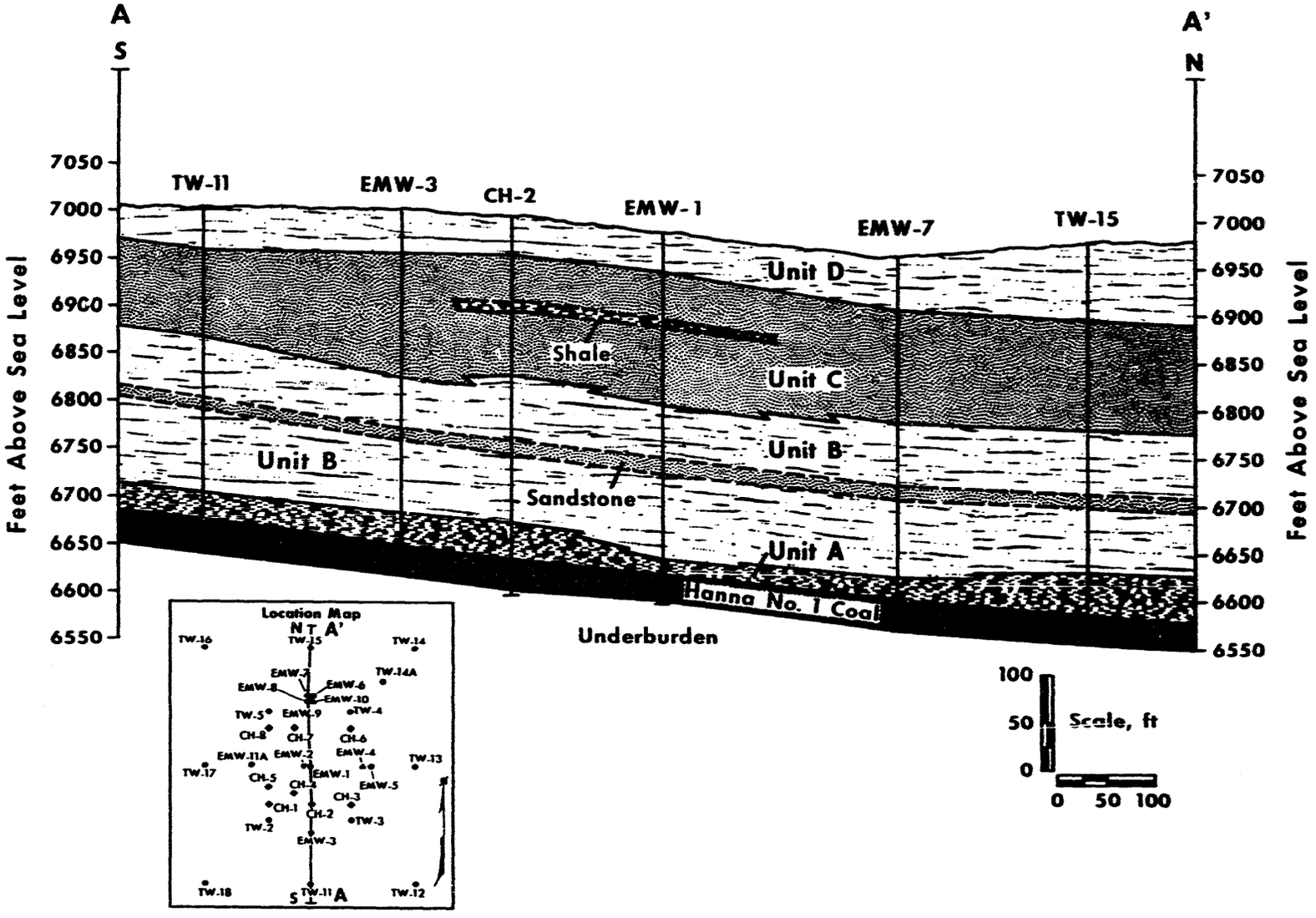


Figure 4. Cross Section A-A′ of the Coal Seam and Overburden at the RMI Site, (Mason et al. 1987)

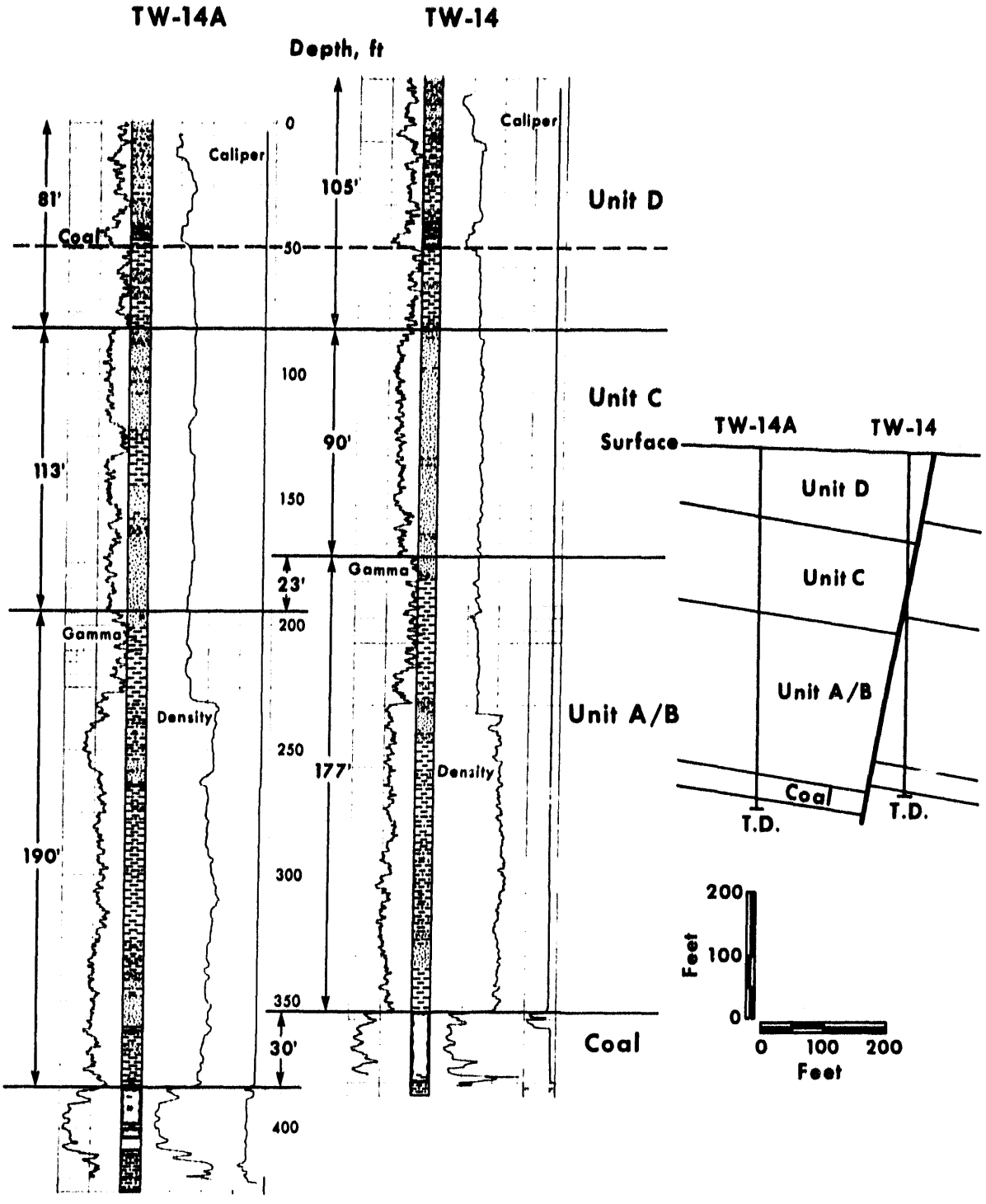


Figure 5. Missing Stratigraphic Section in Monitoring Well TW-14 as a Result of Faulting, (Oliver 1987)

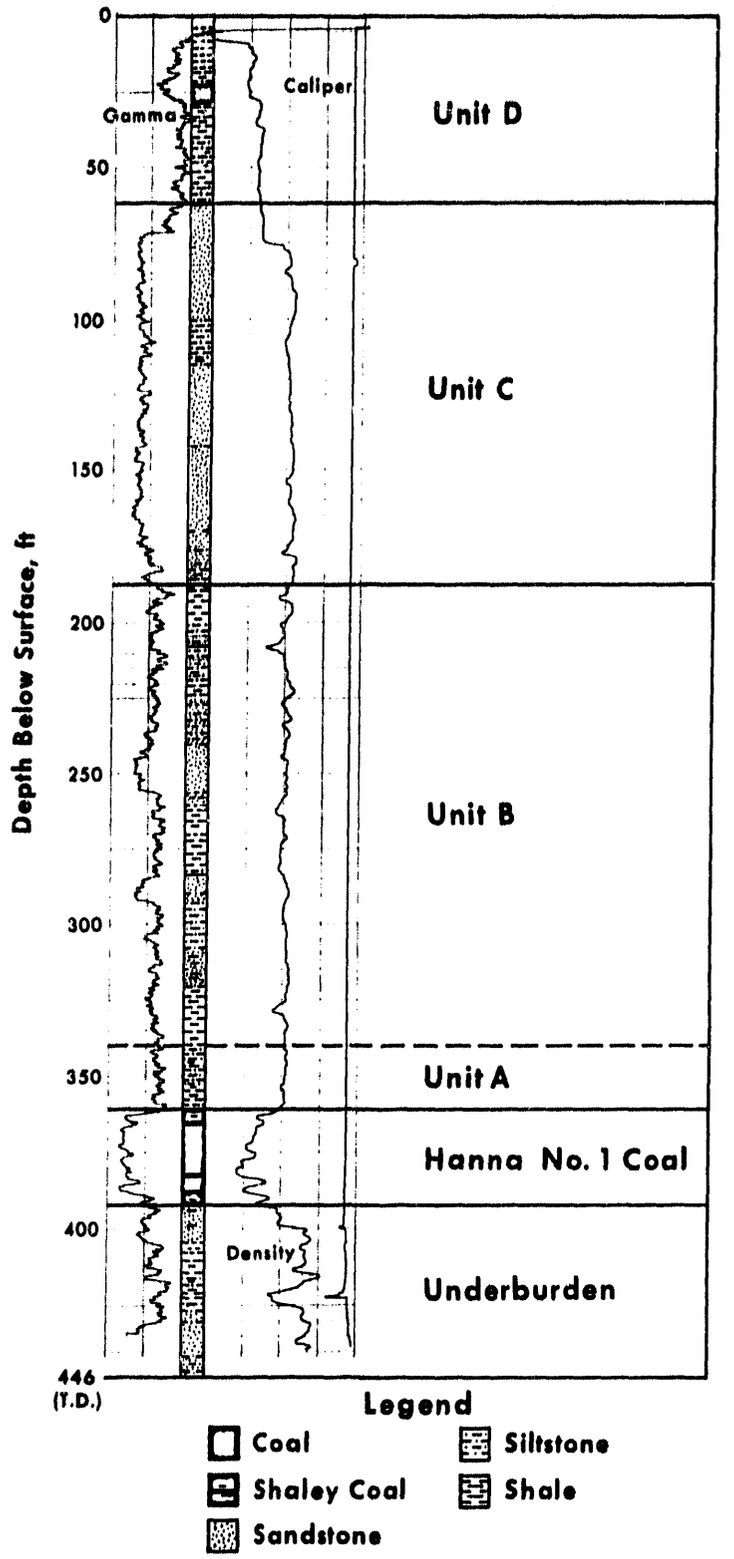


Figure 6. General Stratigraphic Section at the RM1 Site, (Moody 1990)

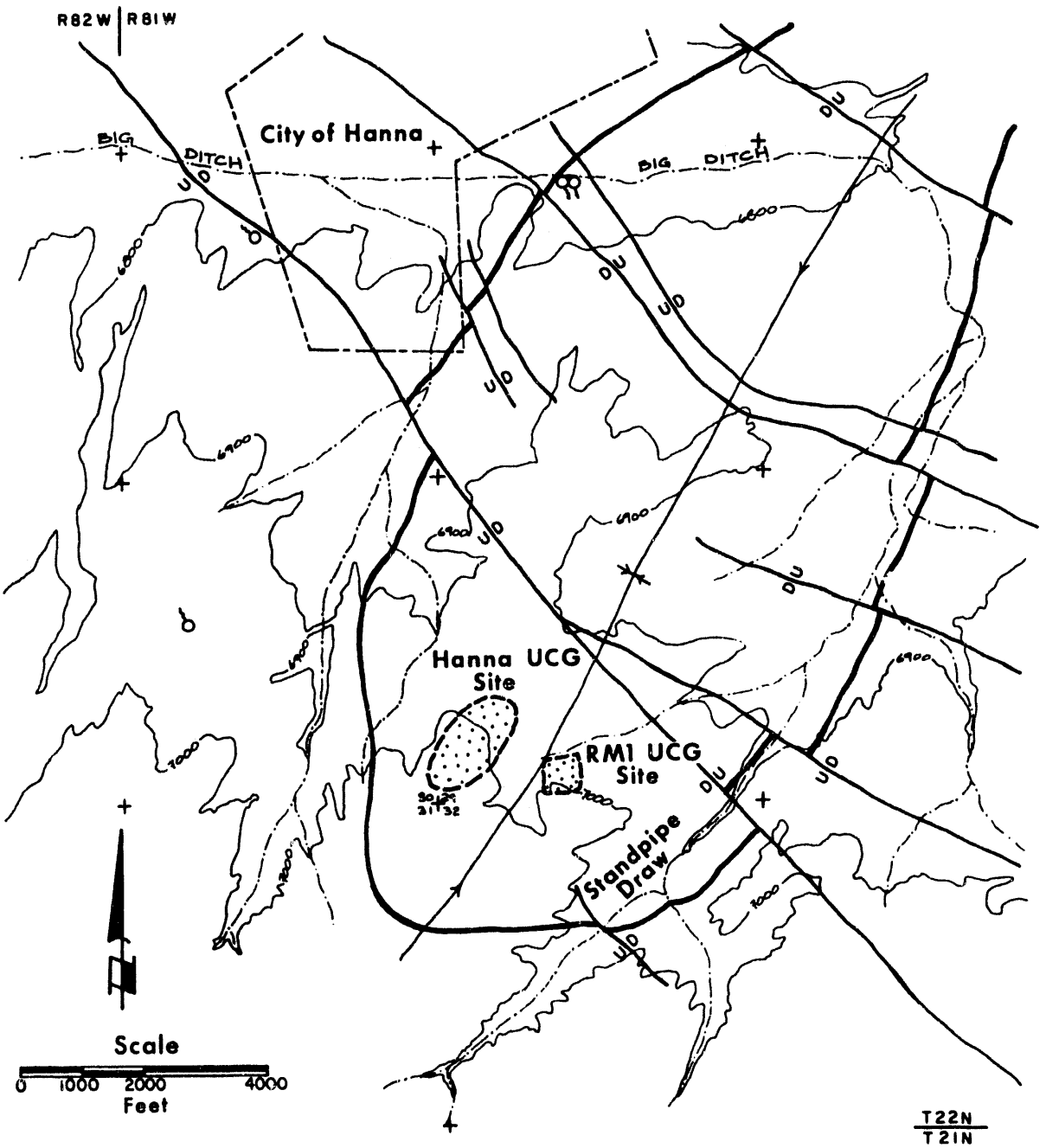


Figure 7. Location of the RM1 and Hanna UCG Sites in Relation to the Hanna Syncline and Topographical Features, (Mason et al. 1987)

2.0 OPERATIONS

2.1 Well Descriptions

Thirty holes were drilled or cored at the site as part of the baseline geohydrologic evaluation. Drill cuttings, coring, and geophysical logging of the holes were used by Oliver (1987) to identify lithology, stratigraphy and structure. Of the 30 holes drilled or cored at the site, 22 were completed as monitoring wells. These wells were used to collect groundwater samples and for aquifer testing. All of the monitoring wells completed for the RM1 test consisted of 7 7/8-inch holes drilled to the top of the target zone, cased with fiberglass, and pressure cemented. The cement plug, casing shoe, and targeted zone were drilled with a 3 7/8-inch bit. The targeted zone was completed as an open hole. A diagram of a typical well at the RM1 site is shown in Figure 8. Wells were developed for 30 to 60 minutes by injecting compressed air into the open interval to remove water, drilling fluid, and cuttings. Completion data for each well are presented in Table 1. Of the 22 monitoring wells installed at the RM1 site as part of this project, 18 were completed into the Hanna No. 1 coal seam, three were completed into the overburden, and one was completed into the stratum immediately beneath the coal seam.

Groundwater monitoring wells were located in two rectangles centered around the two process modules (Figure 9). The 17.3 acres encompassed by the outer ring of wells defined the test site. Each well in the outer ring was placed 435 ft from adjacent outer ring wells, except for well TW-14A. Outer ring well TW-14 was discovered to be hydrologically isolated from the test area by the fault crossing the northeast corner of the site. A replacement well, TW-14A was completed on the test module side of the fault. The purpose of the outer ring wells was to monitor hydrologic and groundwater quality changes away from the immediate process area. The inner ring wells defined a 3.1 acre area containing the two process modules (ELW and CRIP). Each inner ring well was located 190 ft from adjacent inner ring wells. The purpose of these wells was to monitor hydrologic and groundwater quality changes in the immediate vicinity of the two process modules. Inner and outer ring wells are listed in Table 2.

Two pre-existing wells also were used for groundwater quality monitoring. Wells EMW-4 and EMW-5 were steel-cased wells constructed in 1980 to monitor hydrologic changes resulting from the Hanna UCG test conducted in the 1970s. Well EMW-4 was completed in the unit C overburden, while EMW-5 was thought to be completed in the Hanna No. 1 coal seam. Anomalous water level and water quality measurements prompted re-examination of well logs to verify completion data. It was then discovered that well EMW-5 was completed into the top 19 ft of the understrata and the bottom 9 ft of the coal seam (Moody 1990). The well was eliminated from the sampling program because it was not possible to obtain groundwater samples representative of either unit.

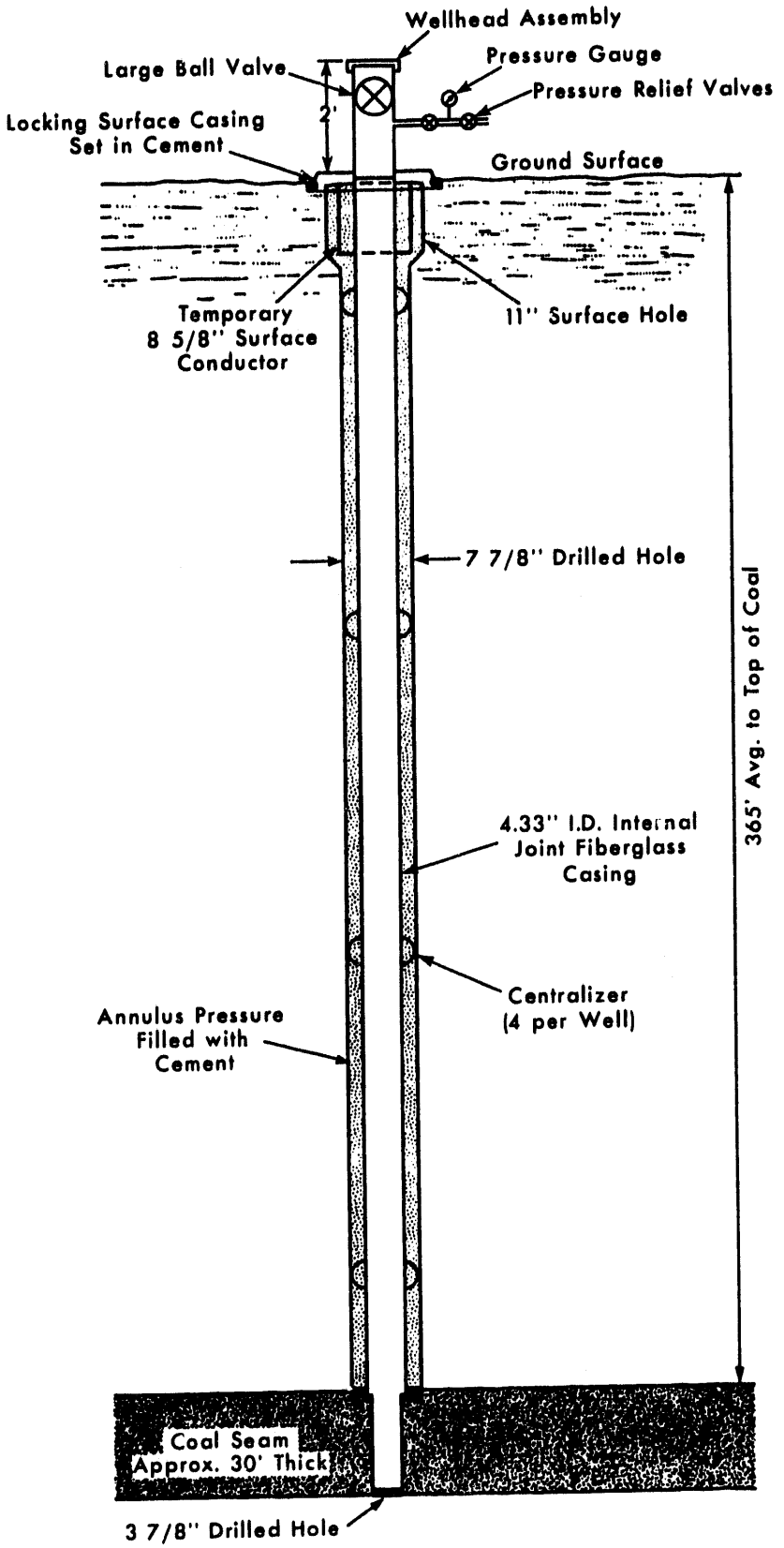


Figure 8. Schematic of Completion Details for a Typical RM1 Monitoring Well Completed in the Hanna No. 1 Coal Seam, (Moody 1990)

Table 1. RM1 Well Completion Data, (Mason et al. 1987)

Well	Wyoming Permit Number	Coordinates [a] NORTH	Coordinates [a] EAST	Date of Well Completion	Casing Diameter (inches)	Diameter of Open Hole Interval (inches)	Unit of Open Hole Interval	Open Hole Interval [b]	Ground Elevation [c]	Elevation of Top of Casing [d]
EMW-1	72479	620.2	2027.2	08 June 86	4.3	6.0	COAL	6597-6628	6983.1	6984.8
EMW-2	72480	620.8	2002.1	09 July 86	4.3	4.1	A	6632-6683	6984.5	6986.3
EMW-3	72485	360.8	2027.9	08 June 86	4.3	3.9	COAL	6628-6659	7004.0	7006.0
EMW-4	52003	519.8	2137.4	23 July 80	5.0	4.5	C	6876-6671	6978.1	6981.4
EMW-5	52017	523.3	2169.7	08 July 80	5.0	4.5	COAL	6560-6586	6977.3	6980.5
EMW-6	72488	896.1	2042.9	11 July 86	4.3	3.9	COAL	6513-6559	6959.1	6960.7
EMW-7	72486	898.4	2016.8	27 June 86	4.3	3.9	COAL	6570-6598	6958.9	6960.4
EMW-8	72487	874.2	2015.4	30 June 86	4.3	3.9	A	6607-6638	6962.5	6964.6
EMW-9	72489	884.8	2029.0	08 June 86	4.3	3.9	COAL	6566-6595	6959.8	6961.7
EMW-10	72490	872.0	2040.3	07 July 86	4.3	3.9	C	6777-6814	6962.0	6964.2
EMW-11A	72491	623.8	1799.6	15 June 86	4.3	3.9	COAL	6602-6629	6978.7	6980.8
TW-2	72481	410.6	1867.7	20 June 86	4.3	3.9	COAL	6626-6654	6994.5	6996.4
TW-3	72482	410.9	2187.6	26 June 86	4.3	3.9	COAL	6617-6652	6996.2	6998.2
TW-4	72483	830.7	2187.0	12 June 86	4.3	6.0	COAL	6560-6590	6962.2	6964.8
TW-5	72484	830.9	1866.8	23 June 86	4.3	3.9	COAL	6581-6607	6966.7	6968.6
TW-11	72492	160.3	2027.2	26 July 86	4.3	3.9	COAL	6648-6674	7005.5	7007.6
TW-12	72493	160.9	2437.8	26 July 86	4.3	4.1	COAL	6636-6662	7007.0	7009.2
TW-13	72494	621.2	2437.3	22 July 86	4.3	3.9	COAL	6575-6615	6976.5	6978.8
TW-14	--	1080.7	2436.7	23 July 86	4.3	3.9	COAL	6545-6570	6948.6	6950.7
TW-14A	72495	956.2	2311.8	27 July 86	4.3	5.6	COAL	6528-6570	6954.0	6956.4
TW-15	72496	1080.0	2027.0	16 July 86	4.3	4.1	COAL	6545-6566	6965.3	6967.4
TW-16	72497	1081.1	1617.5	14 July 86	4.3	3.9	COAL	6568-6589	6984.5	6986.4
TW-17	72498	620.6	1617.4	29 July 86	4.3	3.9	COAL	6615-6642	6971.9	6973.9
TW-18	72499	160.6	1618.3	27 July 86	4.3	4.1	COAL	6679-6699	6992.6	6995.1

[a] Feet from SW corner of Section 29. Section corner referenced as N100.0, E100.0.
[b] Feet above mean sea level. Drilled intervals below the bottom of casing are open. No screens in well.
[c] Surveyed elevation, feet above mean sea level.
[d] Elevation of top of casing determined by adding casing stick-up to ground elevation.

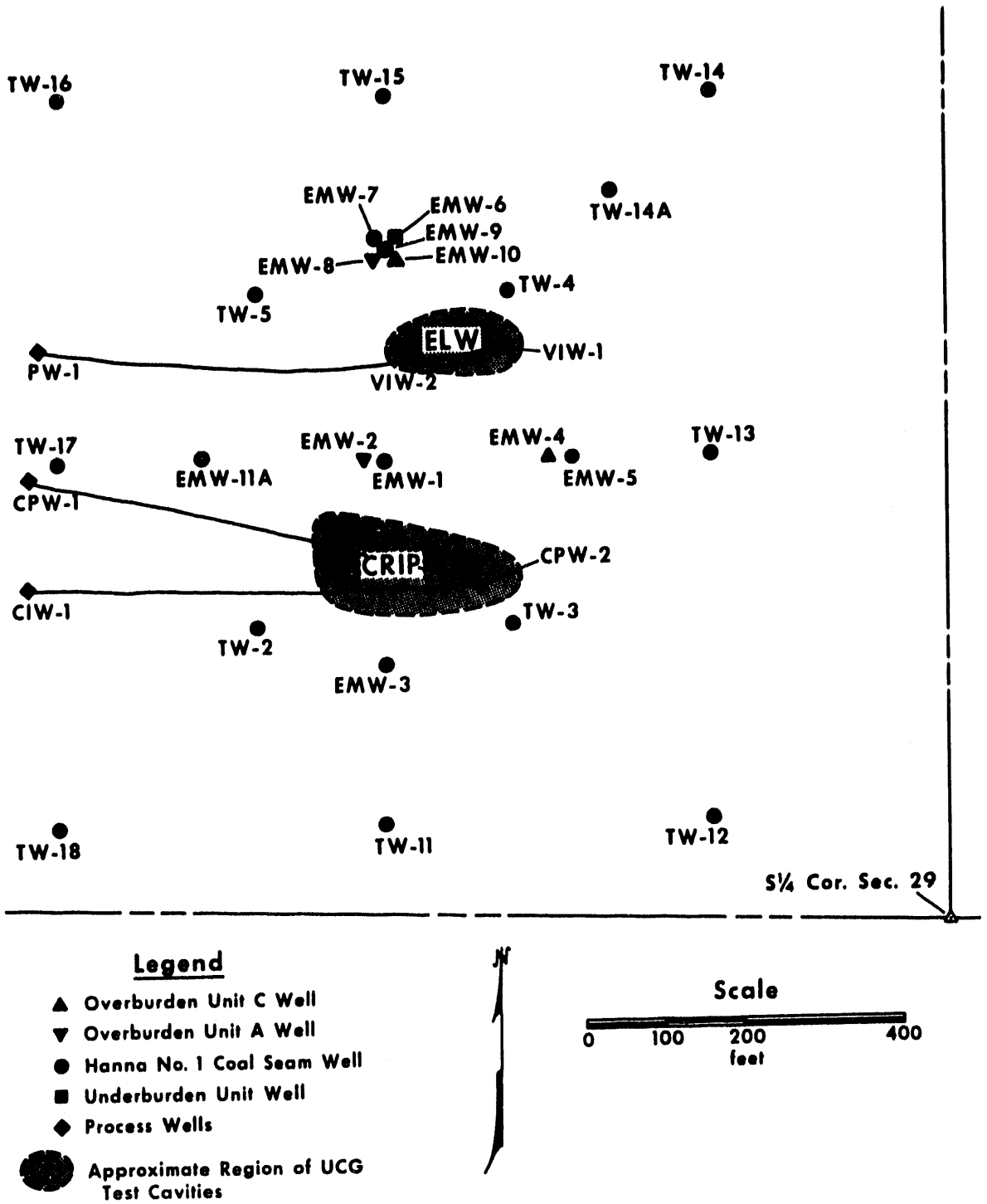


Figure 9. RM1 Groundwater Monitoring and Process Well Network

Table 2. Groundwater Monitoring Wells Sampled During the RM1 Test, (Moody 1990)

Inner Ring		Outer Ring[a]	
TW-2[a]	EMW-4[b]	TW-11	TW-15
TW-3[a]	EMW-5[a]	TW-12	TW-16
TW-4[a]	EMW-6[c]	TW-13	TW-17
TW-5[a]	EMW-9[a]	TW-14A	TW-18
EMW-3[a]	EMW-10[b]		
	EMW-11A[a]		

[a] Coal seam well
[b] Overburden well
[c] Understrata well

Over the course of the RM1 project, subsurface changes have caused problems with some of the wells at the site. Obstructions were encountered in wells TW-14A and EMW-4 during the last two quarterly sampling events of 1990. Coal seam well TW-14A was blocked at a depth of 268 ft, while unit C overburden well EMW-4 was obstructed at a depth of 110 ft. Both wells were eliminated from the postburn groundwater monitoring program with the approval of the Wyoming Department of Environmental Quality, Land Quality Division (WDEQ, LQD). CRIP cavity well CPW-2 was replaced in the sampling program by well CCW-1 after the casing in CPW-2 shifted and prevented the lowering of the sampling pump in December 1990.

2.2 Baseline Studies

Research on the hydrogeology and baseline water quality was conducted by Mason et al. (1987). Process well evaluation and additional site evaluation were performed by Moody et al. (1987). The objectives of the baseline site evaluation were threefold: (1) to use the results of this evaluation as a basis for comparison to evaluate the impacts of UCG on groundwater quality, (2) to identify factors that could influence the UCG test and postburn groundwater restoration, and (3) to satisfy requirements of the WDEQ, LQD included in the UCG permit application.

Tabulation of most of the groundwater field data and analytical data, including baseline data, are provided in Appendix A. Analytical methods; sampled volumes, containers, and preservation techniques; and Quality Assurance and Quality Control objectives are provided in Appendix B.

The drilled holes completed as wells were used not only to collect groundwater samples from the site, but also to determine the hydrologic characteristics of the site. Aquifer testing methods, including packer tests, slug tests, and single- and multi-well pumping tests, were used to determine aquifer parameters and to identify factors influencing the hydrologic system.

Analysis of slug test data was performed using a type-curve fitting procedure (Cooper et al. 1967). Pumping test data were analyzed using the method presented by Papadopulos and Cooper (1967). Results from these aquifer tests, in addition to other field test data, were used as input data for two groundwater models: the Random Walk solute transport model (Prickett et al. 1981) and a finite element model (Contractor et al. 1986). Initially, no field data were available for modeling efforts and input data was estimated. As data from aquifer tests and other aspects of the baseline site evaluation were accumulated, actual field data were used in these models. The Random Walk model was primarily used to investigate various pumping schemes. The finite element model was used to predict contaminant migration in the groundwater after the test. A detailed description of these models and the results obtained were presented by Mason et al. (1987) and Moody et al. (1987). Results from these models cannot easily be compared with long-term groundwater quality data because of postburn restoration measures conducted to remove contaminants from the subsurface.

The baseline groundwater sampling program was designed to characterize the groundwater at the RM1 site and to provide a standard against which the environmental impacts of the UCG test could be assessed. Groundwater sampling on a quarterly basis began in August 1986 and continued until test operations commenced in November 1987. All 24 wells were scheduled for sampling. The inner ring coal seam wells and wells EMW-5, EMW-6, and EMW-10, were sampled for the full-suite set of parameters listed in Table 3. The outer ring wells were designated for the limited-suite parameter set (Table 3).

Baseline samples collected on August 21, 1987 were submitted to Radian Corporation for identification and quantification of organic compounds present in the modified Skinner list. During the design of the RM1 test, questions arose concerning the possible production of chlorinated hydrocarbons during the UCG test and whether the biotoxicity (or lack thereof) of the coal seam groundwater would be changed.

Table 3. Groundwater Monitoring Parameters for Baseline Studies, (Mason et al. 1987)

Limited Suite (LS)	Full Suite (FS)	Field Measurements
Ammonia	Alkalinity	Alkalinity
Bicarbonate	Aluminum	Conductivity
Boron	Ammonia	Discharge rate
Fluoride	Arsenic	Eh
Manganese	Barium	pH
Nitrate	Bicarbonate	Pumping time
Phenols	Boron	Temperature
Sodium	Bromide	Water level
Sulfate	Cadmium	
Sulfide	Calcium	
TDS	Carbonate	
Total organic carbon	Chemical oxygen demand	
	Chloride	
	Chromium	
	Copper	
	Cyanide	
	Fluoride	
	Heterocyclics	
	Iron	
	Lead	
	Lithium	
	Magnesium	
	Manganese	
	Mercury	
	Molybdenum	
	Nickel	
	Nitrate	
	Nitrite	
	Phenols	
	PNA	
	Potassium	
	Selenium	
	Sodium	
	Sulfate	
	Sulfide	
	TDS	
	Thiocyanate	
	Total organic carbon	
	Volatile organics	
	Zinc	

It should be noted that the production of chlorinated hydrocarbons had not been observed during any surface gasification tests, though both chlorine and hydrocarbons were present in the reaction atmosphere with many of the coal feeds used. To determine whether such compounds might be formed under UCG conditions at the RM1 site, it was decided by GRI, DOE, and the other participating organizations to analyze selected groundwater samples for the defined Skinner list. The Skinner list is a modification of the U.S. Environmental Protection Agency Toxic Leaching Procedure Volatile and Semivolatile compounds, that especially includes the identification of chlorinated hydrocarbons. Organic compounds included in the modified Skinner list are presented in Tables 1 and 2 in Volume II, Appendix C. Samples were also collected on August 21 and November 4, 1987 for determination of acute toxicity by ENSR Consulting and Engineering (Appendix D). Acute toxicity tests determine the effect of water quality on test organisms. Acute toxicity of RM1 groundwater was measured using Ceriodaphnia dubia and fathead minnow (Pimephales promelas). A detailed description of this study was presented by Drottar (1990).

Groundwater sampling procedures followed guidelines approved by WDEQ, LQD. Water levels were measured across the site before any groundwater sampling was started. Grab samples were collected with a Bennett® air driven, stainless steel piston pump. In the Bennett® pump, an air motor drives a piston-type fluid pump capable of pumping water from depths of 500 ft. This type of pump eliminates water contact with the atmosphere and minimizes the sample agitation associated with motor-driven submersible pumps. The Bennett® pump was lowered to within 5 ft of the bottom of the well to minimize the time required for purging. Groundwater was brought to the surface through Teflon® tubing. Wells were purged prior to sample collection to ensure that samples were representative of the groundwater in the formation rather than water in the well bore. The field parameters of Eh, pH, temperature, conductivity, flow rate, and water level were measured throughout the purging process. Temperature, Eh, and pH were measured using a Chemcadet model 05986-60 pH/mV meter. Conductivity was measured using a Cole-Parmer model 4070 conductivity meter. Probes for both meters were placed in an in-line flow-through cell. Water levels in the well bore were measured with a Solinst® model 101 water level sounder. Flow rates were measured using a graduated container and a stopwatch. Stabilization of parameters indicated that water was being pumped from the formation. Wells were purged for 80 minutes or longer if parameters were not stable. Groundwater samples requiring field filtration were filtered through an in-line Geotech® 142-mm back flushing filter holder with a Millipore® 0.45 μm nitro-cellulose filter. Field alkalinity titrations were performed immediately after samples were collected.

Wells which could not be pumped were sampled using a 1000-mL Teflon® bailer. Bailed wells were not purged prior to sampling. Field measurements of Eh, pH, temperature and conductivity were measured using approximately 300 mL of sample in a small beaker. No alkalinity titrations were performed on bailed samples. Fractions of bailed samples requiring filtration were filtered in the laboratory.

After sample collection, a label and numbered tag were affixed to each sample-fraction bottle. Each bottle was sealed in a plastic bag and placed in a prechilled, ice-filled cooler until delivery to the laboratory. Once filled, each cooler was sealed with a self-adhesive custody seal for chain-of-custody purposes. Sample identification numbers, corresponding tag numbers, and required analyses were recorded in a laboratory notebook and on chain-of-custody forms. Upon delivery of the samples to the analytical laboratory, the sampling crew relinquished custody to a sample tracker. The sample tracker examined coolers, samples, and chain-of-custody forms; took possession of the samples; signed the chain-of-custody forms; and notified the sampling crew of any discrepancies.

The sampling program contained five quality assurance/quality control (QA/QC) measures: field blanks, standards, duplicates, rinsates, and the use of a referee laboratory for duplicate sample analyses. These QA/QC measures are described in detail below.

- Field blanks consisted of laboratory-generated deionized distilled water placed in sample bottles and submitted for analyses under an anonymous sample designation (TW-30).

- Standards were samples with known concentrations of analytes submitted for analyses under an anonymous sample designation (TW-31). Stock solutions and field preparation procedures were provided by Western Research Institute's (WRI) QA/QC officer. Standards were used to determine any adverse effect on sample integrity due to field conditions and sample handling. Standards were generated and analyzed for the full-suite set of parameters (Table 3).

- Duplicate samples were collected from a well at the site and submitted under an anonymous sample identification code (TW-32). Duplicate samples were collected at the same time as other samples from the well.

- Rinsate samples consisted of two full-suite parameter sets. The first set, designated "RB", contained Laramie tap water. The second set, labeled well "R", consisted of Laramie tap water that had been pumped through the sample lines. These samples were designed to detect any leaching of contaminants from the sample lines.

- A referee laboratory (ACZ Inc., Steamboat Springs, Colorado) analyzed one complete duplicate set of samples to assess the accuracy of WRI's analytical data.

In addition to these precautions, equipment calibrations were routinely performed and duplicates and spiked samples were analyzed to ensure the data quality. These analytical QA/QC procedures were used for all groundwater monitoring during the study (Mason and Johnson 1988). Table B-1 in Appendix B summarizes the analytical methods that were used, as well as the accuracy, precision, and detection limit objectives. The information in Table B-1 can be used to estimate the level of uncertainty associated with the various analyses.

2.3 Groundwater Monitoring During the UCG Test

The purpose of monitoring groundwater conditions during the UCG test was to evaluate chemical and physical impacts of the UCG process on the groundwater hydrology by comparing baseline data with data collected during the test.

Groundwater samples were collected from wells completed into the Hanna No. 1 coal seam, the unit C overburden, and the stratum immediately beneath the coal seam. The wells listed in Table 2 were sampled according to the schedule in Table 4. Each well was sampled at least nine times during the RM1 test. Wells that were subject to product gas excursions, as defined by the In-Situ Research and Development Testing License Application (United Engineers & Constructors 1987), were sampled more often. In addition, groundwater samples were collected on February 3, 1988 and submitted to Radian Corporation for modified Skinner list organic compound analyses (Volume II, Appendix C, Tables 1 and 2). Groundwater sampling equipment and procedures used were the same as those described under Section 2.2, with the following exceptions:

- Wells were sampled in order from lowest to highest concentration of analytes in the groundwater.
- During well purging, field parameters were recorded every 10 minutes in a WRI laboratory notebook.
- The two sample parameter suites were the field measurement and analyses (FMA) suite and the grab suite (Table 5), rather than the full and limited suites of the baseline evaluation (Table 3).

The FMA suite of samples was collected from inner ring wells using the Bennett® sample pump. Parameters in the FMA suite were indicators of gas excursions and resulting groundwater contamination from the UCG process (Cooke and Oliver 1988). Grab samples were collected with a 1000-mL Teflon® bailer from outer ring wells. Sample temperature, pH, Eh, conductivity, and alkalinity were measured immediately after sampling. Phenol concentrations were measured on site using a gas chromatograph. Sample volumes, containers, and preservation techniques are listed in Table B-2 (Appendix B).

Table 4. Groundwater Sampling Schedule During the RMI Test, (Moody 1990)

Outing	Sampling Dates	Resampling Dates	Excursion Wells
1	12/06/87 to 12/09/87	------	------
2	12/16/87 to 12/18/87	12/19/87 to 12/20/87	TW-2, TW-3, TW-12, TW-17, TW-18, EMW-11A
3	12/29/87 to 12/31/87	01/03/88 to 01/04/88	TW-2, TW-11, TW-17 TW-18, EMW-3
4	01/05/88 to 01/08/88	01/14/88	TW-2, TW-17 TW-18, EMW-11A
5	01/15/88 to 01/18/88	01/20/88 to 01/21/88	TW-2, TW-17 TW-18, EMW-11A
6	01/25/88 to 01/28/88	01/30/88	TW-2, EMW-11A
7	02/02/88 to 02/06/88	------	------
8	02/11/88 to 02/17/88	------	------
9	02/22/88 to 02/26/88	------	------

Table 5. Parameters in the FMA and Grab Suites, (Moody 1990)

Grab Suite	FMA Suite
Temperature	Water level
Alkalinity	Flow rate
Conductivity	Purging time
pH	Temperature
Eh	Alkalinity
Phenol	Conductivity
	pH
	Eh
	Ammonia
	Boron
	Cyanide
	Sulfate
	Sulfide
	Phenols
	TDS
	TOC

QA/QC procedures were the same as those described in Section 2.2 on the baseline site evaluation with the following exceptions:

- QA/QC samples (blanks, standards and rinsates) were analyzed for the FMA suite of parameters, rather than the full suite of the baseline site evaluation

- A referee laboratory was not used, however, an independent sampling audit and report was prepared by Dr. Benjamin F. Mason evaluating sampling procedures, sample transport, sample security, chain-of-custody, sample tracking, and data handling. Dr. Mason's report is included in the report by Moody (1990) and indicates that WRI's sampling and analytical methods were satisfactory.

One of the purposes of collecting groundwater samples on a regular basis during the test was to detect any excursions of UCG gases into the surrounding strata. An excursion was defined as an unwanted movement of a constituent out of the production zone as a result of in situ-mining (Moody 1990). A more detailed definition of excursion and a description of the associated hydrologic changes as defined by WDEQ, LQD for the RM1 test is presented in the In-Situ R&D Testing License Application (United Engineers & Constructors 1987).

To identify possible excursions, six parameters that were sensitive to product gas intrusions were monitored as part of the FMA suite. These parameters were ammonia, boron, cyanide, phenol, total dissolved solids (TDS), and total organic carbon (TOC). If sample analyses indicated an excursion, the suspected inner ring well was resampled (FMA suite) within 24 hours of Stearns-Roger Division (the site permit holder) receiving the data. If resampling verified an excursion, the nearest outer ring well was sampled for an FMA sample suite. If the outer ring well samples indicated an excursion, it was assumed that gas had escaped out of the production zone and WDEQ, LQD could have terminated gasification operations. Although outer ring excursions were detected, WDEQ, LQD did not terminate the test. Outer ring wells TW-17 and TW-18 were added to the list of wells sampled for the FMA parameter suite during sampling events 7, 8, and 9 (Table 4) because of repeated detection of excursions from analyses of samples from inner ring wells TW-2 and EMW-11A.

During the burn, water levels were monitored before beginning each sampling event. As a part of this task, water levels, wellhead gas pressures, carbon monoxide readings of well bore gas, odors, and sounds emanating from the well were recorded in a WRI laboratory notebook.

Water level measurements were taken only after wellhead gas pressures were bled off. Beginning on January 22, 1988, in addition to water level surveys performed by WRI, site management (Project Construction Corporation) personnel took daily water level measurements from all the wells at the site.

2.4 Groundwater Restorations

Postburn groundwater restoration at the RM1 UCG site has been reported by Boysen et al. (1990) and Covell et al. (1992). The purpose of the restoration activities was to remove affected groundwater from the subsurface, treat the water for removal of predicted UCG-induced contaminants, and discharge the treated water to the land surface. This was accomplished by maintaining flow of UCG-affected groundwater into the cavities, where it was collected and contained before being pumped to the surface for treatment and discharge.

After the UCG cavities were vented, flushed, and cooled, the cavities remained vented to the atmosphere to promote influx of water to the cavities. Pressures would increase in the cavities and impede the influx of water if the cavities were not vented. Groundwater flow was maintained inward toward the cavities between the venting, flushing, and cooling activities and the first groundwater restoration activity, and between the first and second restoration activities. Groundwater flow into the cavities presumably helped flush any UCG-induced contaminants from the surrounding strata and into the cavities where they could be collected and contained prior to treatment and discharge. In the ELW cavity, a pump was placed in process well VIW-1 at 381 ft below the top of casing. This put the pump near the cavity floor (Oliver et al. 1991). A pump was placed in the UCG process well CPW-1 in the CRIP cavity at a depth approximately 20 ft above the cavity floor (approximately 349 ft below the top of the well casing) as determined by Oliver et al. (1991).

2.4.1 First Restoration Activity

The treatment system used for the first restoration activity was designed to remove oils, dissolved nitrogen and sulfur species, dissolved metals, and organic compounds. The predicted constituents of concern were oils, phenol, TOC, ammonia, sulfides, and heavy metals. The system was designed to lower the concentrations of contaminants to Target Restoration Values (TRV). The TRV for a constituent was derived from the arithmetic mean of baseline concentrations in Hanna No. 1 coal seam monitoring wells. Concentrations below the analytical detection limit were assumed to be zero when calculating the arithmetic mean.

Table 6 shows the TRV as well as the number of samples used to generate the TRV, and the standard deviation. The treatment system consisted of six steps:

- Gravitational separation and air flotation were used to separate oil and water.

- In a flocculation chamber, a chlorine solution was added to oxidize cyanide and ammonia. This was followed by the addition of a 50% NaOH solution to raise the pH and to react with heavy metals to form and precipitate metal hydroxides.

- A tube settler allowed precipitates to settle out. The precipitated solids were removed and incinerated on site.

- A two-stage pressure filter was used to remove suspended solids. The filter consisted of an anthracite coal stage to remove the coarser particles, followed by a silica sand stage for the finer solids.

- In a clearwell compartment, 93-98% H_2SO_4 was added to reduce the high pH resulting from the addition of NaOH in the flocculation chamber. The pH of the water after this step was near neutral.

- Two carbon adsorber units, each containing 100 ft^3 of activated charcoal, were used to remove organics.

A schematic diagram of the treatment system is illustrated in Figure 10. Cavity water was pumped into a holding tank before passing through the treatment system. Treated water was stored in a second holding tank before being discharged to the surface through a network of atomizing spray nozzles mounted atop 6-ft risers. The water was applied to approximately 11 acres of land southwest of the test area.

Water samples were collected for five analytical suites during the first restoration activity: suites A, B, C, D, and E (Table 7). Water samples were collected from several sampling ports at the wellheads and throughout the treatment systems according to the sampling schedule in Table 8. Table B-1 in Appendix B summarizes the analytical methods, and the accuracy, precision, and detection limit objectives. Table B-2 describes the sampled volumes, containers, preservation techniques, and holding times.

During this first restoration activity, treatment influent and effluent were sampled and analyzed on a daily basis for the first three days of the first week of pumping. The influent and effluent were sampled daily and composited for the remaining four days of the week. The treatment influent and effluent were sampled daily and composited weekly for the remainder of the restoration.

Table 6. **RM1 Groundwater Restoration, Target Restoration Values (TRV) (Modified from United Engineers & Constructors 1988)**

Parameter	Number of Samples	Baseline Range[a]	Concentration (mg/L) TRV	Standard Deviation
Alkalinity (field)	62	638-855	748	105
pH (units)	69	7.7-9.24	8.51	0.32
Eh	49	-145-261	105.4	66.4
Conductivity (µmhos/cm)	66	637-5034	2082	844
Aluminum	37	<0.045-0.253[b]	0.207[c]	0
Ammonia	68	2.4-7.9	3.2	1.2
Arsenic	69	0.005	0.005	0
Barium	37	0.016-0.162	0.044	0.030
Bicarbonate	68	653-1038	883	99
Boron	68	<0.02-0.037	0.007[d]	0.001
Bromide	37	<0.1	<0.1	0
Cadmium	37	<0.1	<0.1	0
Calcium	37	4.14-16.8	3.23	2.77
Carbonate	37	0.6-24.0	8.2	4.4
COD	37	56-101	75	11
Chloride	42	2.0-204	12.8	33.2
Chromium	37	<0.008	<0.008	0
Copper	37	<0.006	<0.006	0
Cyanide	37	<0.02	<0.02	0
Fluoride	69	<0.02-2.8	1.35[d]	0.56
Iron	39	0.042-1.060	0.177	0.253
Lead	37	<0.050	<0.050	0
Lithium	37	0.047-0.093	0.061	0.010
Magnesium	37	2.44-12.2	5.14	2.34
Manganese	69	<0.003-0.024	0.014[e]	0.007
Mercury	37	<0.0002	<0.0002	0
Molybdenum	37	<0.01[f]	<0.01	0
Nickel	37	<0.02	<0.02	0
Nitrate	69	<0.05	<0.05	0
Nitrite	37	<0.05	<0.05	0
Phenols	69	<0.020	<0.020	0
Potassium	37	<0.5	5.56[g]	0.73
Selenium	37	<0.005	<0.005	0
Sodium	69	370-737	538	75
Sulfate	69	300-1400	501	223
Sulfide	67	<1	<1	0
TDS	68	1360-2750	1644	307
Thiocyanate	47	<0.5	0.56[c]	0
TOC	68	11-45	27	7
Zinc	69	<0.003	<0.003	0

[a] Baseline water quality data was collected during October, December 1986 and March, August 1987.

[b] Less than (<) symbol indicates analysis below detection limit.

[c] There are only one or two measurements and therefore the mean would be below the detection limit. Thus, the mean is assumed to be equal to the measurement or average of the two measurements, and the standard deviation is assumed to be zero.

[d] Mean is based on the assumption that ND = 0.

[e] There are only nine measurements for manganese and therefore the mean would be below the detection limit. Thus, the mean is assumed to be equal to the average of the nine measurements.

[f] The October, 1986, sampling indicated molybdenum in the ground water monitoring wells. However, molybdenum was not reported in subsequent samplings and the October results are suspect. Thus, molybdenum is assumed to be not detected or below the detection limit.

[g] There are only twenty-three of thirty-seven measurements for potassium, ten of which are the detection limit of 5 mg/L. This results in a mean below the detection limit. Thus, the mean is assumed to be equal to the average of the twenty-three measurements.

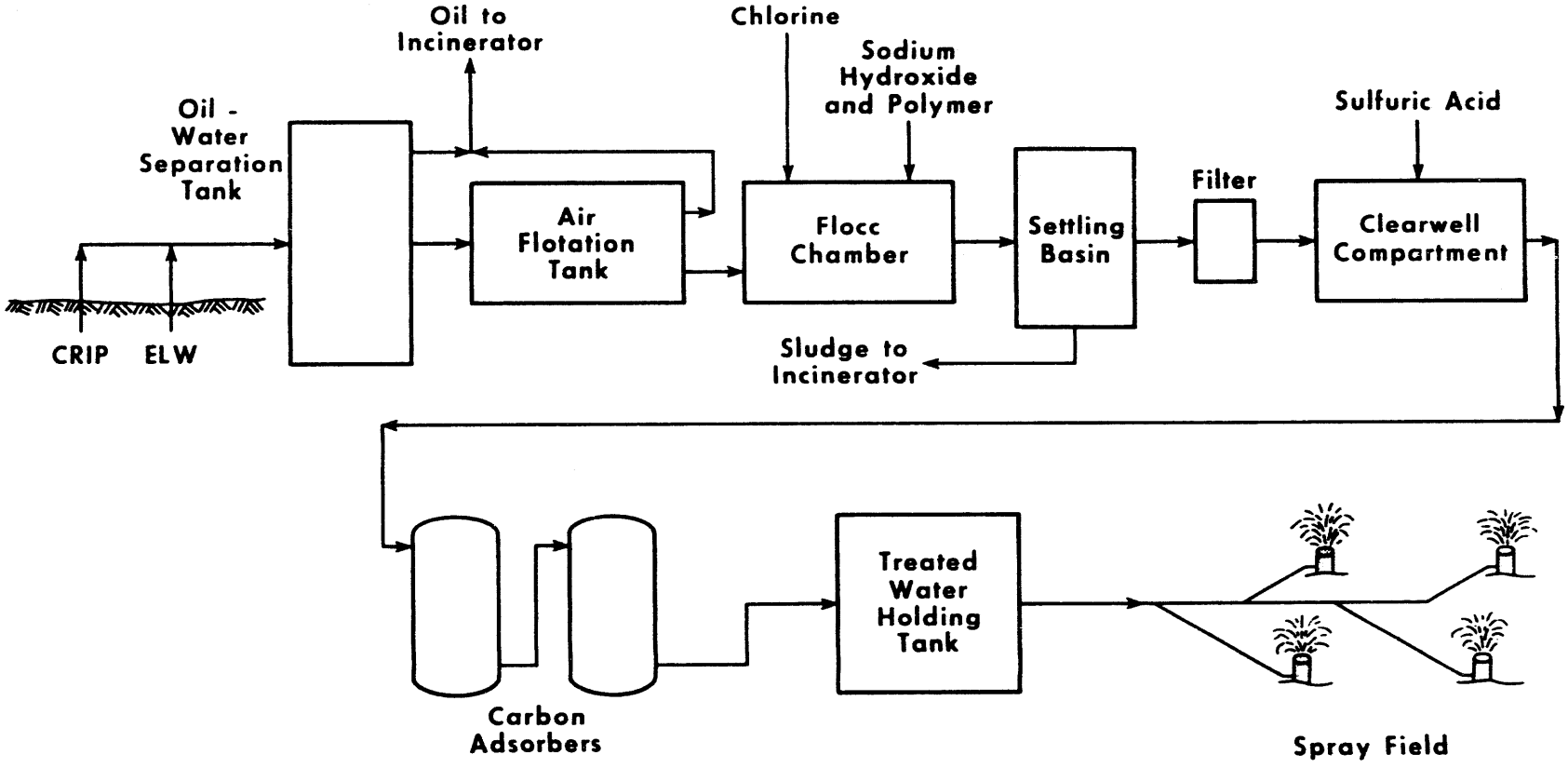


Figure 10. RM1 Groundwater Treatment System, First Restoration, (Covell et al. 1992)

Table 7. Analytical Suites for First Restoration, (Covell et al. 1992)

Suite A

Field Analysis

Alkalinity	pH
Conductivity	Pumping time
Discharge rate	Water level
Eh	Temperature

Laboratory Analysis

Alkalinity	Manganese
Aluminum	Mercury
Ammonia	Molybdenum
Arsenic	Nickel
Barium	Nitrate
Bicarbonate	Nitrite
Borate-thiocyanate	Organics- Acid extractables
Boron	Base neutrals
Bromide	Heterocyclics
Cadmium	PNAs
Calcium	pH
Carbonates	Phenols
Chemical oxygen demand	Potassium
Chloride	Selenium
Chromium	Sodium
Copper	Sulfate
Cyanide	Sulfide
Fluoride	TDS
Iron	TOC
Lead	Zinc
Lithium	
Magnesium	

Suite B

C, H, O, N, S	Density
Simulated distillation	

Suite C

Conductivity	Sulfide
pH	Phenols
Temperature	Boron
Ammonia	Sodium
TDS	Calcium
TOC	

Table 7. Analytical Suites for First Restoration, (continued)

Suite D	
Conductivity	Boron
pH	Sodium
TDS	Calcium
Total suspended solids (TSS)	EP toxicity-metals[a]
Phenols	TOC
Suite E	
Solids Analysis	
Density	Metals[a]
C, H, O, N, S	Proximate
Weight	

[a] Metals analyzed depended on initial concentrations in water

Table 8. Schedule for First Restoration Sampling, (Covell et al. 1992)

Location	Frequency	Compositing Time, days	Suite[a]
Cavity water separation tank			
Water exit	Daily	7	A
	Daily	3	C
Oil	Weekly	0	B
Air flotation tank			
Water exit	Daily	7	D
Overflow	Weekly	0	E,C
Carbon adsorption unit			
Water exit	Daily	7	D
	Daily	3	C
Backwash	Weekly	0	D
Treated water hold tanks	Daily	7	A

[a] See Table 7 for suite contents.

2.4.2 Second Restoration Activity

The second restoration was to begin when groundwater levels had recovered from the first cavity pump out. The second restoration was initially delayed because the treatment system was not designed for winter operation and water quality in and around the cavities did not warrant removal and treatment. However, groundwater samples collected in June 1989 contained small amounts of benzene and this prompted the decision to proceed with the second restoration.

The second treatment system was modified based on the results of the first restoration activity. The second treatment system did not use the addition of chemicals, because in the first treatment system, these had only a small beneficial effect and resulted in a high TDS level in the treated water. As a result, the six treatment steps used in the first system were reduced to two treatment steps for the second system. A two-stage pressure filter consisting of anthracite and silica sand was used to remove suspended solids. This was followed by two carbon adsorber units containing activated charcoal to remove organic materials. The activated carbon from the first restoration operation was reused for the second restoration. Groundwater was pumped from the two cavities into a holding tank. It then passed through the treatment system before being discharged to the land surface through the same atomizing spray system used in the first treatment. A schematic of the second treatment system is shown in Figure 11.

Cavity and treated water samples were collected daily during the second restoration activity. Samples were collected for a full suite of analyses (volatile organics, semivolatile organics, metals, ammonia, TOC and TDS) and for volatile organic acids (VOA) and total phenols only. The cavity water samples represented combined ELW and CRIP cavity waters. In accordance with permit requirements, some samples were composited and submitted for a full suite of analyses (8/1-8/2/89, 8/3-8/6/89, and 8/7-8/13/89), while some daily samples (7/31/89, 8/14/89, and 8/15/89) were not composited and were submitted for the same suite of analyses (Covell et al. 1992). Samples were collected only for VOA and total phenol on 8/5/89, 8/8/89, and 8/11/89.

2.5 Long-Term Monitoring

Long-term monitoring of groundwater at the RM1 site began at the completion of gasification operations (February 26, 1988). The objectives were to illustrate that restoration activities were successful in reducing long-term groundwater impacts, and to satisfy the requirements of the primary state regulatory agency (WDEQ, LQD).

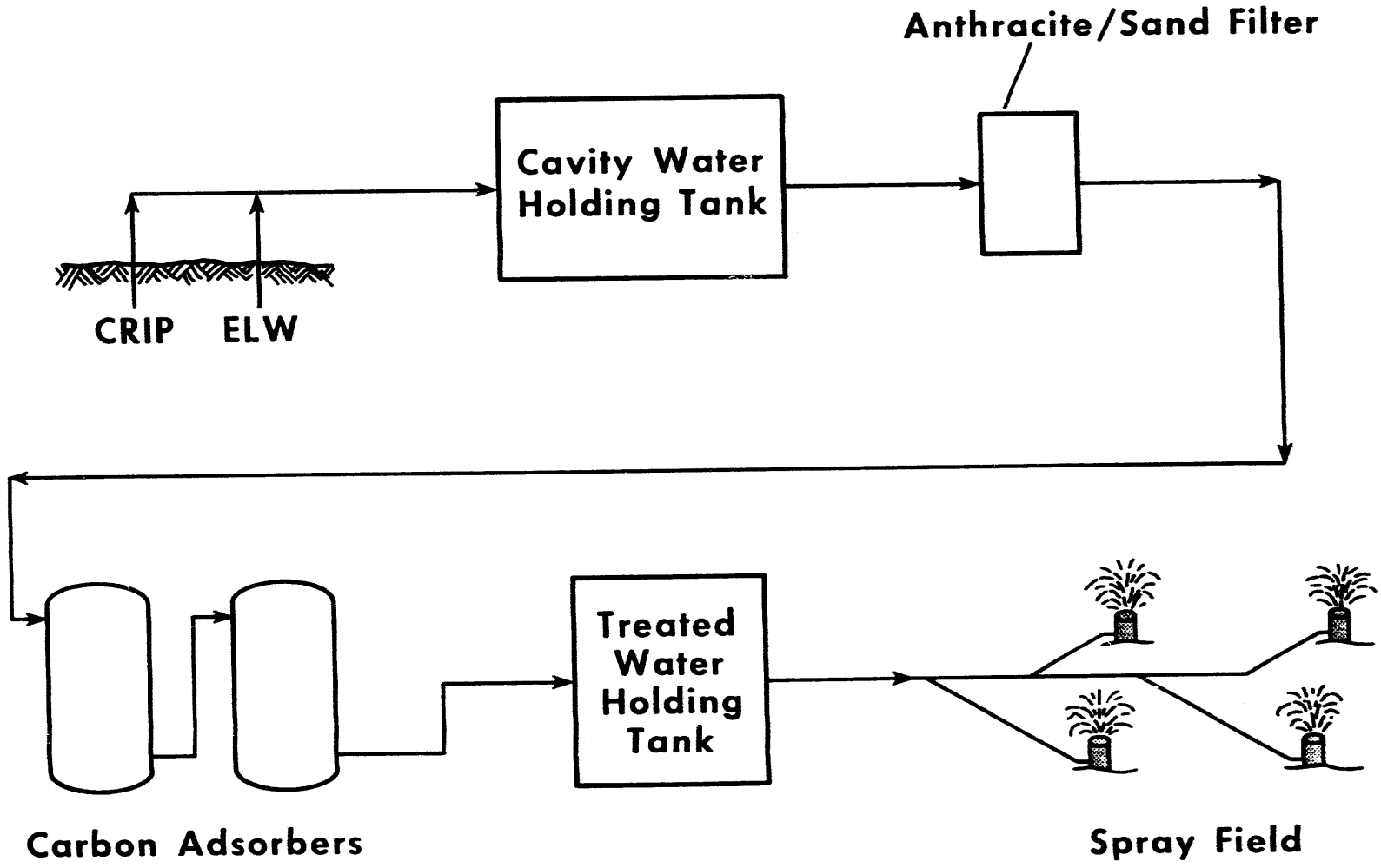


Figure 11. RM1 Groundwater Treatment System, Second Restoration, (Covell et al. 1992)

A site sampling plan was drawn up prior to the start of long-term monitoring (Mason and Johnson 1988). This plan described site safety considerations; WRI standard operating procedures (SOPs) for groundwater sampling; QA/QC procedures; and sample volumes, preservation technique, and analytical methods. These are summarized in Appendix B, Tables B-1 through B-3. Quarterly sampling was started after both the CRIP and ELW modules were shut down, and was conducted from February 1988 through December 1990. Semiannual sampling was conducted in 1991 and 1992. Groundwater sampling activities were completed in December 1992.

Twenty-two wells were designated for groundwater sampling during postburn groundwater monitoring (Figure 9). Of these 22 wells, eight were outer ring wells completed in the Hanna No. 1 coal seam, eight were inner ring coal seam wells, four were completed in units A and C of the overburden, and two were process wells in the UCG cavities (Table 1). Several of these wells developed complications that prevented sample collection. As discussed in Section 2.1, these wells were eliminated from the sampling program. In some cases, alternate wells were used for sample collection.

Three different suites of samples were collected for analyses in accordance with the sampling schedule shown in Table 9. The sample suites consisted of the compliance suite, the limited suite, and the full suite (Table 10). The majority of the compliance suite represented parameters required by WDEQ, LQD for permit compliance. Sulfate and sulfide are the only two analytes in the compliance suite that did not represent permit requirements. The additional parameters in the limited and full suites represented both permit-required analyses and a research component of the monitoring program. The modified Skinner list of organic compounds was targeted for analyses on samples collected in September 1990 and submitted to Radian Corporation.

Sample collection equipment was identical to that described under previous tasks. Procedures differed in the following respects from previous sampling tasks:

- Samples were collected for the compliance, limited-suite and full-suite sets of parameters (Table 10).

- Field parameters of Eh, pH, temperature, conductivity, flow rate, and water level were measured and recorded every 20 minutes in a WRI laboratory notebook.

- Bailed samples requiring filtration were filtered in the field using a Geotech® 142 mm-filter holder, Millipore® 0.45-μm nitro-cellulose filters, a filtering flask, and a vacuum pump to draw the sample through the filter.

- QA/QC samples consisted of standards, duplicates, and rinsates. Trip blanks were not included in the QA/QC samples for this task. WRI's QA/QC procedures for this task are included in Appendix B.

Table 9. RMI Long-Term Groundwater Monitoring Schedule, (Mason and Johnson 1988)

Year	Quarter	Inner-Ring Wells	Outer-Ring Wells	Cavity Wells
1988	1. March	FS	FS	FS
	2. June	CS	CS	FS
	3. September	CS	CS	CS
	4. December	CS	CS	CS
1989	1. March	CS	CS	CS
	2. June	CS, VOA	CS	CS, VOA
	3. September	CS, VOA	CS	CS, VOA
	4. December	FS	FS	FS
1990	1. March	CS, VOA	CS	CS, VOA
	2. June	LS, VOA	LS	LS, VOA
	3. September	CS, VOA	CS	CS, VOA
	4. December	FS	FS	FS
1991	2. June	LS, benzene	LS	LS, benzene
	4. December	FS	FS	FS
1992	2. June	LS, benzene	LS	LS, benzene
	4. December	FS	FS	FS

CS - Compliance Suite
LS - Limited Suite
FS - Full Suite
VOA - Volatile organic analysis

Table 10. RMI Groundwater Analytical Suites for Long-Term Monitoring, (Mason and Johnson 1988)

Compliance Suite	Limited Suite	Full Suite	Field Measurements
Ammonia	Ammonia	Alkalinity	Alkalinity
Boron	Bicarbonate	Aluminum	Conductivity
Cyanide	Boron	Ammonia	Discharge Rate
Phenols	Cyanide	Arsenic	Eh
Sulfate	Fluoride	Barium	pH
Sulfide	Manganese	Bicarbonate	Pumping Time
TDS	Nitrite	Base Neutral Acids	Temperature
TOC	Nitrite	Boron	Water Level
	Phenols	Bromide	
	Sodium	Cadmium	
	Sulfate	Calcium	
	Sulfide	Carbonate	
	TDS	Chemical Oxygen Demand	
	TK Nitrogen	Chloride	
	TOC	Chromium	
		Copper	
		Cyanide	
		Fluoride	
		Iron	
		Lead	
		Lithium	
		Magnesium	
		Manganese	
		Mercury	
		Molybdenum	
		Nickel	
		Nitrate	
		Nitrite	
		pH	
		Phenols	
		Potassium	
		Selenium	
		Silver	
		Sodium	
		Sulfate	
		Sulfide	
		TDS	
		TK Nitrogen	
		Thiocyanate	
		TOC	
		Volatile Organics	
		Vanadium	
		Zinc	

3.0 RESULTS

3.1 Subsurface Hydrology

3.1.1 Baseline

Figure 12 shows the baseline potentiometric surface of the Hanna No. 1 coal seam in the vicinity of the RM1 site. Static water level measurements prior to the UCG test indicated an upward hydraulic gradient from the coal seam to the overlying units. Water level data are presented in Appendix A. Groundwater movement in response to this gradient was limited by the extremely low permeability and hydraulic conductivity of the overlying unit A/B. Baseline water level measurements taken in October 1986 showed a horizontal hydraulic gradient of 0.0064 ft/ft from southeast to northwest (Figure 13). This gradient was measured from southeast (TW-12) to northwest (TW-16). Variation in the hydraulic gradient exists and is probably due to differences in transmissivity throughout the coal aquifer. In most other situations, the potentiometric surface parallels the dip of the aquifer. At the RM1 site, however, the southeast to northwest gradient is oblique to the dip of the coal seam. This is probably caused by the northwest-southeast trending fault across the northeast corner of the site. The fault affects the potentiometric surface by acting as a barrier to groundwater flow (Mason et al. 1987). This hydrologic barrier causes groundwater in the coal seam at the RM1 site to flow from southeast to northwest (Mason et al. 1987), rather than in a more northerly direction as seen on a regional scale. The isolation of the coal seam aquifer on either side of the fault is illustrated by the difference in static water levels measured in coal seam wells on either side of the fault (TW-14 and TW-14A). Water level differences as great as 35 ft were measured between TW-14 and TW-14A during the baseline evaluation.

Slug tests were performed in coal seam wells to determine the variability of hydraulic conductivity (K) across the site. Hydraulic conductivity values determined from slug tests are only representative of the K in the immediate vicinity of each well. They provide an estimate of the degree of heterogeneity of hydraulic conductivity across the site. Heterogeneity refers to the variation of a parameter between points in the aquifer. Results from slug tests indicate that hydraulic conductivity is heterogeneous across the RM1 site. Hydraulic conductivity values ranging from ~0.1 to 5.1 $gal \cdot day^{-1} \cdot ft^{-2}$ were measured. The highest values for K were found in the southwest corner of the site, in the area of TW-18 and EMW-11A (Table 11). These anomalously high K values may be due to a large number of fractures in the coal seam in the vicinity of these wells (Mason et al. 1987).

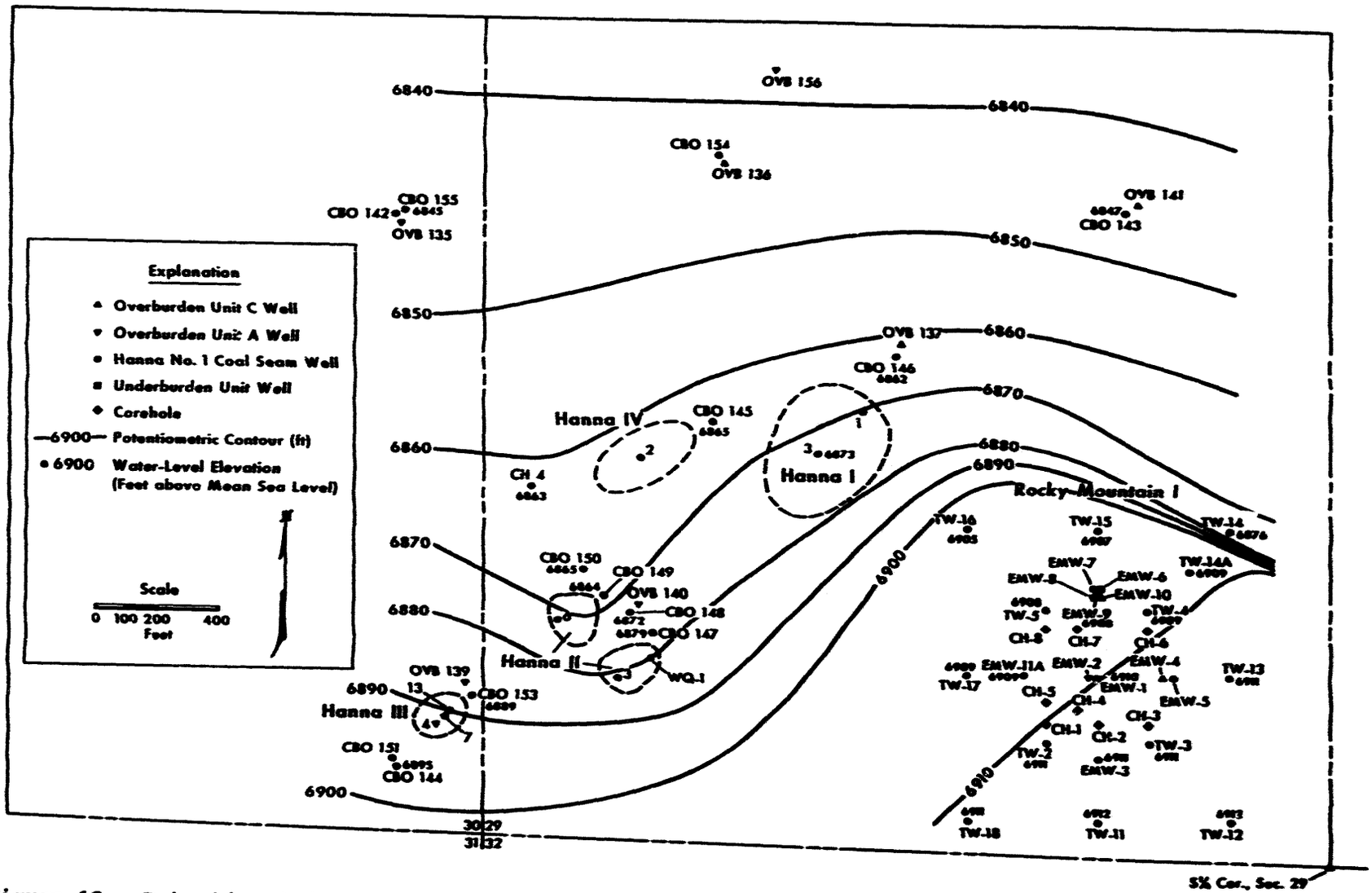


Figure 12. Potentiometric Surface Map of the Hanna No. 1 Coal Seam Aquifer at the Hanna and RM1 UCG Site, October 23, 1986, (Mason et al. 1987)

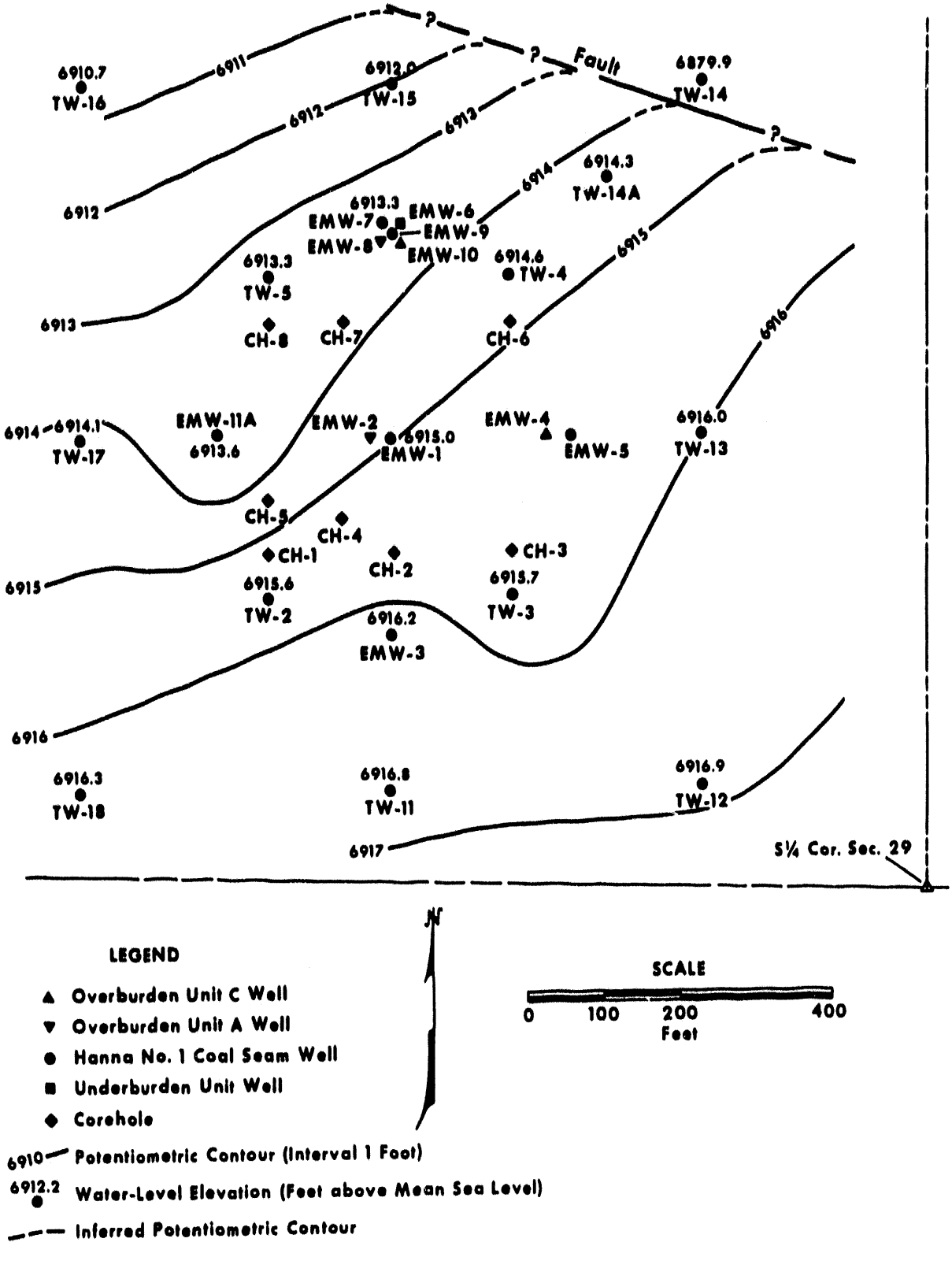


Figure 13. Potentiometric Surface Map of the Hanna No. 1 Coal Seam Aquifer at the RM1 Site, October 23, 1986, (Mason et al. 1987)

Table 11. Results of Slug and Single-Well Pumping Tests, (Modified from Mason et al. 1987)

Well or Corehole	Unit Tested[a]	Lithology[b]	Interval Depth (ft)	Slug Test		Single-Well Pumping Test		
				T[c]	K[d]	T	K	S[e]
EMW-1	Coal	C	357-390	28	0.8	72	2.2	.00079
EMW-3	Coal	C	343-373	36	1.2	51	1.7	.00008
EMW-5	Coal	C	374-420	2.1	0.1	--	--	--
EMW-7	Coal	C	360-390	25	0.9	--	--	--
EMW-9	Coal	C	369-394	59	2.4	57	2.3	.0009
EMW-11A	Coal	C	351-379	120	4.4	110	4.1	.00087
TW-2	Coal	C	342-369	50	1.9	57	2.1	.000077
TW-3	Coal	C	344-381	43	1.2	--	--	--
TW-4	Coal	C	375-405	13	0.4	--	--	--
TW-5	Coal	C	360-387	43	1.6	47	1.7	.00067
TW-11	Coal	C	331-360	62	2.1	--	--	--
TW-12	Coal	C	343-373	15	0.5	--	--	--
TW-13	Coal	C	362-403	10	0.2	--	--	--
TW-14	Coal	C	372-404	3.3	0.1	--	--	--
TW-15	Coal	C	391-422	5.5	0.2	--	--	--
TW-16	Coal	C	385-418	64	1.9	--	--	--
TW-17	Coal	C	328-359	20	0.6	--	--	--
TW-18	Coal	C	295-325	150	5.1	--	--	--
CH-7	Coal	C	354-380	--	--	--	--	--
TW-14A	Coal & 12' Unb	C, Slt, Sh	385-428	4.2	0.1	--	--	--
CH-2	Coal & 13' Unb	C, SS, Slt	355-396	--	--	--	--	--
CH-4	Coal & 6' Unb	C, SS, Sh	354-392	--	--	--	--	--
EMW-6	Unb	SS	420-446	--	--	--	--	--
CH-3	Unit A	Sh	328-342	--	--	--	--	--
EMW-8	Unit A	Sh	326-357	0	0	--	--	--
EMW-2	Unit A	Sh, Slt	301-351	0	0	--	--	--
CH-7	Unit B	SS, Sh	238-262	--	--	--	--	--
EMW-10	Unit C	SS	149-187	6.0	0.2	--	--	--
EMW-4	Unit C	SS	110-195	36	0.4	--	--	--

[a] Unb is the underburden beneath the coal
Other terminology by Craig et al., 1982

[b] C - Coal
Slt - Siltstone
Sh - Shale
SS - Sandstone

[c] Transmissivity as gal/day/ft
[d] Hydraulic conductivity as gal/day/ft^2
[e] Storage coefficient

Anisotropy of hydraulic conductivity at the site was evaluated through pumping tests in coal seam wells. Anisotropy refers to the degree of variability of a parameter as a function of the direction of measurement. For example, if the hydraulic conductivity at a point has different values in the north-south and east-west directions, the aquifer is said to be anisotropic at that point. Anisotropy of hydraulic conductivity in the coal seam was indicated by elliptical cones of depression resulting from drawdown of the potentiometric surface during pumping tests. This drawdown was measured in observation wells adjacent to the pumping well. Drawdown extended further from the pumping well in the direction of greatest hydraulic conductivity. Thus, the major axis of the elliptical cone of depression represented the direction of highest hydraulic conductivity. The major axis of the ellipses defined by the pumping tests and the direction of major hydraulic conductivity was N42°E. This coincided with the orientation of the face cleat in the coal seam (Mason et al. 1987). The hydraulic conductivity along the major axis was determined to be 5.31 $gal \cdot day^{-1} \cdot ft^{-2}$ while along the minor axis (N48°W), K was 1.27 $gal \cdot day^{-1} \cdot ft^{-2}$. The subdominant set of cleats is oriented at N55°W. (Mason et al. 1987).

A second important aquifer parameter is transmissivity. Transmissivity is a function of the hydraulic conductivity and the saturated thickness of the aquifer at the point of measurement. Unlike hydraulic conductivity, values of transmissivity from two or more wells cannot be directly compared unless the thickness of the aquifer is relatively constant over the area of interest. Transmissivity values were determined from both slug tests and pumping tests on coal seam and boundary strata wells. Data from both slug tests and pumping tests gave similar values for transmissivity and hydraulic conductivity (Table 11). Unit A/B (EMW-2 and EMW-8) transmissivity values were reported as approximately zero. Transmissivity of unit C wells (EMW-4 and EMW-10) was determined to be 36 $gal \cdot day^{-1} \cdot ft^{-1}$ and 6 $gal \cdot day^{-1} \cdot ft^{-1}$, respectively. Transmissivity in the coal seam ranged from 2.1 $gal \cdot day^{-1} \cdot ft^{-1}$ (EMW-5) to 150 $gal \cdot day^{-1} \cdot ft^{-1}$ (TW-18). Wells in the west and southwest areas of the site generally had the highest transmissivities, ranging from 62 $gal \cdot day^{-1} \cdot ft^{-1}$ in well TW-11 to the previously mentioned high of 150 $gal \cdot day^{-1} \cdot ft^{-1}$ in well TW-18 (Figure 14). An exception to this pattern of high transmissivity in the south and west areas of the site was seen in well TW-17, which had a transmissivity of 20 $gal \cdot day^{-1} \cdot ft^{-1}$. Wells around the central portion of the site (EMW-1,-3, -7, -9, TW-2, -5) had transmissivity values averaging 33 $gal \cdot day^{-1} \cdot ft^{-1}$. These values ranged from 25 $gal \cdot day^{-1} \cdot ft^{-1}$ (EMW-7) to 50 $gal \cdot day^{-1} \cdot ft^{-1}$ (TW-2). Transmissivity was least in the northeast section of the site, ranging from 2.1 $gal \cdot day^{-1} \cdot ft^{-1}$ (EMW-5) to 13.0 $gal \cdot day^{-1} \cdot ft^{-1}$ (TW-4). The higher transmissivity values seen along the western edge of the site may result from enhanced fracturing within the coal seam. Slight folding of the strata at the site may have expanded fractures and cleats within the coal seam, thus enhancing the capability of the coal seam to yield water (Mason et al. 1987).

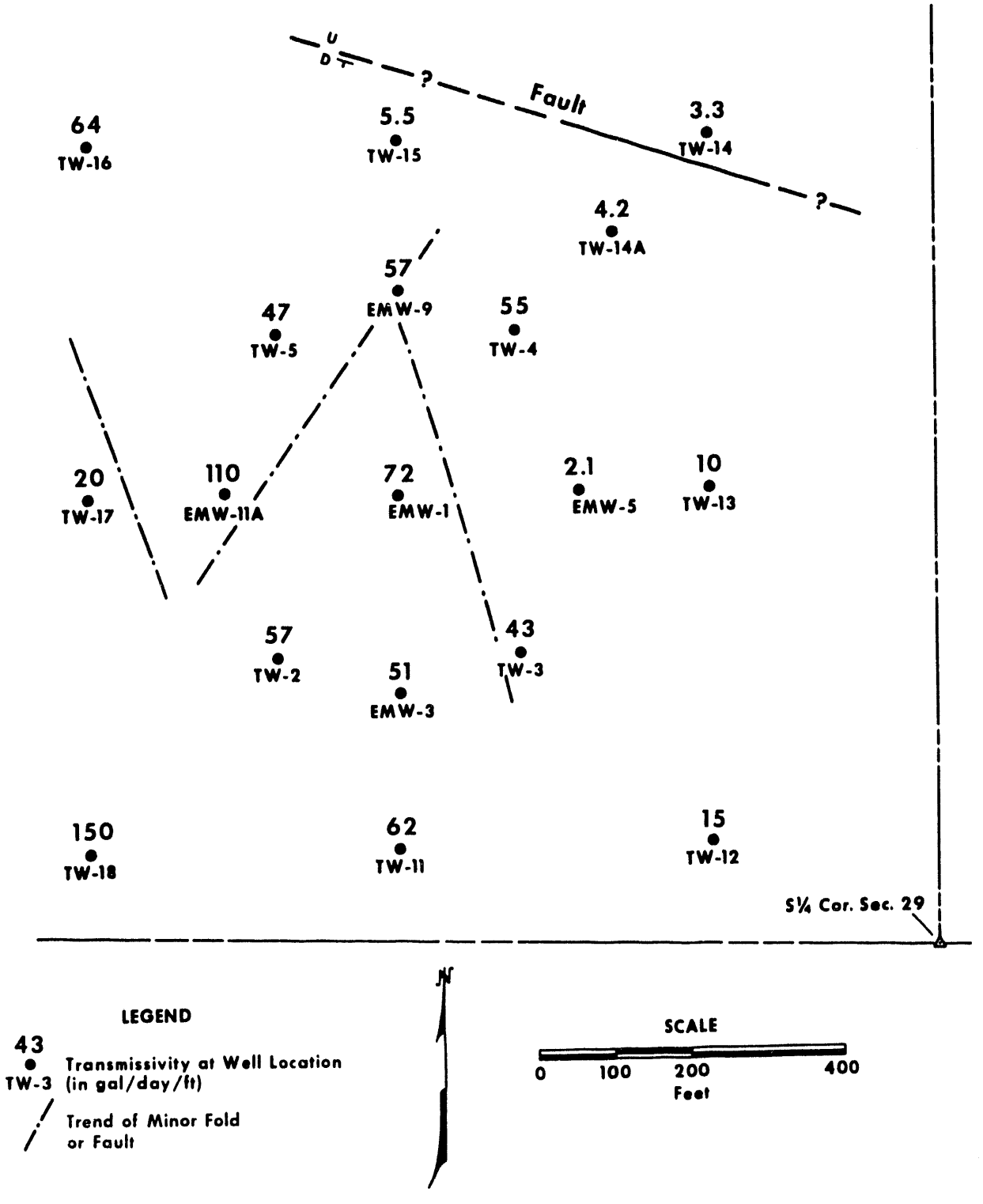


Figure 14. Transmissivity Map of the RM1 Site, (Mason et al. 1987)

3.1.2 UCG Testing

3.1.2.1 Overburden. No communication between the unit A overburden and the Hanna No. 1 coal seam was apparent and the UCG test had no observable effect on hydraulic head in unit A. At the beginning of the UCG test, water levels in unit A well EMW-8 had not recovered from sample purging. Although water levels were rising due to well recovery, no observable changes in water level as a result of the test were detected (Figure 15a). Wells completed in the unit C overburden (EMW-4 and EMW-10) had stable water levels throughout the test. This indicated that there was no hydraulic communication between the unit C overburden and the Hanna No. 1 coal seam and, as a result, no observable effect of the test on the unit C overburden (Figure 15b and 15c).

3.1.2.2 Understrata. The hydrology of the underlying strata adjacent to the coal seam was unaffected by the UCG test. Well EMW-6 was recompleted immediately before the start of the test. During the recompletion, the well bore was filled with water. The gradual decline of the water level in the well to pretest levels, despite a nearby coal seam water level decline of 103.7 ft in 24 hours (EMW-9), indicated that there was no effect of the UCG test on the understrata unit. The drop in water levels on January 14, 1988 and February 26, 1988 (Figure 15d) were due to groundwater sampling of this well.

3.1.2.3 Coal Seam. Water level measurements in the Hanna No. 1 coal seam over the entire site indicated a potentiometric surface with a cone of depression centered in the area of the UCG cavities during the test. As mentioned earlier, this cone of depression indicated radial groundwater flow from higher groundwater elevations in the outer lying areas of the site toward the lower elevations in the cavities. This cone of depression was maintained for the entire test. Variations in the orientation and magnitude of the cone of depression were dependent on groundwater flow boundaries of the coal seam and on removal rates of groundwater from the coal aquifer (Moody 1990).

The cone of depression was centered between the two cavities when both the CRIP and ELW cavities were operating (Figure 16). Drawdown at wells near each cavity were of similar magnitude. Significantly greater drawdown occurred near the ELW cavity after shutdown of the ELW module (Moody 1990). Figure 17 shows that the cone of depression had shifted to center over the ELW cavity as a result of the reduced pressures and steam venting of the ELW cavity.

It is difficult to determine the extent to which heterogeneity and anisotropy in the coal seam affected potentiometric surface patterns. As mentioned earlier, a cone of depression whose shape is affected only by the degree of anisotropy and heterogeneity of the aquifer will have symmetrical groundwater elevation contours forming a circle or ellipse centered on the point of groundwater removal from the aquifer.

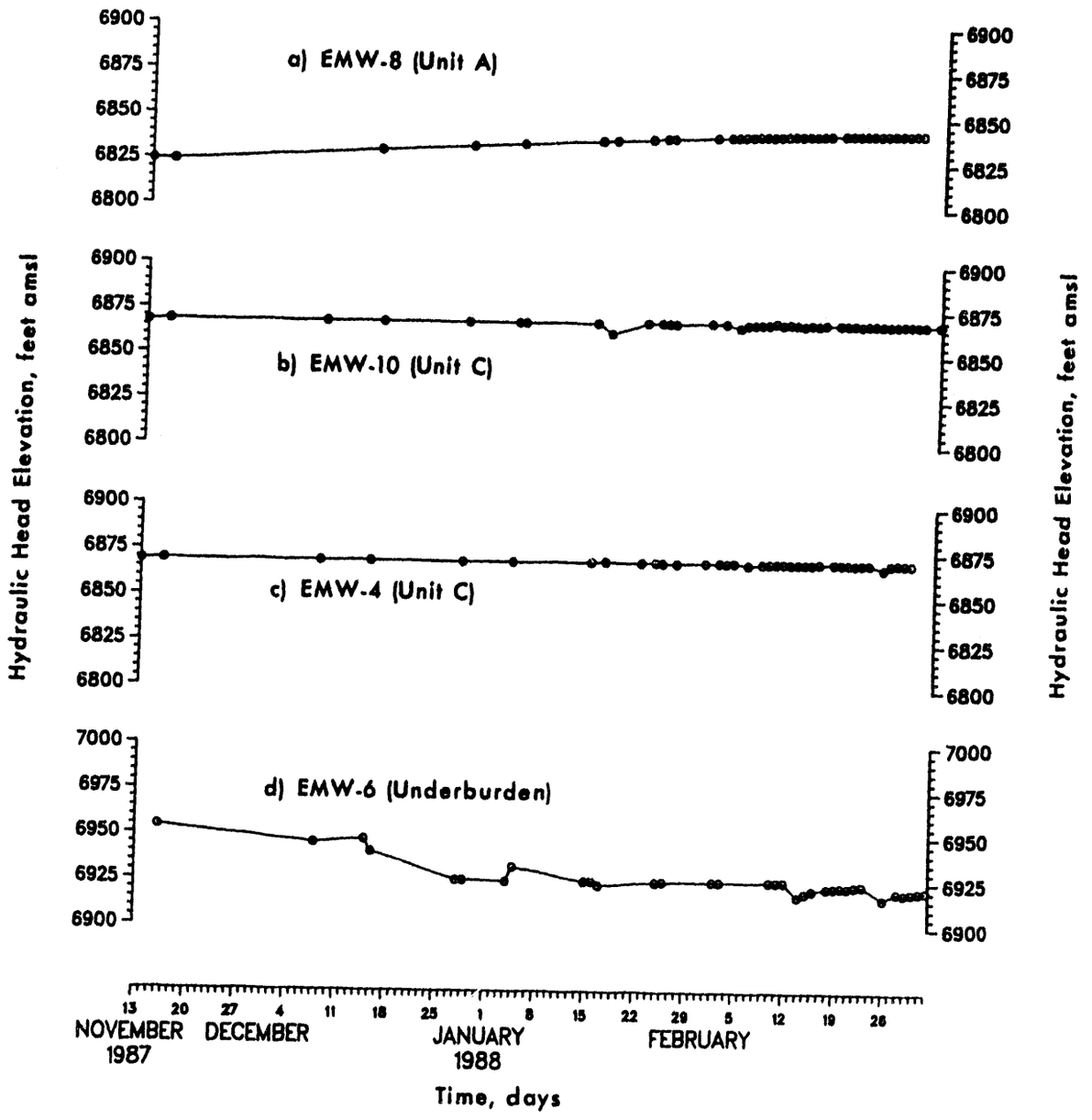


Figure 15. Hydraulic Head Changes During the Test in Overburden and Underburden Units at Wells EMW-8 (a), EMW-10 (b), EMW-4 (c), and EMW-6 (d), (Moody 1990)

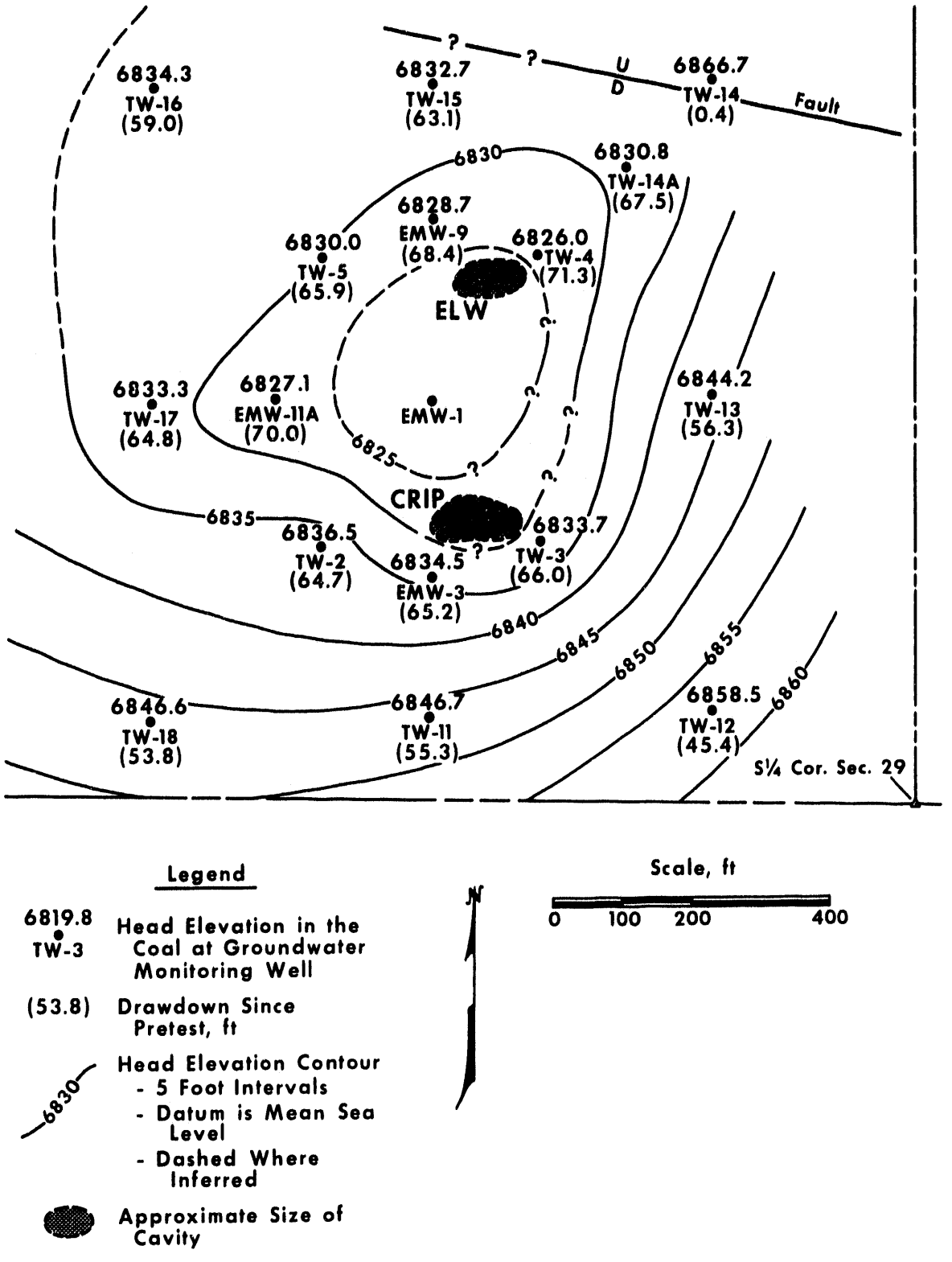


Figure 16. Potentiometric Surface Map of the Hanna No. 1 Coal Seam at the RM1 Site During CRIP and ELW Module Operation on December 18, 1987, (Moody 1990)

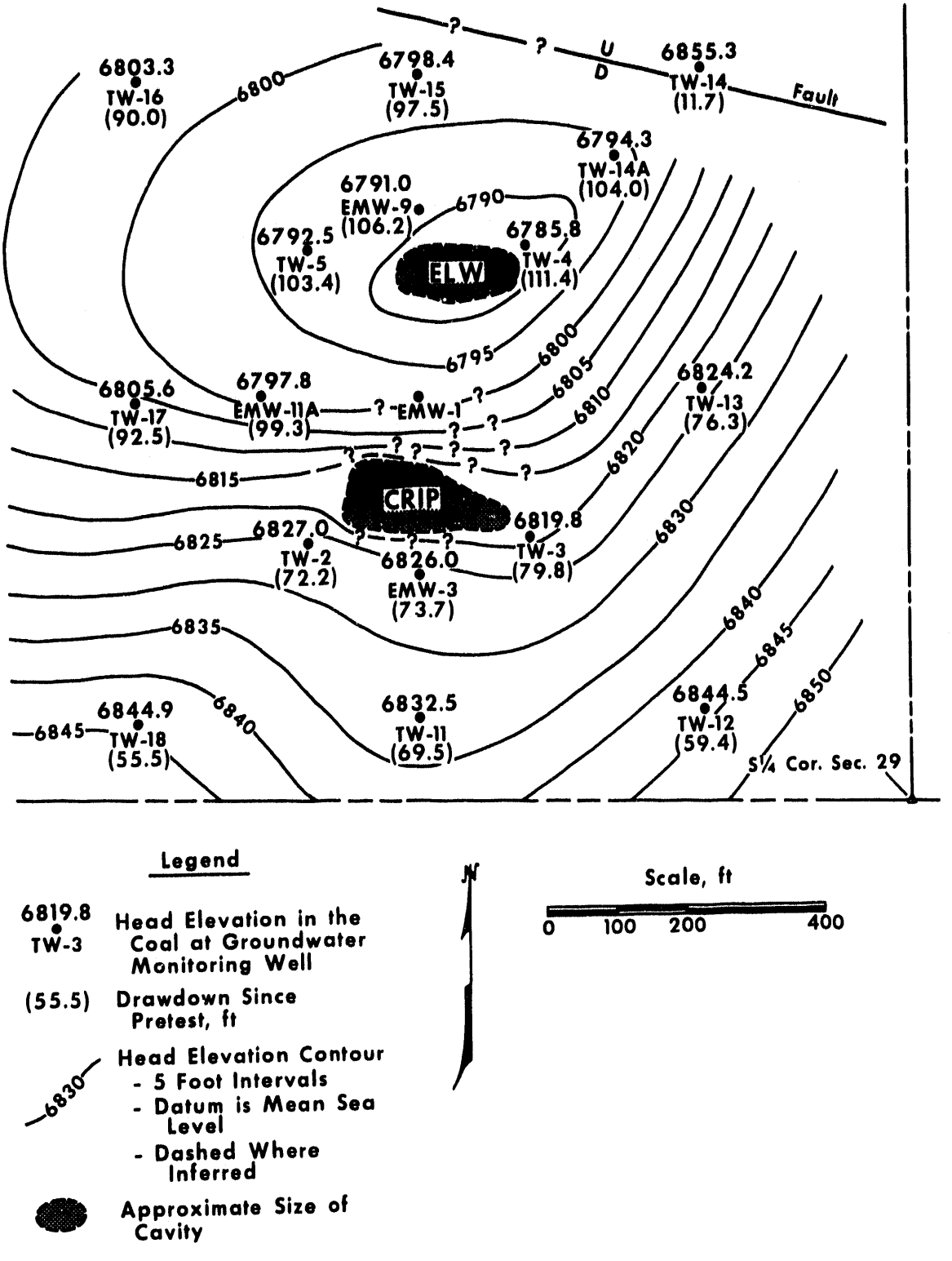


Figure 17. Potentiometric Surface Map of the Hanna No. 1 Coal Seam at the RM1 Site Two Weeks After the ELW Module was Completed, (Moody 1990)

Maps of the potentiometric surface during the test (Figures 16 and 17) show irregular contour lines without a definite circular or elliptical pattern. This indicates that the potentiometric surface was influenced by more than the hydraulic characteristics of the coal seam. According to Moody (1990), the shape of the potentiometric surface was affected not only by heterogeneity and anisotropy, but also by cavity pressure changes, groundwater removal rates, and flow boundaries in the coal aquifer.

3.1.3 Restoration

Pumping and treatment of affected groundwater during both the first and second restoration activities were scheduled to begin when water levels indicated that the cavities had filled and radial flow into the cavities had ceased. Groundwater was pumped from the two cavities using submersible pumps in existing process wells: VIW-1 in the ELW cavity and CPW-1 in the CRIP cavity.

Approximately 2,100,000 gallons of water were pumped from the two cavities between August 22 and September 20, 1988: 1,283,000 gallons from the CRIP cavity and 817,000 gallons from the ELW cavity. This represents about 115% of the calculated cavity void volume (Covell et al. 1992). Pumping stopped when water levels in the cavities dropped below the levels of the pump intakes.

After the end of the first restoration treatment, groundwater continued to flow into the cavities until sometime between November 16 and November 28, 1988. A potentiometric surface map of the Hanna No. 1 coal seam on November 16, 1988 (Figure 18) shows radial groundwater flow into the cavities over the whole site. The map for November 28, 1988 shows linear flow from southeast to northwest across the site through the cavities (Figure 19). (Note: Figures 18 and 19 more correctly indicate the fault line.)

Continuous pumping for the second restoration activity began on July 31, 1989. A total of 1,570,000 gallons of water were pumped: 745,000 gallons from the ELW cavity and 825,000 gallons from the CRIP cavity. Pumping continued until water levels in the cavity dropped below the level of the pump intakes on August 15, 1989.

Evacuation of the cavities during both restoration activities resulted in coal seam water levels at least 250 ft below baseline elevations in the area of the UCG cavities. As described previously, this extremely low water level near the center of the site indicated a cone of depression in the coal seam potentiometric surface centered on or near the two cavities.

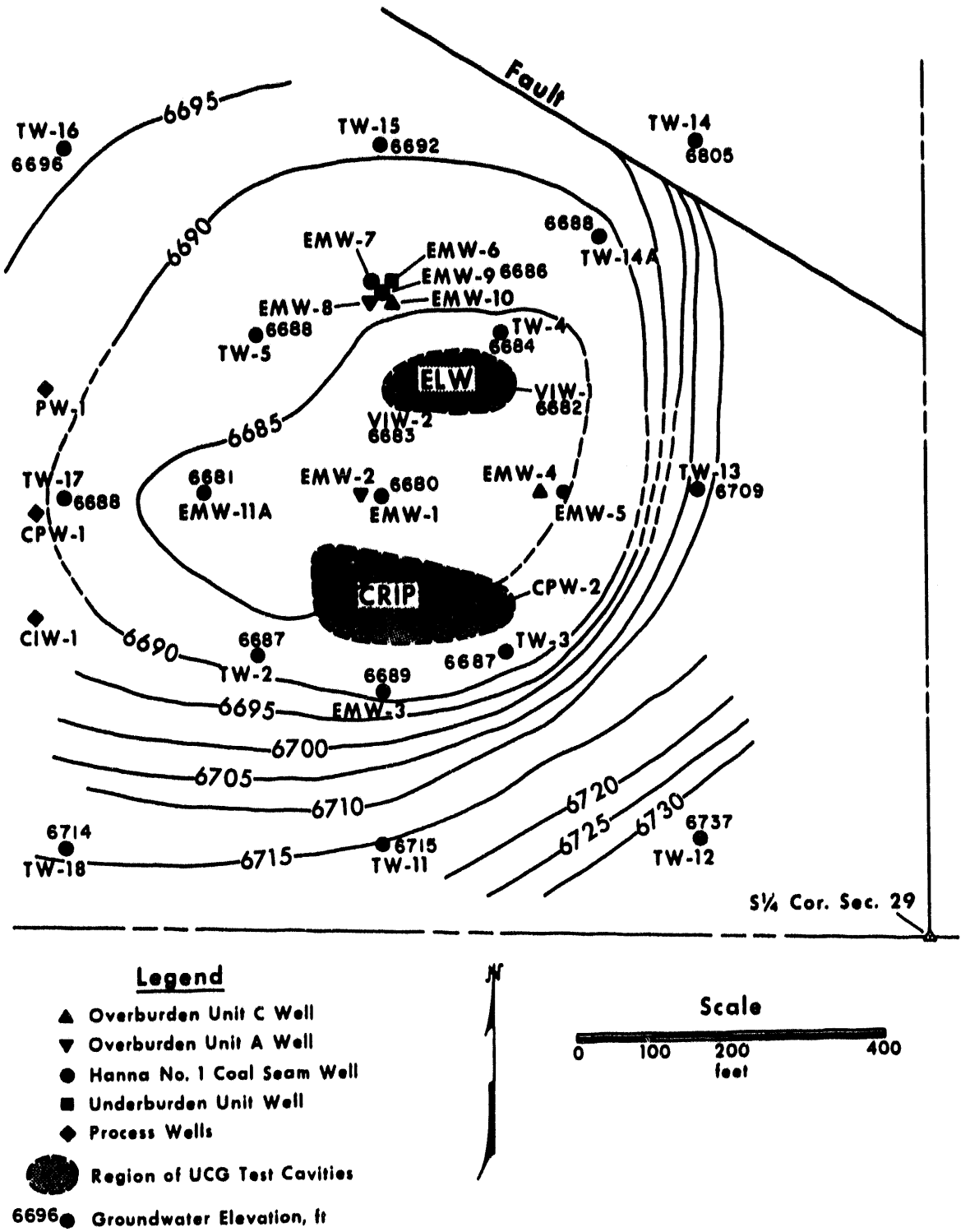


Figure 18. Potentiometric Surface Map, RM1 Site, Hanna No. 1 Coal Seam, November 16, 1988, (Covell et al. 1992)

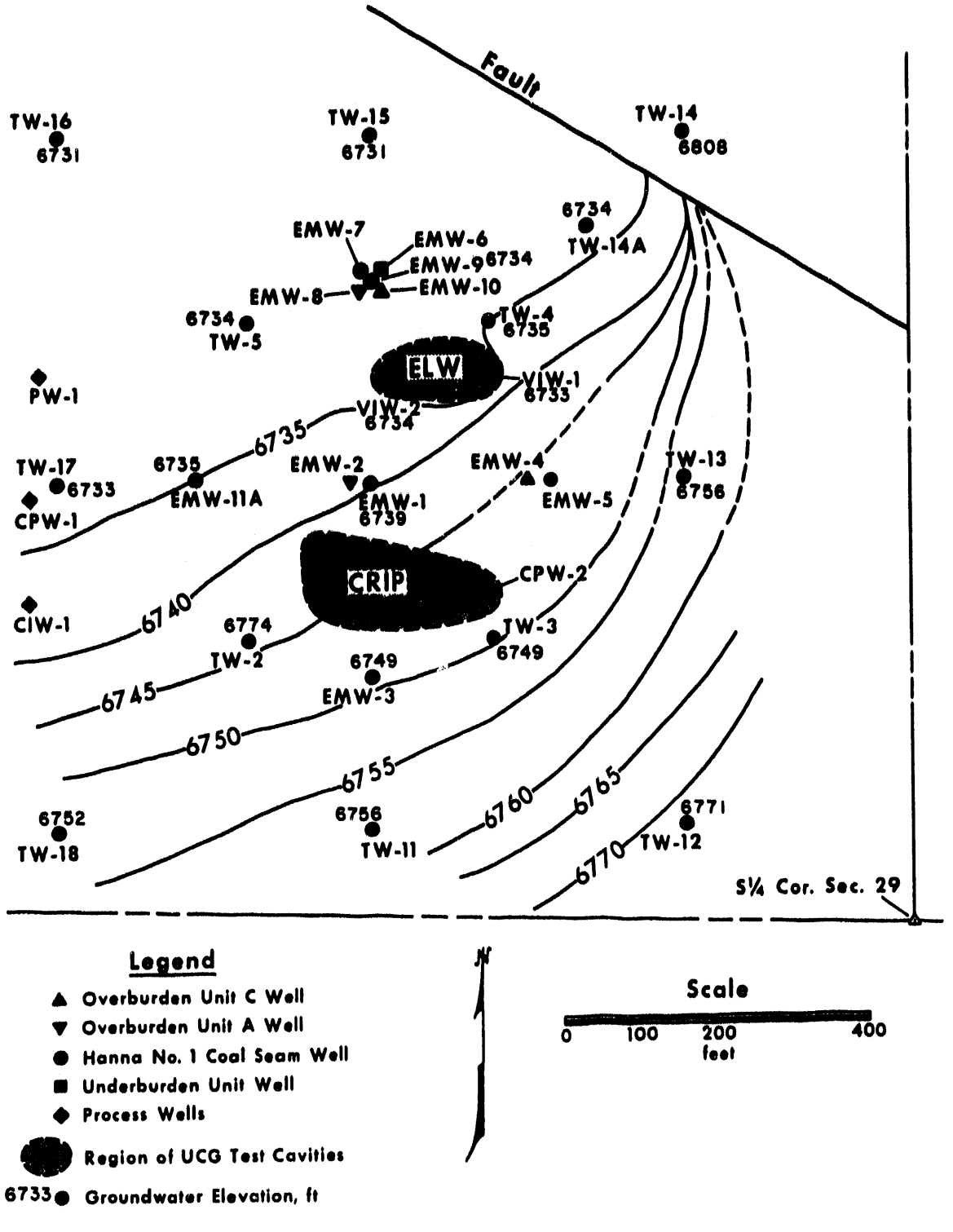


Figure 19. Potentiometric Surface Map, RM1 Site, Hanna No. 1 Coal Seam, November 28, 1988, (Covell et al. 1992)

3.1.4 Long-Term Monitoring

Figure 20 shows the water levels for the different strata at one location, northwest of the ELW cavity. This is the only location where such a comparison of water levels can be made. The different profils of each well indicates that communication does not exist between strata.

3.1.4.1 Understrata. The understrata unit was essentially unaffected by either the UCG test or the groundwater restoration activities (Figure 20). Water levels have remained relatively constant over the course of the RM1 project.

3.1.4.2 Overburden. The two overburden units reacted differently in response to the hydrologic effects of the UCG test and the groundwater restoration activities. The hydrology of the unit C overburden was unaffected by either the test or the subsequent restoration activities and has remained constant through the final sampling event in December 1992 (Figure 20). However, unit A/B showed hydrologic effects of the UCG test and restoration activities.

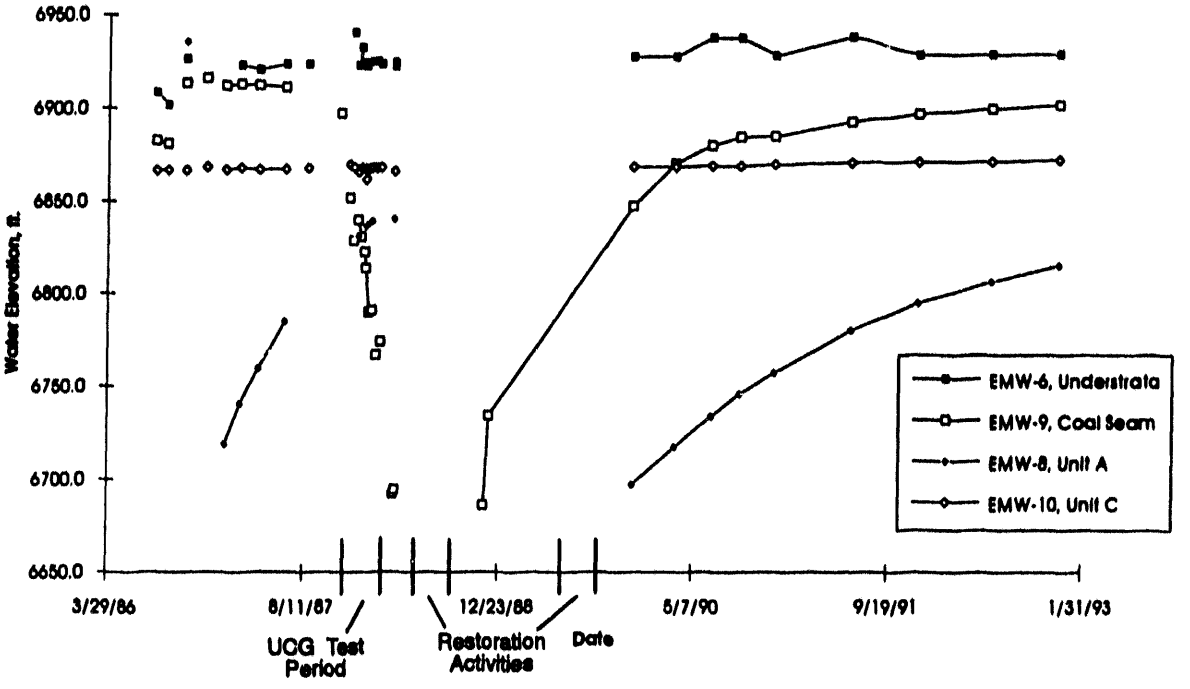


Figure 20. Water Levels for Different Strata by ELW Cavity

Baseline water level data for unit A/B is very inconsistent and sporadic, possibly due to well drilling and aquifer testing for pretest site evaluation and preparation. Water levels measured shortly after the last restoration indicated groundwater elevations 100 to 150 ft below the range of water level elevations measured during the baseline evaluations. Quarterly and semiannual water level measurements since that time have shown a gradual recovery in the unit A/B aquifer to near the range of baseline water level elevations.

3.1.4.3 Coal Seam. The potentiometric surface of groundwater within the Hanna No. 1 coal seam has a consistent pattern across the site, as shown in the northwest-southeast traverse (Figure 21) and the southwest-northeast traverse (Figure 22). Water levels had essentially recovered from the effects of the UCG test and groundwater restoration activities by December 1991. Baseline water levels in the Hanna No. 1 coal seam varied between 6880 and 6915 ft above sea level over the year of baseline evaluation. The most recent water level measurements (December 1992) indicate groundwater elevations of approximately 6900 ft. The cone of depression resulting from groundwater withdrawal during the second restoration activity had disappeared by December 1989. While water level elevations in the coal seam were the most affected by the test, water levels rebounded quickly and have increased gradually over the past two years.

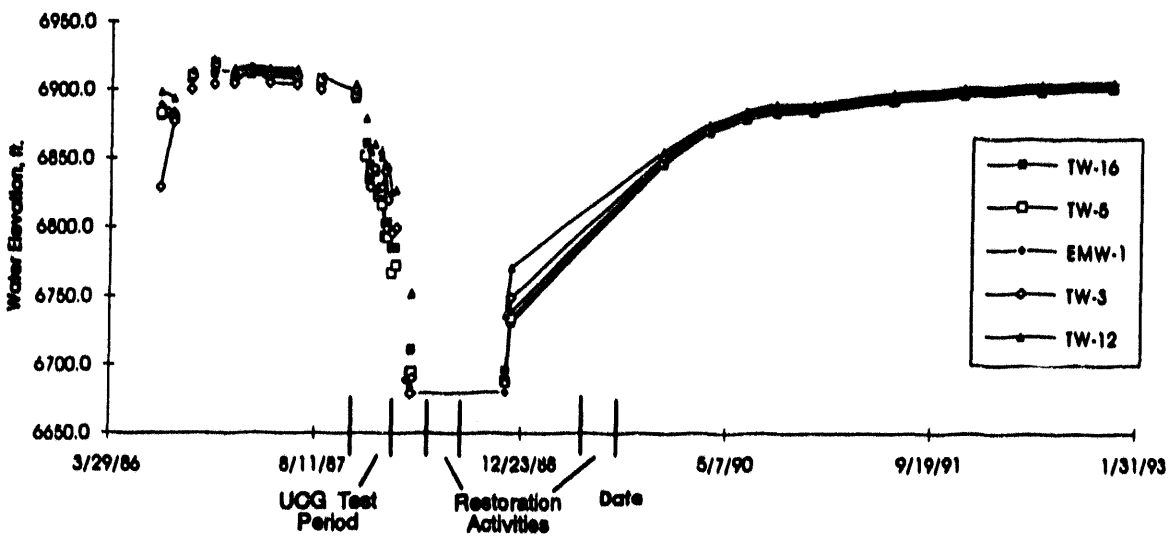


Figure 21. Water Levels in Coal Seam NW-SE Across Site

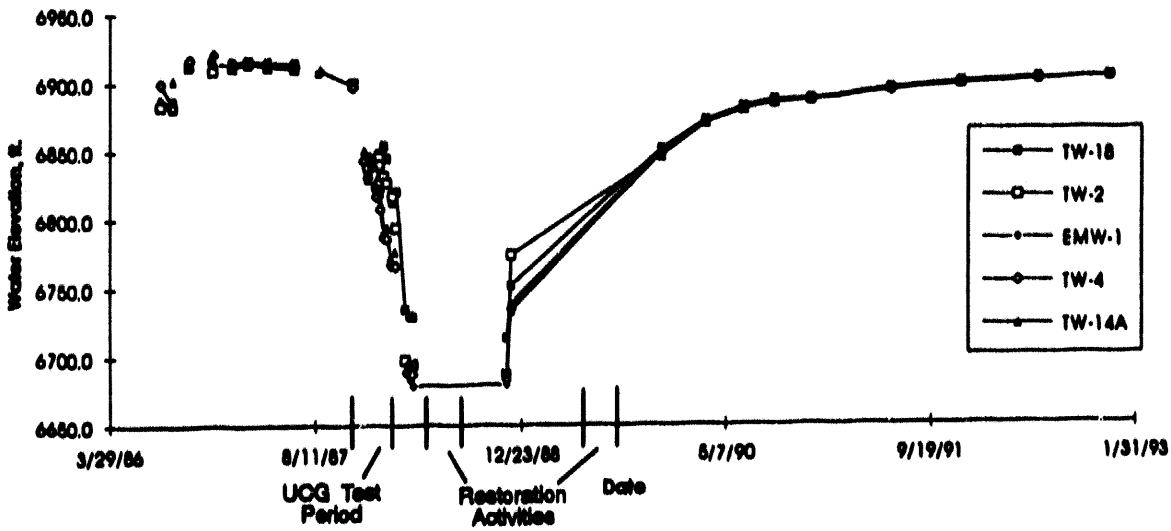


Figure 22. Water Levels in Coal Seam SW-NE Across Site

3.2 Water Quality

3.2.1 Baseline

Baseline water quality was assessed as a part of the baseline site evaluation. Included in the baseline data are the analyses of samples collected in August 1986, although there was concern that some of these samples might have been contaminated, resulting in invalid parameter values.

Characterization of the groundwater in the strata immediately below the coal seam was hampered by problems with the only monitoring well completed in the understrata (EMW-6). Sidewall caving in the open interval caused extreme turbidity in samples collected from the well. The well was recompleted prior to gasification operations (November 14, 1987) with a 6-slot PVC screen and sandpack throughout the open interval. A bentonite seal was installed on top the sandpack and cement tremmied around the annulus of the 2-inch (i.d.) PVC casing.

Analyses of baseline water samples indicated groundwater of similar composition in the understrata, the Hanna No. 1 coal seam, and the overburden (Mason et al. 1987). The dominant ions in the coal seam groundwater were sodium (450 mg/L), bicarbonate (800 mg/L), and sulfate (450 mg/L). These ions in groundwater evolve from calcite dissolution, pyrite oxidation, and ion exchange (Mason et al. 1987). Concentrations of these ions in the overburden groundwater were slightly less than those seen in the coal seam groundwater, while concentrations in the understrata groundwater were slightly higher than in the coal seam groundwater.

Somewhat higher sulfate concentrations were observed in samples from wells in the southwest portion of the site (Figure 23). These higher sulfate concentrations may result from groundwater with naturally higher concentrations of sulfate moving onto the site or may be due to geochemical differences in the coal seam (Mason et al. 1987). In wells to the west and south (TW-2, TW-17, TW-18, and EMW-11A), TDS concentrations ranged from 1162 mg/L to 2750 mg/L. Over the remainder of the site, TDS concentrations in the samples of groundwater from the coal seam ranged from 150 mg/L to 2146 mg/L. Baseline TDS concentrations are shown across the coal seam from southwest to northeast in Figure 24. This same pattern of higher concentrations of analytes in the south and west areas of the site exists for ammonia and total organic carbon (Figures 25 and 26).

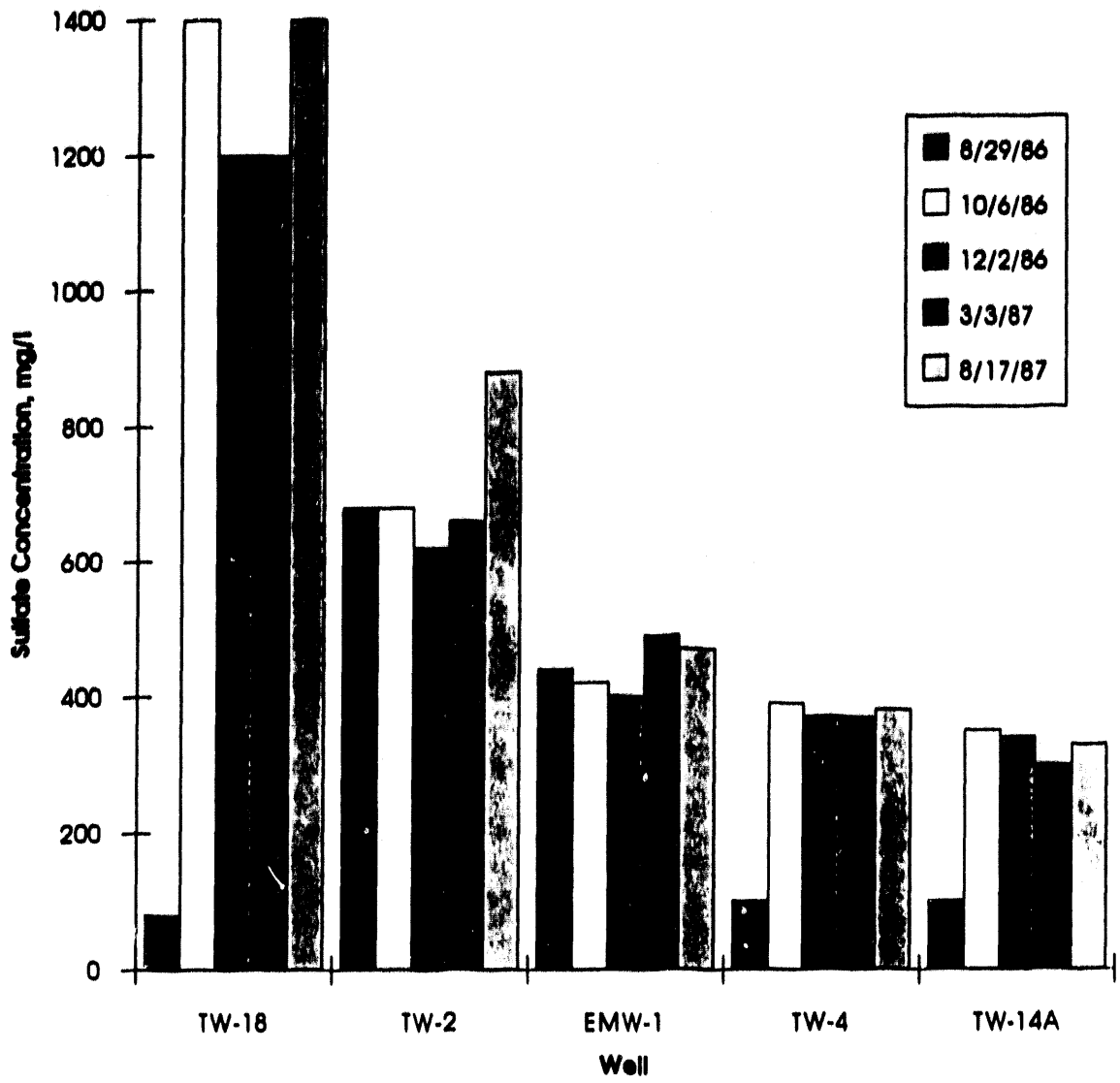


Figure 23. Baseline Concentrations of Sulfate

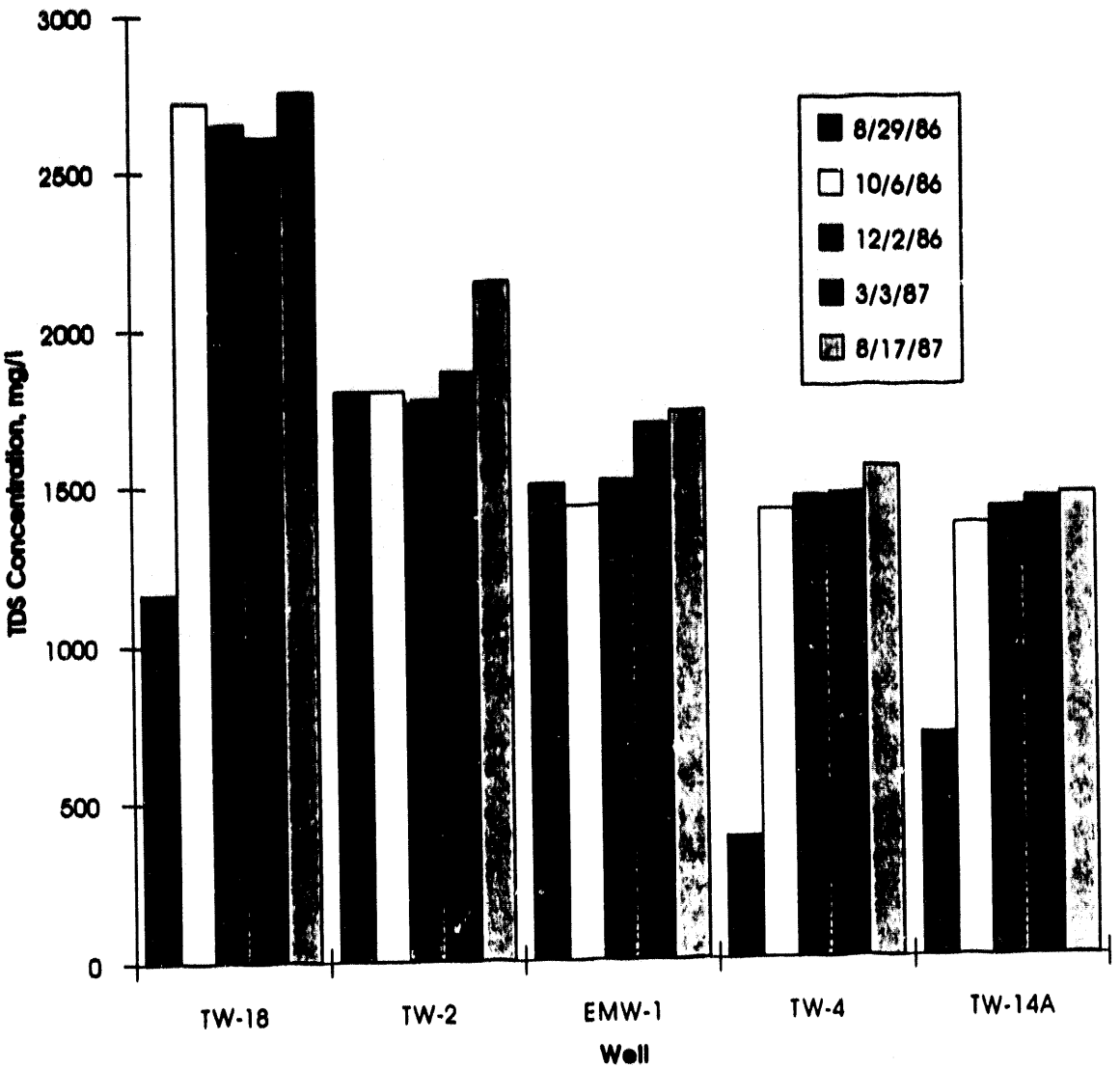


Figure 24. Baseline Concentrations of TDS

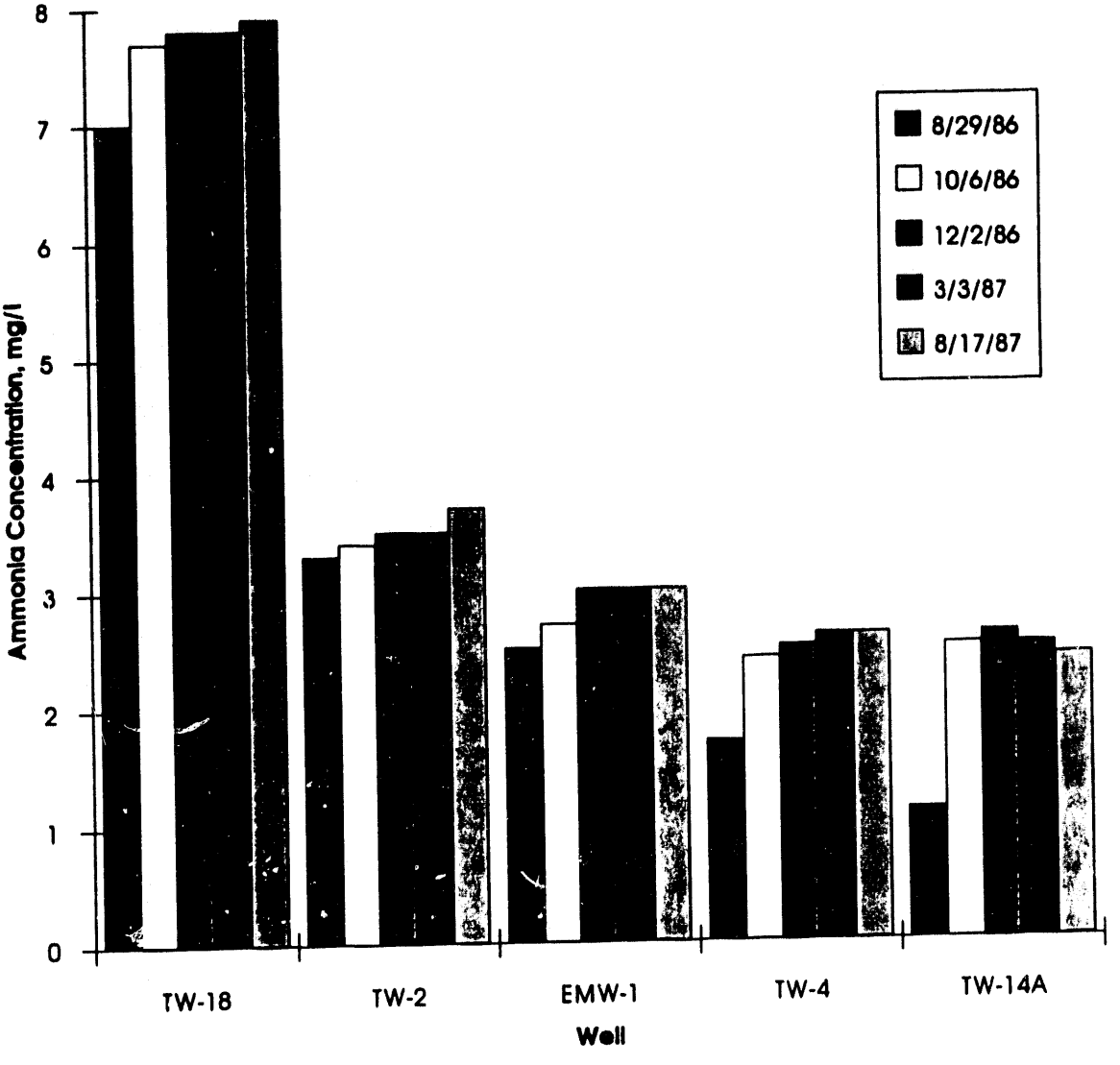


Figure 25. Baseline Concentrations of Ammonia

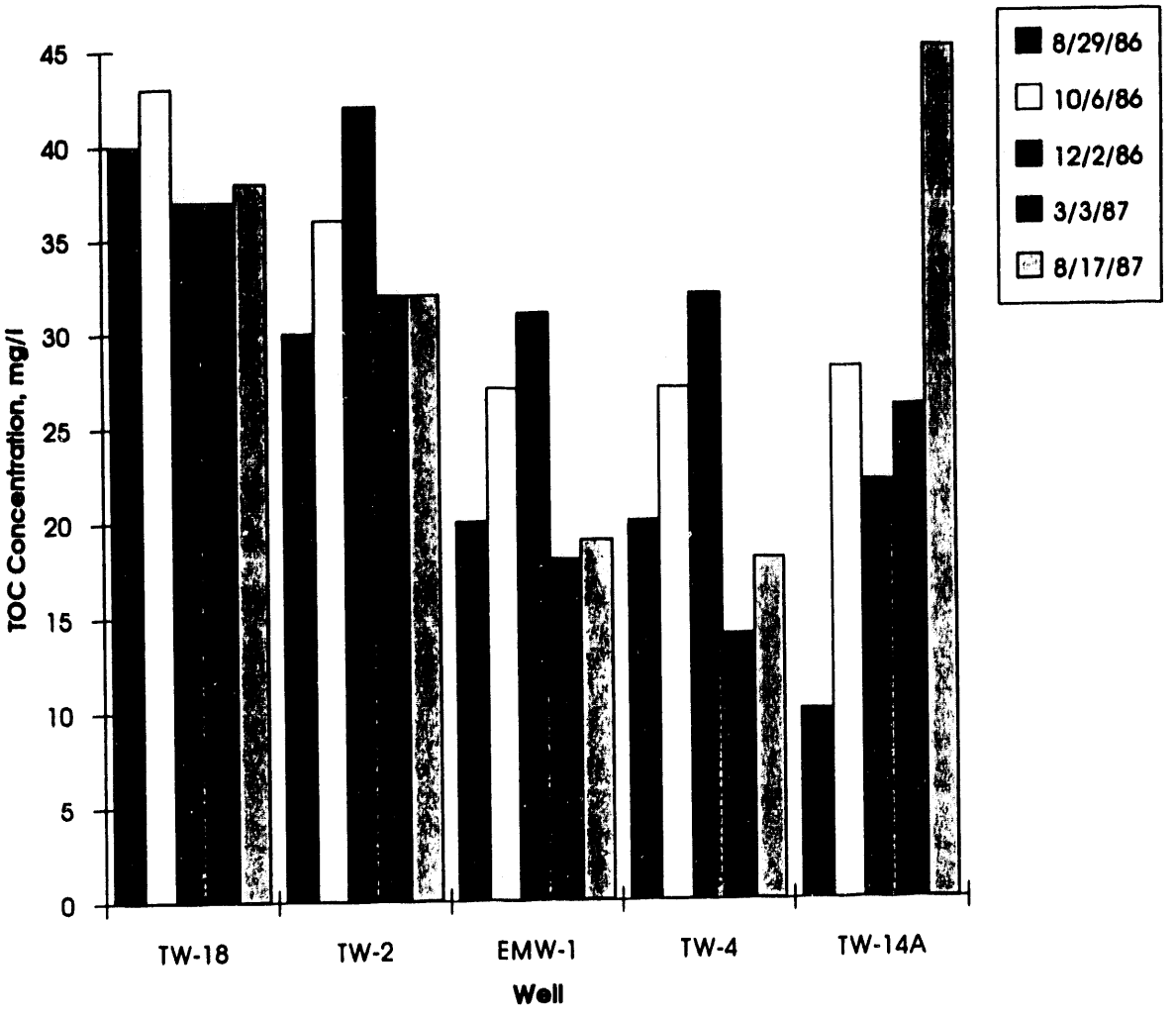


Figure 26. Baseline Concentrations of Total Organic Carbon

With one exception, volatile and semivolatile organic concentrations in groundwater samples were below the analytical detection limits (Appendix A) for all coal seam wells in October 1986. The exception was well TW-5, in which toluene was detected at an estimated concentration of 2 ppb (Mason et al. 1987). Semivolatile results from August 1986 showed significant levels of bis(2-ethylhexyl)phthalate. These levels are most likely the result of field or laboratory contamination because, with the exception of one isolated occurrence in 1990, this compound did not appear in samples from any other sampling event. Phthalates are a common contaminant from plastic. Also, the results of analyses for the modified Skinner list of organic compounds by Radian Corporation showed no targeted compounds were present in pretest RM1 groundwater (Radian Corporation 1990). The toxicity study by Drottar (1990) showed no adverse effects of pretest RM1 groundwater on either test species (Appendix D). However, it was observed during the test that the animals were stressed, indicating that the natural condition of the groundwater may be borderline to being toxic.

3.2.2 Test Period

Changes to the groundwater quality at the RM1 site were evaluated based on those parameters related to the UCG process or of interest due to health risks associated with them. These parameters included pH, alkalinity, ammonia, boron, cyanide, sulfate, sulfide, phenols, TDS, and TOC. Volatile organic acids (VOAs), especially benzene, were also analyzed as part of the modified Skinner list of organic compounds. Analyses of samples for VOAs was not included as part of either regular sample suite (FMA or grab samples) for the task of groundwater monitoring during the test.

3.2.2.1 Overburden. There were two overburden units in which wells were completed for the purpose of groundwater monitoring, unit A/B and unit C. No samples were collected from unit A/B because of the very low recharge rate of the two wells completed in this unit, EMW-2 and EMW-8. The two wells completed in the unit C overburden (EMW-4 and EMW-10) were sampled. Analyses of samples indicated that concentrations of most parameters were similar to baseline conditions (Table 12).

Table 12. Highest Parameter Concentrations in Unit C Overburden Wells During the RM1 Test versus Baseline Concentrations, mg/L

	Baseline				Test			
	TOC	TDS	Ammonia	pH	TOC	TDS	Ammonia	pH
EMW-10	<10	500	3.1	7.81	<10	590	3.8	7.45
EMW-4	10	1020	4.5	7.66	14	1010	4.6	7.62

The pH of groundwater in EMW-10 decreased 0.3 units from baseline; however, this magnitude of variation was also seen during baseline sampling. It appears that the unit C overburden was unaffected by the UCG test.

3.2.2.2 Understrata. The condition of well EMW-6 complicated conclusive evaluation of the impacts of the UCG test on the understrata groundwater quality. Residual drilling gel remained in the well after recompletion. This drilling gel is the probable cause of the high ammonia value measured in EMW-6 (Moody 1990). Most other parameters, with the exception of pH, remained at or below baseline levels for the duration of the test. The pH, however, increased dramatically from 8.1 to 11.3 during the test. According to Moody (1990), it is unlikely that the residual gel could have caused this increase. Because of the low permeability of this underlying unit, it is unlikely that any contamination resulted from direct infiltration of contaminated groundwater from the coal seam into the understrata.

3.2.2.3 Coal Seam. In general, wells to the north and east of the UCG test area showed only slight changes in groundwater quality. Wells to the south and west of the test area showed definite effects of the test on groundwater quality (Table 13). Again, most of this variation in test effects is probably due to the higher coal seam transmissivity in this area of the site.

Table 13. Comparison of Baseline and Test Parameter Concentrations (all Wells Completed in the Coal)

	pH		Alkalinity, mg/L $CaCO_3$		Sulfate, mg/L		TDS, mg/L		Ammonia, mg/L		TOC, mg/L	
Well	B	T	B	T	B	T	B	T	B	T	B	T
North Wells												
TMW-5	8.4	8.2	766	644	440	836	1538	2009	2.6	3.1	27	34
EMW-9	8.3	8.3	786	712	380	525	1484	1611	2.6	2.5	22	25
TW-4	8.4	8.2	785	768	377	368	1466	1471	2.5	2.2	23	22
South Wells												
TW-17	8.4	7.6	762	781	610	1026	1784	2404	3.1	3.5	30	47
TW-18	8.3	7.1	671	753	1300	1605	2683	3106	7.8	8.1	39	54
TW-3	8.4	6.3	807	889	350	432	1597	1650	2.7	2.7	26	36
EMW-3	8.4	6.2	803	1046	402	381	1531	1791	2.9	2.9	29	47
TW-2	8.4	6.3	723	875	710	1382	1894	3028	3.5	5.2	36	55
EMW-11A	8.3	6.5	748	956	497	1060	1699	2620	3.1	4.3	29	59

B = Mean baseline concentration determined from four baseline samples.
T = Mean during-test concentration.

Changes in pH varied across the site. Water from wells to the south and west of the test area exhibited the greatest pH change. The pH in groundwater from wells TW-3, EMW-3, TW-2, TW-18, and EMW-11A decreased from a pretest average of 8.5 to an average during the test of 6.5. Groundwater from wells TW-17 and TW-11 experienced a sharp pH decrease during the first week of January 1988 followed by a gradual recovery to near baseline levels. Groundwater from the remaining wells at the site experienced only minor fluctuations in pH without any observable trends. Changes from alkaline to acidic groundwater conditions occurred in wells where gas excursions occurred. Carbon dioxide (CO_2) represented approximately 45% of the CRIP product gas (Moody 1990). It is likely that migrating gas contacted groundwater in the vicinity of these wells, causing higher concentrations of dissolved CO_2 in the groundwater. The small change in the concentration of dissolved CO_2 between the CRIP cavity and well TW-2 indicated that the groundwater was saturated with CO_2. Dissolved CO_2 reacts with water to form carbonic acid and bicarbonate by the following equations:

$$CO_2 + H_2O \leftrightarrow H_2CO_3$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$$

Carbonic acid and bicarbonate do not completely dissociate. Groundwater pH conditions and the dissociation coefficients of carbonic acid and bicarbonate determine the equilibrium concentrations of these constituents. It is likely that the production of hydrogen ions in these reactions caused the pH of the water to decrease in wells that experienced product gas excursions (Table 14). This pH decrease may also have had a significant effect on mineral solubility. Minerals filling cleats and fractures in the coal seam that were in equilibrium with the slightly alkaline baseline groundwater may have become less stable as the pH changed to slightly acidic conditions. However, the actual effect of the lower pH of the groundwater on the solubility of minerals in the coal seam could not be determined because cation and anion concentrations were not determined during the test.

Table 14. pH Decline versus Number of Gas Excursions During UCG Test

Well	pH Decline	Number of Gas Excursions
EMW-11A	2.25	6
TW-2	2.42	8
TW-12	0.87	0
TW-17	1.78	4
TW-18	1.10	7

Alkalinity is defined as the equivalent sum of the bases that are titratable with a strong acid (Drever 1982). Dissolving CO_2 from the product gas was not the most likely cause for changes in alkalinity because the production of the primary bases responsible for alkalinity (HCO_3^- and CO_3^{2-}) were balanced by increases in the hydrogen ion concentration (Moody 1990). The increased hydrogen ion concentration would, however, lower the pH. Acidic conditions created by dissolving CO_2 would have dissolved some of the calcite ($CaCO_3$) present in cleats in the Hanna No. 1 coal seam (Moody 1990 and Oliver 1987) according to the reaction:

$$CaCO_3 + H^+ \leftrightarrow Ca^{2+} + HCO_3^-$$

The bicarbonate produced in this reaction is the most likely cause of the changes in groundwater alkalinity (Moody 1990). Groundwater samples with lower pH values from the south and west areas of the site had increased alkalinity (Table 13). Groundwater samples showing minor fluctuations in pH, showed the same pattern (or lack thereof) with respect to alkalinity.

Trends of ammonia and sulfate concentration changes were nearly identical. Sulfate and ammonia concentrations increased significantly above baseline levels in groundwater from wells TW-2, TW-17, TW-18, and EMW-11A. No increases in sulfate and ammonia concentrations were detected in groundwater from wells EMW-3, TW-3, TW-4, and TW-11. A pH decrease and high wellhead gas pressures indicated that gas had migrated into the area of these wells. The absence of sulfate and ammonia increases indicated that product gas did not transport sulfate or ammonia away from the production zone. Baseline sulfate and ammonia concentrations were two to three times higher in the southwest area of the site (TW-18) than elsewhere (Figures 23 and 25). UCG induced hydraulic gradients (Figures 16 and 17) resulted in groundwater flow from the area of TW-18 toward wells TW-2, TW-5, TW-17 and EMW-11A. This groundwater flow may have carried sulfate and ammonia onto the site, resulting in elevated concentrations of these two constituents (Moody 1990).

Relatively constant sulfate and ammonia concentrations were seen in groundwater from well TW-5 from the beginning of the test until shutdown of the ELW process module. After January 16, 1988, concentrations in samples from TW-5 gradually increased until the end of the test. Groundwater from well EMW-9 exhibited similar behavior for sulfate, although not as pronounced. This trend of sulfate and ammonia concentration increases in water samples from well TW-5 was explained by Moody (1990) and also applies to EMW-9. A map of the potentiometric

surface prior to ELW shutdown (Figure 16) shows potential groundwater flow toward TW-5 and EMW-9 from the area of TW-16. After the ELW test termination, groundwater began to flow toward TW-5 and EMW-9 from the area of EMW-11A and TW-17. The lower concentrations of sulfate and ammonia seen in TW-5 groundwater prior to ELW shutdown were caused by groundwater of lower sulfate and ammonia concentration flowing from the area of TW-16. The higher concentrations seen later resulted from groundwater with more sulfate and ammonia flowing from the area of EMW-11A and TW-17.

The total dissolved solids parameter is primarily comprised of the ionic species dissolved in the water. Sodium, sulfate, and bicarbonate were the most abundant species detected during baseline sampling, and therefore, were primarily responsible for observed TDS values. Changes in TDS during the UCG test generally corresponded with changes in sulfate and bicarbonate concentrations (Table 15). The relationship of sodium concentration changes to changes in TDS was not determined because samples were not analyzed for sodium as part of the groundwater monitoring during the UCG test.

Table 15. Total Dissolved Solids, Sulfate, and Bicarbonate Concentration Changes During UCG Test, mg/L, (Moody 1990)

Well	Date Interval	TDS Change	Sulfate Change	Bicarbonate Change
TW-2	12/19/87 - 12/31/87	+390	+100	+92
	01/08/88 - 01/14/88	-140	-300	+171
	01/18/88 - 01/21/88	-120	-200	+38
	01/30/88 - 02/05/88	+160	+210	+27
EMW-11A	12/19/87 - 01/08/88	+320	-270	+503
	01/08/88 - 01/14/88	-190	-100	+5
	01/18/88 - 01/21/88	+100	+100	-77
	01/28/88 - 01/30/88	-210	-20	+35
TW-5	01/16/88 - 01/26/88	+130	+170	-39
	01/26/88 - 02/03/88	+90	+130	+2
	02/03/88 - 02/12/88	-40	0	-34
	02/12/88 - 02/23/88	+280	+210	-47

Boron concentrations appeared to randomly fluctuate between a maximum of 0.033 mg/L and a minimum less than the analytical detection limit (0.010 mg/L). Because the boron concentrations were so low, the variations were probably due to inconsistencies in the sampling or analytical conditions (Moody 1990).

Increases in TOC concentration generally occurred in groundwater from wells that experienced product gas influx. TOC increases occurred in wells TW-2, TW-18, EMW-3, and EMW-11A. TOC concentrations in well TW-5 followed the same trends as previously discussed for sulfate and ammonia. Increased TOC values were probably due to higher concentrations of acetic acid, acetone, and trace amounts of benzoic acid in the groundwater (Moody 1990). These compounds were detected by gas chromatographic and mass spectrographic analysis of a sample collected from TW-2. Moody (1990) suggested that changes from alkaline to acidic groundwater conditions may have caused chemical reactions with the coal that increased TOC concentrations.

Concentrations of phenol, cyanide, and sulfide were below the analytical detection limits in all samples collected during baseline testing and throughout the UCG testing.

For the modified Skinner list compounds, groundwater samples collected on February 3, 1988 contained byproducts of the UCG operations. High concentrations were measured of volatile organics, including benzene, ethyl benzene, toluene, and xylenes. Analyses for semivolatile organics indicated significant concentrations of cresols, phenols, and polyaromatic hydrocarbons (Radian Corporation 1990). Chlorinated hydrocarbons were not detected in these analyses. These data are included in Volume II, Appendix A, and the report by Radian Corporation is presented in Volume II, Appendix C.

3.2.3 Restoration

Prerestoration sampling of groundwater showed cavity concentrations of most constituents (boron, ammonia, phenol, and VOAs) were significantly higher than concentrations in the surrounding coal seam strata (WRI 1988a and 1988b). The graphs of ammonia and phenol concentration versus time (Figures 27 and 28) during pumping show a decrease in concentration as cavity water was replaced by influxing, relatively uncontaminated water from the surrounding coal strata.

The trends for TOC and TDS concentrations differed somewhat from phenol and ammonia. Initial concentrations of TOC in the cavities were within the range of baseline concentrations. The concentration of TOC increased sharply (Figure 29) approximately two thirds of the way through the pumping. This was caused by lighter tars and oils floating on the water surface in the cavity, that entered the pump intake when the water level dropped sufficiently (Covell et al. 1992). TDS, on the other hand, showed a sharp, immediate increase as pumping started, followed by a gradual decrease (Figure 30) as cleaner water entered the cavities.

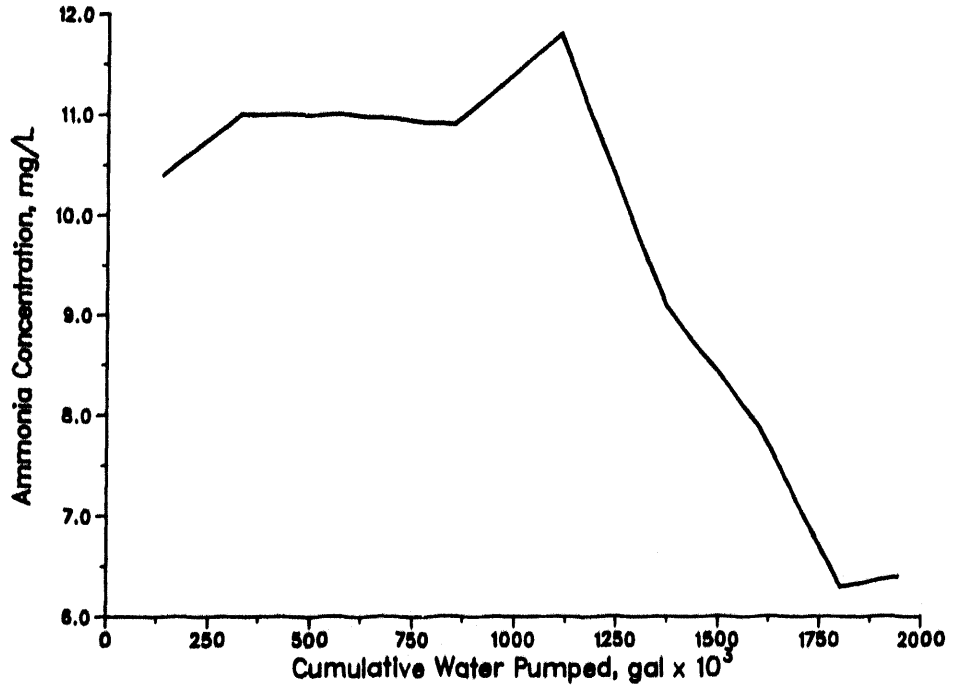


Figure 27. Ammonia in RM1 Cavity Water, First Restoration, (Covell et al. 1992)

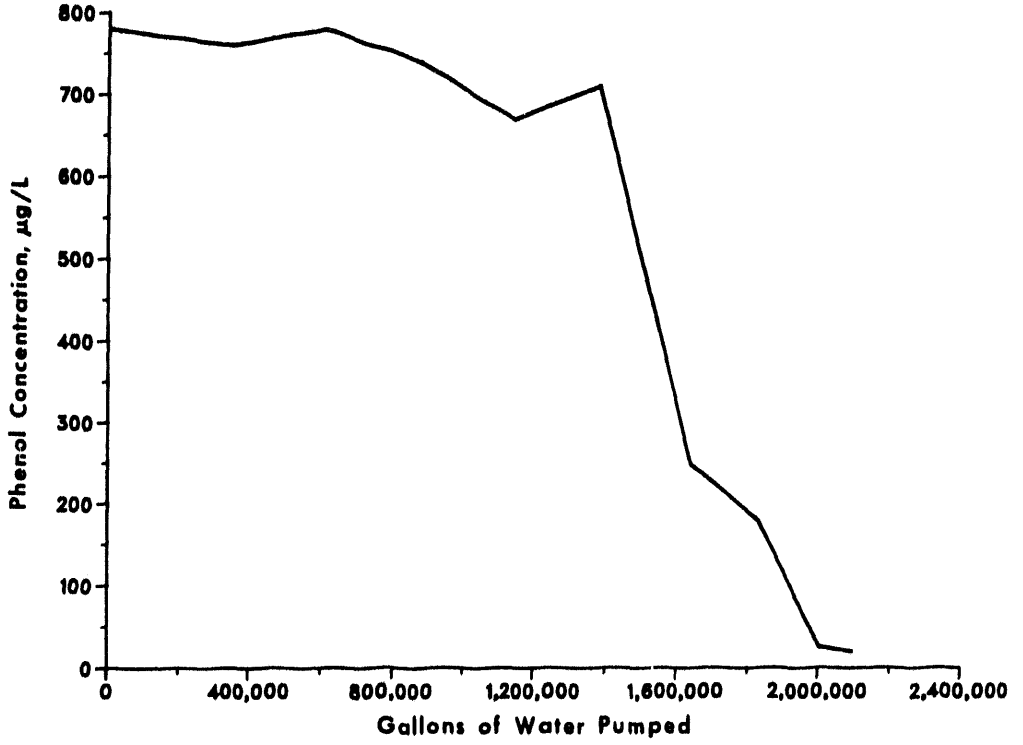


Figure 28. Phenol in RM1 Cavity Water, First Restoration, (Covell et al. 1992)

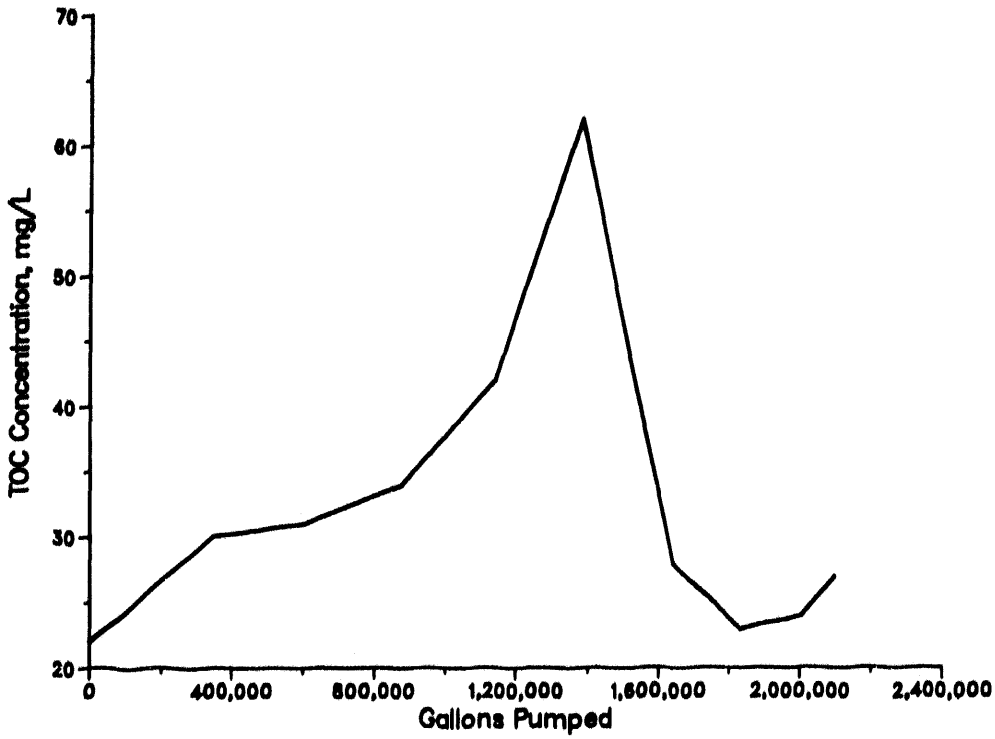


Figure 29. TOC in RM1 Cavity Water, First Restoration, (Covell et al. 1992)

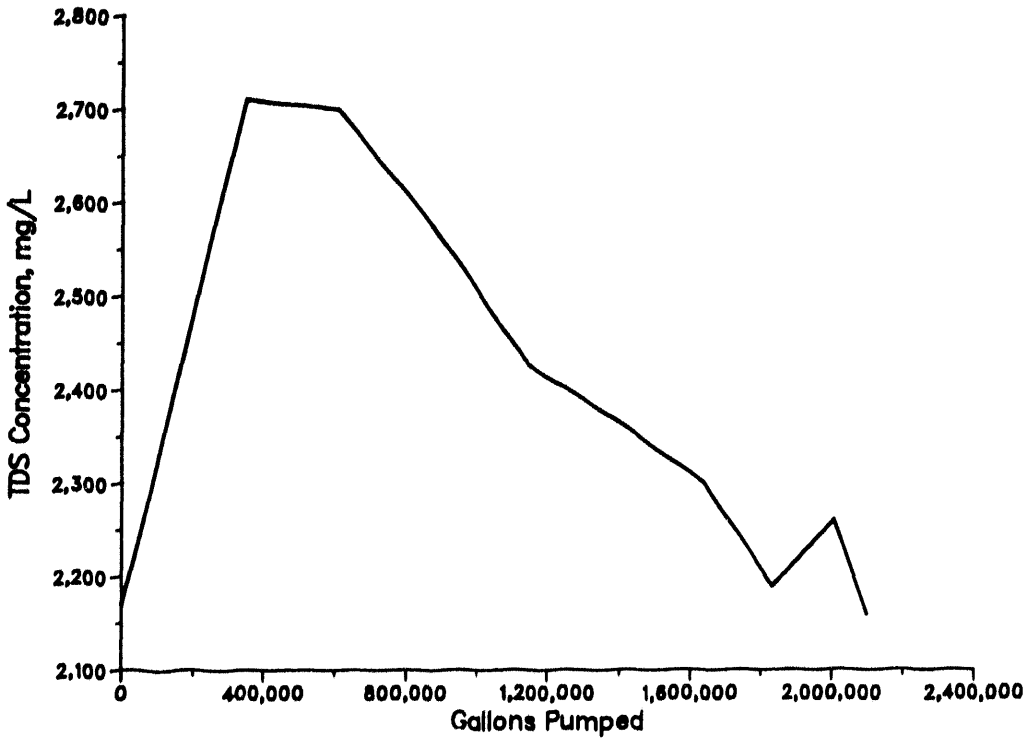


Figure 30. TDS in RM1 Cavity Water, First Restoration, (Covell et al. 1992)

The treatment system used in the first restoration was effective in removing some constituents whose concentrations were above baseline (Covell et al. 1992). Table 16 shows the results of composite analyses of treated and untreated water. Chlorine oxidation was successful in reducing ammonia (91-95% reduction). Carbon adsorption, while effective in removing phenol (>73% reduction), was only partially successful in removing TOC (20-65% reduction). The flocculation chamber was ineffective in removing boron, the only metal present in concentrations higher than baseline. Boron does not easily form hydroxide compounds when mixed with sodium hydroxide and therefore did not precipitate out of the groundwater during treatment.

Total dissolved solids increases of 23-47% were observed between the untreated and the treated water. These increases resulted from the addition of chlorides, sodium, and sulfates (i.e., chlorine, NaOH, and H_2SO_4) during the treatment. While chlorine oxidation did remove ammonia, the ammonia concentrations in the cavity water were only slightly above baseline. Direct aeration with the spray evaporation system would have been sufficient to reduce ammonia concentrations for disposal. As mentioned earlier, the flocculation/sedimentation steps in the treatment system did not reduce the concentration of boron. They did, however, contribute to the TDS increases by adding NaOH and H_2SO_4 as part of the treatment steps (Covell et al. 1992).

Analysis of samples collected from the UCG cavities for the Skinner list compounds showed no indication of chlorinated hydrocarbons. The cavity samples did show other volatile and semivolatile compounds such as might be expected from coal gasification operations.

Cavity water samples collected on September 6, 1988 showed 100% toxicity to both test specimens used for the ENSR toxicity determination. After the cavity water was treated to remove hydrocarbons and metals, samples of this treated water showed no toxicity to either test specimen. While no toxicity tests were performed on the groundwater from the RM1 site after the restoration activities, groundwater samples collected after the second restoration activity were similar in composition to the baseline groundwater and had a lower TDS content than the treated cavity water.

The quality of groundwater during the second restoration activity was near baseline levels while pumping the two cavities. Boron was the only constituent with concentrations significantly higher than baseline. Boron concentrations decreased as water was pumped from the cavities (Figure 31). Phenols were detected at low concentrations during pumping, but not during the final two days (Figure 32). Ammonia concentrations were slightly above the highest baseline concentrations (7.9 mg/L) and gradually decreased with the exception of a one time increase during the second restoration (Figure 33). The improved water quality is likely due to the influx of cleaner water.

Table 16. Analyses of Untreated and Treated Water, First Restoration Activity, mg/L[a], (Covell et al. 1992)

Parameter	8/28	8/31	9/3	9/6	9/6[b]	9/9	9/12	9/15	9/18	9/20
Untreated Cavity Water										
	2.3									
Boron	--	1.61	1.97	2.04	40.0	1.86	1.18	0.879	0.649	0.387
Calcium	--	62.6	52.8	43.1	970	32.5	31.8	21.3	28.9	38.5
Sodium	--	810	820	830	800	710	760	755	730	
	52									
Phenol (µg/L)	760	780	740	670	40	711	250	180	26	21
TOC	30	31	34	42	7.8	62	28	23	24	27
Ammonia as N	10.4	11	11	10.9	2.8	11.8	9.1	7.9	6.3	6.4
Sulfide	5	6	3.3	1.0	2878	11.0	3.7	1.4	<1	1.1
TDS	2710	2700	2573	2428	2370	2300	2190	2260	2160	
	8/25	**8/28**	**8/31**	**9/3**	**9/6**	**9/6[c]**	**9/9**	**9/12**	**9/15**	**9/18**	**9/20**
Treated Water											
Boron	1.05	--	1.68	1.92	2.26	1.97	2.01	1.28	0.818	0.405	0.387
Calcium	5.72	--	8.14	5.49	12.6	7.43	35.9	6.68	7.35	8.20	11.6
Sodium	1140	--	1090	1180	1310	1300	1040	1090	1000	870	855
Phenol, µg/L	<20	23	63	<20	<20	104	<20	<20	<20	<20	<20
TOC	<10	<10	13	25	18	24	58	17	<10	21	20
Ammonia as N	0.3	<0.2	0.6	0.2	0.4	<0.2	0.3	0.2	0.2	0.5	<0.2
Sulfide	<1	<1	<1	2.9	<1	<1	3.4	1.9	<1	<1	<1
TDS	3050	3520	3670	3659	4014	3944	3100	3410	3040	2570	2520

[a] Unless otherwise noted, units are mg/L
[b] From air flotation overflow
[c] From between carbon filters

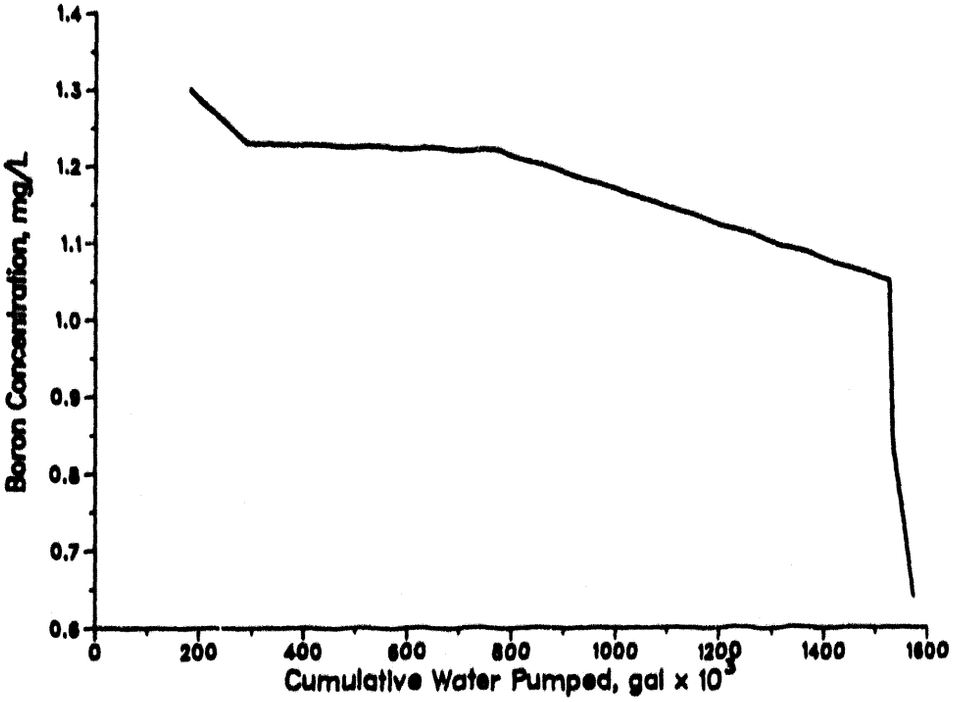


Figure 31. Boron in RM1 Cavity Water, Second Restoration, (Covell et al. 1992)

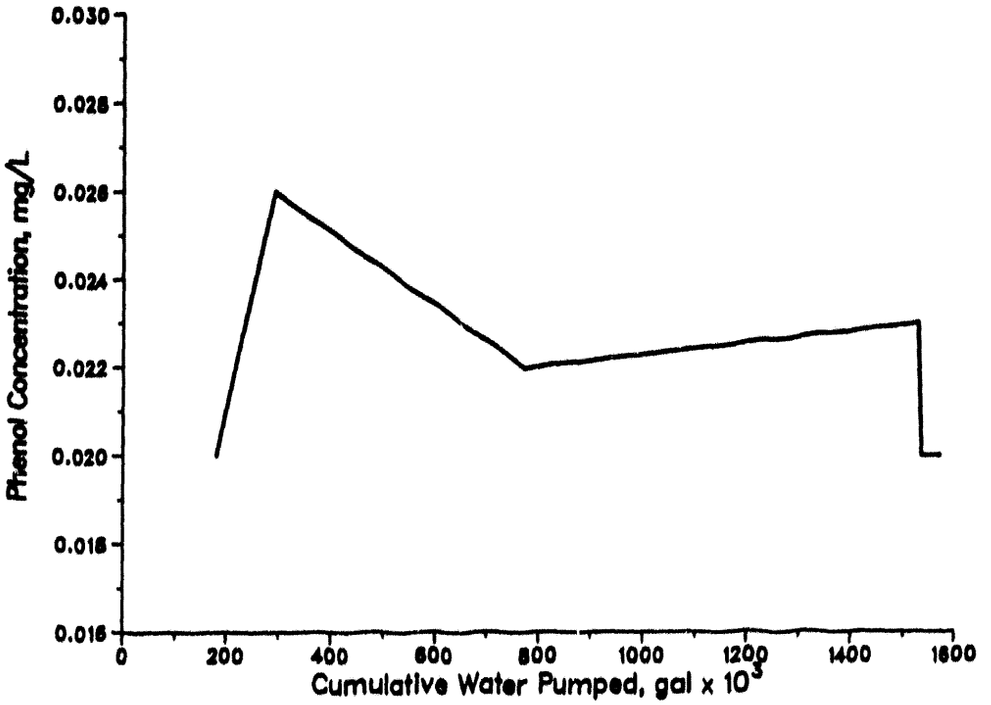


Figure 32. Phenol in RM1 Cavity Water, Second Restoration, (Covell et al. 1992)

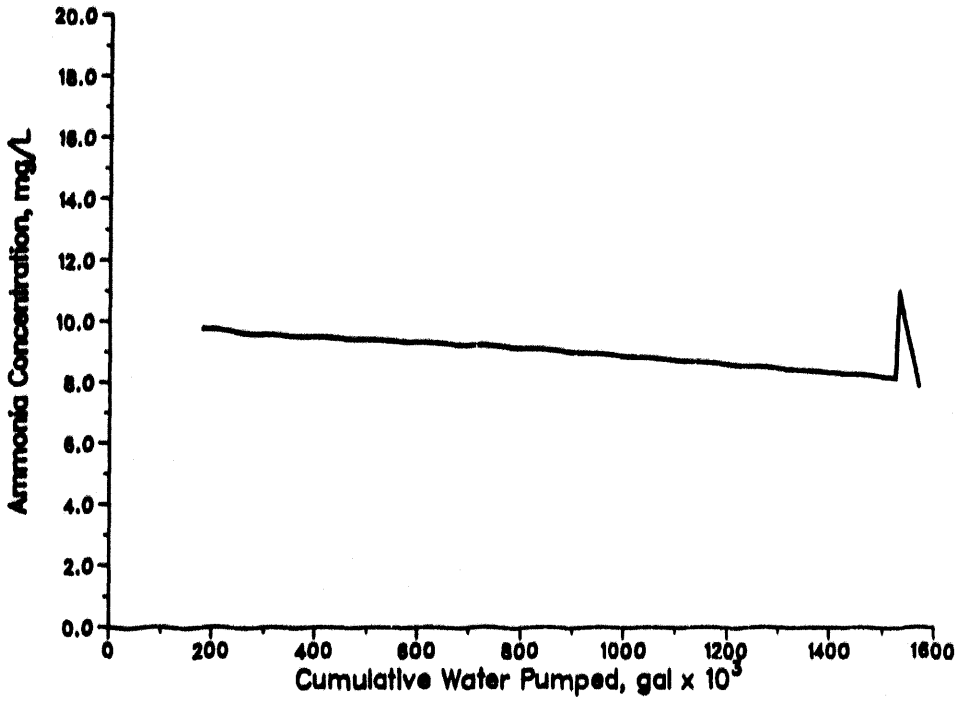


Figure 33. Ammonia in RM1 Cavity Water, Second Restoration, (Covell et al. 1992)

The treatment system was not effective in removing the targeted constituents during the second restoration activity (Table 17). As mentioned previously, the treatment system was modified based on the results of the first restoration and the expected groundwater quality. This second treatment system was designed primarily to remove organic compounds. However, phenols and TOC were not affected by the treatment system. Carbon adsorption should have removed these constituents if the carbon had sufficient activation sites for adsorption. Water samples collected from the treated-water outlet showed relatively high concentrations of chloroform (CF) and bromodichloromethane (BDCM) in the treated water. These constituents were not detected at the inlet to the carbon adsorbers; therefore, they must have been introduced by the carbon adsorbers themselves. Analyses of carbon samples from the adsorbers detected not only CF and BDCM but also bromoform. This was the same carbon used in the first treatment, and it is probable that the chlorine added as part of the first treatment system partially chlorinated some organic compounds that adsorbed onto the activated carbon. Because the adsorber units were sealed and stored on site between treatments, it is possible that anaerobic bacterial reactions broke down the higher molecular weight organic compounds into lower molecular weight compounds such as CF and BDCM. These constituents can load activation sites on the activated carbon and greatly reduce the effectiveness of carbon adsorption treatment.

Table 17. Analyses of Combined Cavity Water and Treated Water During the Second Restoration Activity, (Covell et al. 1992)

	Benzene	Chloroform	BDCM*	Phenols	Ammonia	TOC	TDS	Boron
Cavity Water								
7/31/89	<0.005	<0.005	<0.005	<0.020	9.8	17	2890	1.30
8/1 - 8/2/89	<0.005	<0.005	<0.005	0.026	9.6	17	2820	1.23
8/3 - 8/6/89	<0.005	<0.005	<0.005	0.022	9.2	19	2750	1.22
8/5/89	<0.005	<0.005	<0.005	0.040	-	-	-	-
8/8/89	<0.005	<0.005	<0.005	0.027	-	-	-	-
8/11//89	<0.005	<0.005	<0.005	0.033	-	-	-	-
8/7 - 8/13/89	<0.005	<0.005	<0.005	0.023	8.2	18	2440	1.05
8/14/89	<0.005	<0.005	<0.005	<0.020	11.0	19	2330	0.84
8/15/89	<0.005	<0.005	<0.005	<0.020	7.9	22	2280	0.64
Treated Water								
7/31/89	<.005	0.100	0.016	<.020	9.6	17	2890	1.30
8/1 - 8/2/89	<.005	0.081	0.017	<.020	9.6	16	2810	1.28
8/3 - 8/6/89	<.005	0.044	0.008	<.020	9.0	16	2760	1.30
8/5/89	<.005	0.055	0.009	0.020	-	-	-	-
8/8/89	<.005	0.049	0.006	0.020	-	-	-	-
8/11/89	<.005	0.033	<.005	0.020	-	-	-	-
8/7 - 8/13/89	<.005	0.033	<.005	0.022	7.9	16	2460	1.04
8/14/89	<.005	0.030	<.005	<.020	10.0	18	2290	0.86
8/15/89	<.005	0.031	<.005	<.020	7.6	20	2280	0.72

* BDCM = Bromodichloromethane

After the restoration operations, groundwater quality in the cavities was near baseline conditions (Table 18). Boron was the only inorganic constituent analyzed that was significantly higher than its baseline levels. The groundwater restoration activities were not effective in removing boron from the groundwater. Benzene, while detected in small amounts in the cavities during groundwater sampling after restoration, is most likely associated with tars in and around process well piping.

Table 18. Comparison of Combined Cavity Water Concentrations After Second Restoration to Highest Baseline Coal Seam Concentrations, mg/L

Parameter	Combined Cavity Water	Baseline
TOC	22	45
TDS	2280	2750
Boron	0.641	0.037
Ammonia	7.9	7.9
pH	6.98	9.24
Phenol	<0.020	<0.020

3.2.4 Long-Term Monitoring

3.2.4.1 Inner and Outer Rings of Coal Seam Wells. Ten parameters: pH, alkalinity, sulfate, ammonia, TDS, TOC, boron, phenol, cyanide, and sulfide were evaluated for long-term effects in the coal seam around the cavities. During the long-term monitoring, similar trends were observed for TDS, TOC, sulfate, and ammonia, as were seen during the baseline site evaluation. Concentrations tend to be higher in the western and southwestern portions of the site. This is probably due to the higher transmissivity of the coal seam in these areas. The higher transmissivity would allow the influx of waters with naturally higher concentrations of the four noted water quality parameters (Moody 1990).

The pH decreased drastically in some wells at the site during the UCG test, probably due to influxing product gas with a high CO_2 content (Moody 1990). Long-term monitoring has shown a return of pH levels to baseline conditions (Appendix A).

To evaluate the long-term water quality, plots were developed for the inner and outer rings and compared to the highest baseline concentrations (HBC). For example, the HBC of alkalinity is 856 meq $CaCO_3$, which is the highest observed value in the coal seam in the August 1986 through August 1987 set of measurements. Zero value points on water quality plots are for measurements below detection limits. Figures 34 through 37 show the profiles for alkalinity in the inner and outer rings of the coal seam following the UCG test. The alkalinity is gradually decreasing throughout the coal seam, with most values being below the HBC of 856 meq $CaCO_3$. Wells in the west central area of the site have alkalinity levels above the HBC.

Figures 38 through 41 show the profiles for ammonia. The concentrations have remained below the HBC of 7.9 mg.L and stabilized throughout the site, except for well TW-18. The ammonia concentration at this location appears to have stabilized at about the HBC, which was observed at this well.

Profiles for sulfate concentrations are shown in Figures 42 through 45. These concentrations were affected by the test, but have decreased and stabilized to below the HBC of 1400 mg/L in the coal bed around the test burns in the past three years. The one exception to this is at well TW-16, which shows increasing sulfate concentrations. However, they are well below the HBC.

Total dissolved solids concentrations are shown in Figures 46 through 49. The coal seam in the southwest part of the site experienced increased TDS during the later part of 1988 and in 1989. This is attributed to the influx of water to the site caused by the extensive pumping of the cavities associated with restoration activities. Since then, concentrations in this area have decreased to below the HBC of 2750 mg/L. Concentrations in the rest of the area have remained below the HBC.

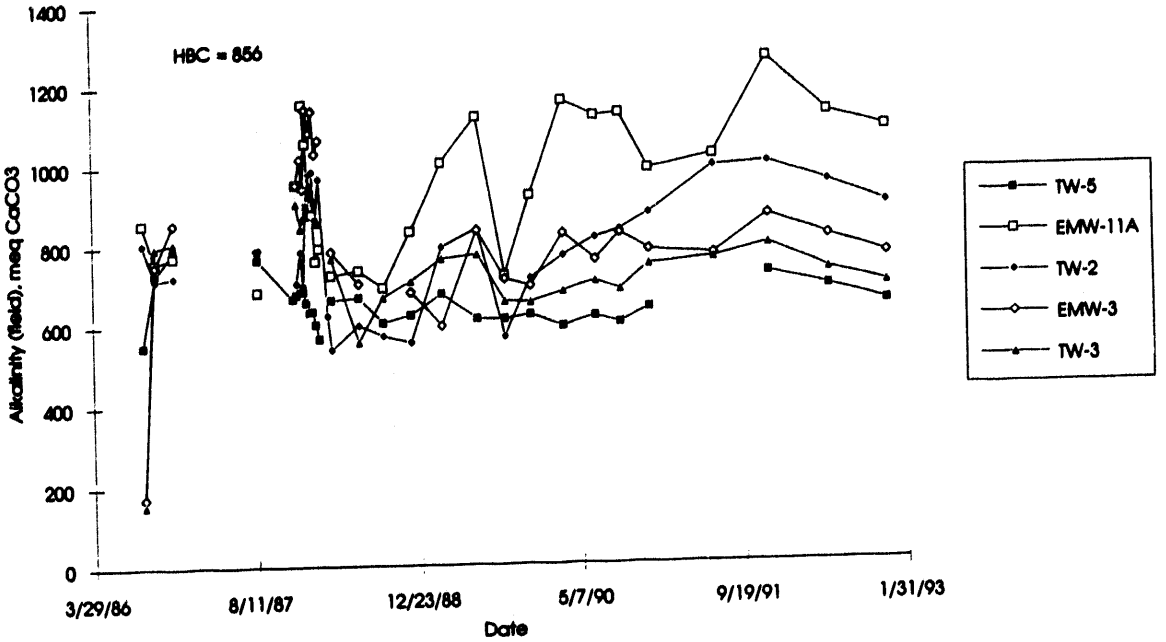


Figure 34. Alkalinity for Coal Seam West and South Inner Ring

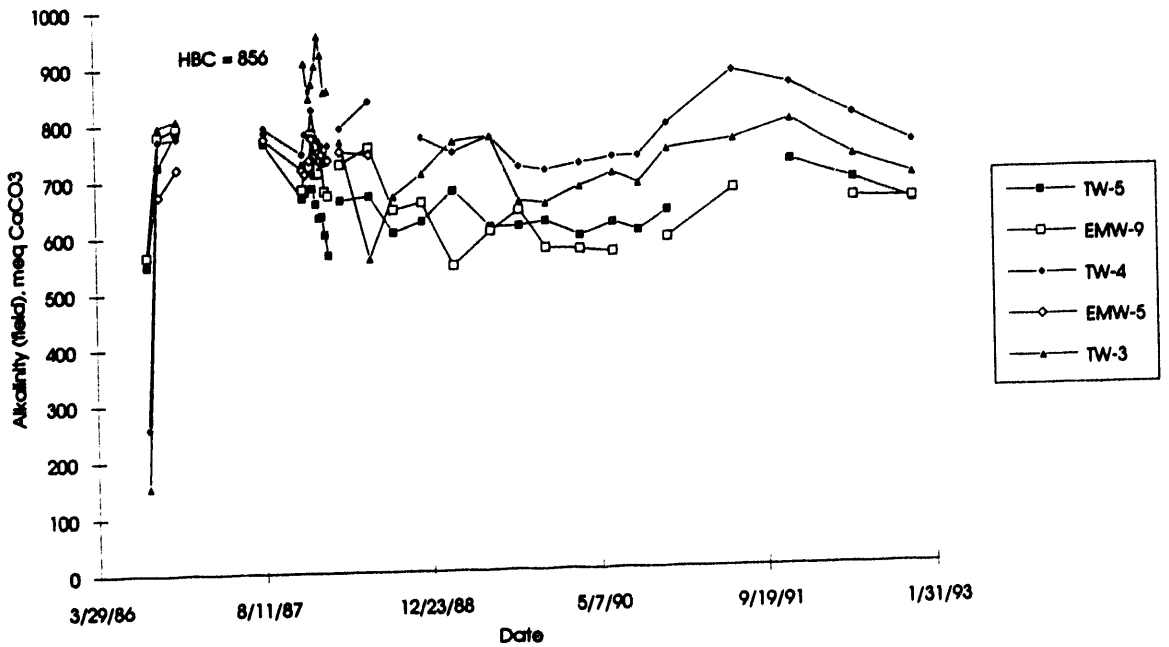


Figure 35. Alkalinity for Coal Seam North and East Inner Ring

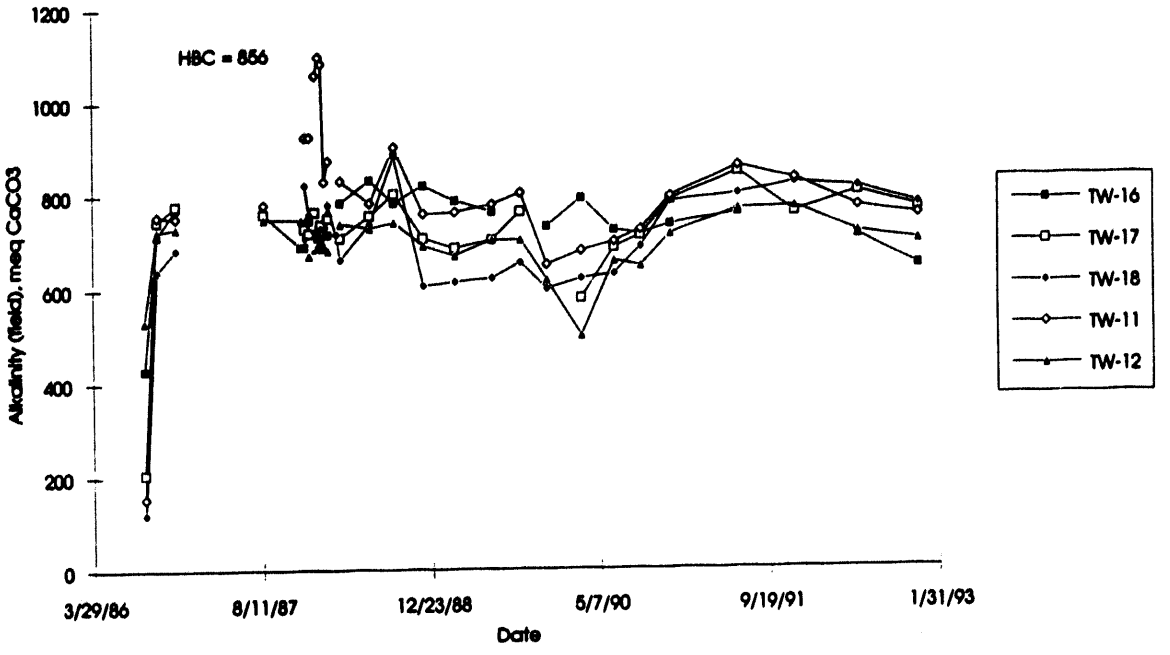


Figure 36. Alkalinity for Coal Seam West and South Outer Ring

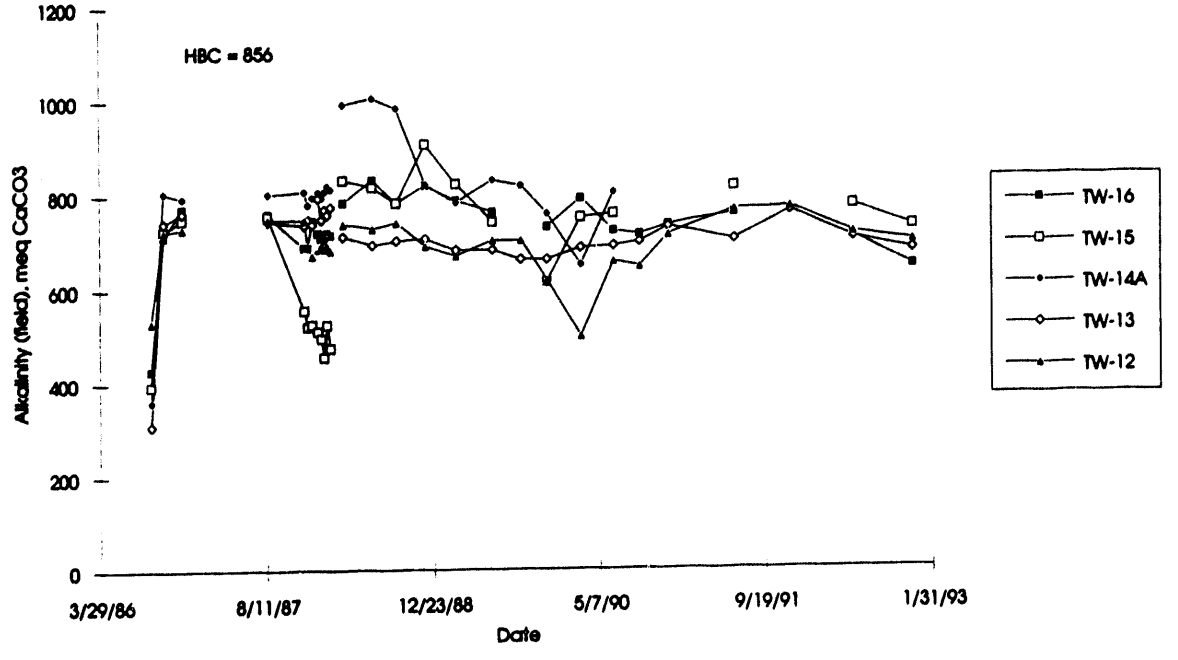


Figure 37. Alkalinity for Coal Seam North and East Outer Ring

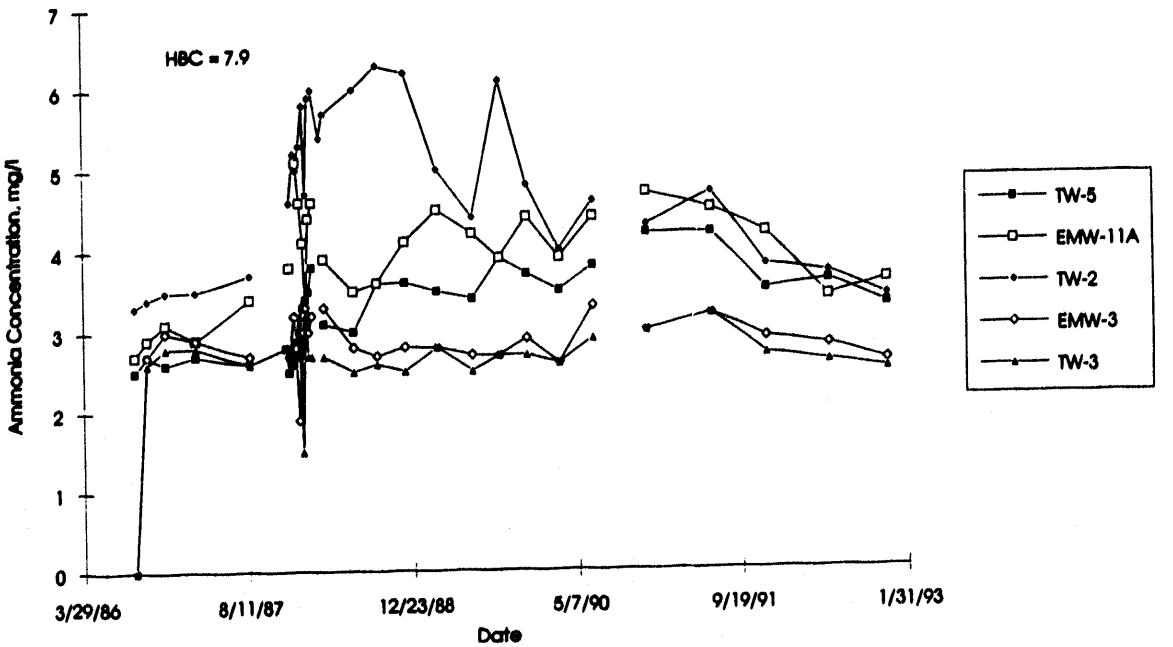


Figure 38. Ammonia for Coal Seam West and South Inner Ring

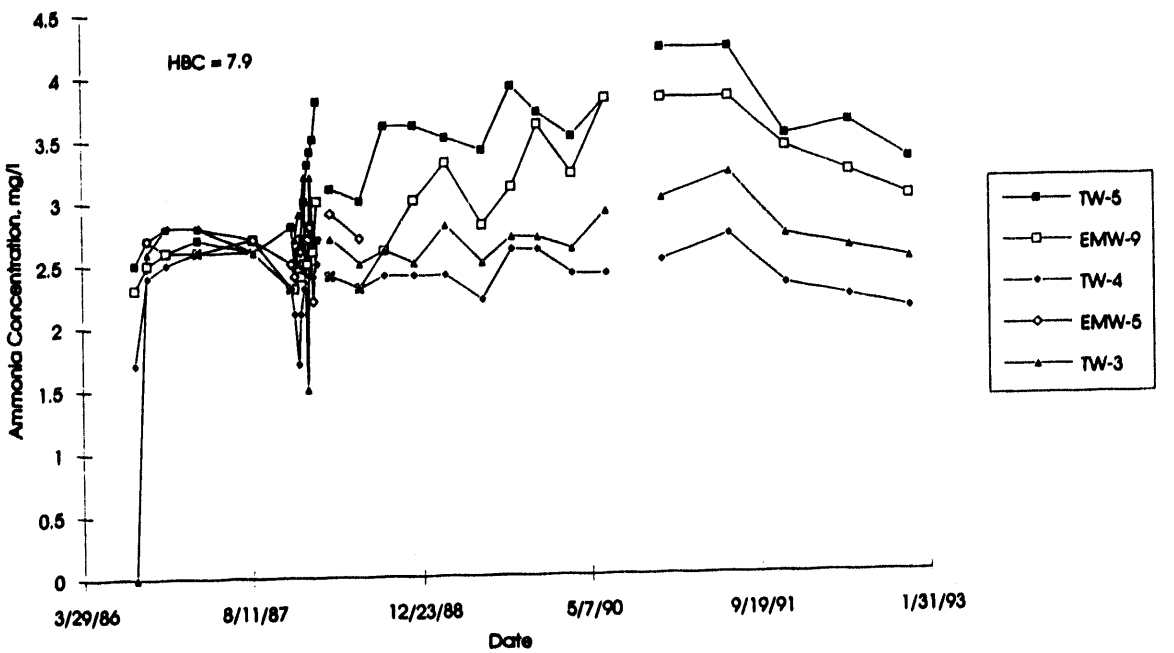


Figure 39. Ammonia for Coal Seam North and East Inner Ring

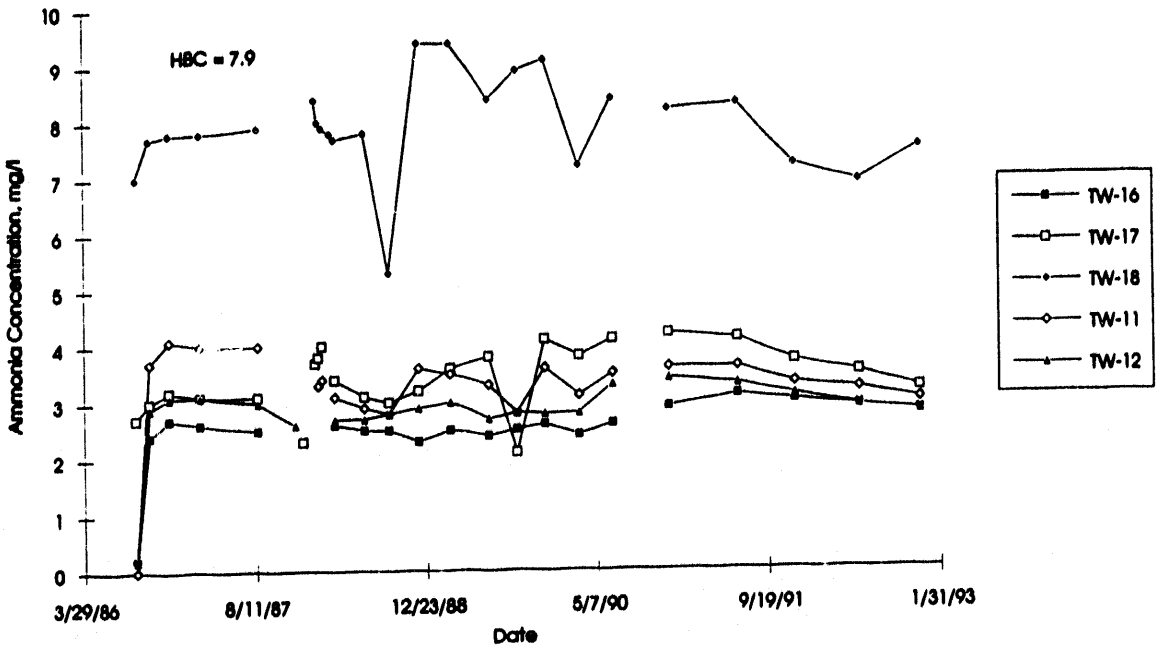


Figure 40. Ammonia for Coal Seam West and South Outer Ring

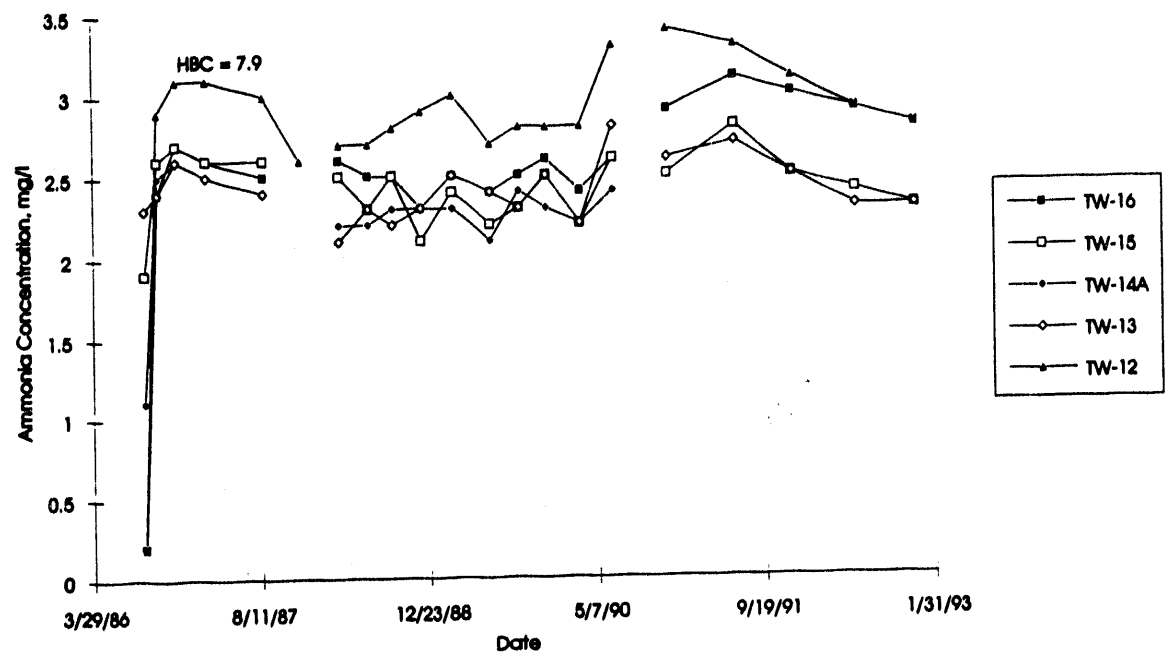


Figure 41. Ammonia for Coal Seam North and East Outer Ring

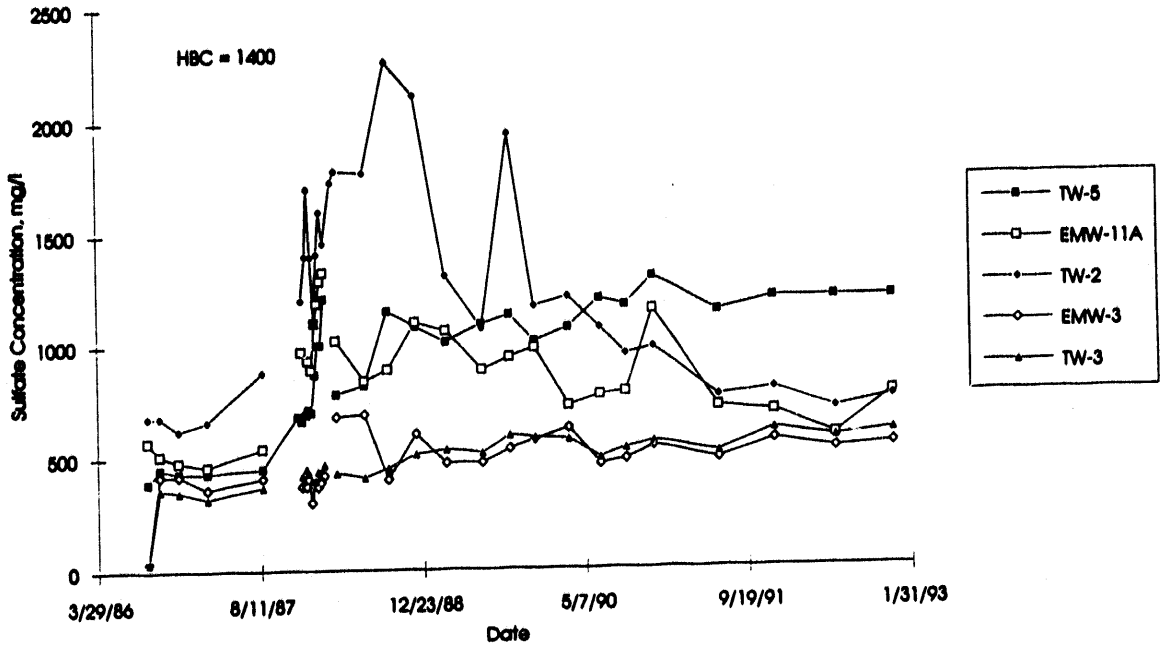


Figure 42. Sulfate for Coal Seam West and South Inner Ring

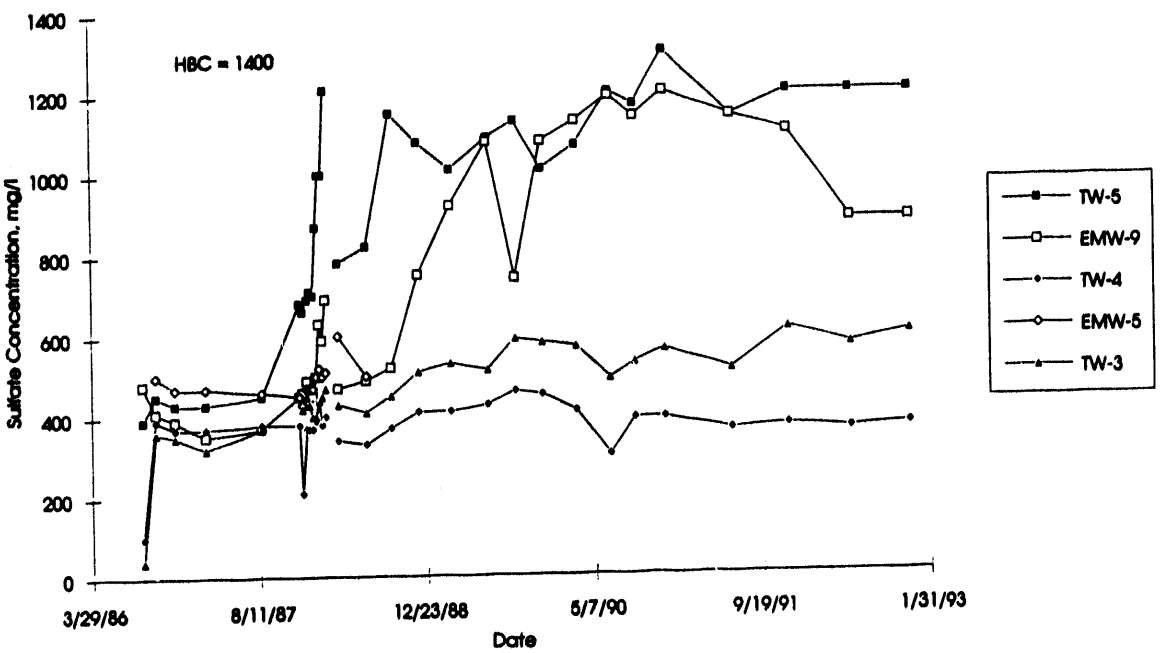


Figure 43. Sulfate for Coal Seam North and East Inner Ring

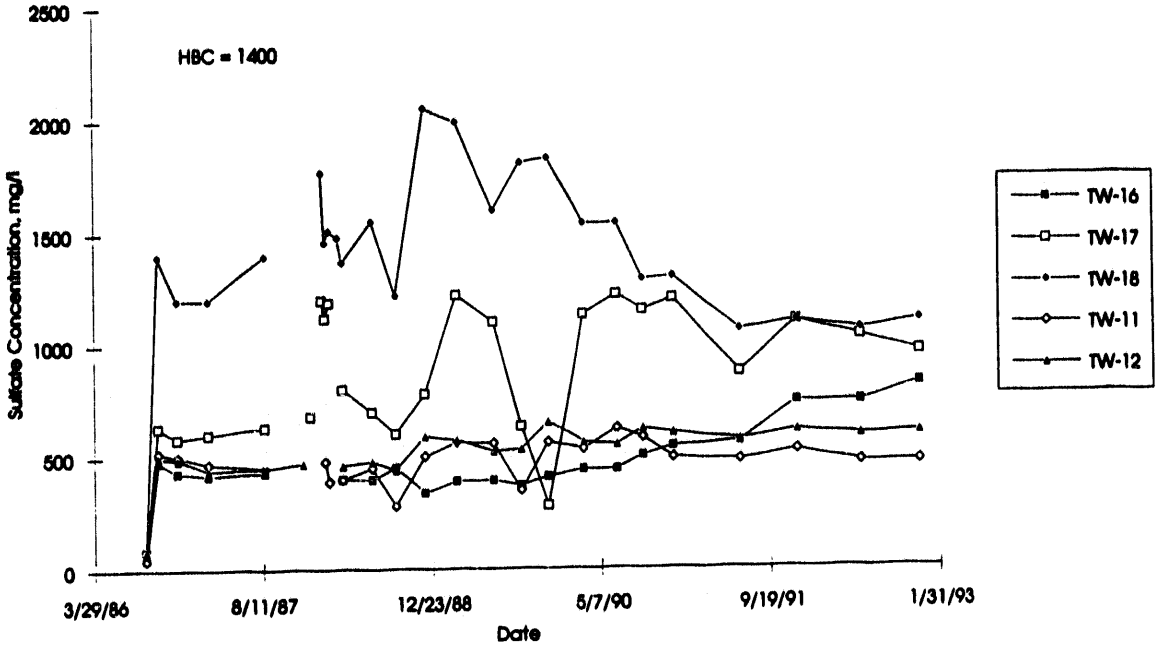


Figure 44. Sulfate for Coal Seam West and South Outer Ring

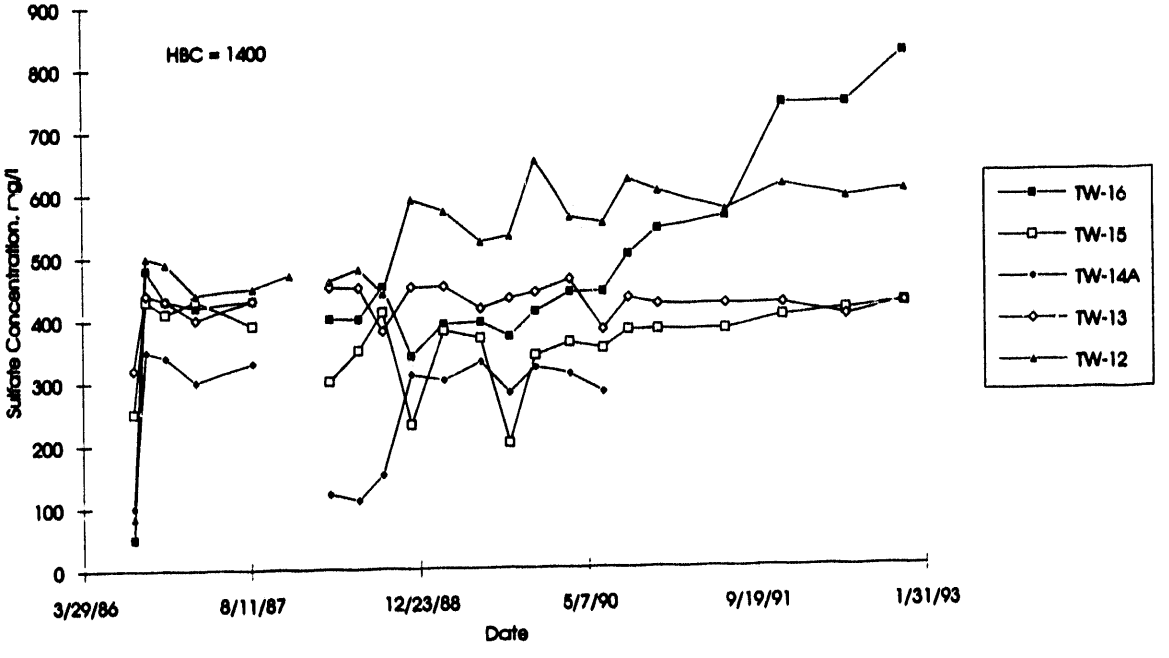


Figure 45. Sulfate for Coal Seam North and East Outer Ring

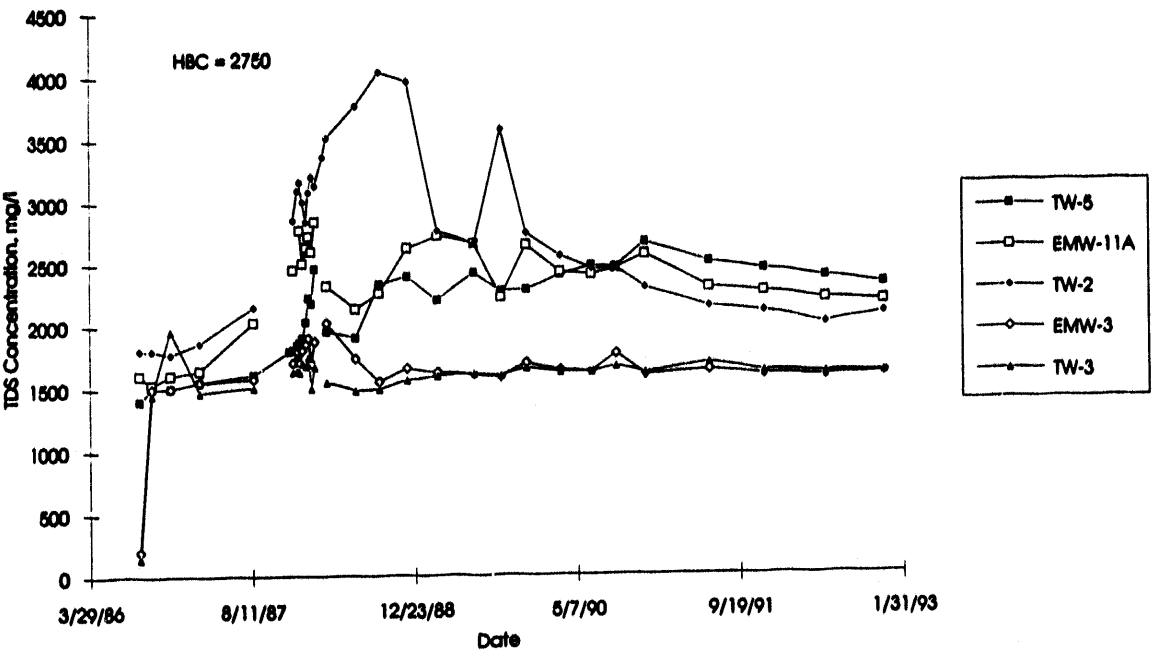


Figure 46. Total Dissolved Solids for Coal Seam West and South Inner Ring

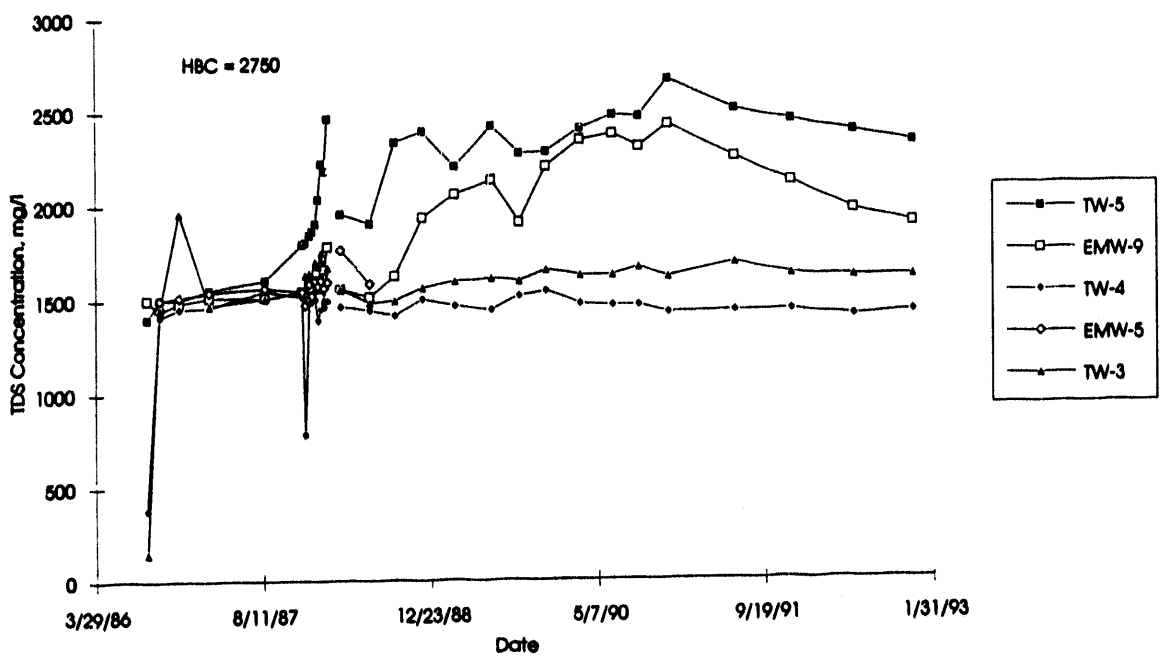


Figure 47. Total Dissolved Solids for Coal Seam North and East Inner Ring

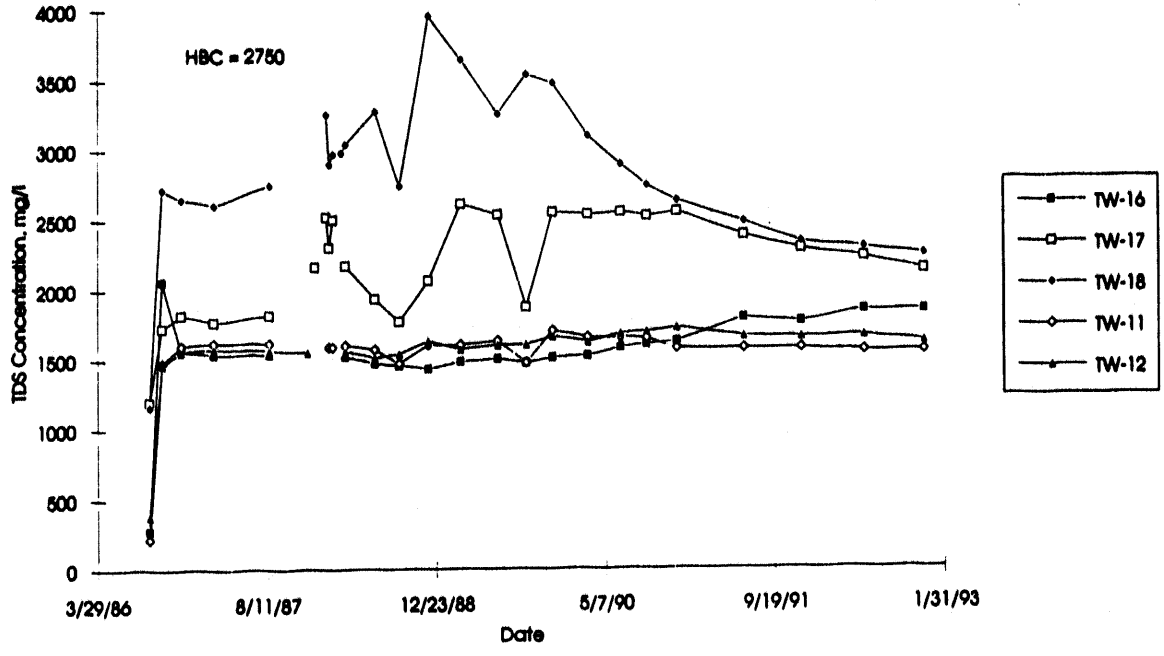


Figure 48. Total Dissolved Solids for Coal Seam West and South Outer Ring

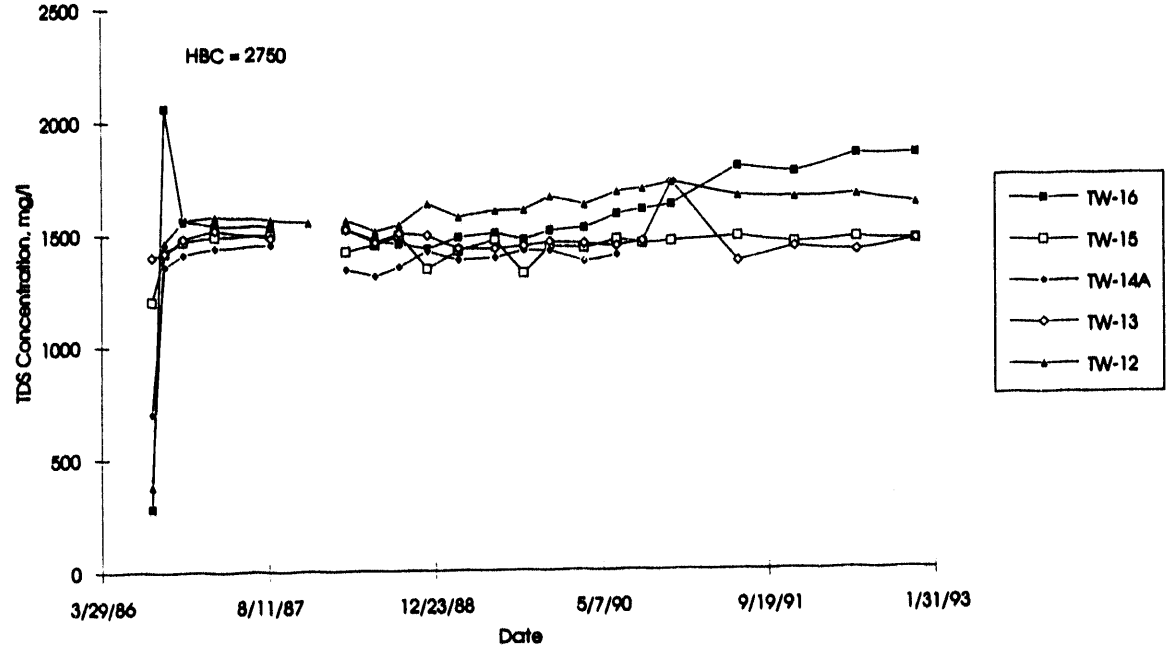


Figure 49. Total Dissolved Solids for Coal Seam North and East Outer Ring

More variability occurred in the total organic carbon measurements (Figures 50 through 53). The largest fluctuations have occurred in the west and northwest portion of the coal seam. General trends indicate TOC concentrations decreasing and stabilizing to levels below the HBC of 45 mg/L. Recent increases in TOC in December 1991 and June 1992 for the west and north portions of the coal seam were reversed in the December 1992 observations.

Concentrations of boron vary greatly. Figure 54, which is a northwest to southwest cross-section for the coal seam, typifies boron concentrations observed across the site. Although some values exceeded the HBC of 0.037 mg/L shortly after the UCG test, more recent measurements are below the HBC. Values plotted as zero are measurements below detection limits.

Very few occurrences of phenol were ever observed in the coal seam groundwater (Appendix A) and those were at low concentrations. More occurrences of phenol were observed in the overburden unit A at EMW-2. These occurrences were between March 1988 and June 1991 and ranged from 0.020 to 0.098 mg/L. Subsequent measurements at EMW-2 were below detection limits (0.020 mg/L). With only two exceptions, other semivolatile organics have remained below analytical detection limits since the second and final restoration activity. The compound Di-n-octylphthalate was detected in December 1989 and bis(2-ethylhexyl)phthalate was seen in December 1990. Because they did not occur at any other time (except bis(2-ethylhexyl)phthalate in August 1986), they are probably the result of field or laboratory contamination.

Concentrations of cyanide and sulfide have remained below the analytical detection limits (Appendix A, Table A-2) in all areas of the site for the entire project.

3.2.4.2 Test Cavities. Figures 55 through 60 show TDS, alkalinity, ammonia, sulfate, TOC, and boron concentrations within the cavities. With the exception of boron, these parameters have decreased to near or below their HBC for the CRIP cavity. Boron concentrations remain high in both cavities. TDS and sulfate are still higher than their HBC for the ELW cavity.

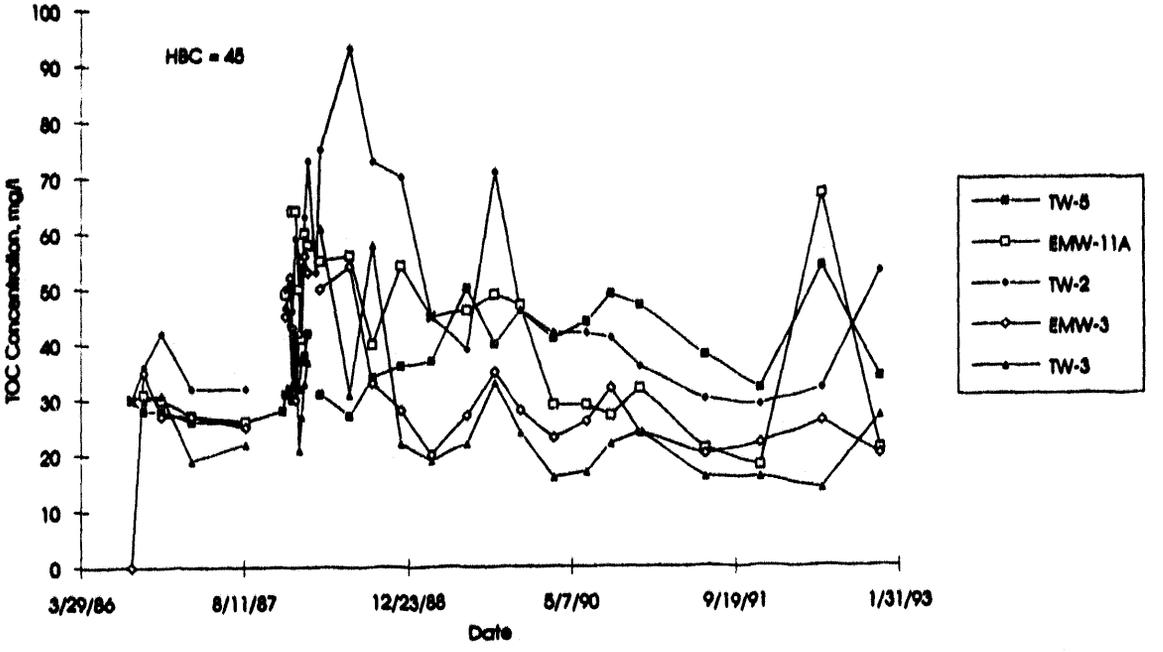


Figure 50. Total Organic Carbon for Coal Seam West and South Inner Ring

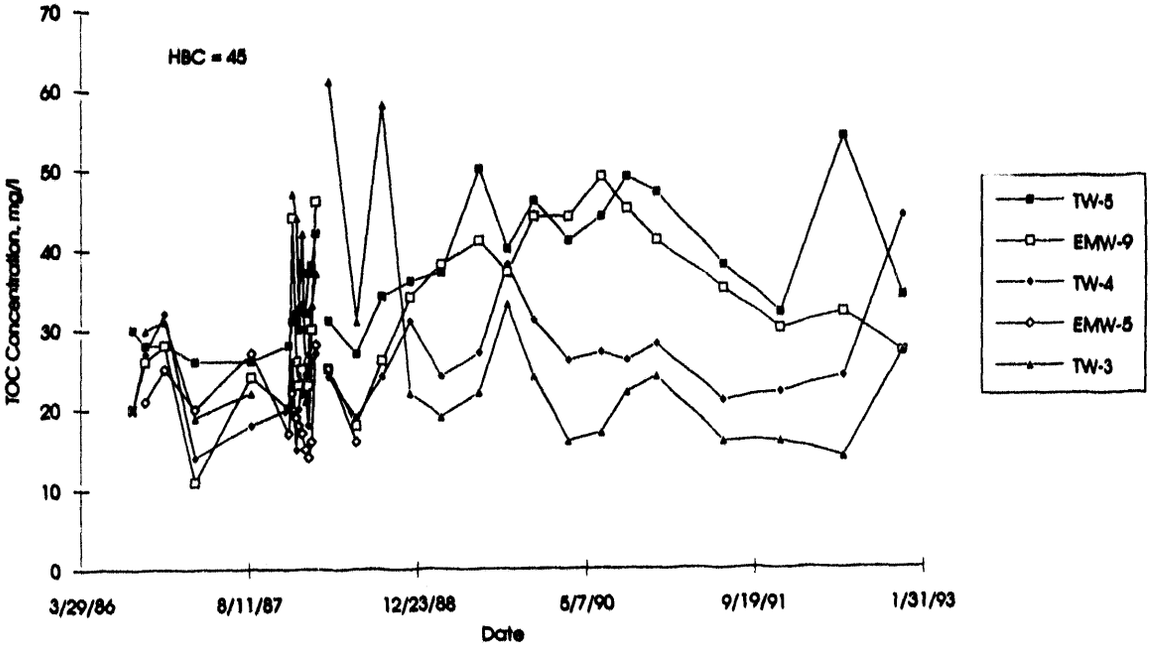


Figure 51. Total Organic Carbon for Coal Seam North and East Inner Ring

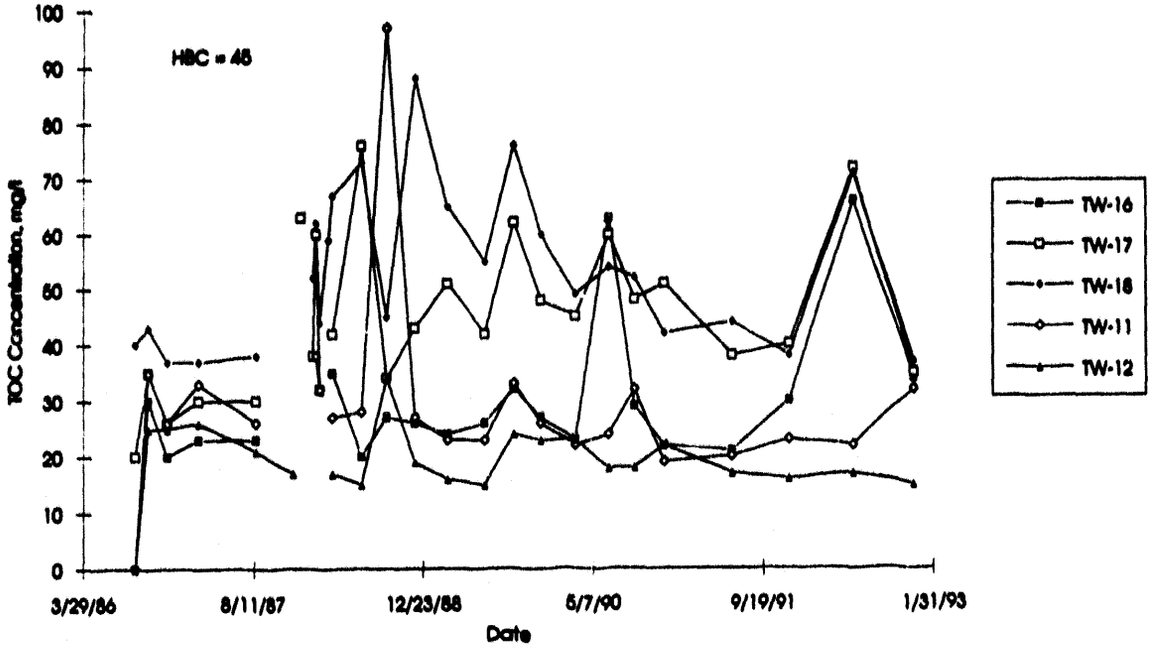


Figure 52. Total Organic Carbon for Coal Seam West and South Outer Ring

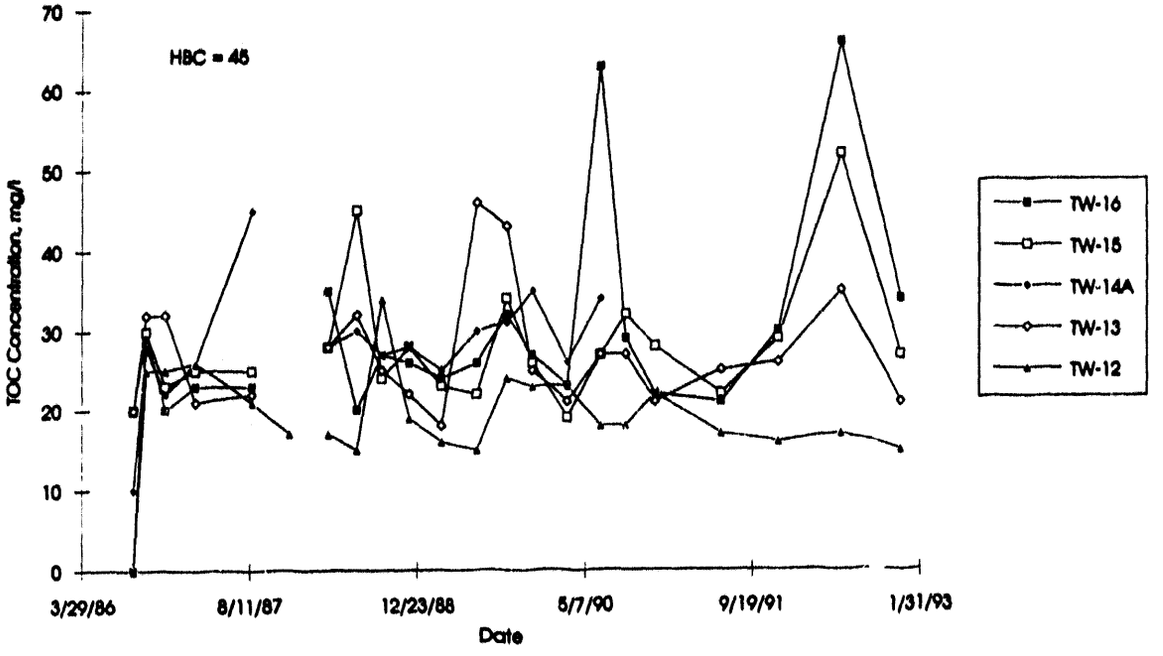


Figure 53. Total Organic Carbon for Coal Seam North and East Outer Ring

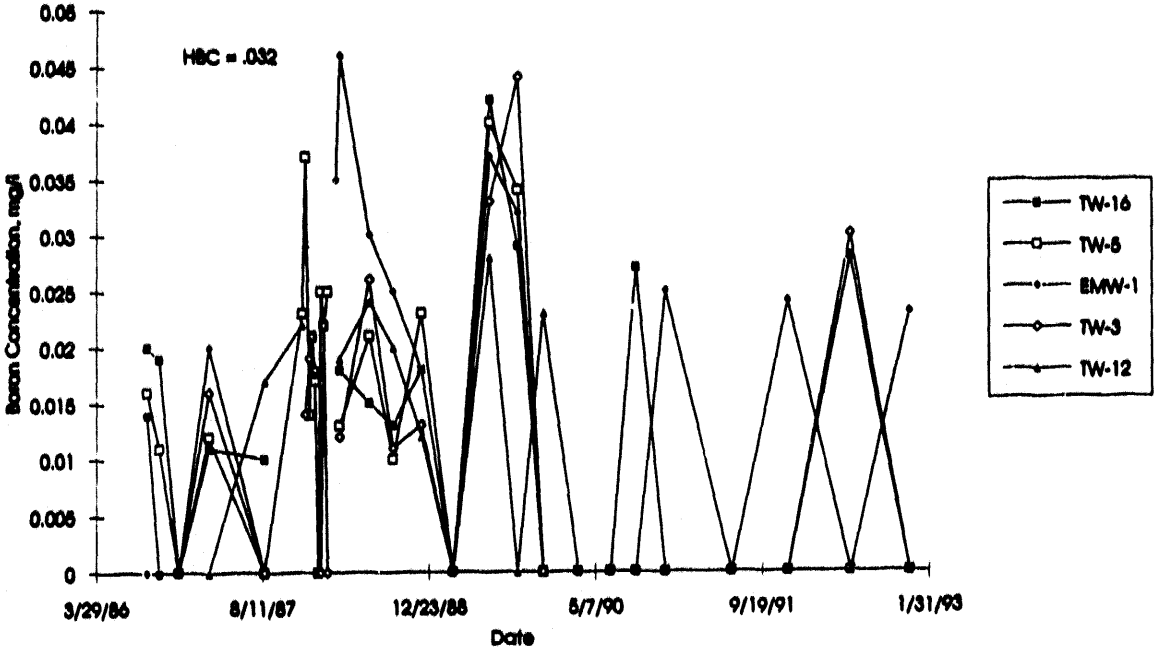


Figure 54. Boron, NW-SE Across Coal Seam

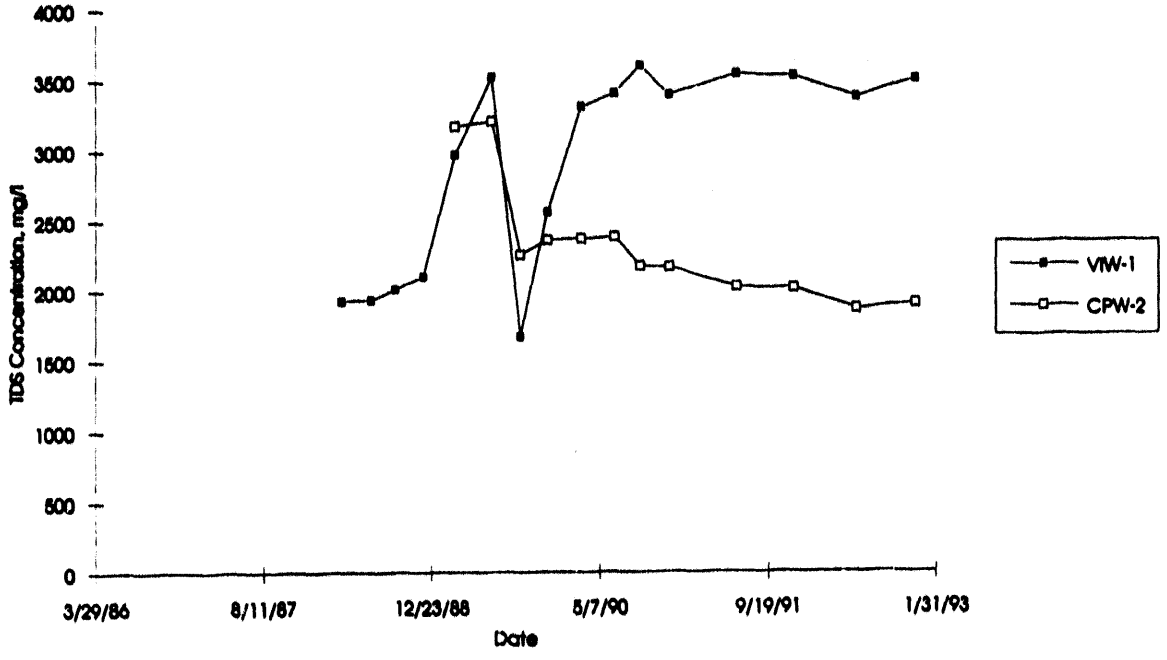
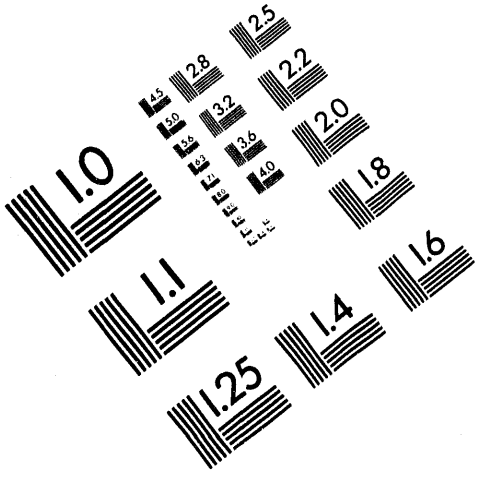


Figure 55. TDS in RM1 Cavity Water



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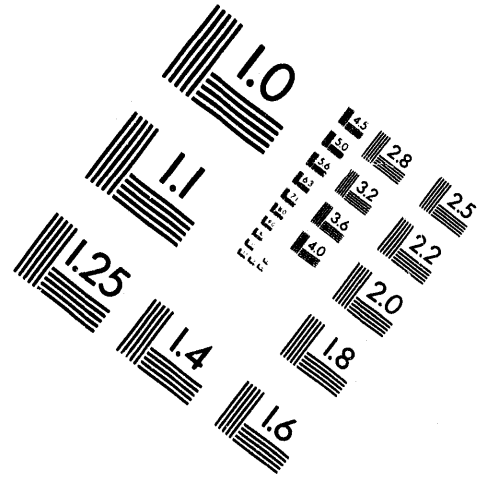

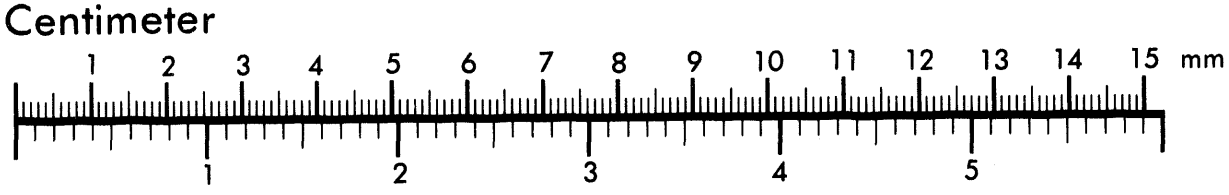

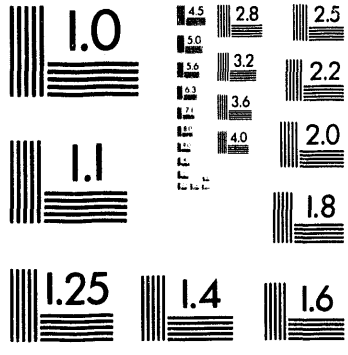

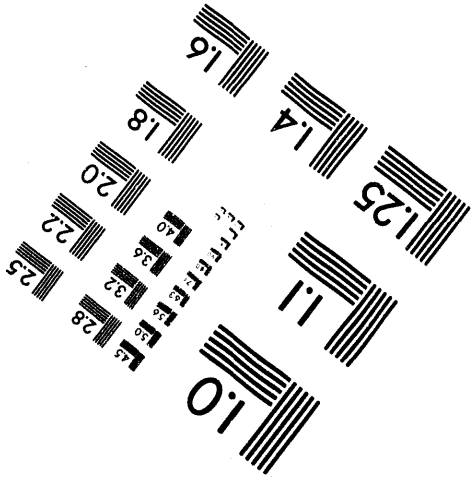

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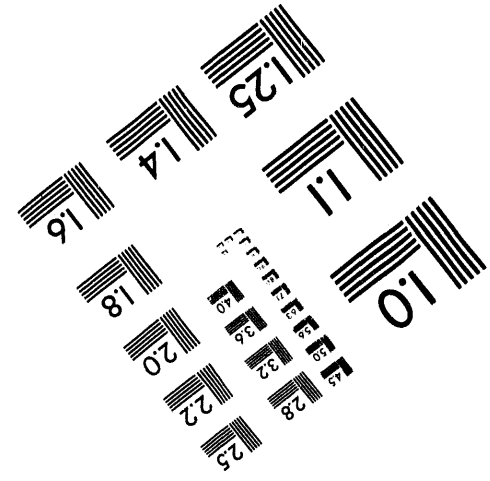

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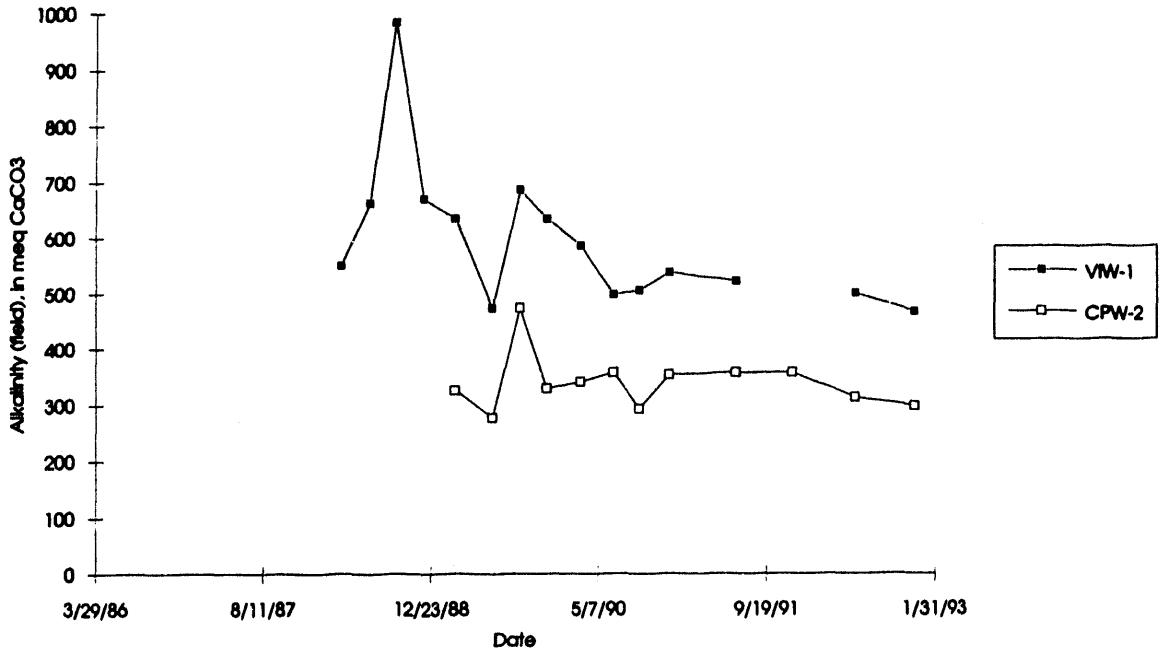

Figure 56. Alkalinity in RM1 Cavity Water

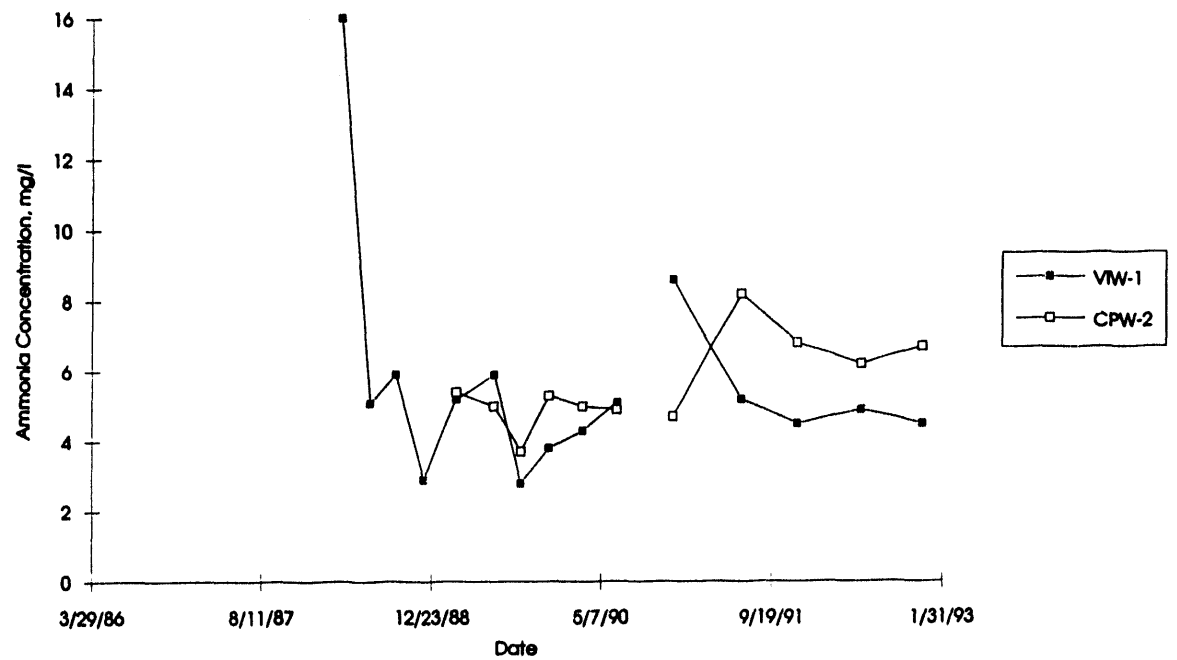

Figure 57. Ammonia in RM1 Cavity Water

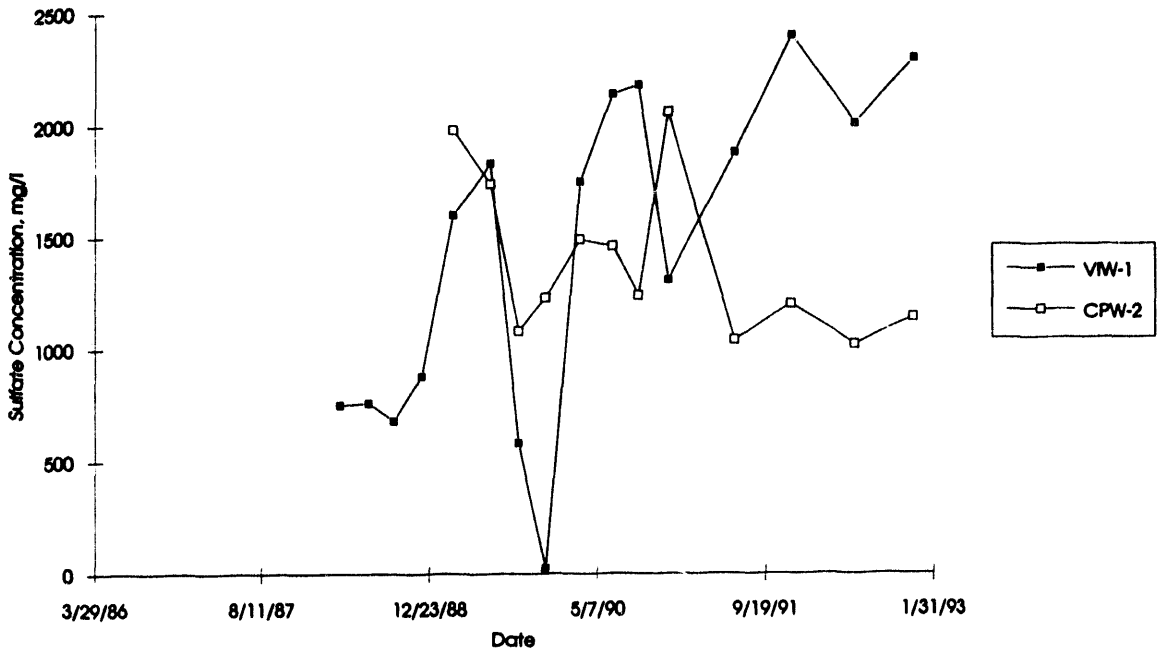

Figure 58. Sulfate in RM1 Cavity Water

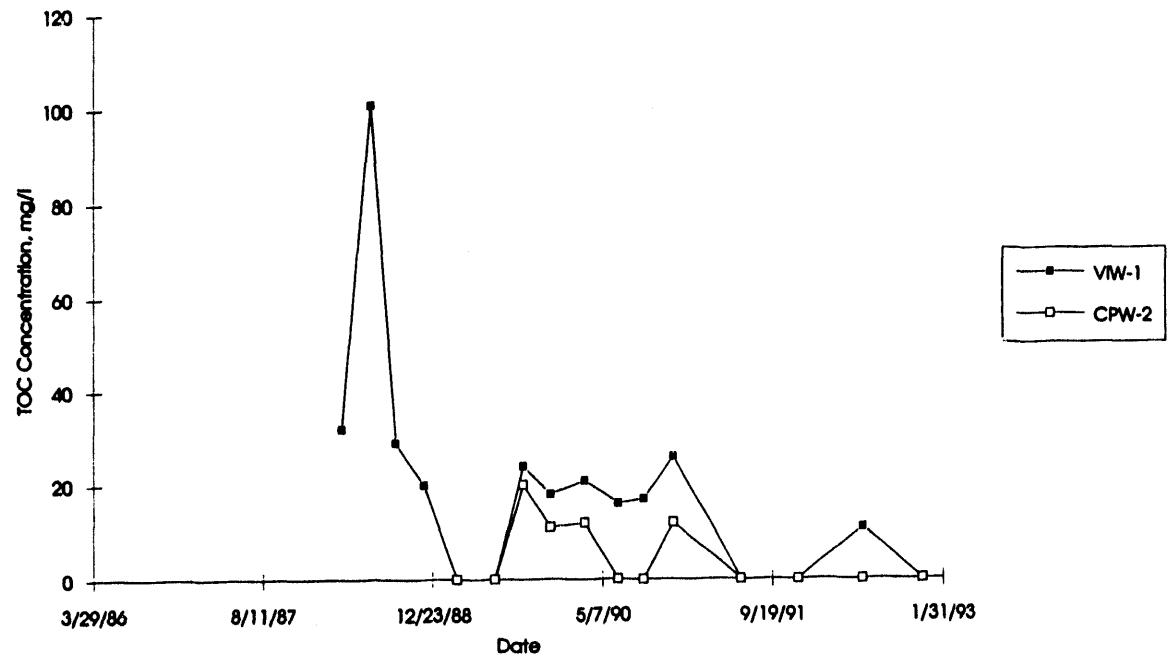

Figure 59. TOC in RM1 Cavity Water

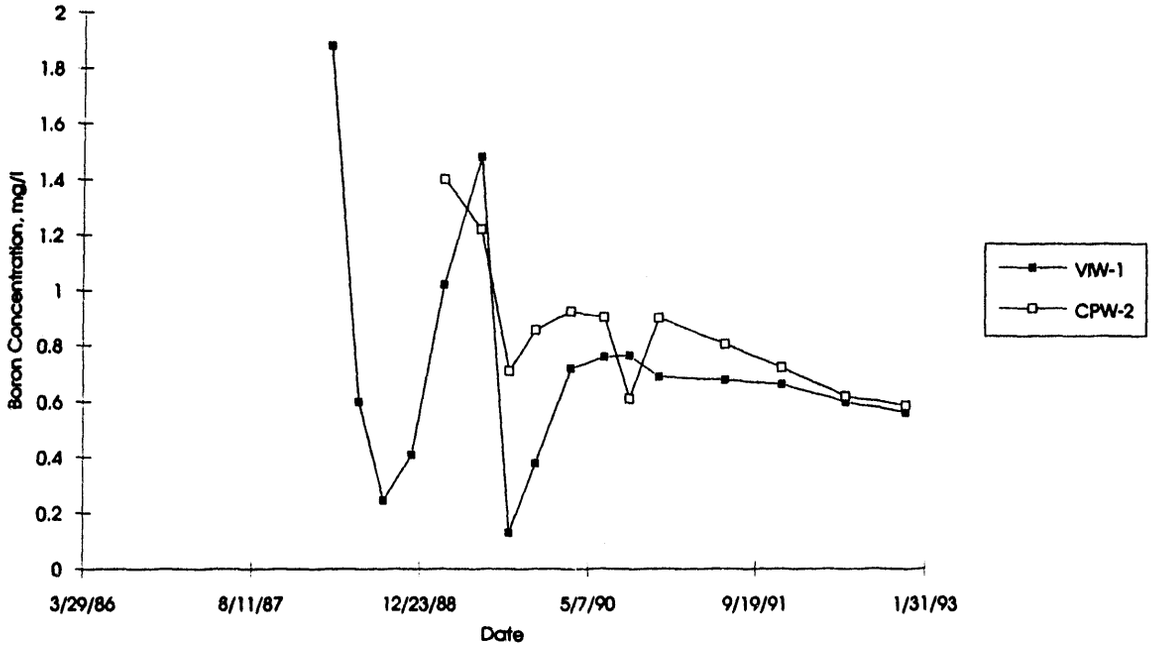

Figure 60. Boron in RM1 Cavity Water

Low concentrations of benzene have persisted in a few wells at the RM1 site. The groundwater sample collected from ELW cavity well VIW-1 had a high concentration of 380 μg/L for benzene near the end of the UCG test. However, benzene concentrations were significantly lower after termination of the test. Benzene was detected again in well VIW-1 during March 1989, after the first restoration activity. Benzene concentrations were observed until December 1989, when they dropped below the analytical detection limit. Benzene concentrations in VIW-1 have remained below the detection limit since December 1989. Water samples from coal seam well EMW-3 have occasionally contained benzene, although at low concentrations (<20 μg/L). Coal seam well EMW-1 has most frequently yielded water with low to moderate concentrations of benzene. For several years after the second restoration activity, water samples from EMW-1 have contained concentrations of benzene ranging from below the analytical detection limit to as high as 44 μg/L. Over the last year of the study, benzene concentrations have stabilized at approximately 20 μg/L. Well EMW-1 is between the two process modules, and it experienced some escaping UCG product gas during the test. Covell et al. (1992) speculated that some of these escaped gases condensed in the form of coal tars around the EMW-1 casing. If so, these tars may continue to leach low concentrations of benzene for some time.

4.0 CONCLUSIONS

The RM1 test had significant ephemeral impacts on the hydrology of the primary aquifer at the site, the Hanna No. 1 coal seam. Lesser impacts were detected in the strata above the coal seam and no impacts were observed below the coal seam.

Water levels, which had decreased over 200 ft near the center of the site during the UCG test and postburn activities, have completely recovered. The groundwater flow patterns observed during the baseline site evaluation have been reestablished. No remaining effect of the RM1 test on groundwater elevations is apparent.

The UCG test did affect groundwater quality at the site on a short-term basis. However, long-term monitoring has shown that procedures undertaken during the test, in addition to postburn restoration measures, were effective in minimizing the spread of contaminants and in removing most contaminants from the subsurface environment. Boron in the two UCG cavities remains an order of magnitude above baseline concentrations. This is not the case over the remainder of the site, as boron in groundwater samples from all other wells has remained below baseline concentrations for the last two years. Low concentrations of benzene have frequently been detected in a few inner ring coal seam wells. The benzene is probably associated with coal tars in the vicinity of these wells. The majority of wells at the site have shown no evidence of widespread benzene contamination. Total organic carbon and total dissolved solids concentrations have often been detected above baseline levels in peripheral wells along the western edge of the site; however, it is doubtful that these higher concentrations resulted from byproducts of the UCG test. Except for these instances, water quality parameters at the site are now at or below baseline levels.

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