Rocky Mountain 1
Underground Coal Gasification Test Project
Hanna, Wyoming

Final Technical Report for the Period 1986 to 2006

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1. Gas Technology Institute (GTI) is the new corporate name of the merged GRI (formerly Gas Research Institute) and the Institute of Gas Technology (IGT).
2. The U.S. Department of Energy's Morgantown Energy Technology Center (METC) became the National Energy Technology Laboratory (NETL).
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4. Anadarko Petroleum Corporation (APC) is the name for the merged Anadarko Petroleum Corporation and Union Pacific Resources (UPR).
5. The University of North Dakota (UND) Mining and Mineral Research Institute is now known as the Energy and Environmental Research Center (EERC).

In this report when there are references to historical documents, the project participant names under which these documents were issued are still used. Thus, references to GRI, Raytheon Engineers & Constructors, Inc. (Raytheon) and UPR are continued.

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ABSTRACT

The Rocky Mountain 1 Underground Coal Gasification (RM 1, UCG) Test was jointly sponsored by the U.S. Department of Energy and an Industry Consortium chaired by the Gas Research Institute. The test was conducted from November 16, 1987 through February 24, 1988. Two UCG technologies (Extended Linked Well (ELW) and Controlled Retracting Injection Point (CRIP)) were evaluated for a number of parameters for commercial application and to collect for the first time detailed environmental data in relation to process data. The test was conducted under various permits primarily issued by the Wyoming Department of Environmental Quality (WDEQ). The test site was reclaimed in 1993 following the successful clean up of groundwater from the test cavities. WDEQ subsequently deemed site reclamation a success the Fall of 2005 and released the project from further responsibility for the site.

ROCKY MOUNTAIN 1
UNDERGROUND COAL GASIFICATION TEST PROJECT
FINAL TECHNICAL REPORT FOR THE PERIOD 1986 TO 2006

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EXECUTIVE SUMMARY

The Rocky Mountain 1 (RM1) Underground Coal Gasification (UCG) Test located near Hanna, Wyoming was a cooperative venture led by the U.S. Department of Energy (DOE), the Gas Research Institute (GRI) and an industrial consortium chaired by GRI. The test started in mid-November 1987 and ran through February 1988. The test objectives called for the demonstration of two different UCG technologies and compliance with an environmental program to reduce ground water impacts resulting from test operations. The two technologies were the CRIP (Controlled Retracting Injection Point) and the ELW (Extended Linked Well) Technologies. A design basis was laid out for the test and a Facilities Design Criteria document that supported the design basis was developed. The facility presented very few operational problems which allowed the test objectives to be met. The CRIP process was successfully demonstrated on a scale that is consistent with commercial operations. Three CRIP maneuvers were performed and subsequent gasification reactors were developed. In the ELW module, gasification of the first reactor was successful, however, switchover to the second injection well with subsequent gasification was not achieved. The environmental controls implemented during the test significantly reduced groundwater impacts resulting from UCG operations.

Prior to the test, environmental studies were conducted to establish baseline information, in particular for groundwater. The baseline information also was used to obtain the required regulatory agency permits/approvals for the project. The main permits that allowed the project to be built and operated were the Wyoming Department of Environmental Quality (WDEQ) Authority to Construct for air emissions and In-Situ Research and Development (R&D) License No. 15. The latter governed all aspects of the test including construction; what surface facilities were used; pre-test, during the test and post-test groundwater monitoring; test operating conditions; post-test cavity or module groundwater clean-up; site reclamation activities; and vegetation and soils studies conducted to be released from R&D License No. 15 and associated responsibility for the project site.

The coal seam in which gasification occurred was the Hanna No. 1 coal seam that is approximately 30 feet thick and 350 feet below the surface. The test objectives achieved were:

- Identification and measurement of data for economic evaluation of commercial UCG options.
- Identification and measurement of data to develop plans to actively control possible environmental impacts.
- Identification and control of the factors that govern resource recovery.
- Identification and measurement of data for design of a prototype surface processing facility.

During the initial phase of the test when the operating pressure exceeded the hydrostatic pressure, product gases migrated updip through the coal fracture system. This migration was reflected in the coal seam groundwater samples collected and the operating pressure was reduced. The majority of the coal seam monitoring wells did not show any increases above their baseline concentration of parameters monitored.

The hydrologic system at the site responded quickly to operations-related hydraulic stimuli and also quickly readjusted. It was generally observed that within one day, the effect of test operations (e.g., operating pressure changes) was felt across the RM 1 site.

The Clean Cavern Concept was implemented during the RM 1 UCG Test to minimize environmental impacts, in particular groundwater contamination. This involved containment of produced gases within the test cavity boundaries by controlling pressure below the hydrologic confining pressure during gasification. Also, after operations, the following procedures were followed:

- The test cavities were vented to evacuate the gasification and pyrolysis gases.
- Flushing the cavities with steam or water to cool the cavity rubble and to strip residual containments.
- Removing and treating cavity water while contaminants were still contained.

These Clean Cavern Concept activities significantly reduced the environmental impacts from test operations.

Following the removal and treatment of cavity water, the WDEQ approved site reclamation. The site was subsequently reclaimed the Fall of 1993 and the project entered a ten year visual monitoring period for Bond Release. During the last three years of this period, one soil and three vegetation samplings were conducted. The results of these samplings indicated that the site had been successfully reclaimed per WDEQ criteria. Therefore, the project was released from the site and Bond Release was approved the Fall of 2005.

SECTION 1 INTRODUCTION

Over an approximate fifteen year period, starting in the 1960s, the U.S. Department of Energy (DOE) funded the Underground Coal Gasification (UCG) Program of research into the in-situ gasification of subbituminous coal. The techniques developed under the program were applied to the Rocky Mountain 1 (RM 1) UCG Test Project near Hanna, Wyoming. The project was jointly supported by DOE, the Gas Research Institute (GRI) and an industry consortium.

Pre-rest design and environmental studies began in 1986. This information was used to obtain the permits/approvals for the project, including the Wyoming Department of Environmental Quality (WDEQ) In-Situ Research and Development (R&D) License No. 15 that governed the overall activities of the project.

The RM 1 UCG Test was conducted from November 16, 1987 through February 24, 1988 near the town of Hanna in Carbon County, Wyoming. Hanna is located in the Hanna Basin, 75 miles northwest of Laramie via U.S. Highway 30 and 40 miles east of Rawlins via Interstate 80 and Highway 30. A generalized location map of the Hanna Basin and surrounding mountains and uplifts is shown in Figure 1. The location of the RM 1 license area is shown in Figure 2. The RM 1 site was located on land now owned by the Anadarko Land Corporation and was formerly owned by the Union Pacific Land Resources (UPR) Corporation.

The RM 1 UCG Test Project was jointly sponsored by the U.S. Department of Energy's (DOE) Morgantown Energy Technology Center (METC now the NETL, National Energy Technology Laboratory) and an Industry Consortium chaired by the Gas Research Institute (GRI now the Gas Technology Institute, GTI). Other members of the consortium were Amoco Production Company, Electric Power Research Institute and Union Pacific Resources Company (now Anadarko Petroleum Corporation). Stearns-Roger Division of the United Engineers and Constructors Inc. (formerly Raytheon Engineers and Constructors, Inc. and now Washington Group International) was the overall project manager with Lawrence Livermore National Laboratory (LLNL), Western Research Institute (WRI), Energy International Inc. (EI), Project Construction Corp. (PCC), and North Dakota Mining & Mineral Resources Research Institute (NDMMRRI, now Energy and Environmental Research Center) participating as project team members. Construction and support for the test was provided by PCC and EI was the test operations manager; LLNL provided instrumentation and analytical support during the test; WRI was responsible for environmental/ groundwater monitoring activities; and NDMMRRI evaluated site hydrogeology and conducted analysis on overburden core samples collected after the test, including mineralogical and morphological analyses, and correlated test process and environmental data.

Rocky Mountain 1
Underground Coal Gasification Project

Figure 1
General Location Map of the
Hanna Basin and Surrounding Basins and Uplifts

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During the test, two UCG technologies were tested: Extended Linked Well (ELW) and Controlled Retracting Injection Point (CRIP). The ELW technology is a basic design that was used in most previous UCG tests. For the RM 1 UCG Test, the ELW module consisted of two vertical injection wells (VIW-1 and VIW-2) approximately 100 feet apart for oxidant injection, the cavity of which was linked to a horizontally drilled gas production well (PW-1).

For the CRIP module, two directionally drilled horizontal holes were drilled into the coal seam: one for steam oxygen injection (CIW-1) and the second for product gas recovery (CPW-1). The CRIP module also had a vertical start-up well (CPW-2).

For the CRIP configuration a metal liner was inserted through the casing and the open hole of the injection well to the desired initial gasification point. A mobile ignitor and burner was inserted inside the liner some distance back from the end of the liner. After ignition, air or oxygen was injected through the liner during gasification. Overburden material became exposed to the process as the gasification cavity expanded and gasification efficiency began to decline because of heat loss to the overburden. The burner was retracted to the next injection point when the efficiency declined to a predetermined point. The liner was burnt off, exposing fresh coal to the UCG process, which resulted in increasing gasification efficiency. The ignitor and burner was shut off and retracted to the next injection point. This resulted in multiple gasification cavities from a single injection borehole.

For the ELW configuration gasification operations were initiated when oxygen flowed into the first injection well and produced gases were withdrawn from the production well. Subsequent vertical injection wells intersected the horizontal production well as the active gasification zone propagated away from the initial injection well along the horizontal production well.

The coal in both modules was ignited using a silane/methane igniter. Steam/oxygen mixtures (ratios from less than one to one to three to one) were used as the oxidant.

During the test, the two UCG technologies were simultaneously demonstrated on the Hanna No. 1 coal seam in an area 30 feet thick and 350 feet below the surface. Approximately 260 feet of overburden siltstone, sandstone, claystone, and shale overlies the coal seam. 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 feet 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 feet. 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 the lithologic basis, therefore the unit has been designated Unit A/B (Oliver, February 1987).

The coal seam is a confined aquifer. The hydrostatic head in the coal seam is 280 feet above the top of the aquifer. The Unit C aquifer is also confined, although the hydrostatic head rises only about one foot above the top of the aquifer.

There is a vertical upward component to the hydraulic gradient at the RM 1 site. Hydrostatic head in the underburden is higher than the coal, and similarly the hydrostatic head in the coal is higher than the Unit C aquifer. The effect of water leaking upwards into the coal from the underburden was expected to be minimal since perturbations to underlying units as a result of underground coal gasification activity typically do not occur. Leakage from the coal aquifer

upwards into Unit C also was expected to be minimal due to the siltstones and claystones in Units A and B. These units act as a confining layer to the coal seam and impede the upward vertical migration of water.

The potentiometric surface of the coal seam dips to the northwest and is affected by a fault that exists at the northeast corner of the site. The fault is probably also oriented in a northwesterly direction, and affects the localized flow regime by diverting ground water to the northwest. The fault acts as an impermeable boundary within the coal seam. The first encountered ground water at the site is in the coal seam at depths ranging from approximately 47 to 97 feet below the surface.

At the RM 1 site, 22 ground water monitoring wells were installed: one in Unit C, one in the underburden, two in Unit A (overburden directly above the coal), and 18 in the coal seam as discussed below. Water level measurements obtained from the wells were used to construct potentiometric surface maps, interpret the hydrologic flow regime, and determine hydrostatic head.

In order to establish the ground water quality in the vicinity of the RM 1 site, a ground water monitoring plan was incorporated into R&D License No. 15. The plan included a pre-test site evaluation/monitoring; monitoring during the test; and post-test monitoring. This was accomplished by installing and monitoring the network of wells. The network consisted of an outer ring of wells (TW-11 to TW-18) which surrounded an inner ring of wells (EMW-1 to EMW-11A; TW-2 to TW-5). All of the outer ring wells and eight of the inner wells were completed in the coal seam. Two wells (EMW-8 and EMW-2) were completed in an upper water-bearing unit, and one well (EMW-6) was completed in the adjacent underburden.

The ground water monitoring wells were situated in approximately two rectangles centered around the two process modules or test burn cavities. The purpose of the outer ring wells was to monitor hydrologic and ground water 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.

The groundwater monitoring wells installed in the overburden, coal seam and underburden were used for baseline studies and monitoring during and after the test. The baseline and post-test monitoring was used to evaluate groundwater quality; the test monitoring was used both to help control groundwater contamination during the test and to evaluate groundwater quality. The major parameters of concern were ammonia, boron, cyanide, phenols, TDS and TOC. These parameters had been historically shown to be the major contaminants from UCG.

The RM 1 UCG Test surface facilities consisted primarily of aboveground piping connected to control and analytical trailers, and an incinerator and flare. The latter were used after the produced gas had been analyzed for various constituents.

The facility was designed and operated in accordance with the Facility Design Criteria and the RM 1 Operations Manual, respectively. An integral part of the test was the implementation of the Clean Cavern Concept that was developed to minimize potential UCG impacts on groundwater.

SECTION 2 PURPOSE AND TECHNICAL OBJECTIVES

The purpose of the RM 1 UCG Test was to evaluate the two different technologies (ELW and CRIP) for UCG by:

- Identifying and measuring data necessary for economic evaluation of appropriate commercial UCG options.
- Identifying and measuring data necessary to develop plans to actively control environmental impacts.
- Identifying and quantifying factors which control resource recovery, and
- Identifying and measuring data necessary to design a prototype surface processing facility.

The test also had a number of technical objectives as follows:

- Drill and complete appropriate process wells.
- Design and construct surface facilities to accepted industrial standards.
- To determine test module or reactor life.
- Evaluate linking technology for the completion of drilled links.
- Gather data to be used in designing a product gas clean-up system.
- Obtain data necessary to develop plans to control interaction of active modules.
- Determine the mineralogy of the unaltered and altered RM 1 Unit A overburden, and correlate the mineralogical transformations to the temperature and time of thermal treatment.

SECTION 3 METHODOLOGY

The RM 1 UCG Test Project had three phases:

- Pre-Test Activities;
- Test Activities; and
- Post-Test Activities.

These activities are summarized below.

3.1 Pre-Test Activities

3.1.1 Site Selection and Characterization

During the Summer 1986, an extensive site selection and characterization program was conducted by WRI (Oliver, February 1987 and Mason et. al., 1987). This included installing thirty site characterization and hydrology wells to provide pre-test geologic and hydrologic information. The geologic information was used to assist in the placement of process wells. The hydrologic information was used to measure the suitability of the site for gasification against predetermined site selection criteria such as seam thickness, quality and dip, faulting, overburden strength and presence of aquifers. It was also used to evaluate groundwater parameters both during and after the test.

As part of the Site Selection and Characterization Phase, the process and facilities for the test were designed by the Stearns-Roger Division of the United Engineers & Constructors, Inc. This information was then used to obtain the appropriate Wyoming Department of Environmental Quality (WDEQ) permits including those for air emissions and the WDEQ, Land Quality Division (LQD) In-Situ Research and Development (R&D) License No. 15. These permits specified the environmental and engineering conditions under which the test was conducted. They included both test and post-test requirements in order for the project to be released from the site by WDEQ. As part of the regulatory requirements, the WDEQ established bond requirements to ensure that the project was conducted and completed per permit requirements.

3.1.2 Clean Cavern Concept

Prior to the RM 1 UCG Test, the technical feasibility of UCG had been successfully tested at a number of locations in the United States. However, there was uncertainty with respect to environmental impacts that result from UCG operations. Field tests conducted near Hanna and Hoe Creek (south of Gillette), Wyoming during the 1970's introduced UCG-produced organic and inorganic constituents into the groundwater at the two sites (Barrash et al., 1988a and b). The major organic constituents included phenols and total organic carbon (TOC); whereas, the major inorganic constituents included ammonia, sulfate, boron, and total dissolved solids (TDS). Contamination of the sites produced a perception that UCG was an inherent environmental damaging process and its continued development was environmentally unacceptable. As a result of this perception, WRI was directed by the DOE to investigate UCG environmental impacts and mitigation technologies required to establish the actual impacts of UCG operations

and to develop methods to reduce these impacts. After this program was established, GRI expanded the program.

WRI conducted a thorough investigation of the environmental impacts and operational histories of previous UCG test sites. Based on these evaluations, a conceptual model of the contamination process was developed and tested in the laboratory. From the test results, techniques designed to minimize the introduction of contaminants into the subsurface environment were formulated into operational controls called the Clean Cavern Concept (Boysen et al., 1988).

The Clean Cavern Concept was developed to reduce the generation, deposition, and transport of UCG-associated groundwater contaminants. Review of the Hoe Creek UCG tests showed that, to control water influx, operation pressures often exceeded the original hydrostatic pressure of the coal seam. This likely resulted in large gas losses, as high as 20% (Hill et al., 1980), with corresponding contamination of the coal seam and overburden aquifers during Hoe Creek operations. Because gas losses can introduce large quantities of contaminants into the groundwater, reducing the losses will reduce groundwater contamination.

Control of the UCG cavity pressure should control gas loss during operations. Containment of product gases depends on the permeability of the cavity boundaries, and on the pressure gradients between the cavity pressure and the hydrologic confining pressures (i.e., the coal and overburden). If the cavity pressure exceeds the hydrologic confining pressures product gases are forced into adjacent regions of the coal and overburden. The distance these gases can penetrate into adjacent regions depends on the permeability of the coal and overburden, and on the magnitude of the cavity pressure. Contaminants are introduced into the groundwater through condensation of UCG products (e.g., phenols) and the dissolution of gases (H_2S and NH_3). As long as the cavity pressure stays below the hydrologic confining pressures, the product gases should be confined within the cavity boundaries.

Another aspect of process control involves postoperation procedures. Residual heat in the rubble of the cavity can continue to generate pyrolysis products and can increase cavity pressure. If the cavity pressure is not relieved, it can become greater than the hydrologic confining pressures and cause movement of pyrolysis gases into unaffected regions of the coal and overburden. Not only can this cause transport and deposition of contaminants away from the cavity, but it can also cause additional pyrolysis and groundwater contaminants.

When the cavity pressures are maintained below the hydrologic confining pressures, the direction of convective transport is away from the coal. Water influx toward the cavity is converted to steam as it passes through the hot cavity walls. This provides a cooling effect on the cavity walls and opposes conductive heat transport and limiting postoperation pyrolysis. Laboratory tests show that the net heat transfer into the coal can be zero or negative (Boysen et al., 1987) at certain water flux rates. Maintaining the cavity pressure below the hydrologic confining pressures keeps the pyrolysis products confined to the cavity and reduces postoperation pyrolysis of the coal.

Flushing the gasification cavity with steam or water, helps cool the cavity rubble and walls. At gasification termination, the cavity rubble can be at temperature above 1000°C. The addition of a cooling media such as steam or water can accelerate cooling. Steam, and added water converted to steam in the cavity, can strip residual contaminants and will help evacuate the cavity gases.

The final step of the postoperation control removes residual contaminants from the groundwater while the contaminated groundwater is confined to the cavity. This helps contain the contamination to the area of the cavity and allows the affected groundwaters to be processed efficiently. Treatment of a smaller volume of concentrated contaminated groundwater is more efficient than treatment of a larger volume of diluted contaminated groundwater.

In summary, the components of the Clean Cavern Concept are designed to minimize contaminant deposition into the groundwater, reduce postoperation production of contaminants, and remove residual contaminants from the subsurface system before they can be introduced into unaffected regions of the coal. The Clean Cavern Concept has been successfully verified in laboratory testing (Boysen et al., 1987) and demonstrated in the RM 1 UCG Test as follows:

- 1) Maintaining cavity pressures below the hydrologic confining pressures during gasification. This minimized gas losses and contaminant deposition and transport.
- 2) Venting the cavities after operations to evacuate the gasification and pyrolysis gases from the cavities.
- 3) Maintaining as low a cavity pressure as possible so subsurface fluid transport is toward the cavity. This confined contaminants to the cavity and permitted influxing water to cool the cavity walls and rubble.
- 4) Flushing the cavity with steam or water to cool the cavity rubble and to strip residual contaminants.
- 5) Removing and treating cavity waters while contaminants were still contained.

3.1.3 Process Well Installation

A Drilling Plan was prepared that set the criteria for design and placement of the project's process wells (EI, 1986). Process well drilling was conducted in the Spring of 1987 and consisted of drilling six wells which were divided into the two parallel modules. The ELW module included two vertical injection wells (VIW-1 and VIW-2) and one directionally drilled medium radius production well (PW-2). The CRIP module included one directionally drilled medium radius injection well (CIW-1), a directionally drilled medium radius production well (CPW-1) and a vertical startup well (CPW-2).

The CRIP module wells were drilled to intersect at an angle of approximately 13°. The wells were approximately 1,200 feet in length with 900 feet of cased hole and 300 feet of open hole. The open hole portion of the wells ran parallel to and in the bottom one third of the coal seam with the production well crossing over the injection well. The third well required for the CRIP module was a vertical well (CPW-2) located just beyond the intersection of the two directionally drilled wells. This well was used as a start-up well.

The ELW module required one directionally drilled product well (PW-1), also approximately 1,200 feet in length with 900 feet of cased hole and 300 feet of open hole. The open hole portion of the well ran parallel to and in the bottom one third of the coal seam. Two vertical injection wells (VIW-1 and VIW-2) were installed and intersected the horizontal production well.

The process wells were designed to meet the following requirements:

- Placement within the defined coal seam area and tolerances to allow for full seam gasification; and
- Elimination of all leaks within the well annulus and casing zone to preclude toxic gas from surfacing from the reactor cavity or penetrating into other ground water zones.

The horizontal sections of the medium radius wells were placed along the bottom of the coal seam and three vertical wells were drilled relative to the directionally drilled holes (Logan, August 1987). The vertical holes were required to be within 3 to 5 feet of the horizontal sections so that communication could be made.

3.1.4 Surface Facility Construction

At about the same time that the process wells were being installed, surface facilities construction was started. These facilities were constructed between June and October 1987 during which aboveground piping was installed to carry the produced gas to an area with administration and analytical trailers, and then to an incinerator and flare.

The surface facility systems consisted of an Oxidant Injection System; a Produce Gas System; a Gasification and Linking Air System; Utility Services; Personnel Facilities; Process Instrumentation; a Product Gas Analysis System; and a Data Acquisition System, as described below.

1. Oxidant Injection System

The oxidant injection system consisted of an oxygen system, steam generators and the product gas piping system. The oxygen system was a commercially available system and included dual storage tanks and steam vaporizers. Two standard design steam boilers were used. Steam was provided for steam injection, oxygen vaporization and utility services.

The process steam and oxygen were delivered directly to steam/oxygen mixing chambers. The mixing chambers blended the steam and oxygen to the required injection ratios. The CRIP and ELW modules each had their own mixing chambers which allowed for independent steam/oxygen ratios to each module.

2. Product Gas System

The product gas system consisted of the piping from the production wellheads to a flare. A slipstream for product gas analysis was located after each wellhead for both modules. The production piping from the CRIP and EIW modules were metered and brought to the flare in separate pipelines. An incinerator was installed in the product piping directly before the flare to accommodate process excursions and incineration of nonflarable products.

3. Gasification and Linking Air Systems

The gasification air system was a low pressure high volume air system that was used to stabilize the reactor and as a backup oxidant system in the event of an oxygen or steam system failure.

Linking air was high pressure low volume air that was delivered to each module. The air system was used during initial dewatering to lift formation water up the wells and also during linking to complete the communication between the injection and production wells.

4. Utility Services

Utility services for the RM 1 project included water storage and delivery, propane storage and delivery, and electrical power. These services were designed to support the process as required.

5. Personnel Facilities

An administration area included trailers for site construction, operations personnel, storage and lunch room facilities.

6. Process Instrumentation

Process parameters measured were pressures, temperatures and flows. Critical process parameters were interfaced to the Data Acquisition System

7. Product Gas Analysis System

A product gas analysis system was designed and implemented to support the test. Two slipstreams (one for each module) was brought to the gas cleanup area from the main product gas lines. The gas was cleaned and components such as carbon monoxide, carbon dioxide, hydrogen, methane and other hydrocarbons were monitored. The product gas from each module was sampled prior to being combined into a single stream and incinerated or flared.

A data acquisition system was installed on site with the appropriate software to support the test. Raw data such as pressures, temperatures and flows was collected. The computer performed calculations on the data to give mass balance and process efficiency values. Hard copy reports with critical operating data were printed regularly. Monitoring screens displayed operating data in real-time. An interactive system with plotting capability was available to assist operating personnel in making process decisions. All final test data was incorporated on a tape at the end of the field test.

Control boards were located in the operations trailer in the administration complex. All monitors, printers and interactive systems were located in this area.

3.2 Test Activities (Operations)

3.2.1 Design Basis and Operations Philosophy

A Facility Design Criteria document established the design basis of all the surface facilities required for test operations (EI, 1987). The surface facilities were designed in accordance with the appropriate Federal and Wyoming Occupational Safety and Health Standards, and to comply with WDEQ permit requirements in particular R&D License No. 15.

The design process flow parameters for the test were derived using the LLNL process equilibrium model (Cena, 1987). The process flow parameters are shown in Table 1 and a Block Flow Diagram is shown in Figure 3. The facility was designed to allow for the defined process parameters to be used. However, procurement problems and other factors caused the actual process conditions to be modified during the test.

The primary operational objective of the RM 1 UCG Test was to collect all relevant technical and operational information required to meet the technical objectives of the program in a safe manner and in compliance with all environmental requirements. The test operations were performed in a fashion that was consistent with industrial practices with personnel safety of primary concern. The facility was designed and staffed to provide a minimum of down time which provided for maximum collection of data. The staffing level allowed for quick repairs to all systems with minimum interruption of operations. The site staff was required to attend a five day training course to become familiar with the systems, perform facility checkouts and learn about site safety. An Operations Manual (EI, 1987), provided the basis for the operational procedure and test schedule.

Table 1

RM 1 UCG Test Process Design Flows

	<u>Flow (scfm)</u>			<u>Pressure (psig)</u>		
	<u>Minimum</u>	<u>Nominal</u>	<u>Maximum</u>	<u>Minimum</u>	<u>Nominal</u>	<u>Maximum</u>
<u>Oxygen</u>						
Per Well	300	750	1,200	36	108	144
Total	600	1,500	2,000	36	108	144
<u>Steam</u>						
Per Well	300	1,000	2,000	36	108	144
Total	600	2,000	3,000	36	108	144
<u>Air</u>						
High Pressure	25	50	200	--	250	440
Low Pressure	500	2,500	3,500	36	108	144
<u>Wet Product Gas</u>						
Per Well	2,320	6,746	8,545	24	72	96
Total	4,640	13,492	16,726	24	72	96

Source: Bloomstran, M.A. et al., August 1988. Rocky Mountain 1 UCG Operations. In Proceedings of the Fourteenth Annual Underground Coal Gasification Symposium, Chicago, IL DOE/METC-88/6097 (DE88001093).

3.2.2 Operations and Facility Performance

3.2.2.1 General

The test facility operated for over 100 days with a minimum of down time due to equipment failure or maintenance requirements. However, certain changes to the test schedule were imposed due to equipment sizing and environmental or economic limitations.

The design basis called for operating pressures of up to 96 psig based upon the hydrostatic pressure in the coal seam. This pressure was demonstrated at first but had to be decreased due to communication between the two modules. Extremely low pressures could not be utilized because of excessive water influx and high velocities causing particulate production. Therefore, the majority of the test was operated over a small pressure (60 to 100 psig) range and the effects of pressure on the system performance could not be effectively tested.

The design basis also called for nominal oxygen injection rates of 750 scfm with experiments at rates of 300 to 1200 scfm. Most of the experiments were run in the oxygen ranges of 600 to 750 scfm. Lower rates were not tested because it appeared that higher rates were necessary to maintain desired coal gasification rates. The higher rates were not tested because higher flows tended to pressurize the monitoring wells.

The steam/oxygen ratio called for in the Test Plan ranged from 1.0 to 3.0. For most of the testing period, the actual ratio was at or above 2.0 because of high production temperatures at ratios of 1.0 (risk of burning CRIP liner) and the steam system was not capable of handling the higher steam ratios at high oxygen flows.

The test operations consisted of the following phases: air acceptance testing, dewatering, ignition, linking of injection and gas production wells, stabilization, oxygen gasification, CRIP maneuvers, well switchover, and shutdown. A brief summary of the operations of each phase is discussed below.

3.2.2.2 Air Acceptance Testing

Air acceptance testing was performed prior to test operations to determine the degree of natural or drilled communication between the process wells. Pressures of up to 220 psig were placed on the system, well in excess of the hydrostatic pressure. This may have caused excessive communications between the CRIP and ELW modules which were designed to not interact.

The monitoring wellhead flanges were not designed to withstand the pressures during air testing and some failed. It was not expected that such high pressures would be seen at the monitoring wellheads.

3.2.2.3 Dewatering

The process wells were dewatered immediately prior to ignition. This was accomplished through the use of air pressure and diptubes. There was a problem with diptubes plugging during dewatering. The CRIP cooling water diptube was plugged for the duration of the test.

3.2.2.4 Ignition

Ignition was accomplished by injecting pyrophoric silane into the vertical wells (VIW-1 and CPW-2) which were designed for ignition. The silane was followed by a methane/air mixture causing the coal seam to ignite. In both the CRIP and ELW modules, the first few attempts failed. After the first ignition attempt in the ELW module, the ignition tube was pulled and a nozzle was installed on the bottom of the tube. This seemed to help ignition as it was achieved on the second attempt. The CRIP ignition assembly was modified also. Some problems were encountered with freezing of the lines, but some of this was expected due to the below freezing temperatures during the test.

3.2.2.5 Linking Phase of Injection and Gas Production Wells

Linking of the ELW module was achieved by operating VIW-1 as a borehole producer at 155 psig with the product well PW-1 pressurized to 200 psig. Air injection flows to VIW-1 were 300 scfm. The link was completed after three days and was seen by equalization of the pressures in VIW-1 and PW-1.

When the link was complete, the flow patterns were switched with injection to VIW-1 and gas production from PW-1. Early in the linking phase, portable flares designed to handle particulate production and water were used to accommodate low product flows. Problems were encountered with the control systems on one portable flare which was equipped with bottled nitrogen as a valve actuator. The valve failed open on loss of nitrogen pressure causing a rapid venting of the cavity. This forced particulates and water to the surface causing plugging of the valves and dip tubes.

The CRIP linking phase was slightly more complex than the ELW linking because it required the linking of three wells instead of just two wells. The linking was accomplished by operating CPW-2 as a borehole producer at a pressure of approximately 150 psig. The two horizontal wells (CIW-1 and CPW-2) were pressurized with air to 170 psig. System pressure was frequently dropped to encourage the link. After three days, the link between CPW-2 and CIW-1 was established with the second link immediately forming after the first one. Production flow was switched to CPW-1 once the links were formed.

There was a problem with removal of produced foul water from the portable flares. This was handled by putting the water into barrels and dumping it into the foul water system to be disposed of by incineration. A piped system would have relieved many operational problems, however, this was not installed as a cost-saving measure.

3.2.2.6 Stabilization

The ELW stabilization period lasted for seven days. During this time air flow rates to VIW-1 were increased to 1000 scfm allowing for the development of the ELW cavity. The cavity pressure was kept high (up to 130 psig) to try to maintain somewhat equal pressures between the ELW and the CRIP module.

The CRIP stabilization period lasted for three days with air flows up to 1000 scfm. Pressures on both modules were maintained around 100 psig until switchover to oxygen could be made.

The switchover from air to steam and oxygen on both modules was delayed due to a problem with the oxygen flow meters. The flow meters were not the correct size for the range of oxygen flows to be used. Auxiliary flow meters had to be purchased which caused the delay.

3.2.2.7 Steam/Oxygen Gasification

Both ELW and CRIP systems were stabilized on oxygen flow prior to beginning the test schedule. Baseline conditions were set at 500 scfm oxygen, 1000 scfm steam and 100 psig pressure.

The test schedule was interrupted due to a site power outage which occurred on process day 14. The implications of the power outage were mainly to the production pressure which had to be manually controlled.

The test schedule was resumed and the facility ran with minimal operational problems. Process parameters, including production pressure, oxygen flow rate and steam/oxygen ratio were varied during the remainder of the test.

The primary mode of gasification for the CRIP module was injection through well CIW-1 and production from CPW-1. CRIP maneuvers were performed in well CIW-1. Three CRIP maneuvers were performed allowing for four CRIP reactors which were operated sequentially. A retractable ignitor assembly was used in well CIW-1 which worked well in preserving the CRIP ignitor during gasification. Average gasification rates of up to 200 tons/day were achieved in the CRIP module. More than 11,000 tons of coal were gasified over the 100 days giving an average gas heating value of 287 Btu/scf (Thorsness, 1988).

The primary mode of gasification for the ELW module was injection through either VIW-1 or VIW-2 with production through PW-1. The first reactor (VIW-1 injection) in the ELW module operated for approximately 45 days before a decline in gas quality was seen. Over 4,000 tons of coal were gasified in the first reactor giving an average gas heating value of 265 Btu/scf. Preparations were made for switchover to well VIW-2 but this was not successfully achieved. High oxygen levels were seen in the product gas during this switchover to VIW-2 even though many attempts were made to correct the situation, the module was shut down due to safety considerations.

3.2.2.8 Environmental Monitoring

As indicated in Section 3.1.1 groundwater monitoring wells were used to detect changes in groundwater quality during the test and following subsequent restoration of the site. As indicated above, the groundwater monitoring network shown in Figure 4 consisted of an outer ring of wells (TW-11 to TW-18) that surrounded an inner ring of wells (EMW-1 to EMW-11A; TW-2 to TW-5). All of the outer ring wells and eight of the inner wells were completed in the coal seam. Two wells (EMW-8 and EMW-2) were completed in the adjacent overburden unit, two wells (EMW-10 and EMW-4) were completed in an upper water-bearing unit and one well (EMW-6) was completed in the adjacent underburden. The wells were sampled on a minimum 10-day cycle and analyzed for a number of indicator compounds discussed below.

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This monitoring plan was incorporated into the WDEQ, LQD approved In-Situ Research and Development Testing License requirements. Samples from the inner ring of monitoring wells were analyzed for ammonia, boron, cyanide, phenols, TDS, and TOC (the parameters historically associated with UCG groundwater contamination). If the analytical results indicated an excursion of these constituents, as defined by the WDEQ, LQD, the project resampled the suspect well to verify the excursion. Following verification, selected outer ring wells were sampled and analyzed for the constituent(s) that showed an excursion.

Excursion criteria were based on the concentrations of indicator constituents in the groundwater and certain physical measurements. Negotiations with WDEQ, LQD established a three-tier system of excursion criteria outlined below:

1. If, during the 10 days before sampling, cavity pressures did not exceed hydrostatic pressures and water levels did not increase in the inner ring monitoring wells (indications of fluid transport away from the cavity(ies)), an excursion was defined as at least one indicator constituent exceeding the highest baseline concentration of that constituent in the same stratigraphic unit.
2. If water level increased in one or more of the inner ring monitoring wells, an excursion was defined as in (1), or as three or more indicator constituents exceeded the well's baseline mean plus two standard deviations.
3. If the nearest outer ring well exceeded that well's baseline concentration mean plus two standard deviations for the same constituent as indicated in (1) or (2), an excursion was progressing out of the test area and the WDEQ, LQD could terminate UCG operations.

In addition to the groundwater monitoring, trace gases and particulates were sampled from the UCG product gases and particulates were sampled from the UCG product gases and analyzed. Gaseous nitrogen, sulfur, and higher hydrocarbon species concentrations were measured. Particulate loading and chemical composition were also evaluated.

3.2.2.9 Test Shutdown

During shutdown the ELW system was maintained in a venting mode (with incineration) with steam injection to VIW-1 and from PW-1. The CRIP system was in forward gasification operating at a pressure of 60 psig. The ELW pressure had been held at similar levels to the CRIP module. Both modules were depressurized simultaneously over approximately an eight hour period. Initially, oxygen injection to the CRIP system was reduced slowly with the reduction in pressure while attempting to maintain velocity through the reactors. Both modules were shutdown successfully with no operational problems. The modules continued in a venting mode in preparation for ground water restoration (Boysen, 1988).

3.3 Post-Test Activities

After the test the project proceeded with the following activities as described below:

- Venting, flushing and cooling of the cavities;
- Subsurface or groundwater cleanup;

- Groundwater monitoring;
- Post-test coring and drilling; and
- Site restoration/reclamation and bond release

3.3.1 Venting, Flushing and Cooling of Cavities

After test operations were completed, the cavities were vented to permit pyrolysis gases to escape and to reduce cavity pressures. The gasification cavities were flushed with steam to cool the rubble, evacuate pyrolysis gases, and strip residual contaminants from the cavities as described in more detail below.

Test termination venting, flushing and cooling procedures were developed to meet the following objectives in accordance with R&D License No. 15:

- Sweep organic volatiles and water soluble gases from the subsurface before they can migrate into the ground water system.
- Contain residual contaminants within the cavity before processing the cavity water.
- Control groundwater and any associated UCG contamination transport toward the gasification cavities.
- Reduce or eliminate contaminant generation after test termination.
- Reduce residual contaminant levels in the cavity water.

The operations to achieve these objectives were as follows:

1. After the cavities had been depressured following the test, steam was used to flush the cavities. The steam helped speed cavity cooling and sweep the remaining UCG product gas from the cavities and to the surface where they were incinerated. The gases were incinerated until WDEQ, Air Quality Division approved venting directly to the atmosphere where H_2S levels were below the $40 \mu\text{g}/\text{m}^3$ standard.
2. After steam flushing, the cavities were maintained at near atmospheric pressure. This allowed ground water and associated UCG-induced constituents to flow into the test cavities. The water cooled the cavity rubble and walls thereby reducing continued coal pyrolysis which is the source of volatile organics and water soluble inorganics (NH_3 and H_2S) most associated with UCG affected ground water.
3. Once pyrolysis had stopped and the cavities had begun to cool, the production wells were left open and vented to the atmosphere to prevent pressure buildup in the reactors due to continuing steam generation.

After venting, flushing and cooling or test termination procedures were completed, the next stage of aquifer restoration activities was initiated. Cavity water was sampled and because the water was degraded relative to baseline conditions, plans were made to pump the cavity water to the surface for treatment and discharge.

3.3.2 Subsurface or Groundwater Cleanup (Aquifer Restoration)

During 1988 and 1989, subsurface or groundwater cleanup activities involved pumping water from the cavities to the surface for treatment and land application. A water treatment skid was purchased to precipitate or remove a number of organic and inorganic parameters from the cavity waters. The treated water was then sampled for analyses and sprayed upon the land near the RM 1 UCG site.

The results of the samplings were submitted to WDEQ, LQD for review to determine if the groundwater was similar to pre-test conditions.

When the RM 1 project was being planned, the UCG process was a relatively recent development and its interaction with the subsurface environment, in particular groundwater, was only beginning to be understood. Thus, a major emphasis of the project was placed on groundwater. As previously discussed, a comprehensive groundwater monitoring and treatment program was developed for the RM 1 project based on the Clean Cavern (Cavity) Concept. This concept was developed to reduce the generation, deposition and transport of UCG-associated groundwater contaminants. The components of the Clean Cavern Concept were:

1. Maintain cavity pressures below the hydrologic confining pressures during gasification. This was to minimize gas losses and contaminant deposition and transport.
2. Vent the cavities after operations to evacuate the gasification and pyrolysis gases from the cavities.
3. Maintain as low a cavity pressure as possible so subsurface fluid transport was toward the cavity. This was to confine contaminants to the cavity and permit influxing water to cool the cavity walls and rubble.
4. Flush the cavity with steam or water to cool the cavity rubble and to strip residual contaminants.
5. Remove and treat cavity waters while contaminants were still contained.

Following the test, groundwater restoration activities were performed in two phases: the venting, flushing, and cooling phase; and the pump and treatment phase. The objectives of the groundwater treatment program of the RM 1 project were to remove affected ground water from the subsurface environment; treat the affected water for removal of UCG-induced constituents; discharge the treated water to the land surface; and evaluate the effects of gasification and restoration through postburn groundwater monitoring. The approach was designed to maintain transport of UCG-affected groundwater into the gasification cavities where the groundwater could be collected and contained instead of the affected groundwater moving away from the cavities; the affected groundwater could be pumped from the cavities; to the surface, and the affected water could be treated for surface discharge.

The RM 1 project's In Situ Research and Development Testing License Application specified that two cavity groundwater pump and treatments could be required. The amount of water to be removed from the cavities was based on either estimated cavity volumes or physical indication that the cavity water had been evacuated from the cavities. The cavity volume was estimated from the coal volume consumed during gasification minus the ash volume. Physical indications

of water evacuation from the cavities were water level measurements and submersible pump cavitations.

The gasification cavities remained vented to the surface to promote influx of water into the cavities after the venting, flushing, and cooling operations were completed. Pressures in the cavities would increase and impede groundwater flow back into the cavities if venting was not performed. The direction of groundwater flow was inward toward the cavities, flushing any groundwater contaminants from adjacent areas back into the cavities. Maintaining water influx into the cavities ensured that groundwater affected by the UCG process could be collected and confined to the cavities. Then, it could be pumped to the surface for treatment and discharge.

Groundwater levels were measured at monitoring wells across the site to determine flow gradients around the cavities. Groundwater levels showed a cone of depression around the gasification cavities that indicated groundwater flow was directed into the gasification cavities because groundwater flows from higher potentiometric surface elevations to lower elevations. A cone of depression defines radial flow into a center of low hydrologic potential from surrounding areas of higher hydrologic potential. Little potential for contaminant transport away from the cavities existed under these conditions.

The pump and treatment phase of the RM 1 groundwater restoration began when hydrologic information indicated that the cavities created during gasification had filled with groundwater. Water levels in the monitoring wells completed in the Hanna No. 1 coal seam showed that the cone of depression had shifted away from the cavities and that the potential for contaminant transport away from the cavities existed. Water influx and cavity volume estimates also indicated that the cavities had filled with groundwater. Water levels in the wells completed in the cavity also confirmed that the cavities had filled with groundwater.

The treatment system used at RM 1 was designed prior to any on-site gasification or remediation activities. The system was designed to achieve target restoration values (TRV) that were based on the arithmetic mean of baseline concentrations in the Hanna No. 1 coal seam monitoring wells.

Groundwater was pumped from the two cavities using submersible pumps in existing process wells. The pumped water was treated to remove oils, dissolved nitrogen and sulfur species, dissolved metals, and organic compounds. The primary constituents of concern were oils, phenols, TOC, ammonia, sulfides, and heavy metals. The first treatment system consisted of six steps to prepare the pumped ground water for land application: oil and water separation, chloroxidation, heavy metal precipitation, settling and filtration, neutralization, and activated carbon adsorption. The treated water was discharged to the surface through a network of atomizing nozzles to promote dispersion and evaporation. The treatment system was permitted by the Wyoming Department of Environmental Quality, Water Quality Division (WQD) (Stearns-Roger Division, United Engineers & Constructors, Inc. February 1988).

3.3.3 Groundwater Monitoring

Following the test groundwater was monitored during the groundwater cleanup activities to determine when the groundwater flowing into the cavities reached or was near pre-test water quality. When the groundwater sampling indicated that the pre- and post-test groundwater quality were similar, WDEQ, LQD released the project from further groundwater cleanup activities and approved a well groundwater sampling schedule for 1991 and 1992. At the

conclusion of this sampling, WDEQ, LQD agreed to allow the project to proceed with site reclamation/restoration activities.

3.3.4 Post-Test Coring and Drilling

In order to determine thermal penetration in the overburden resulting from the RM 1 UCG Test, overburden core samples were collected from the altered and unaltered Unit A overburden. The samples were then subject to mineralogical and morphological analyses in order to correlate the mineralogical transformations to the temperature and time of thermal treatment.

3.3.5 Site Restoration/Reclamation and Bond Release

During 1993 the RM 1 site was reclaimed by removing all surface facilities; plugging and abandoning all wells; redistributing topsoil over the site; and re-seeding the site per R&D License No. 15 requirements. Following site reclamation, the site was visually monitored for reclamation success as part of WDEQ, LQD bond/site release requirements. Then in 2001, the project began activities required for Bond Release during 2003 to 2005 including: (1) the development of a draft bond release document for submittal to WDEQ, LQD, and (2) drafting a scope of work for vegetation and soils studies required as part of bond release.

Three vegetation samplings were conducted during the summers of 2002, 2003 and 2004, and one soil sampling was conducted during 2002. Vegetation samplings were conducted for the following parameters:

- Absolute and relative % of vegetative cover by species;
- Absolute % of bare ground;
- Absolute % total cover (sum of vegetation, litter and rock);
- Production;
- Shrub density;
- Species present in order to construct a list from sampling and observations; and
- Frequency of species.

The results of the samplings were then compared with WDEQ, LQD bond release criteria.

The soil sampling was conducted to determine if any contaminants were present in the soils where the treated groundwater had been sprayed. The parameters analyzed were similar to those for which baseline data was available.

SECTION 4 RESULTS AND DISCUSSION

4.1 Process Well Installation

The process well drilling was successful since the wells were all placed within the defined tolerances and targets as indicated by the downhole directional surveys with the exception of the casing end point of the ELW vertical process wells. The linking phase during test operations confirmed that the ELW vertical wells did not intersect the horizontal boreholes but that they were within 5 to 10 feet of each other at the time of startup. Although the specifications called for completion of the vertical wells to be 5 to 10 feet into the top of the coal seam, they were cased only 1 to 2 feet into the top of the seam (Bloomstran et al., August 1988).

4.2 Operations

The RM 1 UCG Test facilities generally met the project's objectives and resulted in a wealth of data that can be used in the development of future UCG programs. The RM 1 test featured parallel modules operating simultaneously to permit the evaluation of two different approaches to underground coal gasification. One method, the controlled retracting injection point (CRIP) process, permitted selective relocation of the point of injection of steam and oxygen. The second module consisted of a modification of a vertical injection well design called extended linked well (ELW), a basic design that has been used in most previous UCG tests. A drilled link of production wells and injection wells is required for CRIP; whereas, a variety of methods can be used for linking vertically injected modules. At RM 1, both the CRIP module and the ELW module employed a medium-radius directional drilling method to create the gas path between the process wells (Logan, August 1987).

The parallel UCG modules were operated for a 102 day period during the winter months of 1987 to 1988. During this period, operational parameters were varied to investigate the effects of steam flow rate, oxygen flow rate, steam-oxygen ratio and cavity pressure. The process data collected included gas composition (CO , CO_2 , H_2 , H_2O , CH_4 , H_2S , NH_3 , C_2S), tar/oil production rate, total gas flow rates and cavity pressure.

During the testing period, three new cavities (CRIP Maneuvers) were created in the CRIP module by withdrawing the igniter back into the unreacted coal seam and injecting propane/oxygen to initiate coal reactions in that area. The CRIP module was successfully operated during 93 days of the 102 day test. The ELW module was operated successfully for the first 51 days through one vertical injection well. Attempts to initiate a new cavity through the second injection well were unsuccessful and the experiment in the ELW module was discontinued after 51 days.

Table 2 shows the chronology of the RM 1 UCG Test starting with module ignition. Only one module, cavity or reactor was established using the ELW methodology. Four CRIP reactors were established and operated as a result of three CRIP maneuvers.

A summary of the test results is shown in Table 3. It is apparent from the data that the ELW module produced a lower heating value gas which contained much greater amounts of water than the gas from the CRIP module. In addition, the ELW module was exhausted in about one-half the period that was planned and the module had to be shutdown prematurely.

Table 2. RMI UCG Test Chronology

<u>Module</u>	<u>Activity</u>	<u>Date</u>
ELW	Ignition	11/17/87
	Oxygen Injection	11/26/87
	Shutdown	01/16/88
CRIP	Ignition	11/22/87
	Oxygen Injection	11/28/87
	#1 Maneuver	01/08/88
	#2 Maneuver	01/28/88
	#3 Maneuver	02/17/88
	Shutdown	02/26/88

Table 3. RM 1 UCG Test Summary

<u>Parameter</u>	<u>ELW Module</u>	<u>CRIP Module</u>	<u>Total</u>
<u>Injection</u>			
Oxygen, MSCF	44,461	86,650	131,111
Steam, MSCF	83,716	176,904	260,620
<u>Production</u>			
Dry Gas, MSCF	167,140	454,402	621,542
<u>Heating Value, Btu/cf</u>	275	295	
<u>Coal Gasified, Tons</u>	4050	9800	14850
<u>Gas Composition, Mole %</u>			
H ₂	32.7	39.6	
CH ₄	10.1	10.3	
CO	8.2	11.9	
CO ₂	45.7	35.3	
H ₂ S	0.8	0.6	
N ₂	0.5	0.5	
Ar	0.2	0.1	
Higher Hydrocarbons	1.8	1.7	

Source: Martin, J.W. and A.M. Hartstein. August 1988. UCG Program Overview. In Proceedings of the Fourteenth Annual Underground Coal Gasification Symposium, Chicago, Ill. DOE/METC 88/6097 (DE88001093).

4.2.1 Operating Conditions

As the test proceeded, data were summarized daily by operations staff to assist in monitoring the progress of the burn and to provide a basis for controlling experimental conditions. The following summarizes the operating conditions for pressure, oxygen flow rates, steam/oxygen ratio, gas composition and residence time, groundwater influx, and cavity vent and flush operations.

- Pressure – There was a general reduction in production pressure with time for both modules from 110 to 70 psia. This was the result of monitoring the pressure in adjacent groundwater wells during the test. Pressure reduction was necessary to minimize movement of groundwater away from the modules and contamination of surrounding strata.
- Oxygen Flow Rates – Generally oxygen flow rates increased with time from about 300 to 900 SCFM during the first fifty days for both modules. Subsequently, flow rates for the CRIP module were held virtually constant at 1000, 750, and 750 SCFM for the second, third and fourth cavities, respectively. The maximum flow rate of about 1200 SCFM oxygen was employed for one day during the first few days of the second CRIP cavity.
- Steam/Oxygen Ratio – It was planned to conduct a series of experiments on the effects of steam/oxygen ratio on both modules. However, this was only accomplished for the ELW module. Steam/oxygen ratio was maintained at 2:1 for most of the CRIP operation because of a concern of the effects of a 1:1 steam/oxygen ratio on the CRIP liner. Accordingly, limited tests were conducted on the CRIP module at a 1:1 ratio in the fourth cavity during the last two days of the test. The ELW module was operated for two days at a ratio of 3:1 and seven days at 1:1 during the first thirty days of the burn.

The results obtained for the steam/oxygen experiments suggest that dry gas production maximized somewhere between 1:1 and 2:1 at RM 1. These results correspond with the steam/oxygen ratio of 1.3:1 usually employed in the British Gas/Lurgi slagging gasifier. Because the operational characteristics of slaggers permit optimization of steam injection, the RM 1 observations may be significant for UCG operations.

- Gas Composition and Residence Time – The day-to-day gas composition data for the CRIP and ELW modules were examined with respect to water gas shift and direct methanation equilibrium. The specific equilibrium reactions are:

For each equilibrium, the corresponding ratios of gas composition and pressure were calculated using the experimental data. These “equilibrium constants” were then used to estimate an apparent temperature using equilibrium constant-temperature relationship derived from the thermodynamic data available in the JANAF Tables.

For both modules, the temperatures associated with the individual equilibria fall into a relatively narrow range and, in both cases, the temperature associated with the shift

equilibrium was typically 90° to 180°F lower than the calculated temperature of the methane equilibrium. A comparison of the corresponding temperatures for the ELW module are 100°F higher than the temperatures in the CRIP module. The equilibrium temperatures for ELW also increased slightly with time, whereas the temperatures remained relatively constant for the CRIP module. In comparison, moving bed gasifiers tend to show equilibrium methanation temperatures lower than that for shift because significant methane is produced high in the bed by devolatilization.

The average gas residence times in a UCG cavity are relatively long compared to surface coal gasifiers regardless of the method of coal/gas contracting because of the large cavities and long exit channels. Nominal gas residence times for surface gasifiers are: entrained flow – 1 second; fluid bed – 10-60 seconds; and fixed bed – 1-3 seconds.

Because the long residence times in a UCG cavity can influence factors such as gas composition, approach to chemical equilibrium and tar make and quality, estimates were made of the gas residence times for both the CRIP and the ELW cavity. These estimates assumed a nominal temperature of 1340°F, for the gases in the cavity. Residence times for the ELW and CRIP modules averaged about 10 and 20 minutes, respectively, during their operating periods.

- Groundwater Influx – The influx of groundwater into the UCG cavity from the coal seam and the adjoining geological strata is a major concern for UCG operations. This additional water provides an element of uncertainty regarding inputs into the cavity. The ELW module was at a lower elevation than CRIP due to dip of the seam thereby providing a potential for higher water influx.

At the start of the experiment the water influx rate in the ELW module was about a factor or two higher than in the CRIP module. For the ELW module, the initial water influx rate was about 4 gal/min and in the CRIP module it was about 2 gal/min. Water influx rates in both cavities increased with time to about test day 50. After test day 50, influx in both modules decreased until about day 100, apparently due to depletion of water in the seam. These results indicate one reason for better performance of CRIP, particularly for cavities two through four.

- Cavity Vent and Flush Operations – Analyses of the cavity vent gases and condensibles showed that the gasification cavities were rapidly cooled. A substantial amount of potential contaminants produced during and after gasification were removed from the cavities through the vent and flush operations.

4.2.2 Facility Performance Problems

During the test, there were problems with steam production, flow measurement, service air systems and oxygen flow.

- Steam Production – The design allowed for 100% backup capability for steam production to provide reliability in the facility operation. The boilers, as procured, did not perform to the specified capacities due to the site conditions (i.e., altitude and cold temperatures as well as operational problems). Also, more steam was required than planned because the steam/O₂ ratio was maintained higher than anticipated.

- Flow Measurement – All injectant flows and product gas flows were continually monitored throughout the test. To perform the experimental variations in steam/O₂ ratios and flows, a wide range of injectant flows was required, and shedding vortex meters were selected to provide a greater turndown capability. In operation the vortex meters were found to be very sensitive to the process environment. Physical vibrations and pressure waves through a fluid are sensed by the shedding vortex. In design, the meters must be properly located to enable them to sense a smooth flow with little vibration. The gas vortex meters were able to accurately measure the flow rate once initial startup problems were resolved. The vortex meters on the water system had particular measurement problems because of the incompressible fluid and the location of the meters. Once properly installed, the meters performed well.
- Service Air Systems – During startup, freezing problems occurred in the skid air system. Dry air was not utilized for this system, and with the cold temperature sufficient moisture was present to collect in the orifice taps and freeze. The instrument air system had dryers and did not experience any freezing problems.
- Oxygen Flow – The oxygen flow was difficult to control at a steady rate because of pressure fluctuations through the vaporizers. The problem was never exactly defined in the test, but was probably caused by inadequate heat transfer in the oxygen vaporizers because of lower than anticipated steam pressure supply and possible fouling. The flow rates required constant monitoring to maintain a steady flow.

4.2.3 Attainment of Operational and Technical Objectives

The following operational and technical objectives were attained.

- To drill and complete process wells suitable for the implementation of the test plan – A review of the state-of-the-art in directional drilling techniques and control methods was performed before selecting the drilling team. Criteria for the process wells called for placement of the directional wells in the lower one-third of the coal seam to allow for full seam gasification. It also called for near intersection of the horizontal and vertical wells. Test results during linking showed that the wells were probably within 5 feet of intersection and that they were placed in the lower half of the coal seam. However, well casing completion in the vertical wells was not made within design depth in the seam. This may have had an impact on the test program.
- To design and construct surface facilities for the test according to accepted industrial standards – The facility was designed and constructed to allow for continuous test operations for 100 days. The installed facility was built according to established industrial standards and was operated continuously with no down time or lost work time due to accidents.
- To determine reactor/module life – The first ELW reactor was operated for 45 days until the criteria for switchover was met. Four CRIP reactors were operated to establish useful reactor life cycles.
- To determine operational parameters – Operational data was collected for both modules over a wide range of conditions and for an extended period of time. Pressure experiments were limited due to environmental implications. Oxygen injection rate and steam/oxygen ratio experiments were conducted. Gasification rates were within the

predicted range with a maximum of greater than 190 tons/day achieved with the CRIP module.

- To obtain the data which can be used to compare the CRIP configuration to the ELW configuration – The CRIP system operated more efficiently than the ELW system and burned for a longer time due to the unsuccessful attempt at well switchover in the ELW module. The technical and operational data which was obtained may not allow a fair comparison of the CRIP and ELW configurations. Differences in operational data of the two modules may be due to either placement of the horizontal boreholes or differences in the geologic and hydrologic structure of the two modules.
- To evaluate linking technology for the completion of drilled links – Combustion linking was utilized to establish the fluid communications required for forward gasification in each of the modules. In each case, total communication was established in less than 4 days. Therefore, it appears that the vertical and horizontal boreholes were in close proximity to each other.
- To gather data to be used in designing a product gas cleanup system – Samples of particulates, condensable organics, and condensate water were collected under representative operating conditions and were analyzed to provide a basis for design of a cleanup system.
- To obtain the data necessary to develop plans to control interaction of active modules – Fluid interaction of the two modules were seen during the startup operations. Operating procedures were modified to minimize interactions of the two modules during operations.
- To develop an environmental data base and to demonstrate active ground water cleanup – The environmental data base was developed and includes data prior to, during and after test operations. Provisions for active ground water restoration were made and implemented.

4.3 Laboratory Characterization of Overburden Cores

The high temperatures in UCG cause thermal alteration of the overburden. Post-burn mineralogical analyses of overburden cores provided information concerning the local temperatures achieved during UCG and the thermal penetration depth that must be considered in environmental impact assessments. To calibrate these post-burn mineralogical analyses, however, it was necessary to understand the mineralogical response of the overburden material to a known thermal history.

Unit A (immediately above the coal seam) overburden cores from the RM 1 UCG site were subjected in the laboratory to a constant temperature of about 1000°C at one end and heated in an inert atmosphere for a period ranging from 15 hours to 10 days. The thermal history of the heated cores was determined via transient heat conduction calculations which were validated with point thermocouple measurements.

Mineralogical and morphological analyses comprising x-ray powder diffraction, scanning electron microscopy, and electron microprobe analysis then were corroborated with the inferred local core temperatures. Mineralogical characterization of the unaltered and the thermally treated core samples by x-ray diffraction (XRD) indicated decomposition reactions of clay and carbonate minerals and the formation of a “protomullite” ($\text{Al}_6\text{Si}_2\text{O}_{13}$) at the hottest end of the

core. These mineral transformations were correlated with temperatures in the core. Visual and XRD examination indicated partial oxidation of the core in its hotter regions. SEM characterization of the morphology of the polished surfaces of three areas of one sample showed a change from sedimentary textures in the cold end to a sintered texture in the hot end. The results of these experiments will be useful in modeling low to moderate temperature alteration of overburden under oxidizing conditions.

4.4 Groundwater Monitoring

As part of the RM 1 UCG Test program, groundwater wells were established around the site area to establish pre-test, test and post-test conditions as discussed below. This information was used to determine regulatory compliance, in particular with R&D License No. 15.

4.4.1 Pre-Test Groundwater Sampling

During the pre-test groundwater sampling a number of organic and inorganic parameters were sampled. Of primary importance were the UCG indicator parameters: ammonia, boron, cyanide, phenols, TDS and TOC because of their historical association with groundwater contamination from previous UCG tests. Groundwater may carry deposited contaminants with it in addition to leaching contaminants from cavity/module rubble and walls. Contaminant transport will be toward the cavity as long as a pressure gradient (high to low) is maintained in this direction. As the cavity fills, however, the natural flow gradient will eventually be re-established and groundwater will transport contaminants out of the cavity.

The results of the pre-test or baseline groundwater sampling for the UCG indicator species are shown in Table 4.

The results of the baseline or pre-test groundwater sampling showed that groundwater chemistries of the coal seam, Unit C overburden, and the underburden are similar. The groundwaters are high in sodium and bicarbonate ions which is typical of waters evolved through calcite dissolution and ions exchange. The baseline analyses indicated at the time of sampling that:

- Groundwater from the overburden Unit C is not suitable for WDEQ Class I, (Domestic Use) and Class II (Agriculture Use) as it exceeds standard concentrations of TDS, ammonia, iron and SAR.
- Groundwater from the Hanna No. 1 coal seam also is not suitable for Class I (Domestic Use) and Class II (Agriculture Use) as it exceeds standard concentrations of ammonia, sulfate, TDS, pH, fluoride and SAR.
- Groundwater from the underburden is not suitable for Class I (Domestic Use) and Class II (Agriculture Use) because it exceeds standard concentrations of ammonia, sulfate, TDS and SAR.
- All three groundwaters are suitable for Class III, Livestock Use.

Table 4. Summary of Baseline Sampling Groundwater Results for the RM 1 UCG Test Site (mg/L).

	<u>RANGE</u>	<u>MEAN</u>
Coal Seam		
Ammonia	2.04-7.09	3.2
Boron	<0.01-0.037	0.007
Cyanide	<0.02-<0.02	<0.02
Phenol	<0.02-<0.02	<0.020
TOC	11-45	27
TDS	1360-2750	2683
Overburden		
Ammonia	3.1-4.7	4.1
Boron	0.029-.071	0.050
Cyanide	<0.02-<0.02	<0.02
Phenol	<0.02-<0.02	<0.02
TOC	<10-10	<10
TDS	500-1040	794
Underburden		
Ammonia	4.2-6.7	5.1
Boron	0.037-0.131	0.071
Cyanide	<0.02-<0.02	<0.02
Phenol	<0.02-<0.02	<0.02
TOC	16-145	81
TDS	2250-2397	2336

Note: Values below the detection limits were assigned a zero value in computing the mean.

4.4.2 Test Groundwater Sampling

During the RM 1 UCG Test, the first groundwater sampling began approximately ten days after test startup. A number of updip wells could not be sampled because the gas communication with the gasification cavity(ies) created high wellhead pressures. It is believed that operating pressures in the CRIP cavity exceeded the hydrologic confining pressure of the coal. As a result, the cavity gases expanded into the coal seam. Gas expansion extended beyond well TW-18, however, the extent of expansion beyond TW-18 could not be determined. The operating pressure of the CRIP module was reduced when it became evident that gas loss, with resultant contamination of the coal aquifer, could occur. The pressure reduction caused expanded gases to recede back to the vicinity of the cavity boundary and permitted sampling of the updip wells.

Subsequent sampling of the monitoring wells that were in communication with the gasification gases showed that concentrations of TOC and TDS in the groundwater increased. The pH of the water was also significantly reduced from a predisturbed range of 8.0 to 8.4 to as low as 5.8. Gas from the monitoring wells may explain this reduction in water quality.

The only change in the water quality surrounding the test area occurred in the updip wells. Even the groundwater updip of the test area was not significantly affected. TOC concentrations were only elevated by a factor of 1.5 to 3.0 above baseline. TDS concentrations were only elevated a maximum of 1.25 times baseline concentrations. The increased concentrations did, however, exceed the concentration limits defining excursions in both the inner and outer rings of wells. The WDEQ, LQD could have terminated test operations, however, due to interim actions to reduce operation pressures to reverse the excursion, they allowed operations to continue. No further deterioration in water quality was observed during the remaining period of operation.

During the test there was a gradual lowering of groundwater levels across the site as water flowed toward the cavity and became involved in the gasification process. Superimposed on this general test-long pattern of decline was the effect of the shutdown and venting of the ELW module in mid-January. When this took place, the water levels in the monitoring wells closest to the ELW cavity all began to drop at an accelerated rate relative to the CRIP-related wells.

When the RM 1 test was completed in late February, water levels dropped as much as 100 feet, or as close as fifty feet to the top of the coal aquifer. This extreme drop in water levels was the result of venting of the cavities to atmospheric pressure subsequent to shutdown, creating a relatively larger hydraulic gradient from the undisturbed portions of the coal aquifer toward the burn cavities. A brief period followed during which the levels increased slightly before beginning to slowly fall in response to cavity venting and cooling. This trend persisted until mid-April 1988, this rate of rise began to level off and a period followed that was characterized by reasonably stable head over the site.

4.4.3 Post-Test Groundwater Sampling

The first post-test groundwater sampling was completed in March 1988. Of the monitoring wells completed in the coal seam, only six wells showed elevated contaminant concentrations (Table 5). All of these wells had contact with gasification gases during the gas expansion described in the Test Monitoring Section. None of the other coal seam monitoring wells showed increases above their baseline concentration. Table 5 also lists the constituent concentrations for the ELW cavity (VIW-1) which was sampled at the same time.

Table 5. RM 1 UCG Test Groundwater Contaminant Concentrations in Affected Wells (mg/L).

<u>Well</u>	<u>TOC</u>	<u>TDS</u>	<u>Phenols</u>	<u>Ammonia</u>	<u>Boron</u>
VIW-1	32 (-)	1920 (-)	10.0	16.0 (-)	1.88 (-)
EMW-1	49 (24)	2520 (1590)	0.031 (<0.02)	4.1 (2.9)	0.046 (0.020)
EMW-3	50 (29)	2020 (1531)	<0.02	3.3 (2.9)	0.023 (0.018)
EMW-11A	55 (29)	2320 (1699)	<0.02	3.4 (3.1)	0.019 (0.011)
TW-2	75 (36)	3510 (1894)	<0.02	5.7 (3.5)	<0.040 (0.016)
TW-3	61 (26)	1550 (1597)	<0.02	2.7 (2.7)	0.012 (0.016)
TW-18	67 (39)	3040 (2683)	<0.02	7.7 (7.8)	<0.010 (0.011)

Note: Values in parentheses () are average baseline concentrations, if available.

The March 1988 groundwater sampling of the RM 1 site showed significant increases of TDS (<25%) in only four of the seventeen coal seam monitoring wells and significant increases of TOC in six of the monitoring wells. A small increase in boron was observed in one well (EMW-1). The concentrations of phenols, ammonia, and boron in the ELW cavity were 10.0, 16.0, and 1.88 mg/L, respectively. These concentrations subsequently decreased to 0.081, 8.1 and 0.805 by May 27, 1988.

Groundwater sampling continued through November 1992. Groundwater quality at the site continued to approach or be similar to baseline concentrations for most parameters. Higher than baseline concentrations continued to be observed primarily for total organic carbon (TOC), total dissolved solids (TDS) and ammonia in the southwest quadrant of the site. WDEQ, LQD agreed with the project that these elevated concentrations were probably due to the influx of groundwater from offsite areas. In 1993, the WDEQ, LQD agreed that no further groundwater sampling was required and the site could be reclaimed.

4.5 Test Cavity Groundwater Cleanup

In order to reduce the impacts of the test on area groundwater, the project was required by WDEQ, LQD to treat two cavity volumes of water for metals and organics. This was accomplished by bringing a groundwater treatment skid on-site and spraying the treated water on the land near the test site. The first treatment started during August, 1988 and the second treatment started during July, 1989.

During the first treatment from August 22, 1988 through September 20, 1988, approximately 2,100,00 gallons of water was pumped from the two cavities: 1,283,00 gallons from the CRIP cavity and 817,000 gallons from the ELW cavity. This total volume represented approximately 115% of the calculated cavity void volume (1,800,00 gallons). The calculated cavity void volume was based on the volume of coal consumed minus the ash volume. Operations ceased when the water levels in the cavities dropped below the level of the pump intakes.

The results of the first treatment of RM 1 ground water indicated that:

- Contaminated groundwater was effectively collected and contained in the gasification cavities. Prior to treatment the cavity water was within baseline concentrations for most parameters.

- No oil was observed in the oil and water separation system.
- Oxidation using chlorine effectively reduced the ammonia concentration. The concentration of ammonia in the cavity water was only slightly elevated above baseline concentrations. Direct aeration with the spray system would be sufficient to reduce the ammonia concentration of the ground water for disposal. Ammonia deposition on the soil would not pose any environmental concern because the vegetation will use the ammonia as a nutrient.
- Carbon adsorption effectively removed phenols from the groundwater but was less effective in reducing TOC concentrations.
- The ground water did not contain measurable concentrations of heavy metals. This was not known until after UCG operations were completed. The treatment design plan to add sodium hydroxide had little positive impact on reducing dissolved metals concentration. It did raise the sodium concentration of the treated water.
- Boron, the only inorganic constituent that was significantly above baseline concentration, was not significantly reduced in the treatment system. Boron concentrations were low enough that it was not considered an environmental problem.
- The addition of chlorine, sulfuric acid, and sodium hydroxide increased the TDS concentration of the treated water that was deposited on the soil.
- Vegetation in the spray field/land application area was greener and healthier as a result of the moisture addition.
- In the second treatment, if required, where groundwater quality is similar or better, it is sufficient if only carbon adsorption and spray evaporation are used for treatment.

The use of carbon filters for processing groundwater the second time was verified in correspondence with WDEQ.

Between November 16 and November 28, 1988, groundwater in the Hanna No. 1 coal seam again shifted from radial flow into the test area to linear flow across the site. The second pump and treatment operation was not required at this time because ground water quality was near baseline conditions. In the spring and summer of 1989, benzene was detected in some ground water wells and prompted a second pump and treatment operation.

The treatment system for the second groundwater restoration was based on the results of the first treatment and on the expected quality of the cavity water. The oil-water separation tank and the air flotation tank were eliminated because they had little effect during the first treatment. The flocculation, sedimentation, and oxidation system remained in the process loop; however, it served only as a surge tank and filter. No attempts were made to provide coagulation, sedimentation, or oxidation with chemical additions.

During the second treatment, approximately 1,570,000 gallons of groundwater was pumped from the two cavities: 825,000 gallons from the CRIP cavity and 745,000 gallons from the ELW cavity. Pumping and treatment occurred from July 31, 1989 through August 15, 1989 and was terminated when the water levels in the activities dropped below the level of the pump intakes.

The results of the second treatment indicated that:

- The water quality of the cavity water continued to be very similar to the baseline (pregasification) water quality.
- Boron was the only constituent significantly elevated above the baseline concentration range of less than 0.037 mg/L. Phenols were detected at low concentrations during pumping; however, they were not detected during the last two days of pumping. Ammonia concentrations were slightly elevated above the baseline range of 2.4 to 7.9 mg/L. This increase in concentration may have resulted from groundwater movement from areas of higher naturally occurring ammonia rather than from UCG contamination.
- Benzene was not detected during pumping; however, it was detected in the cavities during quarterly sampling before and after pumping. This may result from local contamination in or around the sampling wells. Both the cavity sampling wells (VIW-1 and CIW-1) were used as process wells during gasification operations. Tars may have condensed in or outside of the well casings. Because of the low solubility of benzene in water, benzene slowly leaches out from the tar. As long as there is little ground water movement around the benzene source, detectable amounts of benzene can accumulate. However, if water movement around the benzene source is rapid and consistent, such as during the restoration pumping, benzene is leached in quantities insufficient for detection. The benzene concentrations during quarterly sampling may not have been representative of the water in the cavities.
- The spray application system operated as in the first pump and treatment operation. No problems were experienced.

As part of treating the groundwater, cavity water was analyzed both before and after the water treatment skid. After the second treatment, the analyses indicated that the groundwater in the cavities had water quality similar to pre-test conditions. Thus, WDEQ, LQD released the project from further cavity groundwater cleanup activities.

4.6 Site Reclamation

The RM 1 UCG Test site was reclaimed the Fall, 1993 per R&D License No. 15 requirements. This started a 10-year Bond Release period during which the site was visually monitored for reclamation success and WDEQ, LQD conducted annual site inspections.

As part of the project being released from the site and to obtain Bond Release from WDEQ, LQD, vegetation and soil samplings were conducted in 2002 and vegetation sampling was conducted in 2003 and 2004. The results of the soils sampling indicated that spraying treated groundwater on the land had not left any residues of metals and other parameters.

After 3 years of sampling the vegetation sampling results were analyzed statistically. The results indicated that all Bond Release criteria were met. In addition, the results of the samplings indicated that:

- The reclaimed area had been successful and had a variety of wheatgrasses dominant.
- The vegetation cover of the reclaimed area was capable of renewing itself under natural conditions due to the adequate presence of tillers and of rhizomatous plant species

noted in field observations. Invasion of desirable species from surrounding undisturbed lands was also noted in limited quantity.

- During the 2002, 2003, and 2004 vegetation samplings, the productivity of the reclaimed area was much higher than the comparison area. Thus, the productivity of the RM 1 site's reclaimed area was equal to the productivity on the area before mining when compared to the 1986 baseline data.
- Shrub density of the reclaimed area appeared capable of sustaining and increasing the population due to the presence of large plots of Wyoming big sagebrush.
- Pre-mining land use of R&D License No. 15 area had been livestock grazing of cattle, sheep and wildlife habitat. The post-mining plan for R&D License No. 15 was also livestock grazing of cattle and sheep in the same pattern. The revegetation area was capable of withstanding this type of grazing pressure again.
- The overall topography of the reclaimed area was generally uniform with some microtopographic variation. The site continued to be generally stable from erosion.

As a result of the 2003 and 2004 vegetation samplings, the following Bond Release criteria were met:

“(1) the vegetation cover of the affected land is shown to be capable of renewing itself under natural conditions prevailing at the site, and the vegetative cover and total ground cover are at least equal to the cover on the area before mining.....”

“(2) the productivity is at least equal to the productivity on the area before mining...”

“(3) the species diversity and composition are suitable for the approved post-mining land use and the revegetated area is capable of withstanding grazing pressure at least comparable to that which the land could have sustained prior to mining, unless Federal, State or local regulations prohibit grazing on such land.....”

“and (4) the requirements in (1), (2), and (3) are met for the last 2 consecutive years of the bonding period.”

During 2005 with the resolution of questions on the statistical analyses of the vegetation sampling data, WDEQ, LQD agreed that these Bond Release criteria had been met. Thus, Bond Release was granted on November 4, 2005 and WDEQ, LQD also terminated R&D License No. 15. This completed all regulatory agency requirements for the project.

SECTION 5 CONCLUSIONS AND RECOMMENDATIONS

The RM 1 UCG Test was an integrated effort by several organizations in which close attention was paid to site selection and characterization, environmental and permitting, process well drilling, facility design and construction, test operations and environmental restoration. The test operations were conducted for over 100 days making the test the longest duration in the history of U.S. UCG field tests. The facility design allowed for continuous operations in which operational problems did not cause a major interruption of the testing schedule. The Test Objectives called for demonstration of the ELW and CRIP modules operating simultaneously. The continuous operations allowed for most of the Test Objectives to be met. The ELW module operated for 51 days with the initial injection well and coal was gasified over a distance of 100 feet. However, switchover to the second injection well was unsuccessful. The CRIP module operated for more than 100 days with three CRIP maneuvers being performed. The RM 1 UCG test brought the CRIP technology to a point where it is ready for commercial demonstration. The test also generated more data than any other UCG test.

An analysis of the RM 1 UCG Test process data indicates the following:

- Directionally drilling of the RM 1 module links was the probable reason for good performance of both the ELW and CRIP modules.
- Based on oxygen utilization, the CRIP module was more efficient than the ELW module.
- The ELW module produced a lower heating value gas that contained much greater amounts of water than the gas from the CRIP module.
- Operation of both the ELW and CRIP modules at a steam/oxygen ratio of 1:1 resulted in about a 15% lower dry gas production rate than at ratios above 2:1.
- Oxygen efficiency decreased rapidly at flow rates above 750 scfm in the CRIP module.
- Groundwater influx was about a factor of two higher for ELW, which reduced efficiency of that module.
- Vertical process wells should be cased near the bottom of the coal seam to help to allow for full seam gasification.
- Air acceptance testing should be conducted carefully so as to not cause the system to fracture prior to startup.
- The CRIP retractable ignitor system worked well and should be considered for future use.
- Process utilities such as air, steam and oxygen should be designed taking into account all aspects such as altitude and temperature so that full design flow is possible and freezing problems can be eliminated.
- New designs for cooling water diptubes should be considered because the CRIP cooling water tube plugged early on in the test.
- Instrument air should be hard piped to all remotely operated valves.

- All critical control valves should have the capability for remote operation.
- The ignition assembly should be equipped with a nozzle to assist in ignition.
- Foul water systems should be hard piped to cut down on field operator work.
- The ELW module decline in performance starting at day 44 was related to the slow advance of the pyrolysis and reaction zones to the casing point.
- Operational performance of the CRIP module was shown to be competitive with surface gasification.
- The environmental controls developed from the Clean Cavern Concept significantly reduced the groundwater impacts resulting from UCG operations.
- When operating pressure was reduced, gas migration away from the CRIP cavity was controlled.
- The RMI UCG Test site was successfully reclaimed.

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