DOE/ET/13108-81

SAN 13108-81

UC-90c

UNDERGROUND GASIFICATION
FOR
STEEPLY DIPPING COAL BEDS
(Phase III)

MASTER

QUARTERLY PROGRESS REPORT
FOR THE PERIOD
APRIL 1 - JUNE 30, 1981

GULF RESEARCH & DEVELOPMENT COMPANY
PITTSBURGH, PENNSYLVANIA

TRW

ENERGY SYSTEMS PLANNING DIVISION
McLEAN, VIRGINIA

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE.

**It has been reproduced from the best
available copy to permit the broadest
possible availability.**

PREPARED FOR THE DIVISION OF OIL, GAS AND IN SITU TECHNOLOGY
DEPARTMENT OF ENERGY

DECEMBER, 1981

DOE CONTRACT NO. DE-AC03-77ET13108

GR&DC CONTRACT NO. 600CH101
CHEMICALS & MINERALS DIVISION REPORT NO. 624RM191

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ABSTRACT

Preparations are being made for the August start-up of Rawlins Test 2. Site construction activities began May 4 with the mobilization of the construction subcontractor. The drilling program was completed this quarter with the installation of instrumentation wells. The Experimental Basis Document, PGA Operating Manual, and DAS Operating Manual have also been completed.

DISCLAIMER

This book was written and as such contains no official endorsement by the United States Government. Neither the United States Government nor any agency thereof nor any of their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
1.0 INTRODUCTION	1-1
2.0 SUMMARY OF ACTIVITIES	2-1
3.0 EXPERIMENTAL BASIS FOR RAWLINS TEST 2	3-1
4.0 SUBSURFACE INSTRUMENTATION	4-1
5.0 PRODUCT GAS ANALYSIS OPERATING MANUAL	5-1
6.0 DATA ACQUISITION SYSTEM OPERATING MANUAL	6-1
7.0 TECHNOLOGY TRANSFER	7-1
8.0 RAWLINS TEST 1 CAVITY DEFINITION STUDY	8-1
9.0 FACILITY CONSTRUCTION	9-1

1.0 INTRODUCTION

This quarter's (April-June) activities focused on preparations for the August start-up. Site construction activities began May 4 with the mobilization of TIC, the construction subcontractor. The drilling program was completed this quarter.

The Experimental Basis Document for Rawlins test 2 has been completed and includes the experimental schedule and experimental contingency plan. (Section 3.0).

All subsurface instrumentation has been installed and is described in Section 4.0.

The Product Gas Analysis Trailer and Data Acquisition System Operating Manuals have been completed and are discussed in Sections 5.0 and 6.0 respectively.

Papers have been prepared by project personnel to be presented at the Seventh Annual Coal Conversion Symposium. Abstracts are shown in Section 7.0.

The reactor cavity from Rawlins Test 1 has been defined and is discussed in Section 8.0.

Facility construction began in May. Completed activities are discussed in Section 9.0.

Major areas of emphasis in the next quarter will be:

- Completion of site construction
- Completion of site operations manual
- DOE briefing
- Training of site personnel
- August 15 start-up and test operations

2.0 SUMMARY OF ACTIVITIES

2.1 Experimental Basis for Rawlins Test 2

The Experimental Basis Document for Rawlins Test 2 has been completed. The purpose of this document is to define the basis for the experimental program for Rawlins T-2. The document discusses process fundamentals, the conceptual model, test objectives, experimental objectives and assumptions, hypotheses, the experimental schedule and experimental contingencies.

2.2 Subsurface Instrumentation

An extensive subsurface instrumentation array was developed for Test 2 to define the reactor geometry, reactor growth pattern, and the extent of roof fall over the gasified zone during the test. In addition, provisions were made to monitor the seepage of product gas to the surface before, during, and after the test.

2.3 PGA Operating Manual

The Product Gas Analysis Trailer Operating Manual has been completed. It describes the procedures for operation of the PGA trailer during Rawlins UCG Test 2. It includes instructions for installation, operation, and calibration of each analytical instrument in the PGA trailer.

2.4 DAS Operating Manual

The Data Acquisition System Operating Manual has been completed. It describes the use of both the UCG/T2 software and hardware systems. PGA, process, downhole and environmental instrumentation are discussed.

2.5 Technology Transfer

Seven papers have been prepared by project personnel for presentation at the Seventh Annual Underground Coal Conversion Symposium to be held at Fallen Leaf Lake, California, September 7-11, 1981.

2.6 Rawlins Test 1 Cavity Definition Study

The reactor cavity from the 1979 DOE-Gulf UCG test has been defined. The study utilized coring, TV logging, sonar logging, mineralogy, and petrography to obtain a fairly complete picture of the cavity shape and location. The presence of the reactor "firepot" was confirmed and the bulking subsidence was indicated. Calculations of the coal removed were consistent with mass balance calculations during the test.

2.7 Facility Construction

Facility construction began in May. Installation of major mechanical equipment such as air compressors, boilers, flares, etc. was completed.

3.0 EXPERIMENTAL BASIS FOR RAWLINS T-2

3.1 Introduction

3.1.1 Purpose

The purpose of this document is to define the basis for the experimental program for Rawlins T-2.

3.1.2 Background

A conceptual model of the UCG-SDB process has been developed based upon:

- Process fundamentals
- Review of the literature
- Insights gained during T-1

As with any conceptual model, there are elements that are not clearly defined and require development of assumptions.

The conceptual model is defined along with a discussion of hypothesis to be tested in T-2. The experimental program is defined that will meet the requirements of the test objectives and testing of the experimental hypothesis. In addition, contingency plans are defined for occurrences that will prevent implementation of the basic program set forth in the test plan.

3.2 Process Fundamentals

3.2.1 Definitions

Process Fuel - The material consumed by oxygen in exothermic reactions to generate process heat.

Process Heat - The sensible heat generated in the oxidation zone that drives subsequent endothermic reactions in the reduction, pyrolysis and drying zones. Excess process heat is produced as sensible heat of the product gas.

Coal/Char - Coal that has dried and devolatilized to the extent that it has lost strength required to keep it in place.

Tars - The liquids produced by pyrolysis of the coal and collected in the tar-water knock-out system in the PGA.

Light Oil - The fraction of liquid products that passes through the knockout system designed to remove tars. This material consists of C_4 to C_8 hydrocarbons and is detected by the process calorimeter.

Steady State Operation - The operational mode where the net generation of process fuel is zero (the amount of fuel produced = the amount of fuel consumed).

Oxidation Zone - The initial combustion processes occur in this zone, raising the temperature from the injection fluid temperature to above 1700°K . The process heat is generated in this zone.

These reactions are extremely fast and occur in a relatively compact zone.

Reduction Zone - The chemistry in this zone is dominated by endothermic reactions.

These reactions consume energy to convert thermal energy generated in the oxidation zone to chemical energy. The temperature range for this zone is 800 to 1600°K .

Pyrolysis Zone - The devolatilization of coal to produce char and fluid products can be expressed as:

The reaction produces valuable components of the product gas ($\text{CH}_4 + \text{H}_2 + \text{CO} + \text{tar}$) as well as providing the primary process fuel (Char). The pyrolysis reactions occur at a very slow rate in the temperature range of 525 to 800°K. The chemical composition and reactivity of the char are greatly affected by the heating rate and maximum temperatures of formation. For subbituminous coals, the early stages of pyrolysis produce a shrinking and loss of mechanical strength.

Drying Zone - The in-place moisture is vaporized at temperatures of 400-500°K.

3.2.2 Process Fundamentals

The UCG process is shown in Figure 1 for both horizontal and steeply dipping coal seams. The major emphasis in technology development has been for horizontal systems with Gulf the only U.S. workers in steeply dipping seams. The system can be divided into four zones (Figure 3-2).

1. Oxidation
2. Reduction
3. Pyrolysis
4. Drying

In the actual 3-d horizontal process, they may be better represented as "halos" around the process wells. As the reactor grows, the oxidation zone expands while the reduction, pyrolysis, and drying zones apparently remain the same size. For steeply dipping seams, the oxidation zone remains relatively small while the pyrolysis and drying zones grow. The partially pyrolyzed coal in the hanging wall weakens and falls into the fire pit, "feeding" the char generation area.

Oxidation and reduction processes are relatively fast and are controlled primarily with O_2 and steam injection rates. The temperatures for these zones respond rapidly to changes in combustion rate. Pyrolysis processes take much longer to equilibrate due to the lower temperatures and the low rate of conductive heat transfer. The rate of heat release would be the primary factor. The consumption of process fuel must be the same as the amount of fuel generation to achieve steady state.

The UCG-SDB process in subbituminous coal possesses unique features. The process consists of a fixed bed reactor gravity fed by partially pyrolyzed coal falling from the hanging wall. The stratified coal/char layer on the rubble bed is pyrolyzed by the hot product gas and serves as the process fuel when contacted with oxygen as it flows through the peaked bed. The rate of fall of the coal/char is determined by the rate of heat transport to the in-place coal and the mechanical strength loss in the thermal gradient zone in the coal. Breaking probably occurs along cleats and local fractures, resulting in relatively large chunks of coal falling periodically into the bottom of the reactor.

Lateral growth probably occurs less dramatically with a "slumping" of the sidewalls in the reactor. The slumping would be constrained by the angle of repose of the coal/char rubble ($\sim 35^\circ$).

The effect of gravity of the weakened coal/char has great significance for gasification of steeply dipping subbituminous coal. As the hot product gas flows up dip to the production well, it will dry and partially pyrolyze the coal, causing it to fall to the base of the reactor. The coal/char forms a rubble bed similar to a peaked bed reactor. As the open cavity above the rubble bed grows, the gas path to the production well broadens.

3.2.3 Rawlins T-1 Observations

Evaluation of T-1 data has led to several conclusions:

1. The "firepit" mechanism is consistent with process data collected.

2. The net char make reached a maximum early in the test and decayed.
3. The CO/CO_2 ratio paralleled product heating value.
4. Methane production remained relatively constant while tar production diminished to zero.
5. There was a difference between calculation heating values (GC) and measured heating values (calorimeter) that correlates with production of light tars.

3.3 Conceptual Model

3.3.1 Description

UCG in steeply inclined beds consists of a series of steps.

Initially the process is confined to the drilled link zone. The combustion zone starts at the base of the injection well with the reaction occurring along the drilled link. The boundaries between the four zones are poorly defined with the oxidation zone growing up the open hole. Hole collapse occurs as dried and partially pyrolyzed coal loses strength and falls to the bottom of the reactor zone, creating a small rubble bed. As long as the partially pyrolyzed coal feed is less than the rate of consumption (i.e., oxygen or oxygen/steam injection) the hole will remain open. As the reactor warms up, the rate of coal/char make increases. The creation of the rubble bed limits the oxidation zone to the area directly around the injection point.

Once the rubble bed is formed and the oxidation zone confined to the base of the reactor, the boundaries between zones become more defined, (Figure 3-3). In this mode of operation, the reactor behaves much like a packed

bed reactor with the coal/char falling into the rubble pile in a gravity feed reactor. (The rate of fall of coal/char is the feed rate to the packed bed gasifier with counterflow of the fluids.) The fluid passes through stratified zones oxidizing, reducing, and pyrolyzing the coal. The fall of coal/char is controlled by the conduction of heat through the in-place coal. Temperature propagation rates of ≈ 2 ft/day have been observed in coke ovens. The coal/char from the hanging wall and side walls of the reactor are fed at roughly that rate into the rubble bed. Once the reactor wall temperature reaches a temperature of 320-350°C loss of mechanical strength occurs and further increase in temperature has small effect on the rate of coal/char production.

In this phase, the reactor will operate much as a continuous process if the rate of coal/char make is balanced with the rate of coal/char consumption, i.e., oxygen/steam injection rate. Since the rate of make is relatively constant ($k \times$ area of coal exposed), the controllable process parameter is oxygen/steam injection rate. Optimization will entail matching the oxygen/steam injection rate to the rate of coal/char make.

Operation in this mode should produce relatively constant gas composition and high chemical efficiency. Particulate production will be sporadic as coal and roof rock fall into the reactor. The reactor should be responsive to variation in oxygen/steam ratios to optimize the effects of the steam/char reaction.

Reactor growth pattern will be determined by the rate of heat transfer to the coal walls. Heat transfer will be by convection from the hot rubble bed and by the hot product gases as they move through the reactor. The dominant growth will occur along the flow path of the product gas (Figure 3-4

The shape of the process fuel consumption surface will be determined by the flow profile of the oxygen/steam mixture. At some point in time, the consumption zone will break through the rubble zone. Tar production will drop off and the product gas temperature will begin to rise. The system may approximate a Winkler gasifier during this transition period.

As the reactor grows and the area of the fuel consumption surface increases, the boundaries between zones will be less defined. Mixing of small amounts of oxygen with pyrolysis products can result in partial oxidation of the hydrocarbons. As the mixing increases, much of the light oils will be gasified preferentially.

The final phase of operation will involve gasification of partially pyrolyzed coal. The coal is consumed as it falls to the bottom of the reactor and along the side walls of the reactor. Product gas temperatures will be extremely high ($>800^{\circ}\text{F}$) and generated tar will be gasified. CO/CO_2 ratios will increase and methane production will decrease. This mode of operation will approximate the Koppers-Totzek system.

3.3.2 Measurable Process Parameters

Product Gas Temperature - Approximate temperature of the open cavity above the rubble bed. Low product gas temperatures ($<600^{\circ}\text{F}$) are indicative of a high chemical efficiency. It serves as an indicator of the effectiveness of the char production mechanism with a optimal utilization of the sensible heat from the redox zones.

Tar Make - The mass of tar produced is a good indicator of char production and is used in mass balance calculations. Early in the process apparently the tar consists largely of compound boiling below 600°F . The tar tends to thicken during the life of a module. A measure of the tar light ends can be obtained from the difference between actual heating values as measured by the process calorimeter and calculated heating values from GC gas consumption.

CO/CO_2 Ratio - The CO/CO_2 equilibrium ratio is a function of the temperature of the reactor. Although other factors, i.e., water influx, char composition, can affect CO/CO_2 values, changes in CO/CO_2 ratios of the product gas can be indicative of changes in the average reactor temperature. Values observed during Rawlins 1 ranged from 4 to 0.9 with most values falling into the 1.3 to 2 range. The higher values are indicative of a more efficient use of oxygen.

Process Pressure - The pressure drop observed between process wells at Rawlins 1 appears to be a unique feature of UCG-SDB in subbituminous coals or lignite. Initially, the pressure between wells will be quite low (<3 psig). As the rubble bed grows, the pressure drop will increase to <20 psig and probably stabilize. The rate of growth of the ΔP should be an indicator of the growth of the rubble bed.

3.3.3 Major Features of the Model

1. The process fuel moves to the oxidizing zone.
2. The composition of the coal/char falling from the roof is constant.
3. The magnitude of pyrolysis varies during module operation.
4. The composition of the process fuel (char) varies during the module operation.
5. The net rate of fuel production/consumption is the critical process parameter.
6. The rate of fuel consumption is directly proportional to the oxygen injection rate.
7. The rate of coal/char falling is a relatively weak function of the oxygen injection rate.
8. Total coal/char fall is a strong function of the area exposed to hot gases.
9. Product gas composition is determined by the oxygen/steam ratio and the composition of the process fuel.

10. The product gas temperature is a function of the thickness or efficiency of the rubble bed.
11. The volume of the oxidation zone will slowly increase during the test.
12. The volume of the oxidation zone will decrease in proportion to the increase of the oxidation zone.

The major unknowns related to the process are:

- Process fuel composition (char)
- Coal/char composite
- Rate of groundwater influx
- Rate of updip growth of the reactor
- Subsidence effects on the VIW
- Chronology of roof fall
- Ability to reverse burn link over a distance of 20-25 feet

During T-1, values for the first four unknowns were estimated. Those estimates appeared adequate and with minor revision will be used for T-2. New assumptions for T-2 are:

- The process module will perform in a fashion similar to T-1.
- Groundwater influx will average less than 1 gpm.
- Massive roof fall will not occur during the test operations.

3.4 Test Objectives

Test 2 objectives have been developed from the general requirements for commercialization of the SDB process and the specific objectives of the Rawlins program. Since this is the second test in the two-test program, remaining data needs must be met.

Objectives for Test 2 have been defined and are presented, along with technical justifications, in decreasing order of importance:

1. Install and operate a deeper and longer module. The base of the module for Test 2 must be at approximately 550 ft true vertical depth. The link zone will be at least 200 ft of open product well and should be in the lower half of the Main G seam.

Justification

Theoretical considerations and the Russian experience suggest that optimum module length is much longer in SDB than in horizontal beds. In addition, depths of up to 2000 ft may be required for commercial operation.

Data from Rawlins T-1 support the desirability of a longer link zone. In Test 1, the link zone was 50-80 ft. For Test 2, a link of 200-250 ft will represent a four-fold increase. Conceptually, a commercial operation could utilize links of 500 ft or more.

The depth of Rawlins Test 1 was 390 ft to the base of the inject well with an up-dip growth to the base of the product well casing. Product gas leakage along the product well casing and the outcrop was a problem. Operation at a greater depth (570 ft) should reduce the leakage problem. Operation at even greater depths would be more desirable for the commercial objectives, but would represent unacceptable increased drilling costs.

2. Verify system design and reliability under a longer term test. Demonstrate a UCG system for the length of time consistent with a commercial operation. The system for Test 2 will incorporate design changes and should be capable of operating for 90 days with minimum downtime.

Justification

During Test 1, operational problems developed with several of the process systems. Among these were:

- Failure of product well completion - excessive gas leakage was experienced during the latter part of Test 1. This required reduction of reactor backpressure creating severe erosion problems in the surface piping.
- Failure of backpressure control system - a high rate of erosion was found on the low pressure side of the backpressure control system. A redesign of the valve skid is required.
- Failure of the product well cooling line - shortly before the end of the test the double wall dip tube for injection of cooling water into the product well eroded through.

In addition, improved reliability is needed in flow and temperature monitoring systems, water analysis, and ventilation of the PGA trailer. Operation for 90 days should be sufficient to verify design modifications.

3. Operate and obtain process data entirely with oxygen/steam injection. Detailed information on the relationships between blast composition and rate with gas composition and production rates will be obtained. Module life and resource recovery with oxygen/steam will be defined for operation of a module over a distance of 250 ft and 90 days.

The test operations should be conducted to an established schedule. Product heating values could average 270 Btu/SCF with energy production of 1.3×10^9 Btu/day. Minimum acceptable gas quality is 210 Btu/SCF and minimum gas production rate is 3.5×10^6 SCF/day.

Justification

The oxygen/steam results from Test 1 were promising but insufficient. They indicated that production of a gas with a heating value of 220-300 Btu/SCF was feasible over the life of a module. Oxygen/steam injection will produce a medium heating value gas or synthesis gas as defined by the desired end use. Preliminary economics developed for horizontal seams favor oxygen injection on a cost/Btu basis.

Based upon the Test 1 experience it is projected that the costs for oxygen/steam injection for the length of the test will be comparable to air injection. If on-site utilization of the product gas as a fuel is realized, the actual costs could be less. Maintenance of high-capacity systems for both air and oxygen injection would be undesirable on a cost basis.

4. Install and operate a vertical injection well. A vertical process well will be installed and operated as an injection well for oxygen/steam for a period of at least 20 days under criteria stated in Objective No. 3. The well will be installed along strike from the primary injection well to simulate start-up in a new module. Process data will be obtained.

Justification

Slant drilling has disadvantages related to time required for well installation and cost per foot of well. Demonstration of a vertical injection well would offer an alternative to the slant injection well. Previous Russian SDB field tests with vertical process wells have been hampered with subsidence-caused well failures caused by weak roof properties. The more competent roof strata at Rawlins warrant an investigation into vertical well performance. A design effort may be needed to improve well design. Testing of an improved well design could provide benefits to horizontal UCG technology as well.

5. Demonstrate stepping. The injection point for the process will be switched from one process well to a second while producing from a single well. This will simulate movement of the process along a module line. Once the switch is made, operation in that mode should continue for at least 20 days to evaluate the effect.

Justification

Stepping from one injection well to another one placed diagonally up-dip should increase the areal sweep around the production well axis and improve the product gas quality. The Russian operations required stepping at Yuzhno-Abinska to replace plugged injection wells, to restore product gas quality, and to improve resource recovery. They operated on a swelling bituminous coal which aggravated the latter two problems. This coal most likely did not form a firepit and tended to channel easily. Channeling decreases both gas quality and areal sweep.

Injection into the up-dip well will continue for at least 20 days under the same criteria in Objective No. 3.

6. Determine environmental effects. The air, water, and surface will be monitored for changes related to the process. The level of effort will be similar to that for Test 1.

Justification

No significant adverse effects on the environment were detected during or after Test 1. The ambient air monitoring program should be expanded to include monitoring for H_2S on an intermittent basis. In addition, procedures for monitoring for amines on-site should be implemented on a routing basis.

7. Define SDB reactor growth patterns. The reactor growth pattern for process will be defined. The growth along strike, along dip, and vertically, must be monitored by the most cost-effective method available.

Justification

The reactor growth pattern for operation of the long module with O_2 /steam must be defined. This information is essential for the evaluation of single module operation and design of a multi-module line burn installation. The shape of the reactor, as defined by its up-dip growth (length) and its across strike growth (width) is of prime importance. Monitoring the growth pattern in real time is a difficult task and requires that the type and design of the reactor definition sensors must be state-of-the-art.

The data collected will be utilized for design of multimodule well fields for subsequent tests.

8. Determine roof strata movement. The roof strata must be monitored during and after the test. The data will be utilized to determine the mode of subsidence occurring in the reactor zone.

Justification

Subsidence has been defined as one of the major problems related to commercialization. Collection of data related to the subsidence process would prove useful for subsequent tests at Rawlins.

9. Demonstrate surface gas cleanup. A first generation prototype cleaning unit will be installed and operated on a slip-stream. The unit design will be based upon results of Test 1 studies.

Justification

Surface cleanup systems may well be one of the more costly of the process systems. Data collected at Rawlins should be applicable to other oxygen-blown UCG operations. A prototype experiment on this test will allow development of the required capabilities at the pilot-plant scale.

10. Evaluate and implement on-site use of product gas. This will involve a feasibility study for utilization of product gas as a substitute fuel for the steam generators. On-site utilization will be implemented only if it is cost effective.

Justification

On-site utilization will be useful for several reasons:

1. Public Relations - on-site utilization has not been done in the U.S.
2. Demonstration of use as a boiler fuel will be applicable on other tests.
3. It offers an opportunity for cost reduction.

3.5 Experimental Objectives/Assumptions

The test plan has developed an infrastructure for the test which will be utilized for the experimental schedule. Ignition and linking procedures have been developed in the test plan and will produce dewatered, linked, and ignited process wells suitable for gasification.

3.5.1 Experimental Objectives

The experimental schedule must define test conditions that will produce data needed to meet the defined test objectives. Specific objectives that impact upon the experimental schedule are:

- Operate and obtain process data entirely with oxygen/steam injection.
- Install and operate a vertical injection well.
- Demonstrate stepping.
- Define SDB reactor growth patterns.

3.5.2 Assumptions

The basic assumptions for the definition of the experimental schedule are:

- The firepit is the primary operating mode with the gas composition controlled by the depth of the char or partially pyrolyzed, coal in the packed bed.
- Updip reactor growth will be 3-4 ft/day at oxygen injection rates of 700-1000 SCFM.
- Optimum steam/oxygen ratios will be between 0.7 and 1.2 (molar).
- As the cavity grows, the flowrate will be held constant to maintain process conditions.
- As the cavity grows, residence time will be increased to maintain a constant coal/char feed rate.

- A net fuel production of zero will be considered as steady state system.

The primary controllable parameters in the process are:

<u>Parameters</u>	<u>Process Effects</u>
O ₂ blast rate	Process heat release oxidation reactions
Steam rate	Steam char reactions steam/oxygen ratio
Pressure	Partial pressure of gases, reactor residence time

3.6 Hypotheses

3.6.1 Major Hypotheses

There are several major hypotheses to be tested during T-2 that are related to the conceptual model. They are:

- The longer open borehole will give greatly extended module life with a longer period of performance as a packed bed reactor.
- The vertical injection well will perform similarly to the slant injection well for the test period.
- The steam/char reaction will have a significant contribution to the CO, H₂ and CO₂ content of the product gas.
- Rate of char production is a primary parameter for process control. Char make can be monitored by mass balance calculations on gas composition and tar production.

- Adjustments of the steam/oxygen ratio in the range of 0.7 to 1.2 will not significantly affect the temperature of the product gas.
- The rate of char/coal fall is directly proportional to the residence time of product gas (reactor volume being constant).

3.6.2 Secondary Hypotheses

In addition to the process model hypothesis to be tested, there are additional hypotheses related to process development. They include:

- The module can be operated at pressures of 80-120 psi without significant leakage along the outcrop.
- A second injected well can be reverse burn-linked to a module in forward gasification.
- Product gas can be utilized as a boiler fuel after preliminary cleanup through a cyclone.
- Barco balljoints can be used to relieve thermal stresses in the hot product lines.

3.7 Experimental Schedule

The schedule will include:

- Reactor stabilization
- Conversion to oxygen/steam
- Forward gasification (SIW --> SPW)
- Simultaneous linking (SPW --> VIW)
- Switch to Module 2 (VIW --> SPW)
- Forward Gasification (VIW --> SPW)
- Shutdown

The schedule for the experiments is based upon certain assumptions:

- Changes in oxygen/steam ratio will require 2-6 hours to equilibrate.
- Changes in pressure will require 2-6 hours to equilibrate.
- Changes in oxygen injection rate will take 2-4 days to equilibrate.
- Forty-eight hours will be required for a system to equilibrate and provide data representative of the flow conditions for changes in oxygen/steam ratio and pressure.
- Five to six days will be required for a system to equilibrate and provide representative data after a change in oxygen injection rate.

During the actual test, the equilibration period will be determined by monitoring critical parameters such as:

- Gas composition
- Product temperature
- CO/CO₂
- Product flowrates

The critical parameters should not change significantly over a 24 hour period when a module is at equilibrium conditions. The actual flow schedule for the experiments will be adjusted in real time as the times for stabilization are determined.

These aspects are discussed in the following sections.

3.7.1 Reactor Stabilization of the S/W Module and Conversion to Oxygen/Steam Reactor Pressure = 80 psig

<u>Process Day</u>	<u>Flows @ S/W (SCFM)</u>			<u>Comments</u>
	<u>Air</u>	<u>O₂</u>	<u>Steam</u>	
1	700	0	300	Increase O ₂ every 6 hr and decrease air as shown.
1	700	40	300	
1	350	170	500	
1	0	300	500	O ₂ flow will be reduced 15% if O ₂ > 0.5% in the product gas is detected 3 hr response time is sufficient.
2	0	375	500	
2	0	475	500	
2	0	600	700	Diameter of reactor is approximately 15 ft after PD 2.
2	0	700	700	
3		700	700	
4		700	700	Reactor grows to full width of seam after PD 5
5		700	700	

Experiments can begin after PD 5.

3.7.2 Forward Gasification Experiments at S/W and Simultaneous Linking to V/W

3.7.2.1 Steam/O₂ Experiments

<u>Process Day</u>	<u>Flows @ S/W (SCFM)</u>		<u>Steam/O₂</u>	<u>Reactor Pressure (psig)</u>	<u>Comments</u>
	<u>Oxygen</u>	<u>Steam</u>			
6	700	350	0.5	74	Keep residence time in packed bed constant by varying pressure.
7	700	560	0.8	77	
8	700	700	1.0	80	
9	700	910	1.3	84	
10	700	1260	1.8	91	
11	700	700	1.0	80	

3.7.2.2

Residence Time Experiments

Process Day	Flows at S/W (SCFM)		Reactor Pressure (psig)	% Change in Baseline Residence Time	Comments
	Oxygen	Steam			
12	700	TBD ^a	70	-10%	During this phase the VIW will be pressurized with air to form a reverse burn link between the V/W and the SPW. After a link is formed air will be injected at 200 SCFM continuously until gasification of the S/W module is terminated.
13-14	700	TBD	90	+10%	
15-16	700	TBD	105	+20%	
17-18	700	TBD	80	0%	

3.7.2.3

Oxygen Flow Rate Experiment

Process Day	Flows (SCFM)		Reactor Pressure (psig)	Comments
	Oxygen	Steam		
19-29	1000	TBD ^b	~115 psig ^b	Note increased coal fall from updip face due to increased heat release. O ₂ flow will be decreased 15% if O ₂ > 0.5% in the product gas is detected.

^a Steam flow will be that which produced the most desirable product gas composition during the former steam/oxygen experiments.

^b A reactor pressure of approximately 115 psig has to be maintained at the increased injectant flow rate to attain the "baseline" residence time which is attained at 700 SCFM steam and 80 psig.

3.7.2.4

Steam/Oxygen Experiments at Increased Oxygen Injection Rate

Process Day	Flows at S/W Oxygen	(SCFM) Steam	Reactor Pressure (psig)	Steam Oxygen	Comments
29	1000	TBD ^a	115	X ^c	O ₂ flow will be decreased 15% if O ₂ > 0.5% in the product gas is detected.
30	1000	TBD	115	1.2 X	
31	1000	TBD	115	1.5 X	
32	1000	TBD	115	1.8 X	
33	1000	TBD	115	2.0 X	

3.7.2.5

Residence Time Experiments at Increased Oxygen Injection Rate

Process Day	Flows (SCFM)			Reactor Pressure (psig)	Steam Oxygen	Comments
	Air	Oxygen	Steam			
34-35	0	1000	TBD ^a	95	-15%	O ₂ flow will be decreased.
36	0	1000	TBD ^a	75	-31%	15% if O ₂ > 0.5% in the product gas is detected.
37-39	0	1000	TBD ^a	115	0%	
40	500	0	0			A continuous air flow down S/W will be initiated and proceed until test termination.

^c The optimum steam oxygen ratio "X" is that determined during the 700 SCFM oxygen tests.

3.7.3 Reactor Stabilization of the V/W Module and Conversion to Oxygen/Steam

Reactor pressure = 80 psia

Process Day	Flows @ V/W (SCFM)			Comments
	Air	O ₂	Steam	
40	700	0	300	Steam cleaning of well on PD 40.
41	700	40	300	Increase O ₂ every 6 hr and decrease air as shown.
41	350	170	500	O ₂ flow will be decreased 15% if O ₂ > 0.5% in the product gas is detected, 3 hr response time is sufficient.
41	350	170	500	
41	0	300	500	
42	0	375	500	
42	0	475	500	
42	0	600	700	
42	0	700	700	
43	0	700	700	
44	0	700	700	
45	0	700	700	

3.7.4 Forward Gasification Experiments at V/W and Air Injection at S/W

3.7.4.1 Steam/O₂ Experiments (PD 46-51)

The V/W module steam/oxygen experiments will be identical to that of the S/W module experiments. A continuous flow of 500 SCFM of air in the S/W will be maintained to keep the S/W open in the event of V/W failure (see Section 7.2.1).

3.7.4.2 Residence Time Experiments (PD 52-58)

The residence time experiments will be identical to that of the S/W module (see Section 7.2.2).

3.7.4.3 Oxygen Flow Rate Experiment (PD 58-68)

The oxygen flow rate experiment will be identical to that of the S/W module (see Section 7.2.3).

3.7.4.4 Steam/Oxygen Experiments at Increased Oxygen Injection Rate (PD 69-73)

These steam/oxygen experiments at increased oxygen injection rate will be identical to that of the S/W module (see Section 7.2.4).

3.7.4.5 Residence Time Experiments at Increased Oxygen Injection Rate (PD 74-80)

The residence time experiments at increased oxygen injection rate will be identical to that of the S/W module (see Section 7.2.5).

3.7.5 Test Termination

The test will be terminated in accordance with the operating manual.

3.8 Experimental Contingencies

Implementation of the experimental program requires certain conditions be met. They are:

- Link established SIW + SPW.
- Link established VIW + SPW.
- Acceptance in injection fluid SIW.
- Acceptance of injection fluids VIW.
- Oxygen availability.
- Steam availability.
- Acceptance of product gas by SPW.

Failure of piping and valves will be treated initially with re-routing. These procedures will be defined in the operating procedures. Occurrence of the critical failures defined above will trigger alternate experimental procedures. Failure modes will be discussed in the following section.

3.8.1 Failure to Link

The test plan calls for linking of the slant injection well to the vertical linking well (VLW). The VLW will be operated as a borehole producer at a pressure of 100-150 psig. The SIW will be pressurized to 600-700 psi (to be determined during the air communication test) to create air flow

SIW→VLW of ~20 scfm.

At these conditions link should occur in 5-6 days.

If link has not occurred within 10 days, the product gas flow will be diverted to the product well (SPW). The air injection down the VLW will be increased to 500 scfm and a reactor stabilization schedule implemented (VLW + SPW) to reach 1000 scfm by t=12 days. The linking air injection into

the SIW will be maintained at a level sufficient for air flow (SIW + SPW) to be ~20 scfm (as measured by He tracer tests). This experiment can be summarized as:

t	Steam		Air Injection		
		VLW+VLW	VLW+SPW	SIW+VLW	SIW+SPW
0	-	150scf (150psi)	--	20scfm (600psig)	-
10	-	--	150scf (150psi)	20scfm (600psig)	-
11	-		500scfm (80psig)		20scfm (600psig)
12	-		1000scfm (80psig)		20scfm (600psig)
15	400scfm (VLW+SPW)	1000scfm (80psig)		20scfm (600psig)	
20	400scfm (VLW+SPW)	1000scfm (80psig)		20scfm (600psig)	

When linkage of SIW + SPW occurs, the experiment will revert to day 6 of the baseline schedule. If linkage has not occurred by t=20, the linking air will be started in the VIW to attempt simultaneous linking of VIW + SPW and VIW + SPW. Air injection at 1000 scfm with steam injection of 400 scfm will be maintained.

This mode will be maintained for 10 days to establish one of the two links. If neither link has been completed by that time, pressures will be increased to the rate limit of the compress and maintained for 5 days.

3.8.2 Loss of the Slant Injection Well

This is defined as an inability to introduce injection fluids into the coal seam by a safe and reliable method. If this occurs before the link with the vertical injection well is complete (VIW + PW) the system will be converted to air injection down the VLW with supplemental steam (air @ 1000 scfm steam @ 400 scfm). This mode of operation will continue until the link (VIW + PW) is complete or the SIW is restored to service.

Once the link VIW + SIW is completed, injection will be started in the VIW and the schedule defined for module #2 will be implemented.

3.8.5 Loss of Oxygen

Interruption of oxygen supply to a wellhead can result from a number of problems. They include:

- Loss of off-site supply.
- Loss of steam.
- Loss of oxygen distribution system.

Interruptions in oxygen flow for a short-term will be dealt with in operative procedures. However there are a few guidelines. Loss of oxygen flow at $t > 15$ minutes should trigger:

Loss of Oxygen System Shutdown

$t > 5$ minutes Cooling Water to P.W.
 $t > 15$ minutes Steam flow reduced to 400 scfm
 $t > 30$ minutes Air flow stable @ 1000 scfm

If the oxygen system stays down for a continuous period of greater than 48 hours, an air-stream experiment will be started. The schedule is:

		<u>Air (scfm)</u>	<u>Steam (scfm)</u>	<u>Pressure</u>
$\Delta t = 2$ days (48 hours)	1000	200	80	psig
$\Delta t = 5$ days	1000	600	80	psig
$\Delta t = 8$ days	1000	800	80	psig
$\Delta t = 11$ days	1000	1000	80	psig
$\Delta t = 14$ days	1000	400	80	psig
$\Delta t = 17$ days	Experiment Complete			

If the oxygen supply is to be down for more than 17 days additional air compressors must be obtained to allow continuation of test. During this time span, additional experiments must be planned based upon the in-hand data and revised test objectives.

3.8.3 Loss of the Vertical Injection Well (VIW)

If the VIW is lost during operation of the module #1 experiment, the entire experimental will be performed in the mode (SIW + PW). The experimental program for module #2 will be used in module #1 (in essence repeating the same experiment).

Loss of the VIW after the module has been started in forward gasification is the more probable occurrence. In the event this happens, an attempt to restart module 1 will be made. If SIW will not accept air or oxygen, the test will be either terminated or delayed until another injection well can be installed.

3.8.4 Loss of Product Well

If the product well is lost either to plugging or failure of the completion a decision must be made to:

- Terminate to test. If $t > 60$ days, and the basic objectives have been obtained this may be the best decision.
- Install a new product well - If $t < 20$ days a vertical well could be installed down dip of the PW casing and utilized for the balance of the test.
- Convert an HFEM well to a product well. This could be a cost-effective alternative to drilling a new product well.

In no case should an injection well be converted to a product well. The flow paths are too short to provide useful information and the surface systems are not designed to deal with the thermal stresses.

The impact of this decision are of such magnitude that it must be made in real time with input from Gulf management and DOE.

3.8.6 Loss of Steam

If the steam supply is lost, the system will be switched to air (flow = 1000 scfm) and maintained until repairs are made. In no case should this delay entail more than five test days.

MODES OF UCG

HORIZONTAL UCG

FIGURE 3-1 UCG PROCESS

I-D THERMAL GRADIENT

FIGURE 3-2

FIGURE 3-3

RUBBLE BED GROWTH PATTERN (EARLY STAGE)

FIGURE 3-4

RUBBLE BED GROWTH PATTERN (LATER STAGE)

4.0 SUBSURFACE INSTRUMENTATION

4.1 General

An extensive subsurface instrumentation array was developed for Test 2 to define the reactor geometry, reactor growth pattern, and the extent of roof fall over the gasified zone during the test. In addition, provisions were made to monitor the seepage of product gas to the surface before, during, and after the test.

The reactor growth monitoring wells include nine HFEM wells and one thermocouple well.

The roof fall monitoring wells include three extensometer wells and 20 subsidence monuments.

Product gas seepage will be monitored by 120 shallow soil gas wells which extend about 20 feet below the surface.

4.2 Instrumentation Array

4.2.1 HFEM Wells

Nine High Frequency Electromagnetic Mapping (HFEM) wells of the construction shown in Figure 4-1 were installed. These wells were steel cased down to 120 feet above the coal seam and fiberglass cased down to total depth.

The HFEM well placement is shown in plan view in Figure 4-2. The three hydrology wells H19, H20, and H22 can also be used as HFEM wells since they were fiberglass cased in the seam. The potential HFEM ray paths are also shown in Figure 4-2. Hot coal anywhere along the ray paths can be detected, thereby outlining the reactor growth areas.

The HFEM wells will also be used to run thermal logs on a intermittent basis to thermally map the coal seam.

4.2.2 Thermocouple Well

HFEM well 2-1 was found to be unsuitable for an HFEM well and was converted to a thermocouple well containing a spare thermocouple string from Test 1. Multi shot logs of this well indicate it is right beside the SPW drilled link. This well should offer an ideal picture of link growth during the test. Figure 4-3 shows the location of the 16 thermocouple points with respect to the "G" coal seam.

4.2.3 Extensometer Wells

Three multiple point borehole extensometers (MPBX) will be used to monitor roof fall. As shown in Figure 4-2, the extensometers are place right above the drilled link which is the major axis of the expected growth area. Figure 4-4 shows the construction of the extensometer wells. Each MPBX contains six anchors grouted between 30-50 feet apart in the coal seam overburden strata. Anchors start at ten feet above the seam.

4.2.4 Subsidence Monuments

A series of 20 subsidence monuments will be installed to measure surface movements. Their location and construction are shown in Figure 4-5 and 4-6 respectively. These monuments will be surveyed at regular intervals before, during, and after the test.

4.2.5 Sniffer Wells

A series of 120 soil gas wells were drilled on site to monitor product gas seepage from the pressurized reactor during the test. These wells are cased with one inch PVC casing and extend about 20 feet below the surface (Figure 4-7). The PVC tubing serves as a collection point from which gas samples are withdrawn and analyzed. Each well also has a thermistor to measure possible increases in soil temperature.

CROSS-SECTIONAL VIEW OF HFEM WELL CONSTRUCTION

FIGURE 4-1

PLAN VIEW OF TEST NO.2 MODULE SHOWING INSTRUMENTATION WELL PLACEMENT

FIGURE 4-2

NOTE: WELL LOCATIONS ARE WELL BASE LOCATIONS, NOT WELLHEAD LOCATIONS

FIGURE 4-3

FIGURE 4-4

LOCATION OF SURFACE SUBSIDENCE MONUMENTS FOR RAWLINS T2

FIGURE 4-5

FIGURE 4-6

SOIL GAS WELL DESIGN
GR & DC UCG TEST SITE
Rawlins, Wyoming

FIGURE 4-7

5.0 PRODUCT GAS ANALYSIS OPERATING MANUAL

5.1 Introduction

This manual describes the procedures for operation of the Product Gas Analysis Trailer during Rawlins Underground Coal Gasification Test No. 2. Reference must also be made to the Gulf Operating Manuals for each analytical instrument for installation, operation, and calibration of each instrument. These are located the Appendices in the back of this manual. This procedure must be used in conjunction with the PGA P & ID shown in Figure 5-1.

5.2 PGA System Description

The Product Gas Analysis (PGA) System is a well equipped analytical laboratory which is used to sample and analyze the gas produced by the Rawlins Underground Coal Gasification Test No. 2. The system consists of various analytical instruments and supporting subsystems.

Gas is sampled from the main product gas stream continually during the test. Sample gas is transferred from the main product gas line to the PGA trailer through 300 feet of 1" I.D. heat traced line. The water content of the gas is measured by both a dedicated Water Gas Chromatograph and a knock/out condenser conditioner system (KOCC). The KOCC system is also used to measure tar content. After passing through the KOCC and various filters, the product gas is then routed to the CO/CO₂ Analyzer, Helium Trace Gas Mass Spectrometer, O₂ Analyzer, H₂S Analyzer, Calorimeter and the Gas Chromatograph to analyze for dry gas components (Figure 5-1).

Data from all analytical instruments is entered into the site computer either manually or directly through the data logger. This data is used throughout the test for data analysis and test evaluation.

5.3 PGA System Equipment

5.3.1 Analytical Instruments

- **3 Gas Chromatographs - 2 HP #5840's**
- **Oxygen Analyzer - Teledyne 320B/RC**
- **Calorimeter - Union C-3**
- **H₂O Analyzer - Beckman GC model 320**
- **CO/CO₂ Analyzer - Anarad model 600**
- **H₂S Analyzer - Texas Analytical Control 901**
- **Helium Mass Spectrometer - Varian 925-40**

5.3.2 Hazardous Gas Monitors

- **CO Monitor/Alarm - MSA 701**
- **H₂S Monitor/Alarm - BioMarine Industries 701**
- **Combustible Gas Monitor/Alarm - MSA I-501**

5.3.3 Process System Alarms (ops Panel)

- **Temperature - TAL 306**
- **Pressure - PAL 308**
- **Flow - FAL 320**

5.3.4 PGA Local Indicators

- **Product Gas Pressure**
- **Differential Pressures**
- **Heat Trace Temperature**

- **Product Gas Temperature**
- **Product Gas Flow Rates**
- **Analytical Instrument Flow Rates**

5.3.5 KOCC System

- **Condensers - 2 sets of 2 in series**
- **Collectors - 2 sets of 2 in series**
- **KOCC Switching Panel**

5.3.6 Support System

- **Instrument air (PI-302) provided by an electrically powered air compressor (5 HP), with a dew point of less than -30°F and a flow rate of 25 SCFM at 80 psig.**
- **Gaseous nitrogen (GN₂) PI-303 will be provided in bottles located in the PGA trailer.**
- **Product gas booster compressor to use in the event of low gas pressure in the main line.**
- **Calibration gases will be located in the PGA trailer.**
- **PGA vent**

5.3.7 Other

- A fresh air circulation system is installed in the PGA trailer.
- Multiple Filters and Coalescers.
- Orifice Plate Flowmeter.
- Dry Gas Flowmeter.
- Fume Hood.
- Local Fume Exhaust Hose.

FIGURE S-1

SEARCHED	INDEXED	SERIALIZED	FILED
APR 10 1968	APR 10 1968	APR 10 1968	APR 10 1968
FBI - MEMPHIS		FBI - MEMPHIS	
TO: DIRECTOR		FROM: SAC, MEMPHIS	
SUBJECT: <u>TRW</u>		RE: <u>TRW</u>	
DATE: <u>4/10/68</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	
DATE: <u>4/10/68</u>		DATE: <u>4/10/68</u>	
TIME: <u>10:15</u>		TIME: <u>10:15</u>	
BY: <u>24</u>		BY: <u>24</u>	

5.4 PGA System Operating Procedure

5.4.1 Gas Transfer to the PGA Trailer

Immediately next to the main product gas line is a blocking valve followed by a small primary cyclone to remove particulates prior to entering the transfer line. A secondary cyclone is located inside the PGA trailer.

Operation of the gas transfer line is as follows:

- 1. Insure that the line 1" HG-307 SST is up to temperature by adjusting the controller in the PGA trailer.**
- 2. Close the product gas blocking valve prior to the secondary cyclone inside the PGA trailer.**
- 3. Open the drain valve in the primary cyclone (not shown on P&ID).**
- 4. Stand clear of the drain valve outlet and partially open HV-107-173. Allow product gas to escape for 10 minutes while the cyclone warms up.**
- 5. Close the PGA primary cyclone drain valve and fully open HV-107-173.**

5.4.2 Pre-start-up Procedure

Prior to introducing product gas into the PGA System, the following steps must be completed:

- Leak check of total system**
- Verify all heat trace systems operate**
- Verify instrument air compressor and dryer operate**
- Verify all filter elements clean and installed**
- Trained operators on-board**
- Verify process transmitters calibrated and installed**
- Verify all analytical instruments calibrated and connected**
- Verify product gas booster pump operates**
- Verify system functional test completed**
- Verify calibration gases available**
- Verify all DAS systems are connected and operate**
- Verify KOCC switch board panel power on**
- Verify all PGA System valves CLOSED**

5.4.3 Start-up Procedure

When main product gas line pressure is 30 psig or greater the PGA system can be put into operation in the following sequence:

- All valves in closed position
- Turn on all heat trace. Adjust to $400^{\pm} 10^{\circ}\text{F}$ (requires approximately one hour to stabilize). All of these controllers are located in the PGA trailer (TIC ML/HT)(TIC-1)(TIC-2)(TIC-3). A slight pressure buildup of up to 7 psig will occur but will not harm the equipment.
- Start instrument air compressor and verify 80 psig (PI-302)
- Turn on instrument air compressor dryer
- Start hot and cold water baths on KOCC. Allow 2 hours to stabilize. Verify temperature TI-317 (hot $190^{\circ}\text{F} \pm 5^{\circ}\text{F}$), TI-316 (cold $24^{\circ}\text{F} \pm 5^{\circ}\text{F}$). Adjust thermostat as necessary.
- When heat trace temperature is stabilized $400^{\pm} 10^{\circ}\text{F}$ open HV 107-173 (valve on main product gas line) see procedure below. Monitor PI-307 (30 psig minimum)
- Open valve V-0 (located just outside the trailer)
- Open valves V-1, V-23, V-24, I-1, I-2
- Monitor PI-307-A (30 psig minimum)
- Open valve V-2
- Open valves I-3, I-4
- Slowly open valve V-3. Adjust V-3 so that orifice meter (DPI 305 indicates $12^{\pm} 1$ SCFM (Refer to curves inches H_2O vs. SCFM). Allow to stabilize for approximately 10 minutes. Readjust as necessary.
- Open valve V-4

- Open valve V-27. Check temperature on hot and cold water baths.
- Verify all heat trace systems are operating (four systems). All should be $400 \pm 10^\circ\text{F}$. Readjust as necessary. Do not proceed to next step unless heat trace is up to temperature.
- On KOCC Switching Panel (KSP) depress and hold "Step Initiate" switch (S.I.S.). Push valve AV-9 switch, then release S.I.S. This allows condenser unit #1 to go in a cooling mode. Monitor TI-315. When temperature is $24 \pm 2^\circ\text{F}$. (approximately 10 minutes) go to next step.

The valve switching panel (VSP) is used to select the proper combination of valves to carry out the various steps necessary for operation of the KOCC System.

Red and green lights on the VSP for each of the main flow valves indicate when valves are open and closed. These signals are sent by position microswitches on the actuators and show actual valve positions not simply the condition that a signal has been sent to operate the valve.

NOTE: In the event of a power failure, flow of product gas through the KOCC to the instrument manifold is automatically terminated and a purge automatically begins. Valves AV-1 and AV-2 are fail closed. The gaseous nitrogen purge begins simultaneously through valves AV-4 and AV-5 which are fail open.

The relays in the switching panel are latch type and hold their position when power is interrupted. Therefore, when power is reapplied, simply pushing the green activate button returns all valves to their previous positions. A detailed KOCC operating procedure is discussed in Appendix C.

- Depress and hold S.I.S. Push valve AV-6 switch. Release S.I.S. This allows product gas to enter the flowmeter.
- Confirm that pressure adjusting screw is fully out on PCV 320
- Open valve V-11 and V-11A (Downstream of dry gas flowmeter FIT 320).
- Open valves V-7, V-8, V-9, V-10.
- Depress and hold S.I.S. Push valve AV-1 switch. Release S.I.S. This allows product gas to flow through condensor Unit #1 to PCV 320 and through the flowmeter (FIT 320).
- Adjust PCV 320
- Adjust V-11A until FIT 320 reads $1 \text{ SCFM} \pm 0.1 \text{ SCFM}$.
- Adjust PCV 320 until PI 320 reads in the 10-20 psig range.
- Readjust flow to $1 \text{ SCFM} \pm 0.1 \text{ SCFM}$ by adjusting V-11A.
- If the above conditions cannot be met with the present valve setting adjust as follows.

For low flow slowly close V-3 while monitoring FIT 320. Allow flow to stabilize. Adjust again if necessary.

For high flow slowly close V-4 while monitoring FIT 320. Allow flow to stabilize. Adjust again if necessary.

NOTE The KOCC is designed to operate at peak efficiency with a flow rate of $1 \text{ SCFM} \pm 0.2 \text{ SCFM}$.

NOTE All of the PGA analytical instruments are now ready to receive product gas.

The following procedures describe how to introduce product gas to each instrument.

CO/CO₂ IR Analyzer

- Open valve V-13 downstream of analyzer
- Open valve V-12 upstream of analyzer
- Adjust valve V-12 until FIT reads 50 cc/min. (± 5 cc minimum)
- Monitor and adjust PCV 320 or V-11A so that FIT 320 indicates $1 \pm 0.1 \text{ SCFM}$.
- Analyzer is now on line.
- Refer to Gulf IR Analyzer Operations Manual located in Appendix H for installation, operation, and calibration procedures for this instrument.

Helium Trace Gas Mass Spectrometer

The Helium Spectrometer is only on line about 2% of the time.
Do not put on line if not needed.

- Open valve V-17.
- Slowly open valve V-16 and monitor FIE 323.
- Adjust valve V-16 so that FIE 323 indicates 100 cc/min.
± 25 cc/min minimum).
- The Trace Gas Mass Spectrometer has two other components associated with it:
 - a. Helium Trace Data Logger
 - b. Trace Gas Injection Switch
- Monitor and adjust PCV 320 or V-11A so that FIT 320 indicates 1 ± 0.1 SCFM
- Analyzer is now on line
- Refer to Gulf Helium Trace Gas Mass Spectrometer operating manual (Appendix L) for installation, operating and calibration procedures.

Calorimeter

- Open valve V-18
- Verify main shut-off valve is closed in calorimeter
- Open valve V-21
- Monitor and adjust PCV 320 or V-11A so that FIT 320 indicates 1 ± 0.1 SCFM

- Analyzer is now on line
- Refer to Gulf Calorimeter operating manual for installation, operating, and calibration procedures. This is located in Appendix E.

H₂S Analyzer

- Slowly open valve V-19, monitor PI-322, adjust V-19 so PI-322 indicates 8 psig
- Adjust internal flowmeter to 0.6 SCFM
- Monitor and adjust PCV 320 or V-11A so that FIT 320 indicates 1 ± 0.1 SCFM
- Analyzer is now on line
- Refer to Gulf H₂S Analyzer manual located in Appendix F for installation, operating and calibration procedures.

O₂ Analyzer

- Open valve V-20
- Refer to Gulf O₂ Analyzer manual for installation, operating and calibration procedures. This manual is located in Appendix G.

Primary Gas Chromatograph

- Refer to Gulf operating instructions for HP 5840 GC located in Appendix I and the HP manual located in the PGA trailer.

- Open and adjust V-22 so that PI-325 indicates 5 ± 0.2 psig
- Monitor and adjust PCV 320 or V-11A so that FIT 320 indicates 1 ± 0.1 SCFM

Secondary Gas Chromatograph

- Refer to Gulf operating instructions for cryogenic HP 5840 GC located in Appendix K and the HP manual located in the PGA trailer.

Room Air Monitors

- Refer to operating instructions for Room Air Monitors located in Appendix M.

6.0 DATA ACQUISITION SYSTEM OPERATING MANUAL

6.1 Introduction

The Data Acquisition System (DAS) operations manual has been written to perform three services for DAS operators:

- Provide a quick reference for solving temporary operational problems.
- Familiarize operators with an overview of the DAS.
- Provide general instructions in the operation of the DAS.

The remaining text in each section describes the hardware, function and/or purpose involved in a particular operating procedure followed by annotated instructions.

Section 2.0 describes the accessible hardware and specific hands-on instructions for restoring the hardware to an operational state. Section 3.0, User Interaction, describes the activities operators will be performing from logging on to specific instructions on generating graphs, reports, obtaining system status information, recovering from system failures, recording operator comments, entering manually acquired data, calculating mass/energy balances, and displaying or modifying the data structures. Section 4.0 discusses messages displayed on the system console terminal and the actions to be taken when these messages are received. Section 5.0 describes the power failure recovery and down logical units recovery procedures. The appendices contain: (A) description of the data base, (B) description of the system common, (C) examples of processor messages, (D) description of system messages, and (E) the contents of CHANID, the data logger channel identification file.

6.1.1 Operator

Three levels of operator capability will be employed on the DAS:

- LEVEL 1 Data display operations, reports and plots
- LEVEL 2 Manual data inputs and data display operations
- LEVEL 3 General data modification and display operations
in addition to level 2 operations

All operators will be calling specific programs to conduct their data handling tasks. The level 1 operators will be working exclusively with generating report and plots from existing data. The level 2 operators will

be entering manually gathered data as well as generating reports and plots. Level 3 operators will have the additional ability to display and modify the contents of common and the data base. This enables them with the capability to change coefficients, software switches, acquired data and derived data. This high level of accessibility to the data also contains the potential risk of destroying good data or corrupting the integrity of the system.

As a means of controlling access each operator will be required to log on. The log on procedure will control the level at which that operator is allowed to interact with the DAS.

6.1.2 Software

The structure of the DAS software is derived from the following major functional requirements;

1. Acquire all relevant data from the UCG test.
2. Process the acquired data to obtain a meaningful form.
3. Archive the processed data for latter detailed analysis.
4. Display the processed data in printed reports and graphic plots during the test for operator evaluation and recording.

The major data paths for the DAS are shown in Figure 6-1. The letters associated with each data path are discussed below:

- a. Periodically (normally every 5 minutes) data measured by the data logger is read into the computer. This data accounts for the vast majority of the acquired data.
- b. The primary gas chromatograph (GC) is one of several instruments measuring the composition of the product gas. Due to the nature of the instrument about 1 or 2 measurements are automatically acquired from the primary GC every hour.
- c. Data which is measured manually (i.e., TDR cables, KOCC tar/water, etc.) is entered to the computer by the operators. These manual entries are initiated by the operators.
- d. The operators can enter comments to provide a permanent log of significant events.
- e. Computer personnel have the capability to display and modify data stored in the data base. In addition, the ability to display and modify parameters and data internal to the software is provided.

FIGURE 6-1: BASIC DATA PATHS FOR THE DAS

- f. Printed reports containing test information can be generated automatically or on operator request. Several different types of reports are available.
- g. Plots present the test information in graphic form. Plots of data for the last 24 hours at 5 minute intervals, or plots of data contained in the data base can be obtained.
- h. The data base contains an hourly average of all the data collected by the DAS and six hour (mass balance, energy balance and operating efficiencies) data. In addition, all the data acquired from the primary GC and the manually entered data is stored in the data base.
- i. The comment log contains a permanent record of all comments entered by the operators.
- j. The processor messages contains a permanent record of errors, abnormal conditions and significant events reported by the DAS.
- k. The data scratch contains all the data in five minute intervals for the last 24 hours. This data is used mainly for high resolution plotting.
- l. The archive tape records all data collected or derived by the DAS and the operator comments.
- m. The backup tape periodically (every 12 hours) saves the condition of all the DAS files. This procedure makes it possible to restore the DAS file if they are somehow corrupted.

6.1.3 Hardware

The hardware configuration for the DAS is designed to support the software functional capabilities described above. Figure 6-2 shows the major components of the DAS hardware configuration. These components consist of the DAS hardware system, the Product Gas Analysis (PGA) instrumentation, the process instrumentation, the downhole instrumentation and the environmental instrumentation.

6.1.3.1 Computer System

Figure 6-3 shows the computer system in more detail. The computer acts as the main controller for the DAS. It collects and logs the test data, does any specified processing on the data and acts as the user/operator interface for the DAS. The elements of the computer system are as follows:

FIGURE 6-2 DAS High Level Hardware Configuration

FIGURE 6-3 HP 1000 Computer System Hardware

- **Central Processing Unit CPU (HP 2113B minicomputer)**
A general-purpose small computer that is especially well suited for real-time applications that demand high performance.
- **384 K Byte Memory**
Error correction capability. Battery backup for power failure situations.
- **Real Time Clock**
Drives the sequencing of program execution within the CPU.
- **HP-IB Interface/Digital Clock (HP 5930A)**
Provides an accurate and reliable time-of-day standard.
- **Disk Interface/Disk Drive (HP 7906)**
Used for operating system, program and data storage. Provides 19.6 mega bytes of on line storage. Two platters (one fixed and one removable). Error correction capability.
- **Mag Tape Interface/Mag Tape Drives 1 and 2 (HP 7970)**
Used to archive data and backup disk storage. Nine track, 800 bpi, NRZI recording technique. 45 ips recording speed.
- **Line Printer Interface/Line Printer (HP 2767)**
Used to print the various reports. Drum printing mechanism. 80 columns wide. 300 lines per minute printing speed.
- **Serial Interface/Printing Terminal (HP 2635A)**
Functions as the system console, providing a permanent record of system activity. Dot matrix (7x9) printing mechanism. 136 columns wide. 180 characters per second printing speed. Keyboards.
- **Serial Interface/Graphics Terminal (HP 2648A)**
Provides the primary mode of operator interaction with the computer system and is located in the operations room. Alphanumeric and graphic capability. Capable of providing hard copy of alphanumerics or graphics via the plotter/printer.
- **Plotter/Printer (HP 7245A)**
Provides a hard copy of graphics or alphanumeric displayed by the graphics terminals.
- **Serial Interface/Graphics Terminal (HP 2648A)**
Provides the primary mode of test director interaction with the computer system and is located in the administration room. Alphanumeric and graphic capability. Capable of providing hard copy of alphanumerics or graphics via the plotter/printer.

- **Serial Interface/Data Logger (Fluke 2240B)**
Provide the primary test data input path. Measures analog signals (T/C's, voltages, 4-20 ma).
- **Serial Interface/Primary GC**
Provide automatic startup and data acquisition capability to the Primary GC.
- **Serial Interface/Spare**
Provide a spare serial interface for replacement in case of hardware malfunction. May be used as helium tracer interface if development schedule allows.

6.1.3.2 Product Gas Analysis (PGA) Instrumentation

Figure 6.4 shows the various components of the PGA instrumentation. The instruments determine the concentrations of the compounds in the product gas. The instrumentation consists of the following items:

- **H₂O Analyzer**
Based on gas chromatography. One 0-1 volt and one switch closure output to the data logger.
- **KOCC Water and Tar Removal**
Removes water and tar from the product gas. Water and tar data are acquired manually and then manually entered into the computer.
- **CO/CO₂ Analyzer**
Infrared spectroscopic analyzer. Measures CO and CO₂ concentrations. Two 4-20 ma volt signals to the data logger.
- **Helium Analyzer**
Based on mass spectroscopy. Measures the concentration of the helium used to determine the reactor void volume. The data is acquired manually and then manually entered into the computer.
- **O₂ Analyzer**
Analog voltage signal to the data logger.
- **H₂S Analyzer**
Dual range, 0-1000 ppm or 0-10,000 ppm. 0-10 volt signal to the data logger.
- **Calorimeter**
Continuous measurement of low Btu gas. Range: 190-350 Btu/scf. Analog voltage signal to the data logger.

FIGURE 6-4 PGA Instrumentation

- **Primary GC (Gas Chromatograph), HP5840**
Provides the primary analysis measurements of the product gas. Measures H₂, N₂, O₂/Ar, CO₂, CO, H₂S, CH₄, C₂H₄, C₂H₆, C₃H₈, C₄H₈, C₄H₁₀ and C₅⁺ concentrations. Internal micro-processor control. Serial interface to the computer.
- **Secondary GC, HP5840**
Performs component analysis of auxiliary gases (e.g., bubbler tube samples, oxygen/argon separation and light oil analysis) The data is acquired manually and entered into the computer. Performs as a backup to the primary GC.
- **PGA Process Measurements**
Monitors flows, temperatures and pressures in the PGA piping. 4-20 ma analog signals to the data logger.
- **PGA Room Air Monitors**
Monitors the concentrations of hazardous gases within the PGA trailer. There are 3 monitors (CO, H₂S and combustible gas). Analog signals to the data logger.

6.1.3.3 Process Instrumentation

The process instrumentation is used to acquire data on the gas and water flows in the above ground process piping. The major parameters measured are the flow rates of the following components:

- **Air injection**
 - Linking air compressor - high pressure
 - Linking air compressor - medium pressure
 - Stabilization air compressor - low pressure
(can also be used to measure auxiliary gas injection)
- **Steam injection**
- **Oxygen injection**
- **SPW cooling water**
- **Steam/Oxygen Mixtures**
 - SIW
 - VIW
- **Product Gas**
 - Product gas to flare
 - Product gas to boiler

Each flow measurement, with the exception of the SPW cooling water, consists of a pressure, temperature and differential pressure measurement.

In addition to flow measurements discussed above, the following measurements are made:

- Wellhead temperatures and pressures.
- Total steam flow generated by the boilers.
- Steam quality.
- Valve controller outputs.
- Switch closures.

Process instrumentation consists of four classes of transducers:

1) flow meters, 2) pressure sensors, 3) temperature sensors, and 4) equipment status.

Flow meters consist of the following:

- Turbine meters.
- Annubars (differential pressure) sometimes called head meters.
- Orifice meters (differential pressure).
- Venturi flow meter (differential pressure).

The pressure sensors used are variable capacitance transducers. All temperature sensors are thermocouples or resistance temperature devices (RTD). The equipment status indicators are:

- Valve controller outputs.
- Switch closures.

All of the process instrumentation signals go to the data logger, and with the exception of the switch closures, are 4-20 ma signals.

6.1.3.4 Down Hole Instrumentation

The down hole instrumentation consists of thermocouples in the four process wells, three extensometer wells, and one thermocouple well. The signals from these thermocouples go to the data logger.

The three extensometer wells contain six anchors each. A thermocouple is located at each anchor, and one thermocouple is placed in the sensor head. In addition a TDR cable is located in each well. The extensometer and thermocouple data is automatically acquired by the data logger, while data from the TDR is acquired manually and then manually entered into the computer.

The thermocouple well contains a leg-branched string of 16 thermocouples. Signals from the thermocouple string go to the data logger. In addition to temperature measurements from the thermocouple string, diagnostic measurements indicating the operating condition of each thermocouple are made. Also located within the thermocouple well is a time-domain reflectometer (TDR) cable. Data from the TDR is acquired manually and entered into the computer.

6.1.3.5 Environmental Instrumentation

Besides the instrumentation discussed in the previous sections, the computer also collects and stores information concerning weather and other facility-related data. This environmental data consists of:

- Weather conditions
 - Ambient air temperature
 - Atmospheric pressure
 - Relative humidity
- Miscellaneous
 - Two trailer temperatures
 - Flare temperatures.

6.2 Table of Contents

The Table of Contents and list of Appendices for the Data Acquisition System Operator's Manual follows;

TABLE OF CONTENTS

	<u>Page</u>
1.0 INTRODUCTION	1-1
1.1 Operators	1-1
1.2 Software	1-2
1.3 Hardware	1-4
1.3.1 Computer System	1-4
1.3.2 Product Gas Analysis (PGA) Instrumentation	1-8
1.3.3 Process Instrumentation	1-10
1.3.4 Down Hole Instrumentation	1-11
1.3.5 Environmental Instrumentation.....	1-12
2.0 ACCESSIBLE COMPUTER HARDWARE	2-1
2.1 Terminals	2-1
2.2 Printer	2-2
2.3 Magnetic Tape Drives	2-2
2.4 Computer	2-2
2.5 Peripheral Restoration Procedures.....	2-2
3.0 USER INTERACTION	3-1
3.1 Levels of Operator Interaction	3-1
3.2 Logging On Procedures	3-1
3.3 Logging Off Procedures	3-1
3.4 Operating Procedures	3-2
3.4.1 Graphs	3-2
3.4.1.1 x-y Plots From Data Base.....	3-3
3.4.1.2 Pie Plots From Data Base.....	3-5
3.4.1.3 x-y Plots From 5 Minute Data	3-6
3.4.2 Reports	3-8
3.4.2.1 Management Report	3-11
3.4.2.2 Shift Report	3-11
3.4.2.3 Hourly Status Report	3-11
3.4.2.4 Current Status Report	3-12
3.4.2.5 Hourly Diagnostic Report	3-12
3.4.2.6 Current Diagnostic Report	3-12
3.4.2.7 Switch Closure Report	3-12

TABLE OF CONTENTS
(Continued)

	<u>Page</u>
3.4.2.8 Mass Balance, Energy Balance and Operating Efficiency Report	3-13
3.4.2.9 Processor Message Report	3-13
3.4.3 System Status	3-14
3.4.3.1 Program Status	3-14
3.4.3.2 Partition Status	3-15
3.4.3.3 ID Block Status	3-15
3.4.4 System Recovery	3-15
3.4.4.1 Power Failure Recovery	3-16
3.4.4.2 Down LU Recovery	3-16
3.4.4.3 Reset Other User Interaction Program	3-16
3.4.4.4 Reset the Whole DAS System	3-16
3.4.5 Operator Comments	3-16
3.4.6 Manual Data Entry	3-17
3.4.6.1 Steam Quality Data	3-17
3.4.6.2 TDR Cables Data	3-18
3.4.6.3 KOCC Tar/Water Data	3-18
3.4.6.4 Helium Tracer Data	3-18
3.4.6.5 Secondary GC - Bubbler Tube Analysis	3-18
3.4.6.6 Secondary GC - Oxygen/Argon Separation	3-19
3.4.6.7 Secondary GC - Light Oil Analysis	3-19
3.4.6.8 Portable Vent to Atmosphere Data	3-19
3.4.7 Mass Balance, Energy Balance and Operating Efficiency Calculations	3-19
3.4.8 Display/Modification of Data Structures	3-20
3.4.8.1 System Common - Display/Modification	3-20
3.4.8.2 Data Base - Display/Modification	3-22
3.4.8.3 Data Base - Initialization	3-26
3.4.8.4 Data Logger Channel Identification	3-27

TABLE OF CONTENTS
(Continued)

	<u>Page</u>
4.0 RECOVERY FROM PROBLEMS INDICATED BY MESSAGES ON THE PRINTING TERMINAL	4-1
4.1 Recovery From System Error Messages	4-1
4.2 Recovery From Processor Messages	4-2
5.0 RECOVERY FROM POWER FAILURES	5-1
5.1 Short Term Power Failure Recovery	5-1
5.2 Long Term Power Failure Recovery	5-2
5.3 Procedures Involved in Power Failure Recovery	5-2
5.3.1 Restoring the Magnetic Tape Drives	5-2
5.3.2 Restoring the Line Printer	5-3
5.3.3 Restoring the Computer (CPU)	5-3
5.3.4 Running Power Failure Recovery Software.....	5-4

APPENDICIES

	<u>Page</u>
A. Data Base Description	A-1
B. System Common Description	B-1
C. Processor Message Description	C-1
D. System Error Message Description	D-1
E. Data Logger Channel Identifier (CHANID) Description..	E-1

7.0 TECHNOLOGY TRANSFER

7.1 UCC Symposium Papers

Seven papers have been prepared by project personnel for presentation at the Seventh Annual Underground Coal Conversion Symposium to be held at Fallen Leaf Lake, California, September 7-11, 1981. Abstracts from the papers are shown below.

7.1.1 Rawlins Test #1 Cavity Definition Study

The reactor cavity from the 1979 DOE-Gulf UCG test has been defined. The study utilized coring, TV logging, sonar logging, mineralogy, and petrography to obtain a fairly complete picture of the cavity shape and location. The presence of the reactor "firepot" was confirmed and the bulking subsidence was indicated. Calculations of the coal removed were consistent with mass balance calculations during the test.

7.1.2 Status and Test Plan for Gasification of Steeply Dipping Coal Beds

Gulf Research & Development Company, in conjunction with DOE, and TRW as a major subcontractor, has successfully completed its initial gasification test of steeply dipping coal beds at the North Knobs site near Rawlins, Wyoming. The second test in this program is scheduled for Fall, 1981. The objective of the test as well as the test facility and its status will be described.

7.1.3 A Two-Dimensional Model of Underground Coal Gasification Cavity Growth with Application to the Canadian Forestburg Test of 1976.

A two-dimensional underground coal gasification cavity growth model has been developed from first principles. The model accounts for injected flow conditions, oxygen-content, coal seam thickness, coal testing value, coal carbon content, and initial link zone cross-sectional area distribution between the injection and production wells. The model calculates as a function of space and time: cavity growth, gas and wall temperatures, heat lost to the

surroundings, the oxygen content of the flow within the cavity, and the coal consumed. Convection, conduction, and combustion heat addition are accounted for in the model. The model can be used to predict multi-cavity shapes, and some preliminary results are given.

The model is used to predict the final cavity shape of the 1976 Canadian Forestburg UCG test. Comparisons of the cavity shapes show good agreement. Further, a parametric study is presented which shows the effects of mass flow and injected oxygen concentration on reactor growth.

7.1.4 Evaluation of Coals from the Rawlins Postburn Cores

In an effort to determine the thermal gradient into the coal seam near the underground gasification cavity, coal samples from the Rawlins postburn coring program were compared with Rawlins G seam coal heated under controlled laboratory conditions. Vitrinite reflectance and proximate analyses were found to be key indicators of thermal change in the Rawlins coal and were utilized for the interpretation of thermal history. Results show that the thermal effects of underground gasification into surrounding areas of the coal seam are not extensive. Coal samples taken near the burn, but not actually within the cavity, are largely unaltered in gasification. One area immediately adjacent to extensively altered rock shows a thermal gradient only 0.5 mm wide along a fractured bedding plane. By contrast, coal from the char bed within the cavity shows a high degree of thermal alteration, suggesting a minimum temperature of 700°C.

7.1.5 UCG Reactor Definition Instrumentation Selection for Rawlins Test 2

Underground Coal Gasification (UCG) shows such promise in providing a relatively inexpensive energy source from currently unmineable coal seams. For any commercial prospect, the impact on profitability, resource recovery, and environmental acceptability must be considered. These three factors are highly interrelated and strongly affected by any reactor growth pattern that results from the process. The ability to control, or at least monitor, reactor shape during a UCG operation is highly desirable. The only reliable way to monitor UCG reactor growth patterns is through field measurements. Many

reactor definition techniques presently available have significant limitations from the standpoint of cost, resolution, or state of the art as applied to UCG. Technique capabilities and attributes relative to one another were studied based on the test objectives, size, constraints, site characteristics and permitting requirements of Rawlins Test 2. The desired boundary resolution of 5 ft. within the coal seam, as well as a need to use as few boreholes as possible to minimize disturbance of the seam, narrowed the instrumentation choice to High Frequency Electromagnetic Mapping (HFEM) to monitor the reactor wall location. Extensometers were chosen to measure the extent and occurrence of roof fall and have been used successfully in other UCG tests.

7.1.6 An Industrial Hygiene Survey at the UCG Project, Rawlins, Wyoming

A comprehensive industrial hygiene survey was conducted at the Underground Coal Gasification (UCG) project in Rawlins, Wyoming. This paper presents and discusses the occupational hazards observed; the industrial hygiene evaluation conducted, and the control of exposure risks at the Rawlins Test 1. Based upon the observations and measurements made during this survey, the major exposure risks identified were product gas exposure, i.e., carbon monoxide, and coal tars containing polynuclear aromatic hydrocarbons (PNA's). When unacceptable levels of CO were determined personnel exposure was reduced by limiting access or taking remedial action. The operational and design conditions of the Rawlins Test 2 currently underway, are also discussed with respect to their industrial hygiene impact. Comparison and projection of the health hazards associated with this UCG site and future proposed, larger experimental, and commercial operations conclude this paper.

7.1.7 Unique UCG Gas Cleanup

Very little emphasis has been directed towards UCG project gas cleanup and upgrading because the greatest uncertainties have been and remain with the underground process. Although much applicable surface processing experience is available from surface gasification and syngas conversion facilities, UCG gas cleanup has some uniqueness. The raw product gas from an underground coal gasification process will emerge from the product wells at 600°F+ and contain particulates, trace metals, alkali, sulfur and nitrogen

compounds, carbon dioxide, condensible hydrocarbons, and moisture. These by-products must be sufficiently removed to ensure reliable operation of the gas gathering and preparation train for the power generation equipment or the chemical conversion facility. The product gas end use will affect the severity and nature of the cleanup requirements.

Gas cleanup problems that are unique to UCG are addressed as related to the effort to develop cleanup technology, using the Rawlins site as a test bed, which will allow the marriage of UCG to conventional processing and syngas conversion technology.

8.0 RAWLINS TEST 1 CAVITY DEFINITION STUDY

8.1 Summary

The reactor zone from the first test in the Rawlins UCG-SDB program has been characterized utilizing core holes, TV and sonar logs, and detailed examination of recovered cores. The results of the study are:

- the firepit mechanism was operative during a part of, if not all, the test
- an open water-filled cavity was formed in the overburden with a volume (7400 ft³) approximately 28% that of the coal gasified
- the reactor had stabilized by bulking
- the thermally altered zone in the remaining coal was quite narrow (<1 ft)
- ash temperatures reached ~1500°C sometime during the test.

The objectives were met with five drilled wells and cores from four of these wells. Sonar logging has been shown to be extremely effective in locating and characterizing the water-filled cavity.

8.2 Introduction

Gulf Research & Development Company has implemented a DOE-sponsored underground coal gasification project in steeply dipping coal beds (UCG-SDB) in order to assess the economic and technical viability of UCG in SDB and to project estimated costs for a pilot plant.¹

The first test in the program was completed in December 1979. The experiment included a 30-day air injection test followed by a 5-day oxygen steam test and gasified approximately 1,200 tons of coal (28,000 ft³) over that period.²⁻⁴

A total of ten boreholes were drilled in conjunction with Module 1 installation (see Figs.8-1 and 8-2). Two expendable wells (E-1 and E-2) were drilled to locate the coal seam in the proposed reactor zone. Three hydrology wells (H-16, H-17, and H-18) were installed to monitor water quality .

The coal seam was ignited near the base of the air injection well (AIW-1). The combustion process expanded to the drilled link portion of the product gas well (PGW-1). The gasification process was initiated with the injection of air down AIW-1 and the recovery of gas from PGW-1.

Due to the accelerated schedule and the relatively small scale of the first test, minimal subsurface instrumentation was installed. A program to characterize the reactor cavity was implemented beginning in the fall of 1980.

Postburn characterization was a key data-collection step in the process of evaluating UCG-SDB. The data to be collected aided in defining the process, the gasification cavity, resource recovery, and will provide input to future predictive modeling efforts.

8.3 Specific Information Needs

The information needs for several aspects of UCG cannot be met by surface measurements on process streams. These are subsidence/roof fall and reactor growth patterns.

Surface monuments which were located along the Test #1 reactor center line projection indicated that no subsidence occurred. This was also predicted by National Coal Board (NCB) calculations. In order to determine roof fall and obtain an estimation of the mechanism involved, it was necessary to determine the location and shape of the open space above the reactor. This was needed to properly plan module configurations and subsurface instrumentation for Test #2.

Data needed to define the subsidence factors are:

- Size, shape, and location of the open cavity
- Roof cores from directly above the cavity
- Estimates of thermal gradients in overburden
- Rubble samples

Reactor growth patterns of horizontal UCG have been studied extensively in tests at Hanna,⁵ Hoe Creek,⁶ and Forestburg.^{7,8} Several mathematical models have been developed that can simulate reactor growth patterns consistent with the field data from those tests. There is no data base for UCG-SDB. Gravity effects should be significant to the manner in which the reactor grows.

Analysis of data gathered during the field test has led to the development of a "conceptual" model of the process. The major growth of the reactor was updip along a reactor centerline established by the casing shoes of the AIW-1 and the PGW-1. The reactor apparently grows via periodic dropping of large chunks of coal and roof rock into the base of the reactor. A rubble bed was established over the base of the AIW-1 and served as a firepit. In the early stages of the process, the oxidation and reduction zones were confined in the rubble bed. As the test progressed, burnthrough of the rubble bed occurred.

Data needed to verify the conceptual model (reactor growth patterns) are:

- Existence and location of rubble bed
- Extent of updip growth in the coal seam
- Composition of the rubble bed
- Composition of coal/char zone

In addition to the above data, water samples from the reactor must be taken periodically and analyzed as a part of the groundwater monitoring program for the Wyoming DEQ.

Considering these specific information needs, the following objectives of the postburn characterization program were developed. They are listed in order of their priority:

1. Determine shape, size, and location of reactor cavity.
2. Confirm the existence and locate the rubble bed.
3. Characterize the rubble.
4. Determine the updip extent of reactor growth.
5. Determine roof fall, overburden alteration and mechanical properties of overburden.
6. Determine product well condition.
7. Collect ash samples from reactor.
8. Collect core samples from coal and char zone.

8.4 Pre-study Data Base

In devising a plan for conducting the field portion of the program, several factors were considered which were either known or assumed. These factors were:

1. The reactor was between AIW-1 and PGW-1.
2. Down-hole thermocouples were destroyed in IW-1 and "significantly affected" in IW-2.

3. There was a pressure drop between AIW-1 and PGW-1.
4. There was a slow leak to the surface near PGW-1.
5. The lack of response on IW-3 indicates that the reactor was not 30 ft south of a line between AIW-1 and PGW-1.
6. The amount of coal burned was 1,200 tons (28,000 ft³).
7. A preliminary conceptual shape of the reactor had been determined.
8. It was assumed that the reactor was symmetric.

Several procedures were available to obtain the desired data. These procedures can be classified as field and laboratory:

8.4.1 Field Procedures

- ↻ Drilling (recover drill cuttings)
- ↻ Coring
- ↻ Borehole geophysical logging
- ↻ Grab samples
- ↻ Sonar caliper survey
- ↻ Down-hole TV camera survey
- ↻ Product well geophysical logging

8.4.2 Laboratory Studies of Cores

- ↻ Proximate analysis (coal)
- ↻ Mineralogic/petrographic studies

8.5 Basic Program

The basic field program consisted of:

1. Running geophysical logs in PGW-1 (natural gamma ray, cement bond, and caliper)
2. Drilling four boreholes:
 - a. Obtain core from all holes
 - b. Set casing in one well
 - c. Plug three wells to surface with cement
3. Running geophysical logs in open drill holes (natural gamma ray, density, resistivity, caliper)
4. Running sonar caliper survey in open (water-filled) cavity through cased well
5. Running down-hole TV camera through cased well
6. Collecting rubble samples

The following well pattern was planned to locate UCG Cavity:

<u>Well Designation</u>	<u>Well Function</u>
PB-1	Locate the main cavity Obtain core samples of the overburden and rubble bed
PB-2	Obtain cores from the outer edge of the reactor and overburden
PB-3	Provide entry of TV and sonar logging tool into the open cavity above the reactor for preliminary measurements

- PB-4 Verify the hanging coal face just above the reactor and obtain cores if possible
- PB-5 Provide a second entry point for sonar logging for a quantitative definition of the open cavity

The planned placements were based upon projection of the conceptual reactor growth patterns described previously.¹

The sequence of operations was:

1. Log PGW-1
2. Drill and Core PB-1. Set casing only if hole encounters cavity
3. Drill and core PB-2. Set casing if not set in PB-1 and if hole encounters cavity
4. Run down-hole TV camera in cased well
5. Run sonar caliper survey in cased well
6. Based on previous results, locate and drill PB-3 and PB-4
7. Drill PB-5
8. Run sonar log on PB-5

The actual location of the wells is shown in Fig 8-5.

8.5.1 Initial Data Collection

An important part of the plan was to determine the condition of the UCG reactor zone prior to penetrating the zone with the postburn wells.

Thermocouple data from one of the vertical instrument wells (IW-1) indicated a reactor zone temperature of 40°C, but it was not known if hazardous gases were present.

The first step was to open valves on the product gas well (PGW-1) and the air injection well (AIW-1). These wells had been shut in since the completion of the field test in December 1979. Monitors at the well head valves detected no hazardous gases.

Next a water level indicator was inserted into a 2 in. dip tube in AIW-1. Water was encountered at a true vertical depth of 269 ft, approximately 50 ft above the expected reactor zone. Subsequent measurements in PGW-1 confirmed the water level depth and the fact that the reactor zone was filled with water.

In order to ascertain the condition of the casing in PGW-1, an attempt was made to remove the cooling water line. This line consisted of a 1/2 in. pipe assembled inside a 2 in. pipe. The line extended approximately 395 ft to the bottom of the casing and would be an obstacle to a planned TV camera run. An initial attempt resulted in the recovery of 371 ft of 1/2 in. pipe and 45 ft of 2 in. pipe. A second attempt recovered an additional 264 ft of 2 in. pipe. The 2 in. pipe collars had been severely eroded by the product gas stream. It was obvious from the condition of the last piece of 2 in. pipe recovered that a collar had failed, leaving the remaining pipe in the well.

On September 22, 1980, a TV camera from the Laramie Energy Technology Center was run in PGW-1 to a measured depth of about 300 ft where the remaining 2 in. pipe blocked any further progress of the camera. The casing

appeared to be in good condition with no breaks or separations. At some joints of the casing, an excessive number of collar threads were visible. This was probably due to incomplete tightening of the joints when the casing was run.

Water samples were collected from PGW-1 by means of thief samples on a wire line. The water temperature was 43°C, which corresponded with earlier thermocouple data from IW-1.

8.5.2 TV Camera Survey

Upon completion of drilling operations, a TV camera was run in the postburn wells which encountered the reactor zone. Nothing could be seen in PB1-1 or PB1-2 due to suspended sediment in the borehole water. Furthermore, caving of the holes prevented the camera from reaching the reactor zone.

The camera run in PB1-3 was much more successful. Once the bottom of the cased portion of the well (260 ft) was reached, relatively large blocks of rubble were visible. These blocks ranged from 6 in. to 1 ft in diameter and larger. Water in the cavity was very clear, enabling small particles to be seen. This material was agitated by the movement of the TV camera and could be seen falling down in front of the camera. Grooves on large blocks of rubble where the core bit had cut material from the block were also visible.

In the interval from about 268 ft to 284 ft, it appeared that a large portion of the cavity was off to one side and beyond the range of the camera. Because there was no orientation device on the camera, it was impossible to determine the direction of the major portion of the cavity.

8.5.3 Sonar Caliper Survey

In November 1980, a Dowell sonar caliper survey was run in PBI-3. This survey utilizes sound waves to measure azimuth and distance from a down-hole instrument to the cavity boundary. The tool is designed to rotate and pivot to obtain three projections of the cavity.

An isometric projection of the cavity indicated that the well was drilled along one wall of the open cavity. This explained inability to rotate and pivot the tool during the survey. A decision was made to drill the fifth well (PBI-5) into the projected center of the cavity. The well was drilled, cased and sonar logged in mid-January 1981. The combined isometric from the two sonar logs is shown in Fig 8-4.

8.6 Core Evaluation

The cored materials from the first four wells (PBI-1 to PBI-4) were logged and examined at the site. The cores were then transferred to the GR&DC facility at Harmarville, PA, for detailed studies. Selected cores were examined by a variety of techniques to gain additional insight into the mechanisms that were active during the growth of the reactor with a particular emphasis on thermal history and chronology of events as derived from the thermal history. No cores were obtained in the last well of the series (PBI-5).

8.6.1 Core Logs

The cores were logged by visual and photographic means. Altered sections were found to be:

<u>Core Hole</u>	<u>Open Hole (i.e., Cavity Zone)</u> (ft)			<u>Altered Cores</u> (ft)		
PB 1-1	293	-	313	313	-	329'9"
PB 1-2	267	-	286	286	-	288
	288	-	304	304	-	307
	307	-	308'4"	308'4"	-	314
	314	-	316	316	-	328
	328	-	342	324	-	346
P 1-B	268	-	311	311	-	334
	334	-	335'6"	335'6"	-	337'11"
PB 1-3	337'11"	-	357'6"			
PB 1-4		none			none	
PB 1-5	257	-	272		none	

8.6.2 Field Evaluation of Cores

Four core holes were drilled during 1980 to obtain information and materials from within and around the Test #1 burn cavity. Cores from these holes provide materials that permit interpretation of some of the conditions in and near the burn and on the development of the resulting burn cavity. The rocks involved in the burn include the G coal seam and the overlying shales and sandstones.³ A brief review of the geology in the immediate area is helpful in understanding the burn.

8.6.3 Description of Unaltered Materials

The overlying sandstone is mainly a massively bedded, impure, poorly cemented rock that contains carbonaceous horizons. The carbonaceous material is present as disseminated grains and as irregular stringers of coal up to about 1/2 in. wide.

The siltstone and shale that is in direct contact with the coal is a thinly bedded material that ranges in color from olive gray to olive black. Adjacent to the coal beds the shales are carbonaceous, and contain both abundant disseminated carbonaceous material and interbeds of coal up to about 1/4 in. thick. The siltstone layers are lighter colored and tend to have thicker layers (up to 2 in. thick) with irregular coloration. Many layers have the appearance of a "fragmented" layer with irregular "fragments" ranging up to 1 in. or more in size.

The coal consists of massively bedded material with abundant cleats and fractures. The upper coal bench appears to be rather shaly, whereas the main coal seam is largely a pure coal. A minor shale horizon is present about two-thirds of the way up the coal seam, and minor calcite veins are present. A minor bedding fault zone is present near the base of the coal and another near the shaly horizon within the main G seam.

8.6.4 Description of the Altered Materials

Altered sandstone was encountered in the drill holes that intersected the burn cavity. The bedding in most of the altered sandstone was at various angles to the axis of the drill core and numerous voids were encountered in drilling the altered material. This suggests that the altered sandstone occurs as randomly oriented slabs that have collapsed into the burn cavity. The alteration consists of burning (pyrolysis) of the disseminated organic material and the irregular stringers of coal, producing numerous cavities within the sandstone. Walls of some of these cavities appear to be glassy and the sand grains are fused to produce a very coherent rock. The

sandstone has a light gray color, whereas the burned-out pores have a black coloration. The sandstone is also converted to a very friable dark gray material, much of which is simply a loose sand in the core.

One of the most abundant materials encountered in drill cores of the altered material is a breccia consisting of angular fragments up to several inches in size in a matrix of a vesicular glassy material. The fragments are mostly sharply angular, have a gray to light brown color, are very fine grained, and have the general appearance of broken porcelain. The fragments are harder than a knife blade, suggesting that they are composed of some type of ceramic minerals. The glassy matrix that welds the fragments together typically is dark gray to black and contains numerous gas cavities of various size. This frothy material clearly was molten during the burn and appears to have formed by the alteration of the siltstone, shale, and carbonaceous shale within and overlying the coal seam.

The breccia materials along with altered sandstone are present in blocks of various size in the cavity. Much of the core consists of a rubble of fragments only one to two inches in size. Sections of core of the breccia several feet long indicate that the breccia is also present as larger blocks or slabs in the cavity. A wide range in the size of blocks is probably present. The presence of voids up to 10 feet long within the cavity suggests the presence of large slabs with smaller rubble partially filling some of the voids.

Alteration of the coal was evidently somewhat irregular. Several drill cores (PB1-2 and PB1-3) encountered unburned coal within the cavity. In

both cases the coal has a partial rind of altered coal several inches thick adjacent to the cavity. In PB1-3 a void underlies unburned coal suggesting that it is a slab of partially burned coal that fell into the cavity after the burn was completed. Subsidence of overburden into the burn cavity makes interpreting the burning of the coal difficult.

8.6.5 Core Analysis

Cores from the coal sections were selected for proximate analyses. No coal cores were obtained from PB1-2 and PB1-5. Since Well PB1-4 did not intersect the seam, three samples were selected along the length of the seam.

8.6.6 Mineralogical Analyses

All cores from the four drill holes (PB1-1, 1-2, 1-3 and 1-4) were lithologically examined by the naked eye, and samples of each lithologic unit were sampled for stereoscopic examination. Samples were selected for X-ray diffraction analyses, thin section analyses, and scanning electron micrographic examination. The purpose of these further analyses is to confirm the presence of new mineral phases and their extent of distribution both vertically and horizontally between drill holes, which resulted from the thermal effect of in situ gasification of coal. The presence of high-temperature minerals was detected in the following cores and intervals by the present investigation.

PB1-1	PB1-2	PB1-3	PB1-4
316'-330'	306'-319'	315'-335'	none

The thermally transformed rocks are characterized by the appearance of newly-formed high-temperature minerals including cristobalite, tridymite, mullite, and cordierite in addition to relict quartz and rare feldspars.

These minerals form different associations in different types of altered rock. The following associations have been recognized.

1. Quartz-cristobalite-mullite
2. Quartz-cristobalite-mullite-cordierite
3. Quartz-cristobalite-tridymite-mullite-cordierite
4. Quartz-cristobalite-tridymite-cordierite
5. Quartz-cristobalite-tridymite-mullite

The variation of mineral associations is likely to be related to original rock types and compositions, and also depends on thermal conditions of the underground burn (e.g., effective temperature, cooling rate, etc.).

Association type 1 is the most common type among the transformed rock materials. It is commonly associated with intensively fused rocks, such as the slag-like fused breccia and some altered sandstones. Type 4 and less common Type 3 are the new components found in a black, cinder-like matrix in breccia (rumble rock), which may be derived from coal ashes and/or debris of carbonaceous shale. Some parts of the black matrix contain tiny glass spherules as observed under microscope. The strata which are not affected by the firing heat are composed mainly of clay minerals (illite and kaolinite) quartz, and feldspars.

8.6.7 Inferred Transformation Temperature

Silica in nature occurs in three different crystalline forms or structures (polymorphs): quartz, tridymite, and cristobalite. The latter two represent the high-temperature phases. Tridymite is the stable form at 867° to 1713°C. Above 1713°C (2062°F), silica forms liquid (or silica glass). However, with the presence of impurities, the two high temperature phases may crystallize at lower temperatures, tridymite, and cristobalite is common in certain ceramic products such as silica brick. Cristobalite has been developed from quartz and kaolinite between 1250° to 1450°C in laboratories. If the original material is high in alumina content mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$) will be formed at about 1000° to 1350°C associated with cristobalite. If the clays contain Mg, Fe, or Ca in addition to Al and Si in composition, cordierite $(\text{Mg,Fe})_2\text{Al}_2\text{Si}_5\text{O}_{18}$ can be formed. Cordierite has reportedly been developed by firing montmorillonite clay at 1260° to 1450°C. For the present analyzed samples tridymite has been found commonly associated with cordierite in occurrence. The presence of Mg and Fe in rock may favor the crystallization of silica in tridymite.

Based on the mineralogical analyses mentioned above, the temperature of the underground fire must have been in the range between 1000°-1450°C. The transformation of the rock materials is substantially restricted to the finely divided particles in the matrix of the sedimentary rocks. The coarser grains in these rocks, sand to silt-size (mainly 0.5 to 0.03 mm) grains of quartz, remain almost entirely unchanged. This also indicates that the temperature was not high enough to melt quartz or reach above 1600°C.

When some parts of the coal seam were burned out, parts of the roof rock caved in and formed a pile of rubble or breccia. The heat of burning coal was confined in the underground space and cooled down slowly. The fragmental rocks of the rubble and surrounding rock wall were softened by the heat, and their volatile material was driven out. The gases caused some fragmental rock bloating and vesicular structure. As the temperature slowly cooled, the heated rocks transformed gradually and were recrystallized to new mineral phases. Some parts of the intensively heated rocks might form glasses at first, but they were later devitrified or recrystallized to crystalline phases. Some parts of the intensively heated rocks might form glasses at first, but they were later devitrified or recrystallized to crystalline phases.

8.6.8 Petrographic Analysis

In an effort to determine the thermal gradient in the coal seam near the underground gasification cavity, several coal samples from the postburn coring program were selected for study. The samples were compared with Rawlins G seam coal heated under carefully controlled conditions in the laboratory. Laboratory work has shown vitrinite reflectance and volatile matter to be key indicators of thermal change in coal, and therefore, proximate and petrographic analyses were utilized for the interpretation of thermal history in the Rawlins postburn cores.

Coal samples near the burn, but not actually within it, appear to be unaltered. This was indicated by proximate analysis and vitrinite reflectance. By contrast, coal from the char bed in the rubble zone shows a high

degree of thermal change. Reflectance suggests a temperature 700°C or above for the coal material, while X-ray diffraction of minerals from the same area indicates higher temperature, above 1000°C.

8.7 Discussion

The findings from the coring and core analyses are summarized in Table 1-1. These data combined with the findings from the TV and sonar provide sufficient base for development of a model for reactor growth during and after the Rawlins Test #1.

8.7.1 Analyses of Sonar Data

The sonar caliper survey was conducted in the two postburn boreholes (PB1-3 and PB1-5) which intersected the cavity. The results of sonar survey provided information regarding the volume of the observed cavity and its location with respect to the G coal seam and postburn wells. Using this information in conjunction with the volume of coal consumed by UCG test, the bulking factor of the affected rock can be calculated, which will indicate whether any relationship exists between the observed cavity volume, projected rubble volume, and the coal consumed.

Figure 8-5 shows the relative locations of sonar survey determined cavity (cross-section in the direction of the G coal seam) with the G coal seam, postburn wells, and the process wells (product gas well PGW-1, and air injection well AIW-1). The area covered by the rock rubble is an approximate projection, which is based on the following:

1. Fayol's¹⁰ experimental study of subsidence in inclined strata, which concluded that the failed zone would spread in the form of a dome with the increased volume of broken material filling the area affected.
2. The outline of the roof of observed cavity has to be a part of the overall roof curvature, or a dome-shape based on 1.

Assuming that coal within the link zone (i.e., between AIW-1 casing shoe and PGW-1 casing shoe) has been consumed, the bottom boundary can be projected. Again, the boundary of a rubble zone between the PGW-1 casing shoe and the right-hand-side tip of the observed cavity is projected as a straight line.

A correlation between the volume of observed cavity, volume of coal consumed, and projected volume of the rock rubble can be established by the following calculation:

According to the mass balance calculations,¹¹ the volume of coal consumed in Rawlins T1 = 28,000 cu ft

Assuming 5% ash content (by volume) of the coal, the volume of ash left in the UCG cavity = 1,400 cu ft

Therefore, the void volume caused by the coal burned = (28,000
-1,400) = 26,600 cu ft

From sonar survey, volume of the observed cavity = 7,418 cu ft

Using corresponding area, the volume of rock rubble = 37,700 cu ft

Total volume of the rock affected = (37,700 + 7,418) = 45,118 cu ft

The volume of intact rock (now in rubble form) = (total volume of affected rock - void volume caused by coal consumed) = (45,118 - 26,600) = 18,518 cu ft

Therefore, the bulking factor of the rock = $\frac{37,700}{18,518} = 2.04$

During postburn drilling some large void spaces were observed within the rock rubble. If these can be accounted for, the bulking factor will be reduced. Assuming that such void spaces constitute 5% of the total rubble volume, the bulking factor will be 1.94; and if void space is assumed to be 10% of the rubble volume, the bulking factor will be 1.84.

Bulking factor, the ratio of the volume occupied by broken rocks to that of intact rock, increases proportionally to reduction in particle size. One source cites the average bulking factor to be 1.6.¹² The other source¹³ provides the following table:

**Fayol's Tests on Volumes of Different Materials,
When Crushed to Granular Size (20 MM) and
Compressed, Original Volume Being Unity**

Rock Type	Increase in Volume (Bulking Factor)	Vol When Compressed	
		By pressure of 1,422 psia ^(a)	By pressure of 2,844 psi ^(b)
Shale	2.29	1.28	1.16
Sandstone	2.14	1.36	1.25
Coal	2.02	1.30	1.25

(a) Corresponds to vertical rock pressure at depth of 1,638 ft.

(b) Corresponds to vertical rock pressure at depth of 3,276 ft.

From the above information, the value of bulking factor ranges from 1.6 to 2.29 for incompresssed rubble. The above calculation has shown the bulking factor to be 1.84 to 2.04, which is within the range of values cited in the literature. It should be pointed out once again that volume figures used in this calculation are only approximations.

8.7.2 Interpretation of the Burn

The basic configuration of the module before ignition is given in Fig. . After ignition the reactor developed along the drilled link initially growing in a long sausage shape. Shortly after startup, the rubble bed started to form as evidenced by a rapid increase in observed pressure drop

between the wells. This increased turbulence at the base of the reactor promoting growth along strike and vertically to the roof of the main bench of the G seam.

Heating of the carbonaceous shale of the upper parting produced spalling of relatively small rock fragments which fell into the main fire pit. Spalling was probably enhanced by expulsion of water from the hydrous clay minerals that comprise the shales. The carbonaceous material present provided sufficient heat to fuse some of this material with the coal ash to form a slag. The temperatures in the slag pit were in the range of 1200-1500°C.

Coal and roof rock continued to fall into the reactor. Exposing the upper coal bench as the burn progressed upward along the coal seam. Spalling of small fragments from the shales and siltstones of the roof rocks above the upper coal bench continued as the burn progressed upward along the coal seam. This produced innumerable, generally small fragments in the lower part of the developing cavity. Fragments of coal were mixed with the rock fragments and burning of this material resulted in fusion of some fragments (perhaps the carbonaceous shale), producing a variably baked and fused rubble within the cavity. Gases from the air inject well bubbled through the partially fused mass, producing a frothy glass surrounding the more resistant angular fragments.

Coal that fell into the reactor was further pyrolyzed to temperatures of 400°C by the hot product gas. As the oxidation front moved through the rubble bed, part of the coal/char zone was bypassed and not gasified. The

in-place coal at the lower edge of the reactor showed little pyrolysis and probably saw temperatures no greater than 150°C.

At some stage of cavity development, large blocks and slabs of the overlying sandstone collapsed into the cavity. Whether the sandstone was altered before or after it collapsed is uncertain. However, the sandstone encountered in the cavity is dominantly altered, suggesting that alteration continued after collapse. The collapse of large blocks and slabs from the roof was probably controlled by bedding planes and joints in the sandstone, but may have been caused in part by expansion of gases as a result of pyrolysis of the carbonaceous material within the sandstone. The final configuration is given in Fig. 8-5 showing the small open cavity in the overburden above the rubble bed.

Collapse of the roof and down-dip sliding of blocks and slabs continued after the burn had ceased. This is indicated by the presence of slabs of unburned coal mixed with fused rocks in the cavity. Thus, the materials in the burn cavity probably were added at various stages of the burn history and from various distances vertically and up-dip from the initial cavity.

8.8 Conclusions

There are several conclusions that can be made based upon the results of the cavity definition program:

1. The postburn data, along with operational data, indicate that the firepit mechanism of reactor growth was operative for part of, if not all, the Rawlins Test #1.
2. There was a molten slag layer at the bottom of the reactor during some part of the test (whether it was produced during the air or oxygen experiment has not been determined). Temperatures were in the range of 1000-1500°C.
3. The shale directly above the coal seam fused with coal ash to produce the slag.
4. The reactor has grown significantly beyond the production well (PGW-1) casing shoe in the coal seam.
5. Groundwater influx occurred while the slag pit was hot (>1000°C).
6. A failure dome was observed for Rawlins Test #1.
7. The volume of sonar observed cavity, coal consumed by the UCG burn (calculated by mass balance equation), and projected rubble volume are consistent with the calculated bulking factor of failed rock.
8. Thermally altered sandstone blocks fell into the reactor after the test was terminated.
9. The in-place coal shows little thermal alteration.

The overall cavity definition program has met the defined objectives. Sonar logging has proved to be an extremely powerful tool for open cavity characterization defining location, shape, and volume with a degree of

resolution not possible by coring. The off-site core analysis program should emphasize mineralogical and petrographic analysis, especially for coal samples.

8.8.1 Acknowledgements

Many people contributed data included in this study. Among these were the Sonar Log by Dowell, TV Survey by DOE-LETC, and the mineralogical studies by Pei-Yuan Chen and John McCullough of GR&DC. Valuable discussions were provided by Dr. D. P. Gold of Penn State University, Dr. C. A. Salotti GR&DC, and Dr. N. Shapiro of Resource Engineering, Inc.

8.9 References

1. B. E. Davis et al., "Test Plan and Status for the Gasification of Steeply Dipping Coal Beds," Proceedings, 5th UCC Symposium, Alexandria, VA, 1979.
2. A. H. Singleton, W. L. Noll, and J. M. Allen, "Summary Report of the Rawlins Test 1 for Gasification of Steeply Dipping Coal Beds," Proceedings, 6th UCC Symposium, Afton, OK, 1980.
3. P. F. Ahner et al., "A Site Qualification Study of the UCG Site at North Knobs," Proceedings, 6th UCC Symposium, Afton, OK, 1980.
4. B. E. Davis et al., "Status of the Rawlins UCG-SDB Program," Proceedings, 7th UCC Symposium, Fallen Leaf Lake, CA, 1981.
5. R. D. Gunn and D. L. Whitman, "An In Situ Coal Gasification Model (Forward Mode) for Feasibility Studies and Design," LERC/RI-76/2, February 1978.
6. R. W. Hill, "Analysis of Burn Cavity Growth in Hoe Creek III," LLNL Underground Coal Gasification Project, Quarterly Progress Report, October through December 1980, pp. 25-35.
7. A. A. Roehl, R. A. S. Brown, W. C. Edwards, and E. J. Jensen, "Underground Coal Gasification Field Test of 1976, Forestburg, Alberta, Vol. II, Interpretation of Results and Recommendations for Future Studies," May 1978.
8. G. J. Harloff, "A Two-Dimensional Model of Underground Coal Gasification to the Canadian Forestburg Test of 1976," Proceedings, 7th Annual UCC Symposium at Fallen Leaf Lake, CA, September 7-11, 1981.

9. N. . Duerring and B. E. Davis, "Evaluation of Coals from the Rawlins Postburn Cores," Proceedings, 7th Annual UCC Symposium, Fallen Leaf Lake, CA, September 7-11, 1981.
10. M. Fayol, "Effects of Coal Mining on the Surface," translated by M. F. Bulman, Colliary Engineering, Vol. 33, 1913, pp. 548-572 and 617-622.
11. R. Lindeman, P. F. Ahner, and B. E. Davis, "Mass Balances for Underground Coal Gasification in Steeply Dipping Beds," Proceedings 6th Underground Coal Conversion Symposium, Afton, OK, July 1980, pp. VIII-14-23.
12. Coal Mine Ground Control, John Wiley & Sons, New York, 1979, p. 222.
13. R. Peele, "Mining Engineers' Handbook," John Wiley & Sons, New York, pp. 10-522, 1966.

FIGURE 8-1 RAWLINS TEST NO. 1 WELL LOCATIONS

"The drilling program entailed drilling, at very acute angles (45 to 39 degrees to the vertical), gasification process and instrumentation wells. Directional control was a paramount consideration and combinations of stiff bottom-hole assemblies and a down-hole mud motor with bent sub and frequent single and multi-shot surveys, collectively provided adequate directional capability."

FIGURE 8-2 RAWLINS 1 WELL CONFIGURATION

REACTOR SHAPES

CROSS-SECTIONAL VIEW OF REACTOR ZONE

REACTOR ZONE VIEW AT 90° TO THE COAL SEAM

FIGURE 8-3

20-JAN-81 10:21
FROM DEPTH: 800
THRU DEPTH: 200
VIEWING AZIMUTH: 171
HORIZ SCALE: 1 IN.=5 FT.
VERT SCALE: 1 IN.=5 FT.

ISOMETRIC VIEW

GULF RESEARCH & DEVELOPMENT CO
NORTH HADD SITE
WELL NO. P01-2 & P01-3
JANUARY 14, 1981

FIGURE 8-4

FIGURE 8-5

Figure 8-6 Sketch showing the pre-burn configuration of the T-I burn. Communication was established between the Product Gas Well and the Air Inject Well.

Figure 8-7. Early cavity development by enlargement of the reactor zone along the Product Gas Well.

Table 1. Mineral Composition of the Post Burn No. 1 Core
Samples Identified by X-ray Diffraction Analysis

Core No. and Depth	Gypsum	Illite	Kaolinite	K- Feldspar	Plagio- Clase	Quartz	Tridymite	Cristo- balite	Mullite	Cordierite	Glass	Lithology
PB1-1												
316a						S	MS	S	-	W	?	Black matrix in breccia
318a						VS	S	VS	-	W		Black matrix in breccia
318b						S	-	S	W	W		Sandstone "xenolith" in breccia
325-326						S	S	VS	W	?		Green-yellow coating on fissures
330						VS	-	S	WM	?		Indurated sandstone
PB1-2												
266-268		M	M	-	MM	VS						Black siltstone
267		VM	MS	S	S	VS						Fine-grained
306						VS	-	-	W?	-		Indurated dark gray siltstone
310a						S	-	VS	WM	-	?	Mud-pebbles in conglomeratic SS
310b				MM	MM	VS	-	M	W	-		Sandstone fraction of 310a
317						S	MS	VS	W	W		Indurated siltstone
344.5		MM	M			S						Siltstone
PB1-3												
311.3	W	W	M	VS	M	VS						Sandstone
312a	S	W	M	VS	VS	S						Finer fraction of the sandstone at 312'
312b	WM	W	WM	S	MS	VS						Coarser fraction of the sandstone at 312'
315a						S	?	VS	W	W	?	SS "xenolith" in breccia
315b						S	S	S	W	W	?	Black matrix of breccia
331-334a						MM	-	VS	M	-		Bubble wall in vesicular slag (fused breccia)
331-334b						MS	-	VS	W	-	?	The inner zone of the bubble wall.

TABLE 8-1

9.0 FACILITY CONSTRUCTION

Facility construction which began in May accomplished the following activities:

- Site grading
- Site electrical grid modifications
- Installation of compressed air piping and manifolds
- Installation of compressors
- Installation of pipe supports
- Installation of flare
- Prefabrication of complex piping designs
- Installation of the VIW and VLW wellheads
- Installation of a data logger trailer
- Installation of oxygen tanks
- Installation of boilers
- Evaluation of existing Test 1 equipment prior to reuse