FIELD FRACTURING MULTI-SITES PROJECT

Annual Technical Progress Report
JULY 28, 1993, TO JULY 31, 1994

DOE AGREEMENT NO. DE-FC21-MC30070

Prepared For
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Contents

1.0 INTRODUCTION	1
1.1 Overall Objective of the Field Fracturing Multi-Sites Project.	1
1.2 Concept of a Hydraulic Fracture Test Site	1
1.2.1 Concept Justification	1
1.2.2 Established Site Characteristics	1
1.3 Verification of M-Site Suitability	4
1.4 Contractor Team and Responsibilities	6
1.5 Project Phases and Task Objectives	7
1.5.1 Project Phases	7
1.5.2 Task Descriptions	8
2.0 WORK PERFORMED FROM JULY 28, 1993, TO JULY 31, 1994	10
2.1 Task 1: Drill, Evaluate and Instrument a Seismic Monitor Well	10
2.1.1 Site Infrastructure	10
2.1.2 Data Acquisition Systems	10
2.1.3 Drill and Evaluate Monitor Well No. 1	14
2.1.4 Monitor Well Instrumentation	18
2.2 Task 3: Conduct Seismic Fracture Diagnostic Tests	19
2.2.1 Objectives of the A Sand Experimentation and Data Acquisition	19
2.2.2 Summary of Field Operations and Data Acquisition for Fracture Diagnostics	20
2.3 Task 8: Project Documentation and Technology Transfer	23

3.0 FUTURE M-SITE ACTIVITIES	24
3.1 Task 2: Conduct Fracture Closure Stress Tests	24
3.2 Task 4: Drill Directional Well Pilot Hole and High-Angle Leg No. 1	24
3.3 Task 5: Conduct Fracture Conductivity and Seismic Tests	24
3.4 Task 6: Drill High-Angle Leg No. 2	24
3.5 Task 7: Perform Fracture Pressure and Seismic Tests	24

Figures

Figure 1 Sandstone Units Used for Diagnostic and Modeling Experiments	3
Figure 2 Location of the Multi-Site Project	5
Figure 3 Layout of M-Site Infrastructure	11
Figure 4 Data Acquisition Systems for Fracture Diagnostics Experiments	11
Figure 5 Instrumentation and Diagnostics Arrays to be Deployed at M-Site	15
Figure 6 Proposed Instrumentation Placement in the Monitor Well No. 1	15
Figure 7 Location of MWX-2 Treatment Well, and Relative Position of Monitor Well No. 1 and MWX-3 Observation Well	16

1.0 Introduction

1.1 OVERALL OBJECTIVE OF THE FIELD FRACTURING MULTI-SITES PROJECT

The objective of the Field Fracturing Multi-Sites Project (M-Site) is to conduct experiments to definitively determine hydraulic fracture dimensions using remote well and treatment well diagnostic techniques. In addition, experiments will be conducted to provide data which will resolve significant unknowns with regard to hydraulic fracture modeling, fracture fluid rheology and fracture treatment design. These experiments will be supported by a well-characterized subsurface environment, as well as surface facilities and equipment that are conducive to acquiring high-quality data. The goal is to develop a fully characterized, tight reservoir-typical, field-scale hydraulic-fracturing test site, to diagnose, characterize, and test hydraulic fracturing technology and performance. Improved fracturing technology should increase natural gas recovery and improve development economics.

1.2 CONCEPT OF A HYDRAULIC FRACTURE TEST SITE

1.2.1 Concept Justification

Research work performed by the Gas Research Institute (GRI) and the U.S. Department of Energy (DOE) over the past several years has been directed at acquiring comprehensive data sets before, during and after hydraulic fracture treatments on a number of wells. Researchers have made significant advancements in several areas from these data, including evaluating formations, modeling fracture propagation processes, diagnosing the azimuth and height of the created fracture, and modeling production from a hydraulically-fractured natural gas reservoir.

Significant advancements have also been made in developing and applying technology to define the stress characteristics of various rock layers, measure important parameters before, during and after a fracture treatment, and use that information in a hydraulic fracture propagation model to predict the shape and extent of the resulting hydraulic fracture. Based on these efforts, GRI and others have concluded that hydraulic fractures tend to be taller, wider and shorter in length than conventional models would predict.

Although considerable advances have been made, some important questions remain. Fracture propagation models used in industry today can vary widely in their results for given input parameters due to various assumptions about the in-situ hydraulic fracturing process. In addition, diagnostic systems developed thus far are capable of determining only fracture azimuth and height. There is no technique available for accurately determining fracture length.

1.2.2 Established Site Characteristics

GRI and DOE determined that a joint effort was necessary to resolve the significant unknowns associated with measuring and modeling the dimensions of hydraulic fractures. The first site proposed for the hydraulic fracture experimentation was the former DOE Multiwell Experiment

(MWX) site located near Rifle, Colorado. The M-Site includes three closely-spaced wells (MWX-1, MWX-2 and MWX-3). The need for and location of future sites for the Multi-Site Project will be determined after an assessment of the results from this first site.

All of the past and planned M-Site experimentation is occurring in several sandstone units present in the upper Mesaverde Group between 4,130 and 5,000 ft. These shallower sandstone units are suitable for multiple reasons:

- 1) The fluvial and paralic depositional environments of the upper Mesaverde were conducive to deposition of thick, laterally-continuous sandstone bodies.
- 2) The previous MWX project did not perform any hydraulic fracture stimulations above 5,500 ft.
- 3) Few (if any) wellbore obstructions (e.g., bridgeplugs) exist above 5,500 ft.
- 4) Shallower target intervals decrease operational costs associated with conducting experiments.
- 5) Shallower depths promote the acquisition of higher-quality data from surface-deployed instrumentation.

Within the gross interval from 4,130 to 5,000 ft, there are three sandstone units suitable for diagnostic and modeling experimentation. These units are informally referred to as the A, B and C sands with the A sand being the deepest and the C sand the shallowest, as shown in Figure 1.

The fluvial and paralic sections of the upper Mesaverde, which includes the A, B and C Sands, is characterized by thick, blanket-like (i.e., laterally continuous), low-permeability sandstone units. For example, the average dry-core permeability of the sandstone unit between 4,290 and 4,366 ft in MWX-2 is 0.107 md and the average porosity is 5.2 percent as determined from core analyses. The uppermost Mesaverde sands are interpreted to have very high water saturations (up to 100 percent). Gas saturations, however, begin to increase with increasing depth below 4,500 ft as determined from existing core and log analyses.

Within the upper Mesaverde test interval, abundant data have been established as a result of DOE's MWX research:

- The interval from 4,170 to 5,550 ft was continuously cored in MWX-1. This core is now stored at Sandia and is available for continued analysis, if required. Routine and special core analyses have already been performed on much of this core to determine rock mechanical and reservoir properties. Mineralogic, petrographic and sedimentological analyses have also already been performed and results documented. MWX-2 was also cored in select intervals of the upper Mesaverde.

Figure 1 Sandstone Units Used for Diagnostic and Modeling Experiments

- Thirteen cased-hole stress tests have already been performed in MWX-2 between 4,170 and 5,502 ft.
- Multiple overlapping runs of high-quality wireline log data exist for this interval and are archived at CER. The log and core data have been compiled into a depth-shifted, digital database which is also maintained at CER.
- Seismic data is available in the form of high-resolution 3-D, vertical seismic profile and cross-borehole.

Below the upper Mesaverde test interval, there are additional data and information useful to M-Site research. These data and information include the following:

- Hydraulic fracture azimuth was determined to be N78°W based on 7 techniques in the deeper Mesaverde in the MWX wells.
- 3-D fracture modeling was previously performed on a hydraulic fracture treatment at 5,530 ft, so there is information on model behavior.
- Natural fractures and the associated onset of over-pressuring are known to occur primarily below 5,500 ft (below the proposed interval).
- Through work in 10 separate completion intervals, there were no indications of any near-wellbore effects during fracturing experiments. Thus, fracture treatment modeling is not expected to be hindered.

As shown in Figure 2, the Multi-Site has close proximity to oil field services and airports, and is located nine miles from Rifle, Colorado. Grand Junction is 60 miles from the site via Interstate 70. Access from the interstate to the site is by paved road maintained by Garfield County.

1.3 VERIFICATION OF M-SITE SUITABILITY

All indications were positive that the MWX wells and the character of the subsurface formations were suitable for fracture diagnostics experimentation. However, a series of technical assessments were planned and executed before proceeding with full-scale project development, to confirm the site suitability from various perspectives. These assessments included: 1) evaluation of confining stresses of the sandstone units; 2) assessment of wellbore (cement and casing) integrity; and 3) capability of remotely detecting seismic signals during a mini-frac.

The site suitability assessments performed involved the use of existing stress data from the MWX wells and the acquisition of new seismic and fracture treatment data collected during field operations conducted in September and October 1992. These assessments indicated the following:

- Wellbore and cement conditions of the MWX-2 and MWX-3 wells were suitable for acquiring high-quality seismic signals with low ambient noise levels.

Figure 2 Location of the Multi-Sites Project

- Log-derived stress data calibrated with in-situ stress test data indicate that a stress contrast ranging from 500 to 1,000 psi exists between the target sandstone units and the bounding lithologies. This stress contrast was considered suitable for limiting excessive fracture height growth.
- There were no unusual occurrences (e.g., near-wellbore effects) in pressure responses which inhibited 3-D modeling of the mini-frac treatment.
- Remote-wellbore monitoring during the mini-fracs was clearly able to identify over 1,000 microseisms during the hydraulic fracture injections. Limited analysis of these data indicated that the seismic signals can be spatially located and used for mapping the hydraulic fracture.

Based on these positive assessments, it was concluded that the MWX site is suitable for conducting additional comprehensive M-Site fracture diagnostics and fracture model verification experiments. Complete documentation of the field operations and results is found in GRI Topical Report No. GRI-93/0050 titled "Multi-Site Project Seismic Verification Experiment and Assessment of Site Suitability."

1.4 CONTRACTOR TEAM AND RESPONSIBILITIES

DOE and GRI are jointly sponsoring the research conducted in the M-Site Project. The contractor team which has been organized to execute the research project includes CER Corporation, Sandia National Laboratories and Resources Engineering Systems. The responsibilities of each of these organizations are described below:

CER Corporation

CER, under contract to both DOE and GRI, has multiple functions in the M-Site Project. These responsibilities are described as follows:

Site Operator - CER has the primary responsibility for the supervision and coordination of field operations and experiments conducted in the project to assure that they are performed safely and efficiently.

Data Acquisition Systems Development and Operation - CER is responsible for developing, installing, field checking and routine operations/maintenance of the conventional-speed data acquisition and networking systems used during the experiments.

Diagnostics and Treatment Experiment Design/Analysis - CER shares responsibility with the other GRI contractors in designing and supervising experiments supporting fracture diagnostics or fracture modeling goals. In addition, CER shares responsibility with the other contractors in designing fracture treatments and evaluating fracture treatment data.

Cost Administration - CER is responsible for field and office administration of the costs of equipment, materials and services required to implement experiments at M-Site.

Sandia National Laboratories

Sandia, under contract to GRI, has multiple responsibilities associated with the M-Site Project:

Fracture Diagnostics and Treatment Design/Supervision - Sandia has primary responsibility for design, technical supervision and interpretation of fracture diagnostics experiments. In addition, Sandia shares responsibility with the other contractors in designing fracture treatments and evaluating fracture treatment data.

Seismic Instrumentation and High-Speed Data Acquisition System Development and Operation - Sandia is responsible for developing, installing, field checking and routine operations/maintenance of the downhole seismic arrays and high-speed data systems used for fracture diagnostics experiments.

Resources Engineering Systems

RES, under contract to GRI, has responsibilities for activities described as follows:

Fracture Treatment Design and Modeling - RES has primary responsibility for fracture treatment modeling efforts conducted in the Project. As a part of this effort, RES shares responsibility for design of fracture treatments and fracture diagnostics experiments.

All of the contractors involved in the project share responsibility for documenting the accomplishments of the research through various means available (e.g., technical papers, topical reports, workshops).

Subcontractors

The technical services of various subcontractors are used to assist in performing experimentation at M-Site. The subcontractors included in the project team are Branagan & Associates and James Fix & Associates, Inc. As the need arises, the technical services of other organizations may also be subcontracted.

1.5 PROJECT PHASES AND TASK OBJECTIVES

1.5.1 Project Phases

The project, as currently defined, is divided into two phases. Phase I involves the installation and testing of fracturing diagnostics instrumentation, and the performance and analyses of a series of field experiments so the geometry of created fractures can be measured. Passive seismic monitoring tools will be installed in MWX-3 and in Monitor Well No. 1. Fracturing tests will be conducted in MWX-2. Phase II will involve the drilling of a special directional well with two or more lateral extensions designed to intersect and characterize created hydraulic fractures. Other objectives of Phase II are to conduct predictive fracturing model verification experiments to measure the performance of various models and to advance fracturing technology.

1.5.2 Task Descriptions

Each of the project phases are further subdivided into tasks which are described as follows:

Phase I Fracture Diagnostics Tests at the MWX Site

Task 1: Drill, Evaluate and Instrument a Seismic Monitor Well

A monitoring well shall be drilled, tested and instrumented adjacent to the MWX well pad. The well is to be drilled to a depth of approximately 5,000 ft, and is to be logged and selectively cored to detail rock properties of the zone of interest. The oriented core will be used to specifically determine the preferred hydraulic fracturing azimuth in the top of the Mesaverde section so that diagnostic instrumentation can be placed effectively. This task includes site preparation and installation of site infrastructure, such as utilities and work housing for researchers and instrumentation. Task 1 has been completed.

Task 2: Conduct Fracture Closure Stress Tests

In conjunction with mini-frac injections into the MWX-2 well, fracture closure experiments shall be conducted in Monitor Well No. 1 and/or MWX-3 to evaluate various independent closure determination techniques. Methods to be evaluated include injection well pressure falloff, inclinometer output from the monitor well, and hydraulic impedance and tubewave characteristics in MWX-2. Task 2 activities will be initiated in the second year of the project.

Task 3: Conduct Seismic Fracture Diagnostics Tests

Using MWX-2 as the frac well and MWX-3 and Monitor Well No. 1 as observation wells, a number of mini-fracs shall be conducted to analyze fracture length and height. Multiple three-component geophone assemblies installed in the observation wells will be used to collect seismic signals generated during the mini-fracs. These signals, along with injection data, will be collected in real time and analyzed to derive fracture geometry and propagation behavior. Fracturing diagnostics tests will continue throughout the period of performance. Work in this task was initiated in the first year of the project and is on-going.

Phase II Fracture Model Verification and Frac Diagnostic Tests

Task 4: Drill Directional Well Pilot Hole and High-Angle Leg No. 1

A new directional well shall be drilled to the south of the projected MWX-2 fracture azimuth. The well will consist of a 5,000-ft deep vertical pilot hole, which will later be plugged back and kicked off to form the high angle leg. The vertical pilot hole will be logged to define reservoir tops and bottoms. The well will then be kicked off at an appropriate depth to intersect the target sand with its propped fracture. Coring and/or frac tracer and logging will be used to detail the fracture intersection. This section of the deviated well will be left as an open hole to permit fracture conductivity testing. This task is planned for the second year of the project.

Task 5: Conduct Fracture Conductivity and Seismic Tests

Fracture conductivity tests shall be conducted utilizing the MWX-2 frac well and the intersecting deviated hole, with both wells appropriately instrumented. Information gathered will be used to verify fracture models. Information will potentially include data on:

- propped fracture width;
- proppant bed effective permeability;
- proppant settling pattern; and
- proppant crushing and/or embedment.

At the same time, diagnostics tests may help to determine propped fracture dimensions. This task is planned for the second year of the project.

Task 6: Drill High-Angle Leg No. 2

A higher sand as an intersection target and kick off a second leg from the pilot hole shall be selected. The new leg intersecting the target sand will be left in an open-hole state to permit fracture pressure testing. The target sand will be cored and/or logged to characterize the intersected fracture and the lateral variability of the reservoir. This task is planned for the second year of the project. This task is planned for the second year of the project.

Task 7: Perform Fracture Pressure and Seismic Tests

Experiments shall be designed and conducted to 1) measure the hydraulic pressure at the leading edge of the fracture, and 2) provide a direct indication of the horizontal growth rate of the fracture wing. The objective is to provide independent comparisons to fracture length from seismic experiments. Data gathered in these tests would support fracturing model verification. The experiments would utilize the high-angle well legs as well as other test site wells. This task is planned for the second year of the project.

Task 8: Project Documentation and Technology Transfer

Complete documentation of activities and results will lead to continuous tech transfer via technical progress reports, technical publications, topical presentations at technical meetings, topical workshops and reports, and direct communication to industry at the field site. Formal topical reports on activities, experiments and results of special technical or newsworthy interest, such as a novel diagnostics experiment and its results, shall be prepared. Work in this task was initiated in the first year of the project and is on-going.

2.0 Work Performed from July 28, 1993, to July 31, 1994

Technical progress in the first year of the project is documented by task number in the following sections.

2.1 TASK 1: DRILL, EVALUATE AND INSTRUMENT A SEISMIC MONITOR WELL

2.1.1 Site Infrastructure

Significant efforts were expended by CER in the first year of the project to extend the site infrastructure necessary for conducting fracture diagnostics experiments. This progress is summarized as follows:

- A leased office/central conference trailer was established on the MWX pad for the project. This trailer includes the primary telephone/fax communications equipment and also houses the computer workstations where researchers receive data from satellite locations during fracturing experiments. Select equipment items to equip the office trailer (e.g., microwave oven) were acquired from DOE excess or surplus at the Nevada Test Site.
- Utilities (e.g., commercial power, water, sanitation) services were established for the trailer. Commercial electric power was also run underground to several satellite locations including the DOE 7-conductor wireline trailer, GRI single-conductor wireline trailer, and the Monitor Well pad located several hundred feet south of the MWX pad. Backup electrical power for the site, in case of commercial power failure, was integrated into the system through the use of a 90 kw generator and several 30 kw generators. Several key data acquisition systems are also equipped with uninterruptable power supplies.
- Road access to the MWX pad was improved by blading a road along the west fence line from the SHCT pad to the MWX pad, as illustrated in Figure 3. This improvement, when combined with the existing road access, created a "loop driveway" and facilitates the ingress and egress of frac trucks and the placement of other equipment (trailers, frac tanks) associated with the project.
- General site and equipment maintenance activities were performed and included site grading, tubing inspection, calibration of surface electronic devices, calibration of the downhole surface readout pressure probe, acquisition of tools and supplies for the wireline units, and other services generally related to establishing or maintaining the site infrastructure.

2.1.2 Data Acquisition Systems

The acquisition of computer equipment and the fabrication of data acquisition systems was a major accomplishment in the first year of the project. Figure 4 illustrates the network of data acquisition systems fielded at the M-Site. These data acquisition systems are subdivided and described as follows:

Figure 3 Layout of M-Site Infrastructure

Figure 4 Data Acquisition Systems for Fracture Diagnostics Experiments

Conventional-Speed Data Acquisition System

The primary objective of this segment of the M-Site project is to provide project field experimenters with easy access to existing, on-site, low- to moderate-speed data acquisition systems (DAS) and assure the acquisition of high-quality data. Three data acquisition systems were designed and constructed to provide the following basic functions:

- uniform signal processing and conditioning;
- local-area data-gathering focal points;
- clean and controlled hardware environments; and
- data communications linkage between satellite locations and the central client server.

Data gathered at these three satellite systems will automatically transfer pertinent information back to the central client/server (located in the conference trailer) in a specific format for systematic review, analysis and archiving.

Each of the DASs were configured to accommodate the currently planned experimental data that includes the following:

- downhole inclinometer signals;
- fracturing service company and project-measured pressure, injection rate and fluid rheology data; and
- bottomhole injection and reservoir monitoring pressures.

These systems include sufficient hardware and software flexibility and expandability to accommodate additional experimental data as they are incorporated into the project plan.

Each of the field-hardened DASs are housed in environmentally-controlled structures which include the following:

- instrument racks, cabling and conditioned power sources and an uninterruptable power supply (UPS);
- 16-channel A/D front ends;
- plug-in cards to accept frequency data;
- 386 PC-based platforms with 8 MB RAM;
- caching and 80 MB hard disk data storage;
- electrical noise isolation; and
- fiber optic ethernet communications networking to the central file server.

Basic data acquisition and display software are available such that the experimenters will be able to monitor the status of their instruments and the acquired engineering data through a series of graphic and tabular screen displays and a variety of print media.

High-Speed Data Acquisition System

The primary objective of this segment of the M-Site project is to provide project seismic and other field experimenters with a data acquisition system that combines high speed with efficiency and cost effectiveness. Sandia National Laboratories had primary responsibility for the design specifications of two data acquisition systems that will serve the microseismic receivers arrays in the two project monitor wells. These two high-speed DAS systems will provide the following basic functions:

- low-noise, high-bandwidth data acquisition sites capable of accepting as many as 96 seismic receivers per well;
- event detection and transferring of specific data across the communications link to the central client server; and
- local high density (DAT) tape storage of all processed signals.

These high-speed DAS were fabricated from existing commercially-available hardware and software, although the integration, testing and interfacing of this complex system required considerable care, effort and technical management both in the development and fielding phases.

Central Computer/Client Server/Local Area Network Hub

A PC-based central computer system functions as the focal point for the project's Local Area Network (LAN) and client server. The purpose of this system is to provide a central hub to receive, distribute and store the large data arrays from the satellite data acquisition systems (high-speed and conventional DASs) as well as to allow each of the project experimenters easy access to all real-time data. The client server includes the following basic functions:

- high-speed Novell LAN system;
- fiber optic and hardwire ethernet connections;
- high-capacity disk storage; and
- work stations and local PCs for real-time analysis.

The LAN client server is located in the conference trailer that also houses work stations and PCs from which experimenters can interact with the data through the client server and with each other. Data from each of the satellite data systems can be channeled to the client server after being explicitly formatted, thereby permitting easy access to the entire data file by any or all of the experimenters. All of these data can be permanently stored on the client server hard disk for subsequent retrieval and analysis.

The LAN client server functions as the focal point for all project-related data. This high-throughput PC-based system incorporates the following basic components:

- high-speed (66 Mhz) 486 PC-based computer;
- large disk caching and high-capacity high-speed disk (1.2 Gb);
- Novell LAN software;
- fiber optic and hardwire ethernet links;
- IRIG timing network for the satellite systems;
- experimenter PCs and work stations; and
- printer, plotting and other peripherals.

A large UPS system is included in the system to offset short duration losses of local power. Data from the large microseismic detector arrays will be scanned and evaluated in the satellite high-speed DAS. If an event is considered significant, it is transported across the fiber optic ethernet line to the LAN client server where it is available for further real-time analysis by the experimenters using either a work station or other project-provided PC systems. All the LAN client server data is permanently stored on a hard drive and backed up on tape after each experiment. IRIG timing provides links from the LAN client server. This link provides the required data timing identification stamp to precisely time tie related events from any microseismic detector at any location. Precise timing between systems is necessary to accurately define the location of microseismic events using triangulation.

Each of the three conventional speed DASs are ethernet linked to the LAN client server which will again serve as a focal point for data distribution and storage. Service company data can be routed through a DAS where it will be formatted and shipped over the ethernet to the LAN client server. There, FRACPRO or other related fracturing programs can access the data from the client server.

2.1.3 Drill and Evaluate Monitor Well No. 1

The specific objective of this portion of Task 1 is to drill and case a specially-designed offset well (Monitor Well No. 1) used to emplace a set of seismic and earth tilt instrumentation. Comprehensive fracture diagnostics experiments could then be performed using a combination of the Monitor Well No. 1, MWX-2 and MWX-3. Figures 5, 6 and 7 illustrate profiles of instrumentation arrays and well locations relative the hydraulic fracture for these experiments. The Monitor Well is necessary because the comprehensive seismic experimentation which has the potential for clearly defining the dimensions of a hydraulic fracture requires an instrumentation array beyond that which can be fielded on a wireline retrievable system. The Monitor Well instrumentation arrays are to be coupled to the formation (cemented in place) and properly located (vertically and horizontally) to be effective in acquiring meaningful data.

The surface location of Monitor Well No. 1 is in the southwest quarter of the northwest quarter (2,509 ft FNL, 770'(FWL) of Section 34, T6S R94W, Garfield County, Colorado. The ground elevation of the staked well location is 5,385.5 ft.

Figure 5 Instrumentation and Diagnostics Arrays to be Deployed at M-Site

Figure 6 Proposed Instrumentation Placement in Monitor Well No. 1

Figure 4 Location of MWX-2 Treatment Well, and Relative Position of the Monitor Well No. 1 and MWX-3 Observation Wells

The specific position of Monitor Well No. 1 was determined by several factors:

- 1) Planned M-Site experimentation includes the initiation of northwest/southeast trending hydraulic fractures from MWX-2 to a point located between two observation wells: MWX-3 to the north and Monitor Well No. 1 to the south of the hydraulic fracture. These wellbore configurations would maximize the opportunity to conduct unique experiments such as shear wave shadowing (i.e., using a seismic source and receiver well pair) or to field complementary seismic monitoring systems (i.e., fixed and wireline retrievable systems).
- 2) Alignment of MWX-3, MWX-2 and Monitor Well No. 1 was not desirable for seismic data acquisition. Thus, if a line were drawn from MWX-3 to MWX-2 and projected 300 to 400 ft south, Monitor Well No. 1 location was intentionally offset to the east to avoid straight-line alignment and to take advantage of favorable topography.

Monitor Well No. 1 drilling operations are summarized as follows:

- Monitor Well No. 1 drilling operations began on February 8, 1994, with a rathole rig which drilled a 30-in. hole to 33 ft. On February 12, 20-in. conductor pipe was cemented in place.

- On February 13, the same rathole rig which started the conductor hole continued drilling the 17-1/2-in. intermediate hole to a depth of 65 ft before rocks and boulders prevented straight-hole drilling. Veco Rig No. 5 was then moved and rigged up to continue drilling the 17-1/2-in. hole. Veco began daywork drilling operations on February 17. The 17-1/2-in. hole was drilled to 295 ft where 13-3/8-in. casing was set and cemented on February 19.
- Drilling resumed on February 20 with a 12-1/4-in. bit. The boulders that are generally characteristic of the upper portion of the hole in this area did not present any severe drilling problems and were encountered from surface to an estimated depth of 710 ft KB. The 12-1/4-in. hole was drilled to a depth of 4,170 ft on March 9. An 8-3/4-in. pilot hole was started at this depth to facilitate the coring and logging operations and was drilled to a depth of 4,605 ft which was reached on March 16. Reaming of the 8-3/4-in. hole to 12-1/4 in. began on March 17 and required a total of 37 hours to open 435 ft of 8-3/4-in. hole. Drilling of the 12-1/4-in. hole continued and reached total depth of 5,000 ft on March 20. Upon completing logging operations, 9-5/8-in. casing was set and cemented on March 22. The drilling rig was released on March 23, and a total of 35 days were required to drill Monitor Well No. 1.
- The drilling fluid used to drill Monitor Well No. 1 was a low-solids nondispersed freshwater system. Mud weights ranging from 8.8 to 9.5 ppg were maintained while drilling. A cost-effective approach to drilling fluids was used and included several solids control equipment items (dual-screen shale shakers, centrifuge and dual pumps) and recirculation of the reserve pit volume to limit costs.
- Wellbore deviation was carefully controlled and measured in the course of drilling Monitor Well No. 1. A well drilled as nearly to vertical as possible was desired to facilitate the subsequent emplacement of the accelerometer and inclinometer instrumentation packages. A pendulum bottomhole assembly was used in the 12-1/4-in. portion of the hole to minimize deviation. The assembly consisted of 5-in. O.D. drillpipe, and 9-in. and 10-in. drill collars. Non-rotating stabilizer rubbers were also used in the assembly but were not considered to be effective; in the final analysis, lost rubber elements caused significant delays in the coring operations. Single shot surveys were taken at approximately 250-ft intervals, and these data indicated deviations between 1/4° and 3/4°. Station measurements taken with the core orientation tool also provided confirmation that wellbore deviation was within acceptable limits. Final confirmation of the wellbore deviation was acquired with a cased-hole gyro survey performed on April 14, 1994. The gyro survey indicated that wellbore deviations were less than 1/2°.
- The cement design for the 9-5/8-in. casing, based on an on-site review of Monitor Well No. 1 caliper log, provided what was believed to be sufficient excess volume to circulate cement to surface. However, cement volume was insufficient to circulate to surface and the cement top was subsequently located at 2,120 ft on the cement bond log.

Data acquisition programs completed during the drilling of Monitor Well No. 1 can be summarized as follows:

- Oriented coring operations on Monitor Well No. 1 were performed from March 12 to March 16, 1994, starting above the C sand at a depth of 4,282 ft. Four coring runs were performed to recover a total of 102.8 ft of core. For each core run, a 6-3/4-in. x 4-in. x 60-ft core barrel and a slip-scribe core catcher housing tungsten-carbide scribe knives made up the barrel assembly, and an 8-3/4-in. Polycrystalline Diamond Compact (PDC) insert bit was used.
- CER processed and handled all Monitor Well No. 1 core using comprehensive techniques designed to provide a consistent, high-quality core product to subsequent analysts. These methods included an on-site core processing facility where core segments were reassembled, marked for depth and orientation, macroscopically described (lithology and fracture), preserved in an oxygen-barrier sleeve material, and boxed prior to shipment to the core analysis service company for plugging and routine porosity/permeability analyses. Whole-core C sand samples were taken on location by Sandia National Laboratories personnel for CVA analysis and rock mechanical properties tests. CER personnel selected additional B sand whole core samples to be shipped to Sandia for CVA analysis.
- An oriented coring assembly was used for each core run to provide data for the orientation of natural and induced fractures and for various fracture diagnostics core analyses. The orientation assembly consisted of a single electronic survey instrument (CHAMP tool) located inside of a monel drill collar. The orientation tool functioned on each core run and provided usable orientation data.
- Monitor Well No. 1 was logged in open hole by Schlumberger. The Formation Microscanner Log was run on March 17 in an 8-3/4-in. hole at a total depth of 4,603 ft after completing the coring operations. The hole was then reamed to 12-1/4 in., deepened to a total depth of 5,000 ft. Run 2 logging was performed with a MAXIS 500 logging unit on March 21-22, 1994, and included the following logging tools: Formation Microscanner/Monitor Log, Lithodensity/Caliper/Gamma, Dual Thermal & Epithermal Neutron, Electromagnetic Propagation End-Fire, Dipole Sonic Imager/Inclinometry Tool/Gamma Ray, Array Induction Log/Gamma Ray, and Oriented 4-Arm Caliper/Gamma.

After drilling Monitor Well No. 1, the reserve pit volume was disposed and the site readied for instrument emplacement scheduled to occur in August 1994.

2.1.4 Monitor Well Instrumentation

Occurring simultaneous to Monitor Well No. 1 drilling activities and the fabrication of the data acquisition systems, orders were placed for the instruments and cabling which were to be emplaced in the Monitor Well. These orders included 6 inclinometers manufactured by Applied Geomechanics, 30 accelerometers fabricated by Wilcoxin, and cabling for both instruments sets manufactured by Tescorp Seismic Products. In addition, CER acquired and retrofitted a small

trailer to be located on Monitor Well No. 1 pad for housing the data acquisition systems. Instruments, cable and the trailer facility were completed and delivered in anticipation of the August 1994 emplacement date.

2.2 TASK 3: CONDUCT SEISMIC FRACTURE DIAGNOSTICS TESTS

2.2.1 Objectives of the A Sand Experimentation and Data Acquisition

In support of the overall M-Site project objective, a series of experiments and data acquisition operations were designed and executed between October 25 and November 5, 1993, in the A sand interval of the Mesaverde section. The A sand data acquisition and experimentation were conducted using the unique configuration and close spacing of the MWX-2 and MWX-3 wellbores. The specific planned objectives of these experiments are summarized as follows:

Characterization of the A Sand Velocity Structure

Knowledge of the three-dimensional velocity structure of the A sand interval substantially improves the interpretation of the location of remotely-detected microseismic events which occur during hydraulic fracturing. Therefore, a borehole tomography survey was planned using the MWX-2 well to emplace a five-level borehole accelerometer package and the MWX-3 well for emplacing an airgun seismic source.

Comprehensive Remote-Well Seismic Event Detection During Mini-Frac Injections

Microseismic monitoring experiments at the M-Site performed in October 1992 used a single advanced-technology accelerometer for remotely monitoring seismic events during a mini-frac treatment. The data acquired from this single-level borehole accelerometer extended the usable frequency range over the conventional wall-locking geophone and allowed more accurate location of seismic events. The objective of the October/November 1993 fracture diagnostics experiments performed in the A sand was to substantially reduce vertical wavefield errors through the use of multiple seismic receivers (accelerometers) in a remote observation well. Thus, the location of treatment-induced seismic events can be more accurately determined, thereby improving hydraulic fracture mapping capabilities. To accomplish this goal, four mini-fracs were planned during which a five-level accelerometer array, placed in the borehole on a fiber optics wireline, would detect microseisms and transmit these data to surface recording systems. Three of the mini-fracs were planned to be fluid only. The fourth mini-frac would include proppant, thereby providing an opportunity to contrast the character of microseismic events from the two types of treatments.

Verification of Treatment Well Fracture Diagnostic Techniques

Prior GRI-funded fracture diagnostics research had demonstrated that fracture height and azimuth could be estimated using seismic data acquired in the treatment well following a fracture treatment. These seismic data were acquired using the conventional wall-lock geophone technology. The objective of the October/November 1993 experiments were to use the new borehole accelerometers to collect seismic data that may then be analyzed with the

h/z technique to determine fracture height and azimuth. The results of the h/z survey can potentially be verified by contrasting and comparing to the fracture height results determined from remote-well (MWX-3 or Monitor Well No. 1) multi-level seismic arrays.

Verification of Convective Processes during Hydraulic Fracturing

The objective of this experiment was to resolve issues concerning the effective placement of proppant in the hydraulic fracture and fluid convective processes which may redistribute this proppant in the fracture or the wellbore. The basic strategy was to pump a mini-frac (Mini-Frac No. 4) in which the fluid and proppant have been tagged with three different radioactive tracers. Wireline logging runs with a spectral gamma ray tool would then be performed to monitor the location of these tracers in and around the wellbore.

This phase of the project (i.e., a set of experiments performed using the MWX-2 for emplacing wireline-retrievable seismic receivers and MWX-3 as a treatment well) represented an intermediate step in definitively determining hydraulic fracture dimensions. The next logical phase of the Multi-Site Project was to emplace a new instrumentation well (i.e, Monitor Well No. 1) that includes a greater number of seismic accelerometers. Using a combination with the existing MWX wells and the Monitor Well No. 1, experiments can then be conducted so the hydraulic fracture may be comprehensively imaged and dimensionally characterized.

2.2.2 Summary of Field Operations and Data Acquisition for Fracture Diagnostics

2.2.2.1 Crosswell Tomography Data Acquisition

The initial phase of field data acquisition was performed October 25-29, 1993, and involved a comprehensive crosswell tomographic survey to characterize the velocity structure of the A sand interval. This survey used MWX-3 for emplacement of the seismic source and MWX-2 for emplacement of the borehole accelerometer array. These equipment components are more completely described as follows:

Seismic Source - Bolt airgun

Seismic Receivers - The seismic receivers used in the tomography survey consisted of five individual accelerometer-based Advanced Borehole Receivers available from OYO Geospace and customized by Sandia National Laboratories. The low-noise piezo-electric accelerometers utilized in the receivers have significant advantages over conventional borehole geophones. In particular, these accelerometers do not exhibit the spurious resonance problem common to geophones. The most important difference, however, is that these custom-designed accelerometers are more sensitive than geophones at the higher seismic frequencies. Previous M-Site work has shown that there is as much as a 10:1 improvement in signal detection at 1,000 Hz using the Advanced Borehole Receivers. The individual accelerometers have electric gear-motor assemblies which drive a rectangular piston perpendicular to the longitudinal axis of the tool to anchor the instruments to the borehole wall. The five individual instruments were spaced at 10-ft intervals on a fiber optics wireline. The design of these accelerometers is identical to the single-level system utilized in the initial M-Site Seismic Verification experiment in October 1992.

Data Acquisition - Bolt system consisting of a high-speed system and fiber optics cable to handle the large stream of data from the five downhole accelerometers.

Complete coverage of the A sand interval was achieved in the crosswell tomography survey by varying the depth interval that the accelerometer array was locked into and by varying the depth of the airgun source.

2.2.2.2 Hydraulic Fracturing

The final phase of experiments performed in the A sand included pumping a series of small hydraulic fracturing treatments in MWX-3 while collecting seismic data in the offset MWX-2 well. These tests were performed November 1-4, 1993. MWX-3 was perforated in the A sand at 4,900-4,920 ft and 4,930-4,946 ft with 72 holes (0.4 in.) at 2 SPF and 120° phasing. Four separate mini-frac treatments were performed, each of which were monitored and analyzed in real-time using FRACPRO. Several rapid shutdowns were made during each of the treatments to evaluate near-wellbore friction. The following is a summary of the field operations and data acquisition for each of the treatments.

Mini-Frac No. 1

The first mini-frac, performed on November 1, 1993, consisted of pumping 450 bbl of 40# linear gel at an average injection rate of 25.0 BPM down the 2-7/8-in. by 7-in. annulus. A prototype wireless bottomhole pressure telemetry tool was run on the end of tubing and positioned below the perforations at about 4,970 ft. Also, a surface readout pressure gauge was run on wireline inside the tubing and hung at 4,890 ft. A secondary goal of this mini-frac was to compare the bottomhole pressure readings of the two gauges. However, the prototype pressure telemetry tool did not function properly and meaningful pressure data was not obtained from it during the treatment. Data that were recorded during the treatment include tubing pressure, casing pressure, bottomhole pressure, pump rate and viscosity of the batch mixed linear gel.

Mini-Frac No. 2

The second mini-frac, performed on November 3, 1993, consisted of pumping 400 bbl of 40# linear gel at an average injection rate of 15.1 BPM down the 7-in. casing. A single seismic receiver was coupled with a gyro orientation tool and hung on a 7-conductor wireline in the casing below the perforations. Following the mini-frac, the seismic receiver was moved at 50-ft intervals to perform h/z surveys for fracture height determination.

Several attempts were made to hang the prototype wireless bottomhole pressure gauge in the casing about 300 ft below the perforations prior to running in the hole with the seismic receiver and pumping the mini-frac. However, the casing hanger (run on slickline) failed to operate properly and the pressure gauge had to be retrieved from the well. As a result, bottomhole pressure was not recorded during the treatment. Data that were recorded during the treatment included casing pressure, pump rate and gel viscosity.

Mini-Frac No. 3

The third mini-frac, performed on November 4, 1993, consisted of pumping 434 bbl of 40# linear gel at an average injection rate of 20.4 BPM down the 7-in. casing. A single seismic accelerometer (without the gyro orientation tool used in Mini-Frac No. 2) was hung in the casing below the perforations on a 7-conductor wireline. Following the mini-frac, the seismic receiver was moved at 50-ft intervals to perform h/z surveys for fracture height determination. Data that were recorded during the treatment included casing pressure, pump rate and gel viscosity.

Mini-Frac No. 4

The fourth mini-frac, also performed on November 4, 1993, included the use of 16,900 lb of 20/40 mesh sand, 617 bbl of 40# linear gel and 3 different radioactive tracers in an attempt to evaluate near-wellbore proppant placement and the process of proppant (slurry) convection. The treatment was pumped down the 2-7/8-in. by 7-in. annulus at an average injection rate of 19.0 BPM. A spectral gamma ray logging tool was left hanging in the tubing at 4,650 ft during the mini-frac to allow for immediate logging runs above and below the perforations following shutdown. Data that were recorded during the treatment included casing pressure, tubing pressure (dead string), pump rate, proppant concentration and base gel viscosity.

2.2.2.3 Microseismic Monitoring

Remote-well (MWX-2) monitoring of seismic events occurred during each of the mini-frac treatments using the seismic receiver array and data acquisition system previously described. Four of the five accelerometers were locked into position prior to the first mini-frac at station depths of 4,885, 4,895, 4,905 and 4,955 ft, and the array was not unlocked until after the fourth mini-frac was completed.

Treatment-well (MWX-3) monitoring of microseismic events (i.e., h/z surveys) was also performed during Mini-Frac Nos. 2 and 3. In Mini-Frac No. 2, the monitoring instrumentation consisted of a single accelerometer coupled with a gyroscopic orientation tool. The assembly was run on a 7-conductor wireline, through a pressure packoff and into the deadstring tubing. The tool assembly resided within the deadstring until after the mini-frac was pumped. When the mini-frac was completed, backpressure was held on the well so that the induced hydraulic fracture would be held open. During this period of holding backpressure, the tool assembly was lowered out of the end of tubing; station measurements of noise polarization were monitored and recorded at the depth stations designed to be below, within and above the vertical extent of the hydraulic fracture.

Treatment-well microseismic monitoring during Mini-Frac No. 3 was performed in much the same fashion as Mini-Frac No. 2 except that the tool assembly did not include the gyro instrument. By experiment design, the gyro was not included so that a comparison could be made of data quality acquired with: a) the short light-weight tool assembly run in Mini-Frac No. 2; and b) the tool assembly that may be susceptible to tool resonances (due to its relatively heavy weight and assembly length) that was run during Mini-Frac No. 3.

2.2.2.4 Post-Frac Gamma Ray Logging

Wireline spectral gamma ray logging was performed prior to and following the fourth mini-frac in support of the experiment to verify proppant placement and convective processes during hydraulic fracturing. This logging initially involved a baseline gamma ray log run which was performed over the interval 5,530 to 4,640 ft prior to Mini-Frac No. 4. This baseline run established the background radiation baseline against which the post-frac gamma ray log runs could be compared. Nine subsequent repeat logging runs were then performed. All of these logging runs were performed as soon as possible after pumping was stopped for shut in. This was accomplished by having the logging tool residing near the end of the dead tubing string during the treatment. During the shut ins, the tool would descend out of tubing and record data. Up-logging speed was maintained at a constant speed for data quality. These repeat runs provided information on the location and estimated volume of tagged proppant.

2.3 TASK 8: PROJECT DOCUMENTATION AND TECHNOLOGY TRANSFER

Two project reports are currently being prepared which document the major M-Site field activities, data acquisition and data analysis. These report titles are as follows:

- "Results of Multi-Site Experimentation in the A Sand Interval: Fracture Diagnostics, Fracture Modeling and Crosswell Tomography" - This report documents the experimentation completed in October 1993. Completion of this report is pending completion of interpretations by Sandia National Laboratories.
- "GRI/DOE Multi-Sites Fracture Diagnostics Project: Monitor Well No. 1 Drilling, Data Analysis and Instrument Emplacement" - This report documents the drilling activities and data analyses which resulted from drilling the Monitor Well. Completion of this report is pending the emplacement of instruments in Monitor Well No. 1.

In addition to these project reports, CER also participated in the DOE contractor review meeting held in Morgantown, West Virginia, in November 1993. The concept of the M-Site project and results as of the meeting date were presented.

3.0 Future M-Site Activities

3.1 TASK 2: CONDUCT FRACTURE CLOSURE STRESS TESTS

Activity in this entire task is scheduled to occur in the second year of the project. No work was performed in the first year.

3.2 TASK 4: DRILL DIRECTIONAL WELL PILOT HOLE AND HIGH-ANGLE LEG NO. 1

Activity in this task is scheduled to occur in the second year of the project. No work was performed in the first year.

3.3 TASK 5: CONDUCT FRACTURE CONDUCTIVITY AND SEISMIC TESTS

Activity in this task is scheduled to occur in the second year of the project. No work was performed in the first year.

3.4 TASK 6: DRILL HIGH ANGLE LEG NO. 2

Activity in this task is scheduled to occur in the second year of the project. No work was performed in the first year.

3.5 TASK 7: PERFORM FRACTURE PRESSURE AND SEISMIC TESTS

Activity in this task is scheduled to occur in the second year of the project. No work was performed in the first year.