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**Hydraulic Fracture Model and Diagnostics Verification at
GRI/DOE Multi-Site Projects and Tight Gas Sand Program
Support**

DOE/MC/30070--99

**Final Report
July 28, 1993 - February 28, 1997**

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Work Performed Under Contract No.: DE-FC21-93MC30070

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1.0 EXECUTIVE SUMMARY

1.1 OVERVIEW

The Mesaverde Group of the Piceance Basin in western Colorado has been a pilot study area for government-sponsored tight gas sand research for over twenty years. Early production experiments included nuclear stimulations and massive hydraulic fracture treatments. This work culminated in the U.S. Department of Energy (DOE)'s Multiwell Experiment (MWX), a field laboratory designed to study the reservoir and production characteristics of low permeability sands. A key feature of MWX was an infrastructure which included several closely spaced wells that allowed detailed characterization of the reservoir through log and core analysis, and well testing. Interference and tracer tests, as well as the use of fracture diagnostics gave further information on stimulation and production characteristics. Thus, the Multiwell Experiment provided a unique opportunity for identifying the factors affecting production from tight gas sand reservoirs.

The purpose of this operation was to support the gathering of field data that may be used to resolve the number of unknowns associated with measuring and modeling the dimensions of hydraulic fractures. Using the close-well infrastructure at the Multiwell Site near Rifle, Colorado, this operation focused primarily on the field design and execution of experiments. The data derived from the experiments were gathered and analyzed by DOE team contractors.

1.2 Summary of Operations

A field infrastructure was developed and enhanced in order to efficiently execute and gather all relevant data that would support the definitive and accurate calculation or measurement of hydraulic fracture shape and extent.

Fracture experimentation was programmed within formations that had been well-characterized to avoid expense and technical risk associated with the collection and evaluation in an unfamiliar area.

The character of the formation selected for experimentation was representative of those encountered by producers in hydraulic fracturing.

A series of successfully executed experiments were conducted to :

- 1) Determine hydraulic fracture dimensions using remote well and treatment well diagnostic techniques, and
- 2) Provide data which could resolve significant unknowns with regard to hydraulic modeling, fracture fluid rheology and fracture design.

2.0 INTRODUCTION AND BACKGROUND

2.1 OVERVIEW

Since 1983, the U.S. Department of Energy (DOE) and the Gas Research Institute (GRI) have sponsored research projects at the Multi-Well Experiment Site (MWX Site) in the Piceance Basin of Colorado to advance hydraulic fracture stimulation. The main objectives have been to: (1) integrate geological, petrophysical and engineering analyses to more effectively complete tight gas sand reservoirs; and (2) develop the ability to accurately analyze the shape and extent of a hydraulic fracture in real-time. In addition, the GRI has conducted a number of field experiments, mainly within the Travis Peak and Cotton Valley Formations in East Texas, the Canyon Sands in West-Central Texas, the Frontier Formation in Wyoming, and the Mesaverde Formation in Western Colorado.

Significant advancements have been made in several areas, including the modeling of fracture propagation processes, formation evaluation, diagnosing fracture azimuth and height, production modeling of hydraulic fractured natural gas reservoirs, developing and applying certain technologies in defining the stress characteristics of various layers of rock, measuring parameters before, during and after a fracture treatment, and using information in a hydraulic fracture propagation model to predict the shape and extent of the resulting hydraulic fractures. Although diagnostic systems developed to this point were capable of determining fracture azimuth and height, there were no techniques available for accurately determining fracture length. Also, there remained some important questions as to fracture propagation. Currently, fracture propagation models used by industry vary widely in their results for given input parameters due to various assumptions associated with the in-situ hydraulic fracturing process.

The proposal titled *Hydraulic Fracture Model and Diagnostics Verification at GRI/DOE Multi-Site Projects*, ("Proposal"), was submitted to the GRI and the DOE in September 1992 by CER Corporation (CER) as an approach to resolve certain unknowns associated with measuring and modeling the dimensions of hydraulic fractures. In particular, the primary focus of that Proposal was to design and execute experiments to acquire high-quality field data. These data were expected to provide the basis for verification of three-dimensional (3-D) hydraulic fracture models, including the FRACPRO model developed through the GRI and through cooperative experiments to confirm the utility of various fracture diagnostics tools and techniques.

The following guidelines provided by the DOE and GRI were used in developing the CER Proposal:

- 1) The experimentation was to gather all relevant data necessary to support definitive and accurate calculation or measurement of hydraulic fracture shape and extent;
- 2) The geologic formations in which such fracture experimentation was proposed, were to be well-characterized in order to avoid expense and technical risk associated with the collection and evaluation of data from unfamiliar areas;

- 3) The character of the selected geologic formation was to be representative of those continuously encountered by producers in hydraulic fracturing; and
- 4) Sites with an existing infrastructure for conducting experimentation were to be used in order to reduce start-up costs and minimize the time required to initiate field work.

Based on these guidelines, CER developed three proposed strategies for future research. They included:

- Close-well experimentation at the DOE Multi-Well Experiment (MWX) Site, termed Multi-Site Project No. 1 (MSP-1);
- Far-field and close-well experimentation at the GRI Red Mountain Test Site, termed Multi-Site Project No. 2 (MSP-2); and
- Producer involved co-op experimentation.

All three proposed strategies involved the use of multiple sites and were therefore termed multi-site projects. Although all three proposed strategies were presented in CER's original Proposal, MSP-2 and producer involved co-op experimentation were not emphasized and as such were not performed in the subsequent work program. Therefore, the following sections describe the infrastructure and operational aspects associated only with MSP-1.

2.2 FIELD FRACTURING MULTI-SITES PROJECT

2.2.1 Objective of the Field Fracturing Multi-Sites Project

The objective of the Field Fracturing Multi-Sites Project ("Project") was to conduct experiments to definitively determine hydraulic fracture dimensions using remote well and treatment well diagnostic techniques. In addition, experiments were to be conducted to provide data that would resolve significant unknowns with regard to hydraulic fracture propagation, fracture fluid rheology and fracture treatment design. These experiments were supported by a well-characterized subsurface environment, as well as surface facilities and equipment conducive to the acquisition of high-quality data. The primary Project goal was to develop a fully characterized tight reservoir-typical, field-scale hydraulic fracturing test site to diagnose, characterize and test hydraulic fracturing technology and performance. It was anticipated that the research conducted by a multi-disciplinary team of GRI and DOE contractors would lead to the development of increased natural gas recovery that would help industry improved development economies.

2.2.2 Site Selection

The GRI and the DOE determined that a joint effort was necessary to resolve the significant unknowns associated with measuring and modeling the dimensions of hydraulic fractures. The site selected for the hydraulic experimentation was the former DOE Multi-Well Experiment Site (MWX-Site) now known as the M-Site, located near Rifle, Colorado (Figure 1). The M-Site infrastructure included three closely-spaced wells, the MWX No. 1, the MWX

Figure 1 Location Map, M-Site

No. 2 and the MWX No. 3 (Figure 2). Upon completion of the MWX experiment, CER acquired the mineral lease and ownership of the wellbores in order to promote continued tight gas sands research. One of the three wells, the MWX No.1, is a producing gas well and was potentially available for experimentation on a limited basis. The No. 2 and No. 3 wells, however, were available for unlimited experimentation. The geologic setting, the existing data base and the developed infrastructure at the M-Site created conditions advantageous for conducting further tight gas sands experimentation.

2.2.3 Test Intervals and Well Schematics

As noted above, the wells which were used in the initial research at the M-Site included the MWX No. 1, the MWX No. 2 and the MWX No. 3. Figures 3, 4 and 5 present the schematics for each wellbore at the beginning of the Project.

All planned experiments were to be executed within several sandstone units of the Cretaceous age upper Mesaverde Group. These shallow water deposits are present at subsurface depths ranging from 4,130 ft to 5,500 ft. These units were selected for experimentation outlined under the Project based on:

- 1) Fluvial and paralic depositional environments of the upper Mesaverde were conducive to the deposition of thick, generally low permeable sands;
- 2) Previous project experiments conducted at the M-Site did not include any hydraulic fracture stimulations above 5,500 ft;
- 3) Few wellbore obstructions (e.g., bridge plugs, etc.) existed above 5,500 ft within the above referenced wells;
- 4) The projected shallow sandstone intervals allowed for decreased operational costs associated with the proposed experiments; and
- 5) The shallow formation depths promoted the acquisition of higher quality data from surface-deployed instrumentation.

Within the gross interval, 4,130 ft to 5,500 ft, there are three sandstone units which were identified for diagnostic and modeling experimentation. These units are informally referred to as the A, B and C-Sand, with the A-Sand being the deepest unit and the C-Sand the shallowest (Figure 6).

The fluvial and paralic sections of the upper Mesaverde, inclusive of the A, B and C-Sands, are characterized by thick, laterally discontinuous and low-permeability sands. As an example, the average dry-core permeability of a sandstone unit between 4,290 ft and 4,366 ft in the MWX No. 2 Well is 0.107 millidarcies (md) with an average porosity of 5.2 percent, as determined from core analyses. Sands within the uppermost Mesaverde section are interpreted as having very high water saturations (up to 100 percent). Generally, gas saturations increase with depth below 4,500 ft.

Figure 2 Surface Locations of the MWX Wells

Figure 3 Wellbore Schematic, MWX No. 1

Figure 4 Wellbore Schematic, MWX No. 2

Figure 5 Wellbore Schematic, MWX No. 3

Figure 6 Test Intervals, A, B and C-Sands of the Mesaverde Group Used for Diagnostic and Modeling Experiments

2.2.4 Existing Data Base

Within the proposed Mesaverde test interval, there were abundant data as a result of the previous research conducted through the DOE Multiwell Experiment. The data included:

- The entire interval proposed for experimentation (4,170 ft to 5,550 ft) was continuously cored in the MWX No. 1 Well. This core was stored at Sandia and was available for continued analysis. Routine and special core analyses had been performed on much of this core to determine rock mechanical and reservoir properties. Mineralogic, petrographic and sedimentological analyses had also been performed and the results documented. The correlative interval in the MWX No. 2 Well was also selectively cored;
- Thirteen cased-hole stress tests were performed in the MWX No. 2 Well between 4,170 ft and 5,502 ft;
- Multiple, overlapping high-quality wireline log data existed over the entire interval. The log and core data was compiled into a depth-shifted, digital database; and
- Seismic data was available in the form of high-resolution 3-D, vertical seismic profile and cross-borehole.

Below the proposed test interval, there were additional data and information which was useful to M-Site research. These data included the following:

- A hydraulic fracture azimuth was determined to be N78°W based on data derived from several techniques utilized within the deeper Mesaverde intervals;
- Information was available on model behavior as a result of 3-D fracture modeling previously performed on a hydraulic fracture treatment at 5,530 ft;
- Natural fractures and the associated onset of over-pressuring were known to occur primarily below 5,500 ft; and
- As a result of previous work performed in ten separate completion intervals, there were no indications of any near-wellbore effects during fracturing experiments which could affect the accuracy of the modeling.

2.2.5 Verification of M-Site Suitability

All indications suggested that the MWX wells and the character of the subsurface intervals were suitable for fracture diagnostics experimentation. This was reconfirmed through a series of technical assessments that were planned and executed before proceeding with full-scale Project development. These assessments included: (1) evaluating the confining stresses of the sandstone intervals proposed for experimentation; (2) evaluating wellbore integrity, e.g. cement, casing, etc.; and (3) assessing the capability to remotely detect seismic signals during a mini-fracture experiment.

The M-Site suitability assessments performed involved the use of existing stress data from the MWX wells and the acquisition of new fracture treatment data collected during

preliminary field operations conducted in September and October 1992. These operations resulted in the following:

- The log-derived stress data calibrated with in-situ stress test data indicated that a stress contrast ranging from 500 to 1,000 psi existed between the targeted sandstone intervals and the bordering lithologies. This stress contrast appeared suitable for limiting excessive fracture height growth;
- Wellbore conditions associated with the MWX No. 2 and the MWX No. 3 wells were found suitable for the acquisition of high-quality seismic signals with low ambient noise levels;
- There were no unusual near wellbore occurrences found in pressure responses which would inhibit 3-D modeling of a mini-fracture treatment; and
- Remote-wellbore monitoring during mini-fracturing experiments clearly identified over one-thousand microseisms during hydraulic fracture injections. Limited analyses of these data indicated that seismic signals could be spatially located and used for mapping hydraulic fractures.

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

2.2.6 Contractor Team and Responsibilities

The DOE and GRI jointly sponsored the research conducted at the M-Site Project. The contractor team organized to execute the research Project included CER Corporation, Sandia National Laboratories, Resources Engineering Systems, and Branagan & Associates. The responsibilities of each of these organizations are described below:

CER Corporation (CER)

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

Site Operator – CER had primary responsibility for the supervision and coordination of field operations and experiments conducted at the M-Site Project, assuring they were performed in a safe and efficient manner.

Data Acquisition Systems Development and Operation – CER had responsibility for developing, installing, field checking and routine operations/maintenance of the conventional-speed data acquisition and networking systems used during the experiments through February 1996.

Diagnostics and Treatment Experiment Design/Analysis – CER shared responsibility with the other GRI contractors in designing and supervising

experiments to support fracture diagnostics or fracture modeling goals. In addition, CER shared responsibility with the other contractors in designing fracture treatments and evaluating fracture treatment data.

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

Sandia National Laboratories (Sandia)

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

Fracture Diagnostics and Treatment Design/Supervision – Sandia had primary responsibility for design, technical supervision and interpretation of fracture diagnostics experiments. In addition, Sandia shared 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 had the primary responsibility for developing, installing, field checking and routine operations/maintenance of the accelerometer package and high-speed data systems used for fracture diagnostics experiments. Sandia also had primary responsibility for analysis of the microseismic data required in fracture mapping experiments.

Branagan & Associates (B&A)

Under contract to the GRI, B&A had responsibilities for the following activities:

Fracture Treatment Experiment Design, Modeling, Analysis and Reporting – B&A shared responsibility with other GRI contractors in designing, supervising, analyzing and reporting on experiments supporting fracture diagnostics and fracture modeling goals. In addition, B&A shared responsibility with other GRI contractors in designing fracture treatment data.

Seismic Equipment – B&A had the primary responsibility for the installation and maintenance of the accelerometer package used for fracture diagnostics.

Resources Engineering Systems (RES)

RES, under contract to GRI, had responsibilities for the following activities:

Fracture Treatment Design and Modeling – RES had primary responsibility for fracture treatment modeling efforts conducted at the M-Site Project. As a part of this effort, RES shared responsibility for the design of fracture treatments and fracture diagnostics experiments.

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

Subcontractors

Technical services of various subcontractors were used to assist in executing experiments at the M-Site, particularly, the services of James Fix & Associates, Inc.

2.2.7 Project Goals and Work Program

2.2.7.1 Project Goals

The goals established for the research conducted at the M-Site included:

- Validate hydraulic fracture height by various techniques including seismic monitoring, shear-wave shadowing and monitoring with borehole inclinometers;
- Test and verify concepts for determining fracture length and width;
- Use data acquired from height and length experiments as well as fracture pressure data to verify the fracture dimensions calculated by the 3-D fracture model FRACPRO; and
- Compare and validate standard (e.g. pressure decline) and experimental (e.g. inclinometer, tube-waves, etc.) techniques for accurate determination of fracture closure pressure.

To accomplish these goals, the following phases of experimentation and operation were established.

2.2.7.2 Project Phases

In order to accomplish the Project goals, the work program was divided into two phases, described as follows:

Phase I: Fracture Diagnostics Tests – Experimentation at the M-Site involved the installation and testing of fracturing diagnostics instrumentation, the monitoring of field experimentation performance and the analysis of a series of field experiments used in measuring the geometry of induced fractures. Passive seismic monitoring tools were installed in an existing MWX well and in a special instrumentation well. Fracturing tests were conducted in another existing MWX well.

Phase II: Fracture Model Verification and Fracture Diagnostic Tests – Involved drilling a special directional well, with several lateral extensions. Placement of lateral boreholes were designed to intersect induced fractures, as well as being positioned to allow for the intersection of subsequent induced fractures.

2.2.7.3 Task Descriptions

Each Project Phase was further subdivided into given tasks as described below:

Phase I: Fracture Diagnostics Tests at the M-Site

Task 1: Site Infrastructure; Placement and Instrumentation of a Seismic Monitor Well

Task 1 included site preparation and installation of site infrastructure, such as utilities and work housing for researchers and instrumentation. This Task also included the drilling, testing and instrumentation of a monitoring well. The well was located at a surface location adjacent to the MWX well pad, drilled to a depth of approximately 5,500 ft, logged and selectively cored. The oriented core was used to specifically determine the preferred hydraulic fracturing azimuth within the upper portion of the Mesaverde section in order to effectively place diagnostic instrumentation.

Task 2: Conduct Fracture Closure Stress Tests

In conjunction with mini-frac injections in the MWX No. 2 Well, fracture experiments were conducted in the monitor well and/or the MWX No. 3 Well in order to evaluate various independent closure determination techniques. Methods evaluated included injection well pressure falloff, inclinometer output from the monitor well, and hydraulic impedance and tube-wave characteristics in the MWX No. 2 Well.

Task 3: Conduct Seismic Fracture Diagnostics Tests, A and B Sands

Using the MWX No. 2 Well as the fracture well, and the MWX No. 3 Well and the monitor well as observation wells, a number of mini-fracs were conducted to analyze fracture length and height. Multiple three-component geophone and accelerometer assemblies were installed in the observation wells to collect seismic signals generated during the mini-fracs. These signals, along with injection data were collected in real-time and analyzed to derive fracture geometry and propagation behavior.

Phase II: Fracture Model Verification and Fracture Diagnostic Tests

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

A new directional well was drilled to the south of the projected azimuth of the fracture found in the MWX No. 2 Well. This well consisted of a 5,000 ft deep vertical pilot hole, which was subsequently plugged back and kicked-off to form a high-angle leg. The vertical pilot hole was logged to define the base and top of the intervals in which experimentation was to be conducted. The well was kicked-off at an appropriate depth to intersect the target interval with its propped fracture. Coring, frac tracer, and logging were used to detail the projected fracture intersection. The deviated section of the well was left as an open hole in order to permit fracture conductivity testing.

Task 5: Conduct Fracture Conductivity and Seismic Tests, B-Sand

Fracture conductivity tests were conducted using the MWX No. 2 Well and the intersecting deviated well, utilizing appropriate instrumentation in both wells. Data collected was used to verify fracture models. Such information included:

- Propped fracture width;
- Proppant bed effective permeability;
- Proppant settling pattern; and
- Proppant crushing and/or embedment.

In addition, it was anticipated that such diagnostic tests would help determine the propped fracture dimensions.

Task 6: Drill High-Angle Leg No. 2, C-Sand Lateral Well

A shallower Mesaverde sand section interval was selected as an intersection target and a second lateral was kicked-off from the original pilot hole. The new leg intersecting the target sand was left in an open hole state in order to permit fracture pressure testing as the hydraulic fracture intersected the wellbore. The target sand was cored and logged to characterize the intersected hydraulic fracture and to determine variability within the interval.

Task 7: Perform Fracture Pressure and Seismic Tests, C-Sand

Experiments were designed 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 was to provide independent comparisons to fracture length from seismic experiments. Data gathered in these tests were used to support fracture model verification. The experiments utilized the high-angle C-Sand lateral as well as other M-Site wells.

Task 8: Project Documentation and Technology Transfer

The documentation of all activities associated with the Project is to lead to continuous technology transfer. Such documentation was to include 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, were prepared as the Project progressed.

Task 9: M-Site Field Administration

In addition to managing the field operations during the hydraulic fracture experimentation program, upon completion of such experimentation, the M-Site was to be restored to its original condition. This included the removal of the infrastructure created in performing the hydraulic fracture experiments, as well as the plugging and abandonment of the wells used in the execution and monitoring of such tests.

3.0 WORK PERFORMED, JANUARY 1993 THROUGH FEBRUARY 1997

The development of the operational infrastructure and the work program conducted during the term of the Project is documented by Task number in the following section.

3.1 TASK 1: SITE INFRASTRUCTURE; DRILL, EVALUATE AND INSTRUMENT A SEISMIC MONITOR WELL

3.1.1 Site Infrastructure

Significant efforts were expended by CER in the first year of the Project to extend the M-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 included the primary telephone/fax communications equipment and also housed the computer workstations where researchers received 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, the GRI single-conductor wireline trailer, and the monitor well drillsite pad, located several hundred feet south of the MWX pad. Backup electrical power for the M-Site, in case of commercial power failure, was integrated into the system through the use of a 90 kw generator. Several key data acquisition systems were also equipped with uninterruptable power supplies (UPS).
- Road access to the MWX pad was improved by regrading a road along the west fence line of the lease to the MWX pad. This improvement, when combined with the existing road access, created a "loop driveway" and facilitated an efficient ingress and egress of frac trucks and the placement of other equipment associated with the Project (Figure 7).
- 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.

3.1.2 Data Acquisition System (DAS)

The acquisition of computer equipment and the fabrication of DASs was accommodated in the first year of the Project. Figure 8, Computer Array, illustrates the network DASs which

Figure 7 M-Site Infrastructure

Figure 8 Data Acquisition Systems for Fracture Experiments

was fielded at the M-Site. The DASs were purchased as GRI property and described as follows:

Conventional-Speed Data Acquisition System

The primary objective for this segment of the M-Site Project was to provide project field personnel with easy access to existing, on-site, low-to moderate-speed DASs and assure the acquisition of high-quality data.

Conventional-Speed DASs 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 the three satellites locations described above were transferred in a specific format to a central client/server (located in the technical evaluation trailer) for systematic review, analyses and archival.

Each DAS was configured to accommodate planned experimental data that included the following:

- Downhole inclinometer signals;
- Fracturing service company and project-measured pressure, injection rate and fluid rheology data; and
- Accurate bottomhole pressure recorded in real-time and reservoir monitoring pressures.

These systems had sufficient hardware and software flexibility and expandability to accommodate additional experimental data as warranted by the Project.

Each DAS was housed in an environmentally-controlled structure which included the following:

- Instrument racks, cabling and conditioned power sources and an 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 were available so field personnel could monitor the status of their instruments and acquire engineering data through a series of graphic and tubular screen displays and a variety of print media.

High-Speed Data Acquisition System

The purpose of the high-speed DAS was to acquire and store microseismic data from two observation wells, the MWX No. 3 Well and the newly drilled monitor well. Sandia had primary responsibility for the design specifications of two DASs that served the microseismic receiver arrays in the two Project observation wells. These systems provided 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 process signals.

These high-speed DASs 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 functioned as the focal point for the Project's Local Area Network (LAN) and client server. The purpose of this system was to provide a central hub to receive, distribute and store the large data arrays from the satellite DASs (high-speed and conventional) as well as to allow each of the project researchers easy access to all real-time data. The client server provided 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 was located in the conference trailer that also housed work stations and PCs from which individual researchers could interact with the data through the client server and with each other. Data from each of the satellite data systems could 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 researchers. All of these data could be permanently stored on the client server hard disk for subsequent retrieval and analysis.

The high-throughput PC-based system incorporated the following basic components:

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

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

Each of the three conventional speed DASs were ethernet linked to the LAN client server which again served as a focal point for data distribution and storage. Service company data could be routed through a DAS where it was formatted and transported via the ethernet to the LAN client server. Through the server, FRACPRO or other related fracturing programs could access the data.

In early 1995, the second year of the Project, the capabilities of the system were incrementally increased by the addition of a data-pack storage system using a compact disk (CD) reader/writer. With these hardware additions, large volumes of data acquired during subsequent experimentation were copied from the field computer hard drives to data-packs for transport to CER's Las Vegas office. These tapes were then reloaded onto a Las Vegas-based computer hard drive for editing and subsequent copying to CDs. The data-packs were then returned to the M-Site for re-use with the duplicate CD available for archiving and/or reference.

3.1.3 Drilling the Monitor Well

The specific objective for this portion of Task 1 was to drill and case a specially designed offset well, (Monitor No. 1 Well), in which seismic and earth tilt instrumentation was emplaced. Comprehensive fracture diagnostics experiments were performed using a combination of the new Monitor Well and the wellbores of MWX No. 2 and No. 3. The Monitor No. 1 Well was drilled in order to field an instrumentation array that was more effective than a conventional wireline system in defining the dimensions of a hydraulic fracture.

The surface location of the Monitor No. 1 Well is the southwest quarter of the northwest quarter (SW/4 NW/4) of Section 34, Township 6 South, Range 94 West, Garfield County, Colorado. Figure 9 illustrates the location of the MWX wells, the Monitor No. 1 Well and the defined azimuth of the hydraulic fracture.

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

- M-Site experimentation included the initiation of northwest-southeast trending hydraulic fracture systems, from the MWX No. 2 Well to a point located between the two observation wells, the MWX No. 3 Well, located to the north of the system and the Monitor No. 1 Well located to the south of the hydraulic fracture system. The location of these wellbores allowed the opportunity to conduct unique experiments such as shear wave shadowing or to compliment field seismic monitoring systems.
- Alignment of MWX No. 2, No. 3 and the Monitor Well was not desirable for seismic data acquisition. The Monitor Well was offset to the east of the north-south alignment of MWX No. 2 and No. 3 in order to enhance seismic acquisition and to take advantage of favorable surface conditions.

The Monitor No. 1 Well drilling operations can be 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. A 20-in. conductor pipe was cemented in-place.
- The same rathole rig which started the conductor hole continued drilling a 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 moved-in 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 at which point 13-3/8-in. casing was set and cemented.
- Drilling resumed on February 20 with a 12-1/4-in. bit. The boulders that are generally characteristic of the upper portion of the geologic formation in this area did not present any severe drilling problems, and were drilled out at an estimated depth of 710 ft. The 12-1/4-in. hole was drilled to a total depth of 4,065 ft by 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 total depth of 4,170 ft. 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 reached a 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 with a total of 35 days required to drill the Monitor Well.
- The drilling fluid used to drill Monitor No. 1 Well was a low-solids, non-dispersed 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

Figure 9 Location of MWX No. 2 Treatment Well, and Relative Position of the Monitor No. 1 and the MWX No. 3 Observation Wells

several solids control equipment items (dual-screen shale shakers, centrifuge and dual pumps) and re-circulation of the reserve pit volume.

- Wellbore deviation was carefully controlled and measured in the course of drilling. A vertical well was required in order 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 the caliper log, provided what was believed to be sufficient excess volume to circulate cement to surface. However, cement volume was insufficient, with the cement top located at 2,120 ft.
- The Monitor No. 1 Well was logged in open hole by Schlumberger. After coring, the Formation Microscanner Log was run on March 17 in an 8-3/4-in. hole to a total depth of 4,603 ft. The hole was then reamed to 12-1/4-in. and deepened to a total depth of 5,000 ft. Log run number two was performed with a MAXIS 500 logging unit on March 21-22, 1994, and included the following logging tools suite: Formation Microscanner/Monitor Log, Lithodensity/Caliper/Gamma, Dual Thermal and Epithermal Neutron, Electromagnetic Propagation End-Fire, Dipole Sonic Imager/Inclinometry Tool/Gamma Ray, Array Induction Log/Gamma Ray, and Orient 4-Arm Caliper/Gamma.

Upon completion of the drilling of the Monitor Well, the reserve pit volume was removed and disposed of at a commercially licensed disposal facility, and the site readied for instrument emplacement.

3.1.4 Instrument Emplacement in the Monitor No. 1 Well

3.1.4.1 Emplacement Design

A comprehensive pack of 30 seismic instruments (accelerometers), 6 earth tilt instruments (inclinometers) and their respective cable systems were fabricated for emplacement in Monitor Well No. 1. The plan for instrument emplacement was to secure the instruments and associated cabling to a tubing string; protect the instruments from abrasion and load shock with decentralizers as the string was lowered in the wellbore; place the instruments between the gross interval of 4,000 ft and 5,000 ft; and cement the entire tubing and instrumentation assembly in the 9-5/8-in. casing to provide a suitable seismic/mechanical coupling with the earth.

3.1.4.2 Emplacement Operations

The instrument emplacement operations were initiated on August 8, 1994. However, upon landing the tubing string/instruments at the approximate planned depth, the inclinometers were malfunctioning. The entire string of tubing and attached instruments were subsequently removed from the well and it was determined that the cable connector on the inclinometers had mechanically failed under hydrostatic pressure. The mechanical failure caused the pins in each instrument to ground which allowed a small amount of water to leak into one tool. The connectors were replaced, the inclinometers re-tested and re-calibrated, and the instrument packages successfully re-run in the wellbore on October 4 and 5, 1995. Personnel from CER, Sandia, B&A and Fix & Associates participated in the emplacement field operations. Quality control checklists were maintained throughout the emplacement operation. The components integral to the emplacement operations are described as follows:

Tubing

A 2-7/8-in. tubing string, from existing inventory, was selected as the carrier for the instruments. Each tubing joint that carried an instrument was individually numbered and measured for length, and a reference line was placed along its long axis to assist in the accurate alignment and depth placement of the instruments.

Centralizers

The accelerometers and inclinometers had diameters of 2.75-in. and 2.95-in., respectively. The geometry of the casing, tubing and instruments required that the tubing be decentralized using custom designed and fabricated equipment. Figure 10 illustrates the final decentralizer design having two, long, fixed bows positioned on the tubing in order to prevent the instruments or cabling (fixed on the same tubing azimuth) to come in contact with the casing. The two shorter bowsprings opposite from the long bows were designed to be collapsible to a certain extent, thereby taking the weight of the string if it should lie on the casing wall.

Accelerometers/Cabling

Each of the 30 accelerometers were steel banded (e.g. stainless-steel, worm-driven hose clamps) to the tubing at nominal 30-ft intervals on the lowermost 875 ft of tubing. Each accelerometer was molded at pre-determined depths into a polyurethane-coated electrical cable having a diameter of 0.84 in. This cable was periodically secured to the tubing with nylon cable ties, hose clamps, and kellys. All of the accelerometers were azimuthally aligned with respect to each other as they were attached to the tubing string. No attempt was made to align the accelerometers to an absolute azimuth. Each accelerometer included a set screw with an Iridium (Ir^{190}) bead affixed to it to provide definitive evidence of the final depth and orientation of each of the accelerometers using an oriented gamma ray logging tool. Testing of the accelerometer instruments after running them into the wellbore the final time indicated that of the 90 data channels (x, y, z axes on 30 instruments), 88 functioned within specifications.

Figure 10 Illustration of the Placement of Accelerometers, Inclinometers and Cabling on the Tubing String

Inclinometers/Cabling

Each of the six Inclinometers were consistently aligned with respect to the instrument X-axis, leveled and secured with steel bands (hose clamps) such that the long axis of each instrument was parallel to the tubing axis. The maximum inclinometer cable size was represented by six 0.415-in. urethane-coated cables molded together every 100 ft. Individual cable connectors on pigtails placed at appropriate depths allowed individual instruments to be connected. Similar to the accelerometers, a set screw with an Ir¹⁹⁰ bead affixed to it was set in each inclinometer to facilitate definitive depth and orientation determination. As shown in Figure 11, inclinometers were placed such that their depth positions occurred in, above and below the C and B-Sand units. All of the earth tilt and temperature sensors in each inclinometer were functioning following the cementing operation.

Cable Spooler

A trailer-mounted, two-reel cable spooler was made available to the M-Site Project from ARCO Exploration and Production Technology in Plano, Texas. This unit was used in the initial emplacement operation to spool off individual reels of inclinometer and accelerometer cabling through sheaves and into the Monitor No. 1 Well.

Monitor Well Instrument Trailer

As each accelerometer and inclinometer was secured to the tubing, a jumper cable was used to connect each cable to the seismic data acquisition panel and one of the conventional-speed DASs located in the specially constructed Monitor Well Instrument Trailer. The cable was tested for continuity and each accelerometer axis was tap-tested prior to lowering it in the hole. Each inclinometer cable and instrument, the cabling from the downhole seismic and the earth tilt instrumentation was run through underground conduit from the wellhead to the Monitor Well Instrument Trailer and connected to the DASs.

Cement

The carrier string, instruments and cables were cemented inside the 9-5/8-in. casing to provide the definitive bond and coupling to the earth. A total of 1,137 sacks of 14.8 ppg, class "G" premium cement was pumped at a average rate of 5 bbl per minute (bpm). This volume of cement brought the cement top to within several hundred feet of the ground surface to dampen or eliminate any tubing vibration (i.e. seismic noise) which could occur if a long length of uncemented tubing began to resonate within the casing. The cement slurry included a gypsum additive to provide a slight degree of expansion and improve cement bond to the casing and tubing, and a small percent (10 percent by weight of cement) or retarder to extend the curing time and minimize potential negative effects of a cement curation spike. Using data from temperature sensors within each inclinometer, the exothermic process of cement curing increased the wellbore temperature to approximately 180°F at about 18 hours after initiating the pumping. The temperature gradually decreased to an ambient formation temperature (at 4,500 ft) of 148°F. Figure 12 illustrates the configuration of Monitor Well No. 1 following the cementing operation including an expanded illustration of the wellhead design.

Figure 11 *Instrumentation Placement in the Monitor No. 1 Well*

Figure 12 Wellbore Status of the Monitor No. 1 Well, Following Instrument Emplacement and Cementing

Figure 13 Cased-Hole Stress Test Intervals in the A, B and C-Sands

Monitor Well instrument trailer and placed on the M-Site computer network to enable simultaneous observations of pressure and tilt data during stress testing.

Hydraulic impedance data were also acquired following stress test injections in several intervals as another independent technique for assessing fracture closure. Data for hydraulic impedance analysis were acquired by generating and measuring wellbore pressure oscillations through rapid opening and closing a bleed-off valve on the pressurized wellbore. Conceptually, this "surging" perturbs flow conditions in the well, causing a pressure wave to travel to the bottom of the well where it was reflected upward. Upon returning to the wellhead, the wave again reflected back downward (i.e. forced oscillations). The process of propagation and reflection continued until the wave was fully damped by friction and by energy losses into the hydraulic (stress test) fracture. The frequency content and damping of pressure oscillations are controlled by a property known as the "hydraulic impedance" of the fracture. Subsequent analysis of the pressure oscillations indicate whether the hydraulic fracture is open or closed.

3.2.3 Results

The stress testing and hydraulic impedance results were assessed by B&A and Sandia. The stress data were used to develop a normalized stress profile for modeling fracture treatments conducted in the B and C-Sand units. The inclinometer data acquired during stress testing was found to be marginally useful. The small injection volumes, separation distances from the injections wells and the Monitor Well, and certain electrical noise problems all combined to substantially mask any subtle mechanical shifts in the earth which may have resulted from stress testing.

3.2.4 Post-Stress Testing Wellbore Remediation

Immediately following stress testing, CER began the process of squeeze cementing four sets of perforations in the MWX No. 2 Well. Pressure testing of the squeezed perforations indicated that the lower two sets could not hold pressure and required re-squeezing. The re-squeeze was successful, and the MWX No. 2 operations were completed on December 6, 1994. No squeezing operations were planned on MWX No. 3 Well, however, the well consistently built up 300 to 400 psi gas pressure at the surface. Gas bubbles bleeding from open perforations and expanding within the wellbore were not desirable since the background noise interfered with the accelerometer instrumentation in the well. Therefore, a background noise survey was conducted in the MWX No. 3 Well, using a single accelerometer on 7-conductor wireline to assess noise levels. Eight measurements were taken starting below the perforations and setting between each of the perforated intervals. Noise levels were found to be 10 to 100 times as great as that of the baseline survey conducted in 1993 and therefore, were judged to be unacceptably high for seismic data acquisition. Subsequent analysis by Sandia indicated that it was not possible to isolate individual perforations as noise sources.

In January 1995, an acoustic/temperature survey was run in the MWX No. 3 in an attempt to identify which perforations and/or bridge plug was leaking gas. This survey was performed under pressurized and depressurized conditions. The acoustic/temperature survey was evaluated but did not clearly define which perforations or bridge plug might be

leaking gas. As a precaution, however, another bridge plug was set immediately above the existing one in the MWX No. 3 Well. Cement was dump bailed on top of the bridge plug in an attempt to prevent gas migration around the plug.

A subsequent acoustic/temperature survey indicated that noise levels were reduced when the well was pressurized. Therefore, a second survey was run with a Sandia single-level accelerometer. This test was again conducted under depressurized and pressurized (1,000 psi) conditions. The survey under pressurized conditions indicated a much reduced and acceptably low noise level. As such, no further remedial action was required in the MWX No. 3 Well. Seismic monitoring would be performed under pressurized conditions using a high-pressure, low-volume pump that was available in the GRI equipment inventory.

3.3 TASK 3: CONDUCT SEISMIC FRACTURE DIAGNOSTICS TEST

3.3.1 Introduction

As noted above, a number of mini-fracs were performed as part of the Project to analyze fracture length and height. Multiple three-component geophone assemblies installed in observation wells were used to collect seismic signals generated during the mini-fracs. These signals, along with injection data, were collected in real-time and analyzed to derive fracture geometry and propagation behavior. Such seismic fracture diagnostics were completed within the informally referred to A, B, and C-Sands during the term of the Project.

3.3.2 A-Sand Experimentation and Data Acquisition

3.3.2.1 Objectives

A series of experiments and data acquisition operations were designed and executed between October 25 and November 5, 1993 within the A-Sand unit of the Mesaverde Group. A-Sand data acquisition and experimentation were conducted using the unique configuration and close spacing of the MWX No. 2 and MWX No.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 substantially improved the interpretation of the location of remotely-detected microseismic events which occur during hydraulic fracturing. Therefore, a borehole tomography survey was run, using the MWX No. 2 Well to emplace a five-level borehole accelerometer package and the MWX No. 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 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. An 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 could 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 four mini-fracs used fluid only. The fourth mini-frac included 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 could then be analyzed with the H/Z technique to determine fracture height and azimuth. The results of the H/Z survey was verified by contrasting and comparing to the fracture height results determined from remote-well, 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 corrective processes which could redistribute this proppant in the fracture or the wellbore. The basic strategy was to pump a mini-frac in which the fluid and proppant had been tagged with three different radioactive (RA) tracers. Wireline logging with a spectral gamma ray tool was run in order to monitor the location of these tracers in and around the wellbore.

This phase of the Project (a set of experiments performed using the MWX No. 2 Well for emplacing wireline-retrievable seismic receivers and the MWX No. 3 Well as a treatment well) represented an intermediate step in definitively determining hydraulic fracture dimensions. Using a combination of the existing MWX wells along with the Monitor Well No. 1, experiments were conducted to comprehensively image and dimensionally characterize hydraulic fractures.

3.3.2.2 Summary of Field Operations and Data Acquisition for Fracture Diagnostics

3.3.2.2.1 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. This survey used the MWX No. 3 Well for emplacement of the seismic source and the MWX No. 2 Well 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. 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 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 cable.

Data Acquisition – Consisted 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 of the accelerometer array and by varying the depth of the airgun source.

3.3.2.2.2 Hydraulic Fracturing

The final phase of experiments performed in the A-Sand included pumping a series of small hydraulic fracturing treatments in the MWX No. 3 Well while collecting seismic data in the offset MWX No. 2 Well. These tests were performed from November 1 through November 4, 1993. The MWX No. 3 Well was perforated in the A-Sand at 4,900 ft to 4,920 ft and 4,930 ft to 4,946 ft with 72 holes (0.4 in.) at 2 JSPF 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 was performed in the A-Sand interval on November 1, 1993, and consisted of pumping 450 bbls of 40 lb/Mgal 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. In addition, a readout pressure gauge was run on wireline inside the tubing and hung at 4,890 ft. A secondary goal of this experiment 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 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 A-Sand mini-frac, performed on November 3, 1993, consisted of pumping 400 bbl of 40 lb/Mgal 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. 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 A-Sand mini-frac, performed on November 4, 1993, consisted of pumping 434 bbl of 40 lb/Mgal 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 A-Sand mini-frac, also performed on November 4, 1993, included the use of 16,900 lb of 20/40 mesh sand, 617 bbl of 40 lb/Mgal linear gel and 3 different RA 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.

3.3.2.2.3 Microseismic Monitoring

Remote-well (MWX No. 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 ft, 4,895 ft, 4,905 ft and 4,955 ft, and the array was not unlocked until after the fourth mini-frac was completed.

Treatment-well (MWX No. 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 the 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 manner 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 resonance (due to its relatively heavy weight and assembly length) that was run during Mini-Frac No. 3.

3.3.2.2.4 Post-Frac Gamma Ray Logging

Wireline spectral gamma ray logging was performed prior to and following the fourth A-Sand mini-frac in order to verify proppant placement and convective processes during hydraulic fracturing. This logging initially involved a baseline gamma ray log run which was run over the interval 5,530 ft to 4,640 ft prior to Mini-Frac No. 4. This baseline run established the background radiation baseline for post-frac gamma ray log runs. Nine subsequent repeat logging runs were then performed. These repeat runs provided information on the location and estimated volume of tagged proppant. All logging runs were performed immediately after pumping was stopped for shut-in, and were maintained at a constant speed for data quality.

3.3.3 B-Sand Experimentation and Data Acquisition

3.3.3.1 Objective

The focus of the second year of the Project was to initiate fracture diagnostics tests in the Mesaverde B-Sand unit. The B-Sand experiments involved a series of field operations designed to extend fracture mapping capabilities and hydraulic fracturing technology. The chronology of field operations for the B-Sand experiments is summarized as follows:

- **Conduct a Staged Series of Fracture Treatments.** A series of seven injections were conducted in the B-sand interval. The initial treatment (Inject 1-B) consisted of a small-volume, crosslinked gel breakdown. Several somewhat larger volume KCl-water pump-in tests were performed in Injection 2-B. Two successively larger volume fluid-only mini-fracs were then pumped (Injections 3-B and 4-B). This was followed by fluid-only injections (Nos. 5-B and 6-B) with even larger fluid volumes and an injection with proppant (No. 7-B). Several RA, chemical and physical property (i.e. color) tracers were included in the fluid of Injections 1-B through 7-B.

- **Drill a Hydraulic Fracture Intersection Well.** The drilling and coring of a new well (Intersection No. 1 Well) to intersect the hydraulically fractured B-Sand at a point some distance from the treatment well (MWX No.2) was completed.
- **Perform Injection/Recovery Treatments.** A series of injections using the combination of the MWX No. 2 treatment well and the Intersection No. 1 Well and connecting hydraulic fracture.

Fracture diagnostics and fracture technology experiments were designed in association with these operations. These experiments are summarized in the following generic categories:

Hydraulic Fracture Mapping/Diagnostics

Microseismic event detection using a wireline accelerometer array (single or multi-level) and the Monitor No. 1 Well grouted-in instrumentation array were active during each of the proposed B-Sand injections. These seismic data were used for accurate mapping of length and height extent of the hydraulic fracture(s). Similarly, the inclinometer data were interpreted in order to determine fracture height. The azimuth of the hydraulic fracture was confirmed by identifying the spacial position of the B-Sand hydraulic fracture in the proposed Intersection No. 1 Well. The azimuth was compared to that of the microseismic event cloud mapped in the B-Sand injections and to the multiple other techniques which have predicted hydraulic fracture azimuth at the M-Site.

Hydraulic Fracture Modeling

With knowledge of stress in layers in and adjacent to the B-Sand and measurements of bottomhole pressure data during the B-Sand injections, fracture modeling was performed to estimate fracture dimensions. The mapped fracture dimensions and modeled fracture dimensions were compared and mechanisms for differences isolated and evaluated.

Hydraulic Fracture Technology

Several experiments were to be performed in the B-Sand which are associated with the development of hydraulic fracturing technology. These experiments are summarized as follows:

Fracture Opening and Closure: Fracture opening and closure associated with each B-Sand injection was assessed with the Monitor No. 1 Well inclinometer array and pressure-based techniques.

Propped Fracture Width Proppant Distribution: Fracture width and proppant distribution were assessed by over-coring the hydraulic fractures within the B-Sand in the Intersection No. 1 Well. Following the recovery of the hydraulic fracture proppant, an assessment of fracture width was determined.

Single or Multiple Fracture Generation: Single or multiple fracture generation were assessed by using various fluid and proppant tracers (RA, colored proppant). The hydraulic

fracture(s), with their unique tracer elements, were identified in the Intersection No. 1 Well core by visual inspection, gamma scanning the core, and spectral gamma ray logging.

Fracture Conductivity: Fracture conductivity testing was performed in the B-Sand perforated interval in the treatment well with bottomhole pressure monitored in the Intersection Well. Fracture conductivities were also measured in propped fractures recovered in B-Sand core samples.

3.3.3.2 Injections Numbers 1-B Through 4-B

Field operations associated with initiating hydraulic fracturing experiments in the B-Sand interval began on April 5, 1995, by perforating the MWX No. 2 Well B-Sand in the interval from 4,527 ft to 4,557 ft (59-19 gram charges, 2 JSPF, 0.5-in. diameter holes, 120° phasing). Following the primary perforating logging run, 9 additional "noise shots" (3.2 gram charges, 0.25-in. diameter holes, 0° phasing) were fired for verification of the Monitor Well accelerometer orientations. These charges were set in the interval from 4,537 ft to 4,548 ft. Figure 14 illustrates the MWX No. 2 wellbore configuration with this perforated interval and the placement of the perforations relative to the baseline gamma ray log.

A gel breakdown and several pump-in/flowback tests were performed during the week of April 17, 1995. Prior to the treatments, additional "noise shot" perforations (3.2 gram charges, 0.25-in. diameter holes, 0° phasing) were fired in the interval from 4,537 to 4,547 ft to orient the single-level wireline accelerometer locked into the MWX No. 3 wellbore. A total gamma ray log was also run in the interval from 4,100 ft to 4,900 ft to serve as the baseline against a post RA material-tagged frac gamma ray log.

The first injection, Injection 1-B, was a gel breakdown treatment, consisting of 1,000 gallons of 40 lb/Mgal, zirconate-crosslinked fluid which had been spotted across the perforations prior to the injection. The fluid was tagged with 1 millicurie of Sc^{46} and pumped down 2-7/8-in. tubing on April 18, 1995. Bottomhole pressures were monitored during and following the treatment. The data acquisition package during Injection 1-B consisted of the following:

- The comprehensive 30-instrument accelerometer and 6-instrument inclinometer arrays in the Monitor Well.
- The single-level accelerometer locked in casing in MWX No. 3.
- Bottomhole pressures were monitored during and following each treatment with a surface readout bottomhole pressure gauge set below the perforated interval at 4,650 ft.
- Following the treatment, a post-frac gamma ray log was run in the interval from 4,900 ft to 4,100 ft.

A step-rate test (Injection 2-B) was performed the day after Injection 1-B and consisted of a total of 27 bbls of KCl water pumped down casing at rates starting at 1/2 bpm and increasing up to 3.2 bpm. No RA tracers were included in this injection. Bottomhole pressures in MWX No. 2 were simultaneously monitored with a wireline bottomhole pressure tool and a wireless pressure telemetry tool (Telemetry Acquisition System

Figure 14 Wellbore, MWX No. 2 Well

developed by GRI contractor ProTechnics) and accelerometer/inclinometer data acquisition were identical to that acquired in Injection 1-B.

Two pump-in tests (Injections 3-B and 4-B) were performed on April 20, 1995 to complete the initial sequence of B-Sand injections. The first pump-in consisted of 104 bbls of KCl water pumped down casing at rates ranging from 0.25 to 10 bpm. The second pump-in consisted of 196 bbl of KCl water pumped down casing at rates ranging from 0.25 to 10 bpm. No RA tracers were used in either of these injections. For both treatments, bottomhole pressures were monitored with redundant wireline and telemetry pressure tools, and fracture diagnostics data were acquired from the Monitor Well array and a single-level accelerometer in the MWX No. 3 Well.

Injections 1-B through 4-B were designed to be relatively small treatments to test instrumentation arrays and to provide data for designing the subsequent injections. These tests are summarized follows:

- The B-Sand injections represented the first opportunity to simultaneously collect inclinometer and accelerometer data from the Monitor No. 1 Well array during an injection. These simple injections, therefore, verified that the systems were functioning properly prior to moving into large and more complex treatment programs.
- The 1,000 gallon crosslinked gel breakdown was designed to initiate a single hydraulic fracture and thereby limit the potential in subsequent treatments for near-wellbore friction created by multiple fractures. The fracture propagated in the gel breakdown was also tagged with RA tracer to facilitate identification in the later intersection well phase of the M-Site Project.
- The step-rate tests and larger volume treatments provided the opportunity to assess fracture opening and closure based on the pressure-independent inclinometer data.
- Data (bottomhole pressure, microseismic, earth displacement) acquired during the treatments provided the basis for fracture mapping and 3-D modeling. These assessments were used to evaluate if fracture height carried growth into the overlying C-Sand and, if so, to more appropriately size the subsequent mini-fracs to preserve the integrity of the C-Sand.

3.3.3.3 Injection Numbers 5-B and 6-B

Two 400 bbl, 40 lb/Mgal linear gel min-fracs (Injections 5-B and 6-B) were performed in the B-Sand of MWX No. 2 on August 9 and 10, 1995. Each treatment was pumped down the casing/tubing annulus at an average rate of 22 bpm. Flowback of Injection 5-B was initiated following a 2-hour shut-in. A 16-hour shut-in was performed after Injection 6-B prior to flowing back. Each of these injections included a RA isotope in microencapsulate form (Fe^{59} in 5-B and Zr^{94} in 6-B) to uniquely tag the hydraulic fracture(s) propagated.

The data acquisition instrumentation used during both injections was identical and included the following:

- The comprehensive 30-instrument accelerometer and 6-instrument inclinometer arrays in the Monitor Well.
- The five-level accelerometer array on a fiber optics wireline in the MWX No. 3 observation well.
- Bottomhole pressures were monitored during and following each treatment with a surface readout bottomhole pressure gauge set below the perforated interval at 4,650 ft.
- Several spectral gamma ray logging runs were performed: one survey before Injection 5-B, a second after 5-B and a third after Injection 6-B. Tagged frac fluid was reversed out of the wellbore prior to the second and third logging runs to avoid saturating the logging tool with RA tracer which had not been injected into the formation.

Injections 5-B and 6-B were designed to accomplish several experiment objectives:

- Duplicate volumes were pumped to contrast and compare microseismic events in unfractured rock (Injection 5-B) and then refractured (Injection 6-B), and map the locations of microseismic events.
- Earth displacement data were acquired in order to define fracture geometry as well as for assessment of fracture opening and closure.
- The fractures propagated in each injection were tagged with unique RA tracers to facilitate fracture identification in the later intersection well phase of the project and to assess near-wellbore fracture height.
- Bottomhole fracture treating pressure data were acquired for inclusion in 3-D fracture models. Data from these fracture models would be compared to fracture diagnostic results and any differences isolated and quantified.

3.3.3.4 Injection Number 7-B

In August 1995, a 40 lb/Mgal crosslinked gel carrying 76,500 lbs of 20/40 mesh resin-coated proppant was performed in the B-Sand. The injection was pumped down casing at an average rate of 20 bpm. Injection 7-B included two RA isotopes (Sr^{192} microencapsulate and Ir^{192} Zero-wash[®] beads) to uniquely tag the propagated hydraulic fracture(s). A final, post-frac spectral gamma ray logging run with two repeat sections were performed from 4,900 ft to 4,250 ft after having circulated the wellbore with clean fluid. In addition to the placement of the RA tracer, the proppant was colored orange, green and brown. The primary reason for the resin coat was to facilitate the coloring of the proppant.

The data acquisition instrumentation used during Injection No. 7-B was similar to that of Injections 5-B and 6-B, and included the following:

- The comprehensive thirty-instrument accelerometer and six-instrument inclinometer arrays in the Monitor Well were operational during the injections;
- The five-level accelerometer array on a fiber optics wireline was operational in the MWX No. 3 Well;

- Bottomhole treating pressures were monitored during and after the treatment with the RTD pressure telemetry tool set below the perforated interval. The pressure tool successfully transmitted data to the surface at one sample per second intervals. Redundant memory gauge data (internal to the RTD tool) was also acquired; and
- A post-fracture spectral gamma ray logging run was performed following Injection 7-B. Tagged fracture fluid was reversed out of the wellbore prior to the logging run to avoid saturating the logging tool with RA tracer which had not been injected into the formation.

Injection No. 7-B was designed to accomplish several objectives:

- Earth tilt data were acquired for further assessment of fracture geometry as well as for the assessment of fracture opening and closure;
- Microseismic data were acquired for fracture mapping during the injection and during the fracture closure on the proppant;
- The fracture(s) propagated in the injection were tagged with unique RA tracers to estimate near wellbore fracture height growth and to facilitate fracture identification in the later Intersection Well B-Sand phase of the Project;
- The fracture(s) propagated in each injection were tagged with RA tracers to facilitate fracture identification in the Intersection Well B-Sand; and
- Bottomhole fracture treating pressure data were acquired for inclusion in 3-D fracture models. Data from these fracture models would be compared to fracture diagnostic results with any differences isolated and quantified.

An H/Z seismic survey, using a single triaxial accelerometer on a seven-conductor wireline, was performed in the MWX No. 2 Well in conjunction with Injection No. 7-B. A baseline H/Z survey was performed prior to the injection and involved acquiring background data at 25 depth stations between 4,100 ft and 4,825 ft. Depth stations between 4,100 ft and 4,350 ft were spaced 50 ft apart and from 4,375 ft to 4,825 ft the intervals were spaced at 25 ft. The H/Z seismic survey was performed following Injection No. 7-B in order to estimate fracture height growth.

3.4 TASK 4: DRILL DIRECTIONAL, HIGH-ANGLE WELL, INTERSECTION NO. 1 WELL (B-SAND LATERAL)

3.4.1 Introduction

The objective of Task 4 was to drill a high-angle lateral well to intersect the B-Sand hydraulic fracture. Task 4 was performed in the third year of the Project. However, in preparation for drilling activities, a well plan was developed in the second Project year. The purpose of the Intersection No. 1 Well was to recover core across a northwest-southeast trending propped and tagged hydraulic fracture treatment conducted in the Mesaverde B-Sand. It was deemed desirable to core across this hydraulic fracture at an angle of 60° off vertical in order to penetrate possible multiple fracture traces. A surface location in close proximity to the Monitor Well provided the most direct and least expensive wellbore trajectory to the B-Sand target.

3.4.2 Drilling Plan

The following basic drilling procedures were followed in the drilling and casing of the Intersection No. 1 Well, B-Sand lateral.

3.4.2.1 Location

The surface location of the Intersection No. 1 Well is located in the southwest quarter of the northwest quarter of Section 34, T6S, R94W, Garfield County, Colorado (Figure 15). The ground elevation of the well location is 5,385.5 ft. This surface location is approximately 18 ft west and 10 ft south of the surface location of the Monitor No. 1 Well. This 20.4 ft offset provided sufficient standoff from the Monitor Well to minimize the chance of the two wellbores intersecting during drilling and allowed the use of an existing location and reserve pit.

3.4.2.2 Drilling Operation

- *Conductor Casing:* Preliminary field operations began on September 1, 1995 with a rathole rig drilling a 28 in. hole to 39.5 ft. A 20 in. conductor pipe was run to a total depth and cemented back to surface.
- *Surface Casing:* A drilling rig was subsequently moved in and rigged up to drill the remainder of the well. An 8-3/4 in. pilot hole was drilled to a depth of 325 ft. The pilot hole was subsequently opened to 17-1/2 in. and 13-3/8 in. casing was run to 318 ft and cemented back to surface.
- *Intermediate Casing:* Due to a boulder field encountered in the four offset wells between the depths of 200 ft and 1,100 ft, intermediate casing was run to eliminate potential for uphole problems during directional drilling operations. Drilling resumed with an 8-3/4 in. bit and a pilot hole was drilled to 1,166 ft kelly bushing (KB). The 8-3/4 in. pilot hole was subsequently opened to 12-1/2 in. and 9-5/8 in. casing was cemented back to surface.
- *Production Casing:* An 8-3/4 in. hole was drilled out from under the 9-5/8 in. casing at 1,155 ft on September 21, 1995 and continued in a vertical mode to the kickoff point at 4,049 ft which was reached on September 30, 1995. The intervals 1,535 ft to 1,796 ft and 1,796 ft to 2,044 ft were drilled with two FlowDril Corporation downhole pumps of slightly differing design. The improvement in rate of penetration with the two downhole pumps over conventional rotary drilling was 1.4:1 (pump 1) and 1.7:1 (pump 2), respectively. (Further information on the downhole pumps being developed through a DOE/GRI coordinated effort can be obtained by contacting Scott Veenhuizen of FlowDril in Kent, WA.)

At 4,049 ft, the drill pipe was strapped out of the hole, a gyroscope survey was run to tie the surface location to the kickoff point; a Sperry Sun directional drilling assembly was run in the hole; the tool face on the directional drilling assembly was gyroscopically oriented to due North; and directional drilling was initiated on October 2, 1995. Directional drilling continued to the end of the build section at 4,606 ft measured depth (MD), 4,524 ft true vertical depth (TVD). Hole angle was built at an

Figure 15 Well Plot, Intersection No. 1 Well

Figure 16 Plan View, Intersection No. 1 Well, B-Sand Lateral

Figure 17 Vertical Section, Intersection No. 1 Well, B-Sand Lateral

Figure 18 Wellbore Diagram, Intersection No. 1 Well, B-Sand Lateral

initial pump phase, no returns were recorded from the Intersection Well. Pumping was continued down the tubing in the MWX No. 2 Well with the Intersection Well open. The Intersection Well began to flow at a cumulative rate of 145 bbls. The Intersection Well was subsequently shut-in while additional fluid was pumped into MWX No. 2. A total of 182 bbls of initial fluid was pumped before the well was shut-in. Rates during the last 2-1/2 hours of the pump-in were approximately 1/4 bpm at 700 psi.

- With the Intersection Well shut-in and with pressure at 200 psi, the MWX No. 2 Well was again opened and fluid was again injected down the tubing at an initial rate of one bpm until the surface pressure reached 700 psi. After which, the injection rate was reduced to 1/4 bpm. Total injected fluid was 250 bbls.
- The Intersection Well remained shut-in as additional pump-ins were performed in MWX No. 2. Shut-in pressures in the Intersection Well at the beginning of the third day of conductivity testing were 319 psi on the tubing and 365 psi on the casing. With the Intersection Well shut-in, another pump-in was executed down the tubing in the referenced MWX well. Pump rates started at 1/2 bpm until surface pressure reached 700 psi, and decreased thereafter to 1/4 bpm. The well was subsequently shut-in. Total fluid injected into MWX No. 2 through day three was 300 bbls.
- An attempt was made to run a spinner survey in the Intersection Well. However, after a number of attempts, the survey was abandoned. With the MWX No. 2 Well open, a pump-in was performed down the tubing in the Intersection Well. Total fluid injected into the Intersection Well totaled 36 bbls. The flowmeter in the MWX No. 2 was reversed to read fluid flow from the tubing into the tank. Total fluid flow recorded from MWX No. 2 was 66 bbls.
- A second injection was initiated in the Intersection Well and monitored at the MWX No. 2 Well. A total of 44 bbls of water was injected into the tubing of the Intersection Well with 48 bbls of discharge water recorded from MWX No. 2.
- A reverse production conductivity test was initiated, using the MWX No. 2 Well as the injector. Approximately 50 bbls of fresh water was pumped down the tubing and out the casing to evacuate gas from the system. Water was then injected into the MWX No. 2 Well with flow rates and pressures recorded at the Intersection Well. A total of 141 bbls of water was injected into the MWX No. 2 Well, with 66 bbls recorded fluid flow through the Intersection Well.
- A final spinner survey was run in the Intersection Well on the last day of testing. However, the tool was again inoperable and this concluded the conductivity test within the B-Sand.

3.6 TASK 6: DRILL DIRECTIONAL HIGH-ANGLE WELL, INTERSECTION NO. 1 WELL (C-SAND LATERAL)

3.6.1 Objective

Following the execution of the B-Sand fracture conductivity tests, the C-Sand experimentation phase of the Project was implemented. To implement the planned C-Sand experiments, a new lateral borehole was emplaced in the C-Sand prior to initiating hydraulic

fracture treatments. This deviated borehole (to 53°) was to be a shallow kickoff from a window cut in the vertical portion of the existing Intersection No. 1 Well, with an openhole completion in the C-Sand to facilitate subsequent fracture pressure and borehole image data acquisition experiments (Injection 1C through 5C).

3.6.2 Location

The surface location of the existing Intersection No. 1 Well is presented as follows:

County:	Garfield
State:	Colorado
Surface:	2,464 ft FNL, 733 ft FWL, Section 34, T6S, R94W
Bottomhole:	2,136 ft FNL, 1,000 ft FWL, Section 34, T6S, R94W; 423 ft N39°E of surface location
Elevation:	5,398 ft KB, 5,385 ft GL
Projected TD:	4,584 ft MD, 4,425 ft TVD

3.6.3 Prognosis

The drilling procedure presented herein outlines the drilling of a 6-1/8 in. diameter build section and a 50° to 55° lateral through the Mesaverde C-Sand to a total depth of 4,584 ft MD. Drilling of the C-Sand lateral provided a monitoring point approximately 300 ft from the MWX No. 2 Well in which a series of hydraulic fracture treatments could be conducted. The C-Sand leg was drilled at a low angle to ensure that the hydraulic fracture would intersect the borehole. The newly drilled C-Sand borehole was left as an openhole completion to facilitate pressure measurements and wireline logging runs made in subsequent experiments. Data acquisition operations in the openhole included borehole image logging, FMS used to establish the baseline formation character prior to fracturing into the borehole. Future FMS log data was compared to this baseline data in order to determine the locations of hydraulic fractures.

3.6.4 Plug and Abandonment Operation

The following basic procedures were followed in the plugging and abandoning of the Mesaverde B-Sand lateral:

- Moved in and rigged up well service unit and installed Blow Out Prevention Equipment (BOPE);
- Pull 2-7/8 in., 6.5 lb/ft N80 tubing from the well;
- Picked up casing scraper and made a scraper run from surface to 4,000 ft. Pulled 2-7/8 in. tubing and casing scraper; and
- Ran and set a Cast Iron Bridge Plug (CIBP) on wireline at 4,500 ft. Placed 10 sacks of cement on top of the CIBP.

3.6.5 Directional Drilling Operations

- An angle-build bottom hole assembly was utilized to drill the angle build section from the kickoff point at 3,725 ft to 4,398 ft MD (4,312 TVD), with a location of 218 ft north and 178 ft east of the surface location. The hole angle was built to 52° off vertical at a build rate of approximately 10°/100 ft using both drilling motors and surface rotation. The hole azimuth was projected at N39°E at the top of the Mesaverde C-Sand. The hole angle and the hole azimuth through the build section were measured using gyroscopic steering up to the point where the wellbore passed the Monitor No. 1 Well. MWD tools were used from this point to total depth. The angle build section began at the casing window, reaching 52° four feet into the C-Sand at 4,387 ft MD. The C-Sand was drilled with an angle-hold bottom hole assembly to total depth (Figure 19).
- Fresh water was used as drilling fluid in cutting the window in the 7 in. casing. Two ditch magnets were used to recover metal at the surface during drilling, and the pits were dumped and cleaned following completion of the operation.
- A polymer gel, low solids non-disperse mud system was used while drilling the 6-1/8 in. diameter hole from the window at 3,725 ft to a total measured depth of 4,584 ft. This highly shear-thinning system was chosen because it has a minimum of solids for improved penetration with minimum viscosity at the bit and a maximum annular viscosity for hole cleaning. Polymer was used to extend the yield of the bentonite while selectively flocculating low yield drilled solids. Polymer was added at a rate of one bucket per 100 bbls of drilling fluid for maximum effectiveness. Caustic soda was used to control pH at approximately 9.0 to 9.5. Drillpac was also used to control filtration at the desired level.
- Solids control was very important in the angle build portion of the hole. Mud weight was maintained between 8.8 ppg to 9.0 ppg from 3,725 ft to 4,584 ft MD. The rig was equipped with one double screen shale shaker, a desander, a desilter and a mud centrifuge.
- Significant torque or drag was anticipated in the angle-build portion of the wellbore. As such, a blend of non-hydrocarbon lubricating agents (TORKease™) was used as a drilling fluid additive to impart lubricity to the drill string, bit and borehole. The coating action prevented the hydration and consolidation of shale cuttings, aided in the elimination of sloughing shales and promoted the effective removal of drill cuttings.
- Upon reaching a total depth of 4,584 ft, an open hole logging suite was run which consisted of the FMS and the Litho-Density, Compensated Neutron Log with Gamma Ray and Caliper Log.
- The open hole section across the C-Sand was plugged back below the C-Sand with 20/40 frac sand and capped with a three sack cement plug. The top of the cement plug was four feet below the top of the C-Sand, at 4,387 ft. MD. This cement plug ensured that there was no circulation of the sand during liner cement displacement.
- A liner consisting of approximately 849 ft of 5 in., 18lb/ft, N80 seamless casing with Hydril 521 connections was run through the angle build to a depth of 4,383 ft MD

Figure 19 Vertical Section, Intersection No. 1 Well, C-Sand Lateral

and tied back to the 7 in. production casing at 3,534 ft. MD. The liner was cemented in place using 100 sacks of Class "G" regular cement.

3.7 TASK 7: CONDUCT FRACTURE PRESSURE AND SEISMIC EXPERIMENTS, C-SAND INTERVAL

3.7.1 Objective

With the successful emplacement of the Intersection No. 1 Well, a series of fracture diagnostics and fracture technology experiments were designed for the C-Sand. The objectives of the C-Sand experiments were to resolve uncertainties associated with the microseismic fracture diagnostics techniques, compare and address any differences between microseismic fracture dimensions and fracture models, and extend the fracture diagnostics capabilities using inclinometer data.

Microseismic events are thought to be shear slippage events occurring along planes of weakness. Locations resulting from B-Sand injections were unable to define a single, well defined plane corresponding to the hydraulic fracture. Rather, a cloud of microseismic events was mapped through which was drawn a linear regression, best-fit line to estimate the plane of the events occurring adjacent to the fracture, i.e. above, below, laterally and beyond the fracture tip. Therefore, the state-of-the-technology was such that the relationship between microseismic fracture dimensions and the true dimensions of the pressurized hydraulic fracture was only an approximation.

It was determined that one approach to resolving this technical challenge would be to perform analyses of the microseismic events wherein the types of microseisms are separated and categorized. Therefore, only those microseismic events associated with rock being broken by the pressurized crack would be used to map fracture dimensions. A complimentary approach would be to perform field experiments wherein microseismic fracture dimensions are compared and contrasted to the actual dimensions of the pressurized crack. These field experiments and resulting data analyses are the objectives of this portion of the M-Site Project.

3.7.2 Technical Approach

The implementation strategy for C-Sand experiments involved a staged approach for injecting fluid in the C-Sand of the MWX No. 2 Well to propagate a hydraulic fracture(s) that would intersect the C-Sand in the Intersection No. 1 Well.

3.7.3 Injection Number 1-C

The objectives of Injection 1-C included:

- Breakdown of the entire near-wellbore C-Sand interval and initiate a single vertical fracture which would connect the entire gross sand thickness, yet having limited lateral extent;

- Monitor fracture growth and determine fracture dimensions with M-Site diagnostics;
- Employ RA tracer to map vertical wellbore height and extension; and
- Monitor pressure response in Intersection Well No. 1 to determine stress induced pressure transients.

Injection 1-C commenced in August 1996 and consisted of a small volume, 100 bbls, of 40 lb/Mgal crosslinked gel which was used to open the perforation, injected at 20 bpm. An encapsulated SC⁴⁶ RA tracer (74-day one-half life) was utilized to help map fracture dimension.

3.7.4 Injection Number 2-C

Injection 2-C consisted of a low viscosity, KCl water, injected into the C-Sand in order to propagate a hydraulic fracture with a lateral extent of no more than one-half the distance from the treatment well (MWX No. 2) and the Intersection Well. Injection 2-C consisted of 250 bbls of 40 lb/Mgal. This volume was carefully determined through pre-frac model runs with particular focus on fracture length. Previous microseismic mapping in the B-Sand indicated that fracture length extension is quite rapid and, therefore, it was necessary to carefully monitor the injection volumes so as to avoid fracturing into the Intersection Well.

Microseismic, earth tilt and pressure data were acquired and evaluated in order to determine two-dependent fracture dimensions. Near real-time estimates of fracture length were provided by existing automatic event detection and mapping software. An unencapsulated SC⁴⁶ RA tracer was also used in this injection to evaluate near wellbore fracture height in the treatment well. The data acquisition arrays for Injection 2-C consisted of the following:

- 5-level accelerometer array on fiber optics wireline in the MWX No. 3 Well;
- 30-level accelerometer array and 6-level inclinometer array in the Monitor No. 1 Well;
- Surface readout of bottomhole pressure tool, which provided treating pressures in the MWX No. 2 Well; and
- An HP gauge on a single conductor wireline in the Intersection No. 1 Well.

3.7.5 Injection Number 3-C

Injection 3-C was similar to Injection 2-C in that the hydraulic fracture(s) were not to be propagated into the Intersection Well. Rather, the fracture(s) were to be extended a distance beyond that attained in Injection 2-C, yet not to a point whereby there was Intersection Well breakthrough within the C-Sand. Injection 3-C consisted of 250 bbls of 40 lb/Mgal linear gel injected at a rate of 20 bpm, with unencapsulated Sb⁴⁶ employed as a RA tracer. The data acquisition array for Injection 3-C included the following:

- 5-level accelerometer array on fiber optics wireline in the MWX No. 3 Well;

- 30-level accelerometer array and a 6-level inclinometer array in the Monitor Well; and
- Surface readout of bottomhole pressure tool in the MWX No. 2 Well.

3.7.6 Injection Number 4-C (Mini-Frac)

Injection 4-C was a repeat mini-fracture experiment in the C-Sand. The work plan allowed for the acquisition of treatment well diagnostics using the multi-level, accelerometer-based receiver system in the treatment well. The procedure consisted of 710 bbls of 40 lb/Mgal crosslinked gel with RA tracer pumped at 20 to 30 bpm with maximum surface pressure of 3,200 psi. The diagnostic objective of the test was to compare treatment-well microseisms with offset-well microseisms (from the Monitor Well). Such data were not obtained on previous treatment-well tests due to failure of several components of the fiber optic wireline/receiver string system. Based on previous knowledge, this procedure was adjusted as follows:

- No RTD tool with its long antenna was used in the treatment well; and
- A four-level system was placed in the treatment well with the formatter and cable head below the major flow interval at the top of the C-Sand

The data acquisition arrays in-place for Injection 4-C included the following:

- 4-level accelerometer array on fiber-optics in the MWX No. 2 Well;
- 30-level accelerometer array and 6-level inclinometer array in the Monitor Well; and
- Surface readout of bottomhole pressure tool providing treating pressures in the MWX No. 2 Well.

The following scope of work was followed in Injection 4-C:

- Ran the Protechnics Imaging Tool in MWX No. 2 to determine the tracer material type, position within the C-Sand and residual level remaining from the first three C-Sand injections;
- Ran the Protechnics RTD pressure telemetry tool on slickline in MWX No. 2 and landed the tool below the lowermost perforations at 4,365 ft, MD;
- Deployed the Bolt 4-level receiver array in MWX No. 2;
- Ran the Bolt airgun in MWX No. 3 so as to orient the 4-level receiver array in MWX No. 2 using the airgun;
- Ran the HP gauge to 4,380 ft in the Intersection Well; and
- Pumped 710 bbls of 40 lb/Mgal. Viking 1D40 crosslinked gel mini-frac fluid at 20 to 30 bpm. The fluid was tagged with 11 millicuries of micro-encapsulated Sb¹²⁴ LZW material. Five (5) millicuries of tracer was injected into the first 175 bbls of frac fluid with the remainder spread evenly throughout the injection.

Displaced the mini-frac to the top of the C-Sand perforations with 160 bbls of water.

Following the completion of Injection 4-C, the Protechnics Spectral Gamma Log was run in both MWX No. 2 (to determine the vertical distribution of the RA tracer material across the C-Sand interval) and the Intersection Well (to determine the potential intersection point). In addition, the Schlumberger Slim Hole FMS log was run in the Intersection Well from 4,522 ft to 4,383 ft to determine the potential fracture intersection point(s) in the high-angle (53°) C-Sand open hole wellbore.

Following Injection 4-C, hydraulic fracture conductivity testing was initiated during the first week of December 1996. The conductivity tests were performed by circulating down one of the wellbores, either the MWX No. 2 Well or the Intersection Well, through the hydraulic fracture and into the opposite wellbore. Pressure, flow rate and temperature data were acquired during the circulation tests. The injections were performed in order to assess:

- Hydraulic fracture conductivity of single-well or multiple unpropped cracks;
- Rheology of fracturing fluids that have been subjected to subsurface temperature and pressure conditions;
- Pressure array in the fracture(s) due to varying frac fluid viscosities; and
- Variation in fracture dimensions as a function of fluid type and viscosity.

The conductivity test consisted of the injection of 288 bbls of water throughout the entire test at rates from 1/4 bpm to 1-1/2 bpm. Communication between MWX No. 2 and the Intersection Well was restricted.

3.7.7 Injection Number 5-C (Propped Frac)

Injection No. 5-C was a propped fracture treatment using a crosslinked gel. Fracture dimensions based on accelerometer and inclinometer data was compared to those achieved with fluid-only injections. The data acquisition package was moved into the MWX No. 3 Well. This final C-Sand injection included proppant stages that facilitated the execution of relevant fracture technology experiments. The experiments associated with this injection included:

- Fracture widths from the previous injection fluid-only treatments were compared to propped frac widths in the C-Sand Intersection Well;
- Proppant concentration and rheology of the slurry at the fracture tip were recorded at the Intersection Well;
- Pressure drop in the fracture due to sand-laden slurry was measured through a comparison of treatment well injection pressure and recorded pressure in the Intersection Well; and
- Fracture dimensions based on microseismic/inclinometer data and fracture modeling were determined and compared to observed intersection at the Intersection Well to give a visual interpretation of length.

Injection 5-C consisted of a 2,000 bbl 40 lb/Mgal. crosslinked gel carrying 248,000 lb of 20/40 mesh sand. Injection pump rates were 10 to 30 bpm with maximum surface pressures of 3,100 psi. The injection was deployed through 150 perforations within the C-Sand, from 4,290 ft to 4,365 ft. All treatment fluid was tagged with 30 millicuries of neuro-encapsulated Sc^{46} LZW material. Eight (8) millicuries of tracer was injected into the first 500 bbls of the treatment with the remainder added evenly over the remaining 1,500 bbls of the treatment. The proppant was tagged with 107 millicuries of Ir^{192} zero wash.

Upon completion of the 2,000 bbl treatment, the following operation was undertaken:

- Removed the seismic package from the MWX No. 3 Well;
- Ran the Schlumberger Slim Hole FMS in the Intersection Well to determine fracture intersection point(s);
- Ran the Spectral Gamma Log in the MWX No. 2 to determine vertical distribution of the RA tracer material across the C-Sand; and
- Ran the Spectral Gamma Log in the Intersection Well, logging from 4,533 ft to 4,290 ft. in order to determine the fracture intersection point(s) in the high-angle (53°) C-Sand open hole wellbore. The gamma ray showed a hot spot at 4,460 ft to 4,470 ft which was a shale layer within the C-Sand unit. There was also a build-up of RA material at the bottom of the hole.

Conductivity testing was initiated upon completion of Injection 5-C. A total of 182 bbls of water was injected with all injection initiated at MWX No. 2. Rates ranged from 1/2 to 1.0 bpm with maximum surface pressure of 1,050 psi. Conductivity testing was completed within the C-Sand in January 1997.

3.8 TASK 8: PROJECT DOCUMENTATION AND TECHNOLOGY TRANSFER

By documenting the processes and operational aspects of the hydraulic fracture experiments conducted herein, it is anticipated that the utility of various hydraulic fracture diagnostics tools, techniques and models can be confirmed and/or modified. Such documentation is in the form of technical progress reports, topical workshops and annual reports which were prepared over the term of the Project. Final topical reports covering the interpretive aspects of the experiments are prepared by members of the GRI/DOE contractors team. To date prepared formal reports include:

- *Results of Multi-Site Experimentation in the A-Sand Interval: Fracture Modeling and Crosswell Tomography*; GRI Topical Report, February 1995."
- *GRI/DOE Multi-Sites Fracture Diagnostics Project: Monitor Well No. 1 Drilling, Data Analysis and Instrument Emplacement*; GRI Topical Report, February 1995.
- *Core and FMS Interpretation of Intersection No.1 Well, Rulison Field, Colorado*; GRI/DOE Technical Report, March 1996.

In addition to these reports, the contractors have participated in a number of GRI/DOE contractor review meetings.

Other relative reports and publications are noted in the bibliography included herein.

3.9 TASK 9: M-SITE FIELD ADMINISTRATION

Upon completion of the hydraulic experiments, restoration procedures were initiated at the M-Site. In addition to the removal and reassignment of certain DOE and GRI equipment and tools, three wells used in the experiments were plugged and abandoned. This included the MWX No. 2 and No. 3 Wells and the Intersection No. 1 Well. This work was completed at the end of February 1997.

CER, as awardee of the contract and operator of the M-Site, submitted a response to the DOE environmental questionnaire upon the termination of this contract. CER's response documents that¹ all waste streams were collected, contained, and disposed of in strict compliance with environmental rules and regulations of the United States Government and the State of Colorado; and that the Project surface location has been restored to conditions of the site prior to contract award.

To the best of CER's knowledge, no contaminated real or personal property remains on the locations from the tasks performed under this contract. In addition, there are no environmental or other issues related to or resulting from the activities of this Project that require additional attention or action by CER Corporation for the DOE.

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