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Introduction to the GRI/DOE Field Fracturing Multi-Site Project

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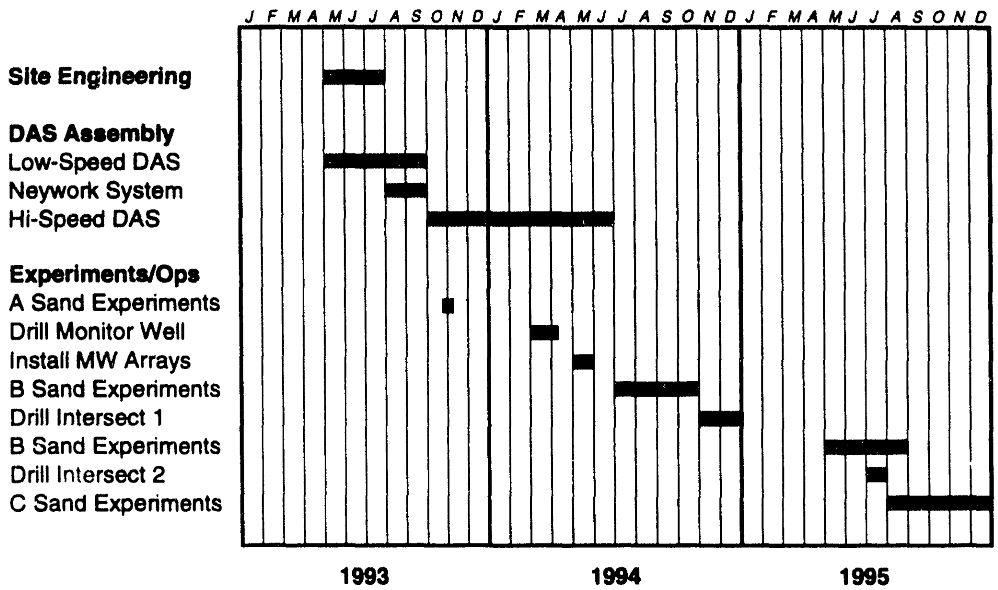
CONTRACT INFORMATION

DOE Cooperative Agreement Number	DE-FC21-93MC30070
GRI Contract Number	5093-221-2553
Contractor	CER Corporation 950 Grier Drive Las Vegas, NV 89119 (702) 361-2700
Contractor Project Manager	Richard E. Peterson
Principal Investigators	Michael L. Middlebrook, CER Norman R. Warpinski, Sandia Michael P. Cleary, RES Paul T. Branagan, B&A
METC Project Manager	Karl H. Frohne
Period of Performance	July 28, 1993 to July 27, 1996

Schedule and Milestones

CY 1993 to 1995 Project Schedule



OVERALL OBJECTIVE OF THE PROJECT

The objective of the Field Fracturing Multi-Sites Project is to conduct field experiments and analyze data that will result in definitive determinations of hydraulic fracture dimensions using remote well and treatment well diagnostic techniques. In addition, experiments will be conducted to provide data that will resolve significant unknowns with regard to hydraulic fracture modeling, fracture fluid rheology and fracture treatment design. These experiments will be supported by a well-characterized subsurface environment, as well as surface facilities and equipment that are conducive to acquiring high-quality data.

It is anticipated that the primary benefit of the project experiments will be the development and widespread commercialization of new fracture diagnostics technologies to determine fracture length, height, width and azimuth. Data resulting from these new technologies can then be used to prove and refine the 3D fracture model mechanisms. It is also anticipated that data collected and analyzed in the project will define the correct techniques for determining fracture closure pressure. The overall impact of the research will be to provide a foundation for a fracture diagnostic service industry and hydraulic fracture optimization based on measured fracture response.

BACKGROUND INFORMATION

Project Justification

Research work performed by the Gas Research Institute (GRI) and the U.S. Department of Energy (DOE) over the past several years has been directed at acquiring comprehensive data sets before, during and after hydraulic fracture treatments on a number of wells. Researchers have made significant advancements in several areas from these data, including formation evaluation, modeling fracture propagation processes, diagnosing the azimuth and height of the created fracture, and modeling production from a hydraulically-fractured natural gas reservoir. Significant advancements have also been made in developing and applying technology to define the stress characteristics of various rock layers, measuring important parameters before, during and after a fracture treatment, and using that information in a hydraulic fracture propagation model to predict the shape and extent of the resulting hydraulic fracture.

Although advances have been made, several important questions remain. Fracture propagation models being used by industry today can vary widely in their results for given input parameters due to various assumptions about the in-situ hydraulic fracturing process. In addition, fracture diagnostic systems developed thus far are capab'e of determining only fracture azimuth and, possibly, height. There is no proven diagnostic technique available for accurately determining fracture length. These deficiencies in fracture diagnostics and modeling provided the basis for GRI and DOE to collectively sponsor a research project having the research objectives stated above.

Characteristics of the Proposed Experimental Site

The site proposed for the field-fracturing Multi-Sites Project (i.e., M-Site) hydraulic fracture experimentation is the former DOE Multiwell Experiment (MWX) site located near Rifle, Colorado, as shown in Figure 1. This site presently includes three closely-spaced wells (MWX-1, MWX-2 and MWX-3), as shown in Figure 2.

All of the proposed M-Site experimentation will occur in several sandstone units, shown in Figure 3 and referred to in this report as the A, B and C Sands, present in the upper Mesaverde Group between 4,130 and 5,000 ft. These shallower sandstone units are desirable for multiple reasons:

1) the fluvial and paralic depositional environments of the upper Mesaverde were conducive to deposition of thick, laterally-continuous sandstone bodies;

2) the previous MWX project did not perform any hydraulic fracture stimulations above 5,500 ft, thereby preserving the subsurface laboratory;

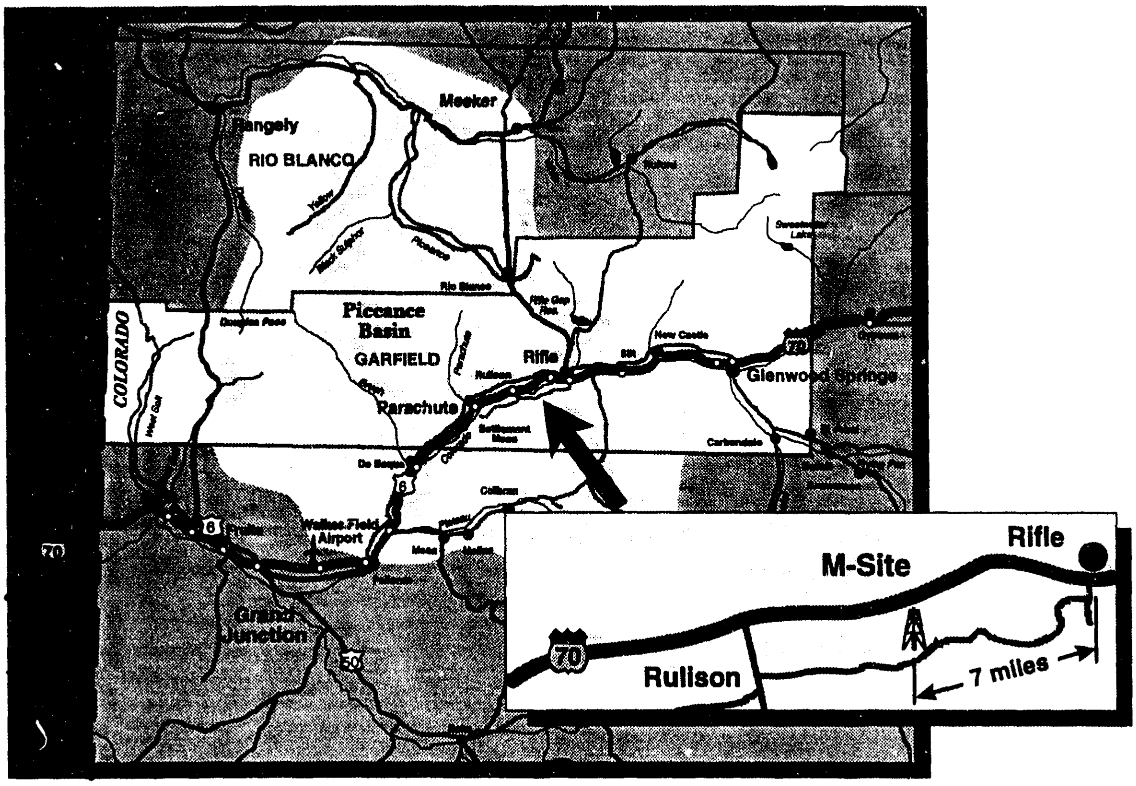


Figure 1. Location of the Field Fracturing Multi-Site Project

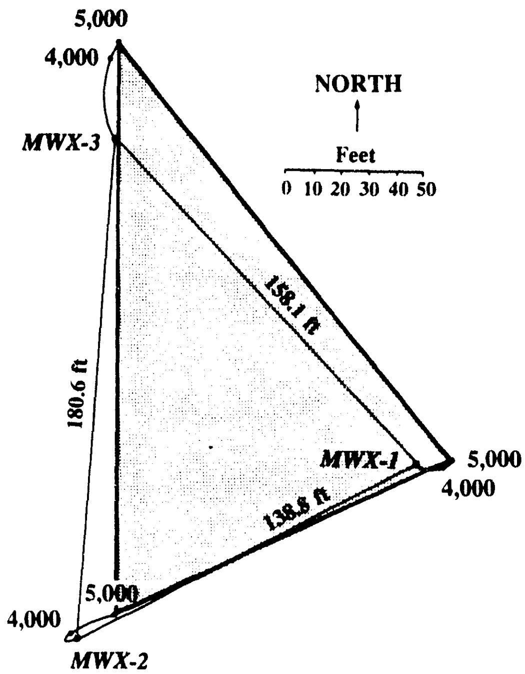


Figure 2. Closely-Spaced Well Initially Drilled as Part of the Multiwell Experiment

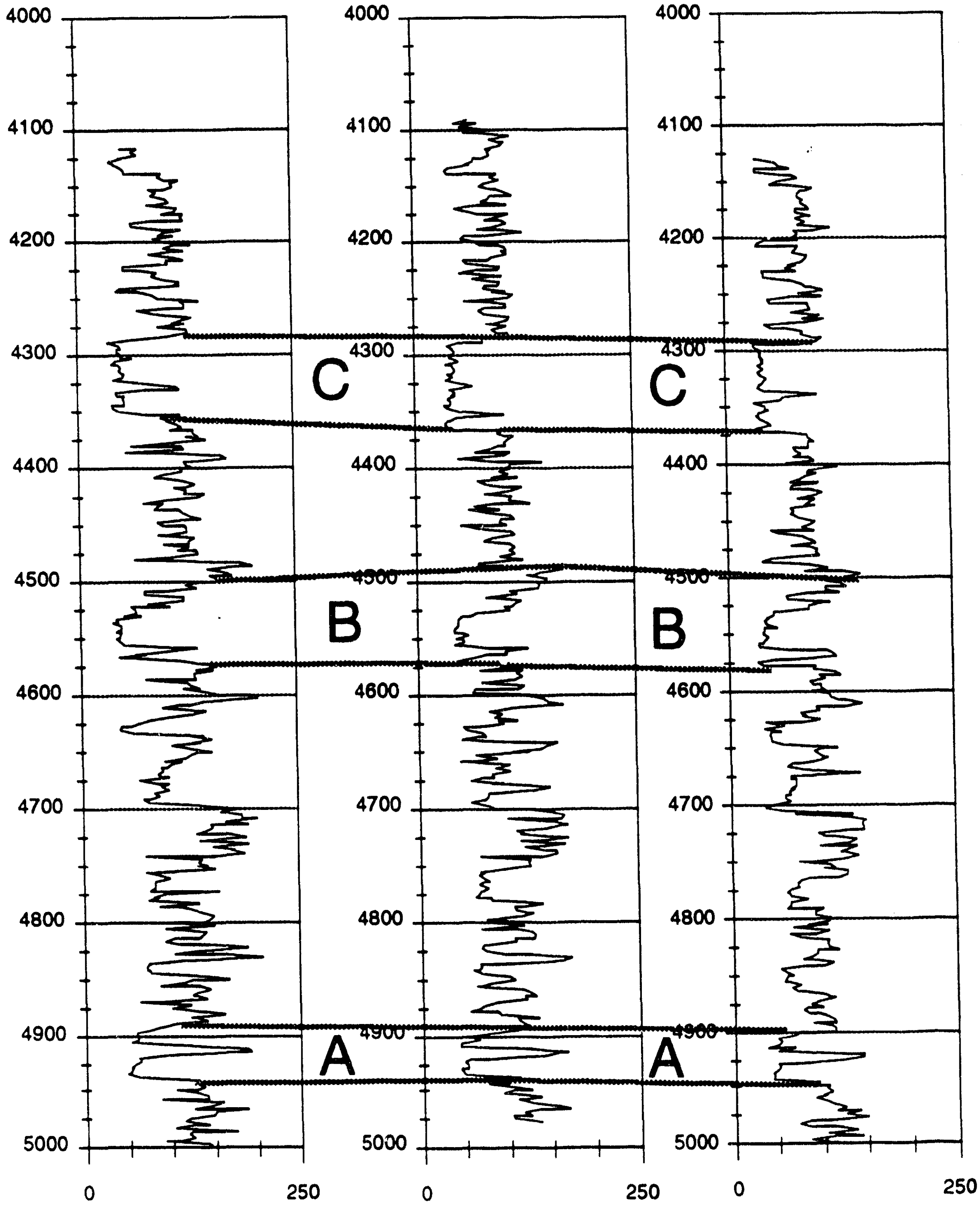


Figure 3. Upper Mesaverde Sandstone Units Targeted for Research in the Multi-Site Project

3) few (if any) wellbore obstructions (e.g., bridge plugs, fishes) exist above 5,500 ft in the existing MWX wells;

4) shallower target intervals decrease operational costs associated with conducting experiments; and

5) shallower depths promote the acquisition of higher quality data from surface-deployed instrumentation.

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

There are abundant data which currently exist as a result of MWX research within the proposed test interval which will be used to the advantage of the Multi-Sites Project:

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

- Thirteen cased-hole stress tests have already been performed in the MWX-2 well between 4,170 ft and 5,502 ft.

- Multiple overlapping runs of high-quality wireline log data exists for this interval and are archived at CER. The log and core data have been compiled into a depth-shifted, digital database which is maintained at CER.

- Seismic data in the form of high-resolution 3D, vertical seismic profile and cross-borehole is available.

There are additional data and information below the proposed test interval which will be useful to M-Site research. These data and information include the following:

- Hydraulic fracture azimuth was determined to be N78°W based on 7 different techniques implemented in the deeper Mesaverde in the MWX wells.

- 3D fracture modeling was previously performed on a hydraulic fracture treatment at 5,530 ft, so there is information on model behavior.

- Natural fractures associated with significant over-pressuring are known to occur primarily below 5,500 ft (i.e., below the proposed interval).

- Through work in 10 separate completion intervals, there were no indications of any near-wellbore effects during fracturing experiments. Thus, fracture treatment modeling is not expected to be hindered.

From a logistical point of view, the Multi-Site Project is suitable with regard to proximity to oil field services and airports. The M-Site is located 9 miles from Rifle, Colorado (see Figure 1). Grand Junction is 60 miles from the site via Interstate 70. Access from the interstate to the site is by a county-maintained paved road.

Verification of Site Suitability

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

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

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

- Log-derived stress data calibrated with in-situ stress test data indicate that a stress contrast ranging from 500 to 1,000 psi exists between the target sandstone units and the bounding lithologies. This stress contrast was considered suitable for limiting excessive fracture height growth.

- There were no unusual occurrences (e.g., near-wellbore effects) in pressure responses which inhibited 3D fracture modeling of the mini-frac treatment.

- Remote-wellbore monitoring during the mini-frac injections was clearly able to identify over 1,000 microseisms. Limited analysis of these data indicated that the seismic signals can be spatially located and used for mapping the hydraulic fracture.

Based on these positive assessments, it was concluded that the MWX site is suitable for conducting additional comprehensive M-Site fracture diagnostics and fracture model verification experiments. Complete documentation of the field operations and results is found in CER and others, 1993.

Contractor Team

The contractor team organized by GRI and DOE to execute the research project and interpret the results includes CER Corporation, Sandia National Laboratories (SNL), Resources Engineering Systems (RES), Branagan & Associates (B&A), and James E. Fix & Associates (F&A). Each organization's responsibilities are listed in Table 1.

Table 1. Contractor Team

Organization	Responsibility
CER	Site operations and data acquisition systems
SNL	Fracture diagnostics
RES	Hydraulic fracture modeling
B&A	Design of data acquisition systems
F&A	Geophysical consultant

DESCRIPTION OF PROPOSED RESEARCH EXPERIMENTS

Experiments are planned for 3-year period from 1993 to 1995, as shown in the project schedule (see Contract Information). These experiments will use combinations of the existing MWX wells and wells which will be drilled. An overview of the experiments to be conducted using the existing and new wellbores is described in the following sections.

MWX Wellbores - Comprehensive A Sand Experiments

The objective of the MWX A-Sand seismic experiments is to determine hydraulic fracture azimuth, height and length, as a function of various fluid viscosities and net pressure. The experiment will involve several mini-frac injections using MWX-3 as the treatment well and the A Sand as the treatment zone. The primary data acquisition equipment, to be run in the MWX-2 well, will be seismic instrumentation (five triaxial accelerometers) on a fiber optics wireline. Fracture pressure data will also be acquired and used to model the mini-frac treatment. However, 3D fracture modeling will not necessarily be constrained by the fracture diagnostics data at this early stage of the project. In addition, a determination of the velocity structure of the upper Mesaverde will be performed to more accurately interpret the seismic data acquired during this and subsequent experiments.

These MWX-based fracturing experiments represent an intermediate step preceding the more comprehensive data acquisition planned for 1994. The data collected in the MWX experiments, however, will be applied as follows:

1) demonstrate the utility of a commercially-available 5-level seismic receiver for enhanced microseismic monitoring of hydraulic fracture dimensions;

2) begin validation of current treatment-well diagnostic technology (h/z, noise polarization);

3) begin validation of current mechanisms used in 3D fracture models; and

4) contribute to the finalization of a new observation well design (see Monitor Well discussion below) with regard to the optimum spacing and total number of seismic instruments to be cemented in place.

Monitor Well and Geophysical Instrumentation Arrays

The objective of this phase of the Project is to drill and case a specially-designed offset well (i.e., Monitor Well) that will be used to emplace an array of seismic and earth tilt instrumentation. Comprehensive fracture diagnostics experiments can then be performed using a combination of the Monitor Well and MWX-3 as monitoring wells and the MWX-2 as the treatment well. The Monitor Well is necessary because comprehensive seismic experimentation, which has the potential for clearly defining the dimensions of a hydraulic fracture, requires an instrumentation array beyond that which can be fielded on a wireline retrievable system. These instrumentation arrays must be coupled to the formation, i.e., cemented in place, and properly located (vertically and horizontally) to be effective in acquiring meaningful data.

Figure 4 diagrammatically illustrates instrumentation and diagnostics arrays to be initially deployed at M-Site. The Monitor Well instrumentation arrays shown in the figure are to be cemented in place in the annular space between the 9-5/8-in. casing and 2-3/8-in. tubing strings. These arrays will be fundamental to fracture diagnostics data acquisition. The instrumentation cemented in place across the B and C Sand intervals will consist of the following:

- six inclinometers to be used for fracture closure experimentation; and

- a minimum of 16 and possibly as many as 64 triaxial seismic instruments for use in mapping hydraulic fracture microseisms and cross-well imaging.

Instrumentation will be secured to the casing string and adequately protected with centralizers when placing them in the hole. Cabling from the instrument arrays will run to the surface and into a data acquisition trailer positioned on the location. Figure 5 illustrates the approximate position of the monitor well, its data acquisition trailer and other infrastructure at the M-Site.

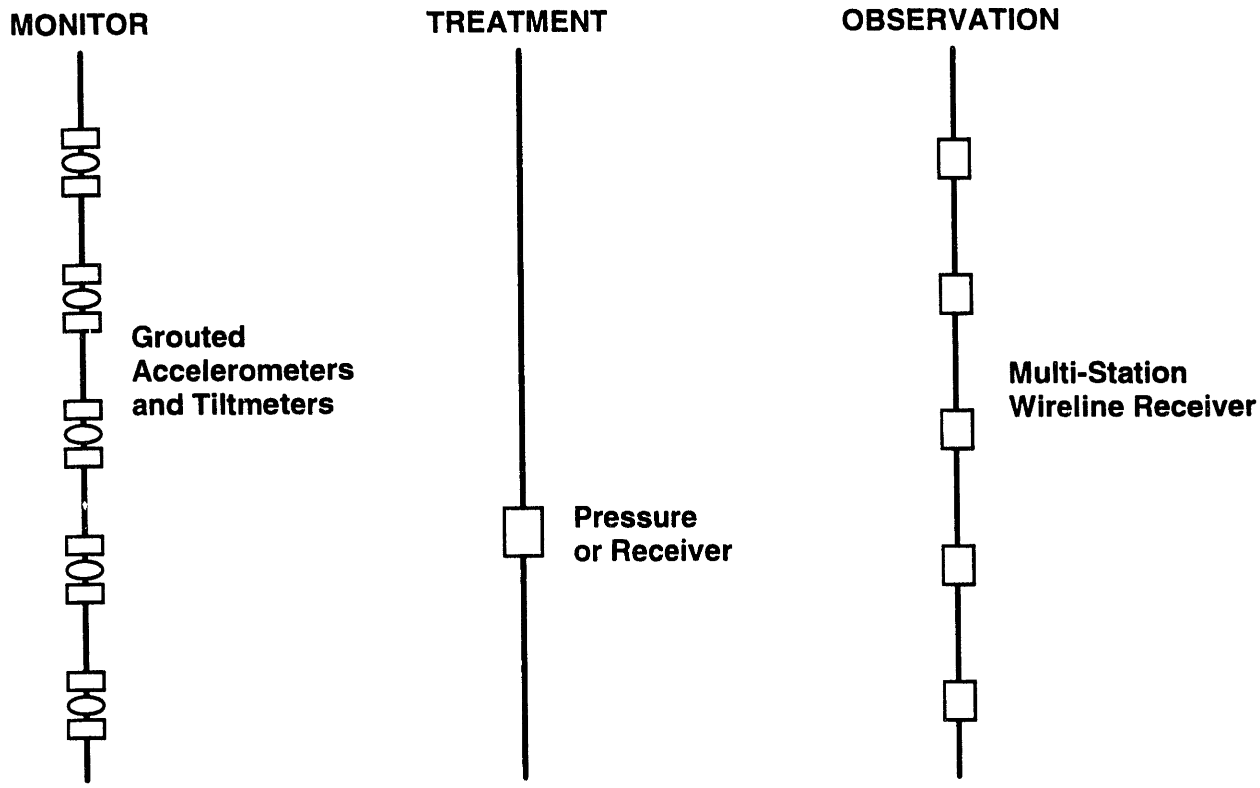


Figure 4. Instrumentation and Diagnostics Arrays to be Grouted in the Monitor Well

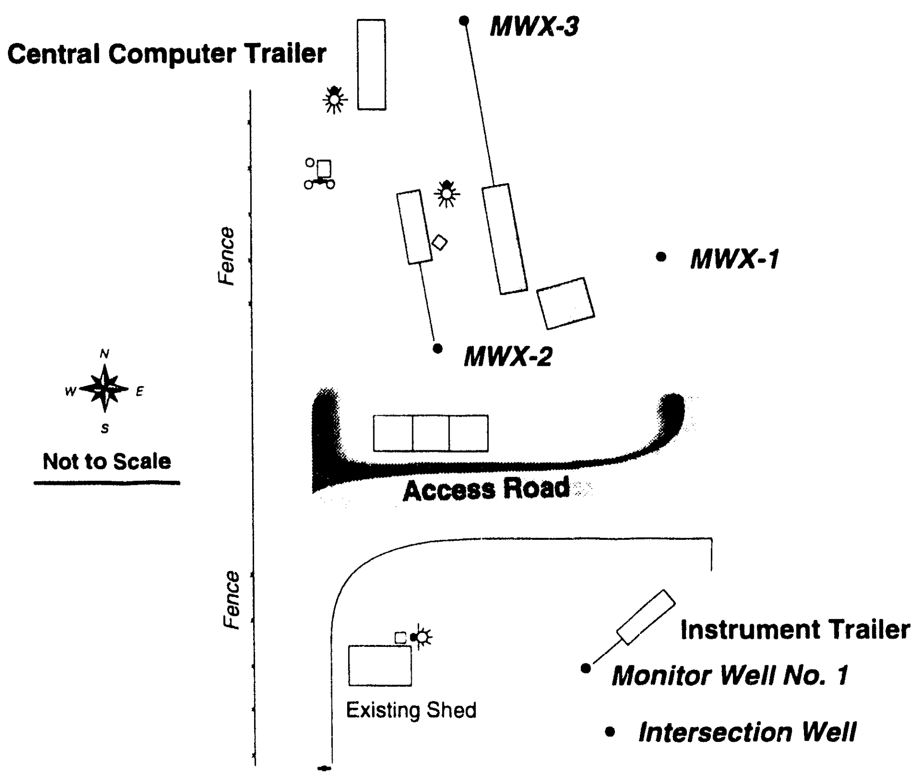


Figure 5. Layout of M-Site Infrastructure

Monitor/MWX Wells - B Sand Experiments

Fracture diagnostics will be the primary focus of this phase of the project which is anticipated to be performed in mid-1994 (see Project Schedule). Several mini-frac injections will be designed to achieve increasing hydraulic fracture length and height using MWX-2 as the treatment well. This fracture diagnostics plan is conceptually illustrated in Figure 6. These treatments, performed in the B Sand, would also have a progression of fluid types (from slick water to gel) pumped at multiple rates. Seismic data collected by the fracture diagnostics monitoring instruments cemented in the Monitor Well and wireline-retrievable seismic instruments in MWX-3 will be recorded during each treatment by the high-speed data acquisition system. The microseismic monitoring system will be capable of detecting, identifying, locating and displaying seismic sources as a function of time. The loci of source locations will be an ellipsoid that defines the extent of the active rock failures. The dimensions, orientation and geometry of the seismically active zone will provide a measurement of the fracture to be compared to the results of the post-fracture history match of various 3D fracture models. The accelerometer instrumentation in the Monitor Well will have continued use throughout the remaining phases of the M-Site project.

One of the potential seismic experiments to be conducted in the B Sand will be to map the shear-wave shadow. Following each injection, shear-wave shadow experiments could be performed using MWX-3 for deployment of a downhole seismic source and the Monitor Well as the seismic-signal receiver well. Execution of these seismic experiments would lead to hydraulic length and height dimensional characterization of the staged treatments being pumped from the MWX-2 well. The last fracture treatment to be pumped in the B Sand would include proppant to facilitate research to be conducted in the next phase of the project.

Intersecting Well 1 - B Sand Experiments

The goal of this phase of the project is to 1) intersect the propped hydraulic fracture created in the last B-Sand injection; and 2) perform hydraulic fracture conductivity tests between the treatment well and the intersection well. A conceptual diagram of Intersecting Well 1 cutting across the B Sand hydraulic fracture is shown in Figure 7. The drilling of Intersecting Well 1 would occur late in 1994 as shown in the Project Schedule.

The Intersecting Well 1 will be drilled on the same drilling pad as the Monitor Well. The initial part of the drilling operation would involve drilling a pilot hole to a depth of 4,750 ft. This pilot hole would be logged with a basic suite of resistivity, porosity and mechanical properties logs. With this information, the depth interval of the B Sand would be defined so that a horizontal wellbore could be kicked off of the pilot hole and directionally drilled to intersect the propped fracture emplaced in the B Sand. A coring assembly will be utilized, as the zone anticipated to include the hydraulic fracture is approached, to cut across the fractured interval and allow direct observation of the character of the fracture recovered in the core. Subsequently, borehole image log data (e.g., FMS or CAST) would be acquired through the fractured interval to fully characterize the fracture. The portion of the borehole which intersects the B Sand will be left open hole to facilitate fracture conductivity experiments as described below.

Fracture conductivity testing will be performed using the combination of the MWX-2 treatment well, propped hydraulic fracture in the B Sand and Intersecting Well 1 which has intersected the hydraulic fracture. Implementation of these experiments would potentially provide data for the verification of the following hydraulic fracture unknowns:

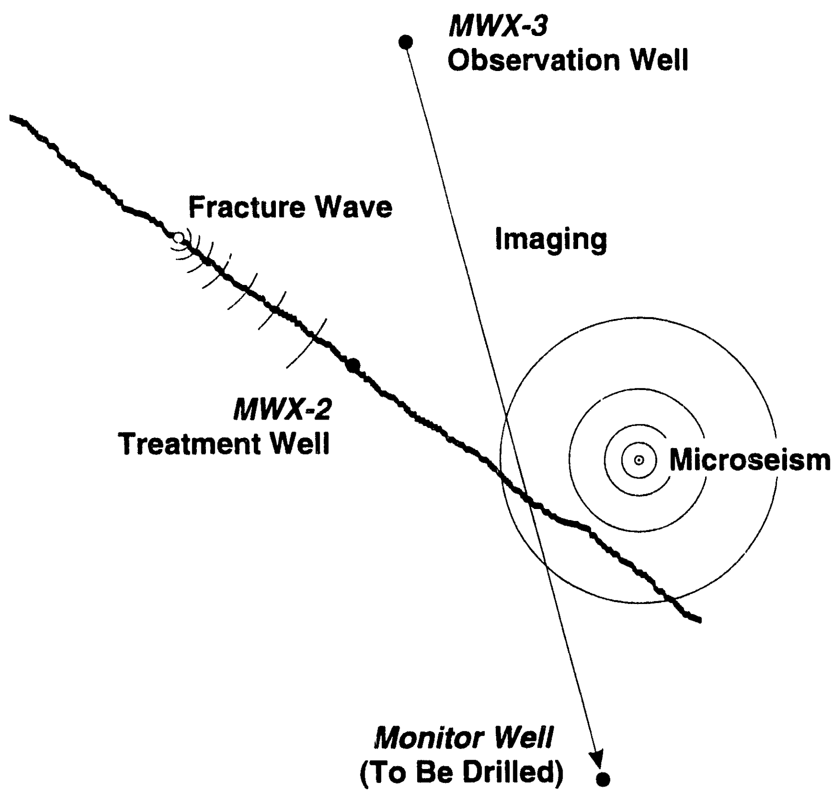


Figure 6. Conceptual Diagram of Fracture Diagnostics in the B Sand

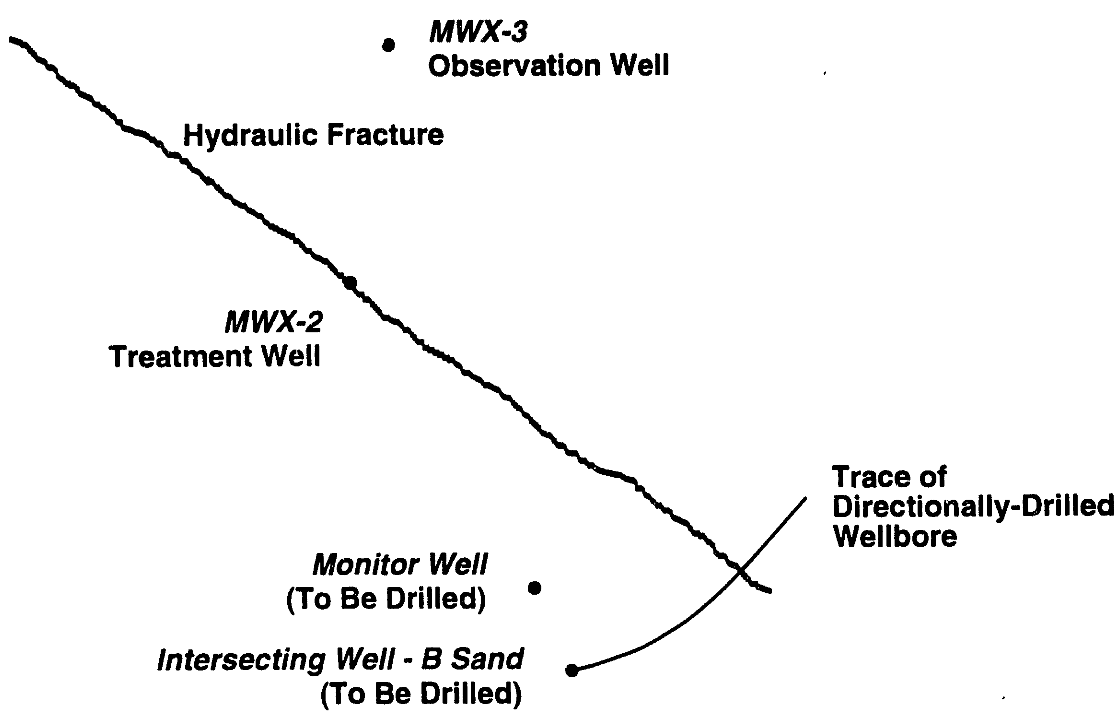


Figure 7. Conceptual Diagram of the B Sand Intersection Well 1

- propped fracture width;
- permeability of the proppant pack;
- proppant convection or settling;
- proppant crushing and/or embedment; and
- pressure drop down the fracture.

In addition, with the propped fracture in place, seismic experiments will be performed to determine the propped dimensions of the hydraulic fracture.

Intersecting Well 2 - C Sand Experiments

A second horizontal wellbore is proposed to be kicked off from the existing vertical pilot hole after fracture conductivity and seismic testing is completed in the B Sand. This borehole, however, would cut across the C Sand and would be in place *prior* to initiation of hydraulic fracture treatments in the C Sand. This borehole would also be left open hole to facilitate subsequent fracture pressure measurements. A conceptual diagram of Intersecting Well 2 resiaing in the path of the propagating hydraulic fracture in the C Sand is shown in Figure 8. Intersecting Well 2 will be cored through the zone which will subsequently include the hydraulic fracture. In addition, a conventional suite of resistivity and porosity log data would be acquired to verify to the lateral variability of the unit.

An experiment will be designed, with the borehole in place in the C Sand, such that the hydraulic fracture will propagate towards and transect the Intersecting Well 2. The intent of this experiment would be to 1) measure the hydraulic pressure at the leading edge of the fracture; 2) provide a direct indication of the horizontal growth rate of the fracture wing and, thus, provide comparisons of fracture length determined from seismic and net pressure calculations; and 3) provide estimates of fracture width. Each of these data sets would assist in the verification of the calculations made in 3D hydraulic fracture models. After this initial experiment has been completed, then various other pressure monitoring and seismic experiments would be conducted using fluids injected at different rates down the treatment well, through the hydraulic fracture and recovered at the intersection well. Through execution of these fluid-only experiments, data would be gathered to evaluate:

- rheology of fracturing fluids which have been subjected to actual subsurface temperature and pressure conditions;
- estimates of the hydraulic width of the fracture;
- additional comparisons of fracture length from seismic and net pressure calculation methods; and
- pressure drop in the fracture due to varying viscosities.

The last injection pumped in the C Sand would include proppant. The following data could be gathered during this treatment:

- propped frac width estimates;
- proppant concentration and rheology of the slurry at the fracture tip; and
- pressure drop in the fracture due to sand-laden slurry (i.e., proppant drag).

DATA ACQUISITION SYSTEMS

The experiments conducted during M-Site investigations will require comprehensive electronic equipment for detecting and storing data. These systems are subdivided into conventional-speed data acquisition systems, high-speed data acquisition systems and a Local Area Netv.ork (LAN) or client server.

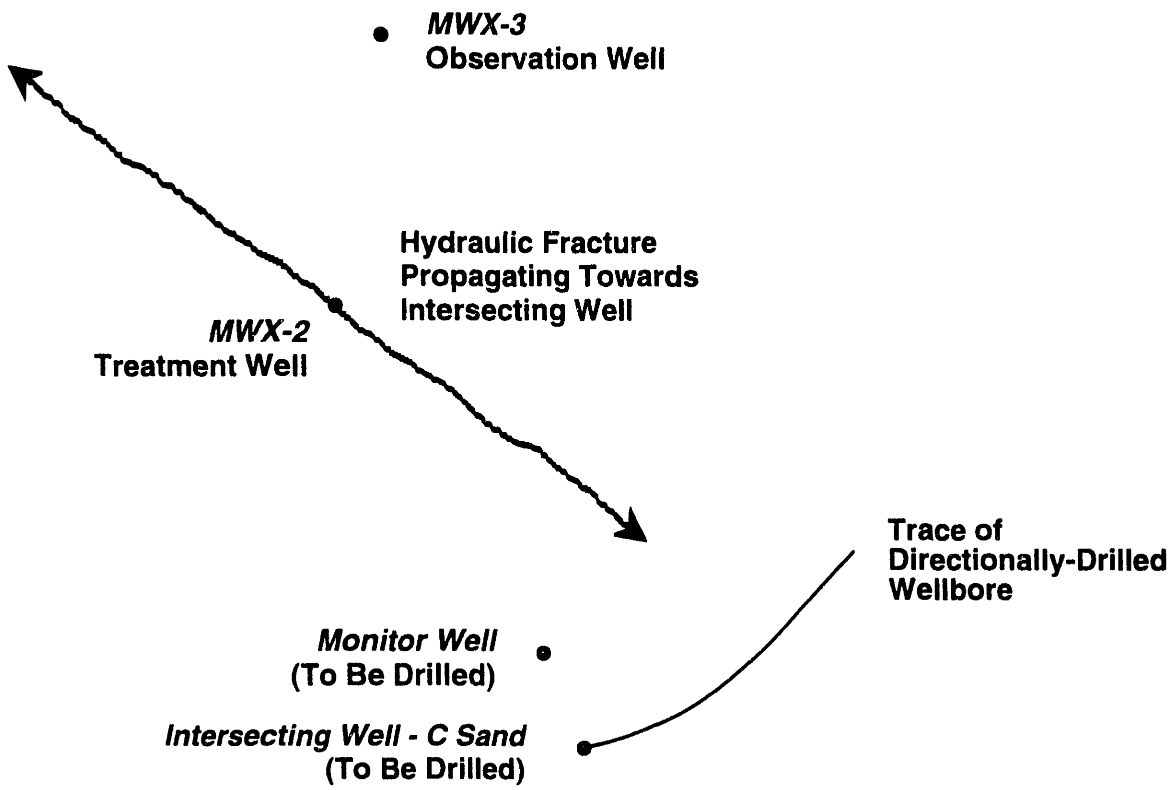


Figure 8. Conceptual Diagram of C Sand Experiments with Intersection Well 2

Conventional-Speed Data Acquisition Systems (DAS)

The primary objective of this segment of the M-Site project is to provide project field experimenters with easy assess to existing, on-site, low- to moderate-speed DASs and assure the acquisition of high-quality data. Three data acquisition systems are currently planned and designed 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 satellites and the central client server.

Data gathered at these satellite systems will automatically transfer pertinent information back to the central client/server in a specific format for systematic review, analysis and archiving. Figure 9 illustrates the conventional DAS system and other related components. These computer systems will be located in the Central Computer Trailer as was shown in Figure 5.

Each of the DASs will be configured to accommodate the currently-planned experimental data that includes the following:

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

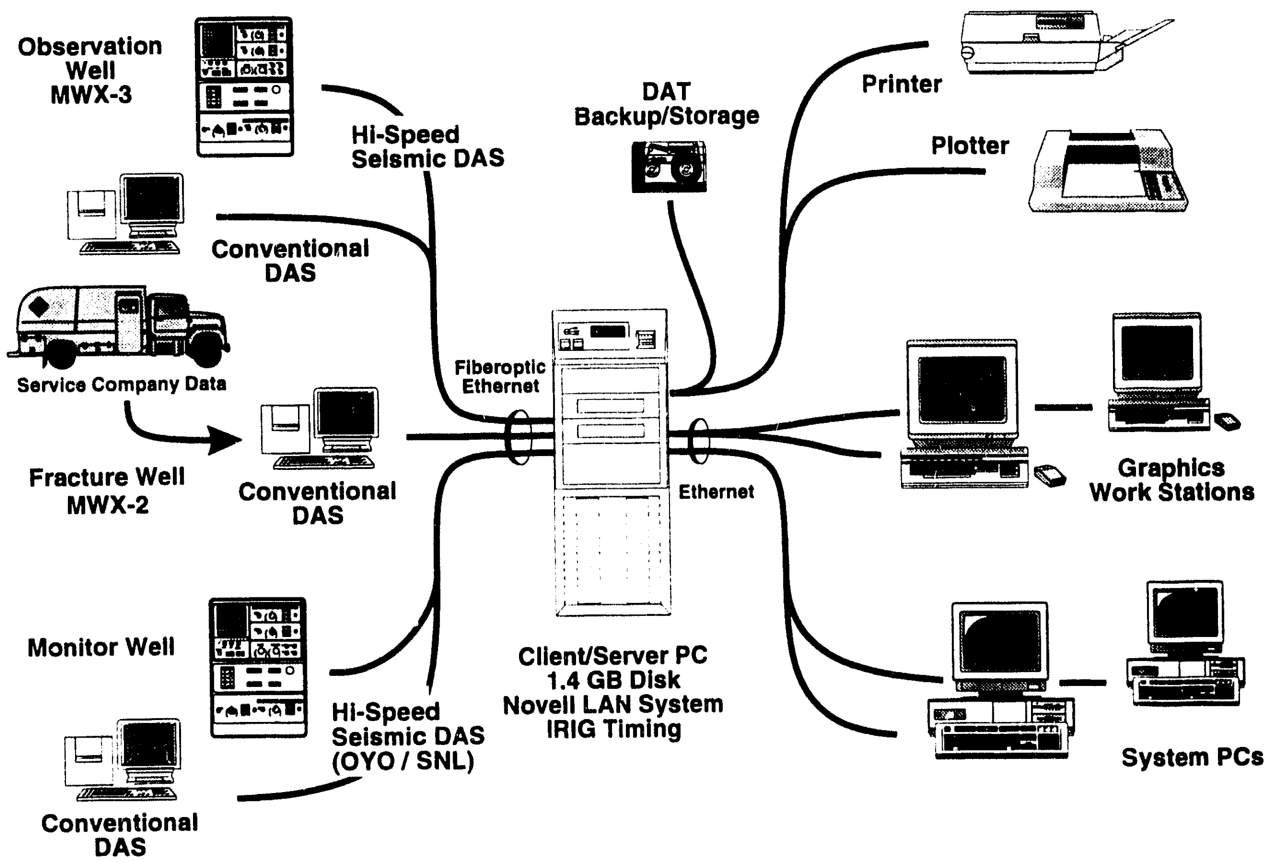


Figure 9. Data Acquisition Systems for Fracture Diagnostics Experiments

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

High-Speed Data Acquisition Systems (Hi-DAS)

The primary objective of this segment of the M-Site project is to provide project seismic and other field experimenters with a data acquisition system that combines high speed with efficienc and cost effectiveness. Sandia National Laboratories will take primary responsibility for the design and fabrication of two data acquisition systems that will serve the microseismic receiver arrays in the two project monitor wells. These two Hi-DAS systems, which are modified versions of an existing SNL/OYO field system, will provide the following basic functions:

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

A Hi-DAS for the seismic array receivers in the existing MWX-3 monitor well will be situated in the DOE data acquisition/wireline trailer. This system will accommodate the expected wireline-run array of 15 seismic channels. Sufficient power, equipment racks and environmental infrastructure presently exist within this facility to accept the proposed Hi-DAS.

An existing instrument trailer is slated to be retrofitted to house the second M-Site Hi-DAS. This system will serve as the focal point for the large array of seismic receivers, up to 96, that will be grouted in place at the bottom of the Monitor Well to be drilled in 1994.

The Hi-DASs will be designed with sufficient hardware and software flexibility and expandability to accommodate moderate alterations that may arise during the course of the project. Local display software will be available such that the experimenters will be able to monitor the progress of their instruments and the acquired engineering data through a series of graphic and tabular screen displays and a variety of print media.

Central Computer/Client Server/Local Area Network Hub

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

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

Data from the large microseismic detector arrays will be scanned and evaluated in the satellite Hi-DAS. If an event is considered significant, it will be transported across the fiber optic Ethernet link to the LAN client server where it will be available for further real-time analysis by the experimenters using either a work station or other project-provided PC systems. All the LAN client server data will be permanently stored on a hard drive and backed up after each experiment on DAT.

IRIG timing will be provided across links from the LAN client server to each of the DAS systems. This link will provide the required data timing identification stamp to precisely time-tie related events from any microseismic detector at any location. Precise timing between systems is critical to accurately define the location of microseismic events using travel-time triangulation.

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

REFERENCES

CER Corporation, Sandia National Laboratories and Resources Engineering Systems, 1993: "Multi-Site Project Seismic Verification Experiment and Assessment of Site Suitability," GRI Topical Report No. GRI-93/0050 prepared under Contract No. 5091-221-2130, February.

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