GRI/DOE MULTI-SITE NO. 1
1993 TO 1995
PROJECT R&D PLAN

Prepared by

CER CORPORATION

BRANAGAN & ASSOCIATES

SANDIA NATIONAL LABORATORIES

RESOURCES ENGINEERING SYSTEMS

JULY 29, 1993

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1.0 Project Concept and Organization

1.1 OVERALL OBJECTIVE OF THE MULTI-SITE NO. 1 PROJECT

The objective of the Multi-Site No. 1 Project is to conduct experiments to definitively determine hydraulic fracture dimensions using remote well and treatment well diagnostic techniques. In addition, experiments will be conducted to provide data 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.

1.2 CONCEPT OF A HYDRAULIC FRACTURE TEST SITE

1.2.1 Concept Justification

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

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

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

1.2.2 Characteristics of the Multi-Site No. 1 Project

GRI and DOE determined that a joint effort was necessary to resolve the significant unknowns associated with measuring and modeling the dimensions of hydraulic fractures. The first site proposed for the hydraulic fracture experimentation is the former DOE Multiwell Experiment (MWX) site located near Rifle, Colorado, as shown in Figure 1. This site, termed the Multi-Site (M-Site) No. 1, includes three closely-spaced wells (MWX-1, MWX-2 and MWX-3), as shown in Figure 2. The need for and location of future sites for the Multi-Site Project will be determined after an assessment of the results from this first site.

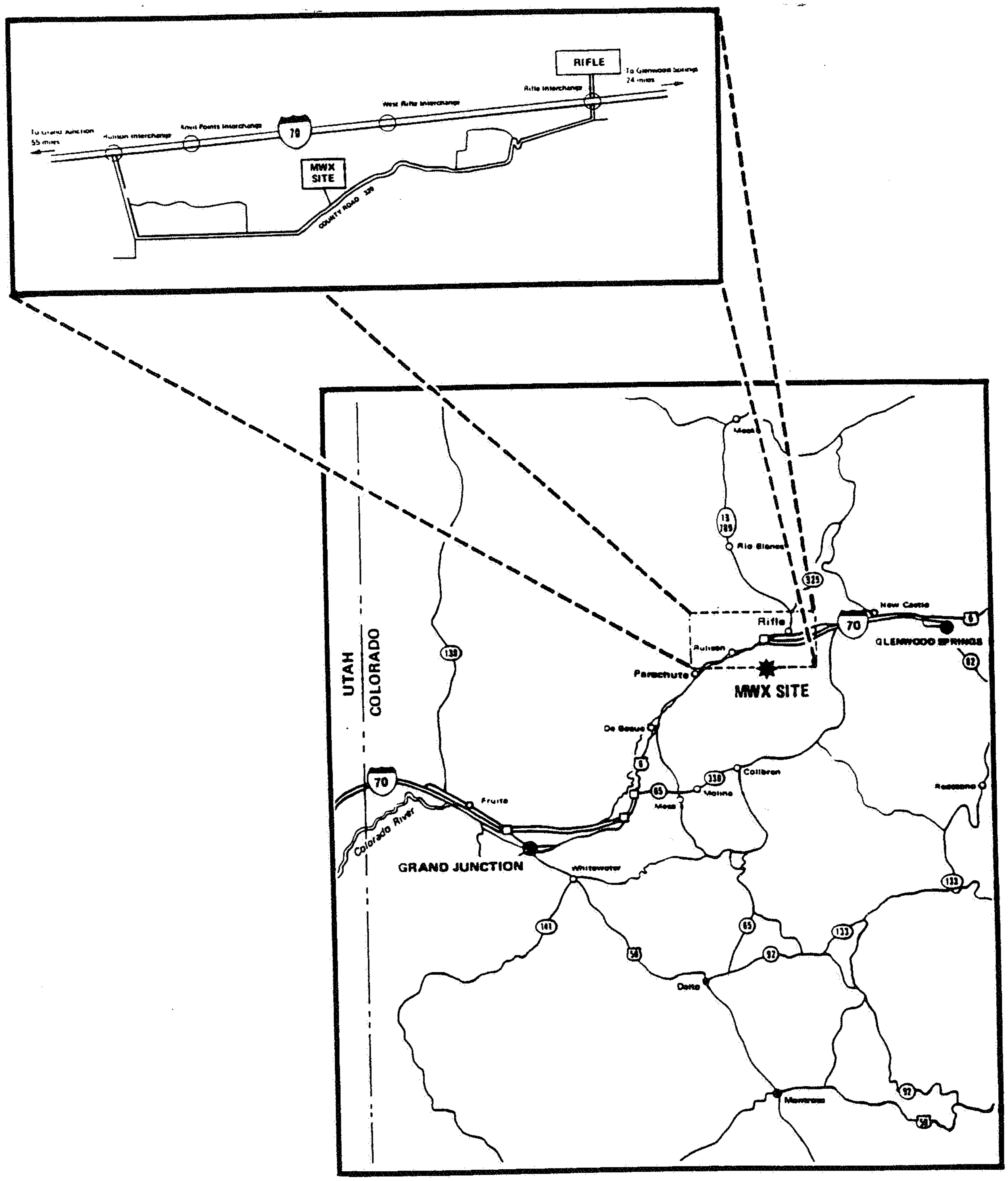

Figure 1 Geographic Location of the Multiwell Experiment Site

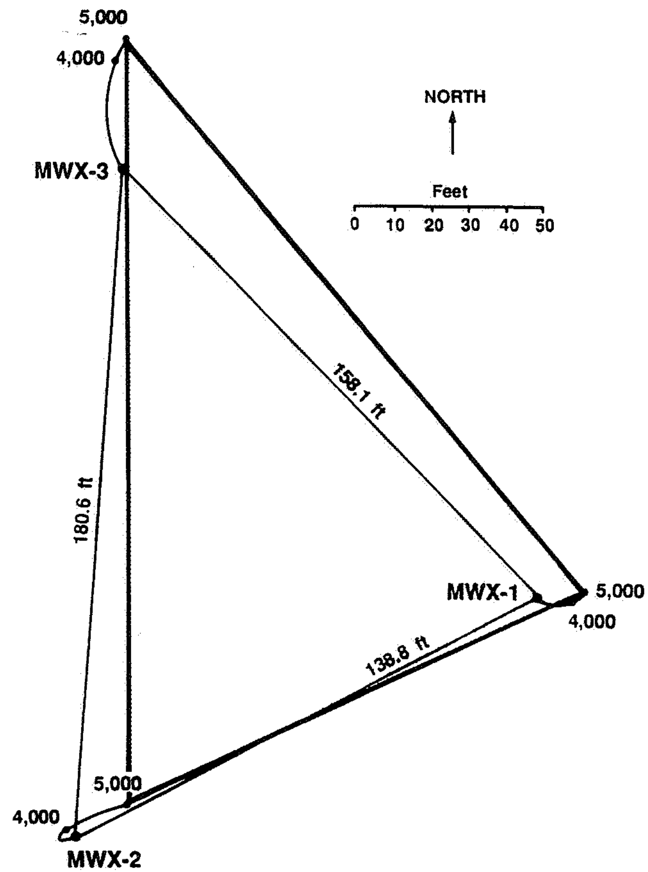

Figure 2 Relative Positions of the MWX Closely-Spaced Wells

All of the proposed M-Site No. 1 experimentation will occur in several sandstone units present in the upper Mesaverde Group between 4,130 and 5,500 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;

3) few (if any) wellbore obstructions (e.g., bridgeplugs) exist above 5,500 ft;

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

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

Within the gross interval from 4,130 to 5,500 ft, there are three sandstone units which are proposed for diagnostic and modeling experimentation. These units are shown in Figure 3 and are referred to in this report as the A, B and C Sands.

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

Within the proposed test interval, there are abundant data which currently exist as a result of MWX research:

- 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 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. The MWX-2 well was also cored in select intervals of the upper Mesaverde.

- 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 also maintained at CER.

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

Below the proposed test interval, there are additional data and information which will be useful to M-Site No. 1 research. These data and information include the following:

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

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

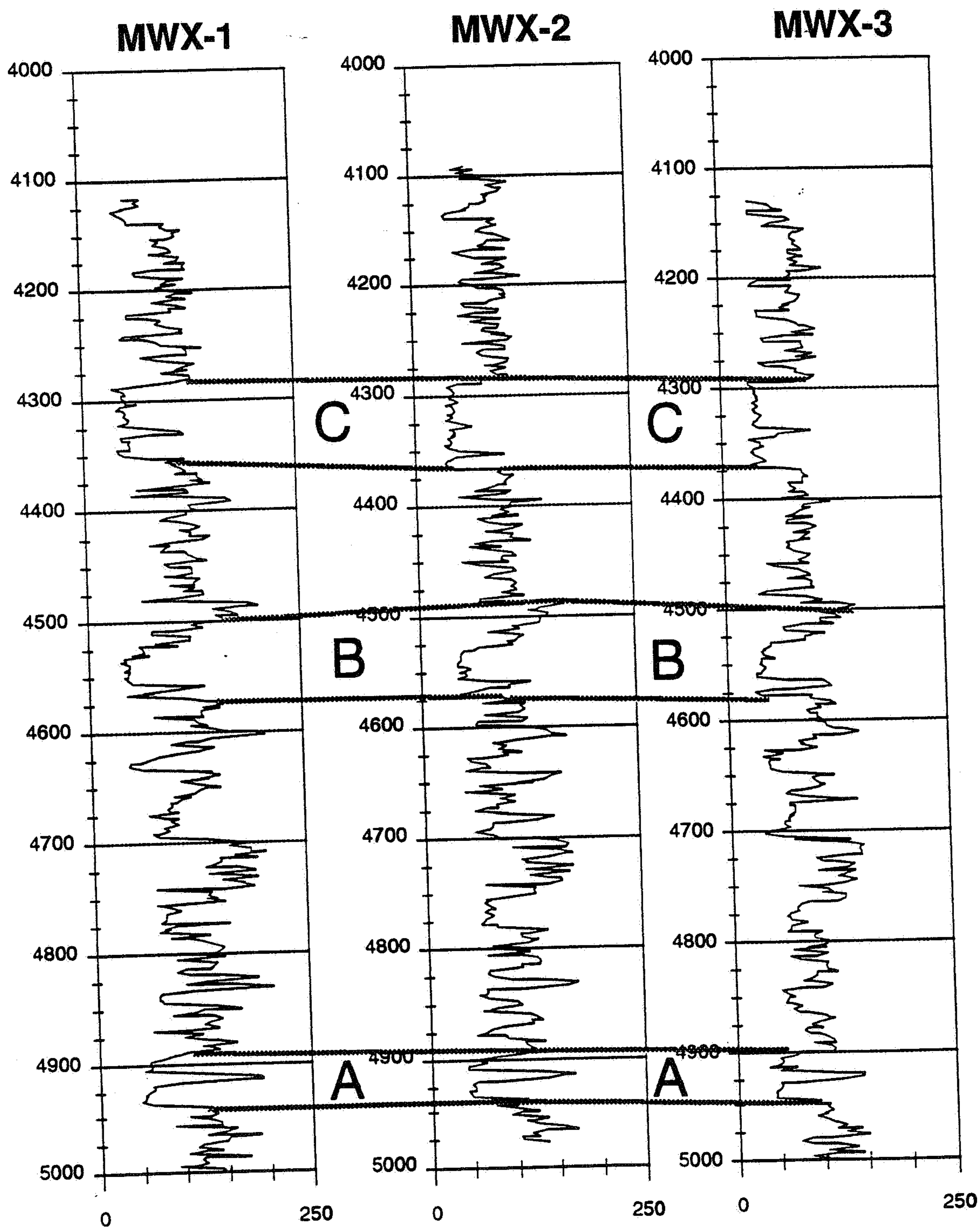

Figure 3 Upper Mesaverde Stratigraphic Section Illustrating the A, B and C Sand Units

- Natural fractures and the associated onset of over-pressuring are known to occur primarily below 5,500 ft (below the proposed interval).

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

The Multi-Site No. 1 site is suitable with regard to proximity to oil field services and airports. The proposed M-Site No. 1 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 paved road maintained by Garfield County.

1.3 VERIFICATION OF M-SITE SUITABILITY

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

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

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

- 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 modeling of the mini-frac treatment.

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

Based on these positive assessments, it was concluded that the MWX site is suitable for conducting additional comprehensive M-Site No. 1 fracture diagnostics and fracture model verification experiments. Complete documentation of the field operations and results is found in GRI Topical Report No. GRI-93/0050 titled "Multi-Site Project Seismic Verification Experiment and Assessment of Site Suitability."

1.4 CONTRACTOR TEAM AND RESPONSIBILITIES

GRI and the U.S. Department of Energy are jointly sponsoring the research conducted in the M-Site No. 1 Project. The contractor team which has been organized to execute the research project includes CER, Sandia National Laboratories and Resources Engineering Systems. The responsibilities of each of these organizations is as follows:

CER Corporation

CER, under contract to both GRI and DOE, will have multiple functions in the M-Site No. 1 Project. These responsibilities are described as follows:

Site Operator - CER will have the primary responsibility for the supervision and coordination of field operations and experiments conducted in the Project to assure that they are performed in a safe and efficient manner.

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

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

Cost Administration - CER will be responsible for field and office administration of the costs of equipment, materials and services required to implement experiments at the M-Site No. 1.

Sandia National Laboratories

Sandia, under contract to GRI, will have multiple responsibilities associated with the M-Site No. 1 Project:

Fracture Diagnostics and Treatment Design/Supervision - Sandia will have primary responsibility for design, technical supervision and interpretation of fracture diagnostics experiments. In addition, Sandia will share 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 will be responsible for developing, installing, field checking and routine operations/maintenance of the downhole seismic arrays and high-speed data systems used for fracture diagnostics experiments.

Resources Engineering Systems

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

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

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

Subcontractors

The technical services of various subcontractors will be used to assist in performing experimentation at M-Site No. 1. The subcontractors to be included in the project team are Branagan & Associates and James Fix & Associates, Inc. As the need arises, the technical services of other organizations may also be subcontracted.

2.0 Multi-Site No. 1 Research Experiments

Experiments are planned to occur over the 3-year project period from 1993 to 1995 as shown in Figure 4. These experiments will be conducted using combinations of the existing wells and wells which are to be drilled. An overview of the experiments to be conducted using the existing and new wellbores is subdivided as follows:

2.1 MWX Wellbores - C Sand Experiments and Section Characterization

2.2 Monitor Well Instrumentation Arrays

2.3 Monitor/MWX Wells - B Sand Experiments

2.4 Intersecting Well 1 - B Sand Experiments

2.5 Intersecting Well 2 - A Sand Experiments

2.1 MWX WELLBORES - C SAND EXPERIMENTS AND SECTION CHARACTERIZATION

The initial research experiments to be conducted at the M-Site No. 1 involve the use of only the MWX-2 and MWX-3 wellbores. All of the experimentation and data acquisition for this phase are anticipated to occur during the fourth quarter of 1993 as shown in Figure 4. The following sections provide detailed descriptions of the planned MWX experiments.

2.1.1 Stress Tests and Stress Profiling

Research Objective

The research objectives of the cased-hole stress testing program are as follows:

a) develop a refined vertical stress profile in and around the A, B and C sands;

b) improve interpretation of fracture closure pressure from CHST data; and

c) provide further field testing of the M-Site No. 1 data acquisition systems.

The justification for this testing is as follows:

a) Stress data from the upper Mesaverde exists from the previous MWX experiments but generally not in or adjacent to the sand intervals of interest. Development of an accurate vertical stress profile will provide a constrained data set for input into the 3D fracture models.

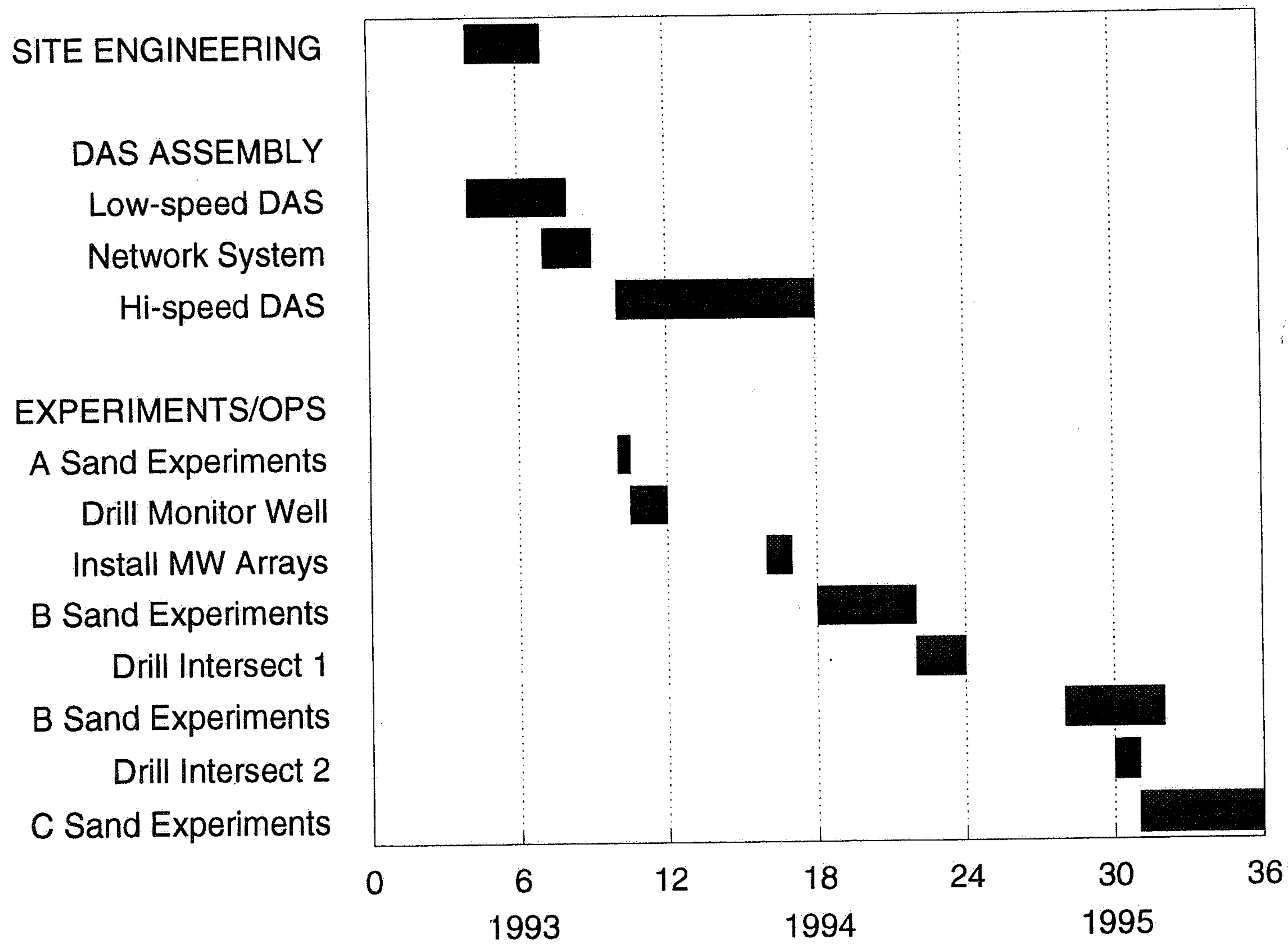

Figure 4 Projected M-Site No. 1 Project Schedule

b) Accurate data will be collected using bottomhole shut-in tools, the surface data acquisition system and state-of-the-art interpretation techniques which are employed to determine the minimum in-situ stress.

c) Data acquisition infrastructure will be constructed during the several months immediately preceding the planned stress testing field operation. The stress tests will provide a relatively simple verification of the functionality of the system.

Experiment Description

Ten cased-hole stress tests (CHST) are planned, three in MWX-2 and seven in MWX-3. The proposed stress test intervals, which can be identified on the MWX stratigraphic section in Figure 3, are as follows:

MWX-2	MWX-3
4,542 - 4,544 ft	4,204 - 4,206 ft
4,928 - 4,930	4,260 - 4,262
4,962 - 4,964	4,432 - 4,434
	4,496 - 4,498
	4,598 - 4,600
	4,768 - 4,770
	4,864 - 4,866

The CHSTs will be performed in a manner typical of those performed in previous GRI and DOE work. Testing procedures would primarily include pump-in/falloff, re-opening and pump-in/flowback tests. If available, other testing techniques such as hydraulic impedance and surge tests would be conducted and compared to the standard testing technique. CER's flowback manifold will be available to precisely measure rates into and out of the well. All of the CHSTs will be performed following the fracturing experiments (see Section 2.1.2) to avoid costly squeeze cementing operations.

An existing cast iron bridge plug will remain at 5,020 ft in MWX-2 to isolate open perforations below that depth. Cement squeezes will be performed in the existing stress test perforations in MWX-2 at 4,330-32 ft; 4,376-78 ft; 4,690-92 ft; 4,724-26 ft; 4,928-30 ft; and 4,962-64 ft in preparation for stimulation experiments to be conducted in 1994.

2.1.2 Microseismic Monitoring/Hydraulic Fracture Modeling Experiments

Research Objective

Using MWX-3 as the treatment well and the A Sand as the treatment zone, the objective of the MWX seismic experiments is to determine hydraulic fracture azimuth, height and length, as a function of various fluid viscosities and net pressure during two mini-frac injections. The primary data acquisition equipment will be multi-level, fiber optics wireline retrievable seismic instrumentation set in the MWX-2 well. Fracture pressure data will also be acquired and used to model the mini-frac treatment. The 3D model would 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 Mesaverde is required to more accurately interpret the seismic data acquired during the treatments.

The justification for the MWX-based fracturing experiments is that they represent an intermediate step preceding the more comprehensive data acquisition planned for the Monitor Well. 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 models.

4) Contribute to the finalization of the Monitor Well design with regard to the optimum spacing and total number of seismic instruments to be cemented in place.

Experiment Description

The seismic experimentation will begin with a crosswell seismic survey performed in the A Sand between MWX-2 (source well) and MWX-3 (receiver well). The velocity structure of the Mesaverde will be determined in this interval by setting the 5-level receivers and an appropriate source at various depths over the 4,800 to 5,000 ft interval. Following implementation of the crosswell survey, the seismic experiment will consist of two mini-frac injections and several injections to reinflate the fracture. These injections are described as follows:

- The fluid-only 500 barrel mini-frac treatment will be pumped in the MWX-3 well with the 5-level seismic receivers in the offset MWX-2 well and a single seismic receiver in the MWX-3 treatment well. This configuration will allow the diagnostic results (e.g., noise polarization, h/z noise logging) from each of these seismic arrays to be compared and a determination made of the advantages of a multi-level tool over a single-station receiver. These results will help define the type of receiver system needed to optimize diagnostic capabilities. The focus of this test, however, will be to evaluate the capability of a 5-level system to determine the size of the entire fracture.

- Several smaller injections (e.g., 200 bbl) are planned after the fluid-only mini-frac to re-inflate the hydraulic fracture. During these treatments, the single seismic receiver will be positioned to collect data below, within and above the perforated zone.

- The final mini-frac treatment will include sand. Microseismic data will be collected only from the offset well 5-level array and will be used as a comparison to the microseisms generated during the fluid-only treatment. The last stage of the sand treatment will be tagged to facilitate a convection experiment. In this experiment, gamma ray logging will be initiated immediately after the tagged sand is injected into the fracture. Repeat logging runs will attempt to resolve relative changes in the R/A intensity with time which can be then correlated to settling of proppant within the fracture.

A bottomhole pressure gauge will be in the treatment well whenever feasible so that data can be collected to compare fracture dimensions with the pressure response.

2.1.3 Reservoir Characterization

Research Objectives

The experimental objective of this reservoir characterization effort is to determine specific reservoir properties that significantly impact the hydraulic fracturing process. The properties that will require definition include the following:

- average reservoir production capacity (kh);
- reservoir pore pressure (p_i);
- permeability anisotropy; and
- effects of high initial water saturations on leakoff.

Justification for Data Acquisition

Each of the reservoir properties described above are requisite parameters for hydraulic fracturing models in both the design and analysis of the stimulation process. Beyond their value in properly defining model parameters, these properties have a real physical influence on the stimulation process that will ultimately determine the actual in-situ fracture geometry. It is this real fracture geometry that will be "viewed" by the fracture diagnostic arrays.

Previous tests in some of the deeper intervals of the Mesaverde indicated that fluid loss or leakoff was not entirely controlled by matrix properties alone but was significantly affected by reservoir complexities that included, natural fractures, elevated reservoir pressure and permeability anisotropy. In the proposed test reservoirs (A, B and C Sands), the added effect of elevated matrix water saturations will undoubtedly influence leakoff phenomenology. Encountering either extensive natural fractures or elevated reservoir pressures in these reservoirs is not anticipated; however, these properties must be accurately defined to assess their impact on the hydraulic fracturing process.

The methodology proposed involves measuring reservoir pressure behavior during a series of transient well tests and then comparing and correlating the resulting reservoir properties with log- and core-derived values.

Data Acquisition Description

A series of pressure transient tests is slated to be conducted in each of the three proposed sandstone units (A, B and C) to measure the specific properties of each reservoir. A series of injection and buildup tests using one of the existing MWX wells will be supplemented by simultaneous interference pressure measurements acquired from the other MWX well.

Test procedures will be similar to those previously performed at this site in the deeper Mesaverde intervals. Those tests provided surprising information concerning the unanticipated effects of reservoir heterogeneities, particularly permeability anisotropy.

In these highly water-saturated reservoirs, water will be injected at pressures well below fracture opening pressure to create a controlled pressure disturbance around the injection wellbore. Pulses and rate variations followed by a buildup will provide values for p_i and average reservoir flow capacity, kh. When available, interference pressure data will be correlated with the injection well data and provide an accurate measure of reservoir permeability anisotropy.

These pulsed injection and buildup tests should be performed prior to any large-scale fracturing experiments to assure a controlled near-wellbore injection profile that will not be affected by the extended length of any previously induced fractures.

In addition, newly-acquired core from the B and C Sands in the Monitor Well (60 ft from each zone is planned) to measure matrix properties (stressed porosity and permeability). These data will be combined with the existing limited set of core data from the MWX project. A combination of well test data and core data should provide insight into the matrix and fracture character of the A, B and C Sand units.

2.2 MONITOR WELL INSTRUMENTATION ARRAYS

Research/Operation Objective

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 a set of seismic and earth tilt instrumentation. Comprehensive fracture diagnostics experiments can then be performed using a combination of the Monitor Well, MWX-2 and MWX-3. This well is necessary because the comprehensive seismic experimentation which has the potential for clearly defining the dimensions of a hydraulic fracture requires an instrumentation array beyond that which can be fielded on a wireline retrievable system. 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. Additional details on the operations of drilling the Monitor Well and the data acquisition programs planned for the well are included in Section 3.3.

Figure 5 diagrammatically illustrates instrumentation and diagnostics arrays to be initially deployed at M-Site No. 1. The Monitor Well instrumentation arrays shown in the figure are to be cemented in place in the annular space between the 5-in. and 10-3/4-in. casing 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 accelerometers 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.

2.3 MONITOR/MWX WELLS - B SAND SEISMIC EXPERIMENTS

In this phase of the project, to be performed in mid 1994, fracture diagnostics will be the primary focus. Using MWX-2 as the treatment well, several mini-frac injections will be designed to achieve increasing hydraulic fracture length and height. 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 (triaxial accelerometers) secured to the outside of the casing cemented in the Monitor Well will be recorded during each treatment by the high-speed data acquisition system described in Section 3.2.2. 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 models. The accelerometer instrumentation in the Monitor Well will have continued use throughout the remaining phases of the M-Site No. 1 project. In addition, the casing diameter of the Monitor Well is such that it allows the flexibility to run wireline accelerometer instrumentation to augment the grouted-in accelerometers.

One of the potential seismic experiments to be conducted in the B Sand is 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 that is described in the next section.

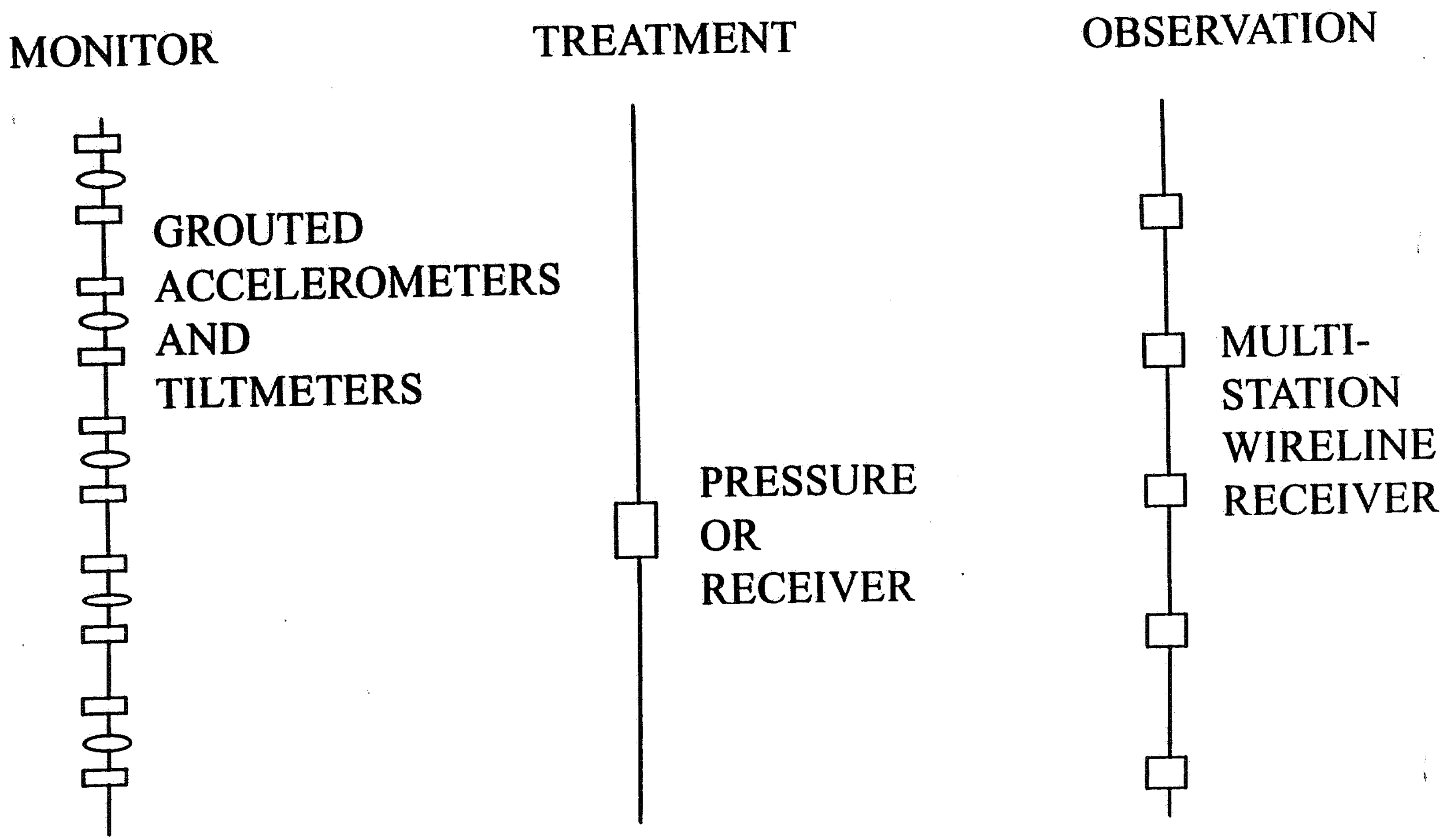

Figure 5 Diagrammatic illustration of M-Site Instrumentation and Diagnostics

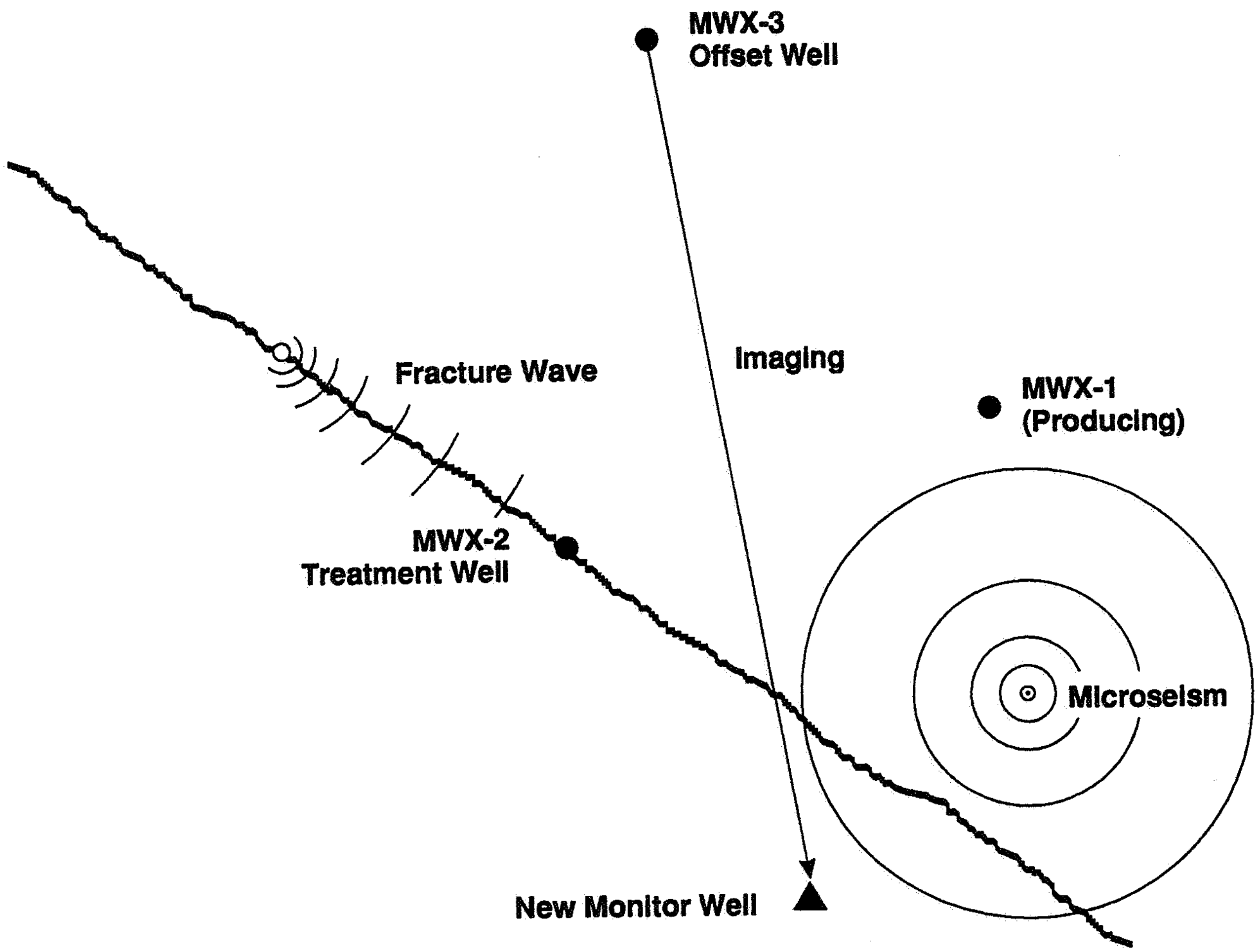

Figure 6 Conceptual Diagram of Fracture Diagnostics Using the Combination of the Monitor Well, MWX-2 Treatment Well and the MWX-3 Observation Well

2.4 INTERSECTING WELL 1 - B SAND EXPERIMENTS

In this phase of the project, the goal is to intersect the propped hydraulic fracture created in the last B-Sand injection described in Section 2.3 and subsequently 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 the pilot hole and Intersecting Well 1 would occur late in 1994 as described in Section 2.3. The experiments to be conducted are described in Section 2.4.2.

2.4.1 Drill Pilot Hole and Intersecting Well 1

The Intersecting Well 1 will be drilled on the same drilling pad that the Monitor Well is located. This surface location of this well was shown in Figure 7. 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 to be conducted.

2.4.2 Conduct B Sand Fracture Conductivity and Seismic Experiments

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 fracture modeling unknowns:

- 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.

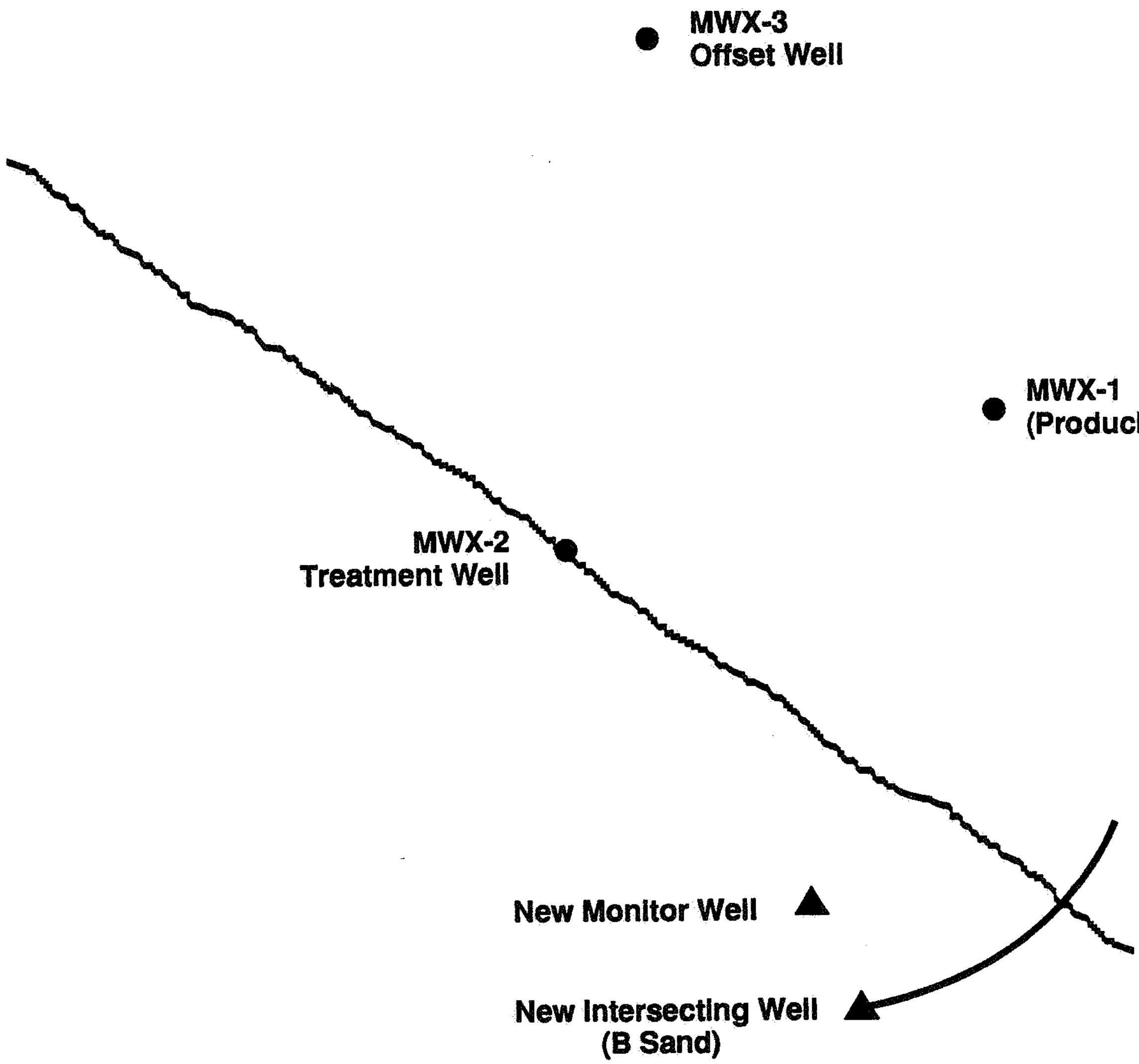

Figure 7 Conceptual Diagram of Intersecting Well 1 Cutting Across the B Sand Hydraulic Fracture

2.5 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 residing 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).

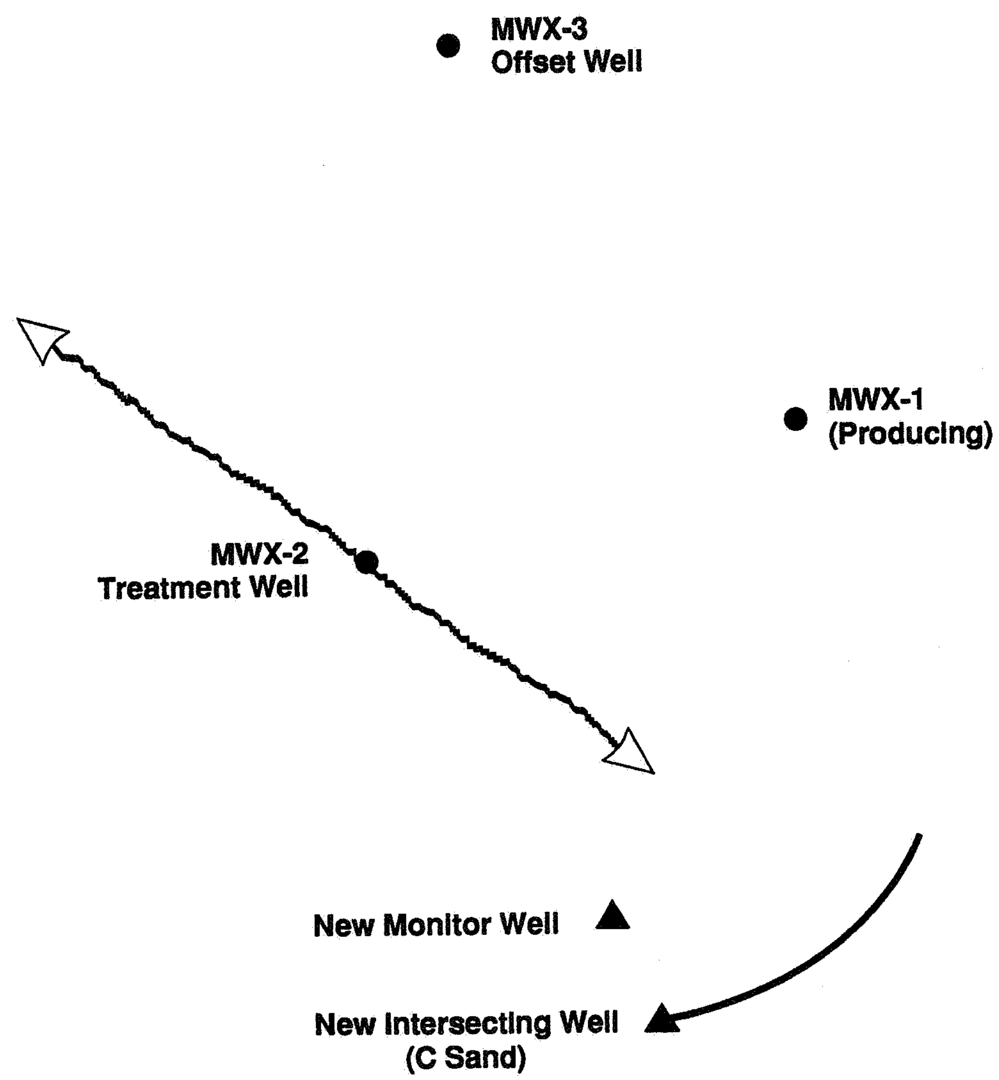

Figure 8 Conceptual Diagram of Intersecting Well 2 Residing In the Path of the Propagating Hydraulic Fracture in the C Sand

3.0 Multi-Site No. 1 Project Infrastructure and Data Acquisition Systems

3.1 SITE ENGINEERING

The site will require incremental improvements in electric power supply, water supply, sanitation and road access to be functional for M-Site No. 1 operations. These improvements are described as follows:

Electric Power Supply

Three-phase commercial power will be extended from the existing lines at the SHCT No. 1 well location to the MWX pad area via aboveground lines. Transformers will be set on the MWX pad and the power distributed around the MWX location via underground cabling. The 3-phase system will be required to power the 7-conductor winch/wireline unit. Single-phase power will be run to all of the other trailer facilities on the MWX pad. Temporary power distribution lines will also be occasionally installed as needed on the site.

Water Supply and Sanitation

Underground water supply lines will be laid to the office trailer located on the MWX pad. The office trailer pad will also have restroom facilities.

Road Access

Road access to the MWX pad will be improved by blading a road along the west fence line from the SHCT pad to the MWX pad. This improvement, when combined with the existing road access, will create a "loop driveway" and facilitate the ingress and egress of frac trucks and the placement of other equipment (trailers, frac tanks) associated with the project.

Communications

The existing digital-switching telephone system present on the site will be extended to the MWX pad area. Three separate outside lines will be available for use during the project. One of these lines will be dedicated to the telecopier. The remaining two lines will be available for voice communication or data transmission.

In addition to these improvements, surface facilities and equipment will be acquired and positioned as shown in Figure 9. These facilities and equipment included the following:

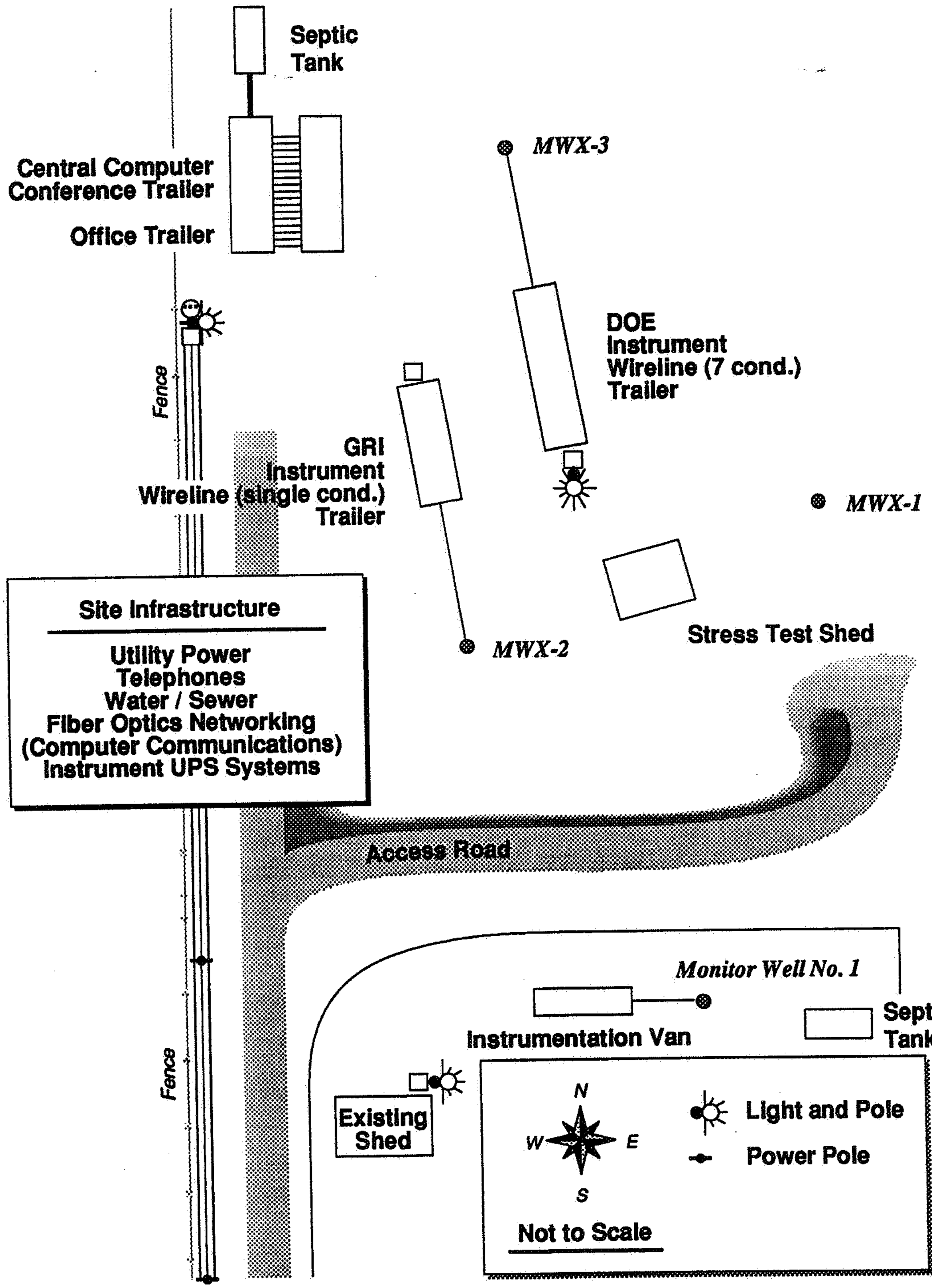

Figure 9 Planned Layout of the M-Site No. 1 Trailer Facilities with Respect to the MWX Wells and Future Monitor Well

Office Trailer

An office trailer facility will be positioned on the MWX pad. This facility will be the central point for administering site activities. The trailer will include phone, fax, basic office equipment, restroom and kitchen facilities.

Single-Conductor Wireline/Data Acquisition Trailer

The GRI-owned trailer which includes 25,000 ft of single-conductor electric line and interior working space will be positioned on the MWX pad and used for data acquisition (e.g., surface readout bottomhole pressure) during various experiments.

7-Conductor Wireline/Workbench Trailer

The DOE-owned trailer which includes the 7-conductor wireline and tool workbench space, will be re-positioned from the SHCT pad to the MWX pad and used for data acquisition in various experiments.

Conference/Control Trailer

A trailer facility will be acquired and located on the MWX pad. This leased unit will be retro-fitted and used as the command/control facility for the computer data acquisition systems.

Skid-Mounted Trailer

A skid-mounted trailer facility will be acquired and located on the Monitor Well pad for Sandia data acquisition equipment.

Each of these trailer facilities will be climate controlled, especially in facilities used to house the computer equipment.

Several miscellaneous equipment items will be available to the M-Site No. 1 Project through the GRI and DOE contracts. This equipment includes the following:

- one 4-wheel drive pickup truck;
- crane truck for hoisting heavy loads and supporting wireline sheaves;
- mast truck for supporting wireline sheaves;
- grease injection system for maintaining wellbore pressure with a wireline in the hole;
- three HP quartz crystal bottomhole pressure gauges;

- three 30 kw and a 90 kw electric power generators to provide auxiliary power as backup to the commercial power service;

- wireline blowout preventors; and

- communications equipment including six two-way radios tuned to a single frequency and two mobile phones.

3.2 DATA ACQUISITION SYSTEMS

3.2.1 Conventional-Speed Data Acquisition System

Research Objectives

The primary objective of this segment of the M-Site No. 1 project is to provide project field experimenters with easy access to existing, on-site low- to moderate-speed data acquisition systems (DAS) and assure the acquisition of high quality data. Three data acquisition systems 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 satellite locations 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 10 illustrates the conventional speed data acquisition system and the other related components.

System Justification

Large volumes of fracture diagnostic data are expected to be acquired during each of the planned fracturing experiments at the M-Site No. 1. The conventional-speed system will be constructed in an effort to:

- assure accurate timing links between experimental data;

- minimize electrical noise and the loss of critical data components; and

- consolidate and maintain uniformity of these various data.

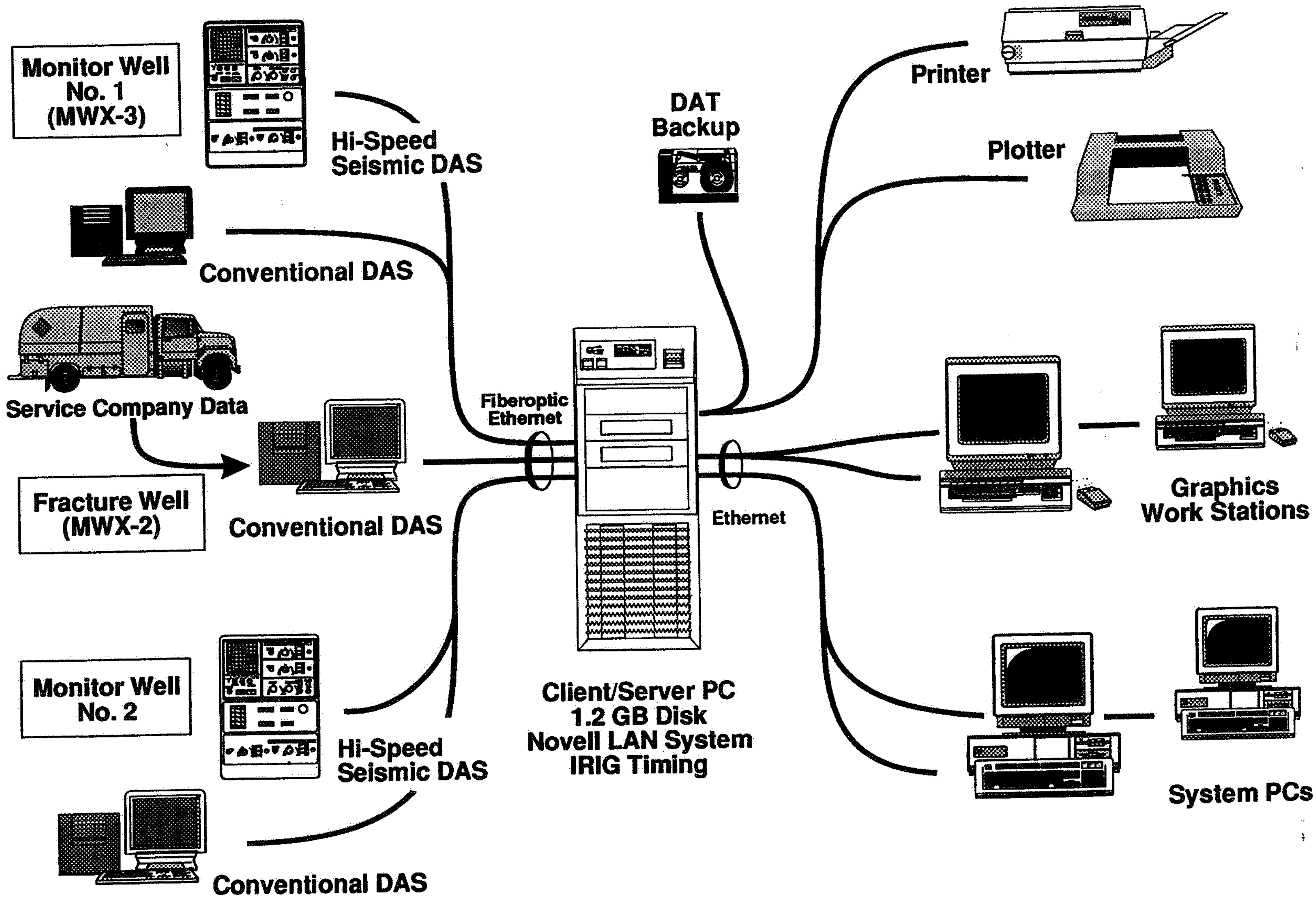

Figure 10 Diagram of the Planned M-Site No. 1 Computer Network

Project-specific DAS are considered an essential element in the M-Site No. 1 data gathering, management and information distribution process.

System Description

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; and
- bottomhole injection and reservoir monitoring pressures.

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.

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

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

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

3.2.2 High-Speed Data Acquisition System

Research Objectives

The primary objective of this segment of the M-Site No. 1 project is to provide project seismic and other field experimenters with a data acquisition system that combines high speed with efficiency and cost effectiveness. Sandia National Laboratory will take primary responsibility for the design and fabrication of two data acquisition systems that will serve the microseismic receivers arrays in the two project monitor wells. These two high-speed DAS systems will provide the following basic functions:

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

System Justification

Large volumes of relatively high bandwidth, 2 kHz, seismic data will be acquired from two proposed fracture diagnostic monitoring wells. One of these wells is presently designed to accommodate up to 96 seismic receivers while the other monitor well may contain 15 to 30 receivers. Each of these large seismic receiver arrays will transmit broad bandwidth time and amplitude data that when combined result in a large rate high-volume data stream. With average events occurring at about 1/sec during critical test periods, the high-speed DAS must be fabricated to possess the following specific capabilities:

- short processing times with rapid event detection;
- extremely accurate time ties between receivers and stations to permit accurate positional analysis for each event;
- low electronic noise and channel crosstalk; and
- high-speed digital tape storage (DAT), fast computer buses and high-speed communications systems.

Although these high-speed DAS are planned to be fabricated from existing commercially-available hardware and software, the integration, testing and interfacing of this complex system will take considerable care, effort and technical management both in the development and fielding phases. Figure 10 illustrated the high-speed data acquisition system in relation to the other data acquisition components.

System Description

Each of these two high-speed DASs will be specially configured to accommodate the data streams from the downhole seismic receiver arrays. These surface high-speed DAS will incorporate the following functions:

- proper signal and power conditioning;
- multiplexed high-speed 18-bit A/D conversion with real-time calibration;
- continuous data processing and DAT storage for each incoming data stream;
- real-time event detection; and
- transferring of event selected data along the fiber optic ethernet to the central client server.

Power UPS systems will be included in each of the high-speed DASs to offset short duration losses of local power. The high-speed DAS will be designed with sufficient hardware and software flexibility and expandability to accommodate moderate alterations that may arise during the course of the project.

The high-speed DAS for the seismic array receivers in the existing MWX-3 monitor well will be situated in the DOE data acquisition/wireline trailer. Sufficient power, equipment racks and environmental infrastructure presently exist within this facility to accept the proposed high-speed DAS.

Another data acquisition trailer located on the Monitor Well pad will house the second M-Site No. 1 high-speed 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 after it is drilled.

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

3.2.3 Central Computer/Client Server/Local Area Network Hub

Research Objectives

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

System Justification

A broad array of diagnostic and fracture-related data is expected to be created during the course of each M-Site No. 1 experiment. This data is normally acquired by various project and service related companies and then consolidated at a later time. Since there is a great deal of real-time interaction and synergism that is required during the execution and monitoring of M-Site No. 1 fracturing experiments, the logic for a central data site seems rather simple and straightforward.

The LAN client server will be located in the Conference/Control trailer that will also house workstations and PCs from which experimenters can interact with the data through the client server and with each other. Data from each of the satellite data systems will be funneled to the client server after being explicitly formatted, thereby permitting easy access to the entire data file by any or all of the experimenters. All of these data will be permanently stored on the client server hard disk for subsequent retrieval and analysis. Figure 10 illustrated the network system and the other related components of the data acquisition systems.

System Description

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

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

A large UPS system will be included in the system to offset short duration losses of local power.

Data from the large microseismic detector arrays will be scanned and evaluated in the satellite high-speed DAS. If an event is considered significant, it will be transported across the fiber optic ethernet line to the LAN client server where it will be available for further real-time analysis by the experimenters using either a workstation 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 provide across links from the LAN client server. 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 necessary to accurately define the location of microseismic events using triangulation.

Each of the three conventional speed DASs 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. There, FRACPRO or other related fracturing programs can access the data from the client server.

3.3 MONITOR WELL DRILLING AND DATA ACQUISITION

3.3.1 Operation Description

Drilling of the Monitor Well is planned for the third quarter of 1993. The well will be located south of the MWX pad where the treatment well is located. Figure 11 illustrates a 300-ft long hydraulic fracture wing originating from MWX-2. The figure also illustrates the proposed surface location for the Monitor Well which is approximately 200 to 300 ft from the fracture. Approximately seven acres of relatively level ground is available to construct the drilling pad for the Monitor Well. The Monitor Well's distance and offset position from the MWX wells (i.e., the Monitor Well does not line up with MWX-2 and MWX-3) will facilitate seismic fracture diagnostics experimentation to be conducted in 1994.

The design of the Monitor Well is driven by the need to cement instrumentation arrays in-place and to insure that the instruments are secured in an environment where they are likely to function for a long time period. Thus, the operational plan is to secure the instrumentation arrays and their associated cabling on the outside of a casing string which is subsequently cemented in place. This "carrier" string, however, will be run inside of an existing casing string, i.e., the instrumentation will be grouted in the annular space of the two casing strings. This design eliminates the risk of pressurized, saline formation waters permeating the instrumentation and reducing their functional lifetime. The dual casing string is also likely to facilitate the successful emplacement of the carrier string without damaging the instrumentation.

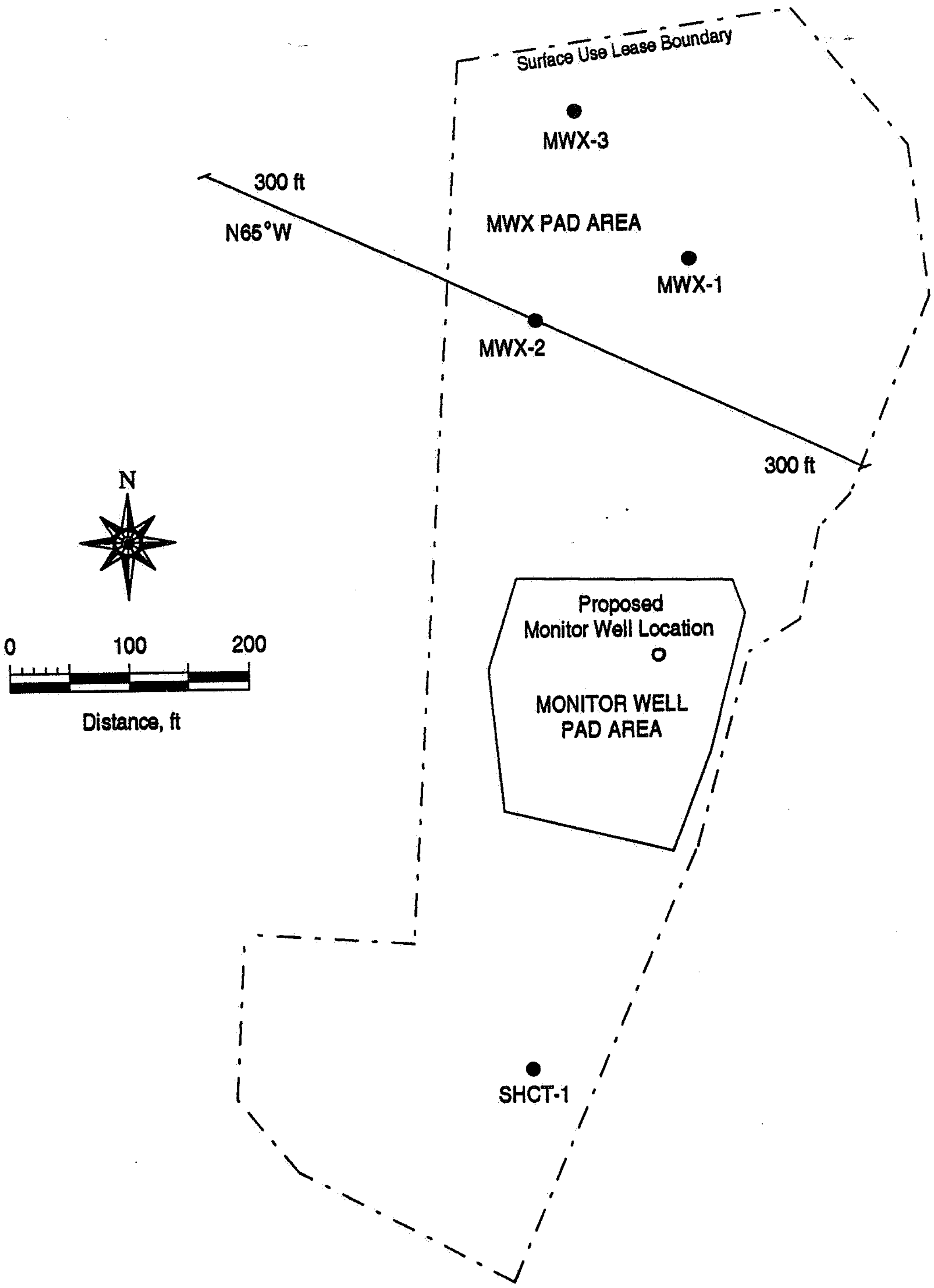

Figure 11 Approximate Location of a Hydraulic Fracture (MWX-2 Injection Well) and of the Proposed Monitor Well

The casing design and therefore the drilling program is determined by the following factors:

- It is desirable to have a minimum of 4-1/2-in. ID on the carrier string so that instrumentation (e.g., additional wireline seismic instrumentation) can be run in the hole. Thus, the minimum size of the carrier string is 5 in., 11.5 lb;

- The inclinometer instruments have a diameter of 3 in. and to have adequate clearance and good cement sheath surround them, the outer string of casing was designed to be 10-3/4 in., 51 lb. Thus, the hole size necessary to run 10-3/4-in. casing is designed to be 14-3/4 in. A wellbore drilled to 5,000 ft would intercept the A, B and C Sands.

The 1993 portion of the Monitor Well drilling would include those operations through cementing the 10-3/4-in. casing. The incremental step of running and cementing the interior casing string with the instrumentation would occur approximately in April 1994. Figure 12 illustrates a proposed wellbore sketch with dual casing strings and the instrumented interval.

The drilling of the Monitor Well will also allow the opportunity to collect core from the B and C zones and acquire additional information to verify reservoir properties and hydraulic fracture azimuth. These data acquisition efforts are described in the following sections.

3.3.2 Monitor Well Data Acquisition - Fracture Azimuth

Research Objective

The objective of this portion of the data acquisition program is to confirm hydraulic fracture azimuth in the upper Mesaverde. Hydraulic fracture azimuth is reasonably well known in the deeper sections of the Mesaverde studied in the MWX project. However, it is prudent to confirm fracture orientation in the uppermost section of the Mesaverde where the A, B and C sands will be hydraulically fractured. Accurate knowledge of hydraulic fracture azimuth will become especially important when the fracture-intersecting well is drilled. At 250 ft from the treatment well, each 1° of uncertainty in the hydraulic fracture azimuth will translate into 4.4 ft. Thus, if azimuth is known to $\pm 10^\circ$ accuracy, then the hydraulic fracture could potentially occur within an 88-ft interval.

Experiment Description

Multiple techniques to confirm hydraulic fracture azimuth are proposed to be performed prior to drilling Intersecting Well 1. These techniques are sequentially described as follow:

1) Interpret fracture azimuth from microseismic data acquired in testing planned in the MWX wells for the August - October 1993 time period

2) During the drilling phase of the Monitor Well, acquire core and borehole-based data sets supporting fracture azimuth determination:

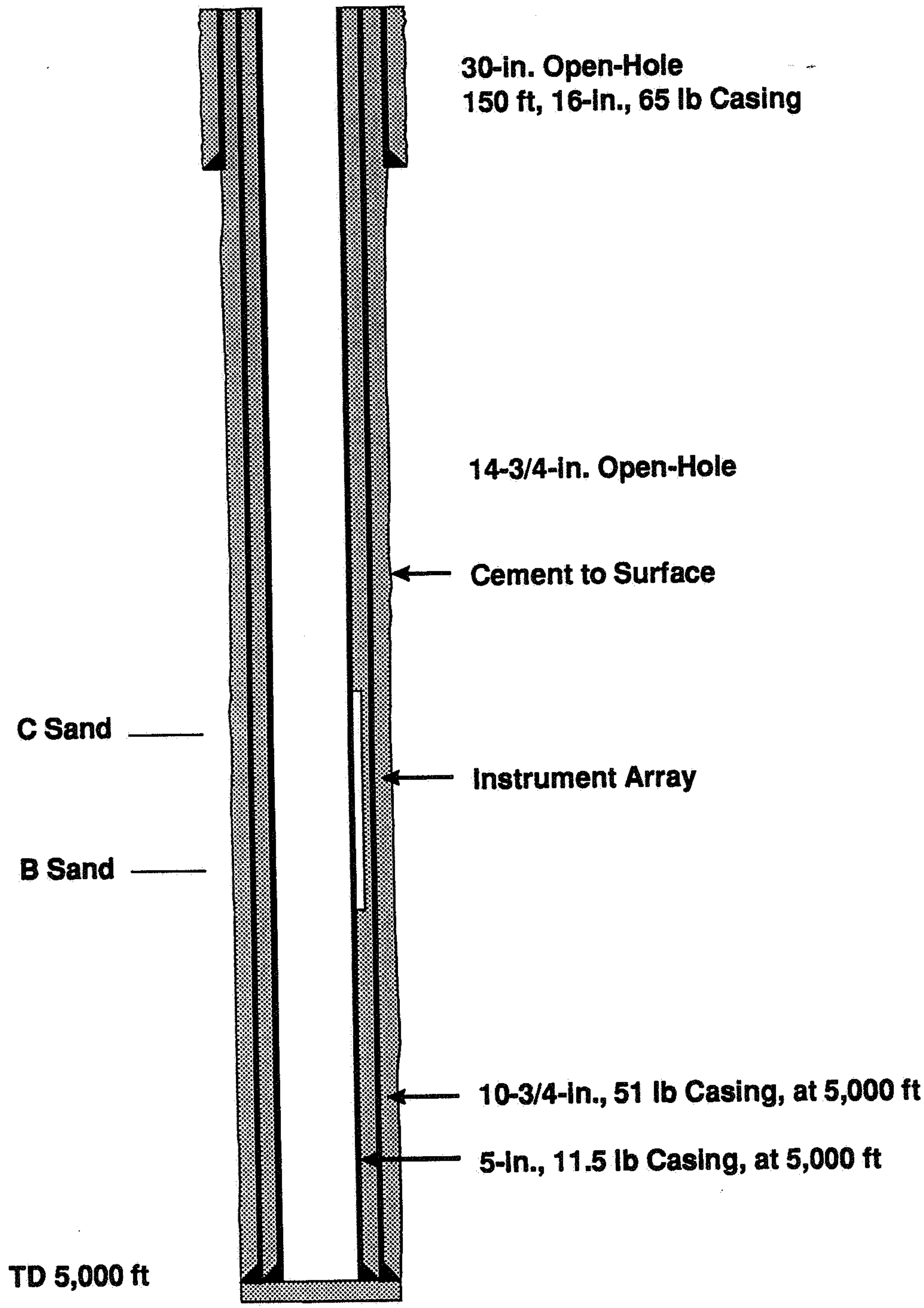

Figure 12 Wellbore Sketch of the Proposed Monitor Well

- Anelastic strain recovery
- Circumferential Velocity Anisotropy
- Drilling induced fractures in core
- Borehole image analysis of drilling induced fractures
- Open-hole formation breakdown and over-coring of the induced fracture
- Borehole image analysis of the induced fracture
- Borehole breakout analysis
- Differential Strain Curve Analysis
- Additional core-based techniques currently under development

3.3.3 Monitor Well Data Acquisition - Wireline Logging Program

Research Objective

The objective of this portion of the data acquisition program is to augment the existing MWX database and determine the petrophysical character of the B and C Sands in the Monitor Well. The drilling of the Monitor Well will present an opportunity to selectively gather data that will facilitate the fracture diagnostics and fracture modeling goals of the project.

Experiment Description

The Monitor Well logging program will provide basic data to determine specific reservoir characteristics including lithology, saturations, porosity, permeability, flushing characteristics, overburden stress, dynamic mechanical properties, vertical in-situ stress profile, induced fracture azimuth, maximum and minimum horizontal stress azimuths, and qualitative horizontal deviatoric stress contrasts. The cased-hole logging program will provide cement evaluation and depth control for cased-hole operations.

For the open-hole logging program, the following logs will be run from total depth (5,000 ft) to above the top of the Ohio Creek Formation (3,700 ft). This logged interval will include the B and C Sand intervals. The LithoDensity and caliper logs will be run back to surface casing set at approximately 150 ft. The specific logs planned for the open-hole logging program are as follows:

PHASOR INDUCTION/SFL - The DITE is required to interpret water saturation and invasion profile.

ELECTROMAGNETIC PROPAGATION LOG - The ADEPT provides dielectric data for compressional and shear wave travel time gas corrections. The corrected travel times result in improved log computations of mechanical properties and log-derived vertical stress. The ADEPT data will also be used to interpret formation water resistivity which is known to vary in the upper Mesaverde sandstones.

LITHODENSITY/CALIPER - The LDT provides information for the interpretation of lithology, porosity, permeability, flushing characteristics, mechanical properties and overburden stress. The caliper log is an integral part of the LDT service and directly measures borehole diameter.

DUAL POROSITY COMPENSATED NEUTRON - The CNT-G provides both thermal and epithermal neutron measurements. It is used to interpret lithology, porosity, permeability, flushing characteristics and the presence of boron which perturbs thermal neutron measurements. Boron is believed to be a significant component of formation water within the upper Mesaverde sandstones.

GAMMA RAY - The GR log is basic to the interpretation of clay volume and is used in the interpretation of porosity, permeability and water saturation. The gamma ray is the basic log used to depth correlate open-hole log data to cased-hole data.

DIPOLE SHEAR SONIC IMAGER LOG - The DSI provides a simultaneous full waveform recording of acoustic data. This tool multiplexes 32 receiver elements which results in the recording of eight analog waveforms that are digitized in the subsurface and processed on the surface to yield high-quality waveform data. This tool results in reliable shear wave velocity computations. This data is required to calculate mechanical properties and is used to generate a log-derived stress profile. In addition, this log may provide information concerning azimuthal variations in acoustic velocity anisotropy.

CIRCUMFERENTIAL ACOUSTIC SCANNING TOOL - The CAST is the Halliburton Logging Services trade name for what is more generically known as the borehole televiewer log. This log uses acoustic pulses from a rotating transducer to circumferentially image the borehole. The log is used primarily to characterize borehole breakouts and drilling-induced fractures. These borehole features facilitate the interpretation of the horizontal stress azimuths and provide an estimation of deviatoric stress contrasts. The log may also be used to interpret the sedimentological features of individual sandstones.

The cased-hole logging program is planned to included the following services:

CEMENT BOND LOG/GR/CCL - The CBL/VDL is used to determine the quality of the primary cement job and is used as the depth control log for cased-hole operations.

CEMENT EVALUATION LOG - The CET is used to interpret cement channeling and zone isolation for cased-hole operations. This log is complementary to CBL/VDL cement interpretation. The cement logs will be run from TD to the top of cement.

3.3.4 Monitor Well Data Acquisition - Coring and Core Orientation

Research Objective

The objective of the coring and core orientation program is to cut and recover 150 ft of rock primarily representative of the B and C Sands (see Figure 3). In addition, the rock composing the upper bounding layer of each sand unit would be acquired. The core would be acquired in the course of drilling the Monitor Well. The core acquired through this program would be directed to several key uses:

- hydraulic fracture azimuth, as described in Section 3.3.2, would be determined through several core-based techniques;
- reservoir data, in terms of porosity and permeability, would be acquired from the core and would supplement the reservoir characterization objectives described in Section 2.1.3; and
- rock mechanical properties from the upper stress boundary would be determined through laboratory tests and would support hydraulic fracture modeling goals.

Experiment Description

The following approximate intervals, depth referenced to MWX-1, would be cored in the Monitor Well:

Interval No. 1 (4,275 - 4,335 ft) representing 15 ft of siltstone/shale and 45 ft of C Sandstone

Interval No. 2 (4,495 - 4,555 ft) 30 ft of siltstone/shale and 30 ft of B Sandstone

Interval No. 3 (4,760 - 4,790 ft) 30 ft of silty sandstone

The larger diameter hole planned for the Monitor Well will result in larger coring equipment. A 12-1/4-in. core bit will be used to cut a 5-1/4-in. diameter core. Core orientation data for the benefit of various core analyses will be acquired using either paleomagnetic or downhole electronic survey instrument techniques.

4.0 Benefits of the Research

It is anticipated that the primary benefit of the experiments described in this document 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 at the M-Site No. 1 will define the correct techniques for determining fracture closure stress. The overall impact of the research will be to provide a foundation for fracture optimization based on measured fracture response and a foundation for a fracture diagnostic service industry.