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MORGANTOWN ENERGY TECHNOLOGY CENTER

TECHNOLOGY STATUS REPORT

Western Gas Sands

Unconventional Gas Projects Branch
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PREFACE

This report describes the state of the art in technology on the subject resource, a part of DOE's research program on unconventional gas recovery. It discusses the technical issues warranting investigation and focuses on current activities that are being supported by DOE. As presented, it is intended to provide an in-depth perspective of the knowledge base required to develop concepts for recovery. As new information becomes available, it will be summarized annually. This will permit timely transfer to the private sector, and then, when market conditions are more favorable, unconventional gas resources can be readily developed.

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EXECUTIVE SUMMARY

Western gas sands research is conducted by the U.S. Department of Energy's (DOE) Morgantown Energy Technology Center (METC) to encourage the development of very low permeability, lenticular gas sands in the western U.S. This research is an integral part of DOE's Unconventional Gas Recovery Program, which is a multidisciplinary effort to develop the technology for producing natural gas from resources that have been classified as unconventional because of unique geologies and production mechanisms.

The purpose of this research is to demonstrate to private industry the feasibility of economically producing natural gas from these low-permeability reservoirs. The reservoirs, which are found within a resource area that covers 311,000 square miles, contain an estimated 466 trillion cubic feet (Tcf) of gas-in-place.

Two broad research goals have been defined: (1) to reduce the uncertainty of the reservoir production potential and (2) to improve the extraction technology. These goals are being pursued by conducting research and encouraging industrial efforts to develop the necessary technology. These efforts involve the following activities:

- Conducting fundamental research into the nature of tight lenticular gas sands and the technologies for diagnosing and producing them.
- Developing and verifying the technology for effective gas production.
- Promoting the transfer of research products and technology advances to the gas industry in usable forms.

The current research is an outgrowth of earlier Government research on tight sands in which nuclear and massive hydraulic fracturing stimulations were tested without definitive results. Based on input from the gas industry, universities, and geologic and engineering consulting firms, activities were broadened to include fundamental research and development (R&D). Consequently, the focus of the research for the last several years has been on improving diagnostic instrumentation for reservoir and stimulation performance evaluation, geophysical and engineering interpretation, and stimulation techniques.

Integrated geologic studies of three depositional basins that contain tight lenticular sandstone units have also been pursued as part of this new effort. These lenticular sands were selected by DOE as priority research targets.

To date, the following tentative conclusions have been formulated:

- The permeability of the tight gas sands can be as much as three to four orders of magnitude lower than that of conventional gas deposits.
- Nineteen western geologic basins and trends have been identified that contain significant volumes of tight gas.
- Gas resources in the priority geologic basins have been estimated as follows:
  - Piceance Basin, 49 Tcf.
  - Greater Green River Basin, 136 Tcf.
  - Uinta Basin, 20 Tcf.
- The critical parameters for successfully developing tight sandstone resources are (1) the presence of natural microfractures within a reservoir, and (2) the effective propped length of hydraulically induced fractures.
- Stimulation technology is presently insufficient to efficiently recover gas from lenticular, tight reservoirs.

Industry is reluctant to risk R&D funds on any but the geologically most favorable unconventional gas resources; this is a key factor that precludes the development of tight gas formations. To make these potentially valuable national resources more attractive the technological risks must be reduced.

Two major technical issues warrant attention: (1) the location and magnitude of the resource and the size of the recoverable reserves must be determined; and (2) current extraction technology, which now can be used to recover only a small portion of these resources, must be demonstrably improved if gas from tight sands is to compete with cheaper gas from conventional resources. The first problem that must be faced to determine the magnitude of a tight gas resource is to define the gross geology of the reservoirs. When this is resolved, the part of the geologic resource base that actually contains recoverable gas can then be determined. Research must provide the ability to predict where the producible gas is concentrated and how efficiently it can be recovered.

Currently, geologic research is aimed at providing a comprehensive analysis of the Greater Green River Basin, the second of the three priority basins to be so evaluated. Geologic support to the multiwell experiment (MWX) in western Colorado is also being performed, both on- and off-site.

The current focus in basic research is to develop an understanding of tight sands and to establish and verify a predictive capability for reservoir and stimulation performance. This research also provides diagnostic support to field experiments. Laboratory research is performed on fracturing materials and their effects on geologic formations, basic reservoir properties of tight sandstones, and fracture mechanics. Specific efforts include the development of a comprehensive technical data base for tight sandstones, long-term development and verification of reservoir and stimulation simulators, and the development and field application of diagnostic instrumentation.

Field verification activities substantiate results that are obtained from laboratory and modeling studies, and help make extraction technology and predictions of recovery efficiency more reliable. To assist in this production research effort, a three-well field laboratory was installed in the Piceance Basin in 1983. Scheduled technical research at this site includes the systematic assessment of reservoir behavior and stimulation performance in the lenticular Mesaverde Group reservoirs by performing specific field tests. Well tests that are being conducted include three-well production testing and fully instrumented simulation experiments on the characterized formation to determine stimulation efficiency. Such a research cycle had been completed in the Paludal zone of the Mesaverde Group, a gas-bearing lenticular interval of high geological complexity. Site activities are now focused on the Coastal zone, where a comprehensive, four-part stimulation/reservoir performance experiment is under way.

Stimulation research in an in situ setting, which serves as a verification interface between the laboratory and the field, is being performed at the Nevada Test Site (NTS). Semicommercial-scale hydraulic and high-energy gas fracturing experiments are being evaluated through mineback operations that permit direct inspection of performance.

With advancements in technology and some imaginative solutions, tight gas resources can double our present natural gas reserves. In addition, these resources can, in effect, provide the time the U.S. needs to make the transition from dependence on nonrenewable fossil fuels to alternative nonfossil sources.

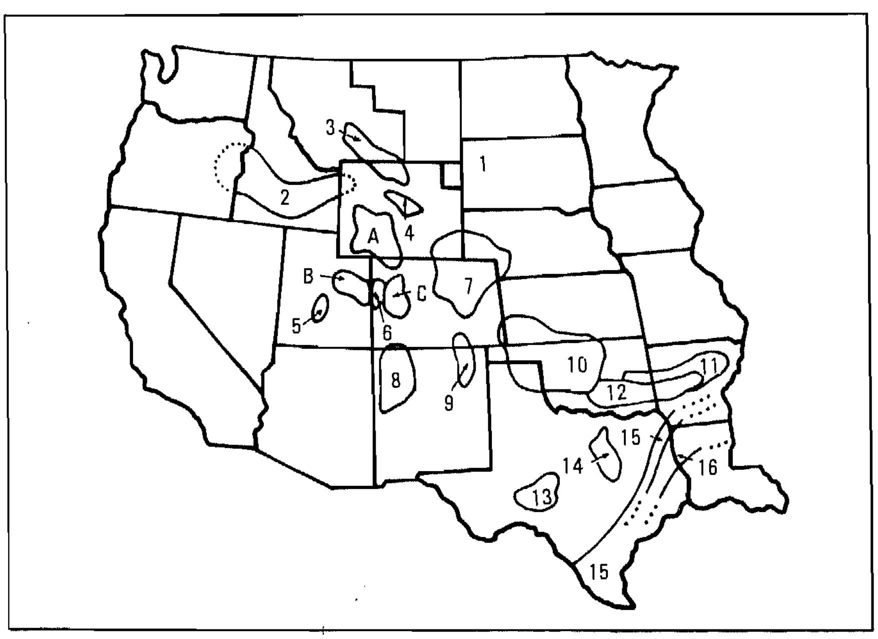
1.0 INTRODUCTION

Large quantities of natural gas are trapped in western gas sands that have permeabilities too low to permit economic recovery by using conventional technology. Nineteen basins and trends have been identified as containing significant amounts of gas in such tight, or very low permeability, formations. These basins reach westward from the Cotton Valley trend in Louisiana, through Texas and the Rocky Mountains, to the Uinta Basin of Utah, then north through the northern Great Plains, the Williston Basin, and ultimately into Canada (Figure 1). Individual formations in many other basins are also termed tight, including some in the eastern U.S.

The permeability of tight sands can be as much as three or more orders of magnitude lower than conventional natural gas deposits. Such reservoirs are generally considered dry, or nonproductive, by conventional standards.

In addition to low permeability, these reservoirs typically have low porosities and high water saturations, which results in gas-filled pore volumes that are low. In many of these basins and trends (e.g., Denver, San Juan, and Cotton Valley), the principal tight formations are broad, continuous reservoirs, or blanket formations. In others (e.g., the Greater Green River, Uinta, and Piceance), the reservoirs are lenticular, or discontinuous lens-shaped sandstone formations that are embedded in highly impermeable shale. The presence of lenticular reservoirs currently sharply restricts the potential gas recovery from an individual well in this type of formation.

These reservoir characteristics have limited the development of tight sands, even though several detailed geological and engineering studies have indicated very large production potentials for these resources. In 1980 the National Petroleum Council (NPC) assessed the potential for finding and producing tight gas in the U.S. as a function of reservoir properties, gas price, and available technology (National Petroleum Council 1980). Depending upon the price and technology considered, potential ultimate recovery was projected to be in the range of 192 to 570 Tcf for the contiguous U.S. This estimate is up to three times that of currently proven reserves and equal to a 20- to 30-year supply at current demand rates. This represents an enormous resource target, and is equivalent in energy to 33 to 99 billion barrels of crude oil. However, recovery might significantly exceed the predicted



*Assessed by National Petroleum Council (1980).

Priority Basins

- * A. Greater Green River Basin
- * B. Uinta Basin
- * C. Piceance Basin

Additional Low Permeability Areas

- * 1. Northern Great Plains Province
- 2. Snake River Downwarp
- 3. Big Horn Basin
- * 4. Wind River Basin
- 5. Wasatch Plateau
- 6. Douglas Creek Arch
- * 7. Denver Basin
- * 8. San Juan Basin
- 9. Raton Basin
- 10. Anadarko Basin
- 11. Arkoma Basin
- 12. Ouachita Mountains Province
- *13. Val Verde
- *14. Fort Worth Basin
- 15. Western Gulf Basin
- *16. Cotton Valley Trend

FIGURE 1. TIGHT SANDS BASINS AND TRENDS

range, given the conservative NPC methodology used to evaluate and extrapolate the resources and reserves. In addition, the NPC estimated that approximately half the ultimate potential could be added to U.S. gas reserves by the year 2000, based on the assumption of a gas price of $5 per thousand cubic feet (Mcf) and a substantially improved technology. By that year, as much as 4 to 16 Tcf of tight gas could be produced annually.

Most tight gas development to date has been been in areas with geologically favorable, blanket-type formations that cover larger geographic areas and have relatively higher permeabilities than lenticular formations. One of the fastest growing of these production areas is the Cotton Valley trend in eastern Texas and northern Louisiana. In the Texas portion of the region, conventional gas production increased by 39 percent from 1974 to 1980. During this same period, production from the tight Cotton Valley formation grew by more than 800 percent.

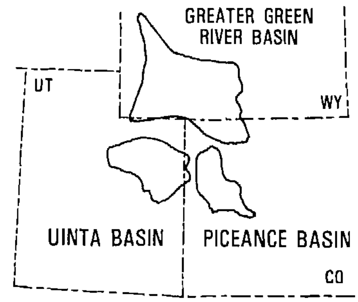
Tight gas currently accounts for about 5 percent of total domestic gas production, or about 1 Tcf annually. The Cotton Valley trend, and the San Juan, Denver, and Sonora basins have the highest production rates, which account for over three-fourths of the tight gas produced. A current estimate of tight gas shows 466 Tcf within a 311,000-square-mile area for the western basins and trends.

2.0 TECHNOLOGY DESCRIPTION

2.1 RESOURCE BASE

Tight gas sands are gas-bearing siltstone or sandstone reservoir rocks that usually have permeabilities of less than 50 microdarcys (<0.05 millidarcys) and a gas saturation of more than 30 percent. Three basins, the Piceance, Greater Green River, and Uinta, have been designated by DOE as priority basins because of their resource potential in thick layers of lenticular sandstone, and because an extensive geological and engineering data base exists.

Within these basins the tight gas formations are of upper Cretaceous and lower Tertiary ages. Natural gas has been produced from specific sandstone formations since the early 1900's, but the total production has been small because of the tight nature of these reservoirs. Figure 2 shows the three priority geologic basins and a tabulation of their resource estimates.



TARGET BASIN	ESTIMATED GAS-IN-PLACE	MAXIMUM RECOVERABLE GAS*
GREATER GREEN RIVER	136	86
PICEANCE	49	33
UINTA	21	15
TOTAL	206 Tcf	134 Tcf

*(SOURCE: NPC, 1980, UNCONVENTIONAL GAS SOURCES)

FIGURE 2. PRIORITY BASINS WITH RESOURCE TABULATION

2.2 RESEARCH APPROACH

There are two aims of the research: reduce the uncertainty of the production potential of the reservoirs, and improve the extraction technology. Specific goals include the following:

- Provide fundamental research into the nature of tight gas sands and the technologies for diagnosing and producing them.
- Verify that the technology to effectively drain tight lenticular formations can be developed.
- Promote the transfer of research products and technology advances to the gas industry.

3.0 STATE OF TECHNOLOGY

The technological and geological factors that constrain the production of gas from tight reservoirs are described in the following sections and in a publication by U.S. DOE/METC (March 1985), and form the basis for DOE research on the subject.

3.1 GEOLOGY

Reservoir conditions have a great influence on the profitability and effectiveness of extraction techniques. Current knowledge on tight gas geology is inadequate to give direction for reservoir analysis and stimulation R&D. This geology is complex and poorly understood, especially in the lenticular formations of the Piceance, Greater Green River, and Uinta basins where only limited actual well data are available. Prior geological studies of these basins focused on blanket formations under, or close to, commercial development. Lenticular formations were not emphasized in these studies because of their low economic performance. Sponsored by the DOE, the U.S. Geological Survey (USGS) has partially remedied this situation over the past five years through extensive basin analyses, but much work remains to be done. A comparable effort for the Northern Great Plains Province has been completed and published.

Major accomplishments to date include the following:

- Cores and logs of tight sand intervals have been obtained from seven wells of opportunity within the priority basins.
- Twenty-two stratigraphic sections and geologic maps have been constructed for the priority basin geology data base.
- The data collection phase has been completed for the three-dimensional seismic analysis of the multiwell site.
- A geologic model has been developed for the Mesaverde Group at the MWX site.
- A comprehensive geologic analysis has been completed for the Piceance Basin of Colorado.

3.2 RESERVOIR ASSESSMENT

Even if a regional geological description of the resource were available, the detailed site-specific characteristics of individual reservoirs would be needed to evaluate gas production potential and to design effective stimulations. Current diagnostic tools and interpretative techniques are limited in their reliability when they are applied to tight gas reservoirs. Improvements in reservoir evaluation tools and interpretive procedures are needed to develop cost-effective extraction techniques.

Permeability, gas-filled porosity, net pay thickness, reservoir geometry, rock mechanical and chemical properties, and natural fracture systems that are controlled by regional stress characteristics all influence tight gas production. These parameters must be known with reasonable accuracy to evaluate a specific reservoir's performance, design effective stimulations, and to predict reservoir and stimulation behavior for performance extrapolation to new areas.

Major accomplishments to date include the following:

- Tiltmeters and surface electric potential and downhole seismic measurement techniques have been developed to determine the azimuth and geometry of hydraulic fractures.
- A three-dimensional lenticular sand model has been developed to use in reservoir analysis and interpretation.
- A lightweight, high-strength proppant production process has been developed.
- Construction and testing have been completed and proof of concept has been established for a nuclear magnetic resonance (NMR) logging tool prototype.
- An enhanced reservoir model has been developed for two-phase flow in naturally fractured tight sandstones.
- Rock mechanics models have been developed to predict hydraulic fracture parameters and performance.
- A proppant transport model has been developed to predict stimulation performance.
- A data base for western gas sands has been established and documented.
- A state-of-the-art assessment of reservoir and stimulation modeling has been published.

3.3 PRODUCTION

Induced hydraulic fractures have demonstrably increased gas production from blanket-type tight reservoirs. However, current fracturing performance, specifically in lenticular formations, is unpredictable for several reasons:

- Poor definition of reservoir properties.

- Inadequate understanding of the physics that control fracture propagation and proppant transport.
- Limited ability to measure, describe, or evaluate the created fracture.
- Uncertainty concerning the relationship of stimulation design variables (fluid chemistry, proppants, pumping rates) to fracture geometry and gas flow performance.
- Uncertainty about the flow capacity of propped fractures over a given period of time through the shales separating the gas-bearing sand lenses.

These difficulties are compounded in lenticular formations since it is not known if multiple lenses can be effectively stimulated with a common treatment.

Currently, the design of fracturing treatments is largely a trial-and-error process. It is difficult to accurately predict or verify fracturing behavior and effectiveness because many formation characteristics that control fracture growth, the geometry of a fracture during and after massive hydraulic fracturing (MHF) treatments, and proppant distribution and placement in a fracture cannot be measured directly. In gas-producing areas where fracturing is used, it is typical for operators to progress through an extensive series of trials by using alternative fluids, treatment sizes, and injection procedures to arrive at a set of standard treatments that provide acceptable results. Blanket-type formations, which have received some industry development, can usually be developed by using a trial-and-error approach because the continuity of the reservoir permits relatively systematic, risk-reducing experimentation. However, lenticular formations do not lend themselves to such an approach because the gas-bearing sand is discontinuous, and the development of any specific site must be based on the reservoir characteristics of that particular site. Additionally, lenticular reservoirs and the surrounding formations are geologically very complex, and present fracturing fluids are incompatible with these formations. This geochemical problem must be solved before stimulation of lenticular sands can be effective.

These factors create the technical and financial constraints that have limited tight gas production. For blanket-type formations, many of these problems can be overcome by systematic trial-and-error development. Fracturing of lenticular formations, however, remains extremely risky; results range from negligible to large gas production, and from zero to significant water production.

Major accomplishments to date include the following:

- The site for the MWX was acquired and the three MWX wells have been drilled, cored, and logged. The installation phase of the field laboratory, therefore, is completed.
- An engineering analysis on reservoir and production characteristics of blanket sands including stress states and reservoir responses has been completed at the MWX.
- Thirty stimulations in 16 wells of opportunity have been performed within the western basins, which begins the assessment of the production potential of tight sands.
- A series of reservoir interference tests has been performed to set the production potential of the lenticular Paludal zone at the MWX.
- A stimulation experiment in the Paludal zone at the MWX has been completed and evaluated.
- The reservoir performance potential has been established for a multi-part stimulation experiment in the Coastal zone at the MWX.
- Hydraulic stimulation effectiveness has been directly measured through mineback experiments at the NTS.

4.0 CURRENT ACTIVITIES

4.1 GEOLOGIC RESEARCH

The economic production of gas from low-permeability, lenticular formations requires a detailed study of the geologic constraints. Such detailed definition provides guidance for the specifications required for reservoir diagnostics, stimulation design, and eventual estimation of gas reserves. Geologic research also helps to update and improve the data base that is used to analyze the technology requirements.

Geologic research currently consists of two activities. The first provides geologic analyses of one of the remaining priority basins (Greater Green River), and the second consists of geologic support to the MWX. Table 1 shows the activities.

TABLE 1. GEOLOGIC RESEARCH ACTIVITIES

Geologic Basin Analysis, Greater Green River

- Reservoir Pressuring Studies
- Seismic Interpretation Studies
- Sedimentology and Stratigraphy
- Source Rock and Maturation Studies

Multiwell Experiment Support

- Core Analysis
- Well Log Analysis
- Rock Engineering Properties
- Reservoir Properties
- Natural Fracturing Patterns
- Geologic Site Model

4.1.1 Basin Assessment

Systematic geologic analyses of the priority basins are performed primarily by the USGS under an interagency agreement. The USGS has completed its investigation of the Piceance Basin, which included the following activities:

- Analyses of stratigraphy and distribution of potential gas zones.
- Analysis of tight gas reservoir characteristics.
- Studies of source rock and thermal maturation.
- Studies of reservoir and boundary rock mechanical properties studies.
- Assessment of integrated geological engineering.

Currently, the USGS is concentrating its efforts on a comprehensive geologic study of the Greater Green River Basin, with some minor preliminary research in the Uinta Basin; and on updating and developing resource estimates for the Piceance Basin. Figure 3 shows results of research into abnormal pressuring of tight sands in the Greater Green River Basin. The research results indicate higher than normal gas-in-place values for these formations.

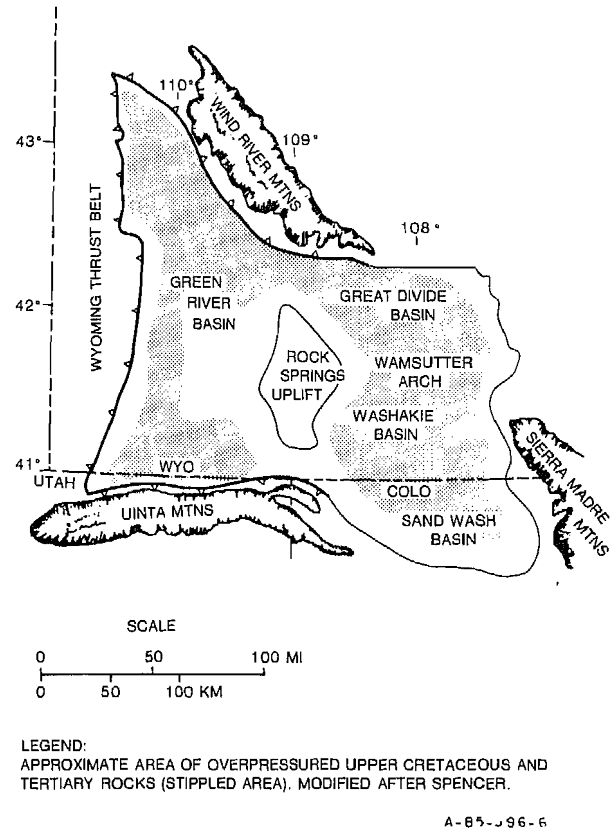


FIGURE 3. GREATER GREEN RIVER BASIN OVERPRESSURE ROCKS

4.1.2 Geologic Site Support

The USGS is also providing geological support at the MWX site. Their detailed sedimentology, stratigraphy, mineralogy, natural fracturing investigations, and seismic interpretation studies of the formations at the test site assist in the analysis of reservoir testing and stimulation experiments. This information is used to help select reservoir test and stimulation intervals in lenticular formations, and to help interpret reservoir and stimulation performance.

Sandia National Laboratories (SNL) and its subcontractors also perform geologic site support at the MWX through core analysis and geochemical and geophysical testing. This work has been combined with the USGS site investigations to formulate a geologic model of the MWX facility.

4.2 RESERVOIR AND STIMULATION MECHANICS, MODELING, AND DIAGNOSTICS

This research is designed to better understand the tight gas sands resource and the technology needed for gas production. The goal of this research is to increase the knowledge, predictive capability, and control of technologies used for effective production of gas from the tight lenticular formations of the western basins. Table 2 lists the activities.

TABLE 2. RESERVOIR AND STIMULATION MECHANICS, MODELING, AND DIAGONOSTICS RESEARCH ACTIVITIES

- Reservoir Properties R&D
  - Matrix Porosity and Permeability Studies
- Fracturing Materials R&D
  - Fluid, Proppant, and Formation Damage Studies
- Fracturing Mechanics Studies
  - Laboratory and Modeling R&D
- Geophysics R&D
  - Crosswell Seismics
- Diagnostic Instrumentation Development
  - Borehole Seismic System
- Predictive Models
  - Reservoir Simulator
  - Stimulation Models
  - Model Application and Support
- Technical Integration
  - Reservoir Test Analysis
  - Log Interpretation
  - Technical Data Base for Tight Sands

4.2.1 Reservoir and Stimulation Research

Research on reservoir mechanics, fluid flow, rock properties, and their interaction is being conducted by the New Mexico Institute, CER Corporation, and the Lawrence Livermore National Laboratory (LLNL). Results from this work will provide an understanding of reservoir behavior. In other work, the University of Tulsa's modeling program has been supported by laboratory research on fracturing fluid chemistry and proppant transport. The National Institute of Petroleum and Energy Research (NIPER) is investigating the interaction of fracturing materials and reservoir rocks. A new line of research has been initiated by the Institute of Gas Technology (IGT) to find and develop a reliable technique to measure relative permeability, one of the major technical uncertainties in tight gas sands.

4.2.2 Predictive Models

Some predictive modeling is being performed at DOE/METC, where the state-of-the-art reservoir and stimulation modeling has been assessed for tight sands application. Modeling needs for predictive uses are being identified. DOE/ METC designed, installed, and documented a technical data base for engineering analysis and predicitve modeling in Morgantown, West Virginia. Predictive models have been developed under contracts with the University of Oklahoma (2- and 3-D reservoir stimulators) and are currently being developed jointly by the University of Tulsa and NIPER (hydraulic fracturing models). In addition, modeling activities are being performed as integral parts of other R&D activities, such as reservoir and rock mechanics research and well test analysis. These simulator developments are being integrated to provide state-of-the-art reservoir and fracturing models.

4.2.3 Diagnostics and Instrumentation

Los Alamos National Laboratory (LANL) is developing the concept of seismic tomography in a geologic environment. This work is a combination of laboratory, analytical and field research, and includes the application of these findings at the MWX site. The objective is to define the geometry of lenticular sand bodies by using remote sensing techniques. The instrumentation includes downhole active/passive seismic sensors, surface data recording devices, and data reduction and analysis codes.

SNL is developing and using diagnostic instrumentation that can help to evaluate the geometry of fractures and the performance of hydraulic fracturing experiments during MWX tests. The available diagnostic array consists of topography tiltmeters, a surface electrical potential system, and a subsurface acoustic measurement system. The latter, a system of passive, seismic borehole monitors emplaced in the two wells offsetting the stimulation well, was successfully field-tested during the Paludal zone fracturing experiment. The acoustic sensor array has recently been redesigned and renovated to provide valuable and reliable information on induced fracture geometry. Figure 4 shows the interpretation of output from these borehole seismic units (BSU) during the Paludal fracturing experiment.

Reservoir performance before and after stimulation at the MWX site is being evaluated by CER Corporation. Reservoir and stimulation performances are assessed through well testing procedures, such as multirate flow tests and well-to-well reservoir interference measurements, and through geophysical log analyses.

4.3 PRODUCTION AND STIMULATION FIELD RESEARCH

This research is intended to develop, test, and verify the techniques needed to improve gas recovery from tight sands. Generic R&D results can be extrapolated into the field environment, and these technologies can be demonstrated to industry in a realistic setting. Results from these other activities are tested and verified at the Piceance Basin MWX laboratory facility and at the NTS. Table 3 shows the activities.

TABLE 3. PRODUCTION AND STIMULATION FIELD RESEARCH ACTIVITIES

Multiwell Experiment

- Comprehensive Multiphased Stimulation Test and Performance Evaluation of Coastal Lenses

NTS Mineback Stimulation Research

- Instrumentation and Execution of an Experiment on Hydraulic Fracturing with Proppant
- Execution and Mineback of High Energy Gas Fracturing (HEGF) Experiments

4.3.1 Multiwell Field Laboratory

The construction of the multiwell facility, located near Rifle, Colorado, was completed in 1983 when the third well, MWX-3, was drilled, cored, logged,

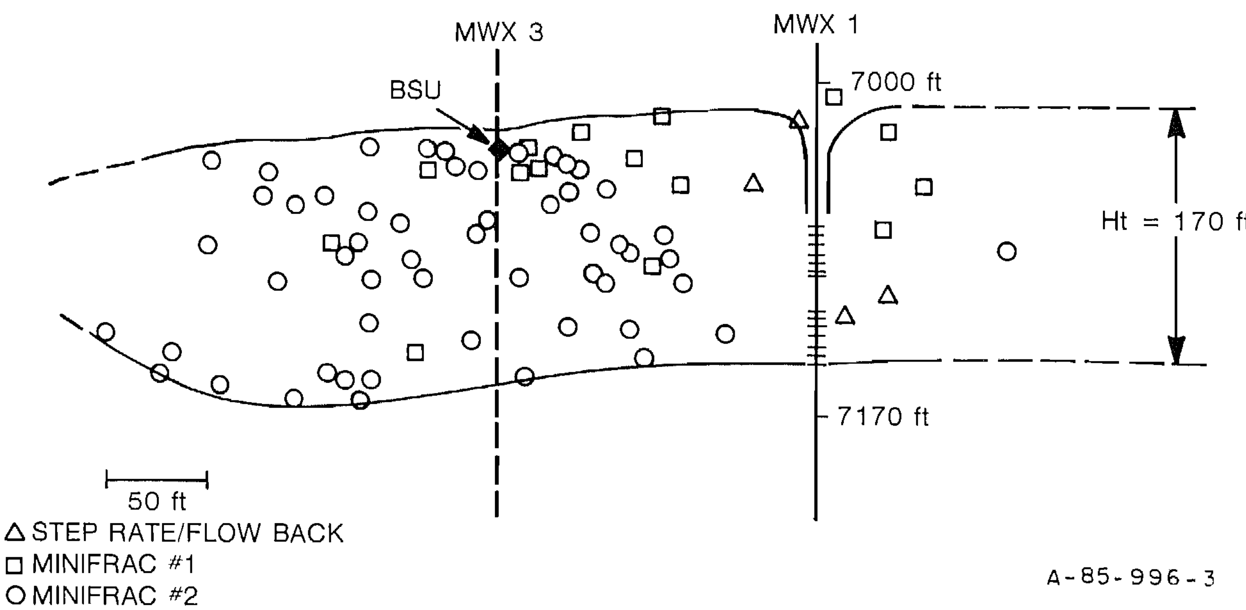


FIGURE 4. FRACTURE PLANE DERIVED FROM BOREHOLE SEISMIC DIAGNOSIS

and tested. Reservoir research performed at the MWX is being used to verify the geological, diagnostic, and stimulation factors that constrain gas extraction from tight, lenticular formations. This research will stand as the most thorough and completely controlled field experimentation that has been performed in tight, lenticular formations. Figure 5 illustrates the MWX facility.

This year, a revision of the research approach at MWX was made from the previous bottom-to-top production profile testing of the Mesaverde to two in-depth fracturing experiments. These two experiments are expected to provide basic production stimulation information that is applicable to tight sands in other areas.

Several MWX activities have been performed to date, and are also described by Northrup and others (1984): extensive coring and core analyses, well-to-well geophysical profiling, single-well tests and interference testing before and after stimulation, and a two-phase stimulation experiment in the Paludal lenticular zone. A comprehensive logging program of conventional and experimental logs has been completed. These data helped to characterize the Paludal zone, and to design a stimulation program that incorporates diagnostic instrumentation. The characterization of the Paludal zone has led to a better evaluation of stimulation effectiveness. In addition, these data have been used to determine quantitatively the critical parameters that affect reservoir performance and production mechanics in tight gas sands.

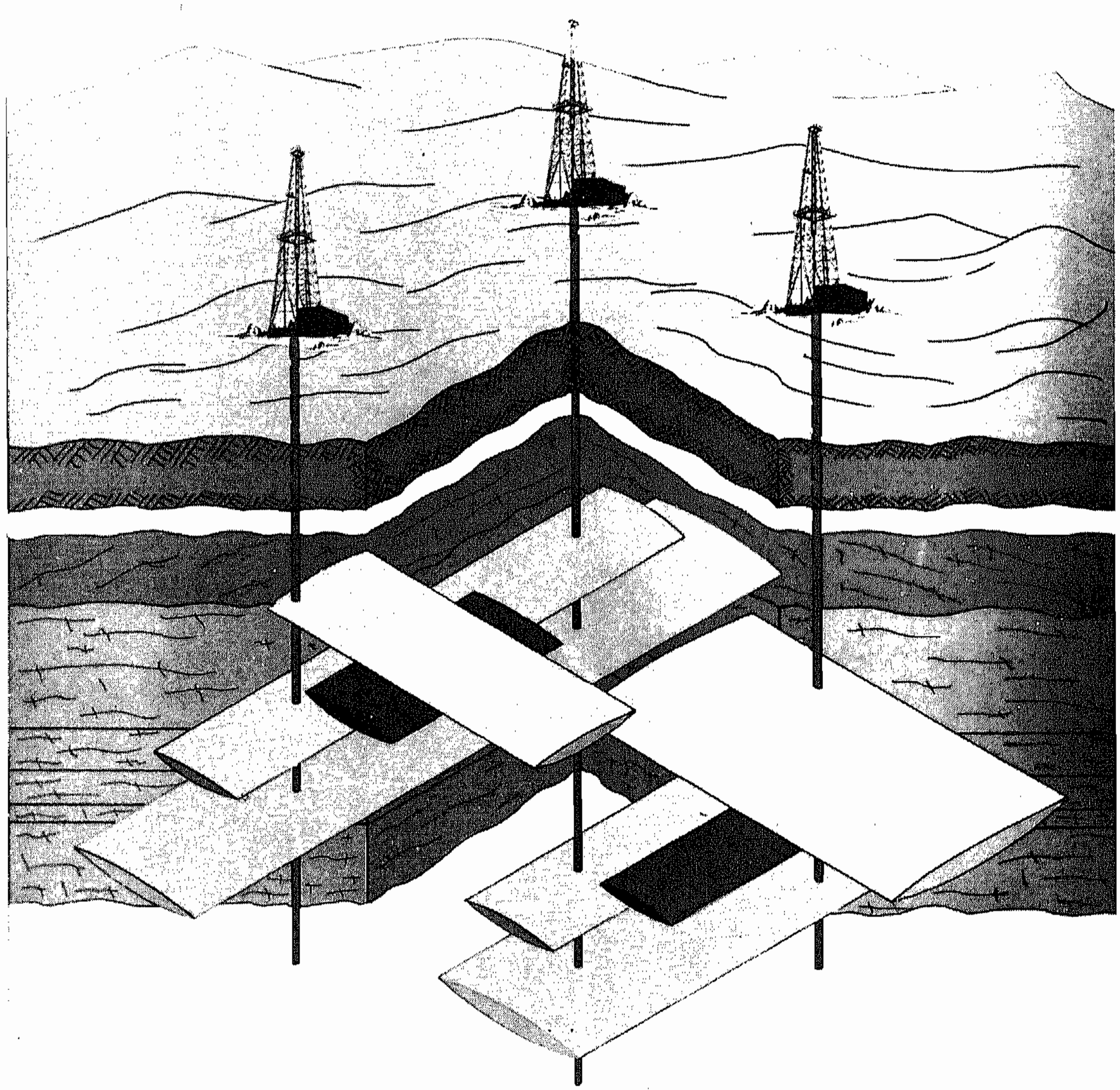


FIGURE 5. MULTIWELL TEST FACILITY IN THE PICEANCE BASIN

MWX field activities are being conducted primarily by SNL and its subcontractor, CER Corporation. CER has performed a reservoir engineering assessment of the blanket sands (Corcoran and Cozzette sandstones) at the MWX site, which completes DOE's research involvement in these more conventional gas reservoirs. SNL and CER have completed the Paludal zone stimulation experiment, including a reservoir performance baseline for the zone, the stimulation of two sand lenses (as a unit), and the evaluation of stimulation performance and post-fracturing gas production potential of the target interval.

However, a major technical problem remaining in the hydraulic fracturing process was identified during this test. State-of-the-art (tailored gel) fracturing fluids and techniques are currently not effective in the complex geology of Paludal lenticular reservoirs. The stimulation test was executed as designed, and the predicted fracture geometry was generated as indicated by diagnostics and real-time pumping pressure analysis. However, after an extended and difficult frac fluid cleanup period, post-frac well testing indicated an effective (gas-conductive) fracture wing length of about 100 feet, only one-fifth of the designed wing length. The abbreviated wing length indicated heavy formation damage. Prior to executing the multiphased stimulation experiment in the Coastal zone, fracture designs have been revised to counter the major problem in the Paludal zone, namely fracturing fluid damage of the formation's permeability.

During the 1985 field season, a refocusing of the research philosophy occurred to use the research facility within present time and fiscal constraints. The original fixed MWX schedule of three stimulation experiments over every two-year period (to cover seven zones of interest over the life of the facility) is unworkable because of current constraints while many technical questions remain unanswered. In its place is a revised activity plan addressing fewer geologic targets in greater depth over the remaining life of the site. Figure 6 shows the revised technical approach and test schedule.

Basically two zones will be evaluated in depth: the Red and Yellow sand lenses of the Coastal zone. The Coastal is recognized as the archetype tight lenticular formation. The targeted sand lenses will be tested in depth by four phases of increased size stimulation experiments that are interspaced with reservoir performance measurements.

The Red and Yellow sands are separated by a 20- to 25-foot-thick shale layer. By isolating the (upper) Yellow sands from the Red sands, and by conducting the four successive frac tests in the Yellow sands,

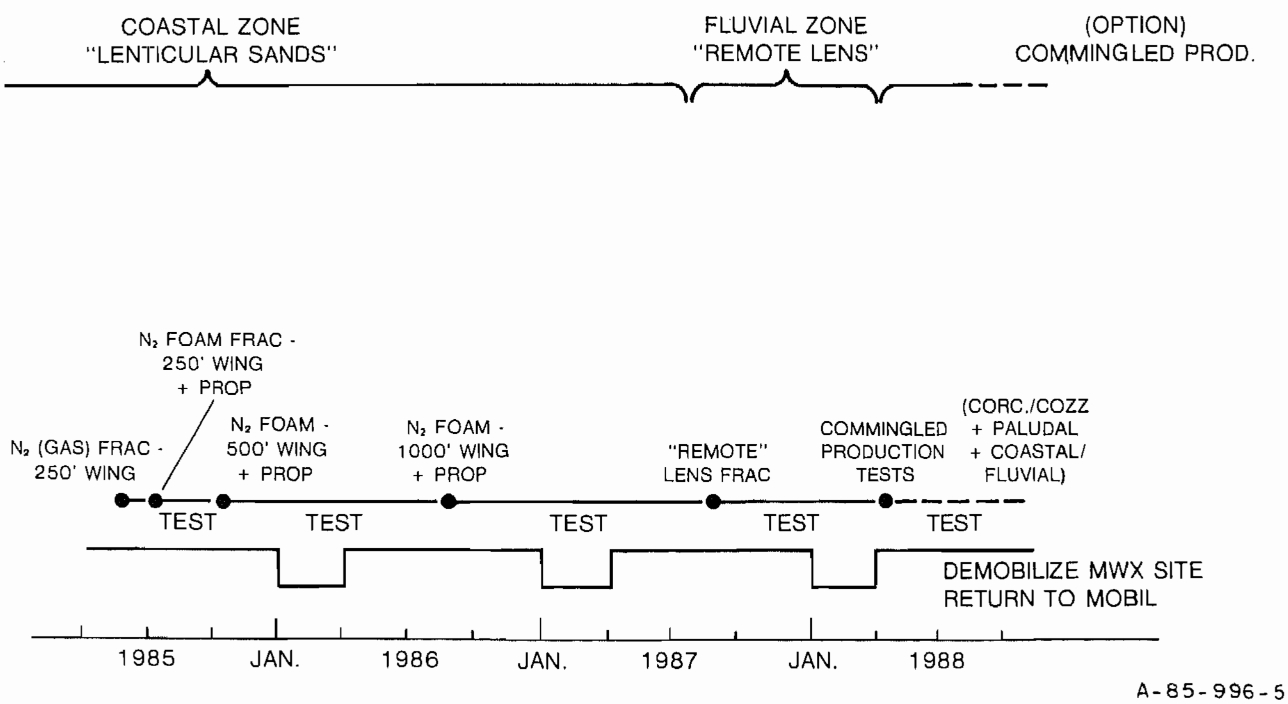


FIGURE 6. MULTIWELL EXPERIMENT TEST PLAN

this Coastal test also becomes a "remote lens" experiment. By instrumenting the Red sand in all three wells with pressure sensors, the expected breakthrough of the fracture into the lower sand will be monitored. Combined with the regular frac diagnostics, the information is providing new insight into the propagation and propping of hydraulic fractures through shales that separate sand lenses. To date, the first two phases of the Coastal experiment have been executed. The first segment was a nitrogen gas chemical tracer test to define the natural fracture trend in the Yellow sand. N_2 was injected into the MWX-1 well while gas chromatographs monitored for N_2 traces in the MWX-2 and MWX-3 wells. The second phase consisted of a small-scale foam (N_2-water) frac, which generated a propped fracture close to the design length of 250 feet per fracture wing. As in the Paludal experiment, data on stimulation performance was gathered from pumping pressure behavior, triaxial geophone monitors in the offset wells, and post-frac well test analysis. This small fracture, which was totally contained within the Yellow sand lens, forms the baseline for phases 3 and 4 of the Coastal experiment. Figure 7 shows a schematic of the Coastal Yellow/Red sands as well as fracture diagnostic instrumentation.

4.3.2 NTS Mineback Stimulation Research

The Tunnel G complex (Figure 8) at the NTS offers a unique research facility that bridges the gap between the laboratory bench-scale and the commerical-scale field test. The complex is located under a mesa that is composed of volcanic ash deposits. These deposits have mechanical and geostress properties that are similar to those of tight reservoir sandstone, but which are relatively easy to mine through. Semicommercial-scale stimulation experiments can be performed at this site, and then the test results can be excavated for analysis. This research is being performed by SNL.

The primary objective of the mineback stimulation research program is to investigate directly the processes and mechanisms that occur in, control, and influence induced fracture behavior and geometry. Improved understanding of and technology for hydraulic and gas fracturing is an essential part of the effort to stimulate and produce the various tight sands reservoirs.

Two lines of stimulation R&D are being pursued: hydraulic fracturing with proppants and HEGF, which uses tailored propellants to generate fracturing pressures. The proppant transport experiments are designed to measure important parameters during the hydraulic fracturing process. An instrumented fracture has been created at the test site, and pressure and width are measured inside the hydraulic fracture while the fracturing is occurring. Different fluids and flow rates are being used for successive tests so that the effects of many treatment parameters can be studied. These data are then correlated with fracture height and length, stresses, and rock properties to provide a comprehensive analysis of frac behavior. When proppants are used, fracture conductivity can be measured after the treatment through injection tests; conductivity is also correlatable with the proppant distribution that is obtained during mineback. Finally, existing models can be verified and corrected by mining through the test zone, exposing the actual fracture, and inspecting the experimental results. To date, the test zone has been cored and stress tested to thoroughly characterize the target interval. A small initial fracture has been fully instrumented with fracture pressure and width sensors. Currently a sequential series of frac extensions is being executed.

Research on HEGF application to tight gas sands has been focused on executing the fracturing operation in cased and perforated boreholes. Figure 9 shows the installation and shot schematic that is typical of the experiment series. To date, four test shots have been completed using different perforation phasing and shot sizes. Main conclusions are verified shot size limits for casing survival, and that perf alignment (phasing) controls the number and orientation of generated fractures. This research has been co-sponsored by DOE's Geothermal Division, which is interested in the effectiveness of the HEGF process in water-filled wells.

4.4 COMPLEMENTARY TIGHT SANDS RESEARCH

GRI complements DOE R&D on tight, lenticular sands by examining potentially commercial practices for use in low-permeability blanket sandstone formations. The GRI research on near-term technical issues dovetails closely with industry development of more conventional gas resources, and so acts as a technology bridge between the high-risk, long-term DOE research and current energy development by the private sector.

Detailed studies show that the basic, longer range R&D that is specifically targeted toward delineating and stimulating lenticular formations is required to fully realize the potential of gas from tight sands.

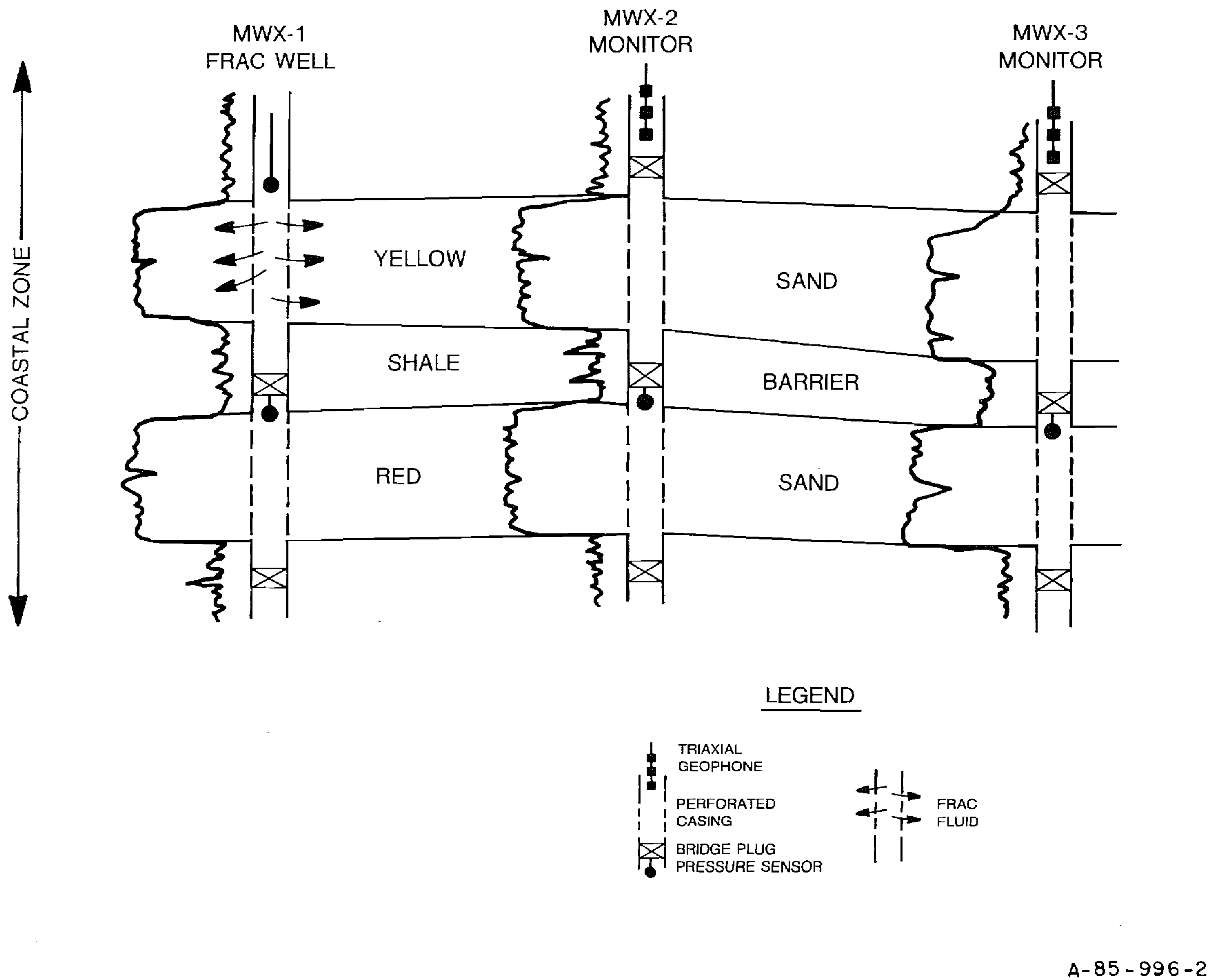


FIGURE 7. SCHEMATIC OF THE COASTAL ZONE STIMULATION EXPERIMENT

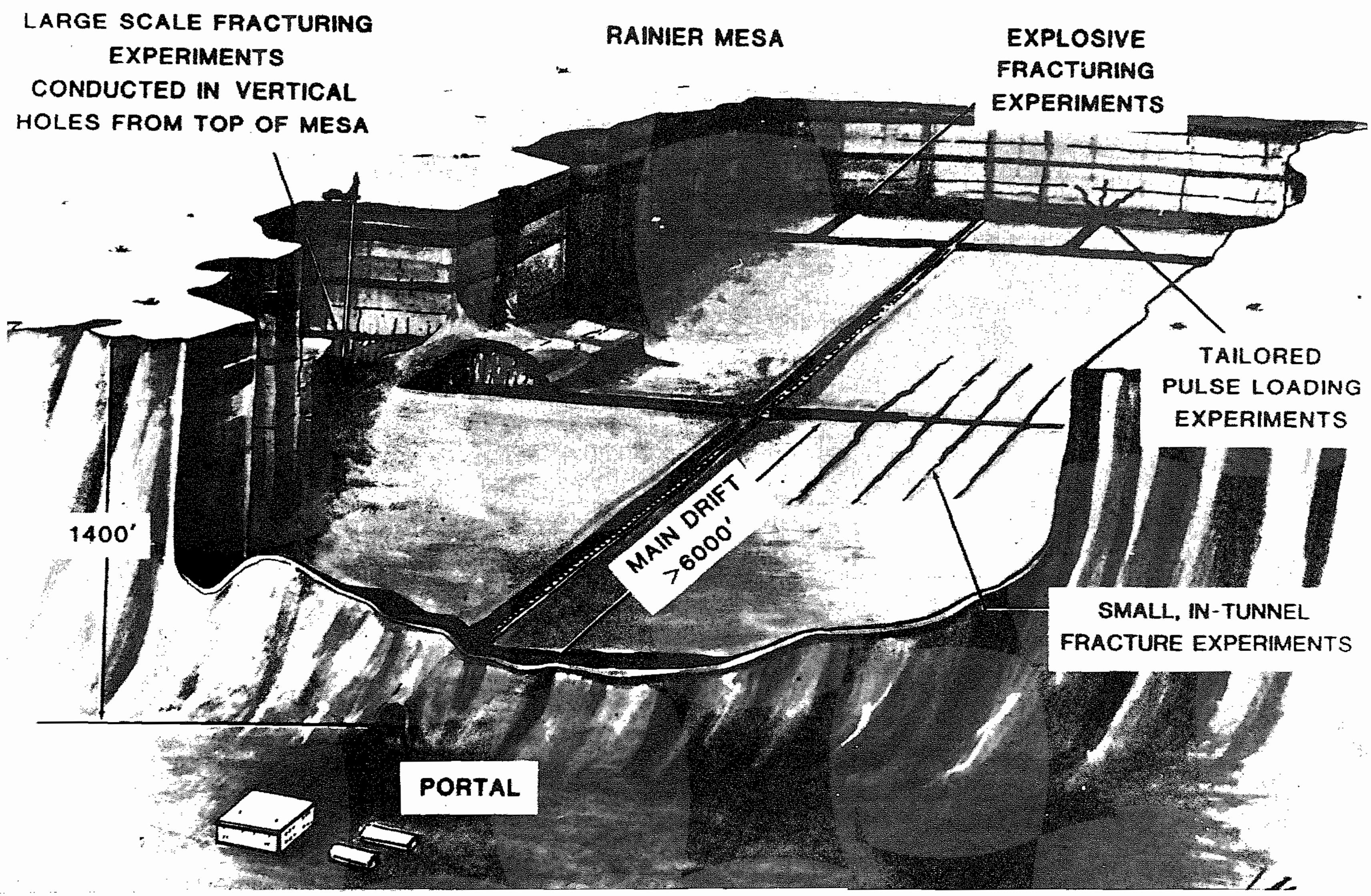


FIGURE 8. SCHEMATIC OF THE NEVADA TEST SITE

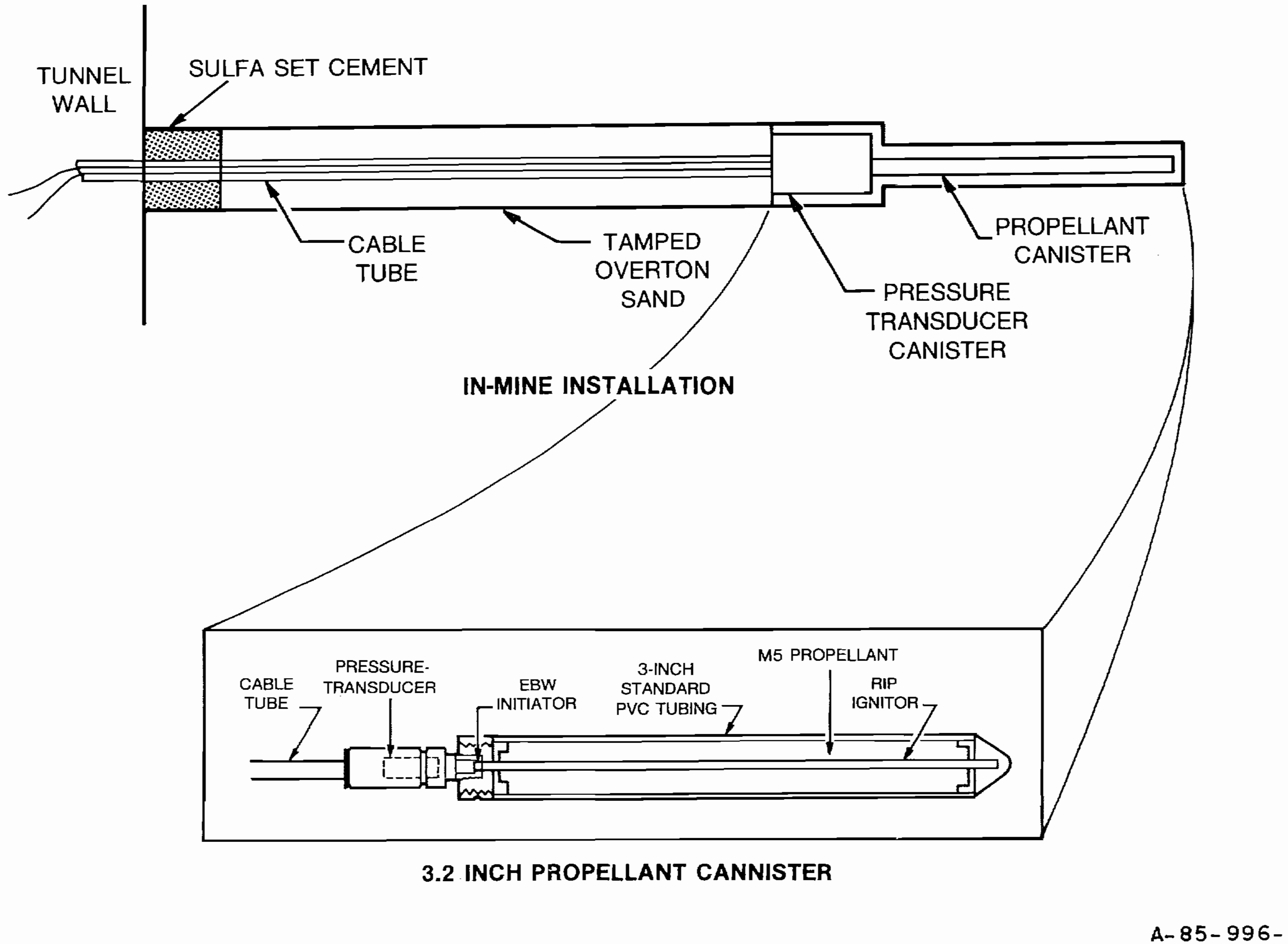


FIGURE 9. HIGH ENERGY GAS FRACTURING IN-MINE EXPERIMENT

Industry's reluctance to conduct this work, due to the high risks and long-term payoffs, points to the need for Government-sponsored R&D.

5.0 FUTURE ACTIVITIES

Geologic research by the USGS and SNL is necessary, albeit at a reduced level of effort, to continue to support the MWX with site-specific geological, geochemical, and geophysical studies. The USGS will continue the comprehensive basin assessment of the Greater Green River Basin. Concurrently, the analysis of the geology and resource potential of the Uinta Basin, the last of the designated priority basins, will be emphasized. Basin tight-gas reserve studies will be initiated, and a feasibility assessment of a multiwell test in the Greater Green River Basin will be made.

Modeling, diagnostics, and fracturing research studies are required to couple mathematical modeling to fracturing mechanics. Predictive capability in both reservoir and stimulation performance areas will be maintained and updated. The University of Tulsa will continue its development of a state-of-the-art fracturing model for lenticular sands. The data base at METC will be updated and maintained to provide effective support for activities such as predictive model verification. LLNL will complete their multi-year rock mechanics and fracturing code development, and NIPER will continue their fracturing materials and formation damage studies. The New Mexico Institute will continue their research on reservoir properties. SNL will continue to update and field test stimulation and reservoir diagnostic instrumentation and techniques. IGT will continue to research relative permeability measurement in tight gas sands, and several universities will be selected to look for innovative approaches to field data analysis.

Production research continues to concentrate on the Piceance Basin MWX. Future stimulations are planned for the Coastal zone Yellow and Red sands, to be followed by the Fluvial zone of the Mesaverde Group. This test will address the question of the flow capacity over time of propped fractures through shales that separate gas-containing sand lenses. Stimulation processes will also continue to be investigated at the NTS, where the 2-year, fully instrumented hydraulic fracturing experiment is now being completed. A similar mineback test series on the effectiveness of high-energy gas fracturing in cased wells is currently under way, and is scheduled for completion.

Multiple field experiments in wells of opportunity must now be considered to (1) measure the production potential of tight, lenticular reservoirs, (2) determine the effectiveness of stimulations in enhancing gas production, and (3) extrapolate MWX-generated reservoir and stimulation techniques to other parts of the lenticular Mesaverde formation. A prime objective of these single-well efforts will be to test and verify reservoir and stimulation models for accuracy in forecasting production. Successful completion of this comprehensive plan will lead to a predictive capability from which estimates of technically recoverable gas reserves can be made for the priority basins.

6.0 ACRONYMS AND ABBREVIATIONS

BSU	Borehole Seismic Unit
DOE	Department of Energy
GRI	Gas Research Institute
HEGF	High Energy Gas Fracturing
IGT	Institute of Gas Technology
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
METC	Morgantown Energy Technology Center
Mcf	Million Cubic Feet
MHF	Massive Hydraulic Fracturing
MWX	Multiwell Experiment
NIPER	National Institute of Petroleum and Energy Research
NMR	Nuclear Magnetic Resonance
NPC	National Petroleum Council
NTS	Nevada Test Site
R&D	Research and Development
SNL	Sandia National Laboratories
Tcf	Trillion Cubic Feet
USGS	United States Geological Survey

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