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Western Gas Sands Project Status Report

1 January 1979 - 31 January 1979

Prepared for
U.S. Department of Energy
Bartlesville Energy Technology Center
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Las Vegas, Nevada

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1. SUMMARY

This edition of the WGSP Status Report summarizes January, 1979 progress of the government-sponsored projects directed toward increasing gas production from the low-permeability gas sands of the western United States. Background information is provided in the *September, 1977, Status Report, NVO/0655-100*.

Don Snyder and Roy Allen of Odessa Natural, Odessa, Texas proposed to the WGSP Project Manager and CER personnel, a multiwell coring and logging program, for wells that Odessa plans to drill next spring in the Northern Great Plains Province.

The USGS, Denver, continued work toward resource assessment in the four primary study areas.

National Laboratory and Technology Center projects generally progressed on schedule during January. Bartlesville Energy Technology Center continued work on fracture conductivity, rock-fluid interaction, and log evaluation and techniques. Lawrence Livermore Laboratory continued theoretical and experimental work on hydraulic fracturing mechanics and analysis of well test data. Sandia Laboratories is doing exploratory coring at the Nevada Test Site to determine the general shape of hydraulic fractures in the Interface Test Series. M. D. Wood, Inc. began a new contract for analysis and documentation of all past DOE supported tiltmeter data and to map hydraulic fractures in low-permeability Western gas reservoirs.

Field tests and demonstrations progressed as scheduled. The CER Corporation RB-MHF 3 is on an inactive status pending satisfactory contractual arrangements to perform additional tests and for final disposition of the well. A draft copy of the RB-MHF 3 final report is being reviewed.

The DOE well test facility is scheduled to setup and test bottom hole pressure and temperature of Miller No. 1, Wattenberg Field, Colorado, in February. Gas Producing Enterprises completed assessment of damage to sample permeability caused by the intersection of fracturing fluids with the host rock. The Mitchell Energy Corporation Muse Duke No. 1 flowed at a rate of 4,600 MCFD. Zone 9 of the Mobil well PCU No. 31-13G was shut in during January and will be opened to sales on February 1.

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2. PROJECT MANAGEMENT

2.1 TECHNICAL MONITORING AND EVALUATION

Don Snyder and Roy Allen of Odessa Natural, Odessa, Texas visited the WGSP Project Manager and CER personnel to propose a multiwell coring and logging program for wells that Odessa plans to drill next spring in the Northern Great Plains Province.

Lincoln Elkins, Assistant to the President, SOHIO Oil Co., Oklahoma City, visited CER personnel and the WGSP Project Manager to discuss WGSP MHF designs and results, and to obtain data on these fracturing experiments.

Merle Hanson and Don Emerson of Lawrence Livermore Laboratory (LLL) visited the WGSP Project Manager and CER personnel to review progress of the LLL gas stimulation program and discuss future work.

L. T. Hodges, CER Corporation, attended a one week well logging course at Scientific-Software Corporation, Denver, Colorado.

2.2 TECHNOLOGY TRANSFER

2.2.1 Documentation and Reports

Data for the Quarterly Basin Activities Report for October, November, and December, 1978 is being compiled. The Status Report for December, 1978 has been completed and will be released shortly. The final draft of CER's RB-MHF 3 report has been completed and will be released during February, 1979. A WGSP Financial Supplement Report for December, 1978, having limited distribution, was released on January 15, 1979. Work is proceeding on the January Financial Supplement and the DOE Well Test Facility Operation Manual is being reviewed.

2.2.2 Project Data Bank

CER has received geologic and energy resource maps of areas of interest to the WGSP. Logs from the four primary study areas were added to the log file. Monthly production data for Utah wells from 1958 to 1979 (partial) have been added to the project data bank.

2.2.3 Articles and Publications

The following articles and publications relate to the WGSP. Abstracts, when available will be included.

*Relation Between Facies and Low-Permeability (tight) Reservoirs
in the Northern Great Plains*
D.D. Rice and G.W. Shurr, USGS

*Continuity and Permeability Development in the Tight Gas Sands
of the Eastern Uinta Basin, Utah*
C. F. Knutson and C. R. Boardman, CK GeoEnergy Corp.

*Investigation of Hydraulic Fracturing Technology
in Tight Gas Reservoirs*
R. M. Forest and S. F. McKetta, Columbia Gas System Service Corp.

*Determination of the Optimum Massive Hydraulic Fracturing
Design for the Stimulation of the Wasatch and the Mesaverde Formations*
R. G. Merrill, Gas Producing Enterprises, Inc.

Vast Potential Held by Four 'Unconventional' Gas Resources
V. A. Kuuskraa, J. P. Brashear, T. M. Doscher, and L. E. Elkins,
Lewin and Assoc. Inc., Washington, D.C.

*Instrumentation for Formation Evaluation
and Advances Logging Techniques*
C. L. Schuster and T. L. Dobecki Sandia Laboratories, Albuquerque, New Mexico

Abstract—Review and evaluation of currently employed methods for direct (via sampling) and indirect (via water catalogues, experience, and geophysical logging) determination of formation water resistivity (R_w) was performed by Sandia Laboratories for the Bartlesville Energy Technology Center during 1978. In addition, Sandia has evaluated several proposed new sampling and logging techniques which may be useful for R_w determination or in the direct calculation/measurement of water saturation, S_w . Principal findings, relative to low permeability, shaley reservoirs, are:

- Modifications to existing formation water samplers, including large volume or continuous sampling with *in situ* resistivity measurements are desirable.
- Novel sidewall corers or instrumented penetrators are not considered cost-effective approaches to improved measurements.

- Standard geophysical logs are not accurate in determining R_w , and subsequently, S_w , under conditions of low permeability, high shale content, and deep invasion.
- New logging measurements, such as variable frequency, high frequency electrical impedance measurements offer promise as a means of direct S_w measurements.

2.2.4 Calendar of Events

The following symposium is of interest to the WGSP.

May 20-22, 1979

SPE-AIME Symposium on Low-Permeability Gas Reservoirs, Hilton Hotel, Denver, Colorado.

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3. RESOURCE ASSESSMENT

3.1 U.S. GEOLOGICAL SURVEY ACTIVITIES

3.1.1 Greater Green River Basin

- Work on stratigraphic analysis of the Greater Green River Basin continued.
- Petrographic examination continued of core chips from Superior-Pac. Crk. Unit well in Section 27, T27N, R103W, Sublette County, Wyoming.
- Relationships of pressure, temperature, and organic maturation in the Pacific Creek area, northeastern Green River Basin are being investigated.
- Surface samples from the northern Greater Green River Basin are being prepared for heavy mineral analyses.
- Work continued on lineament study of the Washakie and Great Divide Basins.
- Cross-sections through the Washakie and Greater Green River Basins are being prepared.
- The well penetration map of the Great Divide Basin is ready for review.
- An exhibit for the annual AAPG-SEPM meeting in Houston is being prepared.

3.1.2 Uinta Basin - Piceance Creek Basin

- Analysis of X-ray diffraction data from the Mesaverde Group and Tertiary formations in the Westwater Canyon area has begun.
- Three cross-sections of Upper Cretaceous and Tertiary rocks in the southern Piceance Creek basin have been submitted for review as USGS Oil and Gas Charts.
- Three cross-sections of Upper Cretaceous and Tertiary rocks in the northern Piceance Creek basin have been submitted for review prior to publication.
- Analysis continued of rock plugs from the Mesaverde Group in the Uinta Basin in the Natural Buttes area for porosity and permeability. All results to date range from 3 to 13 percent porosity and from less than 0.1 to 0.5 md to air. These values are obtained from analysis of plugs cut at each change in rock character through producing intervals at Southman Canyon gas field. All plugs in which fracture were noted were omitted from the analysis. Only one sample of the 18 studied so far from these cores has permeability to air (at surface pressure) of less than 0.1 md.

3.1.3 Northern Great Plains Province

- Preparation of a manuscript on the Bowdoin Field for SPE continued.
- An exhibit for the annual AAPG-SEPM Meeting, April, 1979 is being prepared.
- A paper on the reservoir characteristics of the Eagle Sandstone in the Bearpaw Mountain area is being written.
- Petrographic investigation of shelf sandstones of the Eagle-Telegraph Creek interval in the Joseph J. C. Paine well has begun. Preliminary investigations indicate that the high porosity and permeability values recorded from conventional core analysis resulted from the extensive microfracture system created by desiccation of clays.

3.1.4 Schedule Status

Figure 3-1 is a milestone chart depicting the status of all USGS projects with the WGSP.

3.2 CORE PROGRAM

Good correlation was possible between the logs and core cut in the original Twin Arrow, C&K 4-14 well, Douglas Creek Arch, Colorado. Therefore, additional Core Laboratories analyses were authorized. The final analysis will include:

Whole Core Analyses—Boyles Law Helium (porosity, permeability, grain density)	68 samples
Grain density (shales)	15 samples
Cation Exchange Capacity (absorbed H ₂ O method)	37 samples
Resistivity Index (at 6 saturations)	2 samples
Formation Factor (4 overburden pressures)	2 samples
Acoustic Velocity Measurement (5 overburden pressures)	1 sample
Core Gamma over entire interval	

Companies contacted during the month for possible coring contracts were Fuel Resources Development Company, Cities Service Gas Exploration, and Teton Energy, all active in the Piceance Basin. No agreements were reached at month end.

Figure 3-1 Milestone Chart—USGS

WGSP-USGS	FY-79											
B. NORTHERN GREAT PLAINS PROVINCE	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Preliminary mapping of lineaments from enhanced LANDSAT images for key parts of study area												
Prepare paper for SPE Symposium on Bowdoin Dome area, north-central Montana												
Detailed surface and subsurface mapping of Eagle (Shannon) sandstone on north flank of Black Hills, SE Montana and NW South Dakota												
Prepare paper on the origin of shallow gases												
Petrographic and clay mineralogy studies on outcrop sections and core if available												
Description of selected core in the study area when available												
Prepare abstract and talk on shallow gas potential in eastern Dakotas												
Prepare open-file report on Lake Traverse Section, South Dakota-Minnesota												

WGSP-USGS	FY-79											
B. NORTHERN GREAT PLAINS PROVINCE	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Prepare talk for Potential Gas Committee												
Prepare talk for Rocky Mountain Assoc. Geological												
Analyze gas samples from Suffield Block, Canada for comparison with Northern Great Plains Province												

Figure 3-1 Continued

Figure 3-1 Continued

3.3 LOGGING PROGRAM

Various projects were carried out during the month. D. C. Bleakly and G. C. Kukal logged the Twin Arrow offset well C&K 4-14x, near Rangely, Colorado. Logging operations (January 11-13) were carried out with minimal problems. The suite of logs was as follows:

DIL/SP/GR
DLL/SP/GR
Proximity - Minilog
FDC/CNL/GR
BHC/CAL/GR
Spectralog
Dipmeter

3.4 SURVEY OF BASIN ACTIVITIES

Drilling and testing in the four primary study areas are monitored as part of assessing the resource and to identify possible core sites for the WGSP Coring Program. Figure 3-2 to 3-5 show recent wells with significance to the WGSP and to the core program. Background information on the core areas is given in the WGSP Quarterly Basin Activities Report, April 1, 1978, NVO/0655-05.

3.4.1 Greater Green River Basin

Completed wells of interest to the WGSP in the Greater Green River Basin added 14,502 MCFD of new gas. Twenty-five wells were completed; 17 development wells and 8 wildcats. Four wells were completed D & A. Development wells were 59 percent successful (10 wells out of 17) and wildcats had 25 percent success (2 wells out of 8). Producing horizons were the Mesaverde (2,901 MCFD), commingled Lewis-Lance (789 MCFD), Ericson (1,320 MCFD), Almond (700 MCFD), commingled Ft. Union-Lance (499 MCFD), and commingled Lewis-Hilliard (28 MCFD).

Nine wildcats and 16 development locations were staked during January, and at month end two had been spudded and were drilling ahead.

Wells of particular interest to the WGSP are located on Figure 3-2 and listed in Table 3-1.

3.4.2 Northern Great Plains Province

Thirty wells in the Northern Great Plains Province were completed on locations and in horizons of interest to the WGSP. Twenty-two development wells were finalized with 64 percent success. Six wells were completed D&A. Thirty-eight percent of the wildcats were successful with 3 being D&A. Producing horizons were the Bowdoin, Bow Island, Eagle, Phillips, White River, and White Specks for a total of 5,701 MCFD.

Figure 3-2
Greater Green River Basin Showing
Wells of Interest and USGS Design-
ated Core Areas (refer to Table 3-1)

Table 3-1 Summary of Wells—Greater Green River Basin

OPERATOR	WELL NAME	INDEX NO.	LOCATION Sec/T/R	HORIZON ft.	FINAL TD	FRACTURE TREATMENT	STATUS	IPF in MCFD
CIG Exploration	1-30-17-93 USA	1	sene 30-17N-93W Wild Rose Field Carbon Cty, WY	Mesaverde (10,450)			Wildcat location in core area A	
Smokey Oil	2-18 Bluewater Federal	2	nsw 18/17N/96W Unnamed Field Sweetwater Cty, WY	Mesaverde (12,099- 12,963 gross)	13,007 PB: 12,827	131,400 gal gel 177,750 lb sand	Completed Wildcat near core area A, large frac treatment, Mesaverde discovery- new field	250
Davis Oil	2 Nickle Unit	3	nsw 28/18N/94W Wild Rose Field Sweetwater Cty, WY	Ericson (9,861- 10,138)	10,315 PB: 10,275	3,000 gal acid 131,124 gal oil 250,000 lb sand	Completed well in core A, no cores, large frac treatment	1,320
Belco Petroleum	S28-28 Johnson Ridge	4	swne 28/30N/113W Big Piney Field Sublette Cty, WY	Mesaverde (3,256- 3,434 gross)	3,630	35,700 gal emulsion, 25,900 lb sand	Completed well in core area B ₄ with treatment. No cores or tests.	586

Figure 3-3
Northern Great Plains
Province Showing Wells
of Interest (refer to
Table 3-2)

Figure 3-4
Detail of USGS Desig-
nated Core Areas
(refer to Table 3-2)

Nine new locations were staked during January; 6 development wells and 3 wildcats. At month end three of the locations had been spudded.

Specific wells of significance to the project are located on Figures 3-3 and 3-4, and listed in Table 3-2.

Table 3-2 Summary of Wells—Northern Great Plains Province

OPERATOR	WELL NAME	MAP INDEX NO.	LOCATION Sec/T/R	HORIZON ft.	FINAL TD	FRACTURE TREATMENT	STATUS	IPF in MCFD
Amarada	1 Challenger	1	sesw 22/1N/32E Wildcat Field Big Horn Cty, MT	Muddy (2,700)			Wildcat location	
Milan R. Ayers Calto Dev. Ltd.	Traper 3 State	2	swse 28/29N/3W Unnamed Field Pondera Cty, MT	Second Bow Island (1,060-1,060) open hole	1,468		Wildcat field discovery	577
Red River Oil & Gas	Diamond Shamrock 13-9 Robinson	3	sww 9/31N/2W Morias River Field Toole Cty, MT	Bow Island (1,200)	1,197		Wildcat outpost waiting on completion tools	
Falcon-Colorado Exploration	1-36 State of Montana	4	sww 36/33N/34E Swanson Crk Field Phillips Cty, MT	Phillips (1,216-1,228)	1,450 PB: 1,382	14,600 gal wtr 40,000 lb sand	Completed near core area C, no cores or tests	295
Sumatra Oil	4-16 State of Montana	5	nwnw 16/37N/7E Wildcat Field Liberty Cty, MT	Second White Speck (2,500)			New field wildcat	

3.4.3 Piceance Basin

Horizons of interest in the Piceance Basin produced 10,803 MCFD of new gas during the month. Nine of thirteen completed wells produced from the commingled Rollins/Cozzette/Corcoran (2,304 MCFD), Wasatch (6,730 MCFD), Mancos (247 MCFD), and Emery (1,522 MCFD). Two wildcats were completed D&A.

Eight new locations were reported this month; four development and four wildcat sites. One development well was spudded by month end.

Wells of special interest to the WGSP are located on Figure 3-5 and listed in Table 3-3.

Figure 3-5

Piceance Basin Showing Wells of Interest and USGS Designated Core Areas (refer to Table 3-3)

Table 3-3 Summary of Wells—Piceance Basin

OPERATOR	WELL NAME	NO.	LOCATION Sec/T/R	HORIZON ft.	FINAL TD	FRACTURE TREATMENT	STATUS	IPF in MCFD
CSG Exploration	298-29-2 Govt.	1	senw 29/2S/98W Sulphur Creek Rio Blanco Cty, CO	Mancos (17,800)			Located close to core area A and B	
Fuel Resources Development	0-28-3-101-S Federal	2	swse 28/3S/101W Cathedral Field Rio Blanco Cty, CO	Emery (3,852- 4,137)	4,347 PB: 4,297	54,000 gal gel 244,000 lb sand	Completed no tests	602
Chandler & Associates	15-16 Woodring	3	swse 16/10S/96W Plateau Field Mesa Cty, CO	Cozzette (2,940- 2,958) Corcoran (3,070- 3,141)	3,364	1,000 gal acid 44,836 gal wtr 291,500 lb sand	Completed, no cores or tests, com- mingled	1,020

3.4.4 Uinta Basin

Eleven wells were completed in horizons and areas of interest to the WGSP during January and added 8,055 MCFD of gas. Ten development wells were completed with 80 percent success (8 of 10 wells). The remaining wildcat was a discovery. Producing horizons were the Wasatch (6,983 MCFD), Mesaverde (662 MCFD), and commingled Castlegate/Mesaverde (410 MCFD).

Eleven new development well locations were staked and one was spudded by the end of the month.

Wells of interest to the WGSP are located on Figure 3-6 and listed in Table 3-4.

Figure 3-6

Uinta Basin Showing
Wells of Interest and
USGS Designated Core
Areas (refer to Table
3-4)

Table 3-4 Summary of Wells—Uinta Basin

OPERATOR	WELL NAME	MAP INDEX NO.	LOCATION Sec/T/R	HORIZON ft.	FINAL TD	FRACTURE TREATMENT	STATUS	IPF in MCFD
Pacific Transmission Supply	32-29 PTS Federal	1	swne 29/8S/17E Unnamed Field Duchesne Cty, UT	Douglas Creek (6,322- 6,370 gross)	14,245 PB: 6,402	4,000 gal acid 32,424 gal gel 52,000 lb sand	New field discovery located in core area B	not avail-
Continental Oil	15-2 Chapita Federal	2	sese 15/9S/23E Natural Buttes Field Uintah Cty, UT	Mesaverde (7,834- 8,747) Castlegate (8,875- 9,036)	9,170		Completed located in core area C, no cores or tests, com- mingled	410
Belco Petroleum	33-17B Natural Buttes	2	sww 17/9S/22E Natural Buttes Field Uintah Cty, UT	Wasatch (5,253- 6,742)	6,939 PB: 6,889	107,250 gal emulsion, 264,000 lb sand	Completed located in core area C, no cores or tests	2,558
Pacific Transmission Supply	23-17 Devils Playground Federal	2	nesw 17/9S/24E Natural Buttes Field Uintah Cty, UT	Mesaverde (9,000)			Located in core area C	
Ensearch Exploration	2-11 Jack Rabbit Federal	3	sww 11/10S/23E South Canyon Field Uintah Cty, UT	Mesaverde (9,000)			Located near core area C and D	
Mapco Inc.	7-21F Riverbend Unit	4	swne 21/10S/1E Island Field Uintah Cty, UT	Wasatch (5,318- 6,053)	8,349 PB: 6,600	4,000 gal acid 79,000 gal wtr 92,000 gal gel 288,000 lb sand	Completed in core area A, no cores but large frac treatment	

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4. RESEARCH AND DEVELOPMENT BY ENERGY TECHNOLOGY CENTERS AND NATIONAL LABORATORIES

4.1 BARTLESVILLE ENERGY TECHNOLOGY CENTER

4.1.1 Improved Pressure Coring System

4.1.1.1 Core Retriever Design

An oral review of the Maurer drawings is scheduled with Larry Russel for February 20 at Maurer Engineering in Houston. Possible problem areas will be pointed out to all RFP recipients and an adjustment in closing date will be provided if it is deemed advisable.

A test sub is being designed for testing the pilot core bit at Terra Tek with the low invasion fluid selected by Sandia. This test sub is being designed to provide a fluid flow around the pilot bit similar to that predicted for the actual coring situation.

4.1.1.2 Core Fluid Tests

Plastic viscosity measurements were made for the Brinadd product, "Sanheal" as a function of temperature from -44°F to 196°F. These measurements showed the fluid to be highly shear-thinning with the viscosity well within design limits at the anticipated shear rates in the core barrel. There has been some question about the maximum pseudoplastic fluid viscosity which can be used without causing excessive pressure increases in the core barrel, and further analytical work will be done in this area using the non-Newtonian viscosity properties of Sanheal.

The core holder/filtration equipment from Baroid should arrive before January 31. Testing will begin at that time to determine the optimum particle size distribution and total solids content of the HEC polymer in the Grey Berea and Brown Sandstones and in the Indiana Limestone. Core samples of each rock type are currently being tested for porosity, vertical permeability, horizontal permeability, and pore size distribution in order to correlate laboratory results with the formation rock properties.

4.1.1.3 Bit Design and Fabrication

Stratapax cutters are being brazed to the first pressure core barrel pilot bit body. This bit will be used in laboratory tests with "Sanheal" fluid for cutter cooling and chip removal studies.

Diffusion bonding of Stratapax cutters to a pilot bit body will be attempted when canning fixtures become available late in February.

A redesign of the tooling used in ultrasonic tacking of Stratapax cutters to steel studs is complete and on order. Initial use of this tooling should be in early March.

4.1.1.4 Requests For Proposals

A Request for Proposals has been mailed to thirteen prospective industry participants in the joint industry/DOE Pressure Core Barrel development and field test program.

The January 29 cutoff date for submission of questions concerning the RFP and drawings has passed with no response from recipients. This has been interpreted to indicate that the RFP and drawings contained adequate information for proposal preparation.

Work is continuing to establish a review procedure based on a weighted point system to be used by the review committee.

4.1.2 Interface Conductivity Effects on Electric Logging

Cation exchange capacity (CEC) for six Austral-Hayward cores appears in Table 4-1. The CEC of all samples is very low, approaching that of sand, which suggests a low clay content. It appears that the CEC increases with depth, but this is probably coincidental. The accuracy of the data in Table 4-1 is probably ± 0.001 meg/g or better.

Table 4-1
Cation Exchange Capacity of
Six Austral-Hayward Cores

Depth (ft)	CEC (meg/g) ¹
7,530	.0148
7,553	.0097
7,895	.0157
7,900	.0193
8,066	.0236
8,074	.0234

¹ CEC's were determined using
NH₄ Ac technique.

Table 4-2 Porosity of Cores from Natural Buttes No. 21

Plug No.	Depth (ft)	Bulk vol. (cm ³)	Plug density g/cc	Matrix vol. (cm ³)	Porosity pct
1	4,441.5	85.174	2.64	83.03	2.52
2	4,441.4	86.633	2.71	82.16	5.16
3	4,441.8	86.472	2.68	83.86	3.02
4	4,442.0	86.106	2.68	83.85	2.62
5	4,457.0	85.850	2.68	83.43	2.82
6	4,460.5	86.732	2.69	82.42	4.97
7	4,459.1	87.051	2.69	82.53	5.15
8	4,458.8	86.959	2.68	83.13	4.41
9	4,457.5	87.016	2.68	83.60	3.93
10	4,463.7	87.015	2.69	83.87	3.61
11	4,463.9	86.757	2.68	83.92	3.27
12	6,472.1	87.074	2.64	79.69	8.48
13	6,472.8	85.712	2.67	80.98	5.52
14	6,473.1	86.533	2.67	80.30	7.20
15	6,473.8	86.136	2.65	76.85	10.78
16	4,465.8	86.193	2.70	82.60	4.17
17	6,405.0	49.362	2.58	48.61	1.52
18	6,405.8	86.051	2.68	80.57	6.37
19	6,406.0	85.425	2.68	80.15	6.18
20	6,423.7	86.193	2.70	81.81	5.09
21	7,426.0	86.193	2.74	80.48	6.63
22	7,426.9	86.306	2.71	79.88	7.45
23	7,429.0	85.966	2.76	78.48	8.71
24	7,430.0	86.249	2.69	78.46	9.03
25	7,476.7	86.249	2.75	84.12	2.47
26	7,478.1	86.477	2.73	83.74	3.17
27	7,479.3	86.448	2.68	83.65	3.24
28	7,423.0	83.306	2.70	81.83	5.19
29	7,424.0	86.505	2.73	81.40	5.09
30	7,425.5	86.476	2.72	80.88	6.47
31	7,479.5	86.164	2.70	83.60	2.98
32	7,481.0	86.193	2.70	81.36	5.61
33	7,482.0	86.448	2.69	81.11	6.17
34	7,482.1	86.193	2.68	81.23	5.76
35	8,425.0	86.164	2.64	82.66	4.07
36	8,425.9	86.136	2.62	82.88	3.78
37	8,434.5	86.732	2.67	79.20	8.68
38	8,435.3	86.278	2.65	77.57	10.09
39	8,436.1	63.028	2.63	56.36	8.99
40	8,437.0	86.562	2.63	78.31	9.53
41	8,438.2	86.335	2.64	78.32	9.28
42	8,439.0	86.334	2.61	80.09	7.23
43	8,483.0	79.179	2.67	77.09	2.64
44	8,510.0	64.134	2.71	60.19	6.15
45	8,512.3	81.571	2.64	78.03	4.34
46	8,513.0	68.897	2.68	66.30	3.77
47	8,514.0	68.359	2.68	64.00	6.38
48	8,515.3	66.119	2.66	59.50	10.01

$$\text{Porosity percent} = \frac{\text{Bulk Vol} - \text{Matrix Vol}}{\text{Bulk Vol}} \times 100$$

Figure 4-1 Porosity versus Bulk Density—from Natural Buttes No. 21

Figure 4-2 Porosity versus Acoustic Log Transit Time from Natural Buttes No. 21

4.1.3 Logging Techniques and Interpretations

Forty-eight plugs from Natural Buttes No. 21 in Uintah Cnty., Utah were measured for bulk volume with a caliper. Matrix volume was determined with the helium porosimeter. Resulting porosity determinations from these measurements are shown in Table 4-2.

Schlumberger's Borehole Compensated Sonic Log and Compensated Neutron-Density Log were analyzed to get approximations on travel time and density. Results of crossplots between porosity determinations with density are shown in Figure 4-1. Travel time versus porosity is shown in Figure 4-2.

Conclusions are not possible until the Modified Barnes Method and more detailed core analysis have been finished.

4.1.4 Reservoir Simulation Studies

Pre-fracture pressure buildup data taken on Zone 4A though 7 of Mobil well F31-13G were analyzed using standard pressure transient analysis techniques. The first portion of the work was preparation of type curve plots of the pressure data. These are shown in Figure 4-3 through 4-7.

Figure 4-3 Type Curve Plot of Pre-Frac Pressure Buildup Data from Zone 4A

Figure 4-4 Type Curve Plot of the Pre-Frac Pressure Buildup Data from Zone 4B

Figure 4-5 Type Curve Plot of Pre-Frac Pressure Buildup Data from Zone 5

Figure 4-6 Type Curve Plot of Pre-Frac Pressure Buildup Data from Zone 6

Figure 4-7 Type Curve Plot of Pre-Frac Pressure Buildup Data from Zone 7

A type curve plot is used to determine the time after which the pressure data measured during a buildup test are no longer affected by wellbore storage. The technique is discussed in detail in SPE Monograph, Volume 5, Advances in Well Test Analysis.

Pressure buildup data, dominated by wellbore storage, lie on a unit slope straight line on a type curve plot. As wellbore storage effects die out, the data begin curving away from the unit slope line. They plot on a curve having a very low slope.

The type curve plot of pressure data taken on the five zones all show the unit slope line. This line lasts for a minimum of 1.5 hrs for data from Zone 7 to a maximum of 30 hrs for data from Zone 4B. Data measured during this time are used to estimate the effective wellbore volume, V_w , during the test. This is done by calculating the apparent wellbore storage coefficient from:

$$C = \frac{q B_g}{24} \frac{\Delta t}{\Delta p}$$

where

- q = gas production rate prior to the buildup, SCFD
- B_g = gas formation volume factor, reservoir ft^3 /SCFD
- Δt = buildup time read from the unit slope straight line, hrs
- Δp = the delta pressure read from the unit slope line at Δt , psi

V_w , is then estimated from $V_w = C c_g$ where c_g is the compressibility of the gas in the wellbore.

Table 4-3 gives the wellbore volume estimated from the test data. The calculated wellbore volumes are low when compared to the volume calculated from well completion data. While they are low, the majority are fairly good ballpark values. The exception is the data from Zone 7. Its' V_w is considerably below that of 2-3/8 in. tubing in 7 in. casing without a packer. This may indicate some anomaly in the pressure data or that the annulus was packed off.

All of the type curve plots show the data breaking away from the unit slope line. None of the plots shows the flattening of the data that indicates the end of wellbore storage effects. This means that none of the data can be analyzed from a conventional Horner plot. For this reason, all data were analyzed using type curve plot matching. The technique described in the SPE Monograph, Volume 5, consists of matching the test data to the same type of plot prepared in terms of dimensionless pressure and dimensionless time. For a gas well, dimensionless pressure is defined as:

Table 4-3 Wellbore Volume Estimated from the Test Data

Zone	C, ft ³ /psi	V _w , ft ³	k, md	φ, fraction
4A	2.74	1232	0.037	0.036
4B	1.15	1081	0.025	0.039
5	1.69	1482	0.017	0.035
6	1.79	1207	0.064	0.028
7	0.37	446	0.070	0.089

Note: $s = 0$ for all zones.

Figure 4-8 Computer Match of Zone 4B Pre-Frac Buildup Using Reservoir Properties Given in Table 4-1

$$p_D = \frac{k h [M(p_i) - M(p_{wf})]}{1422 q T}$$

and dimensionless time by:

$$t_D = 0.0002637 \frac{k t}{\phi (\mu c_t)_i r_w^2}$$

where

- k = permeability, md
- h = formation thickness, ft
- q = production rate, MSCFD
- T = reservoir temperature, °R
- t = time, hrs
- $(\mu c_t)_i$ = viscosity and total compressibility at initial conditions, cp/psi
- r_w = wellbore radius, ft
- $M(p_i)$ = real gas potential at reservoir pressure, psi^2/cp
- $M(p_{wb})$ = real gas potential at the flowing pressure, psi^2/cp

The values of porosity and permeability calculated from the test data using type curve analysis are given in Table 4-3. The porosity values seem fairly good but the permeabilities seem high. All of the test data give a good match with Ramey's (1) curves for skin factor of zero.

Values of porosity and permeability obtained from the type curve match were used to simulate the Zone 4B test with the 3-D RDGAS simulator. The results are shown on Figure 4-8. Buildup pressures generated by the simulator are much higher than those measured during the test. The slopes of the two curves are very similar. The simulated data assumed an original reservoir pressure of 4,000 psig. A reduction in reservoir pressure would cause an equivalent reduction in the error between the two sets of data. Reservoir pressure would have to be reduced to approximately 2,300 psig to get the two curves to match. This is extremely low considering the depth of Zone 4B.

Subsequent computer runs in which the value of the skin factor was changed showed improvement, but did not give a good match to the test data. For this reason, matching the test data by varying all of the reservoir data within reasonable limits has been attempted.

The best match obtained thus far is shown on Figure 4-9. The computed data is high during the first 30 hrs, but matched fairly well after that. Figure 4-4 shows that wellbore storage was dominant during the first 30 hrs. The right combination of wellbore volume and skin factor has not been found, since the match is off during this time.

Results of this work demonstrate that conventional pressure transient analysis techniques do not work with the buildup data from Zone 4B. Since computer matching appears to give better results, all of the test data will be analyzed using computer matching.

Figure 4-9 Computer Match of Zone 4B Pre-Frac Buildup

Figure 4-10 Pressure Profile from Injection of 2 percent KCl Solution into the Mesaverde Core with a 0.1 in. wide Fracture Propped with 40/60 Mesh Sand

Table 4-4 Comparison of Statistical Data from Effluent KCl Samples from the Propped Mesaverde Core Experiment

Overburden Pressure psig	Maximum Particle Counts per ml	Means (microns)	Mode (microns)	Average Particle Size Range (microns)
500	40,730	2.28	1.81	1.700- 4.150
		2.28	1.81	1.700- 4.460
1,000	54,576	2.28	1.77	1.700- 4.150
		2.23	1.77	1.655- 4.060
2,000	68,810 68,766	2.39	1.77	1.655- 4.360
		2.44	1.73	1.655- 4.660
3,000	84,402	2.28	1.77	1.655- 4.360
4,000	83,326	2.62	1.73	1.655- 8.100
		2.74	1.73	1.655-12,270
5,000	95,668 97,526	2.62	1.73	1.655- 7.580
		2.68	1.77	1.655- 7.060
6,000	116,634	2.81	2.44	1.540- 9.990
		2.81	2.56	1.655- 8.700
7,000	122,682	3.22	2.74	1.655-10.680
		3.22	2.74	1.655-11.475
8,000	123,282	3.30	2.87	1.655-14.090
		3.30	2.87	1.655-14.090
9,000	119,010	2.87	2.28	1.655- 9.300
		2.87	2.44	1.655- 9.300

4.1.5 Rock-Fluid Interaction

4.1.5.1 Fracture Simulation

A 2 percent KCl solution of demineralized water was pumped through a 10 in. long, 1-1/2 in. diameter Mesaverde core split in half lengthwise and packed with 40-60 mesh sand to form a 0.10 in. wide fracture.

The actual overburden pressures imposed on the core system were: 500, 1,000, 2,000, 3,000, 4,000, 5,000, 6,000, 7,000, 8,000, and 9,000 psig. The initial liquid flowrate (injection rate) through the packed fracture was approximately 2.80 mls/minute.

As overburden pressure was applied up to 9,000 psi, injection pressure varied from 0 to 4.5 psig. A trace of the injection pressure is shown in Figure 4-10. The injection pressure continued to increase during the sampling time when the overburden pressure was constant indicating plugging of pores by the particles from the crushed proppant.

One-hundred ml samples of 2 percent KCl solution containing fines were collected at the exit end of the mounted core for each of the overburden pressures. The first four samples were collected during the flushing operation on the mounted core in order to establish a constant background particle count for the saturation fluid. This background contained fines from the sand proppant and clays from the core face.

Two sand samples were scraped off the faces of the core halves in the center of the fracture and at the exit end (including the sand adhering to the exit screen) at the conclusion of the injection experiments. Each sand sample was then placed in a glass beaker and covered with 100 mls of 2 percent KCl solution. The mixtures were run through a 45 micron sieve to remove the un-fractured material preparatory to analyzing them with the particle counter.

The effluent samples of 2 percent KCl solution and sand fines from the injection experiments were then analyzed with the particle counter. The particle mode increased from 1.77 to 2.87 microns, but the most prominent change was the size range which increased to 12 microns. These particle data are shown in Table 4-4. Particle concentration increased significantly. Since the experiment duration was short, (designed to get the particle distribution), there was not enough time for complete plugging. Pumping a broken gel through will simulate the frac-fluid and will be continued until plugging occurs.

4.1.5.2 In-Situ Permeability

The N₂ permeability for CIGE No. 21 core as a function of overburden pressure appears in Figure 4-11. As the overburden increases, the permeability decreases. Either physical compression of the core or pore plugging by mechanical formation of fines could cause this.

For a constant overburden pressure of 3,375 psi, the permeability decreases rapidly as the applied N₂ pressure is increased. A plot of permeability versus I/P is not linear, indicating a deviation from Darcy's Law (see Figure 4-12).

Next, a 2 percent KCl-brine solution was pumped across the core face at 1.7 mls/min with 3,375 psi overburden pressure. About 0.85 ml/min of brine flowed through the core with a backpressure of 1,400 to 1,500 psi. This is equivalent to a liquid permeability of 0.032 md under these conditions. The first 15 mls of brine collected were very turbid, indicating that colloidal particles were coming from the core. These fines could be those produced during core-cutting, or core relaxation. The pH of this solution was 7.4, whereas the pH of the brine was 5.7. This increase might reflect the natural formation pH, or invasion of alkaline drilling mud.

Nitrogen flow measured just prior to brine flooding gave a permeability of 23.4 μ d for 3,390 psig overburden and 200 psig N₂ pressure. After flooding, it took about 1-1/2 hrs to clear the core and lines of brine, using 200 psig of nitrogen. The N₂ permeability then increased rapidly until after 24 hrs; the permeability had increased to 25.2 μ d, and was still increasing. Greater permeability after brine flooding may be due to removal of fines by the brine. Core drying probably explains the generally slow increase in permeability.

Figure 4-11 Permeability versus Overburden Pressure

Figure 4-12 Permeability versus Reciprocal N₂ Pressure

A high pressure test cell purchased from Core Lab was received at BETC and has been used to study *in situ* formation characteristics of cores. Presently, work is in progress measuring gas permeabilities of cores from Mobil well PCV31-13. Five adjacent plugs were taken from a uniform core interval. Permeabilities were measured for repeatability and data consistency between plugs. These measurements suggest problems with blow-by between the plug and the rubber sleeve. A plug, which was cemented to the rubber sleeve with Pliabond, had a flow of 20 percent of the original value. Work is continuing to establish the severity of blow-by on low permeability cores and possible solutions.

4.1.6 Measurement of Formation Characteristics for Western Tight Sands—Institute of Gas Technology

4.1.6.1 Pressure Dependence of Single-Phase Permeability

To complete the Canyon Largo No. 256 rock series, a test was performed on C. L. No. 256 to No. 7105 for permeability as a function of confining pressure (Figure 4-13, Table 4-5). It follows decreasing trend but at a rate less than that of the other Canyon Largo core. Tests were also conducted on PCU F-31-13G cores No. 8498 and No. 9998 to observe changes in curve shape for previously unstressed core (Figure 4-14, Table 4-6). The unstressed core exhibits a stronger decrease in permeability as a function of confining pressure than the second test on the same core.

This is surprising since it would be expected that some micro fracturing takes place on inducing confining pressure which should result in the opposite trend. Tests are proceeding on the other cores to confirm these results and these cores will be tested again when they regain initial permeability. Whether the difference between the curves is a hysteresis effect or a reflection of precision of core testing is not yet known.

4.1.6.2 Effect of Core Saturation History on Relative Permeabilities to Gas and to Water

Cores were evacuated and resaturated with 10g/l NaCl solution to test for precision of the saturation technique (Table 4-7). The results indicate that differences can be as high as 6.1 percent and less at lower water saturations. These differences in saturated weights probably do not result from variable filling of pore space, but from water on the surface of the core that is difficult to blot to a consistent wetness. A technique to avoid this problem is being developed that involves the use of a humidity-controlled chamber. The effect of permeability on gas for cores No. 7011, No. 8498 and No. 9998, and one point for No. 9957 and No. 7103 are shown in Figure 4-15 and Table 4-8.

The effective gas permeability for the one point determined for No. 9957 agrees very closely with the previously reported curve. These curves are being redone in new low pressure cells with more data points while the high pressure cell will be used to begin high pore pressure tests.

Figure 4-13 Effect of Overburden Pressure on Gas Permeability

Table 4-5 Effect of Overburden Pressure on Initial Gas Permeability

Canyon Largo No. 265, Core No.	K*(md)	Percent Permeability at Overburden Pressures										
		300	500	900	1000	1500	2000	3000	4000	5000	6000	7000
7105	.0334	79.34	70.66	55.09	52.99	43.17	35.48	24.91	18.95	15.33	13.17	11.11

*Permeability at 40 psi inlet pressure and 140 psi confining pressure

Figure 4-14 Effect of Overburden Pressure on Initial Gas Permeability of Stressed and Unstressed Core

Table 4-6 Effect of Overburden Pressure on Initial Gas Permeability of Stressed and Unstressed Core

Core No.	K^* (md)	500	1000	2000	3000	4000	5000
Unstressed 8498	.027	43.8	34.4	23.0	13.3	8.9	5.5
Stressed 8498	.026	--	47.9	--	18.9	--	7.4
Unstressed 8498	.029	48.7	41.0	27.0	17.8	14.2	10.2
Stressed 9998	.031	54.3	47.0	31.0	--	17.1	--

*Permeability at 40 psi inlet pressure and 140 psi confining pressure

From Core Lab core analysis on the PCU F31-13G core, some interesting information was obtained from the Dean Stark fluid saturation determination. Core Lab's Mod II, "Fundamentals of Core Analysis" shows their estimates for reservoir fluid content in core before and after the coring operation. For a water base mud, as was used by Mobil, a gas productive formation that is badly flushed would result in a gas to water ratio about what is seen in these cores. It must be realized that this illustration is qualitative, describing "typical" fluid contents for "typical reservoirs" and not tight sands. In reality, as may be apparent in the logs, these cores may have begun with approximately 50 percent gas in the gas cap.

Table 4-7 Test of Water Saturation Technique Precision

Core No.	A Dry Weight	B 12-27-78 Wet Weight	C 1-22-79 Wet Weight	D B - A	E C - A	$\frac{D - E}{(D + E/2)}$ (percent)
6949	63.11	64.97	64.86	1.86	1.75	6.09
7011	58.82	61.29	61.27	2.47	2.45	0.81
7103	62.46	64.25	64.20	1.79	1.74	2.83
8498	62.60	64.01	64.01	1.41	1.41	0.00
9957	57.31	59.38	59.29	2.07	1.98	4.44
9998	61.45	63.05	63.00	1.60	1.55	3.17

Table 4-8 Effect of Water Saturation on Gas Permeability for PCU F31-13G Core

7011		8498		9998		9957		7103	
S_w (percent)	K_{eg} (md)	S_w (percent)	K_{eg} (md)	S_w (percent)	K_{eg} (md)	S_w (percent)	K_{eg} (md)	S_w (percent)	K_{eg} (md)
63.97	2.86×10^{-3}	61.70	4.67×10^{-3}	54.19	1.15×10^{-2}	48.99	2.08×10^{-2}	50.56	1.68×10^{-2}
53.85	6.25×10^{-3}	47.52	8.88×10^{-3}	39.35	1.91×10^{-2}			29.61	5.07×10^{-2}
43.32	1.12×10^{-2}	34.04	1.53×10^{-2}	26.45	2.60×10^{-2}				
33.20	1.92×10^{-2}	24.82	2.05×10^{-2}	0.00	3.15×10^{-2}				
21.05	3.14×10^{-2}	14.18	2.23×10^{-2}						
11.34	4.08×10^{-2}	0.00	2.76×10^{-2}						
0.00	6.21×10^{-2}								

4.1.7 Schedule Status

Figure 4-16 is a milestone chart and depicts the progress during the reporting period of BETC projects.

Figure 4-15 Effect of Water Saturation on Gas Permeability

Figure 4-16 Milestone Chart-BETC

WGSP-BETC	FY-79											
B. FORMATION DAMAGE	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1. ROCK-FRAC FLUID INTERACTION												
Current research internal report												
Physical measurements												
Core samples												
Filtration tests												
Permeabilities												
Preliminary analysis and data correlation												
Annual report												
2. FORMATION DAMAGE FROM FRAC-FLUID COMPONENTS												
Literature review												
Damage evaluation												

WGSP-BETC	FY-79											
B. FORMATION DAMAGE	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
3. PROPPANT TRANSPORT & EMBEDMENT												
Evaluation of particle transport in proppant beds												
Evaluation of proppant embedment in tight gas sands												

Figure 4-16 Continued

WGSP-BETC	FY-79											
C. LOGGING TECHNIQUES	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1. MAPPING & CONTOUR OF R _w												
Review current research												
Study of current logs												
Internal report												
Extant data assembly												
Isoresistivity maps												
Computer contours												
Annual report												
Report on contour of R _w & water components in Uinta Basin												
Examine and contour R _w & water components in Piceance Basin												

WGSP-BETC	FY-79											
C. LOGGING TECHNIQUES	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
2. LOGGING EVALUATION												
Effects of interface conductivity on electric logging												
Physical measurements												
Core preparation & selection												
Resistivity												
Data correlations												
Conductivities from Rink & Shopper equation												
Permeabilities												
Report												
Study of Logging Techniques												
Neutron log data evaluation												
Acoustic log data evaluation												

Figure 4-16 Continued

Figure 4-16 Continued

4.2 LAWRENCE LIVERMORE LABORATORY

4.2.1 Theoretical Analysis

Massive hydraulic fracturing normally occurs as a series of crack expansions. Each expansion occurs rapidly, supposedly near the elastic body wave speeds. A thorough analysis of hydrofracturing problems requires that the dynamics be included. This is especially true when the fracturing takes place near or through an interface which separates materials of differing elastic properties. In this case there will be reflections of elastic waves at the interface due to impedance mismatch. In most cases it would be expected that the dynamic fracturing would be strongly affected by these reflected waves.

Currently, LLL has not included dynamics in their theoretical analyses of hydrofracturing near an interface. The dynamic model has just been modified to enable simpler analyses.

Eventually, LLL will consider cracking across interfaces. In this case the important mechanisms are flaw joining, and fracturing and frictional slip along the interface. The present model is only set up to do fracturing up to an interface. The crack propagation speed is set at $0.4 C_p$, where C_p is the dilatational wave speed.

In the current model, a two-dimensional bilateral crack initiates in the center of a material that is typified by the elastic Lamé constants λ_1 and μ_1 . This material is sandwiched between two other materials which are characterized by λ_2 and μ_2 . The density of both materials is the same, 2.7 gm/cm^3 . The problem geometry is shown in Figure 4-17.

At the crack speed selected the reflected elastic waves from the far interface just reach the midpoint between $x = 0$ and the near interface when the problem is terminated.

Thus, the data given for points near the interface are the same as the data from an expanding bilateral crack approaching a single interface on one side.

Four cases were considered. The elastic constants used for these cases are given in Table 4-9.

Table 4-9 The Four Cases Described by Material Properties

Case	μ_1, λ_1 (Mbar)	μ_2, λ_2 (Mbar)	Description
1	0.3	0.3	homogeneous
2	0.3	0.1	inhomogeneous
3	0.3	∞	interfaces rigid
4	0.3	0.033333	strongly inhomogeneous

The problem is symmetric about the y axis and the x axis so that fourfold symmetry holds. This makes the numerical computation easier because only a quarter plane is required for modeling purposes.

Figure 4-17 A Pressurized Crack that Propagates Out to an Interface. The Problem is Symmetric about the x and y Axes.

The results from these calculations (Figure 4-18) are the perpendicular displacements of the point $\chi = .429d$, $\gamma = .018d$. The expected maximum displacement is for Case 1, the homogeneous case, when the interface is transparent and there are no reflected waves. Minimum displacements occur for Case 3, when the interface is rigid. In the two other cases the second material is less rigid than the first and displacement decreases as the material becomes more dissimilar.

4.2.2 Experimental Program

Experiments designed to study friction between rock surfaces have begun using the apparatus described in last month's progress report (see Figure 4-19, December 1978 Monthly Report). Thus far experiments have been performed on rough and smooth surfaces between blocks of Indiana limestone and between blocks of Nugget sandstone. Analysis of these experiments is not yet complete and more experiments will be required to obtain statistics due to the variability of rocks. A typical record from an experiment on friction between smooth surfaces of Indiana limestone is shown in Figure 4-19. The horizontal axis is force.

The staircase record is the applied horizontal load, i.e., the normal load across the interface, which is measured by a transducer. The calibration for this load is 666 lb/in. The lower trace is then increased until slip occurs. The normal load is then increased by a 666 lb increment and the vertical force is again increased until slip occurs. This process is repeated as shown in Figure 4-19, the frictional force exhibits a slip-stick character which is typical for rocks.¹ So far only experiments between rocks of the same type have been done. In the future, experiments to look at friction between different rock types, water saturated and dry rocks, and between surfaces of other materials such as PMMA will be planned. These experiments will aid in better understanding of crack propagation across interfaces in and between these materials.

¹Jaeger, J. C., and N.G.W. Cook, *Fundamentals of Rock Mechanics*, John Wiley & Sons, New York 1976, p. 61.

Figure 4-19 Frictional and Normal Forces Across Indiana Limestone Interface

4.2.3 Mechanical Measurements

During the month of January, 1979, work for the Gas Stimulation Program was in planning and specimens for laboratory studies on rocks from the Mesaverde Group, Rio Blanco County, Colorado are being prepared. There are three units of rock to sample: sandstone, shale, and a mixture of these two. The following studies have been planned for the sandstone and shale units.

- Brazil tests (tension), both parallel and perpendicular to bedding.
- Uniaxial stress loading in compression to determine failure envelope. Values of confining pressures (σ_3) range to 0.5 GPa. The major stress axis (σ_1) is either parallel or perpendicular to bedding.
- Pressure/volume determinations at hydrostatic pressures up to 2.0 GPa in specimens with the axis either parallel or perpendicular to bedding.
- Determine the dynamic elastic constant tensor as a function of confining pressures up to 1.0 GPa by measuring ultrasonic velocities in six directions simultaneously.
- Hot-gas permeability measurements, either parallel or perpendicular to bedding, and confining pressures up to 50 MPa and temperatures up to 250°C.

About 90 percent of the specimen preparation for the first three studies has been completed.

4.2.4 Related Activities

During the month LLL provided briefings at the Fossil Fuel Extraction Division at DOE Headquarters on the program's progress and accomplishments.

4.2.5 Schedule Status

Figure 4-20 is a milestone chart showing the progress of LLL projects for FY 1979.

4.3 SANDIA LABORATORIES

4.3.1 EGR Instrumentation and Diagnostic Program

4.3.1.1 Hydraulic Fracture Characterization

The current generator has been modified in an effort to eliminate or at least reduce the transient potentials associated with the measurements observed during the Gordon Turkey Farm D-1 experiment. Techniques have also been investigated for reducing the effects of these transients in the measuring electronics; a satisfactory circuit modification has not been determined.

Figure 4-20 Milestone Chart—LLL

Data from the breakdown tests in Gordon Turkey Farms (GTF) and UPRR50El have been digitized. Analysis of the data after analog and digital filtering indicates a direction of fracture for GTF of approximately N 55° W to S 55° E. Orientation of the fracture on UPRR was from N 46° W to S 46° E.

Directions were obtained by plotting a hodogram of the horizontal geophones and observing the direction of break from noise level. A typical hodogram plot is shown in Figure 4-21. This plot shows a direction of 305° (N 55° W). P-wave and S-wave arrival times are also observable from the hodogram plot. The time difference of these arrivals indicates the fracture length was in the 150 to 200 ft range.

4.3.1.1.3 Borehole Hydrophone Array

Edo Western has completed delivery on the six hydrophones to be used in the first down-hole hydrophone system. End caps were designed and fabricated in order to test the "O" ring seals at each end of the unit. Due to rework on the end threads of one hydrophone, only five of the units were tested to 10,000 psi. All five units passed the test and are now being prepared for electrical testing at high pressures.

High gain amplifier and power supply circuits have been assembled and are functioning properly. The amp mixer-line driver printed circuit board has been returned for rework.

4.3.1.2 Advanced Borehole Logging

The electromagnetic problem of induction coils buried in the earth has received some attention in the past. Most of this work is based upon the assumption that the displacement current is negligible compared to the conduction current, a valid assumption at low frequencies. To utilize the potential information contained in the dielectric constant, high and multiple frequency probes need to be understood. Two efforts are directed along these lines. One is analytical and straight-forward, but will be unwieldy where many dielectric interfaces are present. The other is a very general finite difference solution of the coupled partial differential equations. Although this latter work is far from complete, it was presented to the staff of the Petroleum Recovery Research Center at Socorro.

Before the dielectric measurements can be useful, they must be correlated with flow and other production parameters which are being measured at the PRRC. The field efforts of PRRC can be augmented by Sandia's logging techniques. Both laboratories have agreed to collaborate. This also includes interactions with the Petroleum department at Socorro.

4.3.2 Schedule Status

Figure 4-22 is a milestone chart showing the status of Sandia's WGSP activities.

4.4 M. D. WOOD, INC., TILTMETER

4.4.1 Current Status

On January 12, M. D. Wood, Inc. began a new contract for analysis and documentation of all past DOE supported data and to map hydraulic fractures in low permeability Western gas reservoirs. Experiments will be fielded in Texas and Colorado in conjunction with Amoco Research, Tulsa, Oklahoma, Amoco Production, Denver, Colorado, and Shell Research Labs.

Figure 4-22 Milestone Chart—Sandia

5. FIELD TESTS AND DEMONSTRATIONS

5.1 Background

Field tests and demonstrations are an essential part of the WGSP. Only through practical application can the findings of laboratory tests and modeling studies be verified. The active WGSP demonstrations follow:

- A dry gas injection experiment in the Wattenberg Field, Colorado, by Colorado Interstate Gas Company,
- MHF demonstrations by Gas Producing Enterprises in the Uinta Basin, Utah,
- MHF treatment of the Cotton Valley Limestone Formation in Limestone County, Texas, by Mitchell Energy Corporation,
- MHF demonstrations in the Piceance Basin, Colorado, by Mobil Research and Development Corporation and Rio Blanco Natural Gas Company, and
- A mineback testing program by Sandia Laboratories.

The CER Corporation RB-MHF 3 is on an inactive status pending satisfactory contractual arrangements to perform additional tests, and for final disposition of the well. A draft copy of the RB-MHF 3 final report is being reviewed.

Table 5-1 summarizes both completed and active WGSP MHF treatments. Progress of these ongoing projects is presented in the following sections.

Table 5-1 MHF Contract Locations and Frac Data

COMPANY, BASIN	LOCATION T/R/Sec	WELL	INTERVAL FRACTURED ft	FRAC DATE	FRAC TREATMENT Lb of Sand	INJECTED FLUID 10 ³ Gal
AUSTRAL Piceance, Mesaverde	7S/94W, Sec 3 Garfield Cty Colorado	Federal 3-94	5,170- 6,333	8-25-76	1,140,000	542 Gel Gel H O
CONSORTIUM MANAGED BY CER CORPORATION Piceance, Mesaverde	3S/98W, Sec 11 Rio Blanco Cty Colorado	RB-MHF-3	8,048- 8,078 7,760- 7,864 5,925- 6,016 5,851- 5,869	10-23-74 5- 2-75 5- 4-76 11- 3-76	400,000 880,080 815,000 448,000	117 Gel 285 Gel 400 Gel 228 Gel
GAS PRODUCING ENTERPRISES, INC. Uinta, Wasatch and Mesaverde	10S/22E/Sec 10 Uintah Cty Utah	Natural Buttes No. 18	6,490- 8,952	9-22-76	1,480,000	745 Gel
	10S/21E/Sec 21 Uintah Cty Utah	Natural Buttes No. 19	8,909- 9,864 7,224- 8,676	9-21-76 9-28-76	424,000 784,000	280 Gel 364 Gel
	9S/21E/Sec 22 Uintah Cty Utah	Natural Buttes No. 14	6,646- 8,004	3-15-77	1,093,000	544 Gel
	9S/21E/Sec 28 Uintah Cty Utah	Natural Buttes No. 20	8,498- 9,476	6-22-77	826,000	322 Gel
	10S/22E/Sec 18 Uintah Cty Utah	Natural Buttes No. 22	6,858- 8,550	11-21-77	1,091,000	479 Gel
	9S/21E/Sec 19 Uintah Cty Utah	Natural Buttes No. 9	5,661- 8,934	3-27-78	554,000	349 Gel
	10S/21E/Sec 29 Uintah Cty Utah	Natural Buttes No. 2	7,251- 8,774	8- 8-78	1,965,000	722 Gel
	10S/22E/Sec 7 Uintah Cty Utah	Natural Buttes No. 23	5,080- 6,294	10- 4-78	440,000	240 Gel
DALLAS PRODUCTION Fort Worth, Bend Cong.	Ben D. Smith Survey A-779 Wise Cty Texas	Ferguson A-1	5,957- 6,794	9-10-76	506,000	139 Foam 198 Emul
EL PASO NATL. GAS Norther Green River, Fort Union	30N/108W/Sec 5 Sublette Cty Wyoming	Pinedale Unit No. 5	10,950-11,180 10,120-10,790	7- 2-75 10-20-75	518,000 1,422,000	183 Emul 8 Gel 459 Gel
MITCHELL ENERGY Cotton Valley, Limestone Trend	Limestone Cty Texas	Muse-Duke No. 1	11,220-11,430	11-15-78	2,800,000	891 Gel
MOBIL Piceance, Mesaverde	2S/97W/Sec 13 Rio Blanco Cty Colorado	F-31-13G	10,549-10,680 9,392- 9,538 8,765- 8,972 8,163- 8,650 7,704- 7,794 7,324- 7,476	6-22-77 8-24-77 5-10-78 7- 6-78 9- 7-78 11-15-78	580,000 600,000 388,000 660,000 218,000 700,000	316 Gel 260 Gel 150 Gel 288 Gel 120 Gel 365 Gel
PACIFIC TRANSMISSION Uinta, Mesaverde	8S/23E/Sec 25 Uintah Cty Utah	Federal 23-25	NO FRACS PERFORMED			
RIO BLANCO NATL. GAS Piceance, Mesaverde	4S/98W/Sec 4 Rio Blanco Cty Colorado	Federal 498-4-1	6,150- 6,312 5,376- 5,960	10-22-76 11-30-77	766,000 243,000+ 22,500 Beads	276 Gel 164 Gel
WESTCO Uinta, Mesaverde	10S/19E/Sec 34 Uintah Cty Utah	Home Fed No. 1	7,826- 9,437 10,014-10,202	12-21-76 10- 1-76	500,000 600,000	412 Gel 248 Gel

RIO BLANCO MASSIVE HYDRAULIC FRACTURING EXPERIMENT

EY-76-C-08-0623

CER Corporation
Las Vegas, Nevada

Status: Awaiting Advisory
Committee Decision

Interagency Agreement Date: June 19, 1974
Anticipated Completion Date: July 1, 1979

Project Cost (estimated):	DOE	\$1,975,000
	Industry	1,630,000
	Total	\$3,605,000

Principal Investigator: G. R. Luetkehans
Technical Advisor for DOE: C. H. Atkinson

OBJECTIVE

This stimulation experiment is being conducted in low-permeability, massive gas-bearing sandstone reservoirs in the Piceance Basin in western Colorado, to test advanced hydraulic fracturing technology where it has not been possible to obtain commercial production rates. This test is located about 1 mile from the 1973 Rio Blanco nuclear stimulation site to permit comparison of nuclear and hydraulic fracturing techniques in this area.

5.2 CER CORPORATION

5.2.1 Summary of Past Activities

DOE contract EY-76-C-0623 was awarded to CER Corporation in March, 1974. The original contract provided for the drilling of a new well and two MHF treatments. Contract modifications added two additional MHF treatments and extended the term of the contract to July 1, 1979.

5.2.2 Current Status

Field activities on RB-MHF 3 well have been suspended. Negotiations have taken place with an outside party to complete the commingling of the fractured gas zones to perform additional tests in return for the well and subsequent gas production. Legal documents are being prepared for distribution to the project participants for their concurrence.

A draft of a comprehensive final report is being prepared and is expected to be released for review in February.

WATTENBERG FIELD

EY-77-C-08-1514

Colorado Interstate Gas Company
Colorado Springs, Colorado

Status: Active

Contract Date: September 1, 1977
Anticipated Completion Date: March 1, 1981

Total Project Cost (estimated):	DOE	\$ 75,000
	CIG	99,000
	Total	\$174,000

Principal Investigator: Howard Fredrickson
Technical Project Officer for DOE: C. H. Atkinson

OBJECTIVE

Cyclic injection of dry natural gas is the method to be used to increase production of tight gas sands.

5.3 COLORADO INTERSTATE GAS COMPANY

5.3.1 Scope of Work

DOE and Colorado Interstate Gas Company (CIG) entered into Contract No. EY-77-C-08-1514 on September 1, 1977. The experiment will determine if productivity of wells completed in low-permeability natural gas reservoirs can be improved by reducing the interstitial water saturation by cyclic injection of dry natural gas. In addition, cyclic injection of dry natural gas may improve productivity by dehydrating matrix clays and by removal of formation damage adjacent to the surfaces of induced fractures.

5.3.2 Current Status

The pipeline between the Miller No. 1 and the Sprague No. 1 well has been laid, but the connections have not been completed. The compressor, in storage in east Denver, will be installed and tested after the sixty day pressure test has been completed. The DOE well test facility is scheduled to setup and commence measuring the Miller No. 1 bottom hole pressure in February.

NATURAL BUTTES UNIT, UINTAH COUNTY, UTAH MASSIVE HYDRAULIC FRACTURING DEMONSTRATION

EY-76-C-08-0681

Gas Producing Enterprises, Inc.
Subsidiary of Coastal States Gas Co.
Houston, Texas

Status: Active

Contract Date: July 1, 1976
Anticipated Completion: September 30, 1979

Total Project Cost (estimated):	DOE	\$2,827,000
	Industry (prior costs)	1,881,000
	Industry (new costs)	3,051,000
	Total	\$7,759,000

Principal Investigator: W. E. Spencer
Technical Project Officer for DOE: C. H. Atkinson

OBJECTIVE

To evaluate the effectiveness of massive hydraulic fracturing for stimulating natural gas production from thick, deep sandstone reservoirs having low-permeability.

5.4 GAS PRODUCING ENTERPRISES, INC.

5.4.1 Summary of Past Activities

The GPE wells, Natural Buttes Units 14, 18, 20, and 22 flowed to sales during December. Natural Buttes No. 19 and 21 were shut in and NBU 2 and 23 were also shut in waiting on a pipeline connection.

5.4.2 Current Status

The GPE wells, Natural Buttes Units 9, 14, 18, and 20 flowed to sales during January. Natural Buttes Units 2 and 19 were shut in, and NBU 22 began flowing to sales on January 30. NBU 21 could not be completed in the gas-bearing formations to be tested under the contract because these formations were not gas productive. Figures 5-1 through 5-6 show production figures. Table 5-2 is a summary of MHF treatments performed on GPE wells to date.

Future plans are to flow units 2, 9, 14, 18, 19, 20, 22, and 23, and to temporarily abandon Unit 21.

Work to assess damage to sample permeability caused by the interaction of fracturing fluids with the host rock has been completed by Terra Tek on the Wasatch Formation and Mesaverde sandstone Group. Preliminary data from four fracturing fluid/rock interaction tests is presented in Table 5-2. The tests also investigate the amount of permeability recovery after backflow. Discussion of results will be done after the interaction tests are completed.

Samples were one inch in diameter by one inch in length with the sample axis parallel to the bedding plane. Permeability at atmospheric conditions for as-received cores was determined first.

Pressure and temperature were gradually increased to *in situ* conditions to determine the effect of *in situ* stress and temperature on permeability. After *in situ* conditions were reached, fracturing fluid was flowed across one face of the sample for four hours at injection pressures used to simulate field fracture conditions. After the termination of fracturing fluid flow, permeability was measured to assess damage. Before allowing the fracturing fluid to break, nitrogen was backflowed for 1 to 2 hours to assess any permeability recovery before the gelled fluid broke up. Then, a shut-in time of twelve hours was allowed to assure the gel was completely broken.

Nitrogen, at *in situ* pore pressure, was introduced at the sample back face to simulate clean up.

Figure 5-1
Flow Rate Performance of
Natural Buttes No. 9 Well

Figure 5-2
Flow Rate Performance of
Natural Buttes No. 14 Well

Figure 5-3

**Flow Rate Performance of
Natural Buttes No. 18 Well**

Figure 5-4

**Flow Rate Performance of
Natural Buttes No. 19 Well**

Figure 5-5
*Flow Rate Performance of
Natural Buttes No. 20 Well*

Figure 5-6
*Flow Rate Performance of
Natural Buttes No. 22 Well*

Table 5-2 Summary of MHF Treatments

Well	No. of Zones Perf.	Net Ft. of Pay	Net Ft. Per Zone	Average		% Sd	Type of Fluid	Frac Job Size Gal of Gel	Lb of Proppant	Calc. Frac Length ft	Est. 1st Year Avg. Prod. Rate MCFD
Natural Buttes No. 18 DOE	18	224	12.5	10.0	48	88.0	Versa Frac	695,000	1,480,000	882	1,200
Natural Buttes No. 19 DOE	19	194	10.2	9.5	47	87.0	40# Guar Gum	655,000	1,237,000	950	60
Natural Buttes No. 14 DOE	15	271	18.0	9.9	49	65.0	YF4-PSD	544,000	1,082,000	879	600
Natural Buttes No. 20 DOE	8	65	8.1	9.9	44	88.5	YF4-PSD	309,000	826,000	1,150	800
Natural Buttes No. 22 DOE	24	196	8.1	12.0	45	85.0	YF4-PSD	478,758	1,091,000		
Natural Buttes No. 9 DOE	(35)	779*	22.0*	Unkn	Unkn	Unkn	40# Guar Gum	314,000	553,000		
Stage 1 CIGE 2-29-10-21 DOE	10	91	9.1	10.0	40	80.0	MY-T-GEL III	195,000	170,500		
Stage 2	12	181	15.1	11.3	42	85.0	MY-T-GEL III	805,230	1,956,000		
CIGE 23-7-10-22 DOE	10	156	15.6	9.0	60	78.0	YF4-PSD	240,000	470,000		

*Using GR as only indication of net sand which more closely equals gross sand.

FALLON-NORTH PERSONVILLE FIELD, TEXAS, MASSIVE HYDRAULIC FRACTURING DEMONSTRATION

EF-78-C-08-1547

Mitchell Energy Corporation
Houston, Texas

Status: Active

Contract Date: March 15, 1978
Anticipated Completion: April 30, 1979

Total Project Cost (estimated):	DOE	\$ 553,771
	Industry	<u>1,074,550</u>
	Total	\$1,628,321

Principal Investigator: F. D. Covey
Technical Project Officer for DOE: C. H. Atkinson

OBJECTIVE

To test massive hydraulic fracturing in the Cotton Valley Limestone Formation.

5.5 MITCHELL ENERGY CORPORATION

5.5.1 Summary of Past Activities

The M.E.C. Muse-Duke No. 1 flowed at a initial rate of 6 MMCFD and 80 BBL of frac water after fracturing. A second attempt was made to determine the orientation of the fracture with the Radial Differential Temperature (RDT) tools, but because of "O" ring failures, the tool shorted out. Radioactivity in the well bore from the radioactive sand placed in the proppant could not be located. A sand bridge was located at 11,331 ft covering the bottom seven perforations. It was thought that all of the sand proppant was in the covered lower half of the created fracture which rendered the radioactive sand in the proppant undetectable. Post pressure transient tests were planned after cleaning out the sand and relogging.

5.5.2 Current Status

M.E.C. Muse-Duke No. 1 was flowing 4,600 MCFD and 34 BBL of frac water per day through a 22/64 in. choke with a flowing tubing pressure of 1,800 psi. A total of 11,593 BBL out of 21,223 BBL of frac fluid have been recovered to date. Flow rates and pressures are beginning to level off as shown in Figure 5-7.

Due to cold weather in January, the gas transmission company requested that M.E.C. produce as much gas as possible; therefore, the Muse-Duke No. 1 was not shut in to clean out the sand bridge and relog as planned, nor have the post pressure transient tests been conducted. Work has been postponed until the gas demand slackens.

Mitchell Energy Corporation has received the ultrasonic and radiographic reports of the monitoring of the wellhead valves during the fracturing operations. Very little erosion occurred in the valves during the pumping of 2.8 million lb of sand. Radiographs of the upper valve showed a net bore enlargement of 0.079 in. when compared to the base radiograph. The lower valve showed a net enlargement of 0.103 in. Both valves were relatively undamaged. Seats and bearing areas appeared to have no damage and are in good condition.

Figure 5-7 Muse-Duke No. 1 Well Test History

PICEANCE CREEK FIELD, COLORADO, MASSIVE HYDRAULIC FRACTURING DEMONSTRATION

EY-76-C-08-0678

Mobil Research and Development Corporation
Dallas, Texas

Status: Active

Contract Date: July 1, 1976
Anticipated Completion: June 1st 1979

Total Project Cost (estimated):	DOE	\$2,510,000
	Contractor (prior costs)	2,376,485
	Contractor (new costs)	1,590,515
	Total	\$6,477,000

Principal Investigator: John L. Fitch
Technical Project Officer for DOE: C. H. Atkinson

OBJECTIVE

To evaluate the effectiveness of massive hydraulic fracturing for stimulating natural gas production from thick, deep sandstone reservoirs having extremely low-permeability.

5.6 MOBIL RESEARCH AND DEVELOPMENT

5.6.1 Summary of Past Activities

Zone 9 only was open to flow. The well flowed to the sales line during December, but was shut-in on December 31 due to expiration of the temporary sales permit. A new sales permit is expected to be granted early in 1979.

5.6.2 Current Status

The well was shut-in during January while awaiting extension of Mobil's temporary arrangements to sell gas. This was accomplished and Zone 9 will be opened to flow on February 1.

5.6.3 Future Plans

Zone 9 will be flowed to sales until arrangements can be made to pull the two bridge plugs and clean out the well. Mobil hopes to have all zones flowing to sales by March 1.

RIO BLANCO COUNTY, COLORADO MASSIVE HYDRAULIC FRACTURING DEMONSTRATION

EY-76-C-08-0677

Rio Blanco Natural Gas Company
Denver, Colorado

Status: Active

Contract Date: August 1, 1976
Anticipated Completion: December 15, 1978

Total Project Cost (estimated):	DOE	\$ 410,000
	Contractor	593,000
	Total	\$1,003,000

Principal Investigator: Robert E. Chancellor
Technical Project Officer for DOE: C. H. Atkinson

OBJECTIVE

To evaluate the effectiveness of massive hydraulic fracturing for stimulating natural gas production from thick, deep sandstone reservoirs having extremely low permeability.

5.7 RIO BLANCO NATURAL GAS COMPANY

5.7.1 Summary of Past Activities

DOE Contract EY-76-C-08-0677 was signed with Rio Blanco Natural Gas Company in June, 1976. The first MHF treatment was performed on October 22, 1976. A supplemental agreement, effective October 1, 1977, provided for a second MHF treatment, which was performed on November 30, 1977.

5.7.2 Current Status

Gas flow continued to be restricted due to persistent water production. The present production rate is 200 MCFD plus water, with clean up continuing.

NEVADA TEST SITE NYE COUNTY, NEVADA MINEBACK TESTING

Sandia Laboratories
Albuquerque, New Mexico

Status: Active

Principal Investigator:

D. A. Northrop

OBJECTIVE

To develop an understanding of the fracturing process for stimulation and thereby improve the production of natural gas from low-permeability reservoirs. This will be accomplished by conducting controlled fracture experiments which are accessible by mineback for direct observation and evaluation.

5.8 SANDIA LABORATORIES—MINEBACK

5.8.1 Summary of Past Activities

5.8.1.1 Stimulation Research for Enhanced Gas Recovery

The Formation Interface Fracture Experiment in Hole No. 6 is a field experiment conducted at the Nevada Test Site to determine the parameters that influence and control containment of hydraulic fractures. Grout filled fractures were propagated above and below welded tuff/ashfall tuff interface and subsequently mined back to examine the behavior of the fractures at the interface. It was found that the fracture that was initiated in the low modulus ashfall tuff propagated through the interface into the high modulus welded tuff. This suggests that present rock mechanics models, which predict that a bounding higher modulus material, will contain a hydraulic fracture, are in error.

An exploratory coring program is currently underway to determine the general shape of the fractures. This shape should reflect upon the influence of the interface and the *in situ* stresses on overall fracture propagation and behavior. Figure 5-8 shows the results of this coring program to date with respect to Hole No.6, the fracture intervals and the subsequent mineback. Coreholes in which grout was located are shown as closed circles and the open circles indicate no grout. The four holes designated EV6-15 through EV6-18 are holes that were cored in January. The main thrust of fracture propagation is apparently downward, although the region above the welded zone has not yet been explored.

The Interface Test Series is a set of small hydraulic fracture experiments that will be conducted to determine the effect of pump rate on the containment of a fracture at a geologic, material property interface. Final plans have been completed for the first set of these tests to be conducted in February. Four zones in a hole drilled just below the same welded tuff/ashfall tuff interface utilized in the Formation Interface Experiment will be fractured with 150 gal of dyed water at the maximum flow rate of the in-tunnel pumping system (10 gal/min). These fractures will subsequently be mined back to determine if the fractures propagated through the interface. If the fractures do cross the interface, future fractures using lower flow rates will be conducted. These tests will also provide another look at containment using a different fluid (water vs. grout) and a different configuration (horizontal borehole) as well as the dynamic results.

5.8.1.2 Multiple Fracturing

Last summer, Sandia Laboratories investigated a High Energy Gas Fracturing Concept by conducting three experiments with mineback evaluation at the Nevada Test Site; this activity was supported by DOE Fossil Energy Development Program Funds. The concept is to tailor the pressure-time behavior of the deflagration of a propellant to impart a load to the wellbore of about one order of magnitude above the *in situ* stresses but below the flow stress of the rock. The pressure is applied over an interval on the order of milliseconds to create and extend multiple fractures radially from the borehole. The experiments showed that the concept was valid; one experiment had a pressure loading rate (20 psi/ μ sec) and a peak pressure (13,800 psi) sufficient to initiate and extend 12 separate fractures in random radial directions. Fracture lengths varied from 1/2 to 8 ft for a 20 lb propellant charge in an 8 in. borehole. This is believed to be the first time multiple fracture initiation and extension has been demonstrated under realistic *in situ* conditions. This technique offers a potentially attractive method to alleviate wellbore damage for various in site technology applications.

As a result of these tests, the Morgantown Energy Technology Center has requested Sandia to conduct a series of mineback experiments at NTS to investigate different concepts for multiple fracturing. Representatives from Physics International, Kinetech, DuPont, and others have been invited to an introductory meeting scheduled in Albuquerque in February. The objective of the meeting is to provide familiarity with the different concepts and to obtain sufficient information to allow a detailed experiment plan and cost estimate to be made.

5.8.1.3 Nuclear Containment Studies

Nuclear containment studies, financed by DOE's Division of Military Applications, are investigating aspects of the containment of underground nuclear detonations. With a series of small (8 to 100 lb) high explosive (H.E.) experiments, Sandia is probing the residual stress field that remains after the passage of the dynamic effects of the explosion. These residual stress fields are created when explosives are detonated in geologic media; thus gas stimulation techniques that utilize explosives will generate these effects.

In the past month, Sandia Laboratories have detonated a 100 lb H.E. sphere in the G Tunnel (Test RS-3). Gauges installed close to the instrumentation showed a pressure of 7,500 psi a few seconds after the detonation. Post-shot, a series of zones at various radii from the initial charge center were hydraulically fractured with dyed water to assess the amplitude and direction of the residual stress field. Mineback on this event is expected in the next month.

5.8.2 Current Status

5.8.2.1 Microcrack Model

A rock mechanics/fracture mechanics model was formulated in January that describes the character of the microcrack zone at a crack tip in rock. A straightforward modification of existing theories for metals was made which uses a failure theory more appropriate for rock. Initial calculations and results have already revealed several explanations for "anomalous" behavior in hydraulic fracturing and in fracture toughness testing.

A process zone occurs at any crack tip regardless of the material, and much has been written in particular about the character of the "plastic zone" that occurs in metals. Most metals obey a von Mises yield condition while rocks tend to fail due to the maximum tensile stress. With this in mind, equations for crack tip stresses were used to determine the contour for which the maximum tensile stress is equal to the ultimate stress. With the addition of hydrostatic *in situ* stresses, the equation for this contour becomes:

$$r = \frac{1}{2\pi} \left(\frac{K_{Ic}}{\sigma_u + \bar{\sigma}} \right)^2 \cos \frac{\theta}{2} \left(1 + \sin \frac{\theta}{2} \right)^2$$

where

- r, θ = polar coordinates from the crack tip
- K_{Ic} = fracture toughness
- σ_u = ultimate stress
- $\bar{\sigma}$ = hydrostatic stress

This equation can be made nondimensional and is plotted in Figure 5-9. Initial observations and conclusions from this model are summarized below.

The size of the microcrack zone decreases rapidly with an increase in hydrostatic stress. (Plastic zone sizes in metals are unaffected by hydrostatic stress). For example, calculations for Nevada ashfall tuff indicate that the zone size decreases from 0.4 in. for an unconfined laboratory experiment to 0.03 in. for the *in situ* stress conditions near the Hole No. 5 experiment. This is consistent with the petrographic analysis of tuff samples taken from a hydraulic fracture that indicated little, if any, microcracking (see section on petrographic analysis 5.8.3.4). This dramatic effect of hydrostatic stress leads to the following conclusions.

Figure 5-9 Damage Zone at Crack Tip in Rock Based on Maximum Tensile Stress

Figure 5-10 Finite Element Grid for Hydraulic Fracture in a Layered Medium

- Hydraulic fracture propagation near a parting plane such as in the Hole No. 5 experiment is not affected by the plane itself any more than a large particle affects it. The propagation behavior (containment) must be governed by *in situ* stress variations and it is the parting plane that allows for a discontinuous change in the minimum principal stress.
- Fracture toughness, K_{IC} , of rock has been observed to increase with an increase of hydrostatic stress and this effect is probably a direct result of the decreased microcrack zone size. This behavior for rock has been considered anomalous by some since K_{IC} of metals is generally unaffected by hydrostatic stress.

Unlike the plastic zone size in metals, the size of the microcrack zone is unaffected by out-of-plane stresses (i.e. plane stress vs. plane strain). This is that the K_{IC} of rock and concrete are known not to depend on specimen thickness while the K_{IC} of metals exhibits a strong dependence on thickness. The fact that this result fits observed behavior lends strong support to the model itself.

Additional work is in progress to determine the effect on the microcrack zone of non-hydrostatic *in situ* stress states. In addition, the orientation of the microcracks within the zone itself will be determined. Laboratory experiments are also being indicated that would help verify the model and demonstrate the need to simulate properly the *in situ* stress states that occur in typical hydraulic fracturing situations.

5.8.2.2 Smeared Interface

Results from the Hole No. 6 Formation Interface Experiment have demonstrated that present fracture mechanics analyses that deal with a fracture approaching a material interface are inadequate. Unrealistic aspects of the present models may be avoided by simulating the interface with a gradual change of properties. This "smeared interface" model is being addressed by numerical calculations, material property measurements, and laboratory experiments.

Numerical calculations were begun this month using the APES finite element code which is now operative on the Sandia computer network. A sample grid showing the upper left quadrant of a vertical hydraulic fracture in a layered medium is shown in Figure 5-10. Present calculations are being compared with known analytical results to determine if the grid is sufficiently large to simulate infinite boundaries. Possible code development work for special "infinite boundary elements" and "variable modulus elements" is being considered. After initial checkout is complete the Hole No. 6 experiment will be simulated using the material properties that will soon be measured from core in the Rock Properties Lab.

5.8.2.3 Acoustic Emission During Hydraulic Fracturing

Acoustic emissions during hydraulic fracturing have been successfully recorded using geophones and are being used to map fractures. Particular reference is made here to the Hole No. 6 experiment and the seismic instrumentation and data on that test. In determining the possible sources of these signals some quick calculations were made to indicate the relative energy levels associated with crack propagation and fracture inflation.

It was found that for the Hole No. 6 experiment, the energy of crack propagation was only about 0.5 in.-lb/in.² while the energy required to inflate the fracture was 150 in.-lb/in.² These figures indicate that the acoustic emissions recorded from a hydraulic fracture event are not likely to emanate from the fracture tip. A more plausible mechanism is the release of frictional strain energy associated with small fractures intersecting the main fracture at oblique angles (45° is most favorable) producing mostly shear waves. The energy for this mechanism comes from the large reserve of strain energy stored due to fracture inflation.

5.8.2.4 Fluid Mechanics

A fluid mechanics modeling program to assemble a realistic model of the fluid mechanics of fracturing has been initiated. The purpose of this modeling effort is to obtain a better understanding of the interplaying mechanisms that control the process, aid in the interpretation of previous mineback experiments, provide a basis for the analysis and interpretation of the next large scale mineback experiment where dynamic fracture widths and pressures will be measured, and to provide realistic conditions (e.g., pressure loading in the crack) upon which to apply rock mechanics considerations for the study of the effect of interfaces and *in situ* stresses on fracture propagation.

The proposed model employs a complete width equation (i.e., the width distribution can be determined for any pressure distribution of the fracture), and one dimensional continuity and momentum equation that include the transient and convective terms. The increasing crack length is handled by a transformation that will account for the moving boundary and the system of equations is solved by a finite difference procedure using an iterative technique. This model should provide realistic values of the width, pressure and length, and their time dependence for an idealized system (2-dimensional or penny-shaped cracks).

5.8.2.5 Petrographic Analysis

In order to investigate the significance of microfracturing in the hydraulic fracturing process, a number of thin sections were prepared from rock samples near the Hole No. 6 experiment. The sections were cut both perpendicular and parallel to hydraulic fracture planes in the ashfall tuff. Petrographic examination of these sections has not revealed any significant increase in the number of microfractures near the fracture plane. There is no strong indication that any of the microfractures observed were induced by the hydraulic fracturing. Most of the detected fractures have been reasonably attributed to the section preparation process, the sampling procedure, or were probably induced by natural processes.

Eight 4 in. diameter cores, taken from the ashfall tuff at specified distances from the No. 6 grouted hydrofrac, have been shipped to Mike Feves and Frank Strickland of Dowell in Tulsa, Oklahoma. These samples will be utilized for an independent microfracture detection and analysis.

5.8.3 Schedule Status

Figure 5-11 is a milestone chart showing the progress of individual projects within the mineback program.

Figure 5-11 Milestone Chart—Sandia (Mineback)