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NATURAL GAS MASSIVE HYDRAULIC FRACTURE
RESEARCH AND ADVANCED TECHNOLOGY PROJECT

QUARTERLY REPORT:
FEBRUARY 1977 THROUGH APRIL 1977

CARL L. SCHUSTER AND DAVID A. NORTHROP

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Quarterly Report: February 1977 through April 1977

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MASTER

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I. SUMMARY

This is the third quarterly report of the second reporting year for the Sandia Laboratories Program titled, "Natural Gas Massive Hydraulic Fracture Research and Advanced Technology Project." The program is funded by the Division of Oil, Gas and Shale Technology of ERDA. This report summarizes the activities from February 1, 1977 through April 30, 1977.

During this quarter two field experiments were conducted with the surface electrical potential measurement system. The first was an MHF experiment with G.P.E. (Gas Producing Enterprises) on March 15 south of Vernal, Utah. This fracture was a joint ERDA-industry funded experiment. Approximately 640,000 gallons of fluid and 1.1 million pounds of proppant was injected into multilayered gas pay zones from a depth of 6500 feet to 8000 feet. This analysis of the data has produced several new and different concepts related to fracture design and growth.

The G.P.E. experiment design called for eight stages of pad, proppant and balls to fracture 15 zones. The thinking was that each stage would treat two zones and the balls would seal the perforations taking fluid and new zones would then be treated. Surface electrical potential data was collected every two minutes and was smoothed using digital filtering techniques in the PDP-11. The potential changes that occurred did not agree with the preconceived conceptual plan of eight stages of fracturing operation. The potential changes and their interpretations do shed a completely different light on the fracturing events. The significant interpretations are listed below:

- 1) Fracture initiation and termination is not associated with ball action.
- 2) Fracture growth termination is possibly associated with formation properties rather than pressures, fluid density or pumping rate.
- 3) Only four substantial fractures were created; three in the first stage and one in the fourth stage.
- 4) The balance of the pumping evidently resulted in these fractures being inflated and receiving the proppant.

The second experiment conducted during this quarter was the CONOCO hydrofracture that was performed as a part of their tertiary oil recovery experiment in the Big Muddy Field east of Casper, Wyoming. It was a small fracture (300 bbl) initiated at a depth of approximately 3500 feet. Eighteen pairs of potential probes were placed at 20° intervals around the fracture well at spacings of 1000 feet and 2000 feet. In addition, the relative potential was measured on six wells adjacent (< 1000 feet) to the fracture

well. These wells contained the CONOCO pressure gages to monitor formation pressure during the fracture and subsequent recovery operations. Potential measurements were made at twenty second intervals on alternate current probes: one a downhole sinker bar at formation depth and the other the casing of the fracture well. The downhole data analysis indicates an asymmetric fracture in the easterly direction.

Electrical modeling effort has continued and has been centered on the design and fabrication of the model facility. This facility should be completed next quarter and allow several configurations of fracture to be studied.

Seismic work has been completely shifted to the downhole, wall clamped system. Fabrication has been completed and testing will begin during the next quarter.

Mineback to a multistaged, proppant distribution experiment has been completed at the Nevada Test Site. The mineback has revealed a complex fracture system in which no consistent proppant transport pattern was obtained. The complexity of the fracture is in contrast to previous fracture experiments conducted elsewhere in the tunnel. Further mapping, in situ stress determinations, and material property measurements are underway to examine the phenomena. Planning has been initiated for a formation-interface hydraulic fracture experiment to be conducted later this year.

II. G.P.E. UTAH MHF EXPERIMENT

On March 15, 1977, Sandia participated in G.P.E.'s MHF experiment in their Natural Buttes #14 well is located approximately 40 miles south of Vernal, Utah; the fracture was performed by Dowell. The electrical potential measurement system consisted of 24 pairs of potential probes placed around the well with an inner probe radius of 1800 feet and an outer probe radius of 3800 feet. Field data were collected at intervals of two minutes starting at 0650 hours and continued through 1815 hours. Pumping started at 0715 hours and continued through 1800 hours at a near constant rate of 25 barrels per minute. Approximately 640,000 gallons of pumping fluid and 1.1 million pounds of proppant were injected in a multilayered gas pay zone at depths of 6500 to 8000 feet.

The surface electrical potential system was the only fracture mapping system deployed for the experiment. The G.P.E. well is an old well that was being refractured and where 4-1/2 inch casing was already installed. Hence, a downhole current probe couldn't be utilized and the current was injected at the well head.

G.P.E.'s fracture design called for eight stages of pad, proppant and balls to fracture 15 zones. The thinking was that each stage would treat two zones and the balls would seal the perforations taking fluid and new zones would then be treated. Surface electrical potential data was collected every two minutes and was smoothed using digital filtering techniques in the PDP-11. The potential changes that occurred did not agree with the preconceived conceptual plan of eight stages of fracturing operation. The potential changes and their interpretations do shed a completely different light on the fracturing events. The significant interpretations are listed below:

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These interpretations are speculative in nature and will certainly require further verifications. If true, the surface electrical potential system would provide considerably more insight into fracturing operations than just the orientation. These concepts will be discussed with the producing company, service companies and all interested ERDA contractors in the coming months. Undoubtedly, several fracturing experiments will have to be analyzed before the significance of this data can truly be understood.

An experiment data report containing all the data and its analysis will be prepared and disseminated to all interested organizations in the near future.

III. CONOCO EOR EXPERIMENT

The CONOCO hydrofracture was performed on March 22 as a part of a tertiary oil recovery experiment in the Big Muddy Field east of Casper, Wyoming. It was a small fracture (300 bbl) initiated at a depth of approximately 3500 feet. Sandia Laboratories' objective in this experiment was to test the effectiveness of the surface potential measurement system on a small open hole hydrofracture. In addition to the Sandia array, CONOCO had installed several pressure gages in surrounding wells as a diagnostic tool to assist in determining fracture orientation. The well had been completed, open hole, and a downhole current probe was emplaced. Software modifications to the PDP-11 allowed for two sets of potential data to be collected. One set used the well head, the other the

downhole current probe for injecting the current. Post-data analysis will allow these two configurations to be compared.

Measurements were taken by recording the potentials at 24 locations around the well before, during, and after the fracture. Eighteen pairs of potential probes were placed at 20° intervals around the fracture well at spacings of 1000 feet and 2000 feet. In addition, the relative potential was measured on six wells adjacent (< 1000 feet) to the fracture well. These were the wells containing the pressure gages to monitor formation pressure during the fracture and subsequent recovery operations.

Potential measurements were made at twenty second intervals on alternate current probes. Approximately 12,000 gallons of fluid containing 4% potassium chloride were pumped which was calculated to produce a fracture length of approximately 500 feet. This conductive fluid which results in a changing geometry for the current electrode creates the potential changes that are seen at the surface.

As discussed previously, changes in the surface potential indicate the direction and asymmetry of the fracture. The measurement just prior to breakdown is used as the reference and percentage changes in potential from this reference are plotted versus azimuth. These plots are shown in Fig. 1. Based on the computer modeling calculations, the plots indicate an asymmetrical east-west fracture with the major length of the fracture going primarily east from the fractured well.

Figure 2 is a plot of the data taken on radial A1 located 10° south of East, after being filtered by a 0.004 Hz low pass filter. Fracture growth can be recognized by a decreasing potential. Figure 2 then suggests that the primary time of fracture growth then occurred from 11:12:20 to 11:14:20. Thus, during the first four minutes of pumping, the majority of the electrical length of the fracture was created and during the balance of the pumping this fracture was only made wider.

An experiment data report will also be prepared for this fracture experiment and disseminated.

IV. ELECTROLYTIC MODEL TANK

To date, the primary technique employed for monitoring the effectiveness of massive hydraulic fracture (MHF) programs has been the surface measurement of induced electrical potentials when the fracture, or fracture plus well casing, are charged with electrical current. Mathematical modeling of this boundary value problem has been performed for the case of an homogeneous earth with an uniform casing/fracture source electrode. However,

CONLF4

RADIAL: A1

PERCENT CHANGE FROM REFERENCE VALUE AT TIME 111220

REFERENCE VALUE = .141347

the introduction of layering and lateral inhomogeneity (both in terms of electrical resistivity) in the earth model, imperfect or variable casing-earth electrical contact, or the presence of man-made distortions (other metal well casings in the area) produce mathematical rigors which are not tractable by techniques currently available. As these situations are typically the rule rather than the exception in actual field locations, and as an accurate, quantitative description of the fracture system (length, height, etc.) is desired, an alternate modeling technique was sought which could accommodate those situations met in the field which reduce the applicability of mathematical synthesis. This was the rationale behind the development of an electrolytic model tank.

An electrolytic model tank is basically a water-filled tank with water of variable salinity representing the homogeneous earth. Layering may be simulated by the introduction of sheets of material of varied resistivity into the water. Similarly, casing, ore bodies, cavities or other size-limited bodies may be modeled and placed in appropriate positions within the tank. Scaling of lengths, resistivities, and frequency of applied current from the field to the model is dictated by the following relation (assuming magnetic permeability of model and full scale materials is the same):

$$\frac{\omega' L'^2}{\zeta'} = \omega \frac{L^2}{\zeta}$$

where

ζ' = model resistivity

ζ = full scale resistivity

ω' = model current frequency

ω = full scale current frequency

L' = characteristic model length

L = corresponding full scale length

Our initial interest was to locate an existing model facility and arrange for its use for modeling MHF experiments. To this end, R. P. McCann and T. L. Dobecki visited the electrolytic model facilities at the United States Geological Survey (USGS), Denver and at the Colorado School of Mines (CSM), Golden, Colorado. Both tanks were massive poured cement structures, rectangular in shape, and typically 10 ft. x 15 ft. x 5 to 8 ft. deep. Both tanks were fitted for the performance of electromagnetic model experiments and would therefore require retooling for our galvanic experiments, thereby interrupting the progress of on-going tests. The USGS facility is in current use with projected heavy use by USGS personnel in the near future. The CSM facility, on the other hand, is being terminated for future office space and will not be available. The situation, therefore, dictated construction of a model tank at Sandia.

The electrolytic model tank currently under development at Sandia is of unique design (Figure 3). The tank is much smaller than those described earlier, measuring 5 ft. x 5 ft. x 3 ft. and utilizes a hemispherical aluminum shell (I.D. = 47.750 in.) as the

Fig. 3. Electrolytic Modeling Tank Employing a Hemispherical Return Current Electrode.

return electrode. The reasoning behind the choice of a hemispherical electrode may be explained as follows:

The electrical potential field about a point electrode at the earth's surface, if the return electrode is an infinite distance away, is given by

$$V = \frac{I\xi}{2\pi R}$$

where

I = impressed current

ξ = resistivity of earth material

R = distance to observation point.

All equipotential surfaces are given by $R = \text{constant}$ which are hemispheres centered on the point source. If, on the other hand, the return electrode is made a hemisphere centered on the point source, it becomes an equipotential surface and current flow is radial from the point source to the shell. Therefore, again all equipotential surfaces are hemispheres with the same potential distribution as a point source except for an additive constant. For potential difference measurements, this technique is equivalent to having a return electrode at infinity while maintaining a reasonably small sized tank. For standard four-electrode (Wenner or Schlumberger type, e.g.), the aluminum hemisphere may be removed, and experiments may be carried out in the box itself.

An advantage of a large tank is that high precision in placement of electrodes or in lengths of models is not critical. As the size of the tank is decreased, the scaling relation requires greater precision in the measurement of lengths. A scaled track is fit to the top of the hemisphere upon which moveable potential-measuring electrodes may be located with an accuracy of ± 0.005 in. (± 0.12 mm).

The potential measuring and current source electrodes are made of stainless steel hypodermic needles. Several needle diameters and metal platings will be tested and evaluated in the course of preliminary experiments.

The central current electrode (when utilizing the return hemisphere) will simulate the casing and/or fracture. This will be mounted on the track in a calibrated, rotatable mount. In this way, the orientation of the fracture with respect to the surface potential measuring dipole may be varied from 0° to 360° , again to simulate the field configuration of radial dipoles used in MHF mapping programs. Size of the fracture, casing-earth contact, and other situations peculiar to the casing-fracture system may be modeled by changing the size and material characteristics of the current electrode.

The proposed program of experimentation utilizing the electrolytic tank consists of, generally, tests for evaluation of the tank facility followed by experiments to directly model the MHF process. Each individual test could easily lead to numerous other tests of a related nature, but a tentative program may be outlined as follows:

Test the accuracy of the hemispherical shell electrode as an approximation to an infinitely removed point source for a point source at the center of the tank.

Evaluate various current sources and potential measurements systems for consistency and ease of operation.

Evaluate different model materials and metal platings.

Determine the limits of applicability of the hemispherical tank for centrally-located current sources which are not point sources (vertical or horizontal line sources representing fractures and casing).

Model numerous fracture depths and lengths to derive empirical relations between fracture geometry and surface potential measurements.

Model fracture experiments in the presence of subsurface layering, lateral resistivity variation, etc., to observe the effect of these on surface potential measurements.

Other tests may be proposed for future experiments, however, these are felt most applicable to the MHF program.

V. BOREHOLE SEISMIC LOCATOR

The Borehole Seismic Locator (BSL) was assembled and pressure tested. The geophone section which was fabricated from 304 stainless steel failed at 12,000 psi. This housing has been remade from 4340 steel. Stainless steel was initially used because of its proximity to the compass orientation unit. However, it is felt that because of the battery pack separating it from the compass unit, 4340 steel can be used.

During the following quarter surface explosive tests are planned at the test well recently drilled on Kirtland Air Force Base. The test plan is to detonate a number of various size charges at the surface in a number of locations. The charge sites will be in contact with the limestone bed to which the BSL is coupled. The received signals

will be analyzed for wave content and recognition, amplitudes, frequency content and source location information. Because of the size and weight of the BSL, handling techniques will also be evaluated.

It is also planned to install the BSL on a hydrofracture test at the Nevada Test Site sometime this summer. Seismic events will be recorded in order to obtain information pertaining to the ability of the BSL to map a hydrofracture. Mineback is planned so that precise hydrofracture location will be known.

In late summer or early fall the BSL will be used for recording seismic signals from a hydrofracture of an AMOCO well in the Wattenberg Oil Field in Colorado.

Calibration data has been recorded for the electronic portion of the BSL. Gain and phase characteristics of the amplifiers and voltage controlled oscillators will be determined. This data is still in data reduction but hopefully will be available soon.

VI. DEEP WELL INSTRUMENTATION SYSTEM

Preliminary specifications for the mobile field laboratory for instrumentation to support the western tight gas sands program has been submitted to seven or eight companies. The laboratory will consist of an instrumentation trailer and a mast truck with all of the equipment necessary for long period monitoring of deep wells. Bids have not been received as yet, but are expected shortly. The proposals will be evaluated and an order placed for delivery late fall.

VII. MINEBACK EXPERIMENTS AT THE NEVADA TEST SITE

Mineback operations were conducted during most of the report period on the hydraulic fracture created in Hole U12G10.5 (hole DH-5). This was a vertical hole drilled from the top of Rainer Mesa down to the G tunnel level resulting in a depth of approximately 1395 feet. A multistaged fracture experiment had been conducted in this hole in July 1976, but mineback operations did not commence until early 1977. The first evidence of the fractures were observed in February, and it became readily apparent as mining advanced that a very complex fracture(s) were formed rather than the single vertical fracture that had repeatedly been formed in previous tests at different locations within the tunnel complex.

The complexity of the fracture network made it necessary to slow mining so that sufficient mapping and documentation of the fractures could be accomplished. By the end of April, the injection hole had been reached. At least two fracture systems were induced and the multistaged, colored-sand proppant has shown no consistent transport pattern.

Three diagrams and two photographs (Figure 4-8) are presented to illustrate the complexity of the fracture system. These drawings given here are preliminary as more detailed maps are being compiled from comprehensive data and notes taken during mineback. Figure 4 is a plan view of the mine excavation around Hole DH-5. Figures 5 and 6 are photos showing some of the details of the fractures as they were being exhumed. The fields of view of these two photos are shown on Figure 4 as are the locations of two vertical cross-sections that are presented as Figures 7 and 8.

Figure 5 is looking upwards to the bottom of the drill hole. The position of the hole (hidden in the roof) is located a few feet behind the card being held by the miner. In the right center of the photograph the dark colored face contains sand proppant along what is now one face of the fracture. The width of the fracture was about 3 mm. This fracture terminates abruptly along a horizontal bedding plane as seen in Figure 7.

Figure 6 shows conditions at the working face when a vertical fault was exposed. A low angle fracture is shown curving in from the left center to a position just below the "+6" mark. The fracture terminated at this fault. A high angle fracture is shown on the right. It also terminates at the fault.

Figures 7 and 8 illustrate the nature of the fractures by cross-section. In Figure 7, the extent of the fracture network is shown. The fault on the left is the one which terminated fracture growth to the north. The horizontal bedding plane at an elevation of 6183' stopped vertical growth. The full extent of the fracture has not been explored below 6158'. Figure 8 is a cross-section looking north. Note the high angle fracture is a composite of echelon type fractures. The low angle fracture dips at about 30 degrees to the north.

Future work is planned at this site so as to better understand why a complex fracture system was induced from what was thought to be a simple hydraulic fracture experiment. In situ stresses may be complicated in this particular area, or the stress field could be almost hydrostatic. In the latter case, subtle changes in rock properties would be the dominant factor on fracture growth. Plans include additional in situ stress determinations into the walls of the excavation using both the overcore and small hydraulic fracture techniques. Cores recovered from this work will be tested for additional physical properties.

Planning of an "interface" experiment was initiated at a joint working group meeting between Halliburton, Dowell, AMOCO Research and Sandia held in Tulsa on February 22, 1977; an additional fracture design meeting was held with Dowell (who holds the present service company contract at the NTS) on March 29, 1977. It was the concensus that the experiment

Fig. 4 Plan View of Mineback Operations, Hole DH-5.

Figure 5. View Looking Upwards
to Drill Hole DH-5

Figure 6. View Looking at the Working Face

Preliminary Data

Fig. 8. Vertical Cross Section Near Hole DH-5

should be kept simple in design so as to test fracture growth both above and below a geologic formation interface. This interface consists of a brittle, welded tuff underlain by more porous, softer ash-fall tuff. The plan would be to induce a fracture about 10 feet below the contact followed by a second about 10 feet above. A tentative site for the experiment, designated as Hole U12G10.6 (hole DH-6), has been selected several hundred feet southwest of the staged proppant experiment (Hole DH-5) previously described. Exploratory core drilling to the region is underway. It is anticipated that the west-dipping welded/ash-fall tuff contact will be at tunnel level at this location. Selected core samples of both units will be sent to AMOCO, Halliburton, Dowell as well as commercial testing laboratories.

VIII. TECHNICAL MEETINGS, SYMPOSIUMS & REPORTS

A. Columbia Gas

A meeting on March 8, 1977, at Columbia Gas in Columbus, Ohio was attended by C. Komar, MERC; Darrell Wood, USGS; C. L. Schuster, Sandia; and several local participants. Results from both fracture experiments conducted in 1976 were reviewed and the somewhat unusual results surrounding the screen-out discussed. Still no definitive or substantial results are apparent. Future testing was discussed and three requirements were presented for a meaningful surface electrical potential experiment: (1) add 2% KCl to the frac fluid; (2) resurvey potential probe locations for more optimum locations; (3) provide a downhole current probe. These requirements were reviewed by Columbia and MERC for possible inclusion into the future tests. Their apparent decision was to not go to the expense involved to collect the electrical data for another fracture experiment.

B. AMOCO

A planning meeting was held on April 15, 1977, in Denver with the division office and research personnel of AMOCO. Tentative plans for an experimental series of fractures in the Wattenberg area were formulated. These tests are scheduled for this fall to minimize the interference with the agriculture in the area.

AMOCO is planning to collect orientated cores, run their downhole television system and provide the necessary support for the ERDA experiments.

Sandia will field the surface electrical potential system and hopefully also collect some downhole seismic profiling data. The USGS plans to support these tests with their tiltmeter array. The formation to be fractured is the Sussex at a depth of approximately 4000 feet which is an oil-bearing zone that overlays the deeper Wattenberg gas sands. These tests should provide an intermediate depth for fracture evaluations.

- C. On April 5, 1977, Sandia participated at the MHF-3 Technical Committee meeting in Las Vegas, Nevada sponsored by CER. L. D. Tyler presented a summary of Sandia mineback activities at the Nevada Test Site where hydraulic fractures are being directly observed and their behavior analyzed. D. A. Northrop briefly discussed future plans for the mineback testing program, described the role that such testing would play in the development of MHF technology, and emphasized the need for, and solicited, industrial participation in all aspects of the program.

The next day Sandia Laboratories sponsored a trip for meeting participants to the Nevada Test Site. The tour included a movie on overall NTS test activities and a visit to Sedan Crater. The afternoon was spent at G tunnel, where L. D. Tyler, W. C. Vollendorf and G. R. Griswold described the on-going test activities: (a) mineback at hole DH-3, a fracture orientation test, (b) mineback at hole DH-5, a proppant distribution test with a complex geometry, (c) coring activities to assess the welded-ashfall tuff interface for a future fracture test (hole DH-6), and (d) contained explosive tests. A great deal of interest was shown by the participants in the on-going work. Especially notable were many comments by industry on the value of such a program; several offers of help, future participation, and support were received.

- D. Eric Smith and Steve McKetta of Columbia Gas Company, Columbus, Ohio, visited the Sandia mineback experiments at NTS on April 19, 1977. L. D. Tyler briefed them on the results and activities to date. Their interest stems from a knowledge of Sandia activities on chemical explosive fracturing tests in Devonian shale in West Virginia.
- E. David A. Northrop is a member of a working group charged to develop, by the end of FY 77, a program strategy for enhanced gas recovery. ERDA, ERC, and National Laboratory (LLL and Sandia) members are providing technical direction in the formulation and development of this plan. The first meeting was held April 18-19, 1977 in Washington.

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