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ENHANCED GAS RECOVERY PROGRAM
SECOND ANNUAL REPORT - PART I
OCTOBER 1976 THROUGH SEPTEMBER 1977

MASTER

D. A. NORTHROP AND C. L. SCHUSTER, EDITORS

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ABSTRACT

Massive hydraulic fracture mapping field experiments continued in FY 77 with Sandia participating in fractures with G.P.E., Amoco, Shell and Conoco. The surface electrical potential system has demonstrated that the fracture orientation can be determined to within ± 5 degrees and has clearly shown that most fractures are asymmetrical. This system has been completely documented and has had wide exposure to the industry providing for the transfer of its technology. Improvements in the electrical system, its analytical model and the development of new systems for fracture diagnostics was also continuing.

Hydraulic and explosive fracturing experiments have been conducted adjacent to an existing tunnel complex at DOE's Nevada Test Site and have been directly observed by subsequent mineback activities. Evaluation of a proppant distribution experiment has revealed a very complex fracture system which differed significantly from design; additional in situ stress and material property measurements are being made to quantify observed behavior. An experiment has been designed and

* Part II of this publication is a separate volume and contains all the Appendices referred to in this publication, Part I.

conducted which will examine hydraulic fracture behavior at a geologic interface between formations with significantly different moduli, Poisson's ratios and porosities; mineback evaluation will occur next year. In conjunction with a nuclear containment program, the stresses surrounding a contained explosive detonation have been examined. A 256 lb TNT detonation produced no radial fractures extending from the main cavity, but gases escaping down a borehole did create a 30 x 75 ft fracture in a region of reduced overburden stress caused by the explosion.

Specific aid was provided in the planning and development of the Western Tight Gas Sands Project and DOE's Enhanced Gas Recovery Strategy Plan. A resource survey of the Greater Green River Basin was conducted as part of the latter activity.

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I. INTRODUCTION AND SUMMARY

Sandia Laboratories conducts two projects which are part of the United States Department of Energy's (DOE) Enhanced Gas Recovery Program. One is the Massive Hydraulic Fracture Characterization Project whose objective is to develop instrumentation systems for characterizing fracture systems, formations and other parameters contributing to enhanced gas recovery. The other is the Mineback Stimulation Test Project whose objective is to understand, and thus improve, fracturing processes for stimulation of natural gas production from low permeability formations which contain a high potential resource. This report summarizes activities conducted under these two projects during Fiscal Year 1977: October 1, 1976 through September 30, 1977.

The Massive Hydraulic Fracture Characterization Project began in 1974 with the initial application of Sandia's instrumentation capability in a joint experiment with El Paso Natural Gas in the Pinedale Field, Green River Basin, Wyoming. The initial effort was an attempt to measure the orientation and growth of a massive hydraulic fracture using both surface seismic recording and electrical potential mapping techniques. In the ensuing years, the surface seismic program has been discontinued because of its inability to map fractures from the surface. The electrical potential technique has grown and has been fielded on several experiments over the past three years. This instrumentation system has been deployed on both joint DOE-industry funded and private industry experiments on a non-transfer of funds basis. These experiments have covered a range of stimulation techniques in natural gas, petroleum and tar sands recovery.

The electrical potential technique is based upon the surface measurement of potential changes caused by a changing current electrode geometry. The current electrode is the fracture well and the conductive frac fluid introduced into the subsurface formation causes the geometry to change during the fracture operation. These potential changes are small and require extensive data collection and analysis to ascertain fracture orientation. Model calculations aid in the interpretation of fracture orientation and symmetry.

Recent program activities have focused upon the continued development and application of the surface electrical potential technique as well as a broadening of scope to develop other instrumentation systems and techniques for characterizing geological features such as sand lenses and natural fracture systems, effects due to different stimulation processes, and other factors affecting enhanced gas recovery. A continuing close relationship with industry is anticipated in these activities.

The Mineback Stimulation Test Project was initiated in FY77. However, the program has built upon fracturing and mineback activities which have been conducted since 1974 in G-tunnel, at the Nevada Test Site, as part of a nuclear containment program sponsored by the Division of Military Applications under ERDA. The commonality of objectives between the containment and enhanced gas recovery activities is striking and the continued close relationship between the two programs will be mutually beneficial.

Various stimulation techniques have been applied to the so-called unconventional natural gas resources, such as the western tight sands basins and the eastern Devonian shale formations, with varying, but generally non-economic, results. Massive hydraulic fracturing (MHF) as being practiced is based upon extensive "conventional" fracturing experience, laboratory testing, and empirical design models; the extrapolation to the massive scale has not been generally successful. Dendritic, foam, gas and chemical explosive fracturing techniques have been applied and successes or failures are not well understood. Industry has often stated the need to perform experiments in an environment which allows for direct examination and evaluation.

Mineback evaluation provides this opportunity. A detailed physical description can be obtained directly and which can be correlated with measured geologic material properties, in situ stress distributions, fluid behavior, and the operational parameters of the test. Supportive rock and fluid mechanics laboratory and modeling work will be performed to aid in this interpretation. The mineback also provides the opportunity for the calibration of instrumentation techniques under known conditions. Thus, mineback testing provides significantly more information than the evaluation of a commercial stimulation job which is based primarily upon gas production. Industry and service company participation in the program will ensure that the results will impact the experience and knowledge base used in production; such industry interest has been high. The program will provide a unique opportunity to quantify and understand fracture behavior.

Sandia's projects derive their support from both the Eastern Gas Shales Project and Western Gas Sands Project which are major parts of DOE's Enhanced Gas Recovery Program. Sandia's projects provide a broad supporting research and development capability. Activities are planned, conducted, and reported with the aim of contributing to the objectives of both the Eastern and Western Projects and to the overall development of Enhanced Gas Recovery technology.

The surface electrical potential experiments have covered a wide range of testing situations and have undergone a more intensive analytical study. Sandia participated in fracturing experiments with G.P.E., Amoco, Shell and Conoco. Documentation was completed for the electronic system and several presentations of its capabilities have been made facilitating the transfer of this new technology to industry. For reservoir planning and well placement, the system has demonstrated that fracture orientation can be determined to $\pm$ 5 degrees and that most fractures are asymmetrical. Mapping experiments included 1) a very shallow test for model verification, 2) an enhanced oil recovery fracture, 3) a very tight gas sand, and 4) two Mesa Verde multi zone fractures. Each of these experiments contributed to our overall understanding of the capabilities and limitation of the surface electrical potential technique. Formalization of the analytical work, coupled with an in-house model facility, was initiated and should lead to an even better understanding of these field results. Hole 6 fracture experiment at NTS was instrumented with a seismic recording system and produced several seismic signals during pumping. The analysis of this data could reveal not only fracture locations but the nature of the source mechanisms. Extensive analysis of this data will be persued in FY 78 both in-house and with consultants. The receiving of seismic signals associated with fracturing increases our expectations for the borehole seismic system that currently is under development.

The mineback experiments have provided considerable information during the past year. Fracture evaluation methods have been demonstrated and local geological descriptions have been developed. Mineback evaluation of a propped hydraulic fracture experiment indicated a very complex fracture system was created. Observed fracture lengths were only 5 and 25 ft at the depth of the fracture interval which differs significantly from the design length of 175 ft. The top of the fracture has been delineated and fracture growth must be downwards. No distinct patterns of the different colored proppant were found. Examples of interactions of the fracture with faults and formation bedding are numerous. Additional material property and in situ stress data in this region are being obtained. An experiment to examine the behavior of hydraulic fractures at an interface between different geologic formations has been designed and the first of two fractures has been created. The ashfall tuff and the welded tuff have significant differences in their elastic moduli (0.24 x 10^6 and 3.8 x 10^6 psi), Poisson's ratio (0.312 and 0.238) and porosity (45 and 13%). Conventional fracture calculations were used to design fractures of 50 ft height and 600 ft total length. Evaluation will occur next year. In a containment program activity, evaluation of the region surrounding a 256 lb TNT detonation indicated that no radial fractures extended from the main cavity. However, explosive gases escaping along a borehole from the cavity produced a fracture estimated at 75 ft high in the region of altered in situ stress approximately 10 to 40 ft from the cavity.

Contributions were also made to the development of the Management Plan for Enhanced Gas Recovery and in the Program Plan for the Western Gas Sands Project. A resource evaluation of the Green River Basin was conducted as part of these efforts.

II. INSTRUMENTATION SYSTEMS DEVELOPMENT (C. L. Schuster, Editor)

A. Surface Electrical Potential Method[1]

The surface electrical potential data are taken by periodically recording the potential difference at the earth's surface between 24 data probes, placed every 15° circumferentially around the fracture well, and a reference probe. This potential field is created by injecting electrical current flow through the earth between the fracture well and a return or sink well (Fig. II-1). The current is of a pulse form and the direction is reversed during each measurement period to minimize the effects of induced polarization. The current pulse generator is earth isolated. Electrical connections are made directly to the casings of the fracture and sink wells. Prior to hydraulic fracture initiation, background data are taken to establish the potential levels around the fracture well at the 24 data probes. This then becomes the reference data levels for detecting the changes produced when the conductive fracture fluid alters the electrical geometry of the fracture well. This change in the fracture well current distribution, caused by fracture growth, alters the surface electrical potential around the fracture well. The change influence on the surface potentials tend to be greatest in and opposite the direction(s) of the fracture orientation and is the basis of this development effort.

The instrumentation[2] layout around the fracture well (Fig. II-2) represents the present usage. This layout has evolved from early experiments. Changes which have been made include the replacement of the outer probe by the reference circle. This reference circle is an electrical conductor having the same layout radius as the data probes. The reference circle is connected to the reference probe located a distance of 5 to 10 times the data probe radius from the fracture well and in a direction usually opposite the sink well. This type of layout yields the same basic information but greatly simplifies the fracture well instrumentation set up since only half as many data probe sites need to be surveyed and placed. The data probe radius ranges from 1000 to 1800 ft and is determined from

1. Bartel, L. C., McCann, R. P., Keck, L. J., "Use of Potential Gradients in Massive Hydraulic Fracture Mapping and Characterization," SPE 6090, presented at the SPE 51st Annual Fall Meeting, New Orleans, October 3-6, 1976.

2. Keck, L. J., and Seavey, R. W., "Instrumentation System for Massive Hydraulic Fracture Mapping," SAND-77-0195, April 1977.

a mathematical model[1] which considers such parameters as fracture depth and expected fracture length(s). The instrumentation van is usually placed at a radius approximately equal to the data probe radius and can occupy any one of 24 positions around the fracture well. The location is usually determined, however, by the fracture well access road location.

The instrumentation to sense and transfer the 24 data source pair potentials to the instrumentation van is broken into two parts referred to as the A string (A1 through A12) and the B string (B1 through B12). The electrical potential between each data probe and the common reference circle is input to a Potential Measurement Box (PMB). Each data probe potential source undergoes earth reference isolation, passband limiting, gain, and impression on a FM multiplex subcarrier. The 12 different subcarriers are mixed in a common data cable (A string) for transfer to the instrumentation van. The B string is a duplicate of the A string. The A and B string data cables, in addition, transfer DC power to the PMB's from the instrumentation van.

The 24 data probe potentials are implicitly earth related and some special isolation hardware is necessary to insure against the unintentional relocation of the reference probe. This is accomplished by the isolation amplifier in the PMB whose output has no electrical common tie to the reference circle but is electrically connected to all of the remaining hardware of the data system. The PMB has a passband of .001 to 10 HZ and calibrated gains of 1, 3, 10, 30, 100, 300, and 1000 can be selected. The gain required is dependent on well geometry, data probe radius from fracture well, distance to the reference probe, and pulse current injection level. After undergoing the necessary gain, the surface potential is input to a Voltage Controlled Oscillator (VCO). This FM carrier is combined with the other carriers.

The coaxial cables from the A and B strings enter the instrumentation van from opposite halves of the fracture well circle and connect to the power multiplex filters. These filters route the two sets of 12 incoming carriers to the FM subcarrier discriminators and connect the DC power onto the A and B string cables. The output from each of the 24 discriminators is connected to one of the 64 channels of the analog multiplex portion of the Laboratory Perhipheral System (Fig. II-3). The voltage and current monitor terminals of the pulse current generator are also input to the L.P.S.

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1. Bartel, L. C., "Model Calculation of the Potential Gradients Used in Massive Hydraulic Fracture Mapping and Characterization," presented at the 46th Annual International Meeting of the Society of Exploration Geophysicists, Houston, TX, October 24-28, 1976.

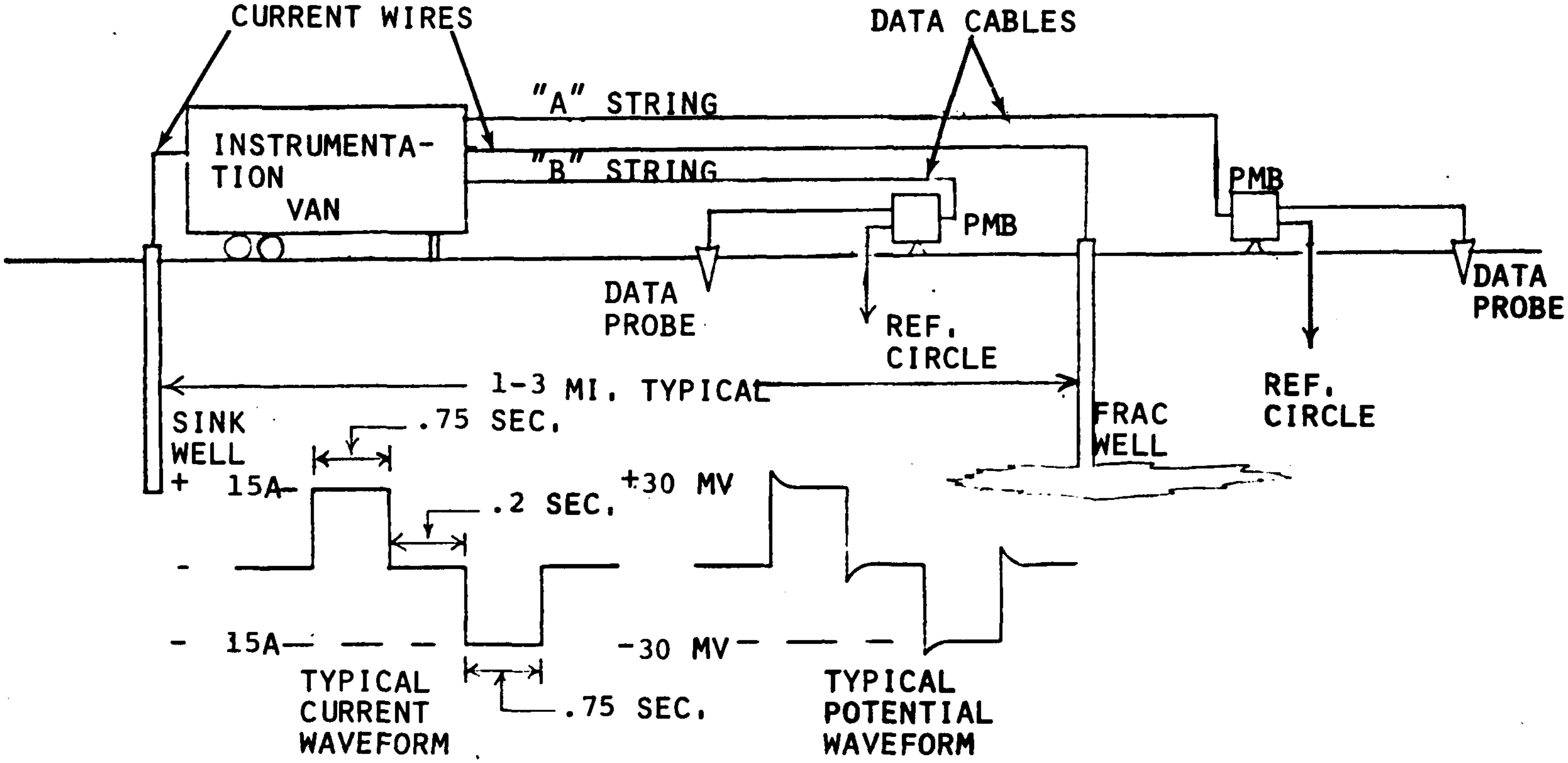


Fig. II-1 - Equipment Layout and Typical Current and Potential Waveforms

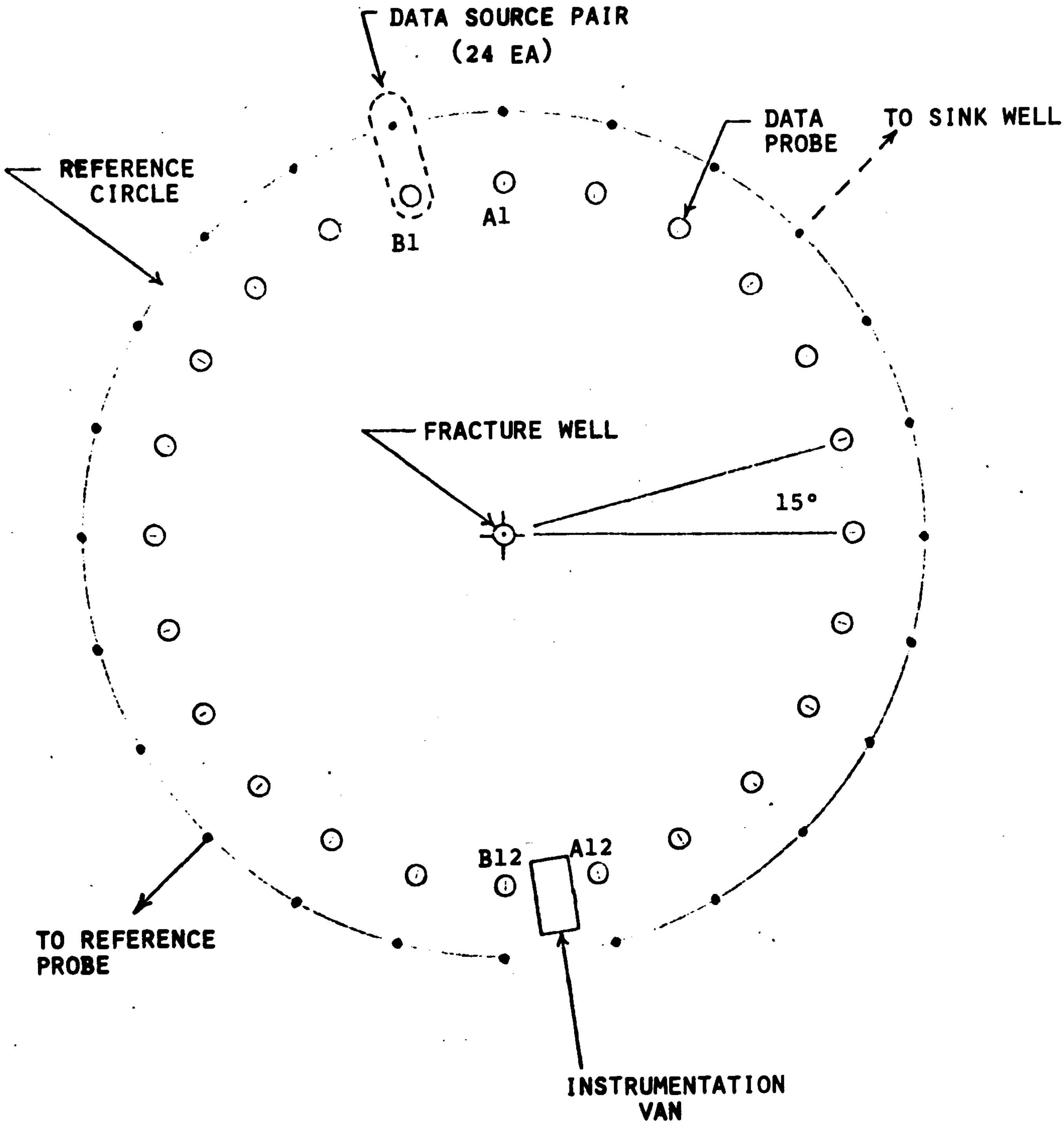


Fig. II-2 - Instrumentation Layout Around Fracture Well

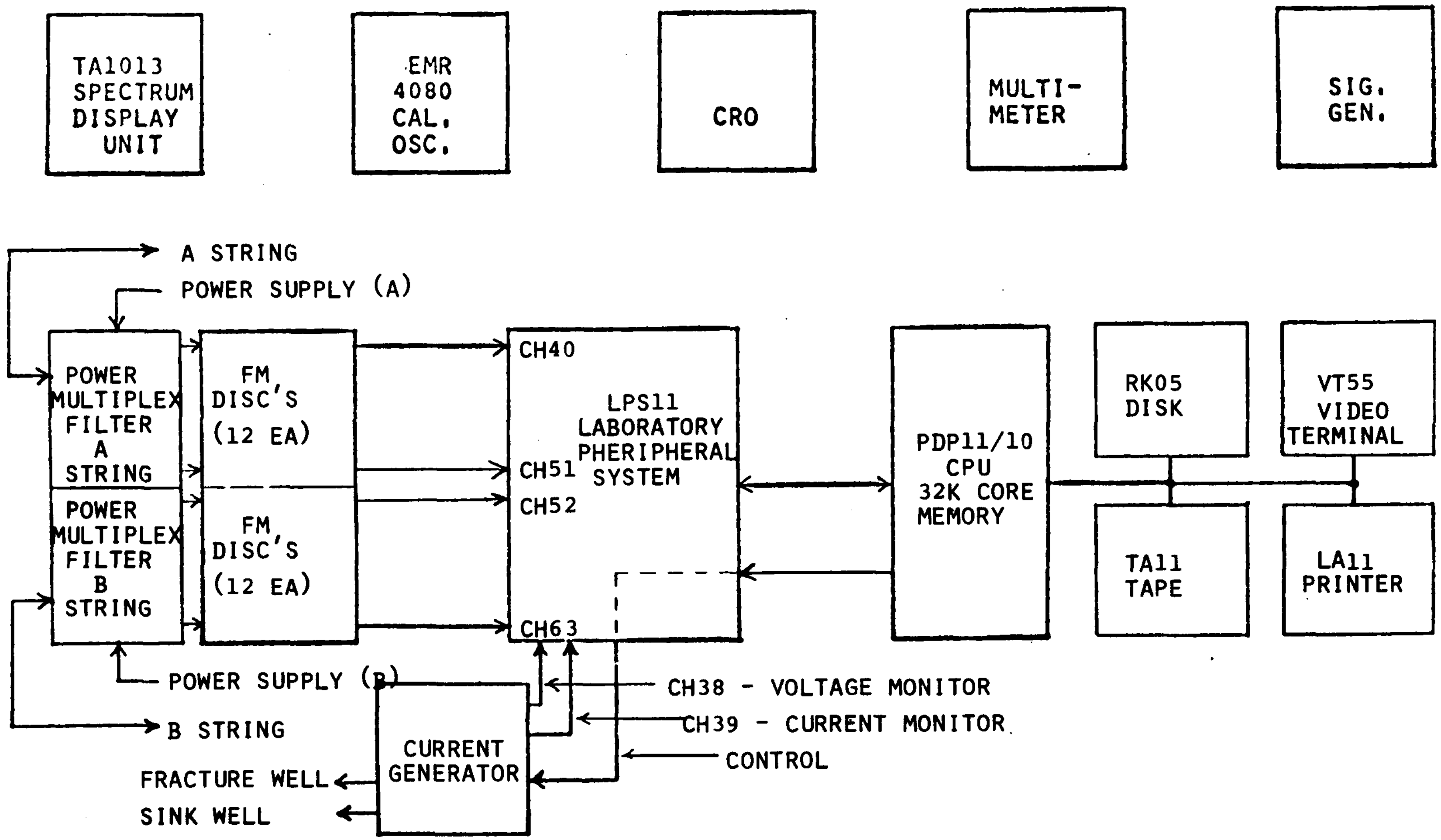


Fig. II-3 - Instrumentation Van

The heart of the current pulse control and data acquisition system is a PDP 11/10 minicomputer with a 32 K core memory. The minicomputer operates under the RT11 operating system and all application programs are written in BASIC.

In a typical fracture mapping test start up, the appropriate data acquisition program is called from the RK05 disk into memory. An example is LARFR1 BAS (Laredo, Texas fracture, version 1 in BASIC), Fig. II-4. The test run is initiated and certain special conditions such as test number, start time, time between tests and the PMB located at north are input to the VT55 computer console. The test number may be the first

```
26-AUG-77
STATE OF DATA RUN
FIELD BOX GAIN:  30
VOLTAGE MONITOR GAIN:  HI
CURRENT MONITOR GAIN:  HI
START TIME:  630
TIME BETWEEN TESTS (MINUTES):  1
POTENTIAL MEASUREMENT BOX AT NORTH IS A3
NOTE:  LIVE RUN, 2ND DAY

TEST NO.  283              TIME:  6:30:26
VOLTS =   185.677    AMPS =  19.3081      RESISTANCE = 9.61651
VOLTS =   179.705    AMPS = -18.9862      RESISTANCE = 9.46503
POTENTIAL, MILLIVOLTS (A1 > A2 & B12 > B1)
 55.8591      54.4213      55.0574      52.153      49.6034      47.8003
 49.5824      51.6115      54.8261      56.0168     57.3862      61.0344
 62.3854      62.8585      64.7536      62.9505     71.0828      68.2441
 69.8764      67.7001      69.4112      59.8096     67.2585      61.0134

U S G S SURFACE TILT DATA - A/D VALUES
 2051   2051   2052   2051   2707   2246      0   1959   4095   3387   2843
 2031   2128   1872   2048   2047   2148   1436   2046   2047   2047   2047
 2664    545

PRESSURE & FLOW DATA, MV. - AC LINE, VOLTS
 50.7813    -87.8908      2.68555     -1.62761      122.607
```

Fig. II-4 - Computer Printout Example

test of a series or it may be a number appropriate after some fracture procedure shut-down and restart. Start time is that future time, one minute or several hours from the present time, when the automated test sequence is to start (the computer has an internal 24 hour clock). Time between test sets the test repetition rate with a range of 30 seconds to several hours. The instrumentation van can be located in any one of 24 positions around the fracture well. When plotting on the VT55 video terminal it is a convention to begin the plot with north and proceed clockwise through east, south, and west back to north. Since the data is not necessarily acquired in this sequence, the "PMB at North" console input is used to rotate the data before plotting. These input conditions are then echoed on the LA11 printer and the software enters the phase of pulsed current application and simultaneous acquisition of the 24 PMB, pulse current, and pulse voltage data values. The peak-to-peak potentials in millivolts input to each PMB is computed using gain correction factors for each PMB data channel. The millivolt level data is written into a data file on the RK05 disk for future evaluation and then listed on the LA11 printer. When the time delay specified by "time between tests" has elapsed, the sequence will repeat with the application of another current pulse.

The surface potential data written onto the RK05 disk can be accessed for many special purposes. Programs to plot this data on the VT55 video console have been written. One such program will compress the fracture time of several hours into a few minutes and quickly indicate fracture progress and direction, if detected. Another program plots the changes in potential at each of the 24 PMB's in reference to time on the LA11 printer.

All of the computer software written for use with the surface electrical potential method of fracture mapping is constantly undergoing changes and improvements. This applies to the hardware as well. These changes are dictated by field experience and the evaluation of the surface electrical potential data in conjunction with other related data sources.

B. MHF Mapping Experiment Results

During FY'77, Sandia Laboratories participated in five MHF experiments and was preparing for a sixth for natural gas and oil recovery stimulation. The first of these (near Tulsa, Oklahoma) was a joint AMOCO/ERDA mini-frac experiment with AMOCO conducting the fracture and Sandia and the USGS participating in the fracture diagnostic instrumentation. Gas Producing Enterprises (GPE) conducted two experiments in the Natural Buttes field south of Vernal, Utah, and a fourth was conducted by CONOCO as a part of their tertiary oil recovery experiment in the Big Muddy field east of Casper, Wyoming. The fifth MHF test was conducted by Shell Oil Company near Laredo, Texas. Preparation was also started for an experiment with AMOCO in the tar sands of Canada.

AMOCO Mini-Frac Experiment -- On November 4, 1976, AMOCO Production Company conducted a small scale hydrofracture experiment located on the Williams Lease site approximately five miles northeast of Tulsa, Oklahoma. The purpose of the experiment was to test various methods of hydrofracture mapping instrumentation. The fracture well was approximately 80 feet depth with an open hole fracture zone in shaly limestone between 40 and 80 feet. The experiment was designed to produce a fracture 40 feet high and 600 feet in length.

The surface electrical potential data was taken by recording the potential differences between 24 pairs of probes placed circumferentially around the test well with an inner probe radius of 150 feet and an outer probe radius of 350 feet. The current pulse was induced directly into the wellhead (source) at the surface of the earth.[1] The return line (sink) was attached to the casing of an abandoned test hole located approximately 1400 feet distance from the test well. Data readings were taken every two minutes from prior to pumping until after flowback. Sandia also digitized and recorded the USGS data on the mini computer concurrently with the potential data.

Surface potential data were recorded prior to, during, and after pumping. Pumping for the fracture occurred in two stages. The first commenced at 0828 hours and stopped at 0842 hours. The second started

[1] L. J. Keck and R. W. Seavey, "Instrumentation System for Massive Hydraulic Fracture Mapping", SAND-77-0195, April 1977.

at 0910 hours and continued until 1002 hours. A constant rate of 2 bbl per min was held for both stages.

The data for the operation are presented in Table I, Appendix A. The electrical potential data was taken at approximately two-minute intervals beginning at 0540 hours and continuing through 1324 hours. Approximately 25 data points taken prior to pumping were averaged and used as the before fracture reference measurement. Figure II-5 shows the potential comparison, $V(\theta)$, for data points taken at the noted time points beginning early in the fracturing sequence through its completion at 1000 hours. The potential comparison, $V(\theta)$, was multiplied by a factor of 10 in order to facilitate computer plotting. The data appear to provide a one-cycle change in the normalized potential differences, thus indicating an asymmetrical fracture was created. When compared with the model calculations[2] the cycle minima appears to lie in the easterly direction, indicating that the fracture is asymmetric with the major wing in that direction. Data taken from the downhole TV camera and the USGS tiltmeters seem to verify this conclusion.

GPE Experiments --

1. Natural Buttes Unit No. 14 -- Sandia participated in the GPE MHF experiment in the Natural Buttes No. 14 well located approximately 40 miles south of Vernal, Utah. The MHF was performed by Dowell for GPE.

The MHF experiment was designed for eight stages of pad, proppant, and balls to fracture 15 zones. The intention was that each stage would treat two zones. At the end of each stage balls would seal the perforation taking fluid and new zones would then be treated.

The fracture zones for the experiment began at a depth of 6294 feet and extended to 8010 feet. The pay interval varied in thickness from 8 feet to 38 feet and the separating shale layers varied from 4 feet to 250 feet. Natural Buttes #14 is an "old" well. Breakdown on the first 12 zones, extending in depth from 6825 feet to 8010 feet, occurred on October 10, 1976 with 10,000 gallons of 15% HCl in 500 gallon stages.

[2] L. C. Bartel, "Model Calculations of the Potential Gradients Used In Massive Hydraulic Fracture Mapping and Characterization," presented at the 46th Annual International Meeting of the Society of Exploration Geophysicists, Houston, TX, October 24-28, 1976 (submitted for publication).

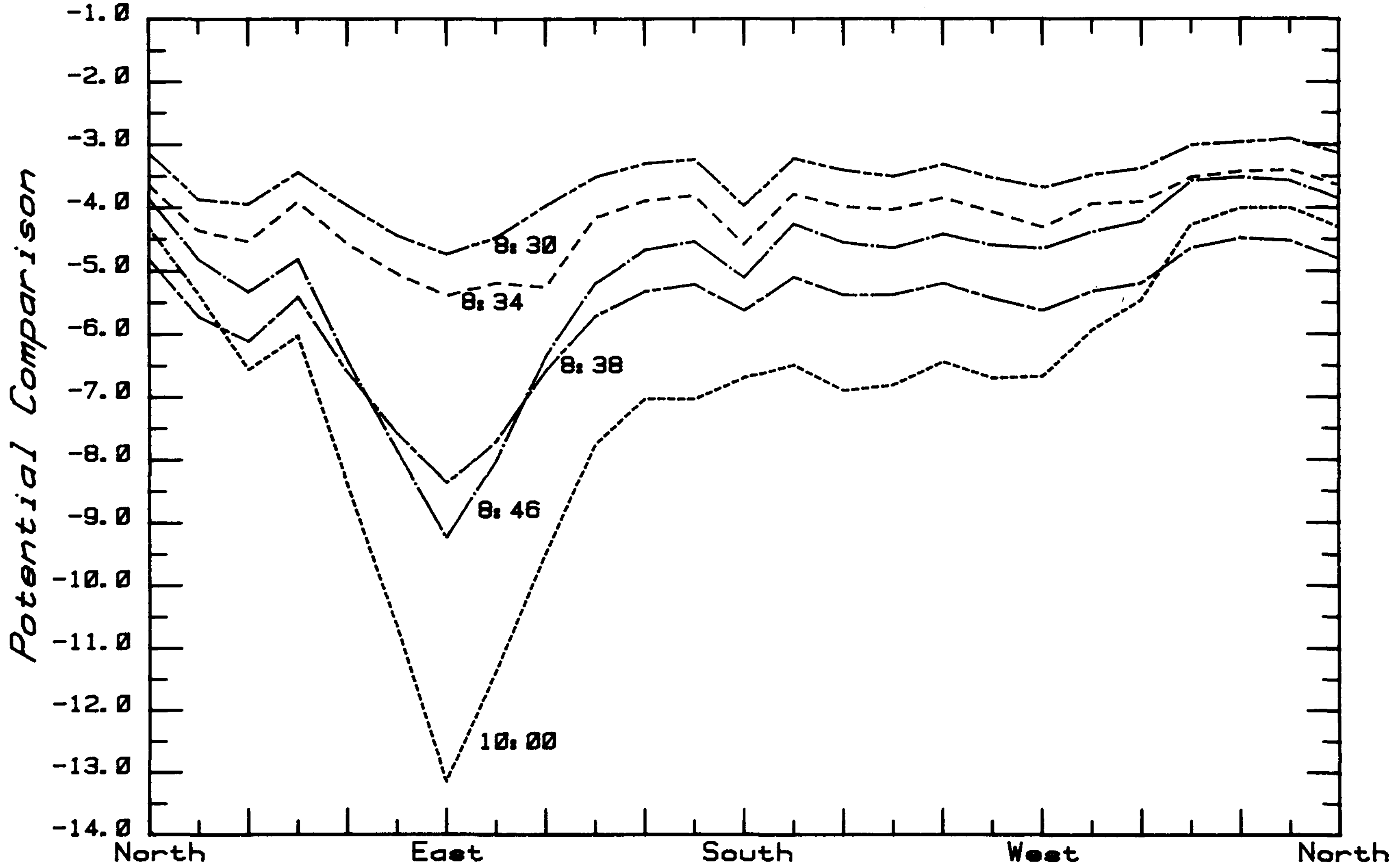


Fig. II-5 - Potential Comparison as a Function of Direction of the AMOCO Mini-Frac Experiment, November 4, 1976.

Perforations were made on three additional zones in February 1977. These zones, extending from a depth of 6294 feet to 6648 feet, did not experience breakdown prior to the MHF experiment on March 15, 1977.

Pumping started at approximately 0715 hours and continued through 1800 hours at a near constant rate of 25 barrels per minute. Approximately 640,000 gallons of fluid and 1.1 million pounds of proppant were injected in the multilayered pay zone.

The electrical potential measurement system included 24 pairs of potential probes placed circumferentially around the well with an inner radius of 1800 feet and an outer radius of 3800 feet. Injection of the induced current into the frac zone by means of a downhole current probe had been planned for this test, however, because a 4-1/2 inch casing was already installed in the well the downhole current probe could not be utilized and the current was injected into the casing at the surface. Field data were collected at two minute intervals starting at 0650 hours and continuing through 1815 hours. The data are presented in Table I, Appendix B. Figures II-6 and II-7 show the potential comparison, $V(\theta)$, for data points coincident with the end of each pre-planned pumping stage compared to data taken prior to the initial start of pumping. For convenience a multiplying factor of 100 was used. Very little change was observed after the fourth stage. The potential changes that occurred did not agree with the eight stage fracturing plan. Indications are that fracturing occurred in a near east-west orientation. The data suggests that early in the pumping process an asymmetric fracture was developing. However, on the basis of a two-cycle recurrence, the data collected at later times (1230 hours through 1800 hours) suggest that a more nearly symmetrical fracture was created. The interpretation may be misleading because of the extreme range in depth of the fracturing zones. The distributions of the fractures and their directions can lead to ambiguous interpretations on the orientation and symmetry. As an example, single asymmetric fractures, one easterly at one depth, and another westerly at a different depth, could be interpreted as a single symmetrical fracture oriented in the east-west direction.

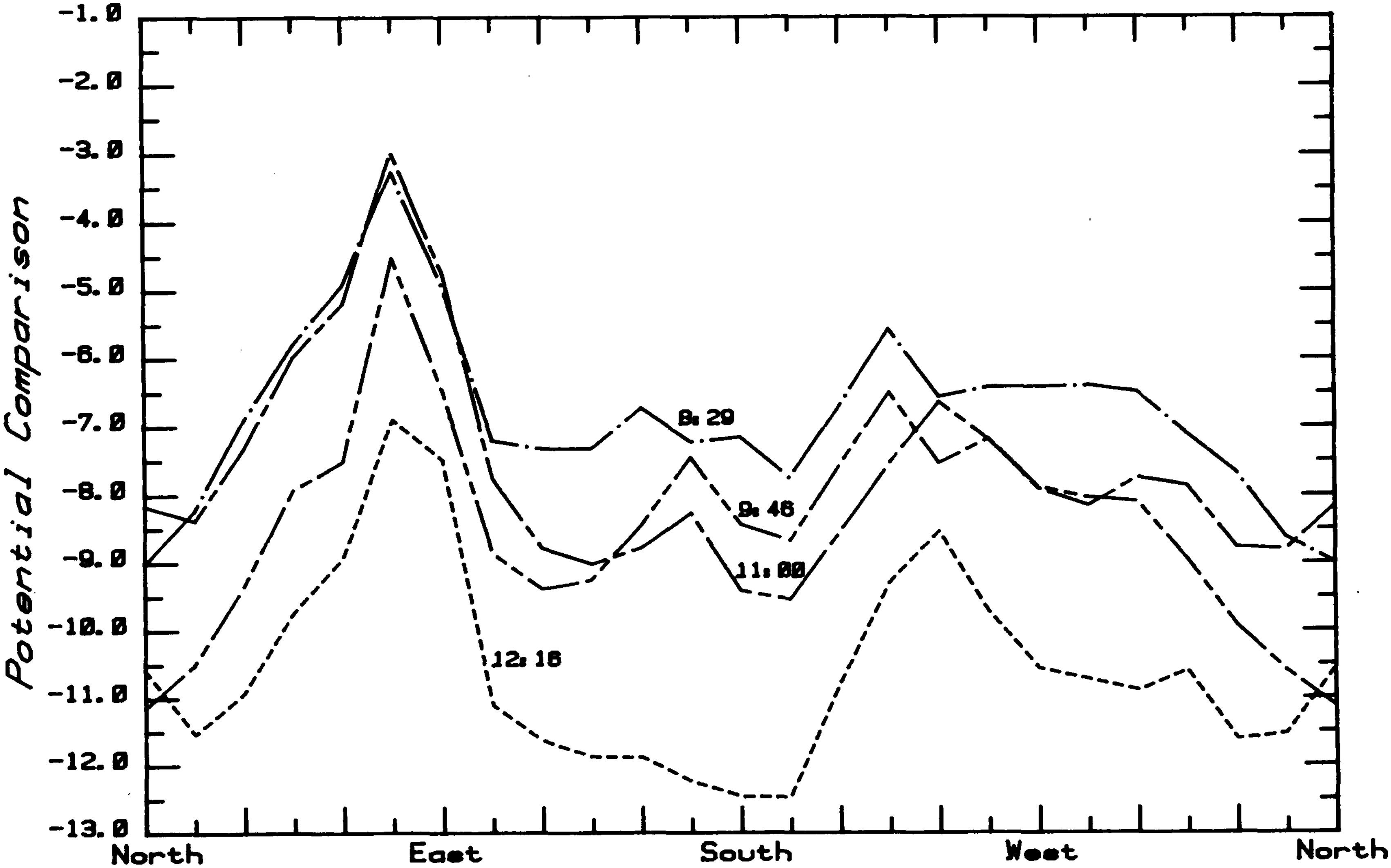


Fig. II-6 - Potential Comparison as a Function of Direction of First Four Stages of the GPE Natural Buttes Unit No. 14 Hydrofracture, March 15, 1977.

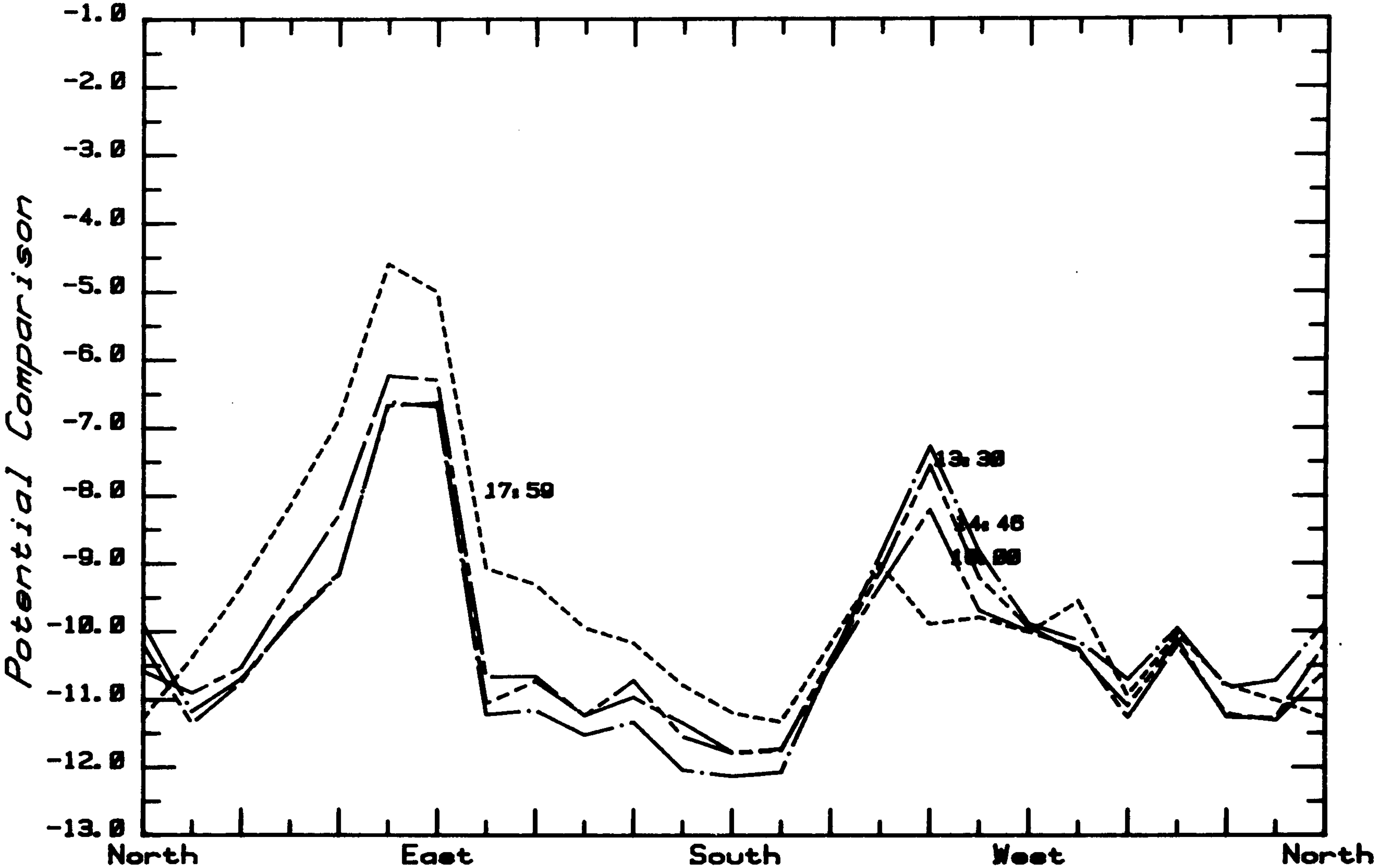


Fig. II-7 - Potential Comparison as a Function of Direction of the Last Four Stages of the GPE Natural Buttes Unit No. 14 Hydrofracture, March 15, 1977.

2. Natural Buttes Unit No. 20 -- Sandia participated in the GPE MHF experiment on their Natural Buttes Unit No. 20 well located approximately 40 miles south of Vernal, Utah. The fracture was performed by Dowell for GPE on June 22, 1977.

The MHF was designed for the limited entry technique. Eight pay zones were selected between depths of 8498 feet and 9476 feet. Approximately 350,000 gallons of fluid and 825,000 pounds of proppant were injected into the multilayered gas pay zone. Pumping started at approximately 0900 hours and continued through 1250 hours at a rate of approximately 40 barrels per minute.

The electrical potential measurement system included 24 probes placed around the well at a radius of 1800 feet on 15 degree intervals. A well casing approximately five miles distant (UT52X) was used as the other voltage probe for the potential measurements. The current was induced into the NB #20 well casing at the surface of the earth. The current return line was attached to NB #4 well casing located to the east at a distance of approximately two miles. The potential field data were collected at one minute intervals starting at 0857 hours and continued through 1307 hours. The data are presented in Table II, Appendix B. Figure II-8 shows the potential comparison, $V(\theta)$, for data points at various times through pumping compared to an average of 51 data points taken prior to pumping. The dashed curve represents the result when approximately 20 data points averaged after pumping are compared to the 51 points averaged before pumping. A multiplying factor of 100 has been used for convenience. The analysis of the data thus far has not produced any definite fracture orientation. It is possible that the electrical length of the fracture is very short and the effect is not large enough to be detected in the surface potential measurements.

CONOCO Experiment -- On March 22, 1977, the Continental Oil Company (CONOCO) conducted a small fracture as a part of a tertiary oil recovery experiment in the Big Muddy Field east of Casper, Wyoming. Sandia Laboratories' objective in the experiment was to test the effectiveness of the surface potential measurement system on a small open hole hydrofracture. In addition to the Sandia surface potential instrumentation,

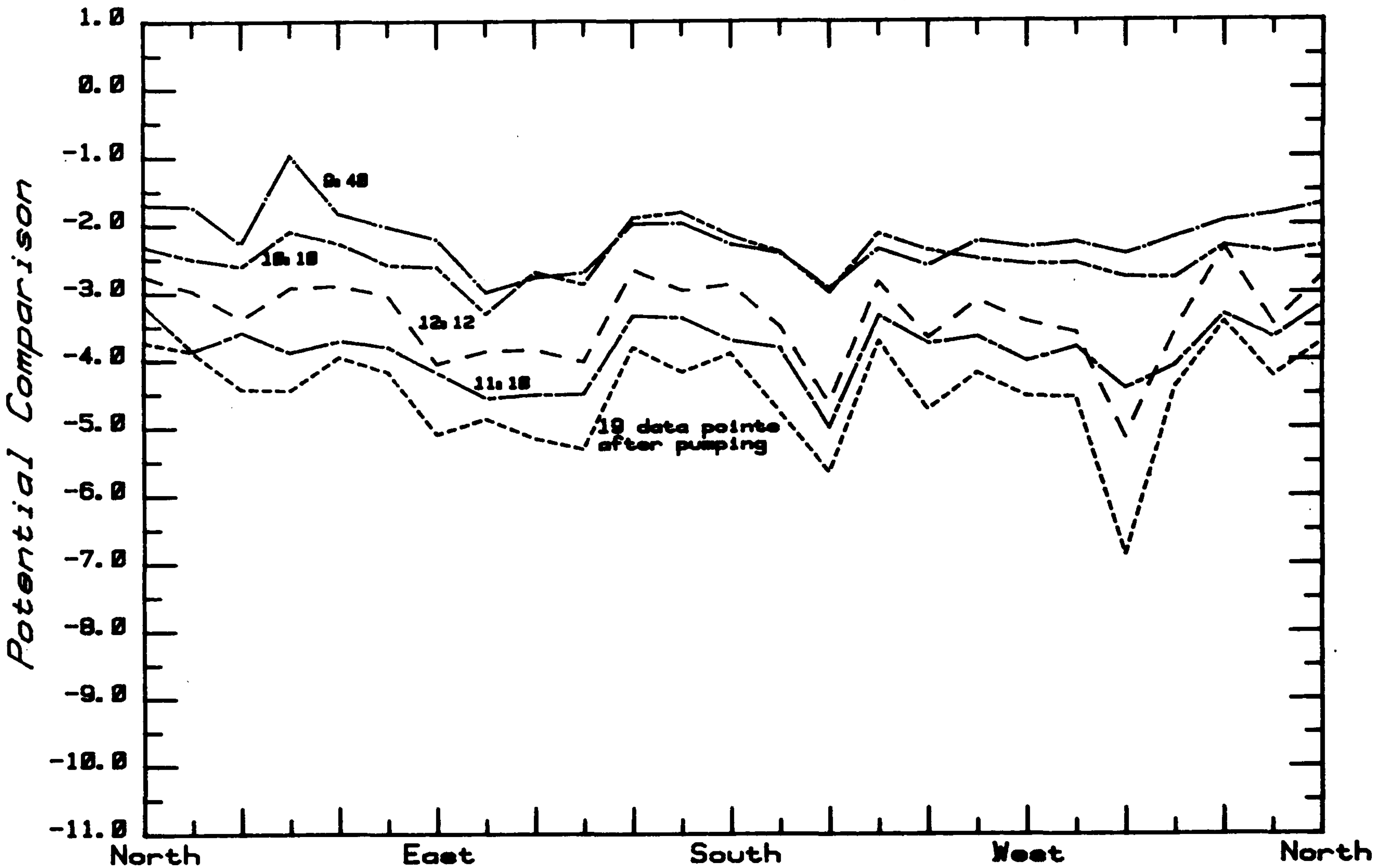


Fig. II-8 - Potential Comparison as a Function of Direction for the GPE Natural Buttes Unit No. 20 Hydrofracture, June 22, 1977.

CONOCO had installed several pressure gages in nearby surrounding wells as a diagnostic tool to assist in determining fracture orientation. The fracture zone consisted of a section of open hole located at a depth of approximately 3500 feet. Approximately 12,000 gallons of conductive fluid was pumped which was calculated to produce a fracture length of approximately 500 feet.

Electrical potential 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 circumferentially around the well at 20 degree spacing with an inner radius of 1000 feet and an outer radius of 2000 feet. In addition, the relative potential was measured by using as probes the casing of six wells located adjacent to the fracture well. In all cases the distance to any one of the six wells was less than 1000 feet from the fracture well. A downhole sinker bar in the fractured well and at the fracture depth served as the induced current probe. The casing of a well approximately 1.5 miles distance was used as the current return. Electrical potential data were taken at 40 second intervals commencing prior to pumping (1113 hours) and continuing through fracture completion (1143 hours).

The electrical potential data are presented in Table I, Appendix C. Approximately seven data points taken just prior to pumping were averaged and used as a before reference measurement. Measurements taken at indicated times shown in Figs. II-9 and II-10 were compared to the before reference data and are plotted versus azimuth. For convenience, a multiplying factor of 100 was used. The data obtained on the northern side of the array was compromised by a high degree of external noise and is, therefore, excluded from the plot.

Data analysis based on the fracture model calculations indicates that the fracture is asymmetric and that the azimuthal direction is from nearly east to west with the major extension primarily to the east. Also fracture growth can be recognized by a decreasing potential thus the data suggest the major growth (at least the electrical length) occurred within the first few minutes of pumping.

<u>Shell Oil Company Experiment</u> -- On August 25 and 26, 1977, Sandia participated in the Shell Oil Company MHF test in the Rachel Foundation No. 2 well located approximately 40 miles northwest of Laredo, Texas. The fracture was performed by Halliburton for the Shell Oil Company.

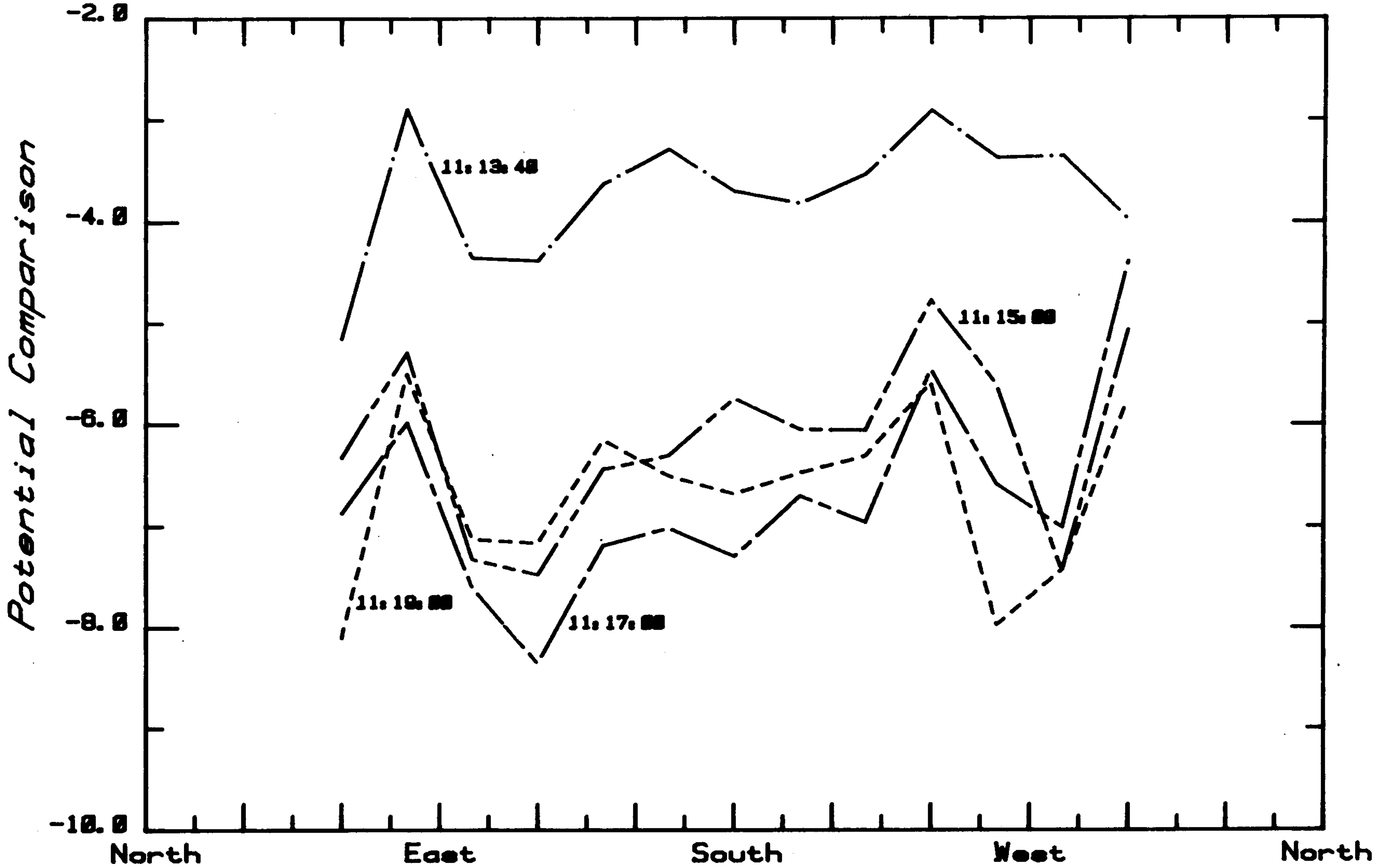


Fig. II-9 - Potential Comparison as a Function of Direction for the CONOCO RBW #80 Hydrofracture. Eighteen Stake Pair. March 22, 1977.

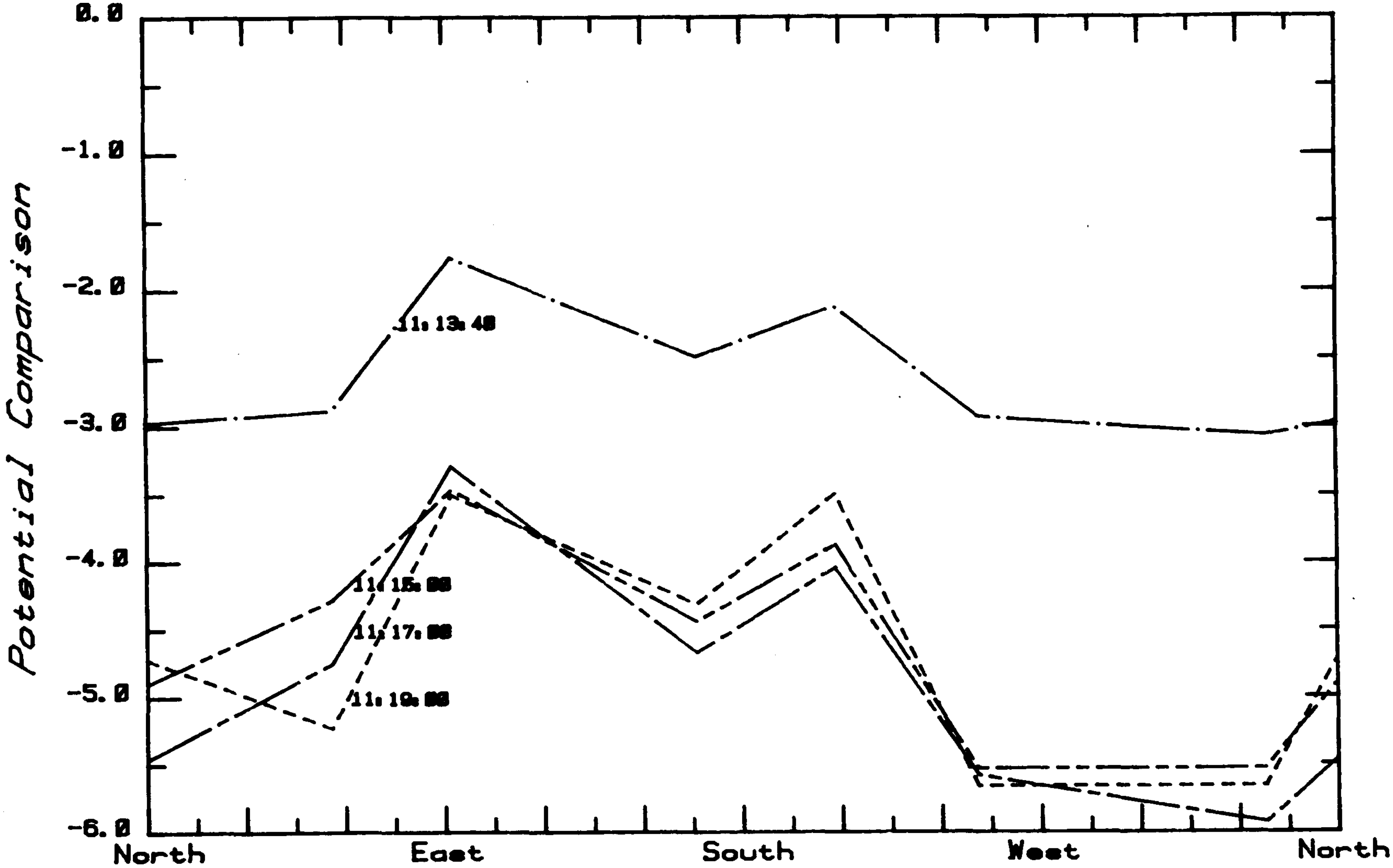


Fig. II-10 - Potential Comparison as a Function of Direction for the CONOCO RBW #80 Hydrofracture. Six Well Casings. March 22, 1977.

The experiment was designed in two pumping stages, the first occurring on August 25, 1977 and the second on August 26, 1977. This was done in order to obtain some logging diagnostics before completion of the fracture.

Three major pay zones were selected between the depth of 5345 feet and 5515 feet. The entry technique was designed such that all zones would take fluid simultaneously.

Pumping for the first stage commenced on August 25, 1977 at 1040 hours and continued through 1325 hours at an average rate of approximately 12.5 barrels per minute. Approximately 80,000 gallons of fluid and 98,000 pounds of proppant were pumped. Surface electrical potential data were recorded at intervals of two minutes starting at 0826 hours and continuing through 1405 hours.

The second stage pumping occurred on August 26, 1977 when approximately 200,000 gallons of fluid and 280,000 pounds of proppant were pumped. The operations started at 0830 hours and continued through 1330 hours. Surface electrical potential data were taken at one minute intervals beginning at 0630 hours and continuing through 1437 hours.

Figures II-11 through II-13 show the results of the data acquired during pumping on August 26, 1977. Each curve is labeled as to the time during pumping when data has been analyzed. The 800 before pumping reference was obtained by averaging the data taken between 0730 hours and 0800 hours. The time shown for data comparison is an average of the data taken during the period of one-half hour prior to that time indicated on the curve. The data was normalized by the induced current for each data point and after the average over a specified time the difference of the "after" and the "before" plotted. For convenience a multiplying factor of 100 was used. When compared to the mathematical model an asymmetric fracture in the northeast-southwest direction is indicated with the major wing oriented to the northeast.

The data are presented in Table I and II, Appendix D.

Surmont Project -- During September 1977, trailer B-59 was installed at the Numac Oil and Gas Ltd. Project Site about 40 miles south of Ft. McMurray, Alberta, Canada.

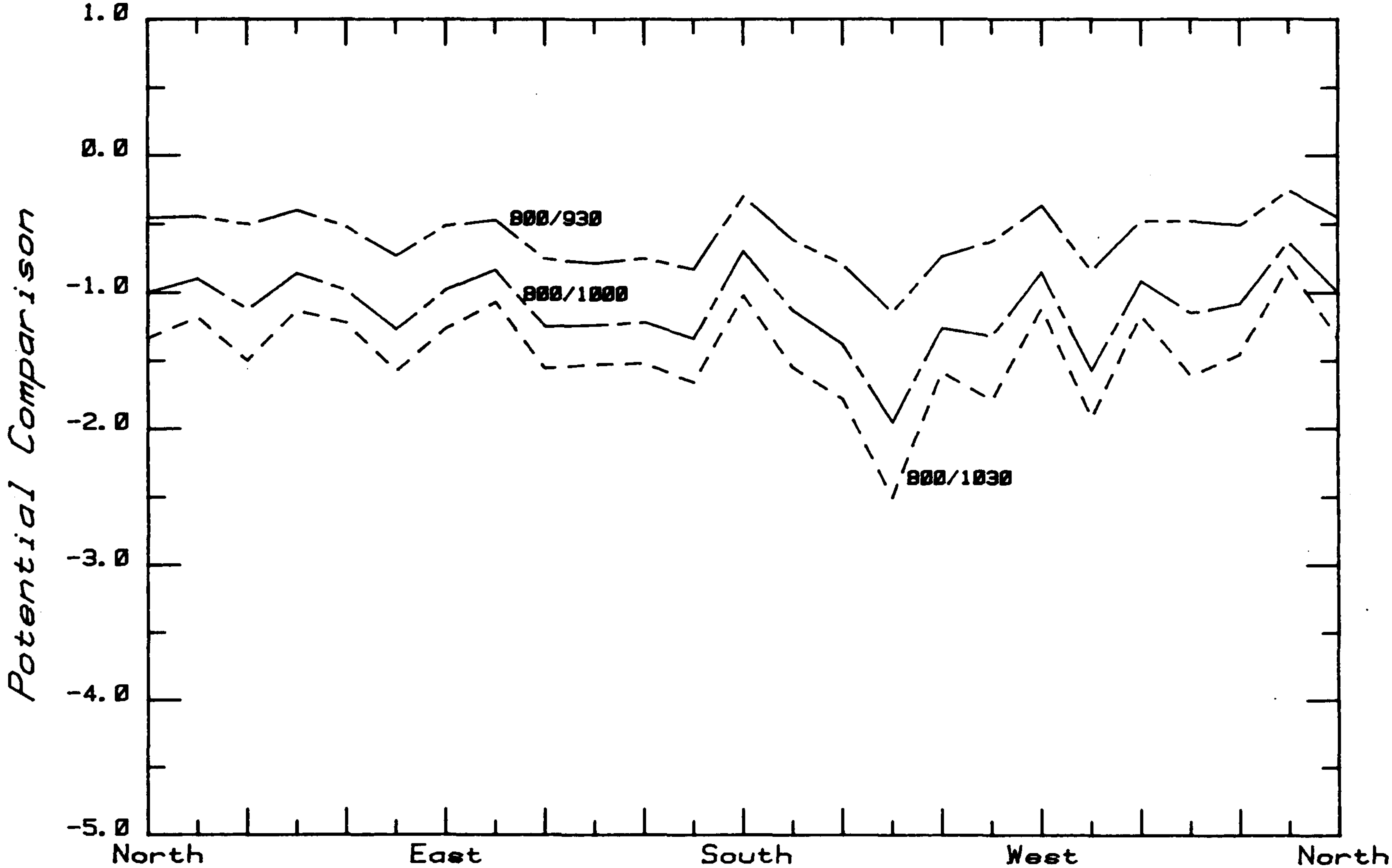


Fig. II-11 - Potential Comparison as a Function of Direction for the Shell Oil Company Hydrofracture, Rachal Foundation No. 2, August 26, 1977. Comparison from 0930 hours through 1030 hours.

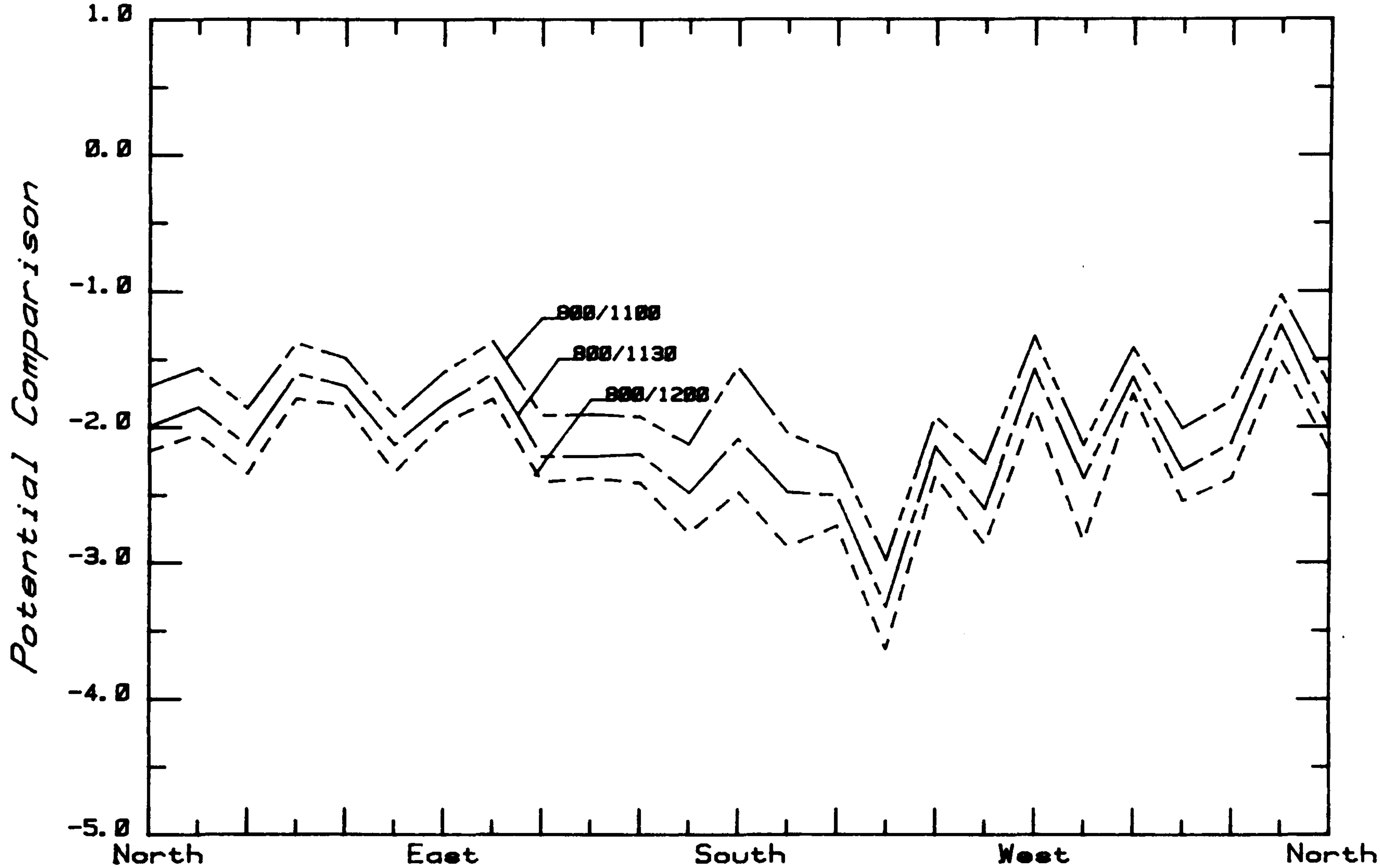


Fig. II-12 - Potential Comparison as a Function of Direction for the Shell Oil Company Hydrofracture, Rachal Foundation No. 2, August 26, 1977. Comparison from 1100 hours through 1200 hours.

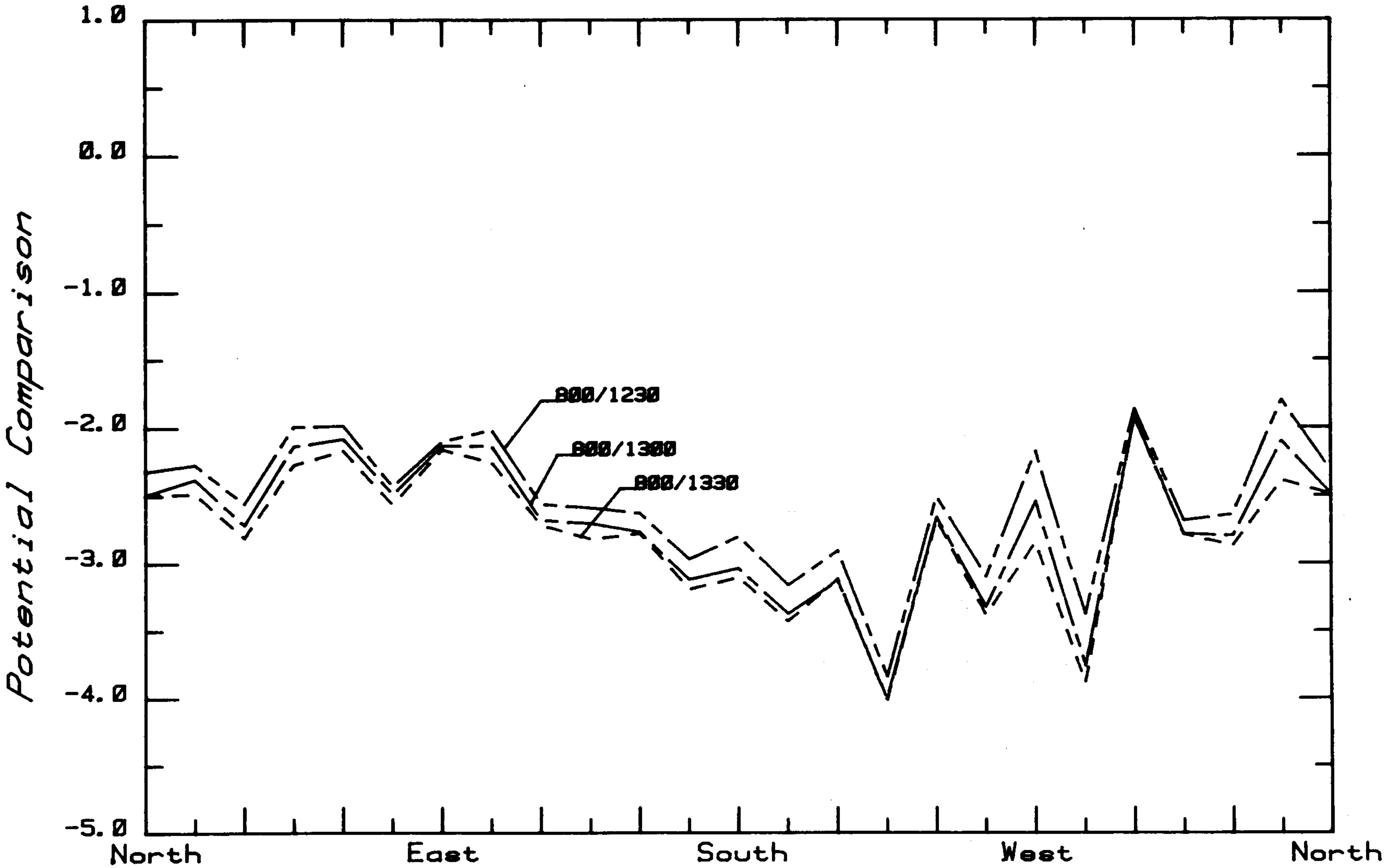


Fig. II-13 - Potential Comparison as a Function of Direction for the Shell Oil Company Hydrofracture, Rachal Foundation No. 2, August 26, 1977. Comparison from 1230 hours through 1330 hours.

Well F-1 will be the fracture well in which two fractures at depths of 1150 and 1100 feet will be performed. The lower zone is at the interface between the tar sands and the Devonian shale. The upper zone is within the tar sands. Pumping rates will be very low in order to initiate a horizontal fracture in the order of 500 feet.

During the fracture current will be injected alternately between the fracture well casing, a downhole current probe and the return well. Additional measurements will include monitoring the potential between the two well casings which should provide a better normalizer base.

The casing potential will also be monitored as the downhole current probe is lowered in order to provide voltage gradient information to verify modeling.

All equipment has been installed and checked out for the fracture which is scheduled for early October, 1977.

C. Electrolytic Model Tank

To date, the primary field 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[1] has been performed for the case of an homogeneous earth with an uniform casing/fracture source electrode. However, 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 (e.g., other metal well casing in the area) produce mathematical rigors which are not tractable by techniques presently available. These situations are typically the rule rather than the exception in actual field locations. 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 applicablity of mathematical synthesis. This was the rationale behind the development of an electrolytic model tank.

An electrolytic model tank is basically a brinewater-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.[2] 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):

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

[1] McCann, R. P., Hay, R. G., and Bartel, L. C.: "Massive Hydraulic Fracture Mapping and Characterization Program, First Annual Report," SAND-77-0286, 1977.

[2] Frischknecht, Frank C., USGS, Denver, Personal Communication.

where

ρ' = model resistivity	ρ = 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 (3 x 4.6 x 1.5 to 2.4 m). 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.

After consideration of the varied tank designs currently in use, space limitations at the SLA test facility, and the particular field procedure which we intended to model, we developed a unique tank design which approximates an infinite sized tank while being significantly smaller than any of those visited. To accomplish this, the tank employs a conductive, hemispherical shell as one current electrode; the other current electrode is placed at the center of the hemisphere, and all potential measurements are made within the hemisphere (Fig. II-14). The reasoning behind the choice of an hemispherical electrode may be explained as follows:

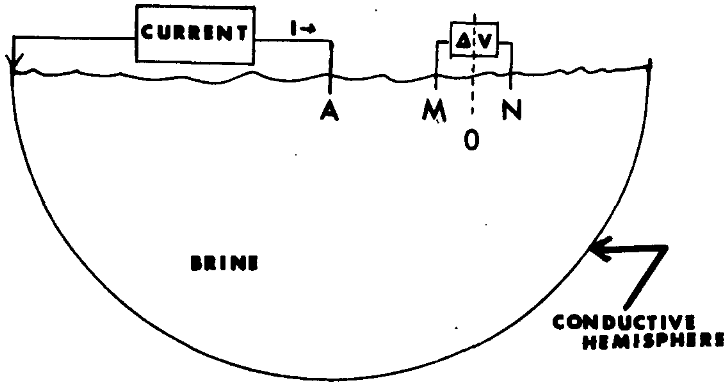


Fig. II-14 - Schematic illustrating an electrolytic model tank design employing an hemispherical return current electrode.

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

$$V = \frac{I\rho}{2\pi R} \qquad (2)$$

where

I = impressed current

ρ = resistivity of earth material

R = distance from point electrode to observation point

All equipotential surfaces are given by R = 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 necessarily becomes an equipotential surface and current flow remains 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.

The electrolytic model tank (Fig. II-15) consists of four basic units: 1) a wooden exterior tank, 2) the aluminum hemisphere, 3) an aluminum probe track, and 4) the resistivity measurement system.

The wooden tank measures 5 x 5 x 3 ft deep (1.5 x 1.5 x 0.9 m) and is constructed of 0.75 in. (1.9 cm) plywood with suitable structural bracing to withstand stresses applied when filled with water. A sealant was applied to the interior to prevent water leakage, and a standard water bibcock was bottom mounted for ease in tank drainage. When filled, the tank holds 75 ft^3 (2124 ℓ), or 2.33 tons (2124 kg) of water. The purpose of this exterior tank is twofold. Firstly, by placing the water-filled hemisphere in a water-filled tank, the differential pressures on the aluminum shell are minimized reducing the chance of warping or collapse. Secondly, for standard four electrode experiments (Wenner or Schlumberger arrays, for example), the aluminum hemisphere may be removed, and experiments are performed in the wooden tank.

The aluminum hemisphere (Fig. II-16) is a 1/16 in. (.16 cm) shell of 47.75 in. (121.3 cm) nominal I.D. After initial testing, the aluminum required an alodine coating to prevent formation of unknown chemical or organic precipitates in the brine solution. This represents the maximum size aluminum hemisphere which could be fabricated in the Albuquerque area, and, therefore, was the main size limiting factor in the tank design.

The aluminum probe track is a slotted, moveable unit which holds the current and potential probes and allows for their precise location.

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

Fig. II-15 - Electrolytic Model Tank Facility at Sandia Laboratories.

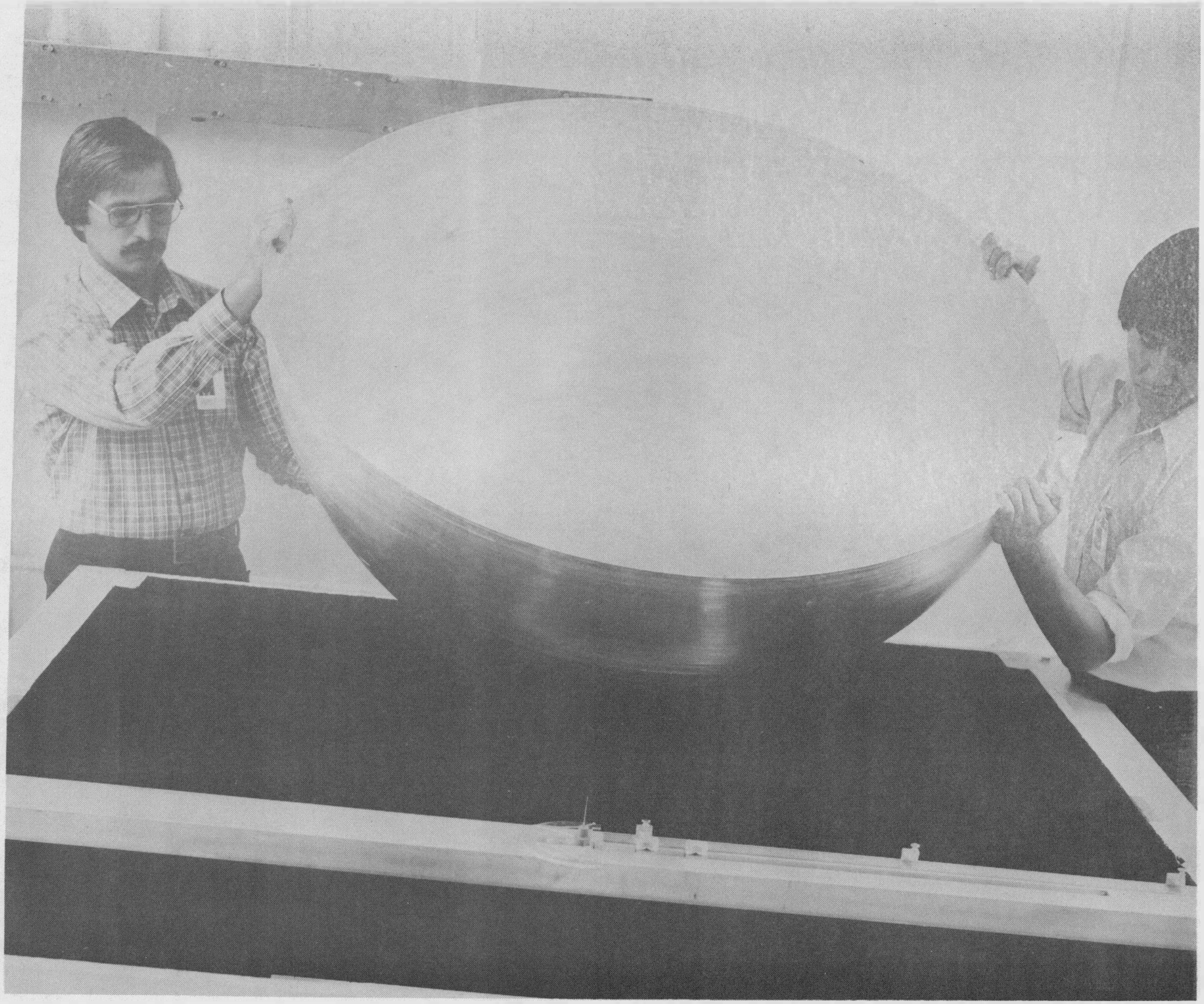


Fig. II-16 - Aluminum Hemisphere Used as Current Return Electrode in Model Tank.

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. (± 0.13 mm).

The potential measuring probes are held in spring-loaded holders which slide in a scale calibrated slot (Fig. II-17). The central current probe, which represents the fracture well, is held in a rotatable, protractor calibrated mount (Fig. II-18). By holding the potential probe positions fixed and rotating the fracture through 360°, the effect of a fixed fracture surrounded by potential probes is achieved. This is the field situation of radial dipoles used in the MHF mapping program which we intended to model.

Several probe materials have been tried including stainless steel hypodermic stock of several diameters, high carbon steel drill stem rod of varied diameter, and Kovar rods. Typical diameter used is in the 0.046-0.050 in. (0.117-0.127 cm) range. In addition, copper and gold platings of these probes are being evaluated. Evidence of instrumental drift suggests instability of the probes tested which may require consideration of platinum or platinized platinum as probe material. The observed drift is slight and decreases with time which, although an inconvenience, may be more attractive than the more expensive platinum alternative.

The resistivity system utilized to date at SLA has been the BISON Model 2350A resistivity meter. This is a bridge null unit which reads directly in units of $2\pi\frac{V}{I}$ in response to a nominal 23 mamp, 10 HZ square wave current.

To date, experiments utilizing the described electrolytic model tank have been of two types: 1) tests to verify the "infinite" size objective in the tank design, and 2) parametric studies of anomaly size and shape for various fracture depths and lengths. These tests will be discussed separately.

As noted in published test results by Goudswaard[3], in a finite sized, box-shaped electrolytic tank, experiments must be limited in

[3] Goudswaard, W.: "On The Effect of the Tank Wall Material in Geoelectric Model Experiments," Geophysical Prospecting, Vol 5, No. 3, pp 272-281, 1957.

laterial dimensions and located near the tank center or else the experiment "sees" the walls and bottom of the tank. Goudswaard eliminated these errors by lining the walls with a conductive grid to enlarge the usable area of the tank. Our use of a conducting hemispheric electrode is intended to accomplish the same results.

The first set of tests were to establish, for a given $\overline{MN}$ spacing (see Fig. II-14), how close we would approach the aluminum shell before our data became inaccurate. For each test, a constant $\overline{MN}$ value was chosen while the $\overline{AO}$ value was varied from its minimum to maximum values. Apparent resistivity was calculated using

$$\rho_a = 2\pi \frac{V}{I} / \left(\frac{1}{\overline{AM}} - \frac{1}{\overline{AN}}\right) \qquad (3)$$

True brine resistivity, ρ, was determined using a conductivity bridge. Values of $\frac{\rho_a}{\rho}$ versus $\overline{AO}$ were then plotted as shown in Fig. II-19. Note that in the worst case the outermost potential electrode can come to within 3 in. (7.5 cm) of the shell before deterioration in data accuracy is observed. The data show an average ρ_a/ρ value near 0.95 rather than 1.0 which we attribute to the 1 kHZ frequency utilized by the conductivity bridge being substantially higher than the 10 HZ used by our system. In addition, the dip cell constant for the conductivity bridge is itself

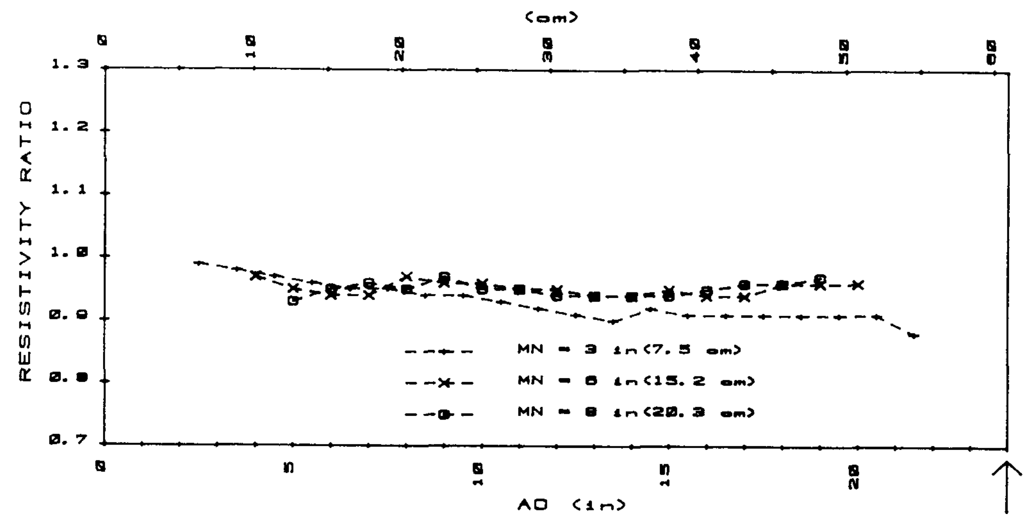


Fig. II-19 Results of experiment demonstrating the effect of the aluminum hemisphere on resistivity measurements. The position of the arrow marks the hemisphere wall.

± 1.0% at best. It was felt that these test results established that we may assume that the return current electrode is effectively at an infinite distance from the center of the hemisphere.

A second test of tank design involved determination of the maximum length central current electrode which could be used in model experiments before experimental accuracy is reduced. Inherent in the tank design is that the central current probe is a point source. At distances greater than a few times the length of a line source, the line source still appears to be a point source. Therefore, line sources at the central tank position may be used only up to a length where the hemisphere "sees" the line nature of the source. This test simply measured the apparent resistivity versus line electrode length at various $\overline{AO}$ positions and compared these values to those which would be measured if a point source had been used. The results (Fig. II-20) show that for near field measurements ($\overline{AO}$ = 3 in.) the measured apparent resistivity drops rapidly as electrode penetration is increased. At a large distance from the central probe ($\overline{AO}$ = 19 in.; near the hemisphere) the change is slight and is only 11% down at an electrode penetration of 8 in. (20.3 cm).

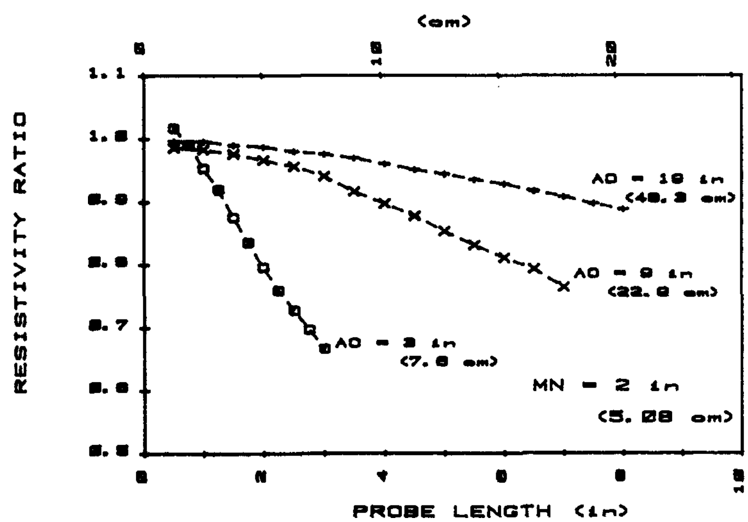


Fig. II-20 - Results of experiment demonstrating the effect of increasing the length of the central current probe upon resistivity measurements.

From these results it is felt safe to use central electrodes up to a penetration of 6 in. (15.2 cm) without fear of violating the central point electrode assumption of the tank design.

The experiment described exemplifies the on-going series of tests being performed to characterize the nature of potential field variation as related to fracture geometry. The experimental set-up is shown schematically in Fig. II-21. In this configuration, both the return electrode and the outer potential electrode are attached to the hemisphere. By placing the outer potential electrode at a practical infinite distance from the center of the tank, we are actually measuring the value

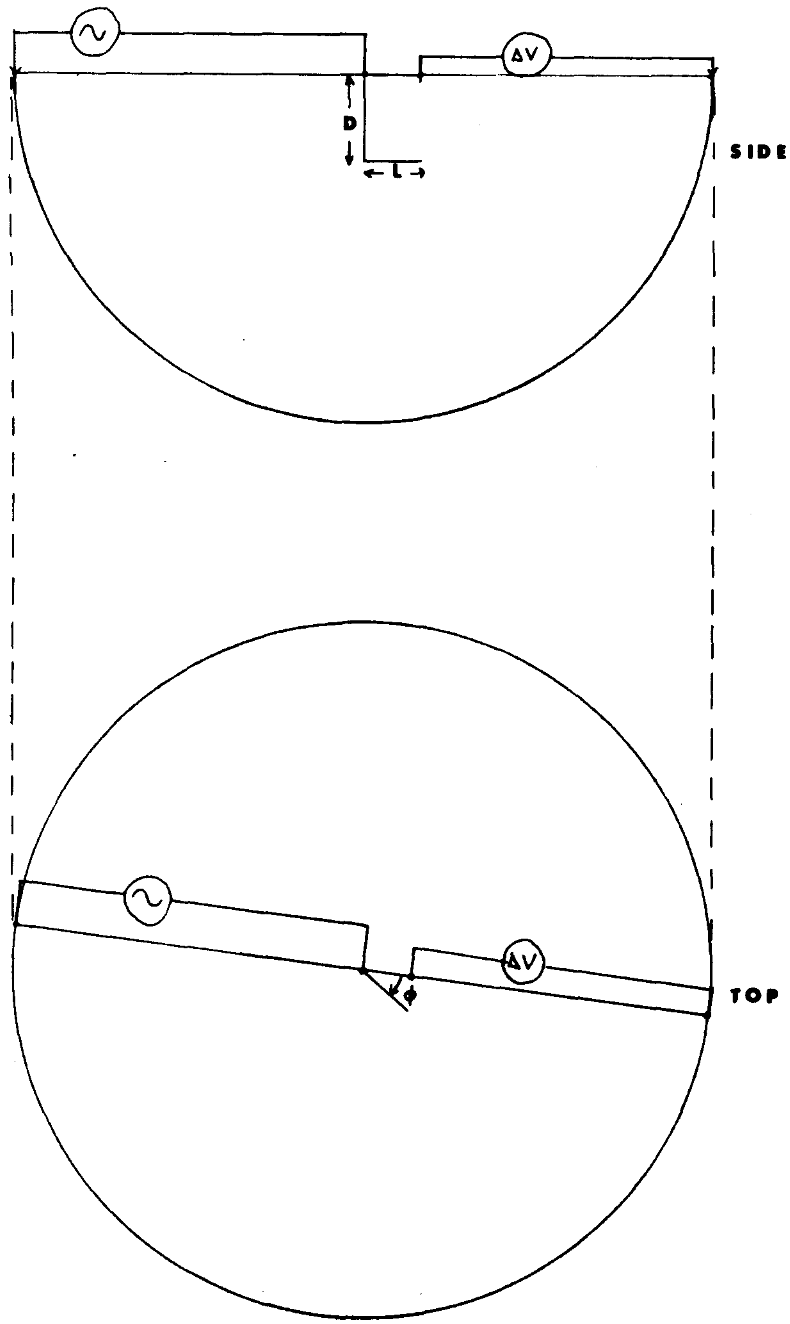


Fig. II-21 - Schematic illustrating the experimental set-up to determine the potential field distribution around an "L" shaped fracture of length, L, at depth, D.

of potential at the position of the inner potential probe. The fracture/well casing is represented by a length of Kovar rod. By putting a right angle bend in the rod, an asymmetric ("L" shaped) fracture may be modeled. Similarly, symmetric ("T" shaped) and various types of asymmetric fractures may be modeled by soldering various length pieces of Kovar to the tip of the Kovar rod representing the well casing. It is important to note that these are preliminary models and do not model relative heights, thicknesses, and resistivity contrast between the casing material and the fluid-filled fracture. These tests are concerned primarily with the effect of fracture length on observed potential distributions.

Figure II-22 shows the results of an experiment for an "L" fracture for fracture length varied from 0 up to one-half the depth of burial (0 to 7.5 cm in model dimensions). Considering the symmetry of the set-up, we would expect the same potential value when the fracture azimuth is ± 90° from the measuring point. Similarly, we expect a maximum in the field when the fracture azimuth is 0° (directly beneath the measuring point) and a minimum value when pointing away (azimuth = 180°). The only correction necessary is to account for a skew in the potential field caused by the casing part of the model not being perfectly straight. Performing the test with zero fracture length with measurements made at 10° intervals completely describes the field of the casing. This measurement allows correction of those tests made with finite fracture lengths to eliminate the effect of bending in the rod. As shown in Fig. II-22, the absolute value of the potential field (actually $\frac{2\pi}{I}*V$) decreases as the fracture length increases. In addition, the amplitude of the potential distribution (maximum value-minimum value) for a given fracture length increases with increasing fracture length as shown in Fig. II-23. From this result, it is suggested that given some knowledge of fracture asymmetry, the amplitude of the potential distribution surrounding the fracture well may provide the information required to deduce fracture length.

Similar parametric studies for other degrees of asymmetry and for symmetric models are presently underway at Sandia. As testing continues, models employed will increase in complexity to more accurately model the fracture/casing situation and to determine the effects of subsurface layering, lateral resistivity variation, etc.

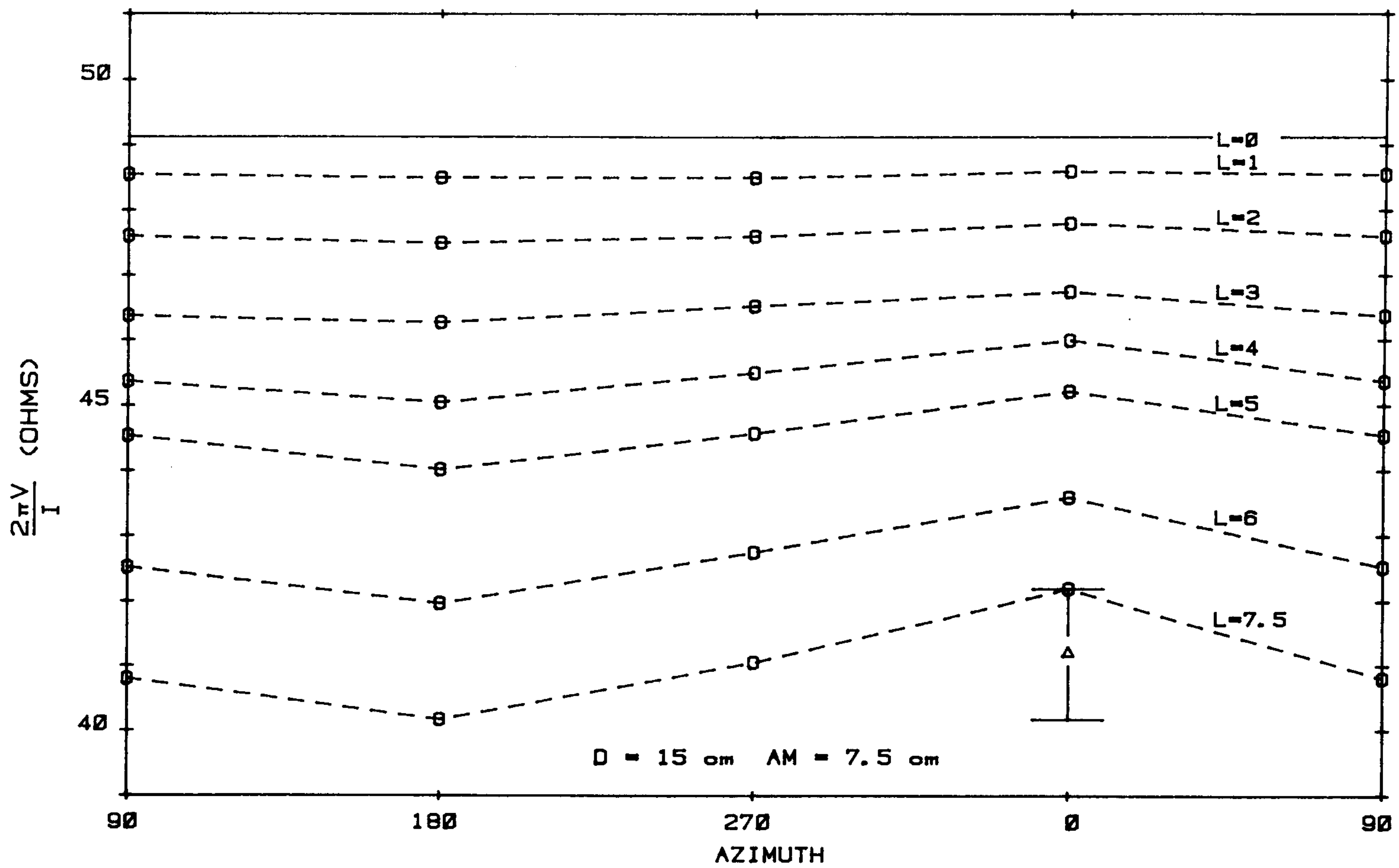


Fig. II-22 - Azimuthal Variation of Normalized Potential for Various Length "L" Shaped Fractures. Fracture lengths (L) in centimeters.

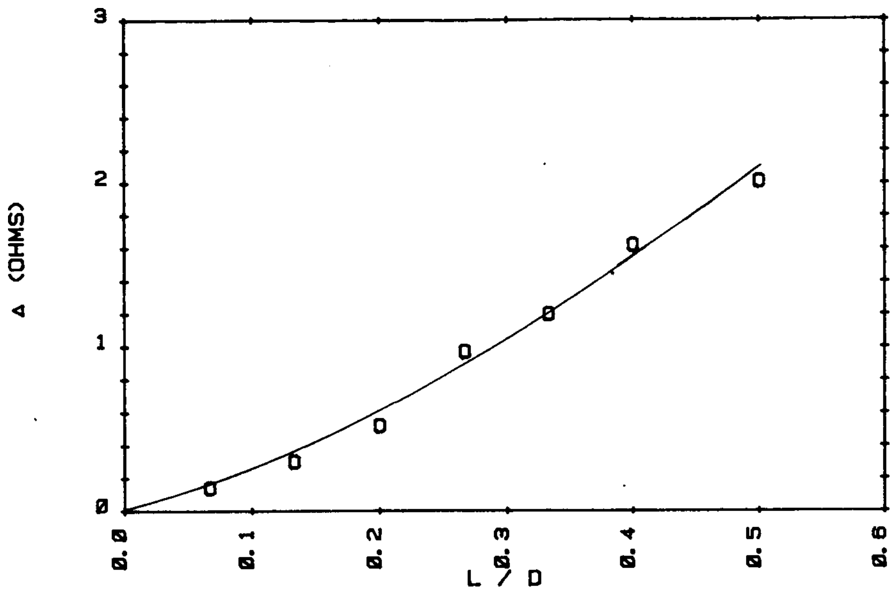
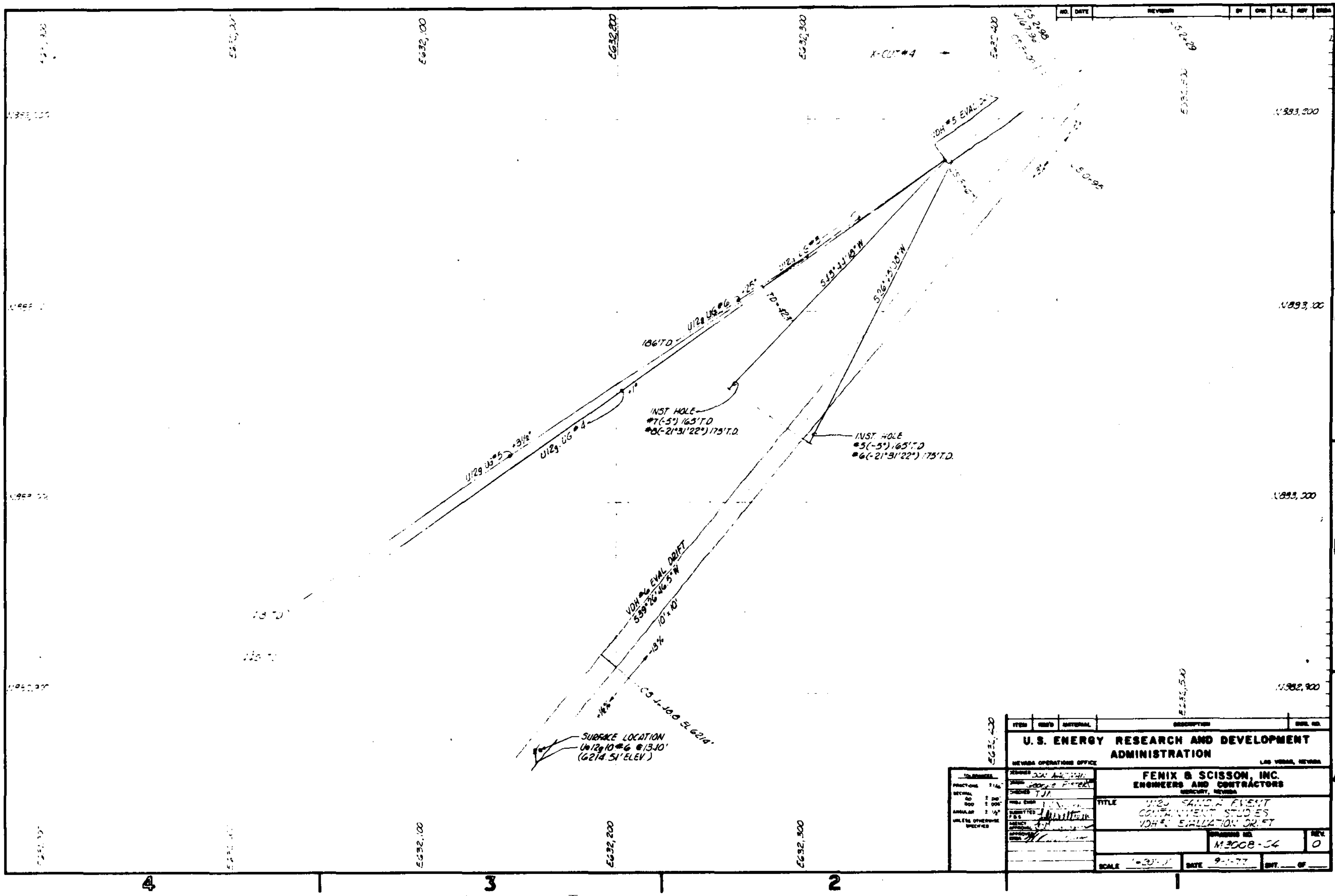


Fig. II-23 - Variation of Δ (maximum to minimum potential values) with increasing fracture length.

D. NTS Seismic Recording

A seismic monitoring system was installed in G-Tunnel at the Nevada Test Site to record seismic signals generated from hydrofractures in well Ue12g10#6. The seismic monitoring system consisted of four triaxial geophone packages placed in holes in G-tunnel such that the geophones were in a vertical plane and spaced to form a fifty foot square approximately 215 feet from the fracture well. Figure II-24 shows the location of the well and geophones. Geophones are in instrumentation holes 5 to 8.

The instrumentation system consisted of four triaxial geophones (Mark Products L25A), amplifiers, power supplies, and line drivers placed at the end of G-tunnel and a magnetic tape recorder located at the G-tunnel portal as shown in Fig. II-25. The geophone signal was amplified by 100 db and modulated voltage controlled oscillators (VCO's) and the mixed VCO signals sent to the tape recorder via a line drive and long cable. Not shown in Fig. II-25 is the power supplies for the amplifiers which are connected to each instrument box and the DC/signal splitting circuits. Power was supplied to the boxes from this instrumentation van at the portal.



X-CUT #4
E632,100
E632,200
E632,300
N893,200
N893,100
N893,000
N892,900
VDH #5 EVAL
186'T.D.
U12g UG #6
U12g UG #5
U12g UG #4
INST. HOLE
#7(-5°) 165'T.D.
#8(-21°31'22") 175'T.D.
INST. HOLE
#5(-5°) 165'T.D.
#6(-21°31'22") 175'T.D.
VDH #6 EVAL DRIFT
10'x10'
SURFACE LOCATION
U12g10 #6 @13.10'
(6214.51' ELEV.)
U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
NEVADA OPERATIONS OFFICE
LAS VEGAS, NEVADA
FENIX & SCISSON, INC.
ENGINEERS AND CONTRACTORS
MERCURY, NEVADA
TITLE
DRAWING NO.
REV.
0
SCALE
DATE
D
C
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A
4
3
2
1

Fig. II-24

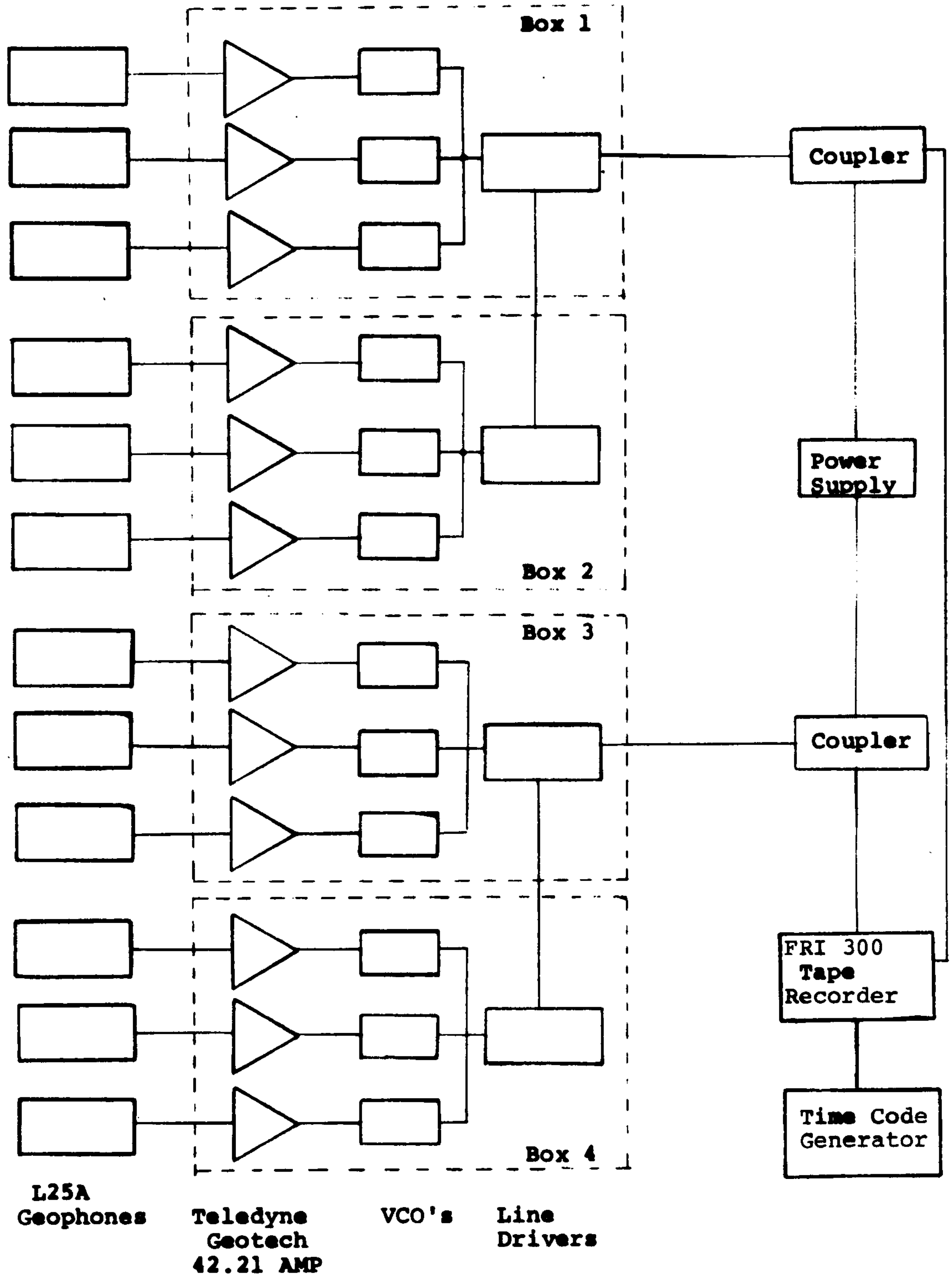


Fig. II-25 - Instrumentation System

Prior to recording the hydrofracture signals, the P-wave and S-wave velocities were measured at the end of G-tunnel, a 100 V, 100 Hz calibration signal was recorded, hammer blows on the drift faces (front, right and left faces) were recorded and the seismic signal generated by setting the packer was recorded.

On August 23, 1977 hole #6 was fractured at the 1352 to 1364 foot zone in ash fall tuff. A number of fracture related seismic signals were recorded. A total of 91 seismic events were noticeable upon initial examination of the data. A typical seismic signal appears in Fig. II-26. Each set of traces consist of two horizontal and one vertical geophone - the vertical geophone in the center trace. The first arrow on each trace indicates the P-wave arrival and the second arrow indicates the S-wave arrival.

Approximately 30 to 35 of the signals will be analyzed for wave content and recognition, amplitudes, frequency content and source location information. The source locations will be calculated using the following techniques.

1. Vector solutions from each triaxial package[1]
   four solutions

2. P-wave arrival times at four stations[2]
   one solution

3. S-wave, P-wave difference times at four stations[3]
   one solution

4. S-wave, P-wave difference times at three stations
   four solutions

---

[1] Los Alamos Scientific Laboratory Progress Report - LA6525PR, "LASL Hot Dry Rock Geothermal Project, July 1, 1975 - June 30, 1976", compiled by A. G. Blair, J. W. Tester and J. J. Mortensen.

[2] E. D'Appolonia Consulting Engineers, Inc., "Manual of Event Recognition and Interpretation Microearthquake Survey", T. L. Dobecki, January 1976.

[3] Bureau of Mines Bulletin 665, "Microseismic Techniques for Monitoring the Behavior of Rock Structures 1974", W. Blake, F. Leighton and W. J. Duvall.

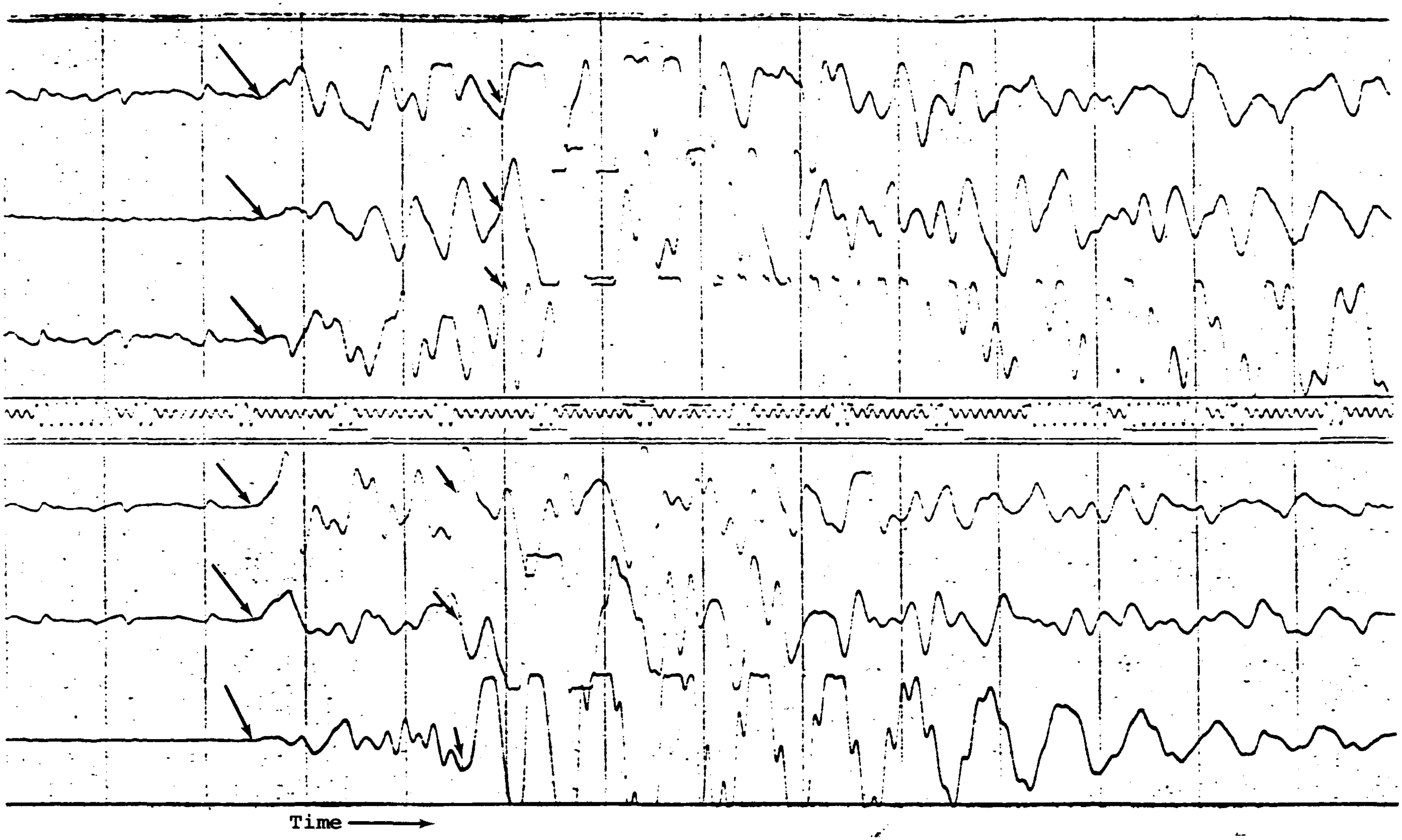


Fig. II-26 - Example of Observed Seismic Signals

The first calculations will also aid in evaluating the Borehole Seismic Locator since mineback will locate the fracture and accuracies can be estimated.

E. Borehole Seismic System

Examination of arrival times and polarization of seismic signals generated by hydraulic fractures may be used to map the size and orientation of those fractures. By employing a triaxial geophone package which is clamped to the borehole near the start of the fracture, the direction and distance to the seismic events created by the fracturing can be determined. Examination of a sufficient quantity of these seismic events may be used to determine the profile and orientation of the fracture near the wellbore.

The signals from two horizontal geophones may be used to calculate the azimuth direction of the event. A vertical geophone in conjunction with the horizontal geophones may be used to determine the angle of inclination to the source. Measurement of the difference in arrival times of the compressional wave (p-wave) and the shear wave (s-wave) may be used to calcualte the distance to the seismic event if the velocities of these waves are known. The addition of a package orientation device permits mapping of the fractures with respect to some geophysical reference.

A Borehole Seismic Locator (BSL) has been designed and has been fabricated. A triaxial geophone system has been incorporated with a mechanism to clamp the BSL to the wall of the borehole. The BSL is 3-5/8 inches in diameter and up to 16 feet long, capable of being locked to boreholes from 4-1/2 inches to 15 inches in diameter.

Figure II-27 shows component arrangement of the BSL. Power is supplied to the unit by means of a single conductor logging cable. Signals are sent to the surface over the same cable. The electronics package provides amplification for the geophone signal and controls for the clamping mechanism. The motor, arm drive, and clamping arm is the means for clamping the BSL to the wall. This unit is a portion of Geo Space Corporation Wall Lock Geophone System. The triaxial geophones are two horizontal and one vertical L-25A geophone produced by Mark Products. Orientation of the BSL is determined by using a photographic compass unit in open holes or a gyro unit in cased holes. The compass

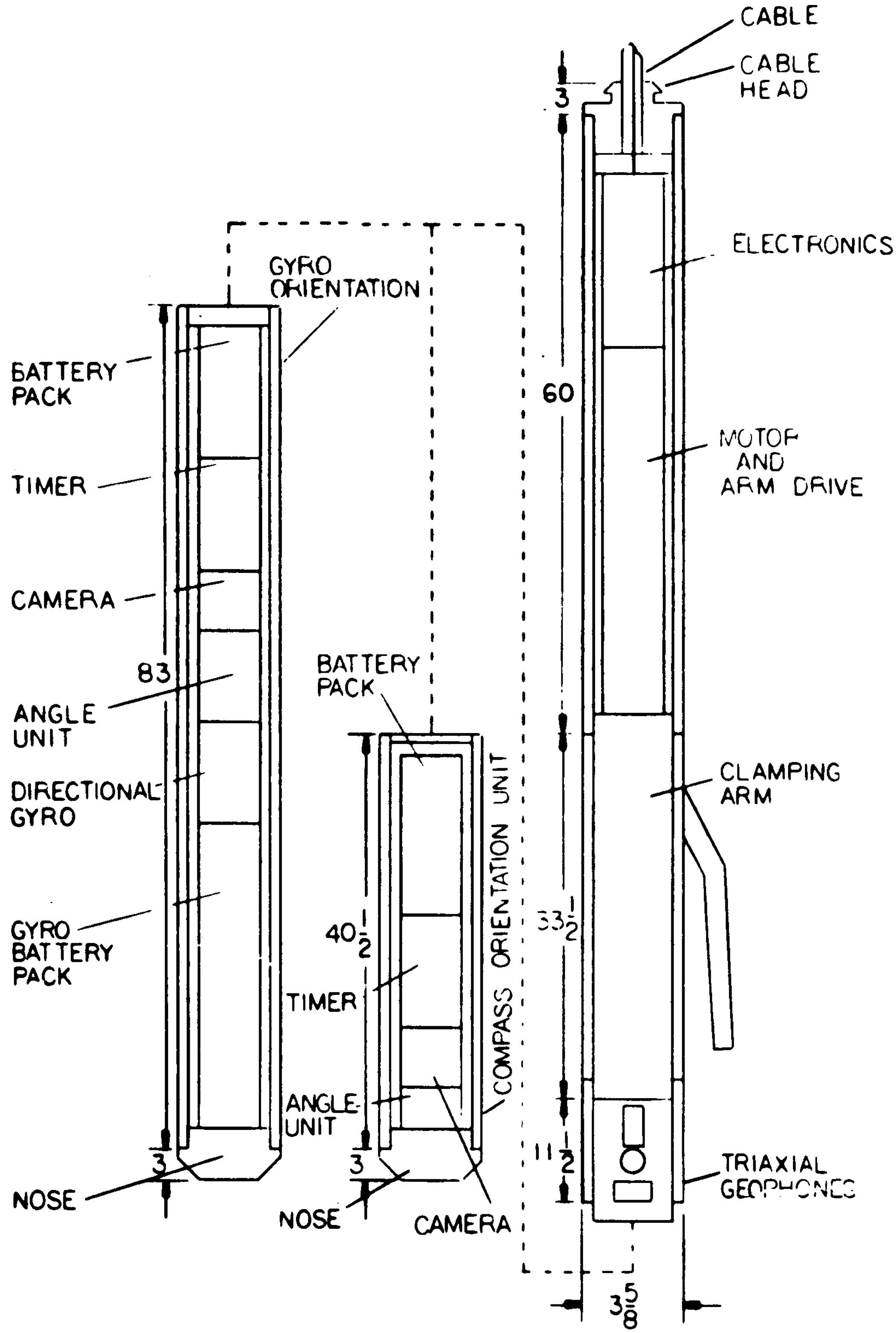


Fig. II-27 - Borehole Seismic Locator

unit contains a timed camera and a magnetic angle unit. Periodic photographs will be taken giving magnetic bearings and angle of inclination of the BSL. The gyro unit utilizes the same photographic unit in conjunction with a directional gyro and a gyro angle unit. The photographs will be developed after the BSL has been removed from the borehole. Both orientation devices have been purchased from Humphrey, Inc. Figure II-28 is a block diagram of the BSL electronics.

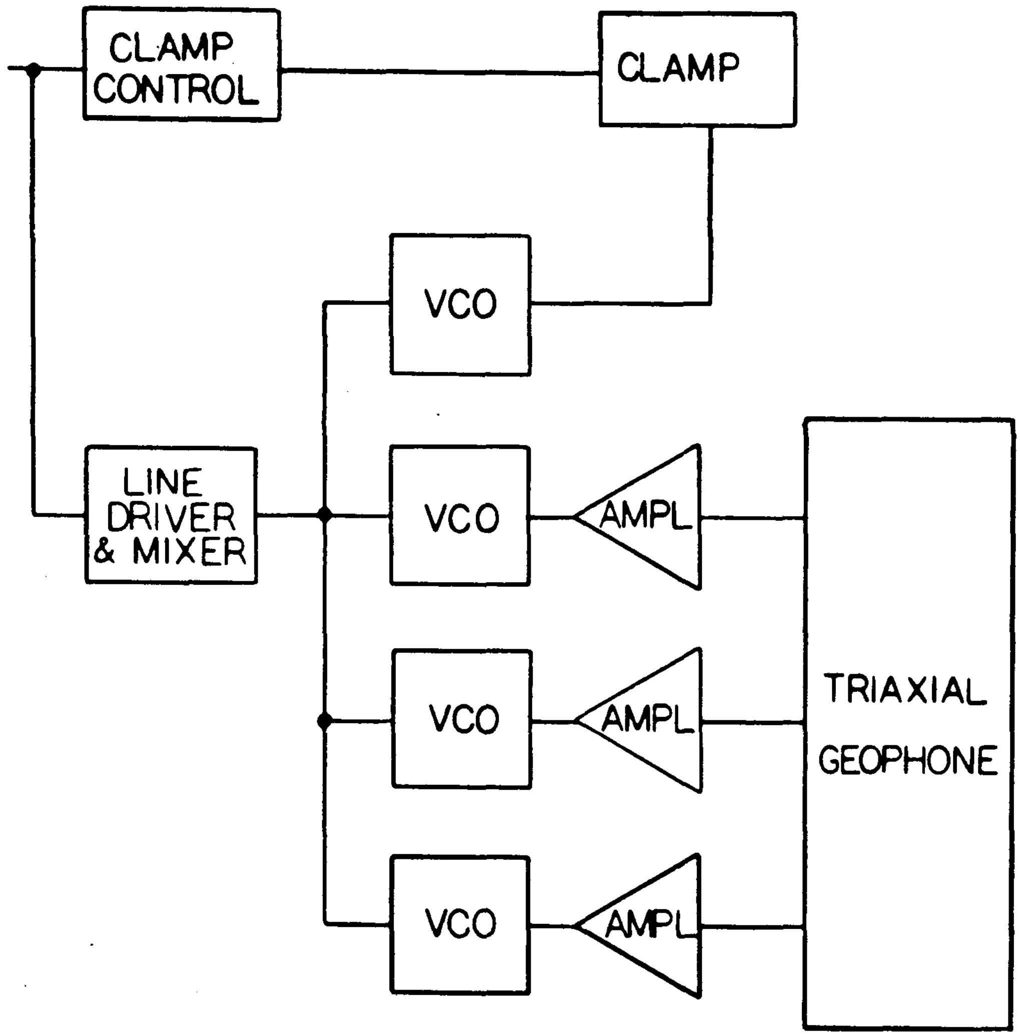


Fig. II-28 - Borehole Seismic Locator Electronics

The signals from the triaxial geophone array are amplified in Sandia Laboratories designed amplifier and modulate voltage controlled oscillation (VCO's). The VCO signals are multiplexed and transmitted to the surface through a line driven and a single wire line. At the surface, these signals will be recorded on a magnetic tape recorder. Power to the system will be supplied from the surface over the same single wire line.

The Borehole Seismic Locator (BSL) was assembled and pressure tested at Southwest Research Institute in San Antonio, Texas. 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 April, surface explosive tests were performed at the test well recently drilled on Kirtland Air Force Base. A number of charges were detonated at the surface in a number of locations. The charge sites were in contact with the limestone bed to which the BSL was coupled. These received signals will be analyzed for wave content and recognition, amplitudes, frequency contact and source location information. Because of the size and weight of the BSL, handling techniques were also evaluated and procedures refined.

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.

During FY 78, the BSL will be used for recording seismic signals from a hydrofracture of an AMOCO well in the Wattenberg Oil Field in Colorado.

Tests were conducted with triaxial geophones at the Nevada Test Site during hydraulic fracturing experiments. Recordings made during these tests will provide fracture seismic signal characterization and provide further information as to the accuracy of the system since mineback is planned in order to determine the size and extent of the fracture.

III. MINEBACK STIMULATION TEST PROGRAM (Edited by D. A. Northrop, 5732)

A. G-Tunnel Site and Mineback Operations
(G. B. Griswold, 5732, and W. C. Vollendorf, 1133)

G Tunnel is one of a number of tunnels that have been driven into Rainier Mesa at the Nevada Test Site for the purpose of conducting underground nuclear tests. This tunnel complex is shown in Fig. III-1. The mesa has strong topographic relief, ranging from an elevation of 6114 ft at the portal of G tunnel, which was driven into the base of the escarpment, to 7600 ft at the crest. The end of the tunnel complex is under 1000 to 1400 feet of cover, and thereby provides an effective maximum overburden stress in the range of 1000 to 1400 psi.

The geologic formations underlying Rainier Mesa are entirely of volcanic origin and a geologic cross section is shown in Fig. III-2. The majority of the section is composed of fairly flat-lying, ash-fall and welded tuffs. In the vicinity of G tunnel, this sequence of volcanic beds have been divided into four major geologic units. In descending order they are: Rainer Mesa Member ($\sim$ 400 ft thick) consisting mostly of dense gray welded tuff, Survey Butte Member ($\sim$ 850 ft) of gray to brown ash-fall tuff, Grouse Canyon Member ($\sim$ 150 ft) of dense gray to reddish welded and ash-fall tuff, and the Tunnel Beds ($\sim$ 1000 ft) of well-layered gray to pinkish brown ash-fall tuff.

The G tunnel complex was driven entirely in bedded ash-fall tuff. It is a near ideal medium to conduct fracture studies because of its uniformity in physical characteristics and absence of zones of native fracturing. Faults are present, but typically are of small displacement and rehealed. Figure III-3 is an enlarged view of the region where these experiments are being conducted. The locations of the Hole 5 (proppant distribution) and Hole 6 (formation interface) experiments are shown. The contact between the bedded and welded tuffs in the Grouse Canyon Member was the interface used in the Hole 6 test and occurred at a depth of 1346 ft.

The in situ examination of created fractures is provided by mining operations. A self-advancing, Alpine miner is used to make successive cuts at the working face. As seen in Fig. III-4, the mining head produces an exceptionally clean face which allows for detailed evaluation. Fracture descriptions are obtained via colored photography and detailed

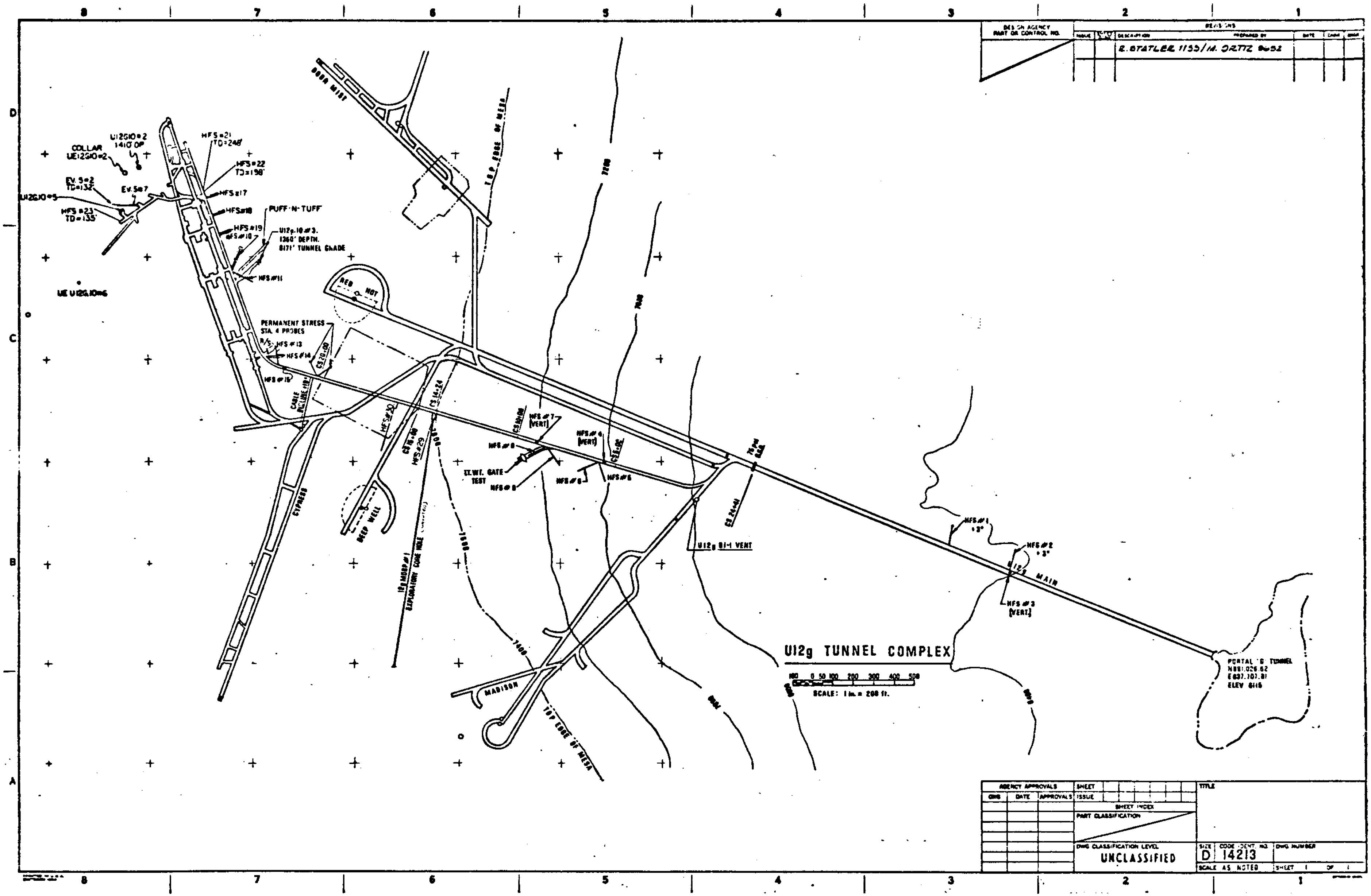


Fig. III-1 - Plan View of the U12g Tunnel Complex

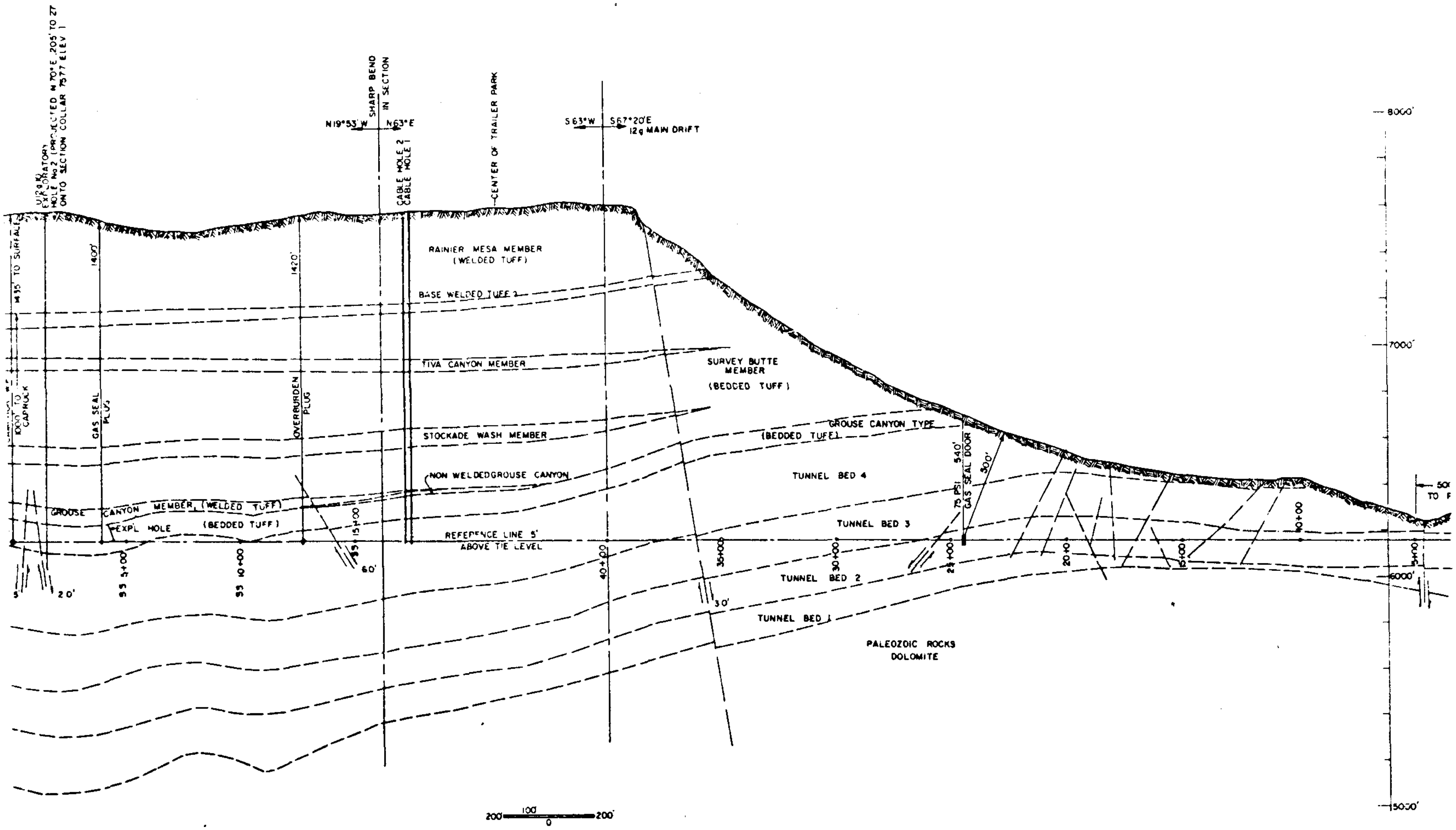


Fig. III-2 - Geologic Cross-Section of the U12g Tunnel Complex

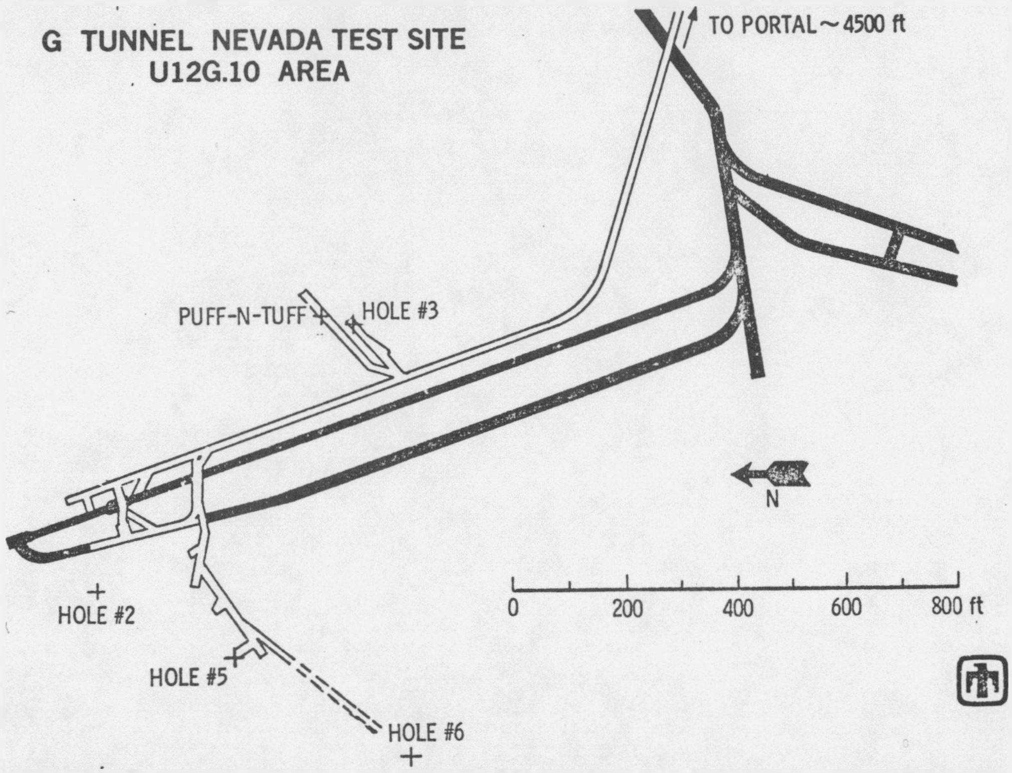


Fig. III-3 - Close-up of Mineback Experiment Sites

Fig. III-4 - View of Alpine Miner's Cutting Head and Uncovered Grout-Filled Fracture and Borehole.

geologic notes and maps. Recently, stereophotography and computer reduction of these photographs have been investigated for additional data presentations. In addition, coreholes are drilled from existing drifts to further delineate the created fracture system. Rock samples can be obtained for material property measurements at specific regions of interest. In situ stress measurements are made via both overcore and small hydraulic fracture techniques*. The latter technique is particularly convenient, as subsequent mineback examination yields the orientation normal to the minimum principle stress.

B. Proppant Distribution Experiment: Hole 5
(L. D. Tyler, 1111, and G. B. Griswold, 5732)

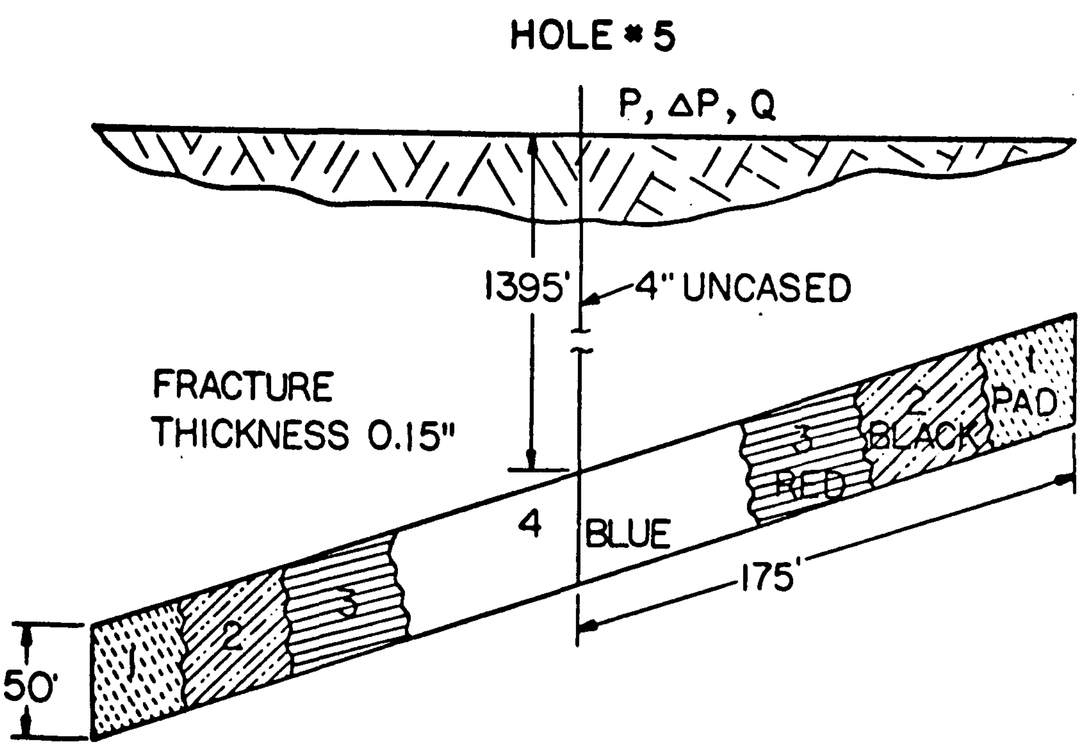
The basic objective of the test was to study sand proppant transport and deposition in a hydraulically-induced fracture. The fracture treatment design was a joint effort between Sandia and technical representatives of Halliburton, Inc., the latter being the service company who actually conducted the fracture operations.

The proper identification code number of the test hole is UE12g10 No. 5. (The code reads that the hole was drilled in Area 12, in G tunnel, in the vicinity of the 10th drift, and is hole No. 5 of a sequence.) The exact location by the NTS coordinate system is 883,237 N and 632,370 E. The collar elevation is 7570 ft and the total depth was 1400 ft. The hole was drilled during 1976. The core log indicated characteristics typical of the Tunnel Beds tuff with a fracture in the zone where the test was to be conducted.

The fracture design is shown schematically in Fig. III-5 and involved the following sequence of operations:

1. Place an HQ rod (3-1/8" ID) inside hole with the packer element on bottom.
2. Circulate the hole with clean water.
3. Set the packer at 1395 feet.
4. Run a string of NQ rod (2-3/8" ID)
5. Conduct the fracture treatment by pumping fluid down the center rod with the annulus between the two rod strings packed off at the surface.

*Haimson, B. C. et al, "Deep Stress Measurements in Tuff at the Nevada Test Site," Proc. of the Third Conference, International Society of Rock Mechanics, Denver, CO, 1974.



HOLE 5-FRACTURE DESIGN

Fig. III-5

6. During breakdown and treatment, the pressure inside the NQ rod string and the static pressure on the annulus would be measured with high sensitivity pressure transducers.
7. Fracture initiation would be under open hole conditions in the 5 foot zone from the packer to the bottom of the hole.

The fracture fluid was specially tailored to the test requirements and was scheduled as follows:

1. Breakdown - 350 gallons of water-based gel
2. 1st Stage - 450 gallons of water-based gel with black-dyed, 20-40 mesh sand at 1 lb per gallon concentration.
3. 2nd Stage - 400 gallons as above but with red sand at 2 lb per gallon.
4. 3rd Stage - 400 gallons as above but with blue sand at 3 lb per gallon.
5. Flush - 320 gallons of clear water to flush the 3rd stage clear of the drill rod.

All fluids were premixed. Once injection commenced, it was to be maintained at a constant rate as possible with no shutdown between stages other than valve switching. The injection rate was to be 4 bbls per minute. The design of the water-base gel (designation PWG/FR26L) called for a viscosity in the range of 30 to 100 cp. Fracture design calculations predicted a distribution of colored sand proppants as shown in Fig. III-5.

The test occurred on August 23, 1976 and proceeded as planned. The results from the pressure and injection rate sensors are shown on Fig. III-6. Significant operational events are also noted on the diagram.

An array of acoustic signal detectors had been placed underground in the tunnel to detect acoustic signals related to fracture propagation. Seismic signals were recorded, but data analysis has revealed that all of the decipherable signals originated from the vicinity of the wellbore; none were detected that could be associated with a growing crack.*

An analysis of the injection records as exhibited in Fig. III-6 has led to these observations:

(1) The pressure spike at point 1 indicates that the formation may have broken down while circulating clear water. The maximum pressure recorded was 975 psi, but this pressure may not represent true breakdown. The record does indicate that the annulus was prematurely closed while pumping. The instantaneous shut-in pressure (point 2) was ~850 psi. Another pressure spike was recorded (point 3) upon initiation of pad injection; this peak was 1060 psi.

(2) Rapid pressure increase was observed during pad injection. At point 4, the pressure was 820 psi and by the time the first stage started to enter the hole, the pressure had climbed to 1100 psi (point 5). The injection pressure continued to climb until the completion of injection (1425 psi at point 6).

(3) An excellent record of the instantaneous shut-in pressure was recorded after shut down (point 7).

*Further details of this aspect of the experiment are given in the first Annual Report of this program: Sandia Laboratories Report, SAND-77-0286, June 1977, p. 62.

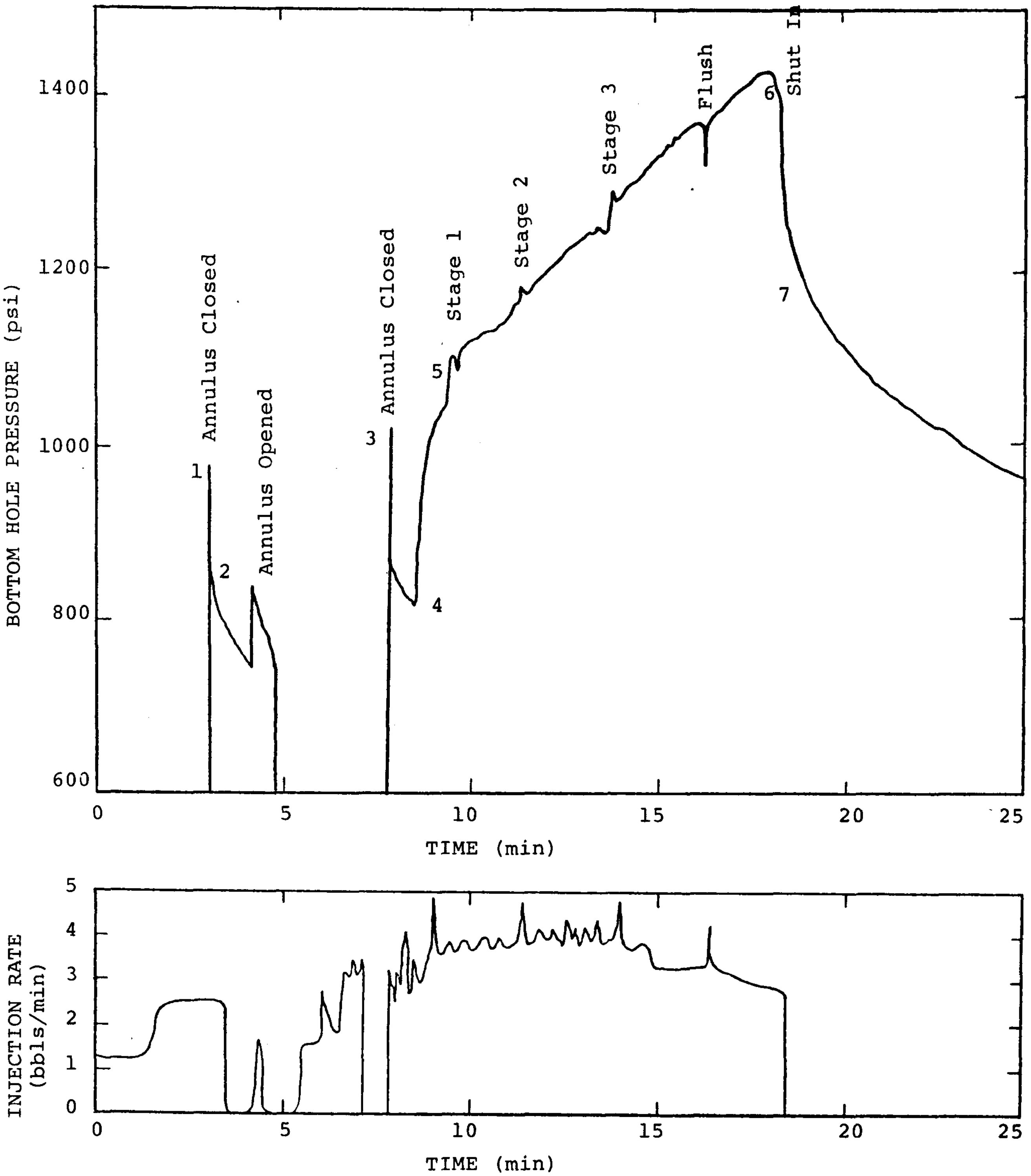


Fig. III-6 - Injection Pressures and Rates, Hole 5 Test

(4) The gross shape of the pressure plot between points 4 and 6 is exponential while the injection rate remained nearly constant. Such behavior should be expected from a constantly growing radial fracture being fed from the wellbore. However, the final injection pressure was 1425 psi versus a minimum rock stress of $\sim$ 850 psi. The 575 psi pressure difference must be ascribed to friction losses, probably very near to the wellbore, because theory states that the pressure required to propagate a fracture is only slightly over the minimum stress.

(5) Seismic signals related to fracture propagation were not detected and this suggests that a normal fracture was not formed.

(6) The friction loss down the pipe, as measured by taking the difference between the surface injection and annulus pressures, of the frac fluid were similar to those for the water flush. Therefore, the conclusion is that the actual frac fluid viscosity was about 1 centipoise. The low viscosity is in agreement with the composition of the frac fluid which contained a friction reducing agent. Under turbulent flow conditions experienced in the pipe the fluid has low ($\sim$ 1 cp) viscosity. Under laminar flow conditions expected in the fracture, the viscosity rapidly increases. The design viscosity for laminar flow was 79 centipoise.

Mineback operations commenced from the end of the then existing tunnel, approximately 200 ft from Hole 5 (see Fig. III-3). A number of mini-breakdown tests were accomplished ahead of the mining sequence for in situ stress measurements. A long horizontal hole had been previously drilled and six breakdown tests conducted prior to fracing Hole 5. The mining plan therefore included mining along that hole while advancing towards the Hole 5 region.

No evidence of the Hole 5 fracture was found in the main drift even after it was driven to a position some 60 ft from the borehole. An exploratory coring program was then conducted to search for the fracture. Seven holes were drilled from stations in the drift or short cross-cuts off the main drift. Evidence of the fracture was obtained only in three of the holes and the decision was then made to cross-cut directly to the borehole. Eventual mineback operations resulted in creating a small gallery in the vicinity of the borehole as shown in Fig. III-7.

A simple fracture was not created by the staged proppant experiment. Details of the fractures are shown in Figs. III-8, 9, and 10. The mine-back has indicated that the main course of the fracture was downward and to the south. The primary fracture was steep but sinuous. A secondary fracture branched off the main zone and its orientation was about 30° from horizontal. Both fractures cut bedding and minor fault planes for most of their course except in two significant cases. Upward growth of the main fracture terminated against a flat bedding plane or parting forcing the fracture to propagate downward. The secondary fracture was effectively terminated by a high angle fault. No distinct distribution pattern of the three stages of colored sand proppant was witnessed during mineback. In most instances the three colors were mixed. The fracture width varied from 1 to 5 mm.

This experiment was conducted closer to a nuclear event than the Hole 3 experiment conducted in 1975 and which produced a more "classical" fracture.* Thus, the results from the Hole 5 test may be confounded by effects from the nuclear event. Nonetheless, significant observations can be made:

(1) fracture growth was limited and affected by faults,
(2) the fracture did not penetrate, and sand proppant was not found in, an open fracture about 3-5 from the borehole,
(3) upwards growth of the fracture was limited by a parting plane (essentially a no strength interface),
(4) no distinct patterns of the three stages of colored sand proppant were observed,
(5) orientation of the minor fracture changes as it passed through different bedding planes, and
(6) observed fracture is dramatically different than the design fracture.

No simple explanation can be given for the fracture complexity observed in this test. Work is now underway to study the in situ stress distribution in the region as well as obtaining a comprehensive set of rock properties. This work will hopefully contribute to our understanding of this complex fracture experiment.

*Tyler, L. D. and Vollendorf, W. C. "Physical Observations and Mapping of Cracks Resulting from Hydraulic Fracturing In Situ Stress Measurements," SPE Paper 5542, 50th Annual Technical Conference and Exhibition, Society of Petroleum Engineers of AIME, Dallas, TX, September 30-October 1, 1975.

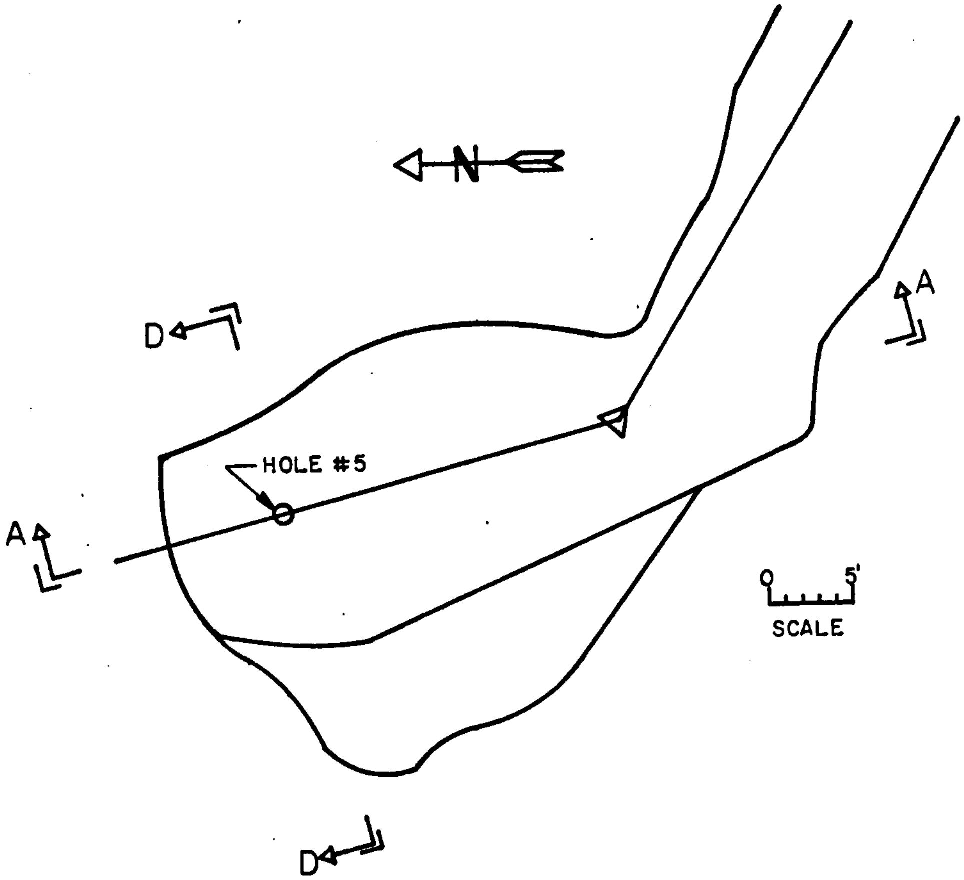


Fig. III-7 - Plan View of Hole No. 5 Mineback Showing Locations of Vertical Sections.

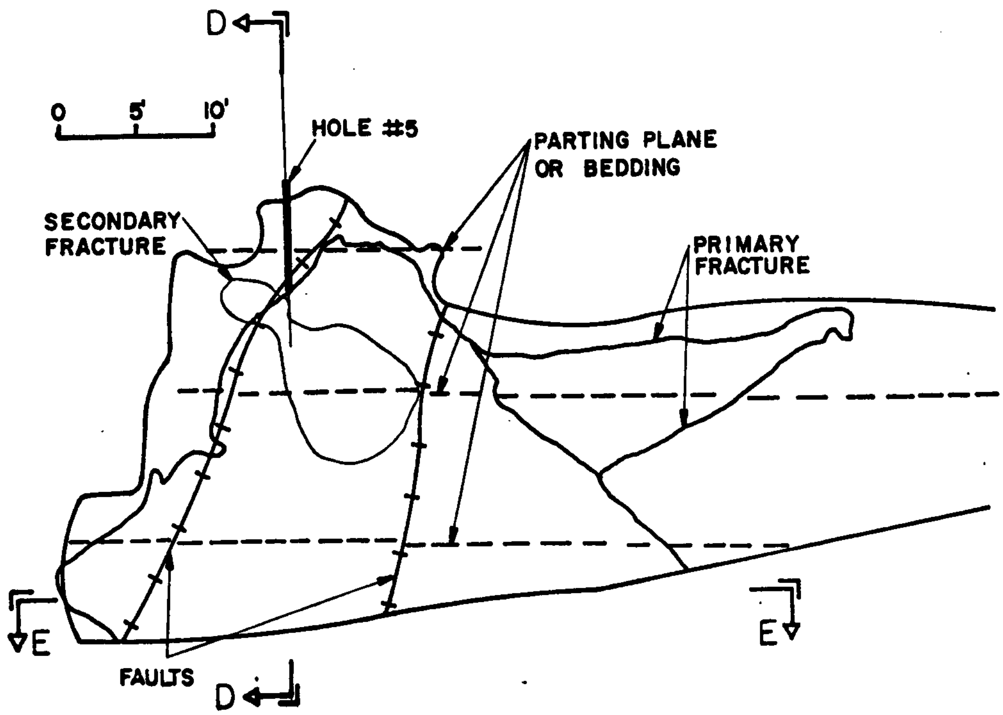


Fig. III-8 - Longitudinal Cross-Section A-A

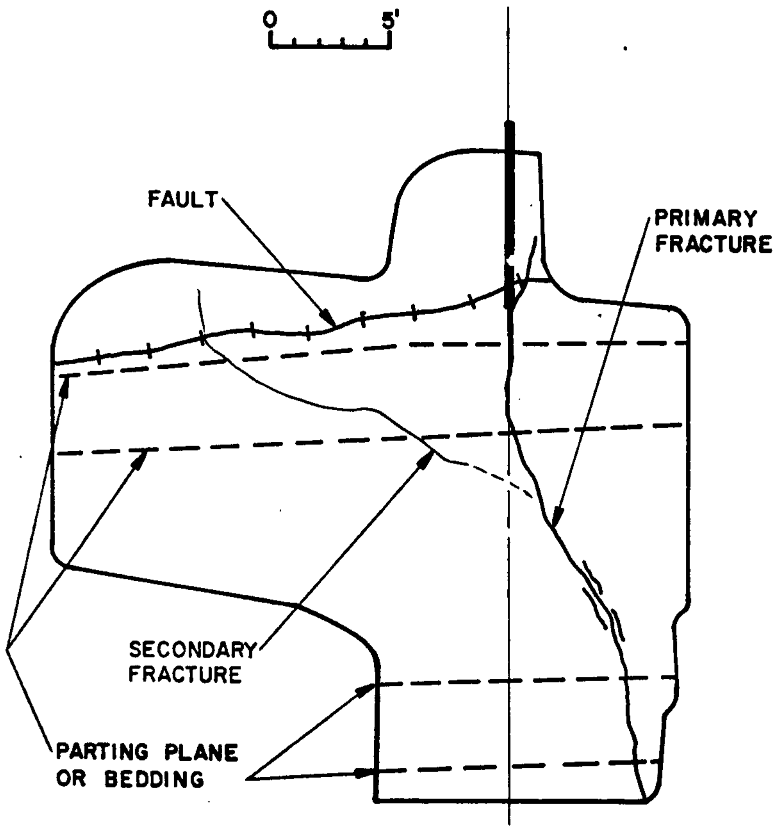


Fig. III-9 - Cross Section D-D, Looking North

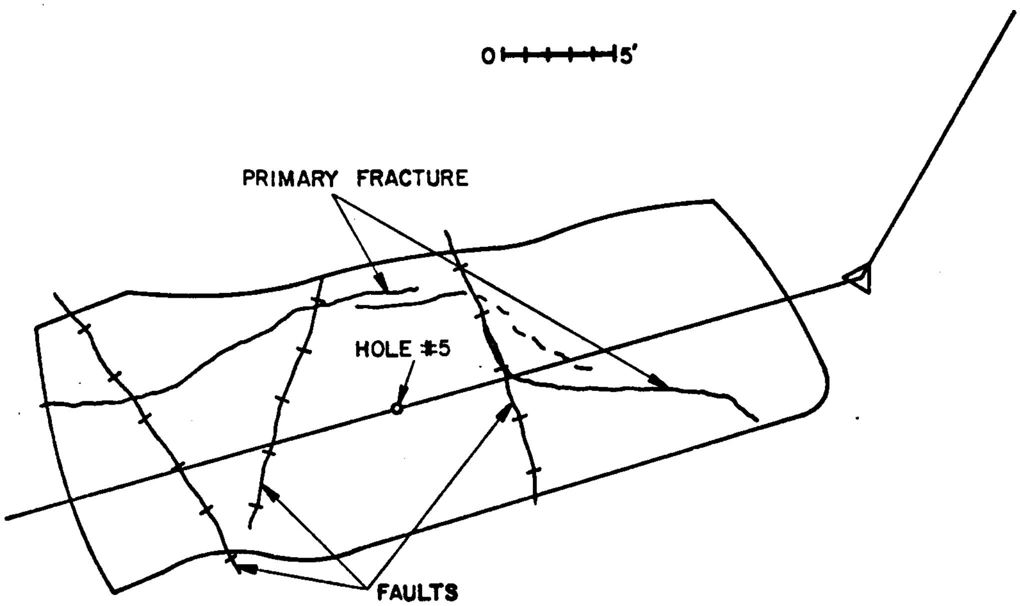


Fig. III-10 - Plan View E-E of Fractures 15 ft Below Bottom of Hole No. 5.

C. Formation Interface Experiment: Hole 6

(N. R. Warpinski, 5732, L. D. Tyler, 1111, and G. B. Griswold, 5732)

The behavior of hydraulic fractures at formation interfaces is not well understood and its investigation is of prime interest to industry. A formation interface between the ash fall and welded tuffs is available in G tunnel and was utilized in the design and conduction of the Hole 6 experiment. The initial test design was formulated at a meeting of Amoco, Dowell, Halliburton, and Sandia representatives in Tulsa, OK on February 22, 1977. Specific fracture design was performed by Dowell and they conducted the actual frac jobs at the Nevada Test Site.

The location of the test hole was chosen at a site 425 feet south southwest of Hole 5. Hole 6, which is officially designated UE12g10#6, is shown in Figure III-3; the exact location is N882,870.34, E632,160.37 referenced to the NTS coordinate system. The hole's collar elevation is 7554.76 feet and its total depth is 1455 ft. The hole was cored and nuclear, density and caliper logs were run. The dense welded tuff unit was encountered from 1320 to 1336 feet as can be seen from a section of the density log in Figure III-11. From 1336 to 1352 feet is a transition region where there are many voids, fractures and breccia. Below 1352, the ash fall tuff is easily identified. The location of the welded tuff unit in the hole is about 50 feet higher than was originally anticipated and will necessitate uphill inclined mining to expose the interface. Table III-1 shows the properties of the various formations as determined from cores of Hole 5 nearby.

On July 8, 1977, a second meeting with Dowell was held in Albuquerque to finalize the design of the experiment. It was decided that each zone of the tuff be fractured separately with Class "A" cement containing 1% D-60 mixed at 15.4 lbs/gal. The properties of the grout are shown in Table III-2. Different colored grouts would be used in each formation to allow easy mineback identification of the cement-filled fractures. Fifty foot vertical fractures with 300 foot wings appeared sufficient for the purposes of the experiment. Given the average reservoir properties shown in Table III-3, Dowell provided a fracture design calling for 8000 gallons of grout pumped at 6 bbls/min for the ash fall tuff and 5000 gallons of grout at the same flow rate for the welded tuff. These designs would produce widths of 0.4 in. and 0.15 in. respectively.

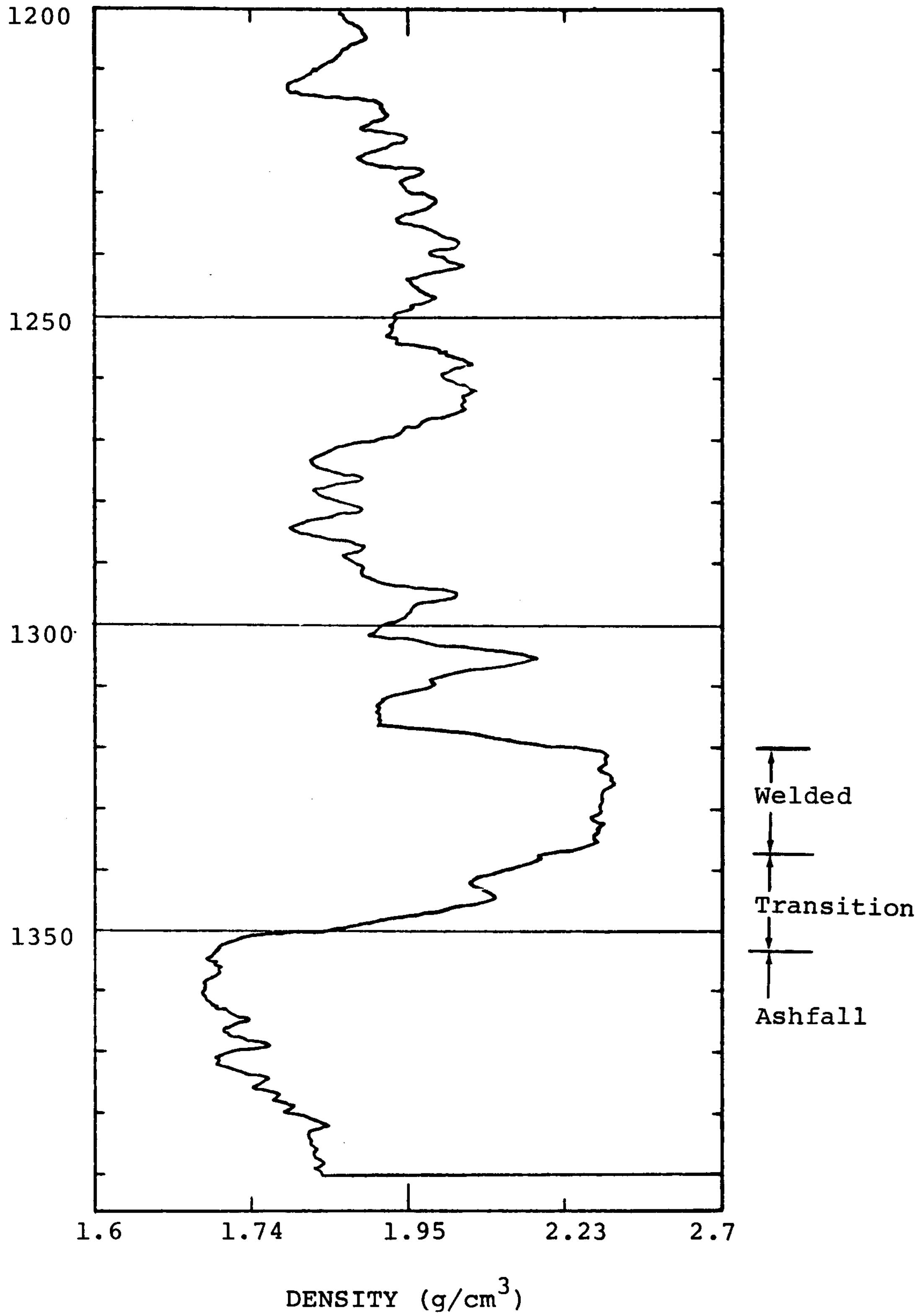


Figure III-11 - Density Log of Hole 6

TABLE III-1

Material Properties

Obtained From Hole 5 Cores

Depth Interval (ft)	Description	Permeability Horiz. (md)	Permeability Vert. (md)	Porosity (%)	Grain Density (g/cm^3)	Bulk Density (g/cm^3)	E (10^6 psi)	Poisson's Ratio
1303.0 1304.0	Upper Transition	0.01	<0.01	13.8	2.30	1.91	2.01	0.13
1338.3 1339.4	Welded Vapor	0.04	0.04	15.1	2.58	2.29	4.94	0.22
1358.8 1359.8	Dense Welded	<0.01	<0.01	9.8	2.50	2.23	Test Failure	
1364.1 1365.6	Lower Transition	0.82	0.88	21.1	2.60	2.12	3.79	0.15
1383.0 1384.3	Ash Fall	1.4	1.4	39.2	2.20	1.39	0.45	0.17

TABLE III-2

Properties of Class "A" Cement
With 1% D-60 @ 15.4 lbs/gal

Yield	1.21 ft^3/sack	
Viscosity	128 cps	
n'	0.86	Pseudo Plastic
k' (not corrected)	0.0031 lb-$sec^{n'}/ft^2$	Pseudo Plastic
η	0.07 lbm/ft-sec	Bingham Plastic
τy	0.23 lb/ft^2	Bingham Plastic
Cw	4.1×10^{-3} ft/$\sqrt{min}$	
Spurt	0	

TABLE III-3

Reservoir Properties

	Ash Fall Tuff	Welded Tuff
Bulk Density (g/cm^3)	1.77	2.37
Grain Density (g/cm^3)	2.42	2.6
Porosity (%)	44.6	13.0
Water Saturation (%)	100.0	100.0
Modulus of Elasticity (10^6 psi)	0.236	3.8
Poisson's Ratio	0.312	0.238
Permeability, (md)	0.01	0.022-2.2
Bulk Modulus (10^6 psi)	0.221	2.44
Shear Modulus (10^6 psi)	0.111	1.5

Details of the fracturing operations were finalized in August and are shown in Figure III-12. The first fracture would be initiated in the ash fall tuff. The well would be back filled with pea gravel to 1364 ft and an inflatable packer would be set with the bottom of the element at 1352 ft. This would provide a 12 foot isolated zone just below the transition region. Downhole pressures would be monitored with an Amerada bomb on a wireline in the open zone and a transducer hardwired to the surface situated in a sub directly above the packer. Wellhead pressure would be obtained from a transducer at the surface and the flow rate would be taken from Dowell's instrumentation. The formation would be broken down with 30 bbls of water. After a short quiet time for acoustic measurements, 4000 gal of green grout followed by 4000 gal of black grout would be injected. This would be displaced from the well bore with 10 bbls of water and then shut in for another quiet period.

The second fracture, also shown in Figure III-12, would be initiated in the dense welded tuff region. The hole would be back filled to 1331 feet and the packer set at 1323.5 feet, leaving an open interval of 7.5 feet. A notch, cut at 1328.5 feet would reduce breakdown pressure and insure that the fracture would initiate at that point. The same pressure and flow rate measurements would be obtained and the same fracturing operation followed, with the exception that only 5000 gal of blue grout would be injected.

An array of four triaxial geophone assemblies were emplaced in coreholes near the fracture region. Further details of this part of the experiment can be found in Section II-C.

The ash fall tuff zone of Hole 6 was fraced on August 23, 1977. A few items on the operational plan were modified as the experiment progressed. The pea gravel was tagged at 1358 feet instead of 1365 ft, leaving an open interval of only 4 feet. This required that the six foot long Amerada bomb be positioned above the packer at 1337 feet. The quiet time after breakdown was eliminated and the fracturing commenced immediately. Dowell injected 128 bbls of green grout and 90 bbls of black grout instead of the original design volume of 96 bbls of each. The pressure transducer at the surface malfunctioned and, consequently, no well head pressure data was obtained. Without this data, the friction losses through the pipe could not be determined. Figure III-13 shows the flow rate and downhole pressure data that were obtained as well as the location and number density of acoustic signals that are believed

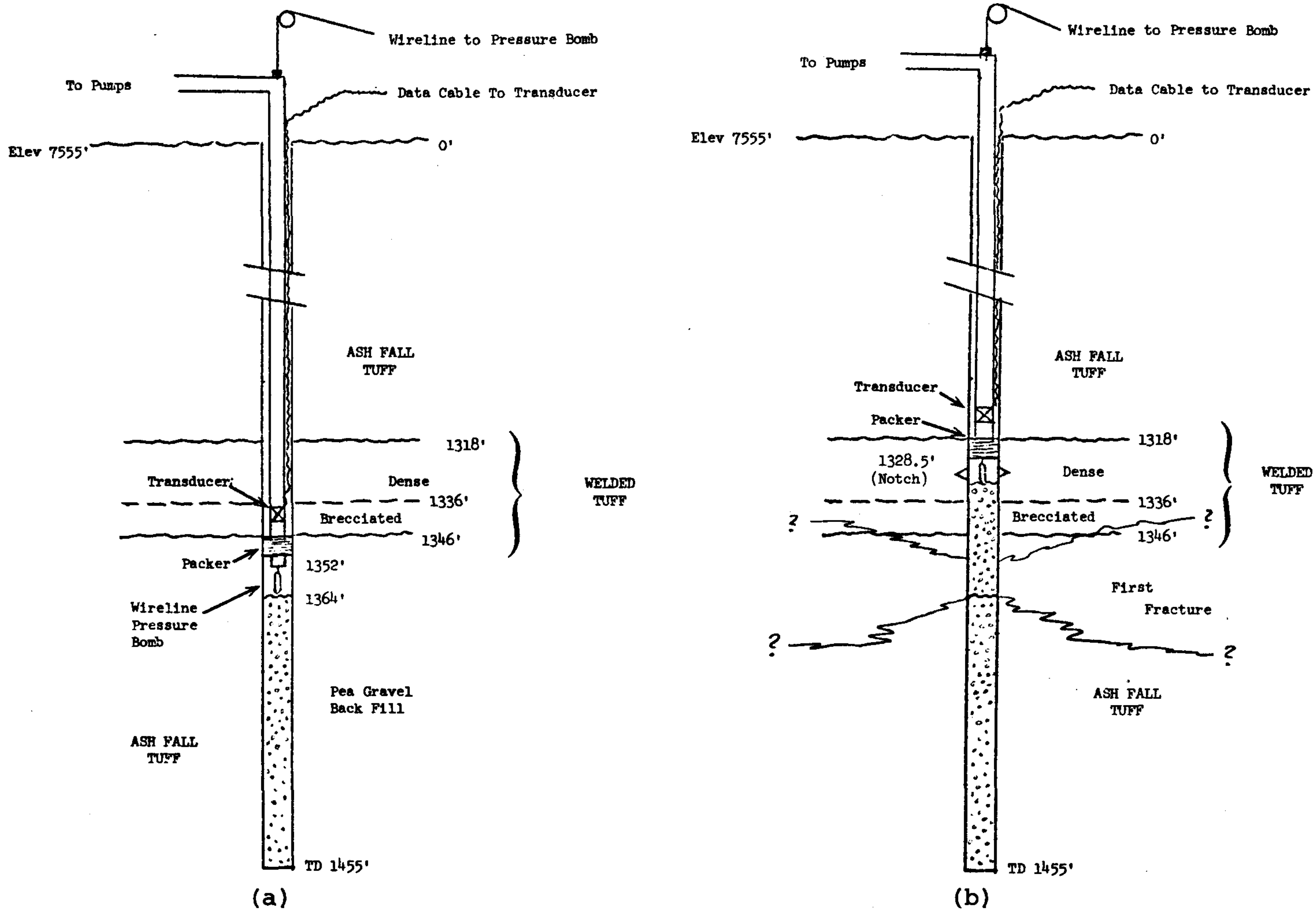


Figure III-12 - Fracture Locations, Formation Interface Test, Hole 6: (a) Lower Frac, (b) Upper Frac

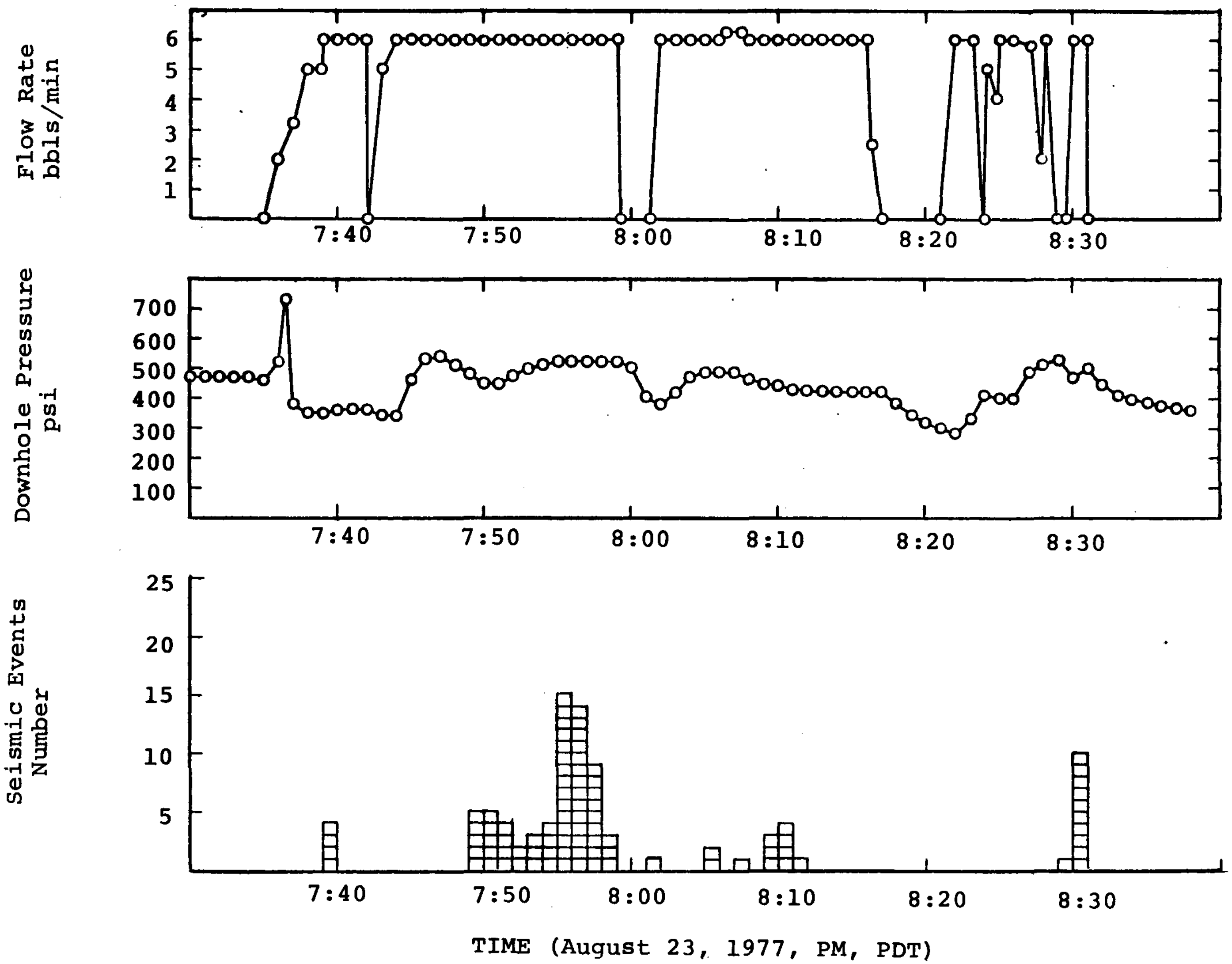


Figure III-13 - Flow, Pressure, and Seismic Data Recorded During the Lower Frac Job in Hole 6 to be fracture related. Not shown on the pressure record are severe fluctuations that are thought to be a result of a water hammer effect. These fluctuations occurred at approximately 7:40 and 8:28 for a duration of about 2 minutes each.

In order to translate the specific results of this experiment into general "fracture-interface interaction" criteria it is necessary to relate the results to their hydraulic fracturing history. For example, filling open fractures will provide no fracture-interface confrontation and unusual in situ stress distributions might produce unexpected results. It is expected that the pressure and flow measurements, as well as the acoustic measurements, can provide information to characterize the fracturing process prior to mineback. A number of preliminary observations have been based on these data.

As indicated in Figure III-13, the bottom hole pressure (BHP) before fracturing was constant at 465 psi. This demonstrates that fluid was not flowing into the formation and the zone was tight. The 730 psi pressure spike at 7:35.30 was coincident with the start of pumping and probably indicates breakdown. Although this is somewhat lower than expected, the minimum in situ stress (σ_{min}) cannot be greater than the smallest pressure (340 psi) observed during fracturing and a breakdown pressure that is 390 psi above σ_{min} is not unreasonable. If it is assumed that the maximum principle in situ stress (σ_{max}) can be calculated from

$$\sigma_{max} = 3\,\sigma_{min} - P_c + \sigma_t\ ,$$

where P_c is the breakdown pressure and σ_t is the tensile strength, and further, that the tensile strength is on the order of 300 psi, then an upper limit on σ_{max} can be placed at 590 psi.

Given the material properties in Tables III-1 and III-3, it is expected that a significant pressure rise would have been observed if the fracture had broken into the welded tuff formation. No such pressure increase is evident in Figure III-13. However, as shown by Simonson et.al.*, tectonic stress variations can also affect fracture propagation. If the in situ stresses in the welded tuff are lower than

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*Simonson, E. R., Abou-Sayed, A. S. and Clifton, R. J. "Containment of Massive Hydraulic Fractures," SPE 6089, 51st Annual Conference and Exhibition, Society of Petroleum Engineers of AIME, New Orleans, LA, October, 1976.

those in the ash fall tuff, the effect would be just the opposite expected from the inherent material property variations. Thus, it is very important that in situ stress measurements be made in both formations at various locations around the fracture. Finally, in order to observe this interaction, it is mandatory that the fracture "climb" as it propagates. This is usually expected in fracturing operations since the fracturing fluid's hydrostatic pressure gradient is less than the lithostatic pressure gradient. In the present case, the lithostatic pressure is due entirely to the overburden and the gradient in the ash fall tuff region is proportional to the tuff density which varies from 1.4 to 2.0 g/cm^3. The hydrostatic gradient, which is proportional to the fluid density (1.90 g/cm^3) is, in general, larger than the lithostatic. This suggests that the fractures may propagate downward.

It should be mentioned that shutdowns must be avoided if the pressure record is to be used for diagnostic information. Interpretation of the BHP in Figure III-13 is quite difficult due to the numerous interuptions in the flow rate. On the other hand, valving was not evident in the BHP record and presented no complications.

A definite shut-in pressure was not obtained because the Amerada pressure bomb surpassed its time limit (1-1/2 hrs) at 8:37. This pressure, which should be equal to σ_{min}, probably is not greater than 340 psi as previously discussed. Knowledge of friction losses through both the drill pipe and the fracture is also quite important. It is estimated that this slurry, which behaves like a Bingham plastic, has a friction loss of 755 psi/1000 ft through the 2-3/8 in. tubing at 6 bbls/min. The pressure gradient through the fracture has not yet been determined.

After completion of the first fracturing operation, fracing of the second zone was delayed when a string of drill pipe was lost in the hole during the notching operation. A fishing operation was successfully completed in September and the second zone will be fraced in late October, 1977. An operational plan has been devised that will insure that the instantaneous shut-in pressure (σ_{min}) and the friction losses through the drill pipe are obtained. Mineback operations have already begun towards the Hole 6 region, but not to an extent that will interfere with the second fracture.

D. Fracture Calculations
(N. R. Warpinski, 5732)

The interface between the welded and ash fall tuffs is not well defined and the rock properties vary widely over a ten foot range. In this region, the rock characteristics are not uniform and there are many voids, fractures and breccia. Since it is imperative to extend the fracture far enough in the ash fall tuff to allow interaction with the welded tuff, the fracture models of Geertsma and de Klerk* and Perkins and Kern** have been employed to study the effect of variations of bulk and matrix rock properties on fracture propagation.

Figure III-14 shows how the fracture length increases with injected volume. The design calls for a 50 ft high fracture with a flow rate of 6 bbls/min and a fluid viscosity of 128 cp. The fracture propagates in a medium where Young's modulus (E) is 2.36×10^5 psi and Poisson's ratio (ν) is 0.312. The fluid loss coefficient (CVW) is as shown on the graph and Dowell's predicted curve is shown for comparison. The two curves with CVW calculated use a porosity of 44.6% and a permeability of 0.01 md.

The effect of Young's modulus (E) on fracture length is shown in Figure III-15. For larger E, the fractures are longer but not as wide. Therefore, no problems are expected as the welded interface is approached since E for the welded tuff is larger than for the ash fall tuff. Figure III-16 shows that variations in ν have a negligible effect on the fracture.

The permeability has a pronounced effect on fracture length as demonstrated in Figure III-17. It is important to remember that even though matrix permeability may be low, a large fracture permeability can greatly reduce the length of the fracture. This is certainly the situation in the interface where voids, fractures and breccia are widespread.

E. Containment Program Activities: Puff-N-Tuff Experiment
(L. D. Tyler, 1111)

The Puff-N-Tuff experiment was conducted in G tunnel for the purpose

*Geertsma, J. and de Klerk, F., "A Rapid Method of Predicting Width and Extent of Hydraulically Induced Fractures," Journal of Petroleum Technology, December, 1969, Vol. 21, pp. 1571-1581.

**Perkins, T. K. and Kern, L. R., " Widths of Hydraulic Fractures," Journal of Petroleum Technology, September, 1961, Vol. 13, pp. 937-949.

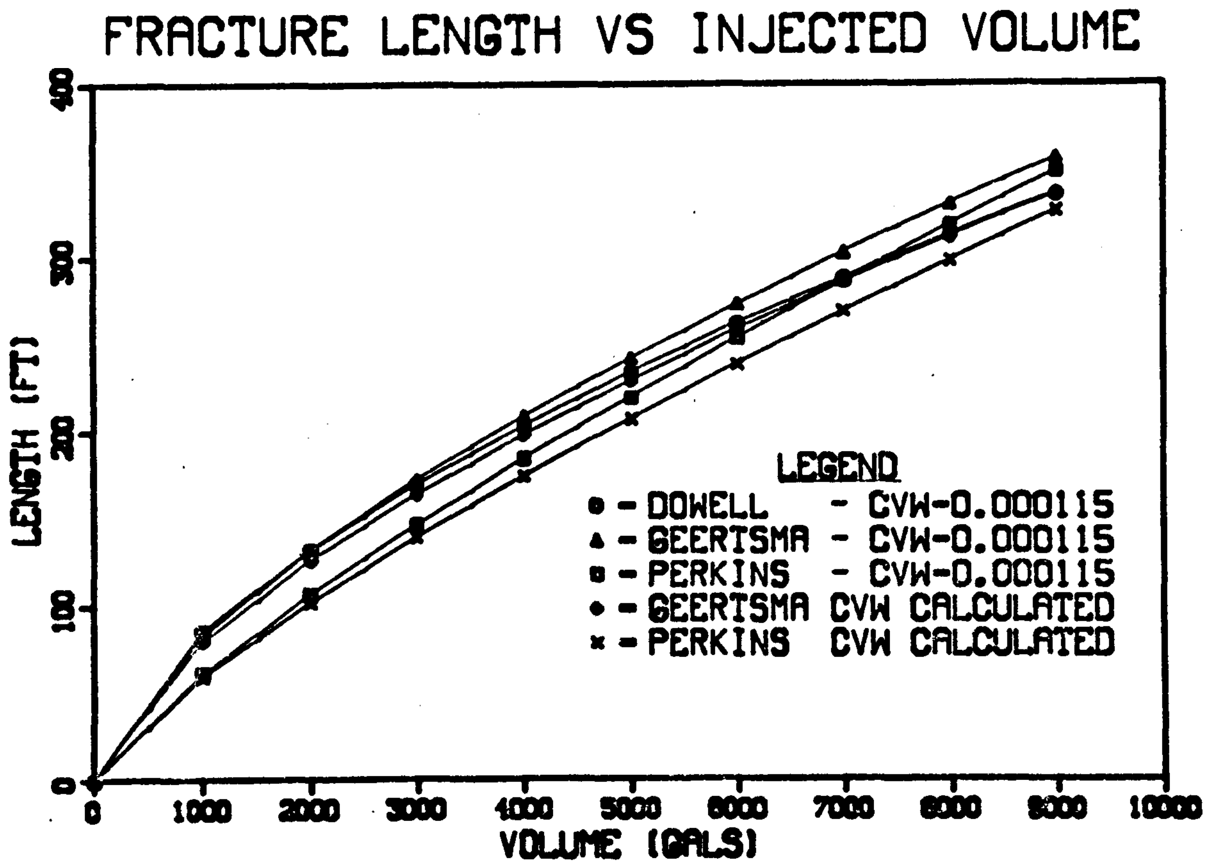


Figure III-14

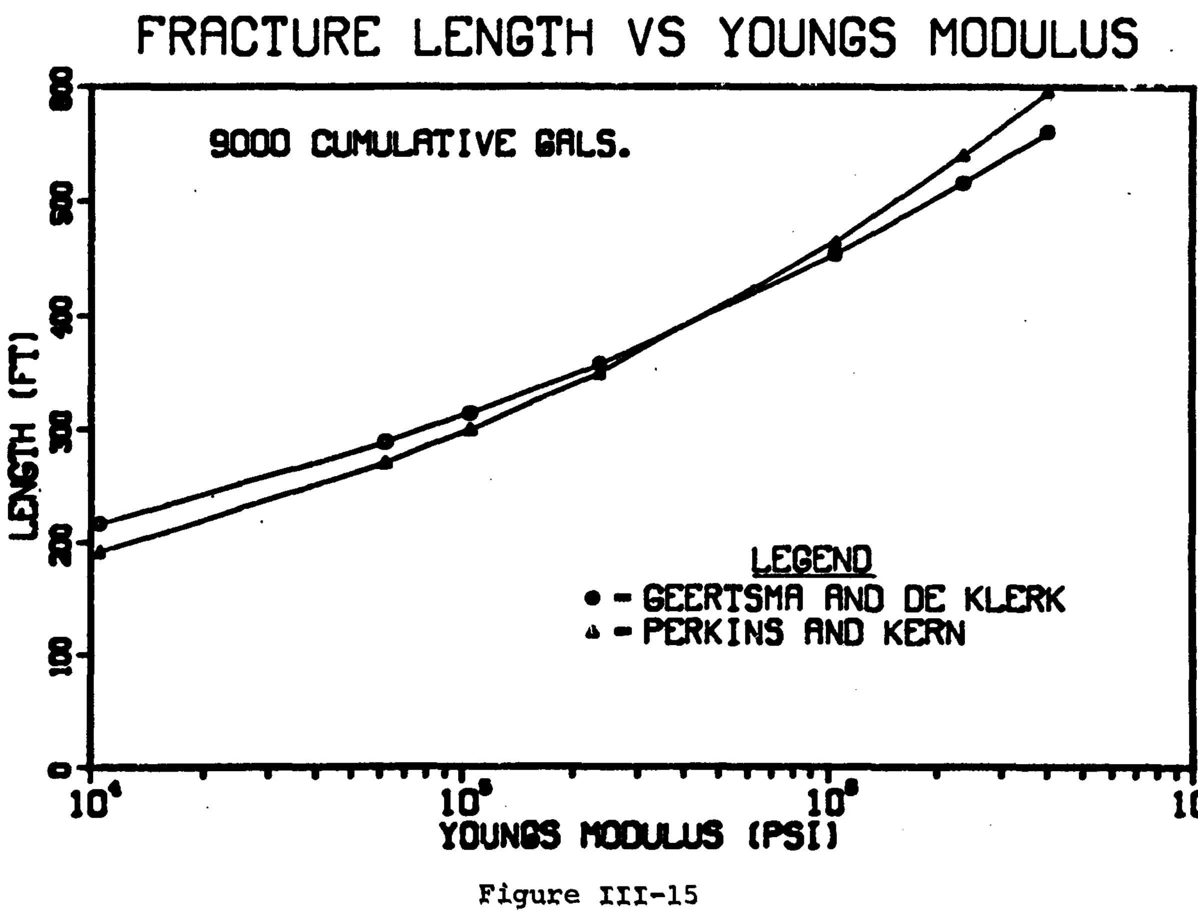


Figure III-15

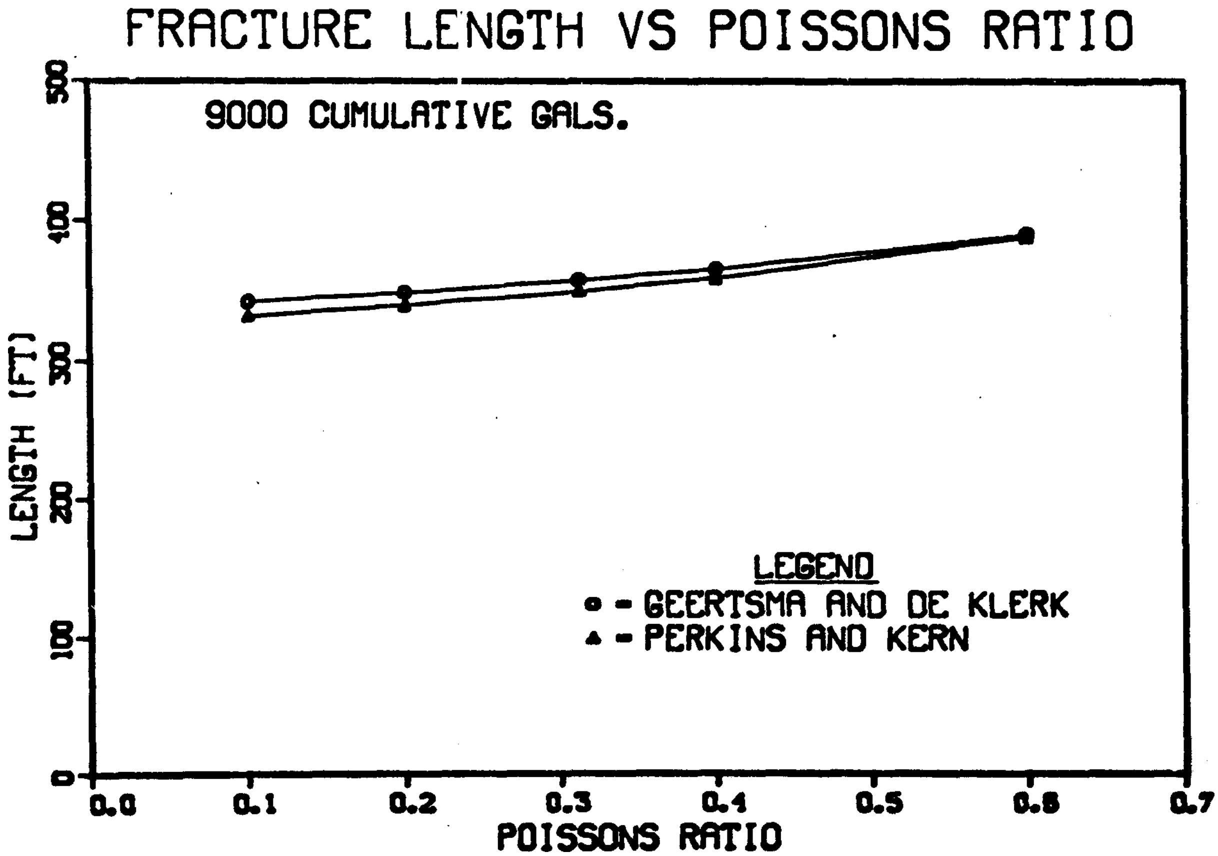


Figure III-16

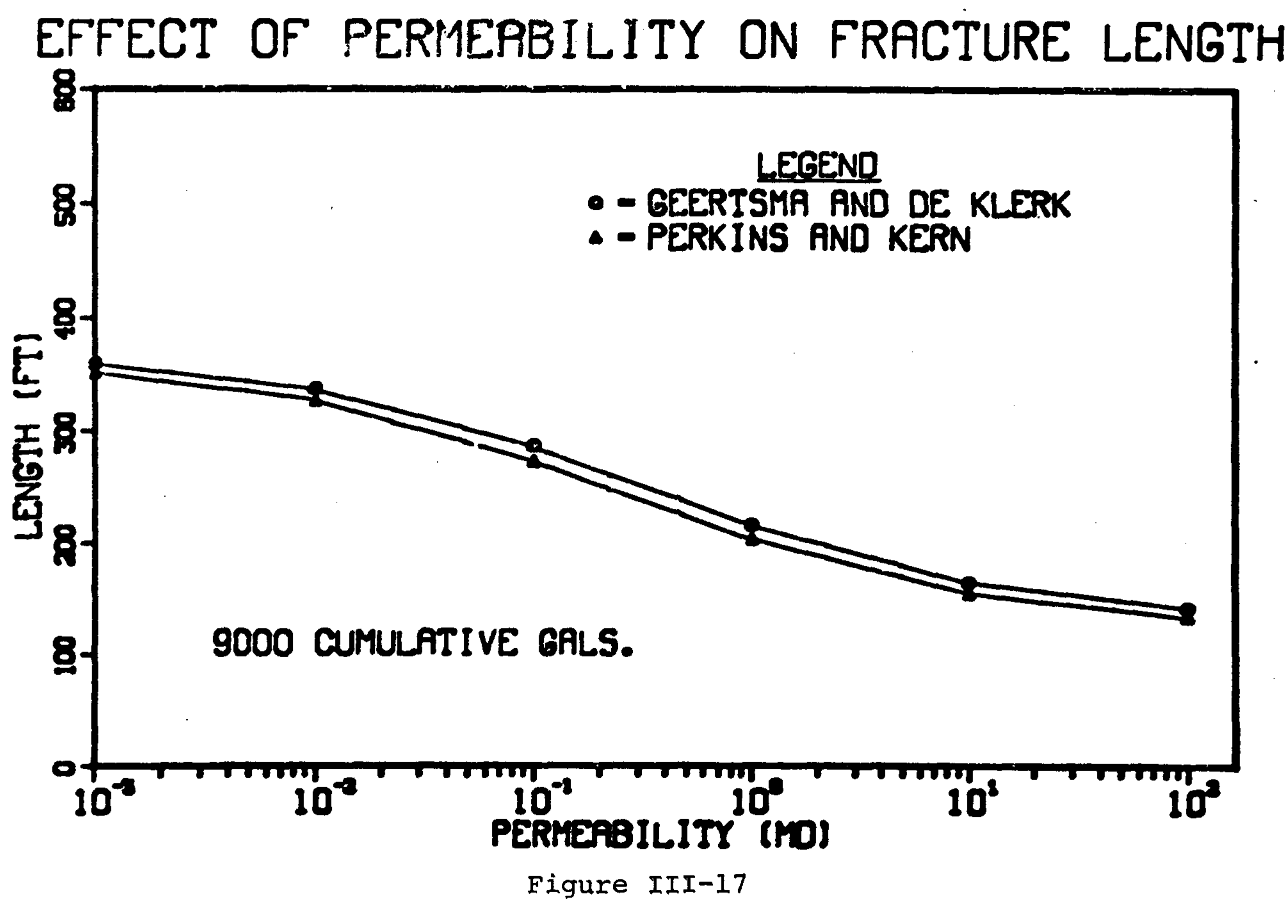


Figure III-17

of studying the effects from an explosion of a spherical charge of high explosive. The principal objective was to study the effect of post-detonation high pressure gases on containment. The work was sponsored by the Division of Military Applications as part of a continuing program to study the containment of nuclear test experiments.

The initial configuration of the explosive test is shown in Figure III-18. A 256 lb spherical charge was placed at the end of a drift 4 x 4 ft cross-section. The charge was then stemmed into the drift with cement grout which closely matched the physical properties of tuff. Two open 6 in. transite pipes extended in opposite directions from the spherical charge; the pipe in the tuff was not grouted. Conical "transition" cones were placed at the junction of the pipes and the sphere. The purpose of these cones was to delay collapse of the open pipes during the short-lived hydrodynamic phase immediately following the detonation. Once the shock waves had dissipated, it was expected that the high pressure gases would escape down the open pipes.

Figure III-19 illustrates the results of the post-detonation mine-back operation in the tuff region "in back of" the explosive cavity. The crosshatched area shows a vertical fracture produced by the explosive gases from the pipe and borehole which extended into the tuff. The pipe that was grouted into the stemmed drift apparently collapsed during the hydrodynamic phase.

The fracture initiated in the tuff is remarkably similar in orientation to that induced by conventional hydraulic fracture techniques at Hole No. 3 which is located nearby. The radial extent of the fracture is in close agreement with a hydrodynamic calculation showing that residual stresses lower than the overburden stress exist in this region. Fracture widths of 2-3 mm filled with black explosive debris were observed. While not uncovered, rough calculations suggest a fracture height of 75 ft.

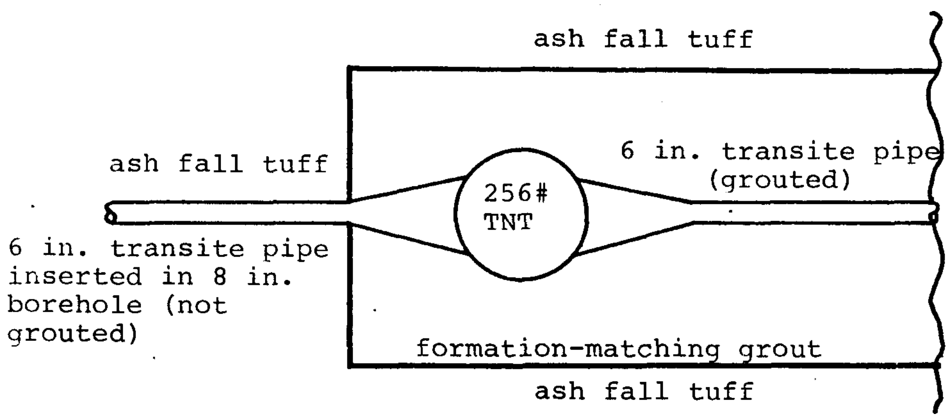


Figure III-18 - Test Configuration, Puff-N-Tuff

IV. ADDITIONAL ENHANCED GAS RECOVERY ACTIVITIES

A. Green River Basin Resource Evaluation
(G. B. Griswold, 5732, and N. R. Warpinski, 5732)

An evaluation of the natural gas resources of the tight gas sands of the Wyoming Greater Green River Basin was conducted in June and July, 1977. The particular gas sands under consideration were the Paleocene Fort Union formation and the Upper Cretaceous Mesaverde group which is comprised of the Almond, Ericson, Rock Springs and Blair formations. The areal extend of the basin is approximately 20,000 square miles and is delineated in Figure III-20. After consultations with the United States Geological Survey (USGS), Amoco, Davis and Colorado Interstate Gas, approximately fifty wells were selected that were considered to be representative of their region and from which considerable information could be derived. The individual well file of each of these wells was obtained from the USGS district office at Rock Springs and the files were searched for information from electric logs, drill stem tests, cores and mud logs that would aid in characterizing the reservoir. In particular, it was necessary to estimate the average depth, gross and net pays, gas porosity, permeability and bottom hole pressure and temperature of the reservoir for each formation at each location. The basin was subsequently divided into a number of subregions and volumetric calculations of the gas in place were performed by extrapolating the information from the individual well files.

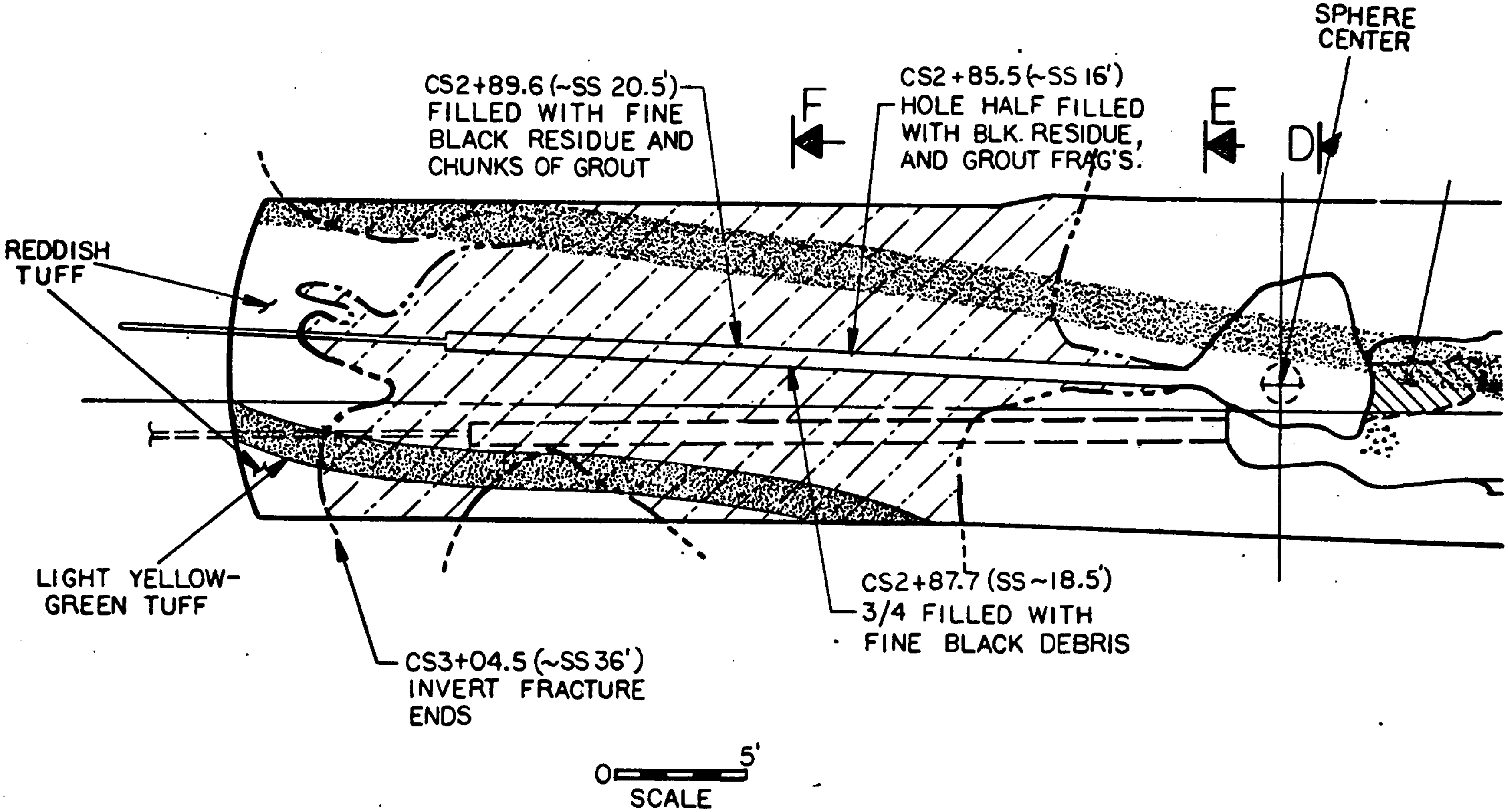


Figure III-19 - Gas Fracture Produced in the Puff-N-Tuff Experiment

Production records of various wells dating back to 1968 were obtained from the Wyoming Oil and Gas Conservation Commission. Production decline curves were computed so that estimates of recoverable gas could be calculated. The recovery factors of various completion techniques (particularly MHF) could then be computed and an estimate of recoverable gas could be presented. For the tight gas sands, however, this data was quite limited and it was suggested that the recovery factors be obtained from other tight gas sand basins where more data has been accumulated.

All of the preliminary results have been sent to an independent consulting geologist for further evaluation and refinement. The final values for the estimated resource will be derived by Lewin & Associates who is combining the results from this study with similar studies in other areas under DOE's enhanced gas recovery program.

B. Program Planning

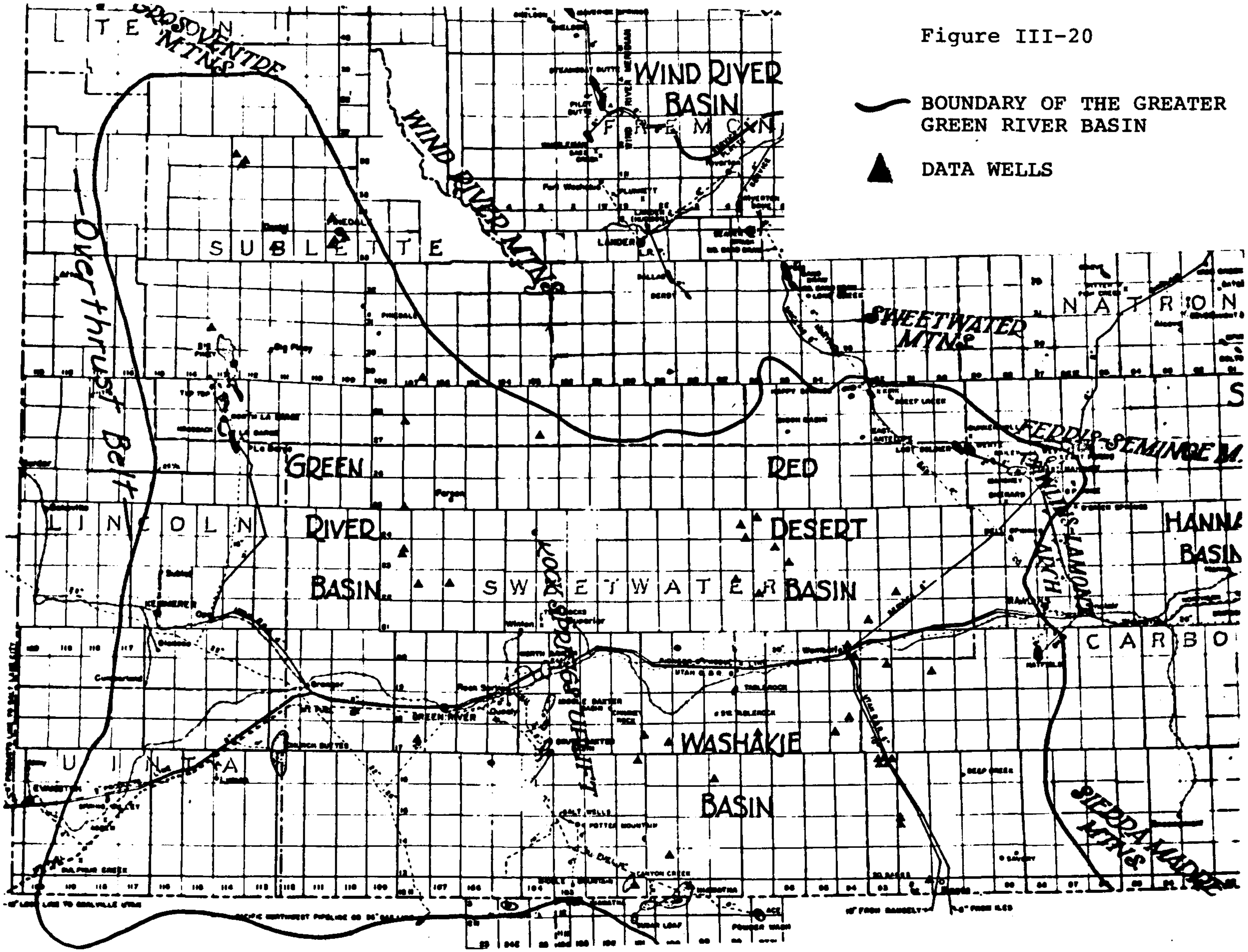
1. David A. Northrop is a member of a formal working group charged with providing technical direction to the development of a Program Strategy Plan for Enhanced Gas Recovery being prepared for DOE by Booz. Allen and Hamilton, Inc. and Lewin and Associates. Meetings have been held in Washington on April 18-19, May 12-13, June 27-28, August 4-5, and September 19-22, 1977. The Green River Basin Resource Survey described above was conducted for this strategy plan.

2. Sandia personnel participated in the design and development of the program plan for DOE's Western Gas Sands Project which was initiated during the past year. Numerous reviews and revisions were prepared with particular emphasis placed upon the laboratory research and development activities. G. B. Griswold spent a week with CER and TRW in Las Vegas in December 1976 in the actual drafting of the plan.

Figure III-20

BOUNDARY OF THE GREATER GREEN RIVER BASIN

DATA WELLS



V. PUBLICATIONS, PRESENTATIONS, AND OTHER COMMUNICATIONS

A. Publications and Presentations

1. L. D. Tyler, W. C. Vollendorf, and D. A. Northrop, "In Situ Examination of Hydraulic Fractures," presented by L. D. Tyler and D. A. Northrop at the Third DOE Symposium on Enhanced Oil and Gas Recovery and Improved Drilling Methods, Tulsa OK, August 30-September 1, 1977. Paper published in the Proceedings, Volume 2, p. F-4/1.

2. C. L. Schuster, "A Status Report on the MHF Mapping and Characterization Program," presented at the Third DOE Symposium on Enhanced Oil and Gas Recovery and Improved Drilling Methods, Tulsa OK, August 30-September 1, 1977. Paper published in the Proceedings, Volume 2, p. F-5/1.

3. C. L. Schuster and R. P. McCann, "Frac Mapping by Surface Electrical Techniques," presented by C. L. Schuster at the Massive Hydraulic Fracturing Symposium, University of Oklahoma, Norman OK, February 28-March 1, 1977. Published in the Proceedings, p. 323.

4. L. J. Keck and R. W. Seavey, "Instrumentation for Massive Hydraulic Fracture Mapping," Sandia Laboratories Report, SAND77-0195, April 1977.

5. R. P. McCann, R. G. Hay, and L. C. Bartel, "Massive Hydraulic Fracture Mapping and Characterization Program: First Annual Report: Augsut 1975 through July 1976," Sandia Laboratories Report, SAND77-0286, June 1977.

6. R. P. McCann, L. C. Bartel, and L. J. Keck, "Massive Hydraulic Fracture Mapping and Characterization Program: Surface Potential Data for Wattenburg 1975-76 Experiments," Sandia Laboratories Report, SAND77-0396, August 1977.

7. C. L. Schuster and D. A. Northrop, editors, "Natural Gas Massive Hydraulic Fracture Research and Advanced Technology Project, Quarterly Report: February through April, 1977," Sandia Laboratories Report, SAND77-1132, July 1977.

8. L. J. Keck and C. L. Schuster, "Shallow Formation Hydrofracture Mapping Experiment," presented by C. L. Schuster at the Energy Technology

Conference and Exhibition, ASME, Houston TX, September 18-23, 1977. Published as ASME paper 77-Pet-51.

9. C. L. Schuster, editor, "Natural Gas Massive Hydraulic Fracture Research and Advanced Technology Project, Quarterly Report: November 1976 through January 1977," Sandia Laboratories Report, SAND77-0475, April 1977.

10. L. C. Bartel, R. P. McCann, and L. J. Keck, "Use of Potential Gradients in Massive Hydraulic Fracture Mapping and Characterization," presented by L. C. Bartel at the 51st Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, New Orleans LA, October 3-6 1977, published as paper SPE 6090.

B. Other Communications

1. D. A. Northrop, L. D. Tyler, and G. B. Griswold met with representatives from Halliburton, Dowell, and AMOCO to review present activites and discuss future directions of the mineback fracture test program; meeting was held in Tulsa OK, February 22, 1977.

2. Project reviews were presented at the 2nd DOE Natural Gas Working Group Meeting, Sandia Laboratories, Albuquerque NM, January 13, 1977: L. D. Tyler "NTS/MHF Simulation Studies," and C. L. Schuster "Electrical Results from Controlled Fracture Experiment."

3. Project reviews were presented at the 3rd DOE Natural Gas Working Group Meeting, Lawrence Livermore Laboratory, Livermore CA, July 12, 13, 1977: L. D. Tyler "NTS Mineback Experiments," and C. L. Schuster "Results of Electrical Mapping Experiments."

4. L. D. Tyler and D. A. Northrop presented a program briefing for H. C. Walther, H. A. Wahl and other personnel at Continental Oil Company, Ponca City OK, May 19, 1977.

5. D. A. Northrop and L. D. Tyler presented a mineback program review for Alex B. Crawley, Fossil Energy/DOE, at the Nevada Test Site, July 14, 1977.

6. D. A. Northrop, C. L. Schuster, and L. D. Tyler visited the Morgantown Energy Research Center to review Sandia's and the Eastern Gas' Shales Program's activities, in Morgantown WV, September 29-30, 1977.

7. Sandia personnel participated in the MHF-3 (Rio Blanco) Technical Committee meeting in Las Vegas NV, April 5, 1977. L. D. Tyler and D. A. Northrop gave presentations on G tunnel mineback experiments and plans for the mineback stimulation test project. The following day, Sandia sponsored a tour of NTS and G tunnel for approximately 30 of the industry representatives.

8. L. D. Tyler briefed E. Smith and S. McKetta of Columbia Gas Company on the mineback testing activities, Nevada Test Site, April 19, 1977.

9. C. L. Schuster presented project review at the Annual Meeting of the Solution Mining Research Institute, Atlanta GA, December 2, 1976.

DISTRIBUTION:

G. Fumich
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H. D. Guthrie, Director
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