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Final Technical Report
for
**Instrumentation of
Dynamic Gas Pulse Loading System**

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1. Introduction and Summary

1-a. Introduction to Stressfrac DGPL stimulation

The Dynamic Gas Pulse Loading (DGPL) process is an hydraulic fracturing method which uses CO₂ and CO gas as a working fluid instead of a liquid. The DGPL system can be used to generate fractures for horizontal and vertical oil and gas well completions in both open hole and perforated casing. The DGPL system provides a cost effective tool for repairing near well bore permeability damage caused by inappropriate chemical treatment, migrating fines and paraffins, or slotted liners blocked by sand. Because the gas is generated from a solid propellant material by chemical reaction, no heavy equipment is required. Tremendous pump rates can be obtained. Peak pressures are naturally localized at the tool position by the tamping effect of well fluids. Thus many of the leakage and sealing problems which plague static hydrofrac processes are completely avoided. DGPL may be effectively used before acid treatment to provide fresh pathways for the acid to reach the formation. The smaller tools may be positioned by wireline, though most Stressfrac tools are tubing conveyed.

An example of a relatively large Stressfrac stimulation is the South Mountain job pictured below in Figures 1-1, 1-2 and 1-3, where 2.375 inch diameter propellant tools were mounted in 12 foot lengths of perforated tubing. Five 12 foot sections were joined on the ground to form 60 foot long tool carriers. Fourteen of the 60 foot lengths were lifted one at a time and joined at the well head to make an 830 foot long tool which was positioned between 3810 and 4640 ft depth. The stimulation was carried out under oil.

Figure 1-1 Stressfrac propellant tools carried to the site by pickup truck are assembled into 60 foot long tool carriers on the ground.

Figure 1-2 Sixty foot long Stressrac tool carriers are picked up one at a time.

Figure 1-3 The sixty foot long tool carriers are joined at the wellhead into an 830 foot long tool and lowered 4,000 feet.

1-b. Project Description (DOE grant application appendix A)

The overall goal of this work is to further develop and field test a system of stimulating oil and gas wells, which increases the effective radius of the well bore so that more oil can flow into it, by recording pressure during the gas generation phase in real time so that fractures can be induced more predictably in the producing formation.

Task 1. Complete the laboratory studies currently underway with the prototype model of the instrumentation currently being studied.

Task 2. Perform field tests of the model in the Taft/Bakersfield area, utilizing operations closest to the engineers working on the project, and optimize the unit for various conditions encountered there.

Task 3. Perform field test of the model in DGPL jobs which are scheduled in the mid-continent area, and optimize the unit for downhole conditions encountered there.

Task 4. Analyze and summarize the results achieved during the complete test series, documenting the steps for usage of downhole instrumentation in the field, and compile data specifying use of the technology by others.

Task 5. Prepare final report for DOE, and include also a report on the field tests completed. Describe and estimate the probability of the technology being commercialized and in what time span.

1-c. Summary of Results

The major achievements under this grant program were:

1. Laboratory scale studies of the pressure differential between the inside and outside of perforated well casing during Stressfrac DGPL stimulation.
2. Development of a practical computer model for Stressfrac DGPL stimulation which takes into account the effects of tool size, fracture gradient, static pressure, casing size, well fluid, and temperature to compute the fracture volume and estimate fracture lengths.
3. Development of an improved laboratory digital data recording system capable of recording up to eight data channels simultaneously. Sampling rates of 40,000 samples per second were obtained on each of three analog signals and a digital port. Techniques for the use of piezoelectric pressure sensors were improved.
4. Development of a compact version of the digital data recording system for field use at the surface, with a portable generator system.
5. Large scale tests of Stressfrac DGPL pressure generators at our Maricopa field test site, using the portable digital data recording system. Important burn rate studies were begun. Video recording was used to obtain additional data.
6. Initial investigation of battery powered downhole pressure recorder designs.
7. Initial exploration of sonic and seismic recording of Stressfrac DGPL stimulations on wells in California and North Dakota. These new techniques provide a promising new source of information about Stressfrac pressure generation and fracture growth.

The Stressfrac DGPL stimulation process has been in commercial use for a number of years. The computer programs, research data and instrumentation systems developed under this grant contributed to a better understanding of the process and have been incorporated in commercial operations.

1-d. Conclusions

Stressfrac DGPL stimulation has been a valued tool of the oil industry for twenty years. During the past five years technical developments have greatly extended the range of stimulation projects that can be handled by this flexible system. Stressfrac DGPL stimulation has an important role to play in economically maintaining production of aging oil fields, and in improving the rate of production and extraction efficiency of new gas and oil reserves. Continued technical development of this process will repay the nation many times over. However, because of the present financial and operational uncertainties in the oil industry, the Stressfrac DGPL process is not currently being widely applied and its potential benefits are being lost.

1-e. Future Plans for DGPL development

There are several new ideas which have emerged during the course of this project. We plan to submit them to NIST for consideration under the Energy Related Inventions Program and directly to the DOE for possible demonstration program funding.

1. Recent work by others in the Michigan Antrim Shale has emphasized the problem of fracturing relatively soft shale formations. If the formation plastically deforms like clay under pressure it is difficult to initiate a fracture. We feel that maintaining a slow rise time of the pressure pulse is a critical factor in such formations. A new variation of the STRESSFRAC system is under development for this application. If successful, this approach could be a key element in the economical production of large natural gas reserves.

2. Another area of development is the perforation and breakdown of limited entry injection wells. The effective and uniform breakdown of each perforation tunnel is critical in establishing control of the injection profile, and thereby efficiently producing the reservoir. A new approach to this problem has been designed which promises to be both economical and effective.

3. The seismic measurement of the fracture production process during Dynamic Gas Pulse Loading stimulation is an entirely new area which was initiated under the present study. The very preliminary data obtained thus far suggests that this measurement can be of significant value in evaluating the effect of DGPL stimulation. The seismic signals provide a direct link to fractures as they are formed and offer new insight into the fracture process.

2. The FRAC Computer Model of the DGPL Process

Engineering practice for DGPL stimulations is based on years of experience. In addition to the technical details of assembly, installation, ignition, and tool removal, there are basic physical laws which govern the operation of the tool. The FRAC computer model was developed under this DOE supported project to compute the effect of these physical effects to guide the DGPL project engineer.

2-a. Physical Basis of the Model

The DGPL system is a gas generator. As fractures form they expand to a maximum volume, and then close again as the gas cools and is forced back into the well. The maximum extent of the fracture network is reached when the gas is relatively cool and motionless, in equilibrium with the pressure exerted by the fractured formation. Thus the FRAC program is based on the thermodynamic law for gas in equilibrium: $V = NKT/P$ (volume is proportional to the number of molecules times the temperature divided by the pressure). Since N is proportional to the solid volume of the tool we can write this as:

$$V = K_2 V_{\text{tool}} T/P.$$

The volume of propellant is calculated from the length and diameter of the tool, the temperature is calculated by assuming a 3% heat retention in the gas after expansion and contact with the fracture walls, and adding the resulting temperature to the ambient temperature of the formation. The "closure pressure" that the fracture walls exert on the gas is determined by the hydraulic fracture gradient, measured in the well or typical of the formation, typically 0.7 psi/ft. This "equilibrium model" determines the total volume of the gas which may be several thousand liters for a large tool at shallow depth, or only a few dozen liters for a moderate tool at great depth.

The well fluid serves as a "tamp" for the gas, preventing it from escaping up the well casing. Usually there is fluid both above and below the tool which is compressed slightly by the gas pressure. The outer boundary of the compressed region moves at the speed of sound in the fluid column. If the tool is at the bottom of the well only the one column of fluid above the tool is compressed. The compressed fluid moves at a velocity, v , of a few meters per second according to a simple law: derived from the conservation of momentum, mass times velocity equals force times time. This velocity, v , is also the velocity of the gas-fluid interface, and is used to compute the volume of the gas retained inside the casing.

$$Mv = Ft$$

Consider a cylinder of fluid of length ct where c is the speed of sound and t the time, in a casing of cross sectional area A . The fluid density is ρ , and so the mass $M = \rho ctA$. The net force F , on the moving cylinder of fluid is the cross sectional area $A = \pi D^2/4$ times the difference between the gas pressure P and the original static hydraulic pressure P_0 . The momentum equation is then:

$$Mv = \rho ctAv = (P - P_0)At$$

cancelling A and t ,

$$\rho cv = (P - P_0)$$

so the velocity of one moving fluid column is given by

$$v = (P - P_o) / \rho c.$$

As the fluid moves away from the gas pressure it leaves an open space for the gas to occupy. Assuming the tool is not at the bottom of the well, there are two open spaces produced, one above and one below the tool.

The volume of gas in the casing, V_o , is then:

$$V_o = V_{tool} + 2Avt = V_{tool} + 2tA(P - P_o) / \rho c$$

The volume of gas forced into the formation to produce fractures, V_f , is:

$$V_f = V - V_o = K_2 V_{tool} T / P - V_{tool} - 2tA(P - P_o) / \rho c$$

or

$$V_f = V_{tool} (K_2 T / P - 1) - 2tA(P - P_o) / \rho c.$$

This relationship shows how the equilibrium fracture volume depends on the tool size, gas temperature, casing diameter, hydrostatic pressure, closure pressure, fluid density, the speed of sound in the fluid, and the gas generation time of the tool. Though this model ignores subtleties such as gas dynamics, in situ stress, fracture propagation, and formation porosity it does provide a consistent engineering estimate of fracture volume based on sound engineering data.

Peak Pressure in the Absence of Fractures

Note that if V_f were constrained to be zero, as by the accidental absence of perforations or a section of unusually strong rock, the resulting peak pressure, P_{max} , can be calculated from the quadratic equation obtained by multiplying through with P_{max} :

$$P_{max} * V_f = 0 = V_{tool} (K_2 T - P_{max}) - 2tA(P_{max}^2 - P_{max} P_o) / \rho c.$$

If the pressure is well above the hydrostatic pressure we can get a simple approximate solution by ignoring the linear terms in P_{max} . This approximate solution shows the effect of tool size, gas generation time, cross sectional area and fluid properties on the maximum pressure with fluid tamping:

$$P_{max} \approx [V_{tool} K_2 T \rho c / 2tA]^{0.5}$$

The exact quadratic solution is easily evaluated also, though less intuitive. Typical maximum peak pressures are around 20,000 psi.

In practice sensible design of the tool provides a gas generation time t , that is long enough to allow the fluid to move out of the way at reasonable pressures that will not damage the casing. It is clear that if the gas generation time, t , of the tool is too short,

the "safety valve" effect of the tamping fluid is lost. As t approaches zero as it does in an explosive, the gas is confined to the original tool volume and the peak pressure is very high. Similarly, a very large diameter casing (large A) greatly increases the gas volume inside the casing, and leaves less gas for the fractures. Note that the volume lost to fluid motion drops to zero if the initial hydrostatic pressure P_0 equals the closure pressure P of the formation. In that case the fluid pressure itself is ready to fracture the formation.

To estimate the effect of fractures on well production it is important to know the length of the fractures. In a simple flow model, the effective wellbore radius is the fracture radius. In formations with low permeability the rate of production is greatly increased by fractures extending tens of feet around a six inch well bore. In older wells, the migration of fines produce a skin around the wellbore that reduces flow, and fractures of even a few inches can make a great improvement in production.

The calculation of fracture radius from the fracture volume requires some geometric assumptions. Accurate calculation of fracture dimensions from first principles can be done for well characterized materials, but the necessary physical parameters are seldom available for a practical oil producing well. Any pre-existing fracture network can play an important role in the growth of fractures. Inhomogeneities and stresses in the formation also play an important role.

To present the computed fracture volume in an easily understood form as an average fracture radius, the following assumptions are made about fracture geometry: The fractures are rectangular wings of width equal to the fracture radius radiating out from the wellbore. The length of the rectangle is equal to the tool length plus 30% of the fracture radius at each end. In open holes the number of wings can be estimated from the pressure rise time vs sound propagation time around the circumference of the wellbore. However, mine back studies show that in perforated casing, the initial fractures are aligned with the perforation pattern and the fractures which follow the natural stress induced fractures in the formation grow to be dominant. Normally two dominant fracture wings are assumed. The average width of the fractures at the equilibrium displacement is assumed to be 0.5 to 1 millimeter. This gives a fracture radius consistent with mine-back studies carried out by Sandia National Laboratories in ash fall tuff. The actual fracture radius will vary along the length of the tool, reaching further out at some points and less at others in response to the natural variations in the formation.

2-b. Applications of the Model

The FRAC program has proven to be a useful guide in the design of DGPL stimulations. The estimation of fracture radius for a given tool size aids in evaluating cost/benefit tradeoffs. The program has been particularly useful in demonstrating the need for larger tools at great depth and in large diameter casing. It also shows quantitatively the effect of such variations as adding gas pressure at the surface to increase the hydrostatic pressure at the tool, and provides a guide for using packers to reduce the gas volume lost in the casing. The FRAC program shows the effect of commonly used well fluids on the tamping action. The role of the gas generation time of the DGPL tool has been quantified, and peak pressure estimates for formations which do not fracture can be made by adjusting the closure pressure until the fracture volume is zero and all the gas remains

In the casing.

2-c. FRAC Program Operation

The FRAC program provides a printed report of the calculation. The first section identifies the well and the stimulation measured depth but none of the identification data is used in the calculation. The second section describes the physical properties of the DGPL tool and the well. The third part of the report presents the calculated gas volumes, including the total gas volume and the casing gas volume, as well as the fracture volume and average fracture radius. Some of the physical parameters of the model may be changed as required, including the number of fracture wings, percentage heat retention, average fracture width, etc. A typical FRAC report is shown in Figure 2-1.

 * Servo-Dynamics Inc. *
 * STRESSFRAC Equilibrium Analysis, Ver. 1.08 2/24/92 *
 * Santa Barbara, California (805) 967-3578 *

Prepared for: Telephone:
 Company: Report Date: 07-10-1992
 Location: Formation:
 Well Number: 600 ft Vertical
 Measured depth 3378 ft. SD Reference #

***** Well and Tool Data *****
 StressFrac Tool Type CT Dia 4.5 in, Length 600 ft
 Casing I.D. 8.5 inches
 Ambient Rock Temperature 133.6 deg F
 True Vertical Depth 3678 feet
 Fluid type & Depth 1% KCl Solution 3678 feet
 Surface gas pressure 0 psi
 Fracture gradient 1 psi/ft.

***** Parameters of Equilibrium Fracture Model *****
 Total Hydrostatic pressure 1623 psi
 Closure pressure 3678 psi
 Fracture time .536 seconds
 End effect dL/R .3
 Number predominant fractures 2 , Perf phase 360 degrees
 Assumed fracture width .0005 meters
 Fraction of heat retained .03
 Gas temperature 217.2 F

***** Fracture Radius Prediction *****

Tool dia inches	Average Fracture Radius, Feet	Total Gas Liters	Tool+Casing Liters	Tool Liters
4	108.2	8531.4	1849.6	1482.7
4.5 <-->	135.1	10797.5	2246.4	1876.5

Velocity of fluid column is 9.416821 m/sec.
 Acoustic wave distance is 813.5899 meters

Figure 2-1 Sample FRAC Report

3. Digital Data Recording Systems

3-a. Digitizers and Computer Hardware

The primary measurement undertaken was the pressure-time history of the DGPL gas generation process with one, two or three simultaneous pressure sensors. One channel is a stainless steel diaphragm/semiconductor strain gauge device from Omega which has DC response capability, and the other two gauges are PCB Piezotronics piezoelectric pressure gauges with integral buffer circuitry. The PCB gauges are capacitively coupled and can not read static pressure. Other interesting sensors have been considered, including contact pins to measure the time of arrival of pressure or temperature changes at different points along the tool.

This project used economical standard computer components to construct high performance digital data acquisition systems. The laboratory system was a 486-33 generic IBM PC clone with a Model ADA-3100-3 analog and digital I/O board from Real Time Devices in State College, PA. This board provides 12 bit conversion of 8 differential input channels with up to 200 KHz throughput. The high data rate is made practical by an on-board FIFO (first in first out) buffer that holds the data when the computer is forced to take time to do other things.

A field portable system was assembled using a gasoline powered generator to produce 110 VAC 60Hz power, and a generic "Lunch Box" style computer using a clone IBM 486-33 motherboard with LCD display and hard disk was purchased. This computer had two free expansion slots, one of which was used for the ADA-3100-3 I/O card. Thus all of the software and analog electronics could be used interchangeably on this system and the laboratory system.

3-b. Software Design and Operation

The custom MONITOR software for pulsed data recording was written under this DOE sponsored project using Microsoft Quickbasic ver 4.5. During data acquisition the computer is totally dedicated to monitoring the data channels and recording data. The data is stored in two buffer areas within computer memory. The pre-shot buffer is circular, constantly re-writing over itself as the system waits for the shot. It typically holds about 100 milliseconds of high speed data for 3 channels. When the pressure reaches a certain pre-defined trigger level on the selected trigger channel, the program moves to the post shot buffer and stores another 100 to 3000 milliseconds of data for the three channels and one digital channel. Sampling rates as high as three channels of 30,000 samples per second per channel are practical. When the buffers are full, the data is written to the hard disk and then displayed on the screen. A series of menu screens allows the user to adjust the parameters of the system, which are stored in an ASCII setup file. The piezoelectric sensors are AC coupled and require several minutes of settling time after power up before a shot, and so the program provides a monitor screen which shows the signal levels up to the time when data acquisition begins.

The MONITOR software has been used both for laboratory and field tests since the auto-triggering on pressure data provides the simplest possible interface to the measured system.

4. Laboratory Cascade Chamber Studies

4-a. Differential Pressure Chamber Concept

One of the interesting questions in the use of Dynamic Gas Pulse Loading is just how much pressure is put on the well casing. Clearly if the casing is sealed, it must support the entire pressure, with the help of the surrounding cement and formation pressure. If the casing is heavily perforated, the gas and fluid are transmitted through the perforations and equalize the internal and external pressure. If the internal and external pressures are equal there is no tension in the casing. In practice, the system works well with rather limited perforations, down to about four 1/4 inch diameter holes per foot for the common 2 inch diameter DGPL tools, though larger or more frequent perforations are preferred. Unfortunately, in a normal well it is not practical to measure the pressure outside the casing and so no field data has been obtained outside the casing, even though peak pressures inside the casing are measured with passive gauges on every stimulation.

The differential pressure chamber was designed to provide some laboratory data on the pressure transfer through a perforation. The test chamber is divided into two parts: a combustion chamber and an expansion chamber. There is a modular orifice between the two chambers and most work has been done with a 0.22 inch diameter orifice. The expansion chamber is fitted with a small diameter hydraulic plunger sealed with o-rings. This plunger simulates the formation of fractures. By using a copper shear pin, the "breakdown pressure of the formation" can be accurately controlled. After the pressure reaches the level required to shear the pin, the gas pressure drives the plunger out of the chamber. Weights on the plunger simulate the mass of the fracture walls, though in these studies there is no restoring force on the plunger to simulate the closure pressure of the formation. Both the combustion chamber and the expansion chamber are fitted with openings for pressure gauges, and usually the PCB Piezotronics piezoelectric gauges have been used to simultaneously record the pressure in both chambers. The burn rate and size of the propellant charge have been adjusted to simulate the peak pressure conditions in a well stimulation.

4-b. Piezoelectric Sensor Technology

During initial experiments the combustion chamber was partly filled with water, leaving an air pocket above the water, with the test propellant mounted in a fitting on top. In order to reach higher pressures and more closely simulate actual field conditions, the volume of the air pocket was reduced to almost nothing. This change resulted in sharper, higher initial pressure peaks at ignition, and the piezoelectric gauges began to show high frequency oscillations with occasional dips below zero pressure later in the process. This unphysical result was puzzling. Eventually the gauges began to fail completely. Consultation with PCB led to the idea that pressure waves reaching the threads of the gauge were compressing the piezoelectric element in three dimensions instead of just on the end diaphragm. To reduce the shock on the gauge body it was suggested that a small extension pipe and Tee fitting be used to isolate the gauge mount from shock, while maintaining contact with the fluid pressure.

We considered using the more expensive 100,000 psi PCB gauges to avoid damage, despite the loss of sensitivity. However, satisfactory results are being obtained with extension mountings for the 20,000 psi peak piezoelectric gauges. No higher pressure gauge has been purchased.

4-c. Cascade Chamber Data

Data for cascade tests 72 and 73 are presented on the following pages. The solid is the combustion chamber pressure while the dotted line is the expansion chamber pressure. The second chart for each run shows the difference in pressure between the two chambers. The shear pin was set for a "breakdown pressure" of about 5,000 psi in run #72 and about 6,500 psi in run #73. Note that the pressure in both chambers is almost equal during the rapid pressure rise, since the fluid in the chamber easily transmits the pressure through the perforation with very little flow. Once the pin shears, simulating the opening of fractures, there is a substantial flow of gas through the perforation orifice. As the expansion chamber piston moves, the expansion chamber pressure drops rapidly. After about 10 milliseconds, the piston is completely outside the expansion chamber and the pressure drops to zero. With real fractures, fracture growth would slow as the gas pressure dropped to the closure pressure and then the flow would reverse, pushing the gas back into the well.

The important conclusions of these experiments are that there is little difference in pressure between the inside and outside of the well casing during the initial rapid rise of pressure. A difference of 10% to 20% of the peak pressure occurs during rapid gas flow into the fractures. These measurements confirm the experience in thousands of wells that the DGPL process, with its properly controlled gas generation time, puts little stress on the well casing.

A test chamber is assembled at the Santa Barbara facility. The hydraulic jack is used for gauge calibrations.

CASCADE TEST #73 10/31/91

Figure 4-1 Cascade Chamber Pressure Measurement Test #72

CASCADE DIFFERENTIAL #73 10/31/91

Figure 4-2 Cascade Chamber Pressure Measurement Test #72 Pressure Difference

CASCADE TEST #72 10/31/91

Figure 4-3 Cascade Chamber Pressure Measurement Test #73

CASCADE DIFFERENTIAL #72 10/31/91

Figure 4-4 Cascade Chamber Pressure Measurement Test #73 Pressure Difference

5. Maricopa Field Studies

5-a Test Site Facilities

Servo Dynamics has developed a field test area near Maricopa, CA to carry out field studies of the DGPL components. Figures 5-1 to 5-5 provide an overview of the test site and some of the test equipment. Pressure-time data for a burn rate test is shown in Figure 5-6

5-b Burn Rate Tests

Field tests at the Servo-Dynamics Maricopa test site in the Taft-Bakersfield area: Surface tests of the DGPL ignition system and 1.25 inch diameter STRESSFRAC tools have been carried out at the field test site using our "lunch box" computer and digital recorder system with a small gasoline powered generator. Important burn rate data was obtained with the digital recorder. Excellent video images of the test were obtained using borrowed video equipment. One important result of the test is that we showed that unsupported ordinary J-55 2 7/8 inch diameter tubing can withstand a peak pressure of 13,000 psi without any damage or distortion. The rise time of the STRESSFRAC system is slow enough that it does not shock the material, and brief enough that it does not fatigue it. In actual downhole applications the well casing is supported by the pressure of the surrounding formation and much higher pressures can be used safely because the net pressure on the casing is reduced by pressure transfer through the perforations.

The burn rate of propellant materials tends to be pressure sensitive. Higher pressure or temperature tends to produce more rapid gas generation. In fact, the Stressfrac tool material in the open air is quite difficult to ignite with a flame, and is far safer than gasoline. For some materials, not used by Servo Dynamics, this pressure sensitivity can lead to a low grade detonation which is very destructive. The DGPL system has been designed to perform reliably under a wide range of environments including high and low pressure, high and low temperature. However, continued study of the detailed performance of the system under different pressure conditions will lead to a quantitative understanding that can be used to enhance the effectiveness of the tool under extreme conditions.

Figure 5-1 An overview of half of the small valley occupied by the test facility shows the setup for a vertical test of 1/4 inch DGPL in the foreground and horizontal racks in the background where Stressfrac tools are tested.

Figure 5-2 A gasoline powered generator supplies 110 volt AC power for the "Lunch Box" recorder system and amplifiers.

Figure 5-3 A video recorder with high speed frame capture was used to photograph the tests from the other side of the valley.

Figure 5-4 The PCB Piezotronics sensor has been mounted on a short stub of pipe filled with water at the end of the test chamber. Data is shown in Figure 5-6.

Figure 5-5 This 35mm photo shows the smoke cloud rising from the 1.25 inch Stressfrac tool test. Video data not shown here provided time resolved images of the gas production. Pressure data from this test is shown in Figure 5-6.

STRESSFRAC 1.5" Dia 12/16/92

Figure 5-6. Pressure time curve recorded for 1.25 inch dia Stressfrac tool, in air, enclosed by 2 7/8 inch diameter tubing with four 1/4 inch dia holes every 2 feet.

6. Downhole Pressure Measurement Techniques

6-a. Wireline with Pressure or contact Ignition

Downhole Pressure Measurement

A new development will allow the existing field digital recording system for pressure measurements to be used for downhole measurement in wells of moderate depth. The recording system was originally conceived for use with wireline tools, and almost all of our recent work has been with tubing conveyed systems. The most common trigger method for tubing conveyed stimulations is to pressurize a continuous length of tubing running from the tool to the surface. After the tool is placed at the desired depth, a surface pump is used to increase the pressure and trigger the stimulation. This system does not lend itself to the use of a local pressure gauge with a coaxial cable to the surface, since it is difficult to place the cable in the pressurized tubing, and the tubing isolates the sensor from the pressure in the well casing. However, an alternate system has been designed in which the tubing above the tool is perforated to allow communication of the wellbore pressure. An alternative trigger method must be used in which a drop bar or "go-devil" is attached to the signal cable and contains the pressure sensor. Contact between the drop bar and the ignition mechanism at the top of the tool would initiate gas generation. This system has not yet been tested but it promises to be convenient for wells of less than 5000 feet depth.

6-b. Wireline with Electrical Ignition

The standard coaxial wireline has only two electrical paths, the center wire and the return path of the shield. The shield is treated as an electrical ground. Thus the problem becomes one of sharing the center conductor between an electrical ignition circuit and the pressure sensor. The pressure sensor requires a constant current of 5 to 20 millamps at a voltage of about 10 volts for a period of several minutes before the measurement to stabilize the output which is coupled through a large capacitor. The dynamic transducer output impedance is approximately 100 ohms. The ignition system is similar to a flashlight filament, and requires 250 millamps at 6 volts. A circuit has been developed to store energy in a capacitor located near the sensor, and coupled to the sensor with a large value resistor which the sensor can easily drive during the measurement. The tool is assembled and installed with the cable shorted out. Then when it is in position, the transducer power is applied and the data recording system is activated. The energy storage capacitor slowly charges over a period of several minutes during which time the sensor stabilizes. Attached to the energy storage capacitor is a sensitive gate SCR transistor which connects the capacitor to the ignition element. A voltage sensing circuit triggers the SCR when the capacitor voltage reaches 7 volts, operating the ignitor and triggering the gas generator. Although this circuit has been breadboarded and tested it has not been used because most recent work has used tubing conveyed tools instead of wireline.

6-c. Downhole recording systems

A downhole recording system has been developed for other DOE applications by SAIC of Las Vegas, Nevada, and has seen limited use in gas fracturing stimulations by other firms. This system was a self contained unit with battery power that recorded and stored the pressure data which was then read out into a computer after the recorder was retrieved from the well. The original design is no longer offered commercially for gas fracturing because of a high failure rate in this application. The combination of high temperature and shock presents a difficult environment for electronics. However, SAIC has expressed interest in updating the design to a new highly ruggedized version. The quoted cost of the design update and a minimum order of recorders exceeds the total funding of this grant.

A limited investigation of commercially available microprocessors systems was carried out in an effort to locate an off-the-shelf system that could be adapted to this application. Small microprocessor boards by Dallas Semiconductor and New Micros Inc. were examined for this application. The New Micros board uses the Motorola 68HC11, one of several microprocessors which incorporate an eight bit analog to digital converter. We also considered an external 12 bit converter which offered higher speed and accuracy at the cost of more power consumption and complexity. These microprocessor boards are small, but they are not designed to fit inside a 1 inch pipe. By the time an appropriate housing surrounds them, the unit would be limited to relatively large wellbores. The mechanical shock and temperature limitations are certainly inferior to the SAIC system, so that use would be restricted to shallow wells and small stimulations. Though the use of a down-hole recorder is a promising option for the future, because of limited time and limited funds our development of this concept has been temporarily halted in favor of the sensor and cable approach.

7. Acoustic and Seismic Measurements

7-a. Sensors and recording equipment

Two new types of measurement were attempted for the first time for DGPL stimulations under this program. The first was acoustic measurement of sounds carried by the well casing, and the second was seismic measurement of vibrations carried by the earth.

Even in a large stimulation like the South Mountain job described in section 1 where two truckloads of Stressfrac tool were used, the workers at the surface did not hear anything during the stimulation. However, by attaching a contact microphone to the well casing and recording the sound with a battery powered stereo cassette recorder, an interesting sonic record was obtained. The sound carried to the surface by the casing resembled distant thunder which continued for several seconds. There were discrete audible events which may be related to fracture formation or may be due to bursts in gas generation. This data record provides useful additional data, not the least of which to assure the crew that the stimulation has in fact occurred. Later, the effect of stimulation was obvious as natural gas pressures rose to levels that had not been observed for 30 years.

The experimental seismic sensor was constructed by weighting the speaker cone of a 3 inch loudspeaker with a large steel washer, and sandwiching the speaker between two boards. Vibration of the boards moves the speaker, and the heavy weight of the speaker cone causes it to lag behind, which causes the drive coil of the speaker to move in the speaker magnet and generate an electrical signal. This simple and economical sensor was connected directly to the second microphone input of the stereo recorder. The resulting traces are quite interesting, and seem to show a series of seismic shocks corresponding to fracture formation. Some of these shocks occur some seconds after the onset of stimulation, and suggest that fractures continue to grow due to in situ stresses even as the gas pressure is dropping. A chart recording of the signal envelope for acoustic and seismic signals in the South Mountain stimulation is shown in Figure 6-1.

7-b. Acoustic and Seismic Data

Seismic Measurements

in the recent North Dakota test the first stimulation showed higher peak pressures than the second, indicating that the non-producing formation was more difficult to fracture. The seismic geophone measurements at the surface were qualitatively different on these two stimulations. The high-pressure, non-producing formation produced about 30 small and rapid seismic signals, while the low-pressure producing formation produced about 5 large seismic signals. The difference in number, amplitude and frequency of the seismic signals suggests that we are measuring qualitatively different fracture processes in these two regions of the same well. The duration of the seismic signals was longer than the expected burn time of the tool, which suggests that the seismic signals may be generated as the gas cools and the formation shifts back to a new equilibrium position. This shifting process may be powered by pre-existing strain in the formation and may supply additional energy to extend the fractures. This very preliminary data suggest that the seismic

measurements may have considerable value, though much additional study is needed. The use of precision accelerometers in a three dimensional vector configuration together with accurately timed recording of motion at several surface locations may provide a much more complete picture of the fracture process.

The acoustic and seismic measurements were repeated with interesting results in two successive stimulations of a horizontal well in North Dakota. These stimulations used Stressfrac tools of about 100 feet in length. The first stimulation was in a very tight formation at the end of the well which lead to relatively high peak pressures, 10,000 psi over static pressure, on the passive pressure gauges. The seismic record of that stimulation showed a tight nest of small seismic events, suggesting short localized fractures immediately around the wellbore. The second stimulation was in a producing zone about 1000 feet from the end of the well. This time the peak pressure readings were lower, 4,000 psi over static pressure, in line with the expected breakdown pressure of the formation. The seismic record in this case showed a smaller number of large seismic events, as though the gas was able to extend each fracture a considerable distance before initiating a new fracture.

ACOUSTIC AND SEISMIC PEAK VOLTAGE DATA FROM 800 FOOT VERTICAL STIMULATION

Figure 6-1 Acoustic and Seismic Data from South Mountain

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