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by

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HYDRAULIC FRACTURE EXPERIMENTS IN GT-1 AND GT-2

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ABSTRACT

Hydraulic fracturing experiments were conducted in granite rock, at temperatures near 100 and 150°C, in two wells 0.785 km (2575 ft) and 1.98 km (6500 ft) deep near Los Alamos, New Mexico. No unusual difficulty was observed in fracturing crystalline rock hydraulically. The apparent surface energy (energy required to create new fracture surface by breaking the rock) was measured as 100 J/m². Orientation of the deeper fracture was measured as N35°E ($\pm 5^\circ$). The fraction of fluid injected into the rock that could be recovered at hydrostatic surface pressure was measured. The efficiency of recovery was as high as 92% after the fracture impedance was lowered by "propping" the fracture with sand. Permeability of the rock over the face of the fracture was compatible with laboratory measurements (10^{-7} to 10^{-8} darcys). Downhole pressures required to extend the fractures were about 150 and 340 bars (2175 and 4900 psi), respectively.

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I. INTRODUCTION

The Los Alamos Scientific Laboratory (LASL) hot dry rock geothermal program is designed to extract energy from hot rocks, which underlie all of the earth's surface. Project experiments are being conducted in a region of abnormally high heat flow ($\sim 15 \mu\text{W}/\text{cm}^2$), where the hot rock is near the surface. If this project proves successful, eventually it should be possible to extract energy from deeper rocks in many areas of the world.

Heat may be extracted from rock by circulating a fluid (usually water) down a pipe drilled into hot rock and up through a second pipe. Because rock is a poor heat conductor, the heat that may be extracted per unit area is small; therefore, a large surface area must be contacted by the circulating fluid. For example, by circulating fluid through a 1-km² crack in 300°C rock, about

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25 MW of thermal energy can be withdrawn for 20 yr. At this extraction rate, fluid temperature drops about 50°C by the twentieth year.¹ However, the phenomenon of thermal-stress cracking, caused by cooling and shrinkage of the rock, has been ignored in these calculations, but this phenomenon, by extending the fracture into fresh hot rock, may appreciably extend the life of a geothermal system.²

The process of hydraulic fracturing, creating a large planar crack in rock by pumping fluid into it under high pressure, is frequently used in the petroleum industry to improve communication with a reservoir. In the LASL hot dry rock geothermal system the plan is to drill a hole into hot rock, create a large hydraulic fracture, then intersect this fracture with a second hole. Ideally, the whole system is maintained at a pressure sufficiently high so that the fracture remains open, and circulation is maintained by the density difference between the descending (or injected) cold water and the rising hot water. Several questions must be answered before the feasibility of the system can be demonstrated. The experiments described in this report are designed to provide answers to the following questions:

- Can large hydraulic fractures be made in hot crystalline rock?
- Is the rock competent and impermeable enough to hold fluid loss from the fracture to tolerable levels?
- What is the surface pressure required to hold the fracture open?

The effect of thermal-stress cracking on the system will be studied in later experiments, after the circulation loop with continuous heat extraction is in operation.

II. HYDRAULIC FRACTURE EXPERIMENTS

A. Geothermal Test Hole GT-1

An exploratory hole was drilled in Barley Canyon on the Jemez Plateau, about 2.5 km west of the ring fault of the Jemez Caldera and about 35 km west of Los Alamos, New Mexico. The location was chosen on the basis of heat flow studies in shallow (~150-m depth) holes around the south and west flanks of the caldera and from geological studies by the U. S. Geological Survey. The GT-1 site is in a region of higher than normal heat flow ($\sim 15 \mu\text{W}/\text{cm}^2$), which is also free of major faults. The hole was drilled to a depth of 785 m, about 175 m into the Precambrian basement rock, and was cased to 735 m with 127-mm-o.d. (5-in.) casing. The bottom-hole temperature was slightly over 100°C.

Seven small fracture experiments were carried out in GT-1. For each fracture, a few liters of water were injected into a chosen interval of rock about 2 m long, sealed at both ends by rubber-covered packers. Leakage around the packers was a continuing problem in these experiments; however, the breakdown and fracture extension pressures, given in Table I, are not affected by leakage. A typical pressure history, showing the initial pressurization, breakdown, and subsequent decrease of pressure, as well as the pressure during a repump of the fracture after venting, is shown in Fig. 1.

After completion of the small fractures, a larger fracture (4500 l) was created between packers placed at 742- and 776-m depths. The downhole pressure during creation of this fracture was about 240 bars, about 60 bars above the estimated overburden weight. After the fracture was created, the well was shut in and a small leakage was observed above the upper packer. The pressure history for the next 6-1/2 h is shown in Fig. 2.

1. Analysis of GT-1 Fracture. From the data shown in Fig. 1, values for the rock strength and the earth stress normal to the fracture may be calculated. For a crack to form, energy is required to crack the rock and to open the crack. The work of opening the crack may be divided into that required to oppose the

TABLE I
DOWNHOLE BREAKDOWN AND EXTENSION PRESSURES

Date 1973	Depth		Breakdown		Extension		Volume (liters)
	(m)	(ft)	(bars)	(psi)	(bars)	(psi)	
3-7	761.4	(2498)	165	(2395)	154	(2234)	10.4
3-14	772.7	(2535)	>227	(>3297)	148	(2148)	-
3-21	751.3	(2465)	169	(2447)	154	(2243)	1.1
					153	(2217)	2.0
3-23	776.3	(2547)	167	(2422)			
3-24	740.4	(2429)	153	(2221)	141	(2052)	2.9
					142	(2067)	5.7
					143	(2077)	14.3
3-27	748.3	(2455)	191	(2765)	163	(2363)	12.6
3-28	745.2	(2445)	177	(2572)	158	(2295)	4
3-28	745.2	(2445)	-	-	153	(2223)	14.3

earth stress and that done against the elastic restoring force of the rock. If the least principal earth stress (positive in compression and including pore fluid pressure) is S , and if V is the volume of the crack, then the work done against the earth stress when a crack is opened normal to the least principal stress is very nearly equal to SV , because displacements along the plane of the crack are small. As the crack begins to open, elastic restoring forces begin to act and the pressure, P , in the crack is greater than S . From the theory of a penny-shaped crack,³ the elastic energy is $(P - S)V/2$. The sum of the elastic work and that done to overcome the earth stress is just that work required to reopen an existing crack, U_r ,

$$U_r = (P + S)V/2 \quad . \quad (1)$$

When the crack is initially formed, additional energy is required, which may be attributed to the creation of new surface. If α is the energy required to form a unit area of new surface, the work required for the initial creation of a fracture of radius R is

$$U_i = (P + S)V/2 + 2\pi R^2 \alpha \quad . \quad (2)$$

The radius, R , may be related to the volume, V , if the Young's modulus, E , and the Poisson's ratio, ν , of the rock are known. The pressure, P_e , at which a penny-shaped crack begins to extend is given by Sack⁴ as,

$$P_e = S + \left[\frac{\pi \alpha E}{2(1-\nu^2)R} \right]^{1/2} ; \quad (3)$$

the volume of the fracture is given by Sneddon³ as

$$V = (16/3) (1 - \nu^2) (P_e - S)R^3/E. \quad (4)$$

From Eqs. (1) and (2)

$$\alpha = (U_i - U_r) / (2\pi R^2) \quad . \quad (5)$$

Equations (3), (4), and (5) may be solved simultaneously for R , $P_e - S$, and α if U_i , U_r , V , and the rock properties are known.

By integrating the pressure-volume curves of Fig. 1, subtracting the work done in compressing the water in the pipe, the result is $U_i = 6.45 \times 10^4$ J and $U_r = 6 \times 10^4$ J. Using the values of E and ν determined from sonic logs, 3.76×10^5 bars and 0.305, respectively, and the volume of fluid in the fracture, 3.85 l, the values of α , $P_e - S$, and R are found to be 100 J/m^2 , 16 bars, and 2.7 m, respectively.

Perkins⁵ has made laboratory measurements of the apparent surface energy of sandstone and limestone. Values for unconfined rock were as high as 130 J/m^2 and increased with confining pressure. Thus, the value of α derived here does not seem unreasonable, although it is appreciably higher than surface energies in the range of 0.1 to 1 J/m^2 measured with pure minerals.⁶ The difference may be due to cracking and overturning of grains in the nonhomogeneous rock along with the increased area due to roughness of the fractured surface.

From Eq. (1) and the value of U_r , 6×10^4 J, $P_e + S = 31.1 \text{ MPa}$ or 311 bars. Subtracting the value of $P_e - S = 16$ bars and dividing by 2, we have $S = 148$ bars. A similar value can be deduced directly from Eq. (1), using the value of P_e , 164 bars, or 16.4 MPa, attained on the repump when the fracture volume was 3.85 l.

The shut-in curve of Fig. 2 shows an anomalously high pressure during the first 6 h. This could indicate that a horizontal fracture was formed when the wellbore was pumped at a high rate. The overburden stress would be 179 bars at a mean density of 2.4 g/cm^3 , and the measured value at the first knee in the curve is about 178 bars. If the second knee corresponds to the closure of a vertical fracture, the earth stress at closure would be 137 bars. However, because no such behavior has been observed after shut-in in subsequent fractures in another hole (GT-2) drilled into granite at greater depths, this interpretation of Fig. 2 now appears questionable.

2. Conclusions from GT-1 Fractures. Fractures were created without difficulty in crystalline basement rock at a measured bottom-hole temperature of 100°C . The apparent surface energy of the rock, 100 J/m^2 , is within the range of laboratory measurements on competent rock. The least principal earth stress is about 147 bars.

B. Geothermal Test Hole GT-2

A second hole was drilled about 2-1/2 km south of GT-1, at a site that was more accessible and where there was room for a circulation experiment. The hole was cased to a depth of 773 m, about 40 m into granite, with 273-mm- (10-3/4-in.-) o.d. casing, and drilling below this point continued with a 244-mm (9-5/8-in.) bit.

After the hole reached a depth of 1936 m, 13 attempts were made to fracture between two packers at various depths from 793 to 1643 m (see Fig. 3). Although packers of varying hardness from three different manufacturers were tried, no unambiguous fractures were created. Usually, leakage was noted into the annulus around the drill pipe on which the packers were mounted. To overcome this problem, the hole was deepened to 2042 m, and a 64-m-long liner of 165-mm (6-1/2-in.) i.d. was cemented into the hole between 1919- and 1983-m depths, leaving 59 m of uncased wellbore below the liner for fracture experiments. Connection to the liner was made with a polished-bore receptacle (PBR), an assembly of Teflon chevron seals along the inside of a polished section of pipe; the entire assembly locked at the top of the cemented liner. This new seal and liner eliminated the packer leak problem.

1. Fracture Experiments between 1983 and 2042 m. The region between 1983 and 2042 m was pressurized 19 times at flow rates from 1.3 to 24 l/s (21 to 378 gal/min). The amount of fluid recovered was measured in most of these experiments, although venting was not always prompt. When the time delay before venting was long, little or no fluid was recovered.

Figure 4 shows the time sequence of the experiments conducted in this region and the volume pumped into the fracture in each experiment. Figures 5-26 show pressure and flow histories of the initial fracture and subsequent repumps and enlargements of this fracture, as well as an additional fracture made through perforations (Figs. 24 and 25) near 1943-m depth, which will also be discussed below.

2. Analysis of Fracture Experiments.

Geometry. Figure 27 shows the physical arrangement of the borehole and the cemented-in liner with perforations. Figure 28(A) shows the relative positions of the fractures near 2-km depth.

To define the lower fracture a spinner survey, made with a logging instrument incorporating a small propeller, was used to measure the flow velocity

of the water in the wellbore while pumping. The propeller spins at a steady rate as it is raised at a constant velocity from the bottom of the hole, until it encounters the water flowing down the wellbore and out into the fracture, whereupon the rate increases in proportion to the additional flow velocity. The result of the survey is shown in Fig. 28(B), which shows two similar increases in rotation rate, separated by a plateau. This indicates that water leaves the wellbore in two regions of similar length, between 1989 and 1993 m, and 1998 to 2002 m, respectively. Packers designed to retain impressions of the wellbore surface were inflated in these two regions and recovered. Figure 29 shows the impression packers after recovery, and Figs. 30 and 31 show tracings of the fractures, formed on plastic sheets rolled around the packers.

The orientation of the packers with respect to the Earth's magnetic field was measured by photographing a compass lowered into a receptacle in the drill string just above the packer. The fracture direction was determined to be $N35^{\circ}E \pm 5^{\circ}$, essentially normal to the inclination of the wellbore, $N70^{\circ}W$. The fracture impressions are almost vertical, and with the measured wellbore inclination of 4.5° and diameter of ~ 0.25 m, each fracture should intersect the wellbore over a distance of slightly more than 3 m, in reasonable agreement with the spinner survey.

Surprisingly, there appear to be two parallel fractures intersecting the wellbore, spaced about 0.6 m apart, accepting equal amounts of fluid at the same pressure. It is not known whether or not these fractures are joined together outside the wellbore, but based on their similar flow behavior, it is likely that they are, otherwise one fracture would be expected to grow more rapidly than the other, become wider at the same pressure, and take almost all the flow, which varies with fracture width cubed at a given pressure drop. Such a double fracture system is not expected to arise from pressurization of the wellbore, but may result from a pre-existing fracture system.

Initial Breakdown. When the wellbore was first pressurized to initiate a fracture, the pressure-vs-time curve (Fig. 5) did not show an initial high-pressure breakdown phase, followed by a lower pressure fracture-extension phase; the observed pressure history is compatible with extension of one or more pre-existing, perhaps weakly cemented, fractures.

Fluid Losses. The permeation of water into the walls bounding a large fracture can be closely approximated as a one-dimensional diffusion problem until the distance through which the water has permeated exceeds one- or two-tenths of the fracture radius. Hydrology tests, which measure the pressure rise or fall in a packed-off section of the GT-2 wellbore due to movement of fluid into or out of the rock, show that the pressure of the pore fluid, P_o , is that of a column of water extending upward to within 500 - 600 m (1700-2000 ft) of the surface. Initially, permeation from a fracture is proportional to the amount by which the fracture pressure exceeds this pore pressure. After the fracture has remained for many days under the pressure of a column of water extending to the surface, a new local pore-pressure field is established. This is the appropriate pore pressure to use for permeation calculations of water losses in short-time experiments.

The one-dimensional diffusion equation, relating pressure, P , to distance, x , into the medium and time, t , is

$$\frac{\partial P}{\partial t} = \kappa \frac{\partial^2 P}{\partial x^2} \quad (6)$$

The value of κ for fluid of compressibility, β , and viscosity, μ , permeating into rock of compressibility, β_r , and porosity, θ , is $\kappa = \frac{k}{\mu\beta_e}$, where $\beta_e = \beta\theta + \beta_r(1-\theta)$. When θ is small, as in granite, β_e is approximately equal to β_r .

From measured compressibilities of granite rocks⁷ a value of $2.73 \times 10^{-6} \text{ bar}^{-1}$ was selected for β_e . The viscosity of water at temperatures near 150°C and pressures near 200 bars is approximately 0.002 P. Because other uncertainties in permeation calculations, such as areas or variations of permeability over a fracture face, are large, these nominal values for compressibility and viscosity have been used for all calculations near 2-km (6560-ft) depth.

Carslow and Jaeger⁸ give the solution to the problem of one-dimensional fluid permeation through an area, A , when a constant pressure, P , over and above the pore pressure, is applied at time $t = 0$. The flow into the face is

$$\dot{Q} = PA \sqrt{\frac{k\beta_e}{\pi\mu t}} \quad (7)$$

The total permeation in time, t , is

$$Q = 2 PA \sqrt{\frac{k\beta e}{\pi\mu}} t \quad (8)$$

Table II gives the water loss to be expected in 1 yr for a fracture with a surface area of 1 km^2 on each face, for a range of permeabilities that might be expected for granitic rock.

Evidently, water losses will not be excessive unless the fracture passes through regions where the permeability is much higher than that of laboratory specimens. Figures 5 - 23 list the fraction of injected fluid recovered in the various pumping experiments. If the fracture intersected a porous zone where pressure was much lower than at the wellbore, a large fraction of the injected fluid would not be recoverable. Recovery of most of the injected water, as observed in the experiments of October 2, 1974 (Figs. 22 and 23), indicates that the geometry is essentially planar and that the local pore pressure has been raised almost to surface-hydrostatic pressure. Four days before the October 2 experiments, the fracture was propped open by injection of sand, as discussed below. This lowered the impedance to flow within the fracture, facilitating fluid recovery. The ability of this fracture system to retain water under pressure without excessive losses, at least for short time periods, has been established.

TABLE II
WATER LOSS IN 1 YR FROM A CIRCULAR FRACTURE OF 564-m RADIUS
(1 km^2 ON EACH FACE), AT AN OPERATING PRESSURE
200 BARS ABOVE PORE PRESSURE

Permeability (darcys)	Water Loss		
	(liters)	(gallons)	(acre feet)
10^{-6}	9.36×10^7	2.47×10^7	76
10^{-7}	2.96×10^7	7.82×10^6	24
10^{-8}	9.36×10^6	2.47×10^6	7.6

Fracture Impedance and Propping. The experiment on September 15, 1974 (Fig. 8), consisted of repeated pump-ups to successively higher pressures, each followed by a shut-in period during which the pressure decayed. If the pressure drop along the fracture face was low, the permeation from the fracture face should obey the law for one-dimensional flow. If the pressure drop was high, the permeation should resemble radial flow into the fracture system. Actually, the observed pressure decays agreed with the radial flow calculation (Fig. 32). If the flow is assumed to be laminar, a fracture width of 40 microns can be deduced from the observed fracture conductance. An experiment was performed to see if the impedance to flow along the fracture could be reduced by propping the fracture open with sand. On September 28, 1974, 3400 kg (7500 lb) of 20-40 mesh sand and 907 kg (2000 lb) of 10-20 mesh sand were injected into the fracture in a polymer solution. The impedance into the fracture was greatly reduced, as demonstrated by the fact that it now took 25 min (Fig. 22) to pressurize the wellbore to 124 bars (1800 psi) at the same pumping rate, 2.65 l/s, at which it took 2 min before the propping (Fig. 18).

Fracture Dimensions. After the sand-propping operation, the impedance along the fracture appears to have dropped sufficiently so that a pressure applied at the wellbore was exerted uniformly over the fracture face. If fluid is pumped into such a fracture at a constant rate, the pressure will rise as the square root of time.⁸ The slope of the p -vs- $\sqrt{t}$ line varies inversely as fracture area times the square root of permeability ($A\sqrt{K}$). Figure 33 shows the straight line plot obtained after the fracture was propped. The value of $A\sqrt{K}$ corresponding to the slope of the p -vs- $\sqrt{t}$ curve is 24 cm^3 . Laboratory measurements of the permeability of GT-2 rock give values in the range of 10^{-15} to 10^{-16} cm^2 (Ref. 9). The corresponding fracture radius, R , is 110-195 m (360-640 ft). By eliminating $P_e - S$ from Eqs. (3) and (4) we derive an expression for fracture volume in terms of the radius and the elastic constants of the rock:

$$V = \frac{16}{d} \left[\frac{\pi\alpha(1-\nu^2)}{2E} \right]^{1/2} R^{2.5} \quad (9)$$

Taking $\alpha = 100 \text{ J/m}^2$, $\nu = 0.25$, and $E = 8 \times 10^{10} \text{ Pa}$ (from the sonic log in this region), and $R = 195 \text{ m}$, then from Eq. (9) $V = 121 \text{ m}^3$ (32 000 gal), which is consistent with the volume of 136 m^3 (36 000 gal) pumped into the fracture

on September 27, 1974, decreased by permeation during fracture extension. The smaller radius (higher permeability) is less consistent with the experimental data.

Perforation Fracture. A final experiment was performed to investigate the interaction of a new fracture with the old one. Eighty-four perforations, each about 1 cm in diameter, were created in the casing between 1.942 and 1.945 km (6370-6380 ft) by a commercial service company, using an array of small shaped charges (Fig. 27).

The perforated region was isolated by packers at each end and was pressurized to create a new fracture. The pressure-time history is shown in Fig. 24. The initial pump-up was terminated at the safe pressure limit of the pumping system, 275 bars (4000 psi). When pumping recommenced, it appeared that a fracture had been created during the initial pressurization phase, and the wellbore pressure did not reach the previous value. As fracture growth continued, the pressure remained consistently higher than when the open-hole fracture was extended. This behavior, at first interpreted as indicating a higher earth stress in the perforated region, was later found to be characteristic of fractures through perforations, and it was concluded that earth stress measurements through perforations are unreliable.

The Sneddon-Sack equation, Eq. (9), predicts a radius of 70 m (229 ft). The lower fracture radius is similarly computed to be ~ 200 m, and because their respective wellbore intersections are separated by less than 50 m along the wellbore, the two fractures should have overlapped. If they were vertical, then from the measured wellbore inclination of 4.75° in this region the fracture faces should be about 3.8 m (12.5 ft) apart. Even over this short distance there was almost no observable communication between the fractures, as determined by a clock-driven pressure gauge in the wellbore near the lower fracture. A slight pressure rise on this gauge corresponded to a leak of less than $1 \text{ cm}^3/\text{s}$ between the fractures. The isolation of the two fractures was confirmed when the lower fracture was isolated and pressurized (Fig. 26) with 1447 ℓ (380 gal) with no observable rise in the annulus which was connected to the upper fracture. These results confirmed the low permeability of the rock near 2-km depth, over areas of more than 1000 m^2 .

Earth Stress. A first approximation to the horizontal earth stress at a certain depth is given by the linear strain approximation, which corresponds

to the horizontal stress that would be induced in a uniform layered medium if gravity could be turned on after the medium was emplaced, i.e., a vertical compression takes place with no horizontal movement.¹⁰ If the pore pressure is P_0 , Poisson's ratio is ν , and the overburden weight per unit area is S_1 , this approximation gives

$$S_3 = \frac{\nu}{1-\nu} (S_1 - P_0) + P_0 . \quad (10)$$

Near 2-km depth in GT-2, with a mean overburden density of $\sim 2500 \text{ kg/m}^3$, $P_0 \cong 135 \text{ bars}$ and $\nu \sim 0.2$, as given by the sonic log near the fracture origin; the predicted value of S_3 is $\sim 223 \text{ bars}$, which would give $\sim 30 \text{ bars}$ (450 psi) as the surface pressure required to open a fracture. The actual surface pressure required was $\sim 140\text{--}150 \text{ bars}$ (2000–2200 psi), so S_3 appears anomalously high, $\sim 340 \text{ bars}$, near 2-km depth.

III. CONCLUSIONS FROM GT-2 NEAR 2-km DEPTH

There was no difficulty in hydraulically fracturing granitic rock at temperatures near 150°C . The low permeability observed in laboratory studies of GT-2 cores appeared also to characterize large surface areas of granitic rock in this region. Surface pressure required to operate a geothermal system at $\sim 2\text{-km}$ depth was higher than suggested by a simplified model, but, at $\sim 150 \text{ bars}$ (2200 psi), was compatible with available surface plant equipment. Impedance to flow along the fracture face was high when the fracture was closed, but could be appreciably reduced by sand propping.

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Fig. 1. Pressure-volume history of GT-1 fracture.

Fig. 2. Pressure-time data during shut-in after large GT-1 fracture was produced.

Fig. 3. Summary of packer experiments in GT-2.

Fig. 4. Summary of pumping experiments in GT-2.

Fig. 5. Surface pressure vs time; initial pressurization.

Fig. 6. Surface pressure vs time; first repump.

Fig. 7. Surface pressure vs time; second repump.

Fig. 10. Surface pressure vs time; experiment of 9-16-74.

Fig. 8. Surface pressure vs time; first ramp experiment.

Fig. 11. Surface pressure vs time; experiment of 9-17-74.

Fig. 9. Surface pressure vs time; shut-in after rapid vent.

Fig. 12. Surface pressure vs time; experiment of 9-19-74 (A).

Fig. 13. Surface pressure vs time; experiment of 9-19-74 (B).

Fig. 16. Surface pressure vs time; third ramp experiment.

Fig. 14. Surface pressure vs time; second ramp experiment.

Fig. 17. Surface pressure vs time; experiment of 9-25-74.

Fig. 15. Surface pressure vs time; experiment of 9-23-74.

Fig. 18. Surface pressure vs time; experiment of 9-26-74.

Fig. 19. Surface pressure vs time; experiment of 9-27-74.

Fig. 20. Surface pressure vs time; experiment of 9-28-74.

Fig. 21. Surface pressure vs time, experiment of 10-1-74.

Fig. 22. Surface pressure vs time; experiment of 10-2-74 (A).

Fig. 23. Surface pressure vs time; experiment of 10-2-74 (B).

Fig. 24. Surface pressure vs time; perforation fracture.

Fig. 25. Surface pressure vs time; shut-in after perforation fracture.

Fig. 26. Surface pressure vs time; communication test.

Fig. 27. Geometry of wellbore, showing cemented liner.

Fig. 28. (A) Geometry of spinner survey and (B) composite of eight spinner runs.

Fig. 29. Impression packers after recovery.

Fig. 31. Tracing of impressions from lower packer.

Fig. 30. Tracing of impressions from upper packer.

Fig. 32. Comparison of computer calculations with first ramp experiment.

Fig. 33. Plot of surface pressure vs square root of time.