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HYDRAULIC FRACTURING TEST AT WEST VALLEY, NEW YORK

Wallace de Laguna

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HYDRAULIC FRACTURING TEST AT WEST VALLEY, NEW YORK

Wallace de Laguna

OCTOBER 1972

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HYDRAULIC FRACTURING TEST AT WEST VALLEY, NEW YORK

Wallace de Laguna

Abstract

The purpose of the test was to determine the geometry of fractures formed hydraulically in flat-lying Devonian shale in western New York. Five wells were drilled--an injection well at the center and four observation wells 150 ft out to the east, north, west, and south. All five wells were 1500 ft deep and were cased through their full depth. The first test was the injection of about 100,000 gal of water at 1450 ft into rock classed as fair for the formation of horizontal fractures. Indications from the pumping pressure, which was low, were that a horizontal fracture had formed, but there was some doubt, as the results differed from those for a similar test at Oak Ridge where the fractures are known to be horizontal. Analysis of the pressure decay after pumping had stopped suggested a horizontal fracture. A second injection at 1450 ft of water containing a radioactive tracer was shown to have formed a group of horizontal fractures. A third injection at 1226 ft, into rock classed as good for the formation of horizontal fractures, was shown by logging of the observation wells to have formed a single horizontal fracture. The pressure decay also suggested a horizontal fracture.

The fourth injection was at 1010 ft into a massive siltstone that was classed as poor for the formation of

horizontal fractures; indeed, a vertical fracture was predicted. The tracer showed that a thin horizontal fracture had formed, but that the main part of the injected water had fractured downward to 1395 ft. Analysis of the pressure decay curve showed no indication of any fracture except the thin horizontal one at 1010 ft.

Two injections were made at 500 ft into rock classed as good for the formation of horizontal fractures. The first was plain water. Again, the injection pressures were low. The pressure decay curve suggested a horizontal fracture, but the interpretation was not clear. The second injection at 500 ft consisted of water, portland cement, and bentonite, as a permanent uplift of the surface was desired. Logging of the observation wells showed that a horizontal fracture had been formed.

We reached two general conclusions: first, that horizontal fractures are to be expected in horizontally bedded shale down to depths of 1500 ft and, second, that the only reliable way to determine fracture orientation is by the use of a radioactive tracer and observation wells.

Introduction

The continued successful use of hydraulic fracturing for the disposal of medium-level radioactive waste at Oak Ridge raises the question

of the possibility of using the method in other areas. The primary factor to consider in the evaluation of another site is the orientation of the fractures that will be produced hydraulically in the bedrock underlying any other proposed area. This can only be found out by actually fracturing the rock hydraulically and then determining the geometry of the fractures that are formed, as data are yet insufficient to verify proposed theories of fracture orientation. The observation of fracture geometry in depth can be done directly by adding a radioactive tracer to the injected fluid and then logging a net of observation wells around the injection well with a radiation sensitive probe. This is the method used at Oak Ridge, both in our earlier tests and also to map the fractures now being formed by our actual waste disposal injections. However, this method, while it does give uniquely positive results, has at least three disadvantages. First is the question of cost. In addition to the injection well, at least four equally deep observation wells are required. These observation wells should be arranged in a square with the injection well at the center so that no matter which direction the fractures follow, at least one observation well will intersect it. In the experiment described in this report, the four observation wells were 150 ft out from the injection well to the north, east, south, and west. This assumes that the fracture will form a pie-shaped wedge covering an angle at the well of at least 90° , but possibly less than 120° , so that three observation wells would be insufficient. To determine the dimensions of the fracture, many more wells would be required. These wells form a major part of the cost of the experiment.

The second possible disadvantage is the need to use a radioactive tracer. One curie of an isotope like ^{137}Cs is theoretically enough to tag 100,000 gal of water or slurry so that it can be picked up by gamma-ray logging, but practical considerations, such as possible uneven mixing, or adsorption of the tracer on the rock walls of the fracture, require that in practice a minimum of about 10 Ci be used. This is a fairly large amount of activity to be handled in the field, and various precautions, which are somewhat tedious and expensive, must be taken. In our work in New York State we used not cesium but ^{95}Zr - ^{95}Nb . For each injection, 2.7 Ci were required. The isotope was brought up directly from Oak Ridge by automobile.

The time required to prepare for the test, and more particularly the time required to drill the wells, is the third disadvantage. For these reasons we have been interested in developing a test method which would be cheaper, simpler, and quicker.

Interpretations of Pressure History at Injection Well

It is generally recognized that, when a horizontal fracture is formed, the fracturing pressure must be at least equal to the weight of the overburden, but that, for a vertical fracture, it may be, but is not necessarily, less than this critical weight.¹ By fracturing pressure is meant the pressure in the fracture immediately after pumping has stopped. This pressure is commonly measured at the wellhead, and allowance must be made for the weight of the water in the well. If the rock has a specific gravity of 2.65, an average value for well-compacted sedimentary rock, then the weight or pressure of the rock cover, as measured

at the surface in a water-filled well, would be the depth in feet multiplied by 0.715. For example, for a fracture at a depth of 1000 ft, the critical wellhead pressure in a water-filled well would be 715 psi. The instantaneous shut-in wellhead pressures at Oak Ridge have all been about twice the pressure due to the rock cover, although the instantaneous shut-in pressure is easier to define than to record in practice. When pumping stops, the pressure drops rapidly at first, in one test 60 psi in the first minute, and then drops more and more slowly. At Oak Ridge all our pressures at shut-in have been well above the critical value, and, as far as we know, all our fractures have been horizontal. Indeed, one of the weaknesses of our position is that we have little experience so far with vertical fractures and therefore no data of our own to show us what to expect. Although many thousands of oil wells are fractured every year, reliable measurements of the instantaneous shut-in pressure are relatively rare. Even rarer is any independent evidence of the orientation of the fracture. Tests as conclusive as those we have made at Oak Ridge are virtually unknown in the petroleum industry. However, for formations 3000 or 4000 ft deep or deeper, the fracturing pressure in oil wells is commonly less than the weight of the overburden and so vertical fractures are inferred. One test of fracture orientation, therefore, is the fracturing pressure, more properly the instantaneous shut-in pressure. If this pressure is less than the pressure of the overburden, then the fracture must be vertical, and, also, at least one horizontal component of the earth stress at the fracturing depth must be less than the pressure of the overburden. If the fracturing pressure is equal to or only slightly greater than the weight of the rock cover,

the geometry of the fracture is indeterminate. If the fracturing pressure is well above the weight of the rock cover, there is a high probability that the fracture is horizontal. In other words, the pressures associated with a fracturing operation can strongly suggest the orientation of the fracture, but only under favorable circumstances can they prove it.

Two attempts have been made to refine the interpretation of the observed fracturing pressures so as to provide a less ambiguous picture of the fracture. The first, derived by W. C. McClain,² requires that the fracturing fluid be water, or some other newtonian fluid. The rate of pumping must be varied stepwise, say from 40 to 100 to 250 gpm, held at each of these rates long enough for the transients to be eliminated, about 20 min, and then the same variation in pumping rates is repeated. From the change in wellhead pressure with pumping rate, it is possible to calculate the pressure losses due to friction and to estimate those due to turbulence, and so derive the pressure at the tip of the fracture. If the fracture is horizontal, this pressure should decrease exponentially as the total volume injected increases. If the fracture is vertical, the pressure may increase or decrease as the total volume injected increases, depending on whether the horizontal component of stress in the rock changes with depth more or less rapidly than a critical value. If the variation with depth of the horizontal stress should be equivalent to the change in head in a vertical column of water, a most unlikely circumstance, then the variation in pressure would be identical with that associated with a horizontal fracture. This method of analysis has been tried with data collected during a fracturing test at Oak Ridge, when a horizontal fracture was formed, and appeared to work well.

The other suggested method of analyzing the pressures associated with the production of an hydraulic fracture makes use of the drop in pressure after the injection has been completed and the well shut in. This drop in pressure is due to at least two factors. The first is a change in shape of the fracture.³ While the injection is going on, an appreciable pressure gradient is required to drive the fluid from the well out to the tip of the thin fracture, possibly as far as several hundred feet away. As the pressure at the tip must be at least equal to the weight of the overburden, the pressure near the well must be somewhat greater than the weight of the overlying rock. This excess pressure must somehow be contained, and this is done by the fluid arching upward and perhaps slightly compressing the cover rock. When pumping stops, this stored energy is released and the fracture tends to close back together near the well. The displaced fluid moves outward and, in so doing, extends the fracture, so that the hydraulic fracturing continues after the pumping has stopped. How long it may continue is not known, but in theory the extension outward of the fracture will stop only when the walls of the fracture are once more in contact. This rock-to-rock contact, which may be at only a few points, will take place when the pressure throughout the length of the fracture has dropped to the weight of the cover rock.

The second mechanism which contributes to the drop in pressure in the fracture after pumping has stopped is leakage. Although the shales into which the injections are made may, for most purposes, be described as impermeable, they are not completely impermeable. Because of the very large surface area of the fractures, which may reach out several

hundred feet from the injection well, and because of the relatively high fluid pressure within the fractures, leakage after shut-in may not be negligible, and the observed pressure drop must be due to both change in shape of the fracture and leakage. Change in shape of the fracture ceases when the rock walls make contact, which occurs when the pressure has reached the weight of the overburden, but drop in pressure due to leakage will continue indefinitely, although at an ever-decreasing rate. A careful analysis of the change in rate of drop in pressure with time should, therefore, show a break at the pressure equal to the weight of the overburden; for at higher pressures two factors control the rate, while below the critical pressure only one factor is operative. A plot (Fig. 1) of the logarithm of elapsed time against the logarithm of rate of change does indeed show such a change at the critical pressure in the case of data collected during the water injection test of December 1967. All other recent injections at Oak Ridge have contained considerable quantities of portland cement and other additives which solidify the fluid after it is injected and so greatly change the rate of pressure drop with time after the injection is completed. It is encouraging that the first set of data that we have from a water injection appears to confirm the validity of the analysis, but more such data must be analyzed before any reliance can be placed in the method. Also, we have so far insufficient data from a vertical fracture; so we cannot tell if, as we suppose, the rate of drop in pressure with time in such a fracture will show a discontinuity at a pressure somewhat below that equal to that of the cover rock. The break should come at a lower pressure if vertical fractures leading upward do indeed form normal to a least stress which is less than the weight of the rock cover.

Fig. 1. Water Injection Test, December 1967; Rate of Change of Pressure as a Function of Time.

There are, therefore, three related but still fairly distinct methods of determining the attitude of a hydraulically produced fracture from the history of the pressures observed at the wellhead. In the first, the instantaneous shut-in pressure is compared to the weight of the overburden. In the second, the pressure drop due to turbulence and friction are first eliminated and the change in pressure at the tip of the fracture is compared to the total volume injected. In the third, the rate in drop of pressure after pumping has stopped is examined to see if there is a discontinuity in the rate at the time when the pressure is equal to the weight of the overburden.

Other Field Test Methods

Two quite different additional methods have been proposed for determining fracture orientation. The first would utilize a net of very sensitive seismometers to detect and plot the location of the origin of the sound waves produced along the tip of the advancing fracture. Preliminary experiments using this technique at Oak Ridge have been mildly encouraging, but further testing was not attempted in conjunction with the trial injections at the New York site for lack of money. The second method which does not rely on observations of pressure would accurately measure the surface uplift resulting from the formation of the fracture. In theory, the amount and distribution of this surface uplift can be interpreted to indicate whether the fracture was vertical or horizontal. The amount of the surface uplift, however, is so very small that it can be measured only with difficulty, and in practice the results may not be definitive.

There is still one more independent approach to the problem, at least in theory. It has been argued that a hydraulically produced fracture will always be propagated normal to the least compressive stress in the rock. If this is true, and it may not be in a well-bedded comparatively impermeable rock like shale, then if one could determine the three-dimensional stress distribution in the rock, one could predict the orientation of any hydraulic fractures that might be formed in it. In practice it may well be the other way around; the pattern of fractures formed hydraulically may well be used to determine the state of stress in a rock, for there are at present no other reliable methods of stress determination in rock masses.

The argument that a hydraulically formed fracture will always be propagated normal to the least compressive stress assumes that the rock is at least slightly permeable to the fracturing fluid and that it is effectively homogeneous. Under these conditions, the fracturing fluid will penetrate into the rock in all directions around the point of entry and will press outwards more or less equally in all directions around this point. The rock will fracture when this imposed pressure reaches and slightly exceeds the least confining compressional stress in the rock, and the fracture will form normal to this least stress. In all other directions the outward hydraulic pressure will still be less than the inward stress in the rock. However, if the rock is composed of layers, like a shale, it will not be hydraulically isotropic. If also, as in the case of a shale, what little permeability there may be is parallel to the bedding planes, the fluid that is forced out of the point of entry will move out into the surrounding shale very largely

along certain beds or bedding planes, and the spacial distribution of the pressure buildup around the point of entry will not be uniform. If one may speak of force as the product of pressure and the area normal to that pressure, then a large force may be locally available to fracture the rock parallel to the bedding planes and very little force available in any other direction. The fractures formed at Oak Ridge have shown, where we have the evidence, a marked tendency to follow the bedding planes even where they have a dip of some 20 degrees. There is no obvious reason why the least compressive stress should be normal to the bedding planes so that the bedding planes themselves appear to have been the determining factor.

The method of well completion may also exert a strong influence on fracture orientation, at least in the opinion of some.⁴ If hydraulic pressure is applied to an uncased hole, the pressure tries to increase the diameter of the hole, and tangential forces are developed. When these forces exceed the strength of the rock, a vertical fracture will be formed. This is particularly true if the pressure is applied rapidly. If the pressure builds up slowly, enough fluid may leak out along a certain bed or bedding plane to produce an appreciable force parallel to the axis of the well and fracture the rock normal to that axis. However, if the well is cased, and hydraulic pressure is applied to the surrounding rock only through a narrow, horizontal slot, then the tendency of the well to expand radially is restrained by the casing, and by far the greatest part of the force applied to the shale is normal to the sides of the slot, and the shale will tend to fracture horizontally.

Purposes of the New York State Test

The purpose of the test program at West Valley in western New York State was to try out in the field, in rocks different from those at Oak Ridge, the several methods of determining the fracture orientation described above. Emphasis will be placed on the three methods which utilize the pressure observed at the wellhead--the relation of the instantaneous shut-in pressure to the weight of the overburden, the variation in fracturing pressure with the volume injected, and the variation in rate of decay of the pressure after the fracture is completed and the well shut in. The U. S. Geological Survey will test a mathematical model developed by R. J. Sun,⁵ of the amount of surface uplift produced in response to hydraulically induced horizontal fractures. Measurements of the surface uplift will be made by precision instrumental leveling and by the operation of three tiltmeters. Also, shear components in the rock mass will be measured with a geodimeter, and a few strain gages will be installed at shallow depths. There are no plans to make seismic recordings.

The first operation, as in the case of all of our fracturing tests, was to drill a core hole to obtain a complete sample of all the rocks to be fractured, and to determine the exact depth for each injection. Our first intention was to core to a depth of 2500 ft, for a well this deep would have penetrated both the Tichenor Limestone and the Onondaga Limestone, both of Middle Devonian Age. The Onondaga, in particular, is well-known over a wide area, and its identification in the core hole would have materially aided in placing the rocks to be tested in the regional stratigraphic column. However, the extra cost of drilling to this greater depth could not be justified, and the depth of the core hole was reduced

to 1500 ft, the depth which had been arbitrarily selected for our deepest injection. Most of the rock penetrated was shale, but much of the shale did not break easily or cleanly along the bedding planes, as does the Ccnasauga Shale at Oak Ridge, and may, therefore, be less apt to fracture parallel to the bedding planes when fractured hydraulically. About 100 ft of the rock penetrated was a sandy siltstone, in part thick-bedded to massive, but even the better bedded siltstone did not tend to break parallel to the bedding. The core samples and the electric log suggest that the siltstone, unlike the shales, has at least some permeability. Some of the dark gray or black shales penetrated, particularly near the bottom of the well, have a distinct odor of petroleum when freshly broken. These oil shales may be the upper part of the Rhinestreet Shale of the Java and West Falls Groups, and the overlying shales and siltstone probably belong to the Canadaway Group. All these formations are of Upper Devonian Age. The log of the well follows: The notations "good," "fair," and "poor" indicate the apparent suitability of the rock for hydraulic fracturing. "Good" means that the core can be easily broken by hand and that the break is closely guided by the bedding planes, although these may be slightly irregular in detail. The notation "fair" means that the core may be broken by hand, but only with some difficulty, and that the break, in general, is guided by the bedding. The notation "poor" means that the core can only be broken by a sharp blow, as with a hammer, and that the break is but little guided by the bedding.

Log of NX Core Hole, West Valley, New York
Drilled May 1969

Feet

0 to 197	Till; clay, silt, a little sand and a few cobbles.
197 to 549	Medium-gray silty shale; thin bedded but bedding is irregular in detail; about 5% is thin beds of light-gray calcareous siltstone showing cross bedding. Good.
549 to 661	Medium-gray silty shale; thin bedded but bedding irregular in detail; 10% or more is thin beds of light-gray calcareous siltstone. Fair; locally good or poor.
661 to 714	Dark gray shale; few scattered beds of medium- to light-gray calcareous siltstone. Locally faint oily smell. Fair, or fair to good.
714 to 800	Medium-gray and dark-gray shale interbedded; a few scattered thin beds of calcareous siltstone. Locally faint smell of oil. Fair to good.
800 to 920	Very fine-grained olive-green shale showing very little bedding, interbedded and irregularly intermixed with dark-gray shale which shows some bedding. Poor.
920 to 958	Black shale, with distinct petroleum smell, interbedded with and irregularly mixed with light-gray sandy siltstone and olive-green shale. Bedding poorly developed. Poor.
958 to 1048	Light- to medium-gray sandy siltstone, locally calcareous; bedding generally indistinct, locally easily visible. Does not break on bedding planes. Poor.

- 1048 to 1093 Dark-gray shale, bedding indistinct, interbedded and mixed with light- to medium-gray siltstone, locally calcareous. Poor to fair.
- 1093 to 1214 Medium-gray shale and dark-gray shale, interbedded. Bedding shows clearly, but rock does not break easily on bedding. Locally contains beds of light-gray siltstone. Fair.
- 1214 to 1274 Medium- to dark-gray shale; bedding thin, regular, and well-developed. Locally faint smell of oil. Good.
- 1274 to 1313 Dark gray shale, almost black. Bedding hardly visible. No oily smell. Fair.
- 1313 to 1410 Black carbonaceous shale, locally faint smell of oil. Bedding almost invisible, but rock is thin bedded. Breaks fairly well on bedding, but considerable force required. Fair.
- 1410 to 1459 Black shale; thin bedding visible when wet; strong oily smell; interbedded with dark gray shale with more evident bedding; faint oily smell. Fair.
- 1459 to 1520 Black carbonaceous shale; thin bedded, but bedding not easily visible. Bedding is regular and rock breaks fairly cleanly on bedding, but considerable force required. Strong oily smell. Fair.

Figure 2 is a graphic plot of a somewhat simplified log of the well.

Log of Injection Well, West Valley.

Fig. 2. Graphic Plot of a Somewhat Simplified Log of NX Core Hole.

Advantages of Drilling Observation Wells Prior to Tests

For the New York test the four observation wells were drilled prior to making the injections. They were spaced 150 ft out from the injection well into the north, east, south, and west, and were cased for their full depth. Prior drilling of the observation well has certain advantages as compared to drilling the observation wells afterwards, if all that is required is fracture orientation as determined in a limited number of wells. If the extent of the fracture or the fracture thickness are required, then the observation wells should be drilled and cored after the injections have been made.

The advantages to be gained by drilling the observation wells before making the injections are as follows. First, if the injection of some arbitrary volume fails to produce definitive results, the slot in the casing is still available and more "tagged" liquid may be pumped in. Second, if there is some doubt as to the pressures that will be required to break down the fracture or to make the actual injection, or if there is some uncertainty as to the volumes of fluid, if any, that it may be necessary to backflow prior to the next slotting operation, it is possible to make a preliminary injection with just plain water. Following all desired backflow from this preliminary nonradioactive injection, a second "tagged" injection can be made into the same slot and under conditions which are now well understood. It is, of course, impossible to pick up a nonradioactive injection in the observation wells. The purpose of the preliminary injection is to expose what problems may be encountered while using a completely harmless fluid; surprises while working with the radioactive fluid under high pressure could be unfortunate.

This is the procedure which was followed in making the first injection at 1950 ft; a preliminary injection was made with water, followed the next spring with an identical injection of tagged water. After this first injection it was not necessary to make trial water injections into the other three slots, although a preliminary water injection was made at 500 ft for other reasons.

A third advantage to making the injections after all the observation wells have been drilled is that it is then possible to avoid all ambiguity as to which fracture resulted from which injection. This is easily done by logging after each tagged injection; any new peaks on the log are clearly the result of what has just been pumped in. This advantage was of particular advantage in the case of our injection at 1010 ft.

Another probably minor advantage to be gained from drilling the observation wells prior to making the injections is that this avoids the necessity of drilling through the fractures and their contained radioactivity, and also that it avoids the necessity of logging in potentially contaminated holes. At Oak Ridge, drilling through fractures containing grout tagged with up to 30 Ci of ^{137}Cs per 100,000 gal was no problem, and it was not possible to detect any activity at the surface either in the drilling water or in the drill cuttings. Similarly, we have had no problem with the contamination of logging equipment in holes drilled through tagged experimental grout sheets. There have been contamination problems in holes drilled through the grout sheets resulting from the actual waste disposal operations, but the amounts of activity contained in these sheets are some thousands of times higher than in the experimental tagged sheets. However, the conditions at the New York site are

still unknown, and potentially embarrassing amounts of activity could bleed out of the fractures into which we propose to inject not a self-hardening grout but a dilute clay-water slurry containing the activity. The clay, about a tenth of a pound of illite per gallon of water, is added so that it may absorb much of the ^{95}Zr - ^{95}Nb tag while the water is moving down the well; illite has a strong absorptive capacity for zirconium. Without this clay carrier much of the zirconium might well be absorbed on the shale walls of the fracture close to the injection well, while for the purposes of the experiment it is essential that the tag be carried to the farthest limits of the fracture. The choice of 0.1 lb/gal is not only based on the absorption characteristic but also on the need to maintain newtonian characteristic of the injected fluid.

Method of Adding Isotope

The isotope used to tag the water injections and the one grout injection was ^{95}Zr - ^{95}Nb with a half-life of 65 days. The isotope was brought up from Oak Ridge by the health physicist who monitored the operation. It was shipped in solution in a small bottle in a lead container, and transferred at the site to the shielded 30-gal stainless steel drum which served as a reservoir. About 8 gal of water was added to the 30-gal drum and also a gallon or so of rhodamine red dye. The purpose of the red dye was to alert anyone in the neighborhood whose well or stream might become contaminated, but this, of course, never happened. The dye was useful, however, in marking any small leaks from the pump or fittings and was well worth the trouble. At the close of the injection, after the drum was essentially empty, clear water was used to flush the lines and

the pump (Fig. 3). Later the drum was rinsed out, and this contaminated water, plus any rubber gloves or contaminated paper towels, were mixed with portland cement and taken to the burial ground at the Nuclear Fuel Services plant. This system worked well, but it was much more difficult to work with the radioisotope in the field than at Oak Ridge.

General Conduct of the Test

The last of the well drilling at the test site at West Valley, New York, was completed in September 1969, and the casings were cemented into all five wells on September 29, 1969. The casing of the injection well was slotted at a depth of 1450 ft, using a hydra-jet tool, on October 8, 1969. The formation at this depth is a somewhat blocky oil-containing shale which does not break easily along the bedding and was rated "fair" for the production of horizontal fractures on the basis of an examination of rock cores.⁶

On October 9, 1969, about 114,000 gal of water was pumped into the slot, producing a fracture or group of fractures. This experiment was intended only to provide preliminary data to aid in planning the more definitive experimental injections scheduled for the spring and summer of 1970. In particular, no radioisotope was added to the injection water so that no use could be made of the observation wells to locate the points where the new fracture or fractures intersected them. Data were desired and were obtained on the breakdown pressure, the injection pressures at various pumping rates, and on the drop in pressure after the injection had ended and the well was shut in. An attempt was made in a preliminary report to interpret these data in terms of the probable fracture pattern formed by the injection.⁷

Fig. 3. Arrangement Used to Feed the Isotope Solution into the Well.

The injection was started very slowly by pumping water at a rate of a very few gallons a minute down the well. The rate was too low to be detected or measured by the Halliburton flow analyzer. Pumping was stopped after a few minutes to eliminate leaks, and then resumed, still at the very slow rate. After 20 min of intermittent pumping, the pressure reached 940 psi, and after 22 min it reached 1400 psi, at which pressure the well apparently broke down. In any case, the pressure dropped to 1040 psi, and then increased to 1100 psi as the pumping rate was speeded up to 16.5 gpm. This initial low-rate injection pressure of 1100 psi is almost the same as the instantaneous shut-in pressure of 1110 psi measured half way through and at the end of the injection.

The injection rate was slowly increased to 30 gpm with no detectable increase in injection pressure and then to 50 gpm, which resulted in an increase in the injection pressure to about 1400 psi.

After about an hour of this preliminary pumping, by which time about 1200 gal had been injected, a regular pattern of pumping was initiated. This pattern consisted of pumping at 100 gpm for half an hour, at 200 gpm for a half hour, and then at 400 gpm for a half hour, when the pattern was started over again.

After some 60,000 gal of water had been pumped, the pumping was stopped for about 45 min at the suggestion of the U. S. Geological Survey. They were interested in observing what effect a complete stop in pumping and a second start would have on the strain gages and tiltmeters which they were operating. When pumping was resumed, we found to our surprise that the injection pressures were consistently higher, for the same pumping rate, than they had been prior to the halt. This was

particularly noticeable at the 200 gpm and 400 gpm pumping rates. For example, just prior to the halt, the pumping pressure at an injection rate of 200 gpm was 1170 psi. After the halt, the same injection rate required 1260 to 1280 psi. Clearly, when pumping was resumed, there was some change in the underground fracture pattern. The most puzzling circumstances relating to the injection were the low pressures required, and the very small increase in pressure required to increase substantially the rate of the injection.

Interpretation of Pumping Pressures

An attempt was made to interpret the pressures measured during the test water injection at West Valley using the theoretical analysis developed for and successfully applied to the test water injection made at Oak Ridge in December 1967.⁸ This theoretical analysis is based on the assumptions that the fracture is horizontal, that it is circular in plan, and that in vertical section it is a very much flattened ellipse. The rock materials are also assumed to behave elastically. The pressure required to force water into and propagate the fracture was then found to be the sum of the overburden pressure, the viscous (laminar) friction losses as the liquid flows through the fracture, which can be estimated from the theory of laminar flow, and the pressure losses in the narrow zone of turbulent flow near the well, which cannot be theoretically determined.

Study of the water injection test at Oak Ridge, where the fractures are known to be nearly horizontal, suggested that the turbulent zone losses are also, like the laminar losses, a complex power function of

the volume injected. Consequently, for this type of fracture, the injection pressure, at any given flow rate, should decline as a complicated power function of the total volume injected. If the relation is, indeed, a power function, then the log-log plot of the pressure, corrected for friction losses, against volume injected, should be a straight line with a negative slope. This was, indeed, found to be the case for the water injection test made at Oak Ridge (Fig. 4). An extension of the theoretical analysis suggested that, even if a horizontal fracture were not circular, the injection pressure should still be a power function of the volume injected, but that if the fracture were long and narrow, the log-log plot might be a straight line with a positive slope. However, if the fracture is not horizontal, almost any type of relation could exist between the injection pressure and the volume injected, and a log-log plot of the relationship could have almost any slope or shape, depending on the earth stresses in the region, the angle of inclination of the fracture, and the density of the injected fluid.

The pressures measured during the test water injection at the New York site, corrected for frictional losses in the well and the static head, are shown on a log-log plot in Fig. 5. This plot may be interpreted by comparison with the result obtained at Oak Ridge. The conclusions reached are:

1. In the test at New York there is only a trivial difference between the injection pressures at the several flow rates. This can only be interpreted as meaning that the situation at the New York site is so different from conditions at Oak Ridge that there is no basis for comparison. These constant injection

Fig. 4. Injection Pressure History for Oak Ridge Water Injection Test.

Fig. 5. Pressures During Water Injection; First Injection Test, West Valley, New York, October 9, 1969.

pressures at the various flow rates are by far the most puzzling aspect of these results.

2. The injection pressure was constant as a function of volume injected. If it were not for item 1 above, it would be tempting to conclude from this that the fracture was not both circular and horizontal; that is, it was either horizontal and very elongated, or nonhorizontal.
3. The unusual pressure behavior following the 45-min period of no pumping suggests that the fracturing process did not begin again at the point where it had ceased, but in some way changed its configuration. This, in turn, suggests that a group or network of fractures may have been formed rather than a single fracture. When the second injection was made at 1450 ft, this turned out to be the case.

In summary, it appears to be impossible to draw any specific conclusions concerning the orientation of the fracture from the examination of the injection pressures. However, it is possible to conclude that the underground situation at the New York site is radically different from the conditions at the Oak Ridge site.

Interpretation of Pressure Decay

The possibility of using the rate of decline in pressure, following an injection into a well by hydraulic fracturing, to determine the probable fracture orientation was first investigated as part of a water injection test at Oak Ridge in December 1967.

When pumping stops and the well is shut in, the subsequent drop in pressure is some very complex function of the change in shape and of volume of the fracture. With so many poorly known parameters to consider, it is futile at this time to attempt a mathematical analysis of the processes involved. However, we do know that the change in shape of the fracture will cease to be an important factor after the pressure has dropped to the pressure equal to the weight of the overburden, and that the subsequent drop in pressure will very largely be governed by a decrease in volume of the fracture due to loss of fluid. The rate of pressure drop in a horizontal fracture may, therefore, be expected to show some discontinuity as the pressure drops below the weight of the overburden, and if such a discontinuity can be identified, it should be evidence that the fracture is horizontal.

Following the water injection test of December 1967 at Oak Ridge, the well was shut in and the pressure recorded, at first at 1-min intervals and then at longer and longer intervals as the rate of drop in pressure declined. These measurements were continued for about 70 days, at which time the rate of drop in pressure was only about 1 psi per day. The initial rate of pressure drop was about 60 psi in 1 min, so that the rate of drop in pressure varied over five orders of magnitude during this part of the injection test. A plot of pressure against time on rectangular coordinates is impractical in the case of this test as a single time scale cannot show the pressure changes which take place in a matter of minutes shortly after pumping stops as well as the pressure changes to be noted only over a matter of days toward the close of the period of record. An obvious alternative is to plot pressure on a linear

scale against time on a logarithmic scale, as is shown in Fig. 6. The curve shows no discontinuity, although there is a point of inflection after about 8×10^3 min, at which time the pressure was about equal to the weight of the overburden. Such a point of inflection in a semilogarithmic plot, however, has no physical meaning but is a result of the method of plotting.

The rate of change of pressure was then calculated for the time intervals between each pair of successive readings, and the result was plotted on a logarithmic scale against pressure on a linear scale (Fig. 7). This plot also shows an inflection but no meaningful discontinuity.

The rate of change of pressure was then plotted against time, both on logarithmic scales, and in this case the resulting curve (Fig. 8) did show a discontinuity. The first part of the plot, out to about 8×10^3 min, is a straight line with a slope of nearly 45° . This suggests that up to this time the rate of change of pressure is approximately inversely proportional to time, although this apparently simple relation may well be fortuitous. After 8×10^3 min the plot continues, not as a straight line but as a curve convex upward, showing that the rate of rate of change of pressure decreases with time and that the rate of change is no longer a simple inverse proportion of the time.

The change in the plot at 8×10^3 min comes at a time when the pressure was just over 600 psi (See Fig. 6 for the pressure after 8×10^3 min.) and is the kind of change that one might anticipate if one of two mechanisms responsible for the drop in pressure had ceased. This by itself would suggest that the fracture was horizontal as, in fact, it is known to be from other evidence. Therefore, it is reasonable to assume

Fig. 6. Pressure Decay; Water Injection Test, December 1967.

Fig. 7. Water Injection Test, December 1967; Rate of Pressure Drop as a Function of Pressure.

Fig. 8. Water Injection Test, December 1967; Rate of Change of Pressure as a Function of Time.

that a similar log-log plot of the rate of pressure decay in a fracture of unknown geometry might show a somewhat similar discontinuity if the fracture were in fact horizontal. However, lacking a proper theoretical background, this method of analysis must be used with caution.

The pressure drop in the injection well at West Valley, New York, following the water injection test of October 9, 1969, resembled the pressure drop in the Oak Ridge well, following the water injection of December 1967, in certain respects but differed markedly in others. The depth of the fracture at Oak Ridge was 852 ft, and the wellhead pressure in a water-filled well required to equal the weight of the cover rock would be 610 psi; the instantaneous shut-in pressure was, in fact, about 2000 psi. The depth of the fracture in New York was 1450 ft, and the wellhead pressure in a water-filled well required to equal the weight of the cover rock (200 ft of clay, specific gravity 2.0; 1250 ft of shale, specific gravity 2.60; the specific gravity of the New York shale varied from 2.49 to 2.79 and is believed to average 2.60) was 950 psi; the instantaneous shut-in pressure was only 1110 psi. This small excess of the instantaneous shut-in pressure over the weight of the cover rock is one of the more obvious differences between the New York and the Oak Ridge tests. Because the instantaneous shut-in pressure is greater than the weight of the overburden, the fracture may be horizontal; if it were less, the fracture would have to be vertical.

The shut-in pressure in the New York well not only started from a lower initial value but fell, at least initially, at a slower rate. The initial rate of pressure drop in the New York well was 10 psi min; in the Oak Ridge well it was 60 psi per min. After some 11,000 min the rate of fall in the New York well was 0.011 psi per min; in the Oak Ridge well

Fig. 9. Pressure Decline First West Valley Test, October 1969;
Slot at 1450 ft.

it was 0.017 psi per min. After this elapsed time the pressures in the two wells were much the same: about 525 psi.

A plot of pressure against time, both on linear scales, was prepared for the first 1500 min of the New York pressure-drop data (Fig. 9). This plot consists of three separate segments. From the first reading to point B, at about 290 min, the pressure drops rapidly at first, and then less and less rapidly. At point B, however, there is a distinct change. The rate of change in pressure increases slightly, from about 0.1 psi per min to 0.174 psi per min and holds this higher rate constant from 290 min to about 1010 min (point C) when the plot becomes slightly concave upward.

The discontinuity at 290 min came when the pressure at the wellhead was 954 psi, as nearly as we can tell the pressure equivalent to the weight of the cover rock. As such, the discontinuity suggests, but in no way proves, that the fracture was horizontal. If the fracture was horizontal, it is possible to explain why the rate of drop in pressure increased slightly at this critical pressure. At 960 psi wellhead pressure, the walls of the fracture, if horizontal, were not yet quite in contact, so that as liquid leaked out the walls were able to move closer together and in this way tended to maintain the pressure despite the leak. At this time the rate of pressure drop was about 0.10 psi per min. A few minutes later, when the pressure had fallen to 950 psi, the walls of the fracture were in contact at many points and so the fracture could not close further. Therefore, the loss by leakage of a small volume of water dropped the pressure more rapidly, as the fracture walls were stationary and only the bulk elasticity of the water and the rock were available to maintain the pressure.

From point B to point C, that is, from 290 min to 1010 min, the rate of pressure drop remained constant at 0.174 psi per min. There is at present no explanation as to why this section of the plot should be a straight line. At point C, that is, after 1010 min when the pressure was 830 psi, the rate of pressure drop again declined and had reached about 0.011 psi per min at 11,265 min, when the experiment was terminated.

Figure 10 is a plot of pressure on a linear scale against time on a logarithmic scale, so that it is possible to present all of the data. The discontinuities or breaks in the plot at point B, 950 psi, and at point C, 830 psi, are not evident on this plot, and we may conclude that this method of plotting this data is not very useful.

Figure 11 is a plot of the rate of change of pressure against time, both on logarithmic scales. We have seen that such a log-log plotting of the data from the Oak Ridge test was the most advantageous method for locating discontinuities. In the case of the Oak Ridge data, the plot consisted of a straight line segment followed by a curved segment convex upward; the contact between the straight line and the curve came at a time when the pressure was equal to the weight of the overburden. The plot of the New York data appears to fall on three straight lines, although the points are scattered. As the rate of change in pressure depends on the difference in pressure between successive readings, small errors in reading the pressure make relatively large apparent variations in the rate. The general shape of the plot, however, is fairly clear; it appears to consist of three straight line segments. The first, from A to B, covers the initial relatively rapid pressure drop and has a slope of about 55° . This suggests that the rate of pressure drop is some power function of the time. The second straight line segment,

Fig. 10. Pressure Decline, First West Valley Test, October 1969;
Slot at 1450 ft.

Fig. 11. Pressure Decline, First West Valley Test, October 1969; Slot at 1450 ft.

from B to C, is vertical, and represents the period during which the rate of pressure change was constant. This rate, as derived directly from the pressure readings, was 0.174 psi per min; from the plot the constant rate appears to be about 0.180 psi per min. There may be some physical reason why the rate remains constant, or it may be the fortuitous result of a combination of circumstances.

The third section of the plot, from C to D, is apparently also a straight line, although the scatter of the points makes this somewhat uncertain. The need to prepare the injection well against freezing during the winter made it impossible to continue the pressure readings for as long a time as would be desirable, even though it is doubtful if additional points would add appreciably to the shape of the plot.

The marked discontinuity at point B in the plot, coming after 290 min, when the pressure of 954 psi was about equal to the weight of the overburden, taken by itself would indicate that a horizontal fracture had been formed. If the next segment of the plot, from B to C, had been a curve convex upward, as it was in the test at Oak Ridge, this conclusion would hardly be questionable. However, in the New York test the break at the critical pressure was followed by a vertical straight line segment for which we have no explanation. This difference, and the associated uncertainty, casts doubt on any interpretation, except the obvious one that the conditions at the New York site differ from those at Oak Ridge.

The nature of the discontinuity at 830 psi (point C) is uncertain. It may result from the fact that the fracture, as suggested by the injection pressure history described above, is complex. Indeed, all of

the evidence now available suggests that a complex fracture pattern was formed. If this complexity includes a vertical fracture that connects to a second, shallower horizontal fracture, and if the closing of this upper fracture is responsible for this second discontinuity, then the indicated depth is 1280 ft. Such a suggestion is, however, highly speculative.

The second injection at 1450 ft was made on June 26, 1970, when 112,250 gal of water, mixed with 1/10 lb per gallon of grundite clay and 2.7 Ci of ^{95}Zr - ^{95}Nb , were pumped underground. The pumping rate (Fig. 12) started slowly and was gradually increased until after 150 min it was nearly 300 gpm. At this time it was necessary to shut down briefly to stop leaks in the system, but then the pumping was resumed. The well apparently broke down at 1700 psi after only 13 min of pumping at a slow rate, but there were further pressure peaks which seemed to indicate the formation of additional fractures. The maximum pressure recorded was 2900 psi. After about 300 min the pressure stabilized at 2000 psi and a rate of 285 gpm, about the same as we had seen on the first injection at this depth.

The pressure decay was followed for a period of 3.7×10^4 min; that is, for about a month. Figure 13 shows a plot of the first day's record. The curve is not entirely smooth. Figure 14 shows the log-log plot of rate of pressure change against time, which in this case is a single straight line without discontinuities. However, the basic data did not seem reliable, as there was a wide scatter to the points. A much better pressure gage was obtained for the subsequent injections.

Fig. 12. Injection Pressure and Rate, Second Injection, 1450 ft.

Fig. 13. Second Injection, 1450 ft, Linear Plot Pressure Decay vs Time.

Fig. 14. Rate of Change of Pressure with Time, Second Fracture at 1450 ft.

Logging of the observation wells showed that a horizontal fracture or rather group of fractures had been formed. The west well showed a single fracture at 1456 ft; the north well showed two fractures at 1430 and 1441 ft; and the south well, two fractures at 1457 and 1465 ft. The east well could not be logged to the depth of interest as it was plugged (Fig. 15).

The third injection was made on August 17, 1970, at a depth of 1226 ft into shale that had been classed as "good" for the formation of horizontal fractures. The pumping was started at a slow rate, but after nearly 100 min, it was speeded up to 235 gpm and maintained at this rate. The well broke down after only a minute or two at a pressure of 1500 psi, after which the pressure dropped rapidly to between 800 and 900 psi which was maintained to the end of the test (Fig. 16). After pumping stopped and the well was shut in, readings of the pressure decay were taken for about a month. The readings of the first 1400 min were plotted and showed a smooth curve--the result, presumably, of the better pressure gage (Fig. 17). All of the readings were plotted on a log-log plot of rate of decline of pressure against time (Fig. 18). This curve showed a marked discontinuity at 110 min, at which time the pressure was 806 psi, the exact pressure due to the clay and rock cover of 1226 ft. This strongly suggested a horizontal fracture. That a horizontal fracture had indeed been formed was shown by the logging of the observation wells. The west well showed a peak at 1228 ft; the north well showed a peak at 1223 ft; the east well showed a peak at 1224 ft; and the south well showed three peaks--at 1214 ft, at 1222 ft, and at 1226 ft (Fig. 19).

Fig. 15. Gamma Ray Logs, Second Fracture at 1450 ft.

Fig. 16. Pumping Rate and Pressure, 1226 ft.

Fig. 17. Linear Plot Pressure vs Time, 1226 ft.

Fig. 18. Log-log Plot Rate of Pressure Decay vs Time, 1226 ft.

Fig. 19. Gamma Ray Logs, 1226-ft Injection.

The fourth injection was made on May 10, 1971, at 1010 ft into a massive brittle siltstone which had been classed as "poor" for the formation of horizontal fractures. A total of 98,733 gal of water containing a tenth of a pound of grundite clay per gallon and 2.7 Ci of ^{95}Zr - ^{95}Nb was injected. The pumping rate was increased from 0 to 300 gpm in 10 min and held at about 350 gpm during the injection (Fig. 20). The pressure went up to 1100 psi in the first 2 min and then fell to between 800 and 850 psi which was maintained. The pressure of the rock cover would be 664 psi. There was nothing in the history of the injection pressure to suggest anything but a simple single fracture. The logging of the four observation wells, however, told a different story. The west well showed a single small peak at 1014 ft; the north well showed a single small peak at 1008 ft; the south observation well showed a single small peak at 1009 ft; and the east observation well showed a single small peak at 1001 ft and also a large peak at 1395 ft (Fig. 21). There was no question but that this peak at 1395 ft was from the injection at 1010 ft. This means that, in addition to the thin horizontal fracture at 1010 ft, the injection had fractured vertically downward from 1010 ft to 1395 ft, and then had turned horizontal and had moved out to the east. The rock at 1395 is classed as "fair" for the production of horizontal fractures. A vertical fracture had been predicted for the injection at 1010 ft, but that it should fracture downward was a complete surprise. Presumably, the liquid injected found and followed a joint, but no joints were believed present in the shale with a vertical height of 375 ft. That a small horizontal fracture was also formed was also unexpected. If the pumping had been continued at a slow rate for an hour or more, instead

Fig. 21. Gamma Ray Logs, 1010 ft.

of quickly accelerating to over 300 gpm, it is possible that only the horizontal fracture would have been formed.

The pressure decay, plotted on a log-log graph showing rate of pressure decline against time (Fig. 22), showed a marked discontinuity after an elapsed time of 5 min when the pressure was 645 psi. The pressure due to the rock and clay cover was 664 psi, so that these two pressures were not in agreement. However, the lower leg of the plot consisted of only five points so that it may not have been well defined. A more difficult problem is represented by the fracture at 1395 ft. The rock cover pressure at this depth is 941 psi; and, except for the first few minutes, the pumping pressure was between 800 and 850 psi, 100 lb too low to form a horizontal fracture at 1395 ft. Although this is what happened, there is no explanation.

Two injections were made at 500 ft into rock classed as good for the formation of horizontal fractures. The first, on May 29, 1971, consisted of 51,000 gal of water, with no radioactive tracer. The pumping rate was maintained low for the first 60 min and then increased to 450 gpm. The well broke down early at 400 psi, and the pumping pressure was in general between 350 and 400 psi. The rock cover pressure at this depth is 301 psi, so that the fracture was probably horizontal (Fig. 23). The pressure decay curve (Fig. 24) shows a marked break at 231 psi, appreciably below the rock cover pressure. There is no explanation for this.

The second injection at 500 ft was made on July 23, 1971, and consisted of 50,000 gal of grout made up of water, cement, and bentonite, to which was added 2.7 Ci of ^{95}Zr - ^{95}Nb . The well broke down at 325 psi and most of the pumping was at pressures between 325 and 350 psi (Fig. 25).

Fig. 22. Log-log Plot, Rate of Pressure Decay vs Time, 1010 ft.

Fig. 23. Pumping Rate and Pressure, Water Injection, 500 ft.

Fig. 24. Log Pressure Rate of Decay vs Log of Time.

Fig. 25. Pumping Rate and Pressure, Grout Injection, 500 ft.

The pressure varied not at all with the pumping rate, which was kept low for the first 100 min and then was increased up to 250 gpm.

Because of the cement, no pressure decay readings were made. However, logging of the observation wells showed that a horizontal fracture had been formed. There was a peak in the west well at 509 ft, in the north well at 508 ft, and in the south well at 499 ft (Fig. 26). The east well was found to be plugged with cement at 495 ft, showing that where the fracture had intersected the well the casing had been pulled apart and the cement had entered. The plugging therefore showed that the fracture had intersected this well at about 500 ft.

Conclusions

The experiment clearly showed that the well-bedded shale fractured parallel to the bedding planes. Taken in conjunction with the similar experience at Oak Ridge, it is tempting to conclude that this is the normal mode of fracturing for well-bedded rocks at least in areas where there has been no recent folding or faulting. However, in the nearly massive siltstone a vertical fracture was formed which went down 385 ft. We have no explanation for this other than the probability that the fracture was guided by jointing.

Attempts to analyze the pumping pressure to determine the orientation of the fracture were unsuccessful; for the pumping pressure in all injections was remarkably constant, despite variations in the pumping rate, and showed no tendency to decrease as the volume injected increased.

Analysis of the pressure decay after pumping had stopped was more encouraging but still not successful. The fracture at 1450 ft showed a

Fig. 26. Gamma Ray Logs, Grout Injection at 500 ft.

break in the decay curve at 954 psi which compared well with the rock cover pressure of 980 psi. Similarly, the fracture at 1226 ft showed a break in the curve at 806 psi which compares well with the rock cover pressure of 810 psi. However, the break in the decay curve of the fracture at 1010 ft came at 645 psi, somewhat below the rock cover pressure of 664 psi, and showed no evidence of the vertical fracture at all nor of the deep horizontal fracture to which it led. Finally, the fracture at 500 ft showed a break in the decay curve at 231 psi, well below the rock cover pressure of 301 psi. We must conclude, therefore, that analysis of the pressure decay curve cannot be used with confidence to determine the fracture orientation.

The determination of the fracture pattern to be expected in a new area considered for waste disposal by hydraulic fracturing can only be answered by actually fracturing the rock in place and using a radioactive tracer and observation wells to determine where the fracture has gone. However, if the rock shows a tendency to split parallel to the bedding, there seems to be a good chance that it will fracture hydraulically in the same way.

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