Open Hole Hydraulic Fracturing

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ABSTRACT

The basic principles of hydraulic fracturing in an open hole are discussed. Field and laboratory tests demonstrate that hydraulically induced fractures propagate according to the principle of least resistance.

INTRODUCTION

Hydraulic fracturing is a petroleum engineering technique routinely carried out at a depth of several thousand feet to stimulate production of oil bearing horizons. It has also been suggested as a possible technique to determine stresses at depth. (Kehle, 1964; Scheidegger, 1962; and Fairhurst, 1964). In both cases an understanding of the basic principles which govern the development of the fractures is a prerequisite to its successful application. We will assume that the hole is drilled parallel to one regional principal stress* R, say and let us denote the stresses normal to the hole axis by P, Q with P < Q. Compression is taken to be positive.

The stress systems around a packed-off borehole:

The pre-existing regional stresses produce stress concentrations close to the borehole with the maximum value of (3Q-P) and the minimum of (3P-Q) in the tangential direction as indicated in Figure 1. The axial compression varies between a maximum of R + 2v (Q-P) and a minimum of R-2v (Q-P), where v is Poisson's ratio (although this variation quickly drops to a constant value of R at a short distance from the wall of the hole. The rock is assumed to be linearly elastic and isotropic.

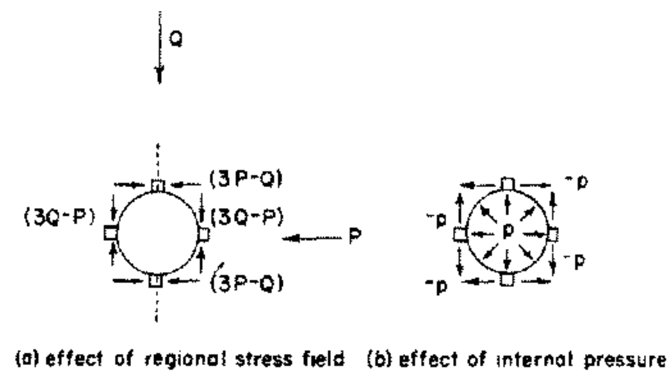

Figure 1. Induced stresses around borehole.

If a section of the borehole is sealed or packed off and pressurized to a pressure p a second stress system will be superimposed upon the one just described. In what follows fluid penetration into the rock is considered negligible. We will have to consider two regions in the sealed interval.

1. The central part of the hole section.
2. The region close to the packers. Kehle (1964) has made an electric analysis of such a packed off borehole in order to determine the stresses around it. He assumed that the packers are held in place by a band of uniform shear stress (Fig. 2). His results

* This is probably reasonable for most geological situations where the hole is drilled vertically. In highly folded or faulted regions, or areas of geological complexity the assumption may be invalid.

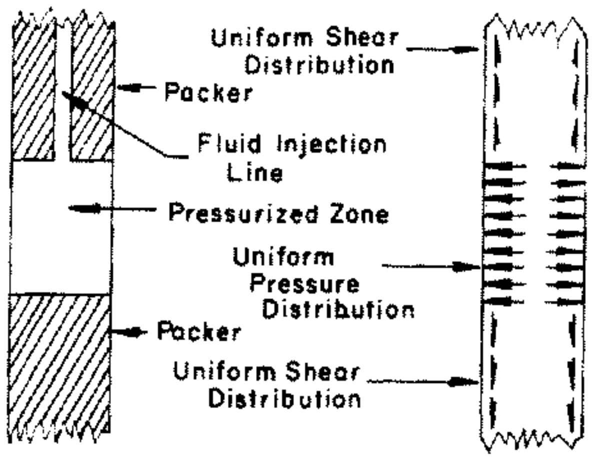

Figure 2. Schematic diagram of (a) Hydraulic fracturing set-up, (b) Associated boundary stress assumed by Kehle.

indicate that high tensile vertical stress of the order of the pressure (-p) is induced in the immediate vicinity of the packers while in the central region of the interval (about 80%) a tangential tensil stress of magnitude -p is generated. (Fig. 3) It is important to note that the axial force generated by the pressure acting against the packer contributes only a small portion to the total vertical tensile stress (σ_z) as indicated in Figure 3 by σ_z packer. The major portion of the axial tension is the result of

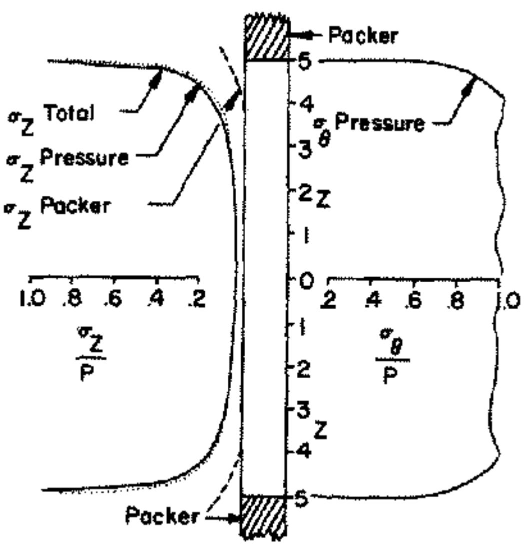

Figure 3. Axial and tangential stresses induced at the wall of the hole due to stresses in Figure 2.

an abrupt change in the borehole pressure at the packer-hole interface (c.f. Fig. 2). If however inflatable packers are used to seal the hole a normal pressure will be exerted by the packing elements resulting in a considerable reduction of the axial tension. Figure 4 illustrates qualitatively the stress distribution around a hole with pressurized packers.

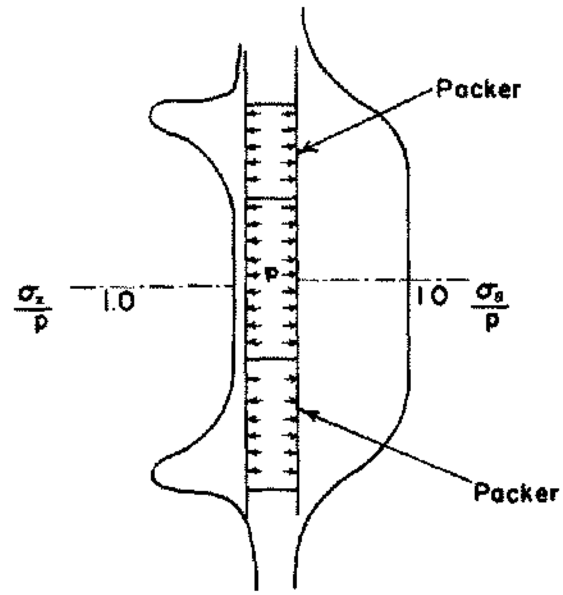

Figure 4. Axial and tangential stresses induced at the wall with pressurized packers.

Fracture initiation

A fracture will be initiated at the wall of the borehole when the tension generated by the fluid pressure is sufficient to overcome the combined effect of the regional compression and the rock strength.

According to Kehle's model we arrive by superposition of the two active stress systems in the packed-off borehole section at the following expressions for the net minimum pressure (least compression).

i. In the central region the tangential stress equals

$$\sigma_\theta = 3P - Q - p \qquad [1]$$

ii. in the region close to the packers the axial stress equals

$$\sigma_z = \frac{R - 2\nu(Q-P) - p}{0.94}$$

$$\text{or} \quad \sigma_z \simeq R - p \quad \text{approximately} \qquad [2]$$

Fracture is assumed to initiate at whichever point the appropriate strength of the rock is first reached.

Under the present assumptions therefore (Fig. 5) a fracture parallel to the borehole axis (or axial fracture) will be initiated if

i. $p = 3P - Q + K_\theta$ and $p < R + K_z$ [3]

Where

K_θ is the rock strength across a plane parallel to the hole axis

K_z is the rock strength across a plane normal to the hole axis

ii. a fracture normal to the borehole axis will be initiated if

$$p = R + K_z \text{ and } p < 3P - Q + K_\theta \qquad [4]$$

If on the other hand pressurized, deformable packers are used Kehle's model will no longer be valid in the vicinity of the packers. Relations [2] and [4] will not hold anymore while [1], [3] will hold approximately over the entire interval including the packers (cf. Figs. 4 & 2). This means that little or no axial tension is generated thus requiring a much higher pressure for the initiation of horizontal fractures. Before such high pressure is reached, however, equation [3] will be satisfied and a fracture will be initiated vertically. Laboratory results (Haimson, 1968) on relatively impermeable rocks such as granite and marble have confirmed these ideas. It must be emphasized, however, that in field applications, factors such as high permeability, joint systems or bedding planes must be expected to seriously affect the fracture initiation and in many cases may favor the development of horizontal fractures.

Fracture orientation

It has been shown in the laboratory that a fracture will propagate parallel to the highest compressive stress and perpendicular to the minimum compression (Haimson, 1968). In other words it will follow the path of least resistance.

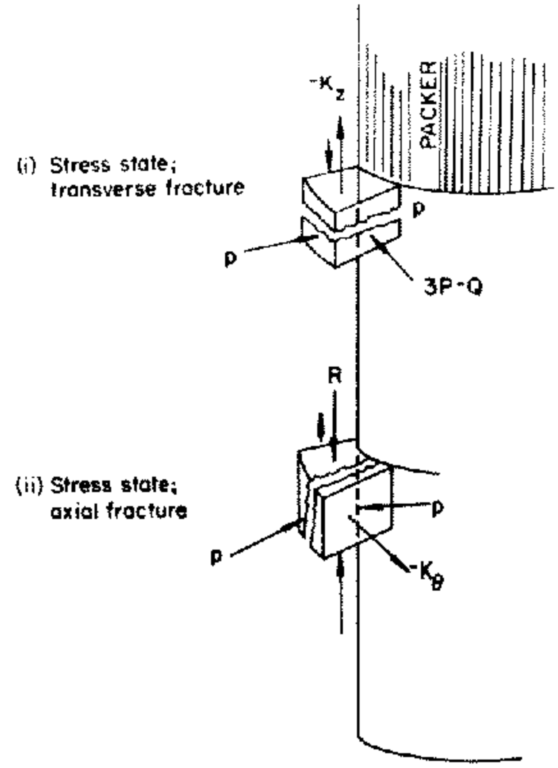

Figure 5. Net principal stresses at the initiation of (i) Transverse fracturing, (ii) Axial fracturing.

Frequently one assumes (Fig. 6a) that the vertical stress (R) is determined by the weight of overlying rock. For average rock density this corresponds to slightly more than 1 psi/ft depth. The lateral stress is also often assumed to be a function of R alone:

$$P = Q = \frac{\nu}{1 - \nu} R, \cong R/3 \qquad [5]$$

where ν is Poisson's ratio. Such a regional stress field would strongly favor the development of vertical fractures at any depth according to the established criteria above.

Equation 5 is derived on the assumption that rock be elastic before it is stressed, a condition that does not seem to realistically model rock deposition processes. In fact, observations in underground structures, quarries and hydraulic fracturing field work seem to indicate, that the horizontal stresses P, Q are not generally equal and do

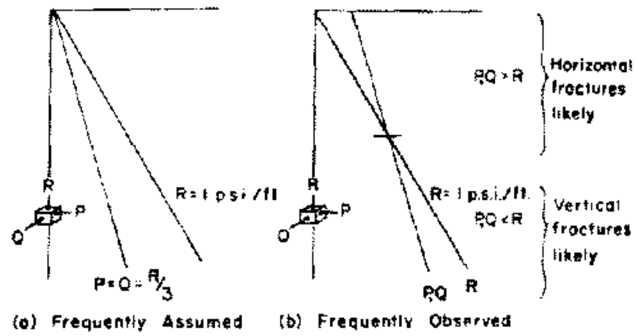

Figure 6. In-situ stress at depth.

not vanish close to the surface, which would be necessary if equation 5 were valid.

Measurements by Host (1964) and others indicate that substantial horizontal compressions may exist even at shallow depths. Thus, although it is probable that R increases from zero at a rate of about 1 psi per ft., it is probable that P, Q vary in a fashion that may not be directly related to R. As illustrated by Figure 6b horizontal fractures are then likely to be propagated in shallower regions up to a certain depth. Beyond this depth the overburden pressure surpasses the lateral stress thus making conditions more favorable for the development of vertical fractures.

Hydraulic fracturing experiments

Some typical pressure vs. time curves recorded down-the-hole during in-situ fracturing tests are shown in Figure 7. The tests were conducted in "impermeable," competent rock. The peak pressures (1) is known as the formation breakdown pressure. It indicates the point of fracture initiation. The sharp drop in pressure is caused by the sudden release of fluid into the fracture which of course will propagate at a pressure (energy level) less than that needed for fracture initiation.

The pressure immediately after the pumping operation has ceased (2) is known as the instantaneous shut-in pressure and is frequently taken as an upper limit for the pressure necessary to keep the fracture open. It therefore constitutes an estimate for the minimum principal regional stress.

The test equipment consisted of several pumps, recording devices, a 2 inch diameter straddle-packer and an impression packer. The latter was used to take borehole impressions prior to fracturing and after fracturing in order to locate any pre-existing fractures as well as to determine the extent and orientation of the hydraulically induced ones. The tool consisted of a 3 foot long inflatable rubber tube with seals at either end. A special rubber sheet was wrapped around its outside capable of retaining impressions for a period of time. Usually the packer was set at a pressure of p = 2000 psi for 20–30 minutes. The straddle packer served to seal a 1 foot section of the borehole by hydraulically inflating its two rubber elements. A pressure transducer was located at the lower end of the tool in order to record the down-the-hole pressure during the entire fracturing operation. By means of a handpump (low rate) or a motor pump (high rate) light weight oil was injected into the packed-off interval and the pressure was increased until the formation broke down. Figure 8 shows an underground test site in

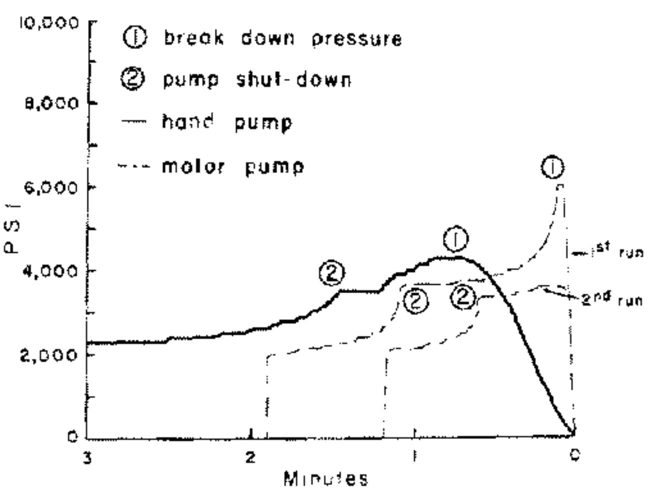

Figure 7. Typical pressure-time records of high and low rate hydraulic fracturing test.

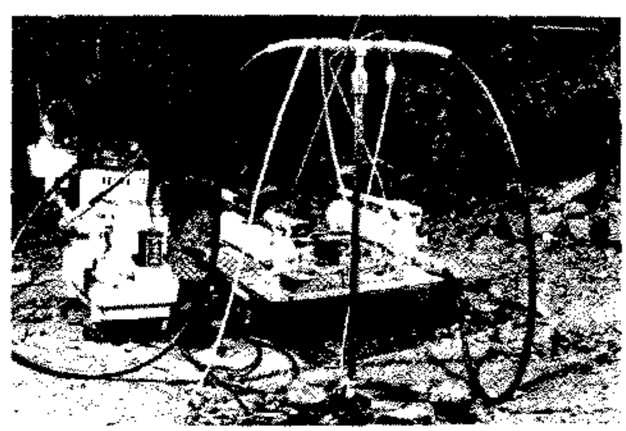

Figure 8. Underground test site with packer installed in vertical hole.

Northern Minnesota 1000 ft below the surface in a gabbro formation.

The experiments were conducted in four 50 ft long boreholes at the end of a drift close to a stope. Three holes were drilled in a horizontal plane at 60° angles to each other. The remaining hole was drilled vertically into the floor.

Several fracturing tests usually 5 to 10 feet apart were performed in each hole. In most cases a second run after having broken down the formation was made. As is illustrated by Figure 7 the maximum pressure was considerably lower than in the first run and remained approximately constant with a tendency to drop slightly over the period of injection. Even though the gabbro did not have any measurable permeability under atmospheric conditions a "rate of loading effect" appeared to be noticeable. When pressurized at a low rate with a hand pump the breakdown pressure was lower than at a higher loading rate (cf. Fig. 7). A possible explanation might be that under the relatively high injection pressures some fluid intrusion does take place. The depth of penetration which will be greater for a low loading rate than for a high rate of pressurization and thus effect the breakdown pressure accordingly. The impression tests indicated horizontal fractures in the vertical and horizontal holes suggesting the presence of a high lateral stress field. These runs were the first in a series of fracturing experiments. The untested equipment developed several shortcomings such as water intrusion into the recording system. With improved instrumentation further underground field tests were conducted in a large shale pillar (100 × 80 × 10 ft) at the 1100 ft level of the White Pine Copper Company mine.

The impression tests indicated that the fractures did not initiate in a preferred plane such as seemed to be the case in the previous study. It is possible that the stress state in the pillar was nearly hydrostatic and thus local inhomogeneities became the determining factor for the fracture direction. High laterial confining pressure in the vicinity of 2000 psi has been reported throughout the underground development. The average vertical stress concentration at a 0.5 extraction is 2 according to Obert, Duvall, et al. We therefore may estimate the vertical stress at the 1100 ft. level to be about 2200 psi.

Laboratory tests

To demonstrate the principle that the fracture propagates parallel to the highest compressive stress, normal to the lowest compression and even changes direction with a changing stress field several laboratory tests on 6" × 6" × 12" samples were conducted. The loading condition P, Q, R is sketched in Figure 9. Boreholes were drilled in the x-z plane at an angle θ = 30 to the x - axis.

The results show that under R = P = O; Q = 1000 psi the fracture trace around the sample

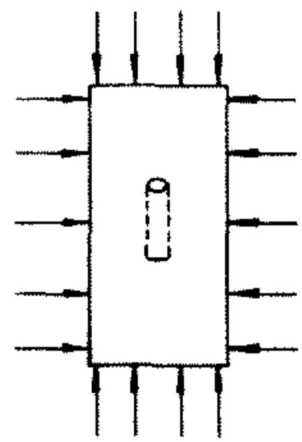

Figure 9. Boundary conditions on sample.

precisely outlines the inclination of the borehold (Fig. 10a). In the case of vertical and lateral confinement R = 1000 psi, Q = 1000 psi, P = 0 the path of least resistance is in the x - y plane (normal to the hole axis). Since packers that exert a normal pressure at the borehole wall were used to seal the hole a fracture did not initiate in that plane for reasons explained above. The fracture initiated parallel to the borehole axis and then changed direction to propagate in the x - y plane, i.e., perpendicular to P, the least compressive stress (Fig. 10b).

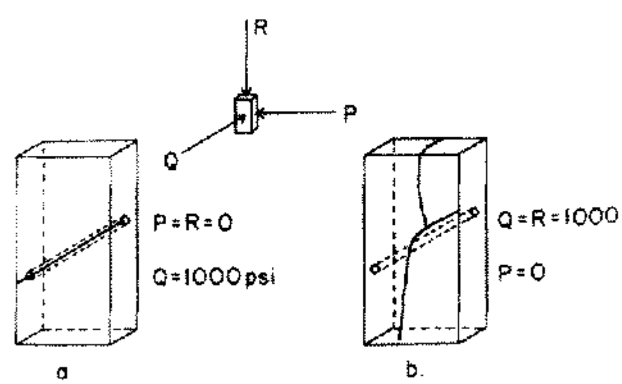

Figure 10. Fractures tracrs around sample for different boundary conditions.

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