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TITLE: HOT DRY ROCK FRACTURE PROPAGATION AND RESERVOIR CHARACTERIZATION

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HOT DRY ROCK FRACTURE PROPAGATION AND RESERVOIR CHARACTERIZATION

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I. ABSTRACT

North America's largest hydraulic fracturing operations have been conducted at Fenton Hill, New Mexico to create hot dry rock geothermal reservoirs. Microearthquakes induced by these fracturing operations were measured with geophones. The large volume of rock over which the microearthquakes were distributed indicates a mechanism of hydraulic stimulation which is at odds with conventional fracturing theory, which predicts failure along a plane which is perpendicular to the least compressive earth stress. Shear slippage along pre-existing joints in the rock is more easily induced than conventional tensile failure, particularly when the difference between minimum and maximum earth stresses is large and the pre-existing joints are oriented at angles between 30 and 60° to the principal earth stresses, and a low viscosity fluid like water is injected. Shear slippage results in local redistribution of stresses, which allows a branching, or dendritic, stimulation pattern to evolve, in agreement with the patterns of microearthquake locations. Field testing of HDR reservoirs at the Fenton Hill site shows that significant reservoir growth occurred as energy was extracted. Tracer, microseismic, and geochemical measurements provided the primary quantitative evidence for the increases in accessible reservoir volume and fractured rock surface area. These temporal increases indicate that augmentation of reservoir heat production capacity in hot dry rock system occurred. For future reservoir testing, Los Alamos is developing tracer techniques using reactive chemicals to track thermal fronts. Recent studies have focused on the kinetics of hydrolysis of derivatives of bromobenzene, which can be used in reservoirs as hot as 275°C.

II. INTRODUCTION

The primary objective of the US Hot Dry Rock (HDR) Project is to develop and demonstrate an economical, commercially usable technology for recovering thermal energy from naturally heated rock at accessible depths in the earth's crust. While other methods are possible in different geologic environments, the Program has so far concentrated on hot crystalline rock of low initial permeability; the use of fluid pressure (hydraulic fracturing) to create flow passages and heat-transfer surface in that rock; and operation of a closed, recirculating, pressurized-water loop to extract heat from the rock and transport it to the earth's surface.

III. FRACTURE PROPAGATION

Most rock masses, particularly crystalline ones, contain pre-existing fractures called joints. When fluid is injected into joints during hydraulic fracturing, several types of joint deformation can take place. At first the pressure rise in the joint is small enough that the joint does not actually open. Nevertheless, the effective closure stress, that is, the difference between the total earth stress acting normal to the joint plane and the fluid pressure, is reduced. If injection continues, the pressure can attain a value high enough that the effective closure stress no longer provides sufficient friction to resist shearing stresses acting parallel to the joint surface, and the joint will slip in a shear mode. If the slippage is sufficient, one rough surface asperity can ride over, or atop another, so that even if the pressure is suddenly reduced the joint opening and permeability are irreversibly increased. This is termed "shear stimulation." If fluid viscosity or injection rates are modest shear stimulation may result in sufficient permeability that no further increase in pressure is attainable. If, however, the formation of void space by shearing is insufficient to accommodate the fluid volume injected into the rock joints, the pressure will continue to rise, and eventually attain a value equal to the earth stress acting normal to the joint. Then the opposing surfaces of the rock that meet at the joint will part. If proppants, either purposely injected with the fluid, or rock chips broken off the joint surfaces, are trapped in a joint following shut-in, the joint opening will again be irreversibly increased, and the joint thus "stimulated."

The kinematic argument for shear stimulation is shown in the Mohr diagram, Fig. 1. A two-dimensional stress state is depicted, in which the principal maximum and minimum compressive stresses are labeled σ_{min} and σ_{max} and the stresses on any other plane can be represented by the Mohr circle connecting the two principal stresses (Jaeger and Cook, 1979). In Fig. 1 a fairly typical stress state is assumed, in which σ_{max} is about twice σ_{min}. The effective closure stresses on a joint are reduced by the pressure, P, within the joint. Consequently, joint separation occurs when the effective closure stress is zero, or $P = \sigma_{min}$. As shown in Fig. 1, separation thus requires that the Mohr circle be moved so completely to the left that by pressurization its left side is coincident with the origin. On the other hand, shearing requires only that the Mohr circle move left sufficiently to encounter the Coulomb-Mohr failure envelope. A mere touching is sufficient if a joint has the optimum orientation, but even if not optimally oriented most joints will shear long before they separate.

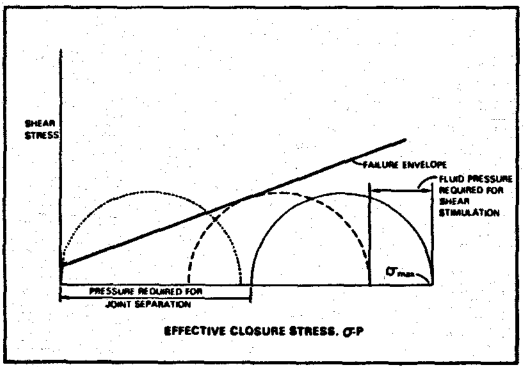

Figure 1. Mohr stress diagram illustrating that lower fluid pressure is required for shear stimulation compared to joint separation.

Shear stimulation is rarely discussed in hydraulic fracturing theory. Lockner and Byerlee (1977), who demonstrated in experiments that slow pressurization could result in shear fracturing of intact, not just jointed, rock specimens, were moved to state that: "in the literature on hydraulic fracture the possibility of producing shear rather than tension fractures is surprisingly disregarded." Subsequently, several other papers (Hast, 1979, and Solberg, Lockner and Byerlee, 1980) have appeared which support the possibility of shear stimulation.

While it thus appears that joints will shear at fluid pressures less than that required for separation, the joint opening, or dilation behavior for slippage and separation is quite different. As pressure increases the dilation is small at first, simply resulting from the decrease of effective closure stress, but then shear slippage ensues. As the joint surfaces continue to slip, they attain a state in which one large roughness asperity lies atop another, and further slippage would allow the largest asperity to slide over and down the other. Thus one expects a natural limit to the shear dilation. This maximum shear dilation is typically of the order of a fraction of a millimeter (Barton et al., 1985). If the joint pressure can be increased so that separation occurs, then the results of conventional hydraulic fracture theory (but taking the tensile strength of the jointed rock to be zero) indicate that the dilation is typically tens of millimeters (Perkins and Kern, 1961; and Daneshy, 1973), many times that of shear dilation. Thus as Lockner and Byerlee correctly foresaw, the key to understanding stimulation is not just rock mechanics, but also fluid dynamics. If a low viscosity fluid is injected into a joint at a low enough flow rate, the fluid volume can be accommodated within the small dilation created by shear slippage. Even though the joint opening and permeability are not increased as much as if by separation, the permeability increase could be sufficient to sustain low flow rates for low viscosity fluids without large pressure gradients, and the pressure need not build up to separation requirements.

In an actual hydraulic fracturing operation the entire spectrum of joint deformation can occur: near the injection well the flow passage area is limited, hence fluid velocities and pressure gradients are large and separation occurs (Bame and Fehler, 1986). But near the tips of joints, far from the injection well, velocities and pressures are much reduced, and shear stimulation occurs. In the most common application of hydraulic fracturing, in petroleum reservoirs, very viscous fluids are normally used and injection rates are high. Consequently, joint separation is dominant, and if few joints are present, as is often the case in petroleum formations, actual fracturing of intact rock occurs. However, in the geothermal reservoir fracturing described below, joints occur frequently, and high downhole temperatures render most viscosifying agents useless, so water is used as the fracturing fluid. Hence, shear stimulation dominates.

1. <u>Reservoir Stimulation Experiments</u>. Hydraulic stimulation experiments were conducted in two Hot Dry Rock (HDR) geothermal energy reservoirs. The first of these is located at Fenton Hill, on the west flank of the Valles Caldera, a dormant volcanic complex in the Jemez Mountains of New Mexico, USA. The second site is at Rosemanowes Quarry, in Cornwall, England. At both sites the reservoirs are jointed, granitic rock.

Early successes with the small Phase I reservoir at Fenton Hill led to the decision to create a deeper, hotter, and larger Phase II reservoir at the Fenton Hill site. Figure 2 shows a perspective view of the two new wells drilled for the deeper reservoir. The upper well, EE-3, which was the intended production well, lies 300 m above the lower injection well, EE-2, in the slanted interval. Temperatures varied from 200°C at 3 km to 325°C at 4.4 km. Also shown in Fig. 2 is a well drilled for the older reservoir which contains a geophone sonde. This geophone and others placed in other nearby boreholes detect and locate the microearthquakes triggered during hydraulic stimulation (House, 1987).

In December 1983 a massive hydraulic fracturing operation was conducted in which 21,000 m^3 (5,600,000 gal) of water were injected at 3.5 km in the lower well at a downhole pressure of 83 MPa and an average flow rate of 0.1 m^3/s (40 bbls/min). Details are provided by Dreesen and Nicholson (1985). Figure 3 shows the locations of the largest induced microearthquakes. The downhole geophones are extraordinarily sensitive, which enabled detection of events with extrapolated Richter body wave magnitudes as low as −5, but Fig. 3 shows only the 850 high-quality events with magnitudes from −3 to 0. The microearthquake locations indicate a zone of stimulation distributed throughout a rock volume that is about 0.8 km high, 0.8 km wide in the N-S direction, and about 0.25 km thick in the E-W direction. The precision of microearthquake locations is 20 m, so the width of the seismic volume, 250 m, is not an artifact of measurement uncertainty. The volume of the stimulated zone is 4000 times greater than the volume of water injected. House, 1987) concluded that the first motions of the microearthquakes and fault plane solutions determined from a surface array of seismometers indicated a

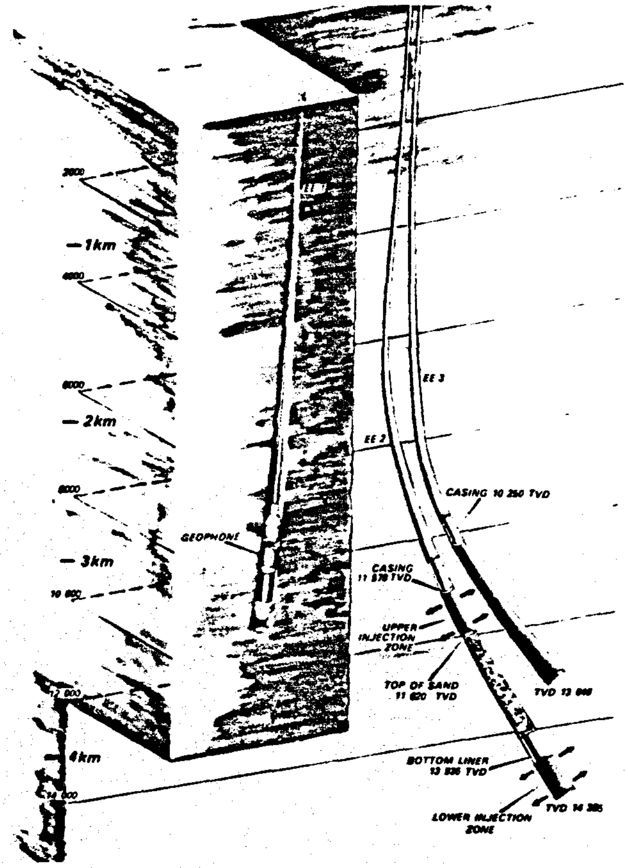

Figure 2. Perspective view of wells and geophone tool placed for microearthquake monitoring during hydraulic stimulation.

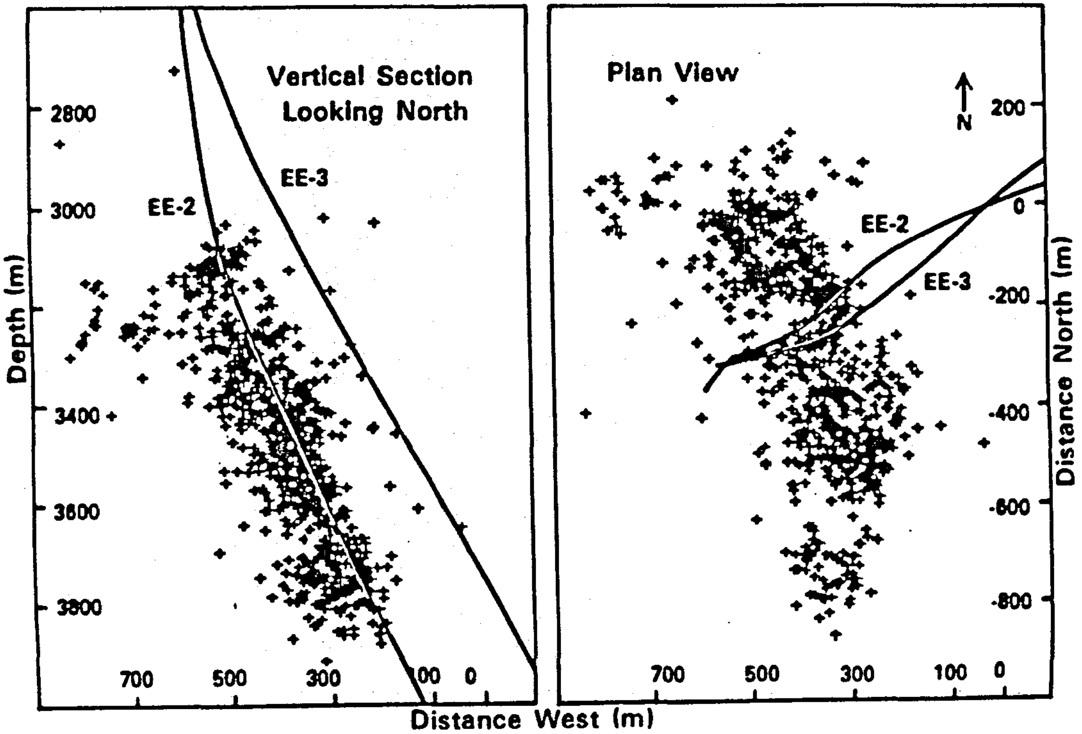

Figure 4. Single joint stimulation induced by shear slippage when frictional resistance to shear slippage is low or the ability to open the joint in shear is high.

shear-slip motion, probably along pre-existing rock joints. This suggests that tensile fracturing, if it occurred at all, generated only very weak seismic signals that could not be detected by the surface seismic array.

These results indicate a fracturing mechanism which is inconsistent with conventional theories of hydraulic fracturing which predict the propagation of a single fracture caused by tensile failure of the rock. However, our results are consistent with Lockner and Byerlee's observation of shear failure in rock specimens at low injection rate. Furthermore, our observations were confirmed at the British Hot Dry Rock reservoir in Cornwall where it was observed (Pine and Batchelor, 1984) that fracturing occurred as a zone of multiple fractures, and that shear slippage along existing joints was the dominant cause of seismicity.

More recenty, we have developed a method, called the three point method, which allows us to identify the most intensively stimulated joints. We applied the method to microearthquakes occurring during many injection experiments, and successfully identified numerous planes along which we believe that fluid flows (Fehler, et al., 1987; Fehler, 1988). The locations of these planes have been correlated with well log anomalies, which provide independent confirmation of the existence of fractures and the correlation is quite good (Dreesen, et al., 1987). Knowledge of the location of these shear slip planes has been used by Dreesen et al. (1987) to develop a three dimensional deterministic model of the larger flow paths through the reservoir.

2. <u>Modeling Shear Stimulation in Jointed Rock</u>. The unexpected stimulation results presented above suggested further study, using a model incorporating detailed fluid dynamics and rock mechanics within jointed rock masses. The Fluid Rock Interaction Program, based upon the calculation method developed by Cundall and Marti (1978), was adapted for this use. Pre-existing rock joints are deployed on a regular rectangular grid and the code permits interactive coupling of fluid dynamics with rock stresses and deformations. For example, an excess of pressure on a block during one

computational cycle will result in compression of the block, and opening (dilation) of the joints next to it, resulting in additional permeability and a changed pressure distribution.

When a computation in which joints were aligned parallel to the principal earth stresses was studied, a process equivalent to classical hydraulic fracturing (but without the necessity of accounting for rock strength) was predicted: a single joint opened at a pressure equal to the minimum earth stress, and the aperture and shape of the opened joint agreed well with conventional hydraulic fracturing theory (Daneshy, 1973). However, when the orientation of the pre-existing joints were rotated 30° from the principal stress directions, and a low viscosity fluid like water was used for fracturing, two types of stimulation patterns occurred. In the first type, typified in Fig. 4, which occurs when frictional resistance to shear slippage is low or when the maximum dilatancy due to shear is large, only a single joint is stimulated. The resolved stresses shown in Fig. 4 result from a principal earth stress of 2σ applied at an angle of 30° to the joints. For simplicity the subscript min has been deleted so σ is the minimum principal earth stress and it acts perpendicular to the maximum stress, 2σ.

In the second type of shear stimulation, corresponding to high shear resistance or small dilatancy, multiple joint stimulation occurs as shown in Fig. 5. Shear slippage along the joints is accompanied by shear-stress drops, and the interaction of these stress drops with the acting earth stresses result in opening of joints more perpendicular to the maximum stress, so that a dendritic, or branched joint pattern occurs. This pattern of stimulated joints and the computed shear-stress drops offer an explanation as to why the previous microearthquake maps are not planar, but are elliptical in shape, and why the observed first motions of microearthquakes indicate a shear mechanism.

The multiple joint stimulation pattern depicted in Fig. 5 has important implications for other energy reservoirs. As suggested in Fig. 6, volume drainage, whether it be of hydrocarbons or geothermal fluids, is more efficient than areal drainage.

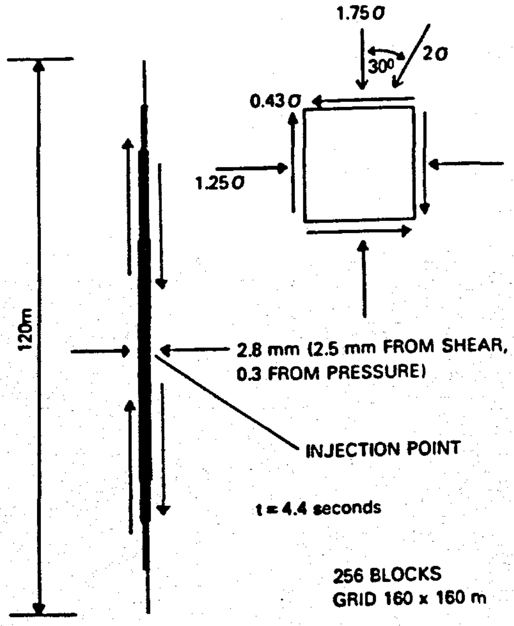

Figure 4. Single joint stimulation induced by shear slippage when frictional resistance to shear slippage is low or the ability to open the joint in shear is high.

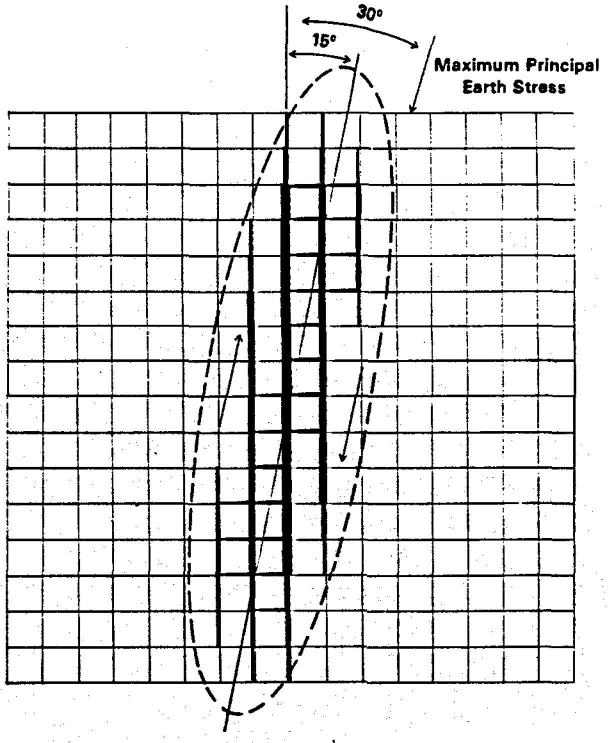

Figure 5. Multiple joint shear stimulation which occurs when shear resistance is high or shear dilatancy is low.

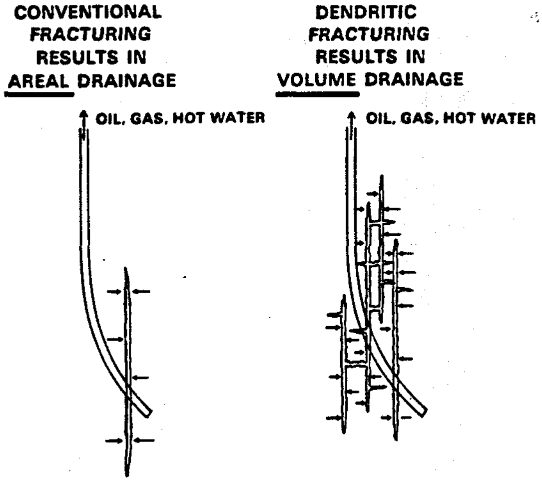

Figure 6. Volume drainage of fluids is more effective than areal drainage.

IV. RESERVOIR CHARACTERIZATION

Briefly discussed here are diagnostic techniques used during early testing of the Phase I reservoir at Fenton Hill. The Phase I reservoir was a small one, created and operated to establish the scientific feasibility of HDR. Following this discussion we present a new technique, chemically reactive tracers, for early diagnosis of the thermal capacity and lifetime of the larger, Phase II reservoir.

1. Thermal-Hydraulic Techniques and Models. During all testing, surface and downhole temperature and flow measurements were made. A spinner/temperature logging tool was used for all downhole measurements. During extended production periods, the spinner/temperature tool was positioned in the production well inside the casing above all production zones. Periodically, logging was accomplished during production using a pressurized cable packoff system mounted in the wellhead.

One model used to estimate the effective heat transfer area assumes 1-D or 2-D steady flow in a planar fracture coupled to 1-D conduction in the rock perpendicular to the flow field. Thus, the rate of production temperature decline or thermal drawdown will be controlled by the areal rather than volumetric features of the rock exposed to the circulating fluid. Although simplistic, this areal sweep model conveniently describes the thermal behavior of a fractured reservoir by matching the observed thermal drawdown with a single adjustable parameter, the fracture area. This fitted area should be regarded as an effective heat transfer area, most useful for modeling purposes.

Large-scale heterogeneities, such as the superposition of flows in multiple joints, undoubtedly exert great influence on heat transfer behavior, since the spatial positioning of these low impedance conduits effectively defines the accessible volume of rock. In the two early HDR reservoirs studied to date, the onset and subsequent rate of thermal drawdown seems to be controlled by that portion of the reservoir surface area of the flow paths directly connecting the wells.

Other heat transfer models have been proposed for fractured HDR systems to account for these complexities. One such model, developed by Robinson and Jones (1987), treats the reservoir as a composite of several zones of highly-fractured rock which behave as a porous continuum. The tracer response, or concentration-time behavior in the produced fluid caused by injecting a slug of tracer in the injection fluid, is used to set the flow rates and fluid volumes of each zone. The principal adjustable parameter is the total rock volume bathed by the circulating fluid.

In summary, computer models have been developed which span the spectrum of fractured reservoir geometries: from single, discrete fractures to situations with such intense fracturing that the rock can be considered a porous continuum. As discussed earlier in FRACTURE PROPAGATION, a single fracture is an unlikely result if jointed rock is stimulated. On the other hand, while many joints are simultaneously stimulated throughout a vast rock region, the 3 point seismic method shows that some joints are preferentially opened, either because they were more permeable to begin with, or their orientations are aligned with the existing earth stresses such that they open more readily. When heat is extracted from the reservoir these preferentially opened joints transmit most of the water flow, so a highly heterogeneous model, using several discrete fractures, usually matches the data best.

2. Tracer Techniques. Throughout the testing periods, pulses of tracers were injected into the reservoir and

monitored in the produced fluid. Both sodium fluorescein dye and neutron-activated ammonium bromide ($NH_4Br[Br^{82}]$) tracers were used to map the flow and mixing patterns in the reservoirs. As described by Tester (et al., 1982), tracer tests provide a direct measure of accessible volume and dispersion levels within the active reservoir. The tracer concentration history in the production well describes a breakthrough curve giving the distribution of fluid residence times within the reservoir. Changes in reservoir mean or modal volume can be obtained easily from a pulse tracer test. The modal volume is simply the volume of fluid produced between the time the tracer pulse was injected into the reservoir and the time the peak tracer concentration appears in the production well. Since the flow channels directly connecting the two wells are apt to have the shortest residence times, the modal volume is most closely related to the fluid volume of the high-permeability paths. The physical significance of the mean tracer volume is that it represents the total volume of all flow paths conducting fluid, regardless of flow velocity.

3. Chemically Reactive Tracers. Figure 7 illustrates the progress of a thermal front in an HDR reservoir. Heat is transmitted from the rock to the fluid by conduction, and the rock gradually cools near the injection well. As time progresses, this cooled region moves closer to the production well. When it finally reaches the production well, the produced fluid temperature starts declining, and then estimates of reservoir size can be deduced from heat transfer considerations. For large reservoirs several years of operation are required to achieve discernible produced fluid temperature decline. Clearly, some other method of sizing an HDR reservoir is required. Chemically reactive tracers are one possible technique.

The kinetics of most chemical reactions are extremely temperature dependent. For first order reactions carried out in a batch reactor, the following rate equation is applicable:

$$\frac{dC}{dt} = -kC$$

where C is reactant concentration and t is time. The rate constant k can normally be described by the following expression:

$$k = A_r \exp(-E_a/RT)$$

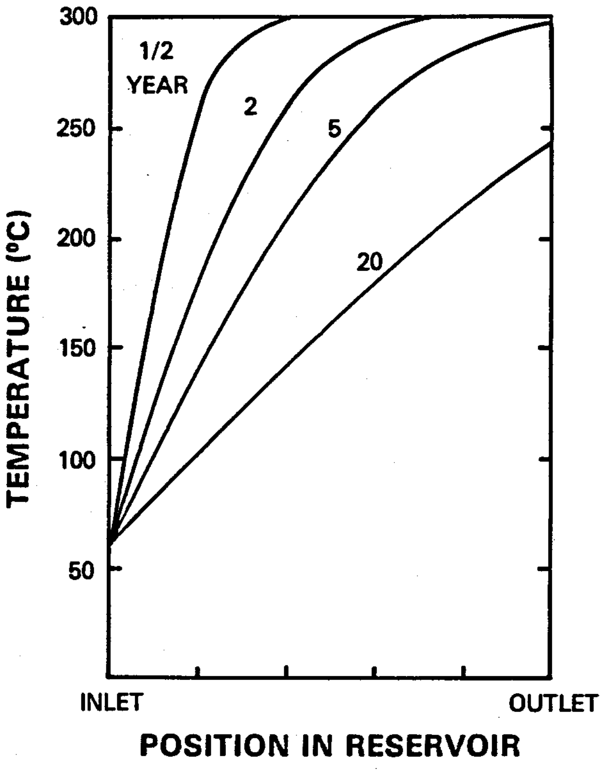

Figure 7. Progress of a Thermal Front Through a Fractured HDR Reservoir Undergoing Energy Extraction.

where A_r is the pre-exponential factor, E_a is the activation energy, R is the universal gas constant, and T is absolute temperature. For typical reactions in solution, k will vary over many orders or magnitude over the range of temperatures encountered in an HDR reservoir undergoing energy extraction.

Figure 8 shows the results of a series of simulations of reactive tracer experiments at different times during a long-term reservoir operation for the temperature patterns in Fig. 7. In each tracer experiment, a step change in tracer concentration is imparted at t = 0, and the extent of reaction is governed by the residence time and temperature field encountered. As the thermal front moves closer to the production well, the tracer experiences less time in hot rock, and the extent of reaction decreases. Thus more unreacted tracer reaches the outlet in each successive tracer experiment. By simulating this behavior using a combined heat transfer and fluid flow model, we should be able to estimate reservoir lifetime early in the production history, well before the thermal front actually reaches the production well.

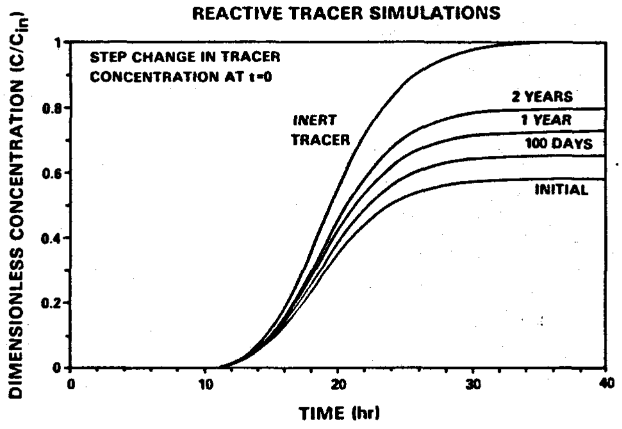

Figure 8. Reactive Tracer Step Response Simulations for the Temperature

Work so far has shown that ester and amide hydrolysis reactions are suitable for low temperature (75 to 150°C) reservoirs. For higher temperatures (up to 275°C), hydrolysis of bromobenzene derivatives is more appropriate. Additional details are provided by Robinson and Birdsell (1987).

Future reactive tracer studies will focus more closely on the bromobenzene compounds, since these have kinetics more appropriate for the Fenton Hill Phase II conditions. The two areas we will address most carefully are adsorption and analytical sensitivity. The reactive tracers we are proposing are designed to react homogeneously in the liquid phase rather than with the rock minerals. Adsorption should ideally be negligible, and preliminary laboratory results indicate that the extent of adsorption is small for these tracers. To perform a field test, extremely sensitive analytical techniques must be used to measure tracer accurately at very low concentrations. Otherwise, the enormous dilution ratios encountered in most field tracer experiments will require large quantities of tracer to be injected. We are developing high-pressure liquid chromatography techniques to detect tracer reactants and products at low levels. Initial investigations suggest that with the proper enhancement techniques, the parts per billion range can be achieved. Finally, the reactive tracer concept needs to be proven in the field to be considered a reliable diagnostic technique. During the upcoming long term flow test of the Fenton Hill Phase II reservoir, we will attempt to demonstrate the utility of reactive tracers to map thermal fronts in HDR reservoirs.

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