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# THE CONTROLLING INFLUENCE OF NATURAL JOINT CONTINUITY ON THE CREATION OF HDR SYSTEMS-EXPERIENCE AND MODELLING

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## ABSTRACT

A brief outline of the development of conceptual designs in Hot Dry Rock geothermal reservoirs, based on heat extraction requirements, leads to todays favoured volumetric models, which depend on the stimulation of natural jointing. Evidence from field experiments is used to demonstrate that no new flow paths have been created by stimulation, and that the nature, particularly continuity, of the natural jointing has a controlling influence on reservoir development.

The paper goes on to show how fracture network models can play a significant role in understanding the development process, and presents a small study undertaken to illustrate the joint continuity problem. The study shows how only a very small number of the larger joints may be required to form a connection between two wells, and how under these circumstances a low area flow path may be created.

It is concluded that connections are likely with only a small percentage of the fractures considered, and that there is a significant likelihood of creating a 'short circuit' connection in the types of network tested. The probability of such a connection increases with the size of the fractures. It is accepted that the size of natural joints is one of the hardest parameters to measure.

## PERFORMANCE REQUIREMENTS FOR HOT DRY ROCK RESERVOIRS

Exploitation of geothermal energy by Hot Dry Rock (HDR) technology is essentially a heat mining process (eg Ledingham, 1986). The objective is to move heat from the rock to the surface by the medium of circulating water and, therefore, the design of HDR reservoirs is dictated by heat extraction requirements. These define minimum rates and temperatures which are commercially acceptable.

Maximum rates and temperatures are defined by the physical limitations imposed primarily by depth, pumping power requirements, and potential temperature drawdown.

Armstead and Tester (1987) concluded that these requirements dictate the following four attributes that any potential reservoir design must have:

1 A very large contact area between the working fluid and the hot rock.

2 Adequate conductive communication between the working fluid and a sufficient volume of hot rock to ensure a long lifetime.

3 Sufficient void volume in the reservoir to ensure that the working fluid exits at as high a temperature as possible, even when circulated at rates well in excess of the economic minimum.

4 A configuration of voids and flow paths that offer minimum impedance to the passage of the working fluid, so minimising pumping power, while also containing it within the reservoir to avoid loss to non-productive regions.

The essential paradox of the creation of HDR reservoirs is immediately evident; the need to create a large heat transfer area and yet allow water to flow easily through it. The most efficient hydraulic system would consist of a single, wide fracture between injection and production points, but this would be inadequate in heat extraction terms. In contrast, a large diffusive system, with narrow, tortuous flow paths and many dead ends may have a very large heat transfer area, but be inadequate in terms of efficiency of fluid transport.

In the design of HDR reservoirs, heat extraction requirements were used to derive heat transfer areas, hence rock volumes, and hence inter well spacing, which is one of the fundamental reservoir design parameters.

This design evolution required assumptions about the available heat transfer area available in a given rock volume, and the effectivenes with which the available area is swept by the circulating fluid.

For example, the targets set out for the design of the Camborne School of Mines (CSM) Phase II reservoir were based on heat transfer calculations, which dictated that an effective heat transfer area of two million square metres was required. This was translated into an active rock volume of 200 million cubic metres, assuming that one square metre of heat transfer area would be available from every 100 cubic metres of rock.

The one in a hundred factor incorporated both the area-volume ratio and the swept-available area ratio. The rock volume could be translated into an approximate reservoir geometry to specify the well spacing. For example, 450 m by 150 m, with a well spacing of 300 m. An assumed flow path width of 1 mm gives rise to a circulating volume of 2000 cubic metres.

## THE EVOLUTION OF HDR CONCEPTS

In recognition of the paradoxical nature of the requirements for a successful HDR system, researchers have strived to develop the best possible compromise reservoir.

Los Alamos National Laboratory (LANL) developed the first conceptual model, comprising a single artificial penny shaped fracture with an injection point at the bottom and a production point at the top. The realisation that to satisfy the heat extraction requirements this fracture would need to be impossibly big led to the development of the multiple artificial fracture models.

At CSM, learning from the LANL experience, emphasis was placed on the role of natural jointing in the reservoir creation process. Researchers at CSM assumed that the stimulation of natural jointing would dominate over the creation of artificial fractures, and a volumetric reservoir would be created.

The evolution of these concepts is shown schematically in Figure 1 a), b) and c), respectively.

Volumetric models are probably the favoured variety today, although they exist in various forms with various assumed configurations. The reservoirs at LANL and CSM both appear to be generally volumetric, although there seem to be a small number of major, probably vertical, structures which tend to dominate the flowing characteristics (Figure 1c).

It is interesting to note that earlier concepts have not been completely abandoned (eg Kappelmeyer and Rummel, 1987; Tosaya et al, 1988).

## STIMULATION

Similar approaches to stimulating large volumes of naturally jointed hard rock masses have been adopted at LANL and CSM. The role of stimulation is to enhance the passage of flow through the potential reservoir region, either by improving existing flow paths or by

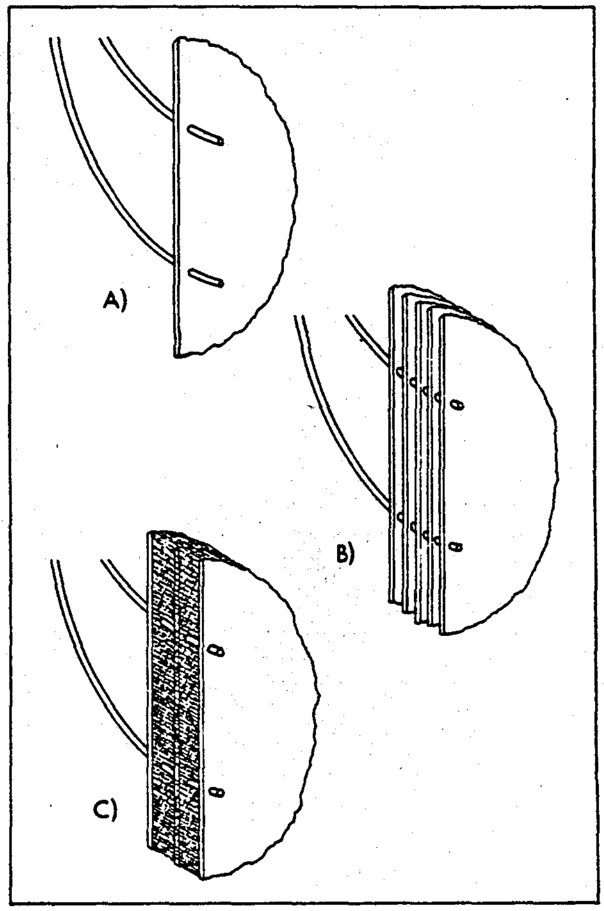


FIGURE 1 a) SINGLE PENNY SHAPED FRACTURE
b) MULTIPLE PENNY SHAPED FRACTURES
c) VOLUMETRIC SYSTEM WITH DOMINATING VERTICAL FEATURES

creating new ones.

Three kinds of improvement of a flow path seem to be potentially possible; increasing the aperture, lengthening, and widening of the flow channel in the joint. Widening here refers to increasing the breadth of the flow channel, or increasing the effective swept area.

There is no doubt that apertures can, and have been improved significantly at the wellbores in all the major field trials of stimulation techniques. This increase can be supported for some distance into the rock mass, but spreading flow and dissipating pressure reduces the stimulating potential of the fluid, and the aperture enhancement reduces.

The length of 'wide aperture' flow paths can therefore be increased to some extent, but at some distance away from the injection point, the stimulation will effectively stop and continued flow will only be possible if the joint has sufficient 'undisturbed' flow capacity. Physical extension of joints by fracturing away from the wellbore is highly unlikley.

The various tracer studies carried out at LANL and CSM (Armstead and Tester, 1987) have shown that the modal volumes of circulating systems are significantly less than the potentially available volume in the joints between the wells. It follows that the effective heat transfer area, or swept area, is less than the joint area available, and it is reasonable to conclude that flow exists in channels in joints.

It is unclear from field experiments whether stimulation increases the breadth of these flow channels, or what proportion of the potential heat transfer area is in fact swept by the fluid. This has significant bearing on the relationship between required area and active rock volume described earlier. However, no increase in channel width will be useful if the flow capacity of the joint is inadequate.

In conceptual terms, therefore, it appears that stimulation can succeed in improving the passage of fluid through the rock mass, possibly for some distance away from the wellbore, but that there is some point beyond which flow can only progress further if there is a pre existing flow path. If this point is nearer to the injection well than the stimulated region around the production well, the wells will not be hydraulically connected unless they were so in the undisturbed state.

There is significant evidence from the Camborne work to support this hypothesis. When the first two deep wells were drilled, geophysical logging showed hundreds of natural joints intersecting each well, but even the earliest hydraulic testing, at low flow rates, showed that only a very few accepted or produced significant quantities of fluid (CSM, 1983).

By the end of the development and circulation stages of the system, some 20 million gallons of water had been circulated, and several vigorous injections had been carried out into both wells, often at pressures in excess of the minimum earth stress. Despite this activity, and although the distributions altered, the flowing joints in the developed system were the same ones that flowed at the outset.

Whilst there was an obvious improvement in the circulation performance of the system (CSM, 1984) the stimulation process did not create any new flow paths identifiable at the wells.

Even more striking was the behaviour of the third deep well, drilled into part of the 'reservoir' developed below the first two wells. Geophysical, and production logging during a gas lift production test identified the joints and flowing zones in the well. All the flowing zones correlated with joints but, as before, only a small number of the joints flowed.

The well was stimulated by a 1.2 million gallon injection of medium viscosity gel at very high pressures and rates (Pine, 1987). Geophysical logging showed that extensive axial fracturing of the wellbore had taken place, but production logging during and after the stimulation demonstrated that the artificial fracture did not accept fluid at any time (CSM, 1988). The only zones in the well which accepted fluid, and which have subsequently produced fluid during circulation experiments, were the joints which flowed just after the well was drilled.

It is therefore clear that the distribution, nature, and particularly the continuity of undisturbed natural joints in the potential resevoir region have a controlling influence on the development of that system.

Conventional fracture models used in HDR development are based on regular, mostly grid-like, joint patterns which have artificially high joint continuities, and which consequently overestimate the degree of stimulation and communication between wells. To properly understand the HDR environment and its potential for exploitation, fracture network models which more accurately reflect the natural situation are required.

## FRACTURE NETWORK MODELS

It is the focus on natural joints and the 3D geometry of the reservoir that make fracture network models attractive. Because they treat fractures explicitly, they are well suited to answering questions about the geometry of flow paths, and flow to area relationships. The incorporation of stochastic network generation means that they can provide answers to questions about the engineering risk of short circuits or high water loss.

Fracture network modelling originated from work on the long term safety of underground repositories for nuclear waste. Much of the original work is related to the joint Swedish - American project at Stripa (eg Rouleau, 1985; Witherspoon, 1979)

A major feature of the models is their reliance on probabilistic methods for generating the fracture network. It is impossible to delineate every fracture in a given reservoir region, and it is therefore necessary to extrapolate inter-well fracture occurrence using statistical methods. This means that models must be run many times to understand the possible variation in results due to the random element. Similarly, any results from the model must incorporate the observed variation. In practice, results are given in terms of mean behaviour and confidence limits.

Three dimensional network models are now in use for modelling groundwater flow around hypothetical underground repositories. It is important to understand the assumptions behind these models, and the problems with using them at great depth.

Network models are based on the following simplifying assumptions, they are drawn from Robinson (1986):

- The rock mass is impermeable.
- Joint properties can be described by stochastic distributions.
- There is no head loss across intersections.

Individual models make further assumptions such as planar flow within the fracture or channelled flow between intersections. Some models even allow some matrix permeability, but most models follow the above assumptions.

It is possible that some of the above assumptions while valid for shallow disposal sites, are not appropriate for models of deep reservoirs at high rock stresses.

There is one further important assumption, that flow can be modelled by using a finite number of fractures. This number must inevitably be smaller than the total number of discontinuities (faults, joints, microcracks...) in the rock. At some point it is necessary to set limits on what minimum size of fracture will be included in the model. A simple cut-off can be derived from the system used to measure the presence of fractures, such a cut-off is valid as long as it can be shown that no appreciable flow occurs away from those fractures that have been detected. Lanyon (1988) used fracture statistics from borehole televiewer logs on the basis that all major flows could be associated with fractures shown on these logs.

## FRACTURE NETWORK INPUT DATA

A major problem in fracture network modelling is the acquisition of input data. If the model is to be used as a predictive engineering tool, rigorous conditions must be met by the input data. This may be prohibitively expensive or impossible for some fracture parameters.

Orientation data has, in general, been relatively simple to collect and analyse for sample bias. Aperture data can be collected from packer tests, but assumptions must be made about the underlying distribution of fracture aperture. These assumptions may cause problems because of the dominating effect of a few large aperture fractures on flow. Figure 2 shows aperture data from a test borehole at Carwynnen in Cornwall (Heath and Durrance, 1984). Note the dominating effect of the permeability of the three largest fractures.

Size and shape data are very difficult to extract from exposure data and impossible to extract from borehole data. Fracture density can be found from fracture spacing data if

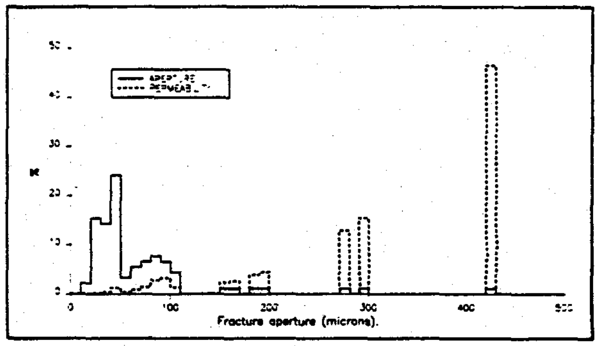


FIGURE 2 FRACTURE APERTURE AND PERMEABILITY DATA FROM HEATH AND DURRANCE (1984)

assumptions are made about the fracture extent.

It is also important to determine any correlations between parameters. Long et al (1987) outlined methods for creating hypothetical fracture networks from borehole data which will have comparable hydraulic properties to those of the measured system. In general, the networks produced will be statistical analogues of the real system.

## A SIMPLE GEOMETRIC MODEL

The rest of this paper outlines how a network model can be used to study the particular problem of prediciting joint cointinuity between two wells in an HDR doublet, and how the inter-well connectivity is affected by fracture size.

The model is based on a percolation theory approach. Fractures from two sets are generated according to a random process to form a complete fracture network around and between the wells (Figure 3). The fractures

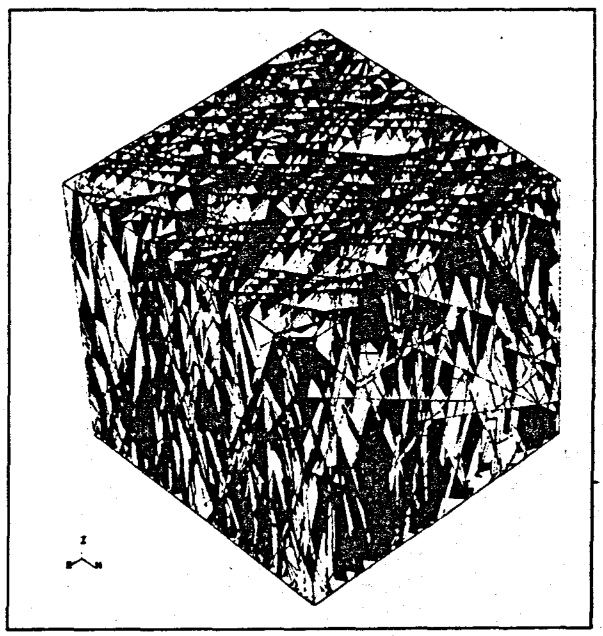

FIGURE 3 SIMULATION OF 50 M CUBE SHOWING ALL FRACTURES

are then considered in order of descending aperture until a link between the two wells is created.

Since the biggest, and therefore the most transmissive, fractures are considered first, the first connection generated will be the one with the highest minimum aperture (ie all other connections include lower aperture fractures). Where the distribution of fracture aperture is highly skewed such a connection will dominate the hydraulic performance of the reservoir.

A 'typical' HDR doublet configuration was used; two wells deviated at 30 degrees from the vertical, separated by 300 m vertically, with open hole lengths of 300 m. A stimulated zone of 20 m radius was assumed around both wells.

Fractures were modelled as constant radius discs whose centres were uniformly distributed by a Poisson process. Numerical experiments, comprising a minimum of 50 realisations were run with fracture radii of 20, 30, 50, and 75 m. The fractures existed in two orthogonal sets offset at 20 degrees to the well direction.

The fracture density was related to the radius used, and was set in each case so that there was a constant mean value of one square metre single sided fracture area per cubic metre of rock. This area to volume ratio was based on the fracture data acquired at CSM and reflects the high frequency of jointing that was measured, typically a joint in the boreholes every two to three metres.

In each realisation, three parameters were derived for the first connection:

1 The percentage of total fracture area needed to form the connection.

2 The number of fractures in the connection.

3 An estimate of flowing surface area of the connection.

The flowing surface area was calculated as the bounding convex polygon formed from all fracture and well intersections on a fracture (see Figure 4).

The model is purely geometric and does not include a flow solving system. Although dead ends are removed from the fracture network, any loops in the connection may be counted as contributing to the surface area. This means that this area estimate is probably optimistic.

**MODELLING RESULTS AND DISCUSSION**

Figure 5 shows a plot of the flowing surface area of the interwell connection against the percentage of total fracture area needed for connection to occur. It is clear that, in all

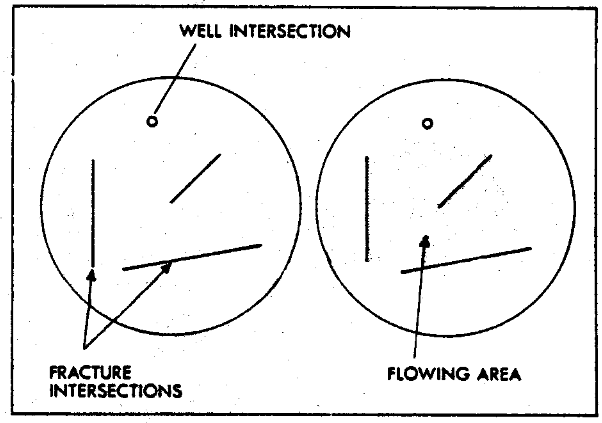


FIGURE 4 ILLUSTRATION OF 'FLOWING AREA' DEFINITION IN THE GEOMETRIC MODEL

cases run, only a small percentage of the total fractures in the model were required to form a connection, and that in the case of the largest joints, only one or two percent were necessary.

This is consistent with the observation at both large scale field experiments that only a very small percentage of natural joints flow.

Where only a few joints were required, the resulting surface area of the connection was rather small, representing the undesirable 'short circuit' connection. In order to achieve a heat transfer area of one million square metres (500 000 single sided area), at least three percent of fractures must be involved, this percentage increasing as fracture size decreases.

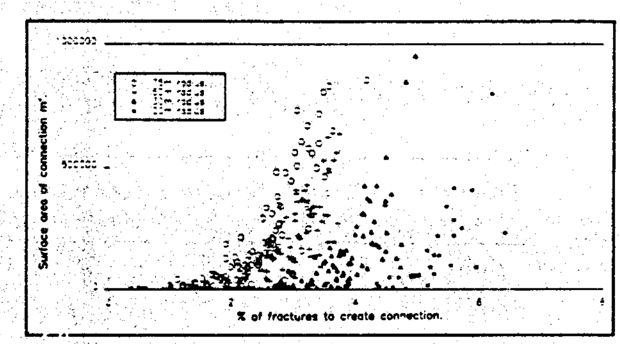


FIGURE 5 COMPARISON OF FRACTURE PERCENTAGE WITH CONNECTION AREA, FOR DIFFERENT FRACTURE RADII

Note that this only represents the first connection. Other connections will increase the area available, but are likely to be subordinate in terms of hydraulic performance to the first one, particularly where the fracture aperture distribution is skewed.

Figure 6 demonstrates that there is a significant risk of developing a 'short circuit' connection. It shows the distribution of generated flowing surface area for each fracture radius considered. In each case the distribution is skewed towards low area. No trends dependent on fracture radius

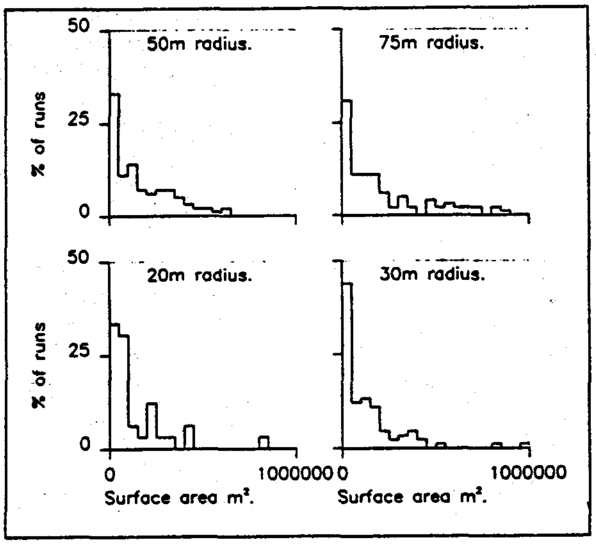


FIGURE 6 COMPARISON OF INTERCONNECTION 'FLOW AREA' FOR VARYING FRACTURE RADII

are apparent, but only a relatively few (50 to 100) realisations were carried out.

Figure 7 shows the distribution of the percentage of fractures required to form a connection at each fracture radius. In general, the unsurprising trend emerges that fewer large radius joints are required than small radius ones.

The same trend is apparent in Table 1, which shows the percentage of runs where very low surface area connections existed, formed solely of fractures in the top one and two percent. This circumstance becomes increasingly more likely with increasing fracture radius.

TABLE 1 FREQUENCY OF LOW SURFACE AREA CONNECTIONS

| Fracture radius | % Connected by top 1% | % Connected by top 2% |
|---|---|---|
| 20 m | 0 | 0 |
| 30 m | 0 | 1% |
| 50 m | 4% | 20% |
| 75 m | 5% | 30% |

**CONCLUSIONS**

1 Experimental results from two major field trials of HDR technology have demonstrated the controlling influence of the character and continuity of natural joints on the creation of successful circulating systems.

2 The importance of realistic fracture network models has been established, and a small study relating to the joint continuity problem has been carried out.

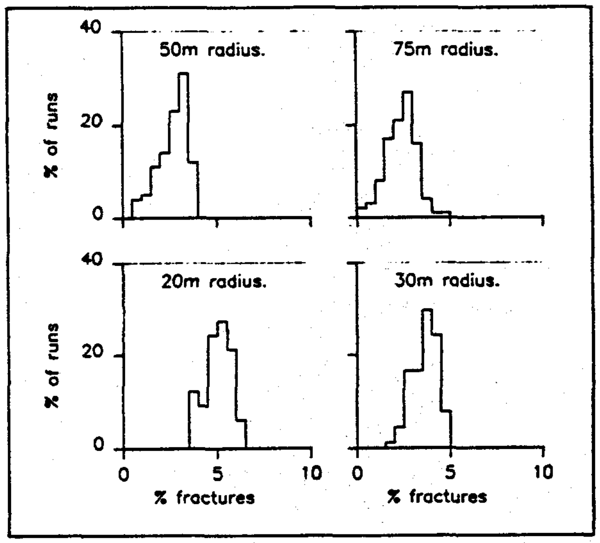


FIGURE 7 COMPARISON OF PERCENTAGE OF FRACTURES NEEDED FOR INTERCONNECTION

3 The study demonstrated how the presence of a few large joints forming a connection between the wells could dominate the behaviour of the system, and that there was a significant probability, in the fracture networks tested, that a low area connection could be formed.

The probability depended largely on the assumed radius of the fractures in the model.

4 The study produced numerical experimental results consistent with field experiments, and suggested that original estimates of joint properties used in conceptual designs were reasonable.

5 Fracture network models offer a valuable tool for the design and understanding of the processes involved in creating HDR systems. Probably the greatest problem facing the modelling effort is the acquisition of reliable input data.

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