PROCEEDINGS, Eleventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 21-23, 1986
SGP-TR-93

RESERVOIR BEHAVIOUR IN A STIMULATED HOT DRY ROCK SYSTEM

Anthony S Batchelor

Camborne School of Mines, Cornwall TR10 9DU, England

ABSTRACT

Research into the stimulation of hot dry rock (HDR) systems in crystalline rock has been underway in Cornwall, England for several years. Two deviated wells were drilled to a depth of 2100 m in 1981 with an interwell separation of 300 m. These wells were connected by massive hydraulic injections using water, but the interconnection was insufficient to permit long term circuation without excessive water losses. In 1985 a third well was drilled to a depth of 2600 m in a direction chosen from the analysis of the reservoir behaviour during the previous circulation. A massive stimulation (200 l/s, 75 bbl/min) of gel was used to connect the wells and circulation was re-established in August 1985.

Reservoir models have been developed from hydraulic analyses, thermal behaviour, microseismic mapping, tracer dispersion and chemical modelling.

The system behaves like an interconnected network of flow paths with a few dominant routes acting as flow conduits. The storage is associated with pressure dependent joint compliance, but it is isolated from the dominant flow paths.

No unique physical model has yet been derived but the various techniques have been used to establish constraints on the geometry and nature of the heat transfer regions. The experiments are still in progress.

INTRODUCTION

Research into the feasibility of extracting geothermal energy by the Hot Dry Rock (HDR) process is underway in several countries, Batchelor 1984. The work in England has been described at two previous Stanford Workshops (Batchelor 1982, Pine 1983) and these papers describe the general location and progress of the research programme up to 1983. The details are not repeated here.

The objective of the work in the UK is to determine whether or not it is feasible to interlink pairs of boreholes by massive hydraulic stimulation in a crystalline rock mass with a low intrinsic permeability in order to form a subterranean heat exchanger. The artificially enhanced flow paths must be associated with sufficient heat transfer area and a low resistance to flow to enable the heat to be extracted as a financially viable process.

The current experiments in the UK have not been directed towards producing a prototype working system; the work has concentrated on developing and understanding of the fundamental rock mechanics processes associated with the stimulation.

BRIEF RESUME OF EXPERIMENTAL PROGRESS

Two deviated wells were drilled in 1981 to a depth of 2100 m; the wells were aligned in the same plane with a vertical separation of 300 m. Fundamental measurements of the in-situ conditions were made at the end of drilling. These included:

i The in situ stress field and its variation with depth.

ii The orientation of the pre-existing jointing.

iii The petrology of the rock fabric.

iv The static and dynamic properties of the rock fabric.

v The in situ dynamic rock properties.

vi The undisturbed hydraulic properties of the rock in-situ.

vii The equilibrium temperature profiles for the wells.

These measurements enabled a conceptual model of the undisturbed conditions to be developed.

An extensive microseismic monitoring net was established (Batchelor et al 1983) and a series of stimulation and circulation experiments took place over a period of 18 months from November 1982.

Figure 1 shows an isometric view of the two wells and the microseismically active region. It can be seen that the active zone grew

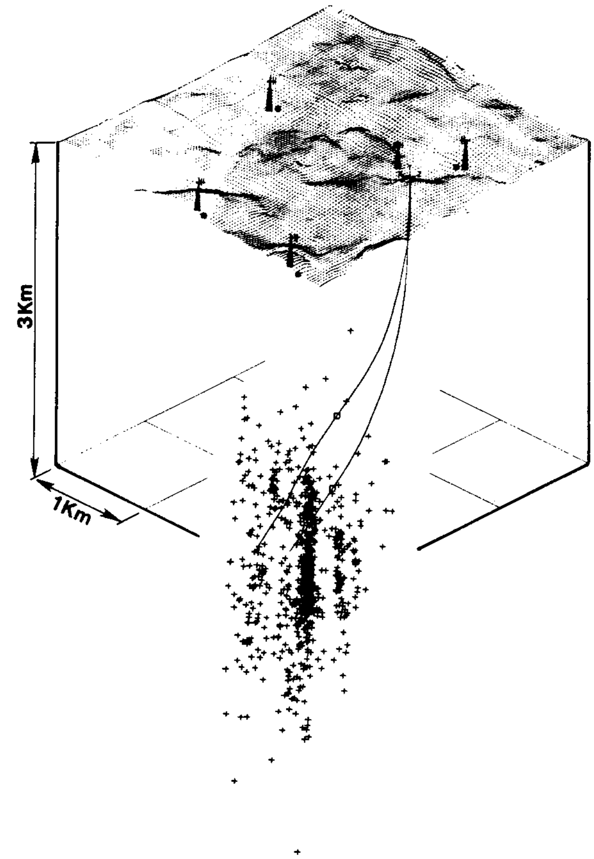

Figure 1 - The first two wells with the associated microseismicty

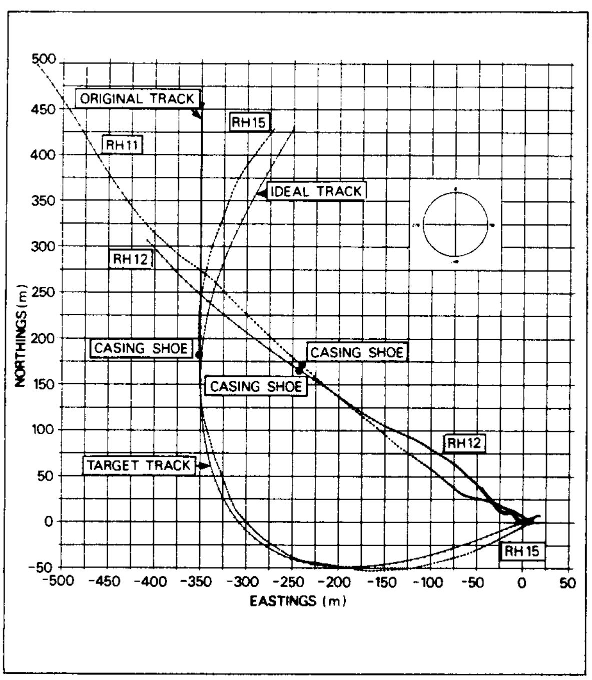

Figure 2 - A plan view of the track of the third well, RH15

downwards and subsequent analysis showed that this was due to the severely anisotropic stress field at the site (Pine and Batchelor 1984). During the circulation trials a total of 300 000 m^3 of water was injected into the system and only 100 000 m^3 recovered. The 'missing' 200 000 m^3 was consumed by the continuous growth of the microseismically active structure which caused large areas of rock to be exposed to moderate pressure and allowed diffusive losses to take place on a substantial scale despite the low initial permeability.

The geometry of the microseismic sensor network was not designed to locate microseismic events at substantial depths below the wells. When the results indicated significant downward growth, suggestions were made that the structure was an artefact of the sensor geometry (Anon 1984). Although definite field evidence was available showing that the bulk of the events were occurring below the wells (Baria 1985) there was no proof that the more permeable region had developed downwards.

It was decided to drill a third well that penetrated the microseismically active region approximately 300 m below the base of the earlier wells to explore this area.

This well had two objectives:

i To intersect any permeable zone of enhanced residual permeability.

ii To make a direct measurement of the relationship between microseismic events and stimulated flow paths.

THE THIRD WELL

Constraints on the surface location of the third well meant that the trajectory had to be drilled as part of a long spiral. A plan view is shown in Figure 2 in relation to the two previous wells. The drilling and completion of this well is reported in CSM 1985. The well was finished in December 1984 and a nitrogen lift production test was run immediately.
Simultaneous production logging took place during this test by running the tool through the drillpipe used for the gas injection. This enabled the flow zones to be identified and correlated with the microseismic cloud. Figure 3 shows the relationship of the flow zones to the microseismic activity and it can be seen that the only section of the well that produced fluid was the zone within the envelope of the microseismicity.

TESTING THE NEW WELL

After completion of the well, a series of low flow rate injection and production experiments took place to determine the nature of the interwell connection. The bases for each of these tests were similar; one well was used for production or injection and the other well for observation. These tests were modelled by

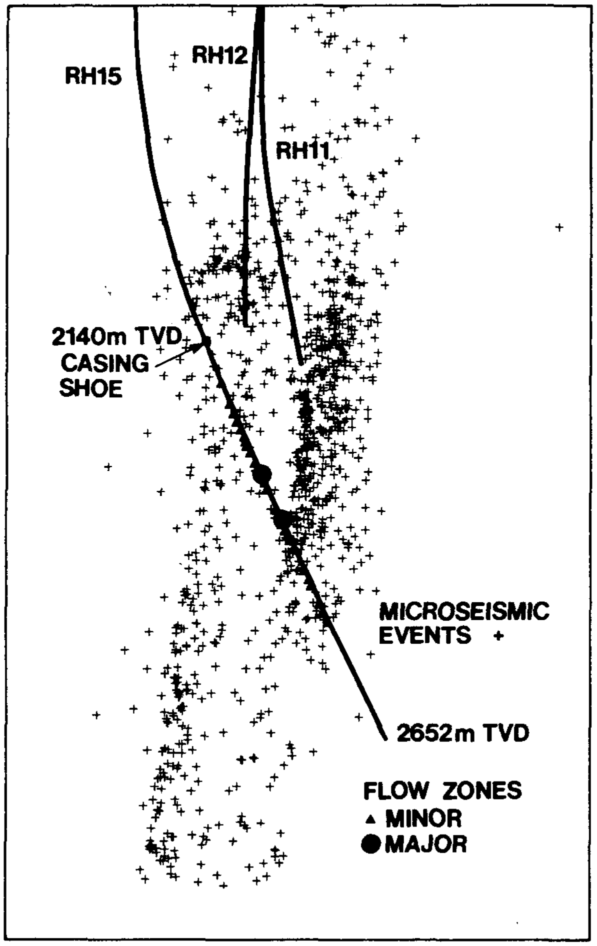

Figure 3 - The flow zones in RH15 with the original microseismicity

superposing two line source models in a uniformly permeable region. No boundaries were detected, Figure 4 shows the excellent match achieved with such a model for both the injection and observation wells. The derived parameters were:

$$\frac{kh}{\mu} = 4.875 \times 10^{-10} \text{m}^3/\text{Pa.s}$$

$$\frac{k}{\mu c \phi} = 0.975 \text{ m}^2/\text{s}$$

A porous media model fitted the data closely and it was possible to derive an impedance value based on superposition,

$$I = \frac{\mu}{4\pi kh}\left[l_n\left(\frac{r^2}{r_w^2 e^{-2S_2}}\right) + \frac{q_1}{q_2} \cdot l_n\left(\frac{r^2}{r_w^2 e^{-2S_1}}\right)\right]$$

(nomenclature at end)

This gives the impedance I in terms of the kh/μ and skin values at the wells; excellent agreement with the measured values was obtained.

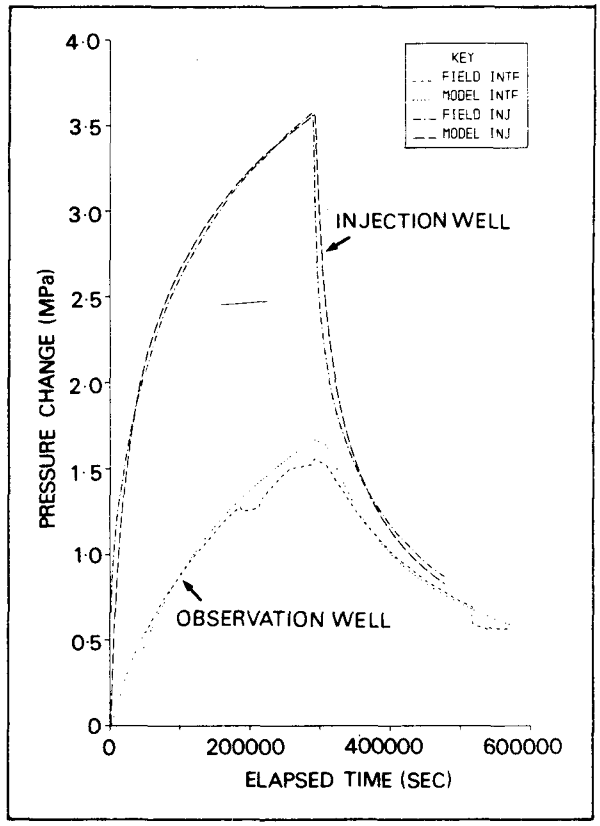

Figure 4 - Field and model results from an injection interference test

At the end of these tests it was concluded that the residual permeability between the wells had been enhanced by the previous massive injection of water but the residual apertures were insufficient to allow circulation to take place without further stimulation.

The design and execution of the stimulation is outside the scope of this paper and will be reported in detail elsewhere. It consisted of an injection of 5500 m^3 (1.2 million galls) of gel injected at flow rates of over 200 l/s (75 bbl/min) and reaching a maximum at 264 l/s (98 bbl/min). This was the largest gel stimulation undertaken in Europe and was run on 4 July 1985. On-line monitoring of the seismicity was able to track the location of the induced events caused by the stimulation during the eight hours of injection. Figure 5 shows a view of the seismicity in relation to the three wells. It can be seen that the active region is contained within the interwell zone. No further seismicity has taken place since that stimulation.

THE CIRCULATION TESTS (To 14 December 1985)

Figure 6 shows the injection flow and corresponding wellhead pressure since 7 August 1985. There have been three flow rates sustained for approximately 50 days each. During the second flow rate period a series of step pulses lasting one day can be seen in the centre of the figure. The corresponding plot of injection

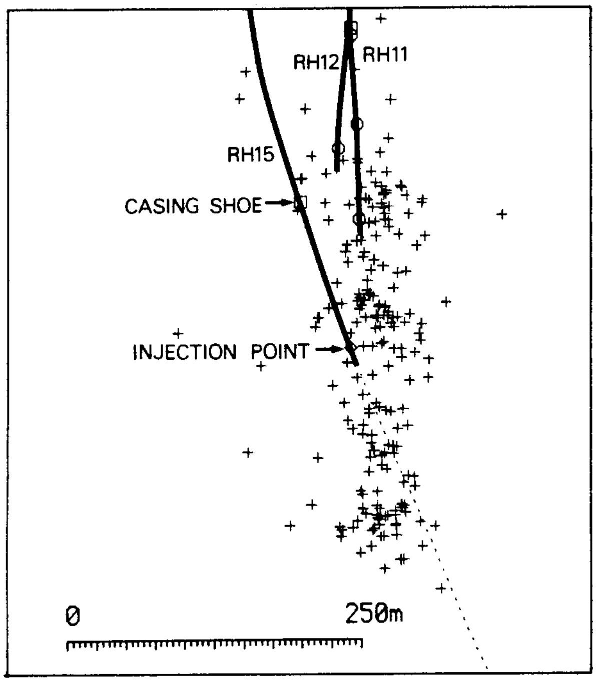

Figure 5 - The induced microseismicity during the massive stimulation with gel

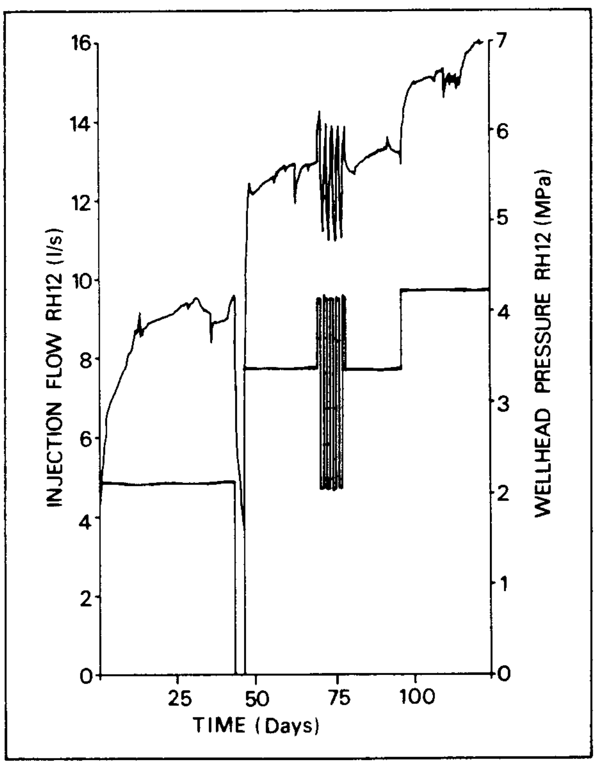

Figure 6 - The injection flow and pressure since August 1985

wellhead pressure versus production flow shows that the impedance in the system has been largely constant throughout that time, Figure 7. In addition, the water loss rate has been found to be reasonably steady, 1.3 l/s.

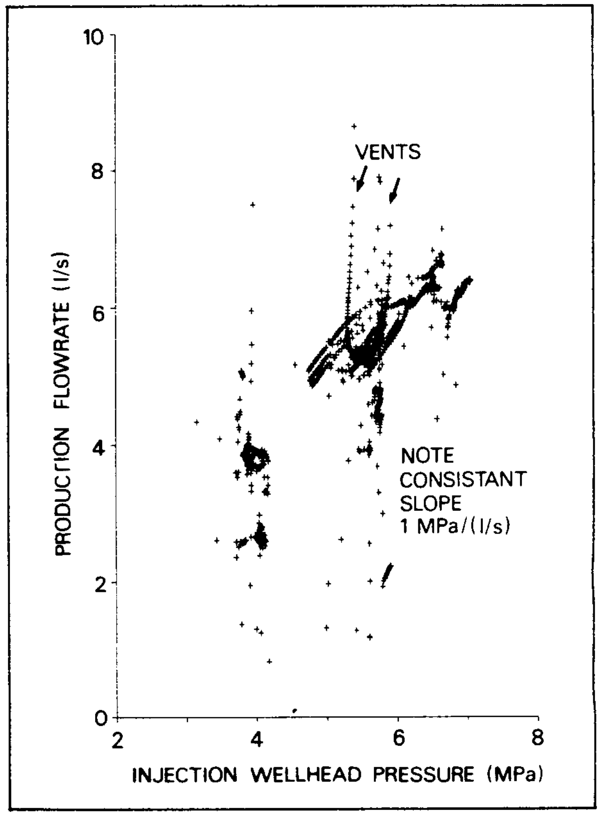

Figure 7 - Injection pressure v production flow since August 1985

HYDRAULIC MODELLING

The successful hydraulic modelling of the early data could not be continued after the fracturing operation. Individual sections of data could be matched to porous media models, but no composite solution could be found. Various finite differences and FRIP, see Pine et al 1985, models were run and none was able to get a match without invoking channeled flow and various constrained boundary conditions.

A finite difference model with the source and sink in a high permeability zone surrounded by a gradational change to low permeability was able to get a reasonable match to some of the behaviour, but there were discrepancies during step changes of either pressure or flow.

It was decided to attempt a simple resistance analogue model to identify the essential components of any physical model. The one that seemed to fit the data most accurately is shown in Figure 8, Lawton 1985. The essential feature of this model is that the flow path is associated with a very small storage term and the majority of the storage is isolated by resistances. In addition, there is a resistance between the heat exchange area and the production well, approximately 20-30% of the total resistance to flow. There is no significant storage after the outlet resistance. This means that when the production well

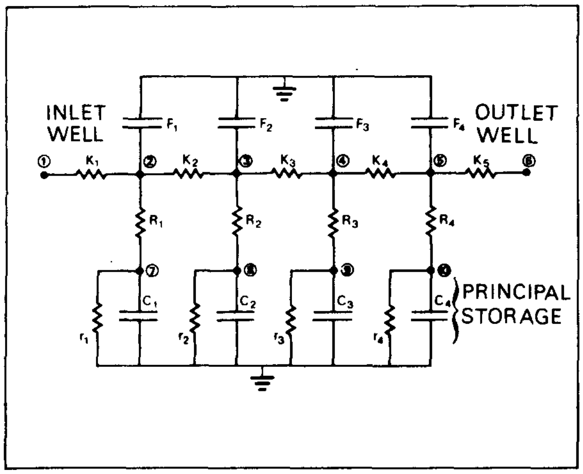

Figure 8 - Electrical analogue circuit to match system performance

is shut-in there is a rapid rise in pressure in the first few seconds. This model was able to match the entire flow history of the circulation since stimulation with reasonable accuracy. The work is now underway to translate the elements into the physical reality of the reservoir.

The overall impedance is approximately 1 MPa/l/s; less than one third of the value before the stimulation. This value has not changed throughout the circulation and is still too high for an economically viable operation.

TRACER TESTS

A tracer test has been run after each flow rate change. During the nominal 10 l/s injection, one non-reactive tracer test was run in late November followed by a combination of a non-reactive and reactive tracer experiment run from 9 December. The theory and some of the results from the reactive tracer test are given in another paper in this volume, Tester et al 1985. Figure 9 shows the superposed curves from the non-reactive tracer studies. It can be seen that there is no effect of the changing flow rate or pressure on the concentration v produced volume relationship, therefore, it may be concluded that the geometry of the flowing regime is similar under all three flow conditions.

The underlying principle of the reactive tracer test is that the tracer is a compound that reacts at a certain temperature and pH condition in the reservoir to form conservative reaction products. The concentration of original tracer and the corresponding concentration of product are measured in the production flow in order to determine the downhole conditions relating to that reaction. The experiment used Ethyl Acetate reacting with water to form Acetic Acid and Ethanol in the reservoir. Figure 10 shows the normalised non-reactive tracer plus the Ethanol and Ethyl Acetate production curves over the corresponding production.

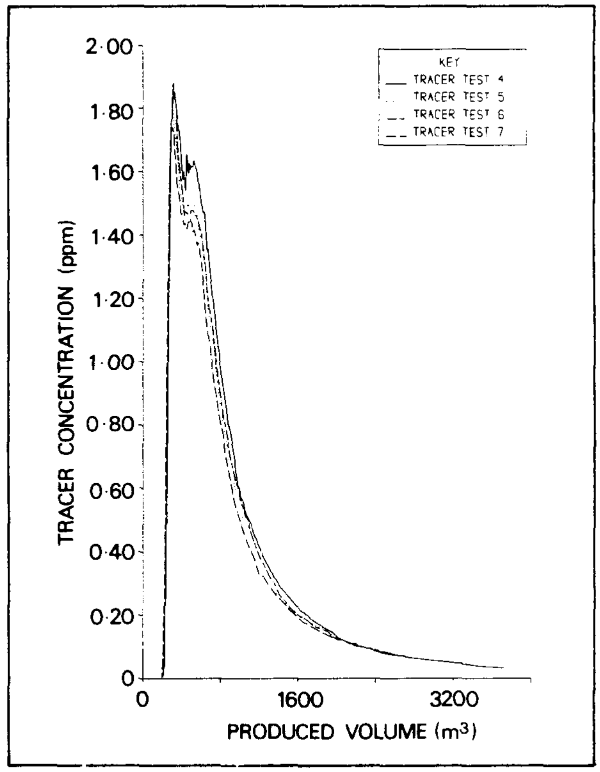

Figure 9 - Tracer distributions during the four tracer tests at various flow rates

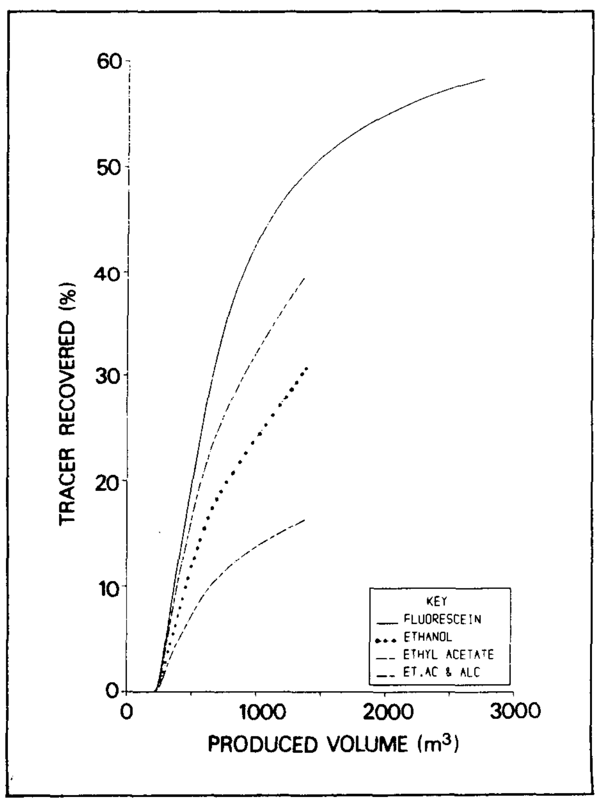

Figure 10 - Normalised tracer recovery during reactive tracer test

The preliminary conclusions from this test are that the longer residence flow paths are less reactive than the short flow paths. This is contrary to an intuitive solution based on porous media analysis. It means that the longer flow paths are either cooler, or have a lower pH, than the principal production flow path. One model that would fit this observation is that there is a system of dominant flow paths that penetrate rock at a higher temperature than the average production. Injection flows circulate below the production well and then cool as they rise to the wellbore. These are coupled with some flow paths that stay up at the top of the structure in a region cooled continuously by the injections and find their way into the production well without warming significantly.

The hydraulic modelling indicates that it is necessary to decouple the 'storage' from the flow system in order to match the data; these tracer results may imply that the bulk of the stored fluid is cooler than the equilibrium temperatures in the storage region.

It will be important to repeat the reactive tracer experiment during the continuing circulation to try and understand whether or not the average reservoir temperature is declining. There is no indication from temperature logging that thermal breakthrough has been detected in the wells.

CONCLUSIONS

Five techniques have been used to derive a working model of the reservoir:

- Thermal behaviour
- Active geochemistry
- Tracer dispersion
- Microseismic event mapping
- Hydraulic monitoring

Formation evaluation has shown that the granite is fractured pervasively by two orthogonal sets of joints containing a range of subvertical members. The joint geometry has created a pattern of interlocking prismoidal blocks of granite. The existing stress field is offset to one of the joint directions by approximately 25° and the anisotropy of the stresses has generated subcritical shear stress conditions on certain of the joints. Very small increases in fluid pressure within the joints has been sufficient to cause shear motion on an individual structure. When water was used as the injection fluid, the seismically active region grew uncontrollably downwards because of the severity of the anisotropy. A massive injection of gel was used to control the viscosity of the stimulating fluid and inhibit far field seismicity. This has been successful.

Despite the extensive stimulation, no new flowing connections have been observed in the production well. The flow has been significantly enhanced on the pre-existing natural joints. The principal flow zones occur on joints that are oriented within 20° of the maximum stress direction. However, not many joints in this direction produce fluid. It has been concluded that the principal limitation to the productivity of an individual structure is related to the connectivity of the joints between the wells.

The action of stimulation is to dilate the natural apertures by raising the pressure and causing both shear and normal motions on the joints.

The heat transfer region is associated with a characteristic flowthrough volume of approximately 200 m^3 of water. The implied apertures of the flow path are of the order of 0.1 mm. The inference from these results is that the heat transfer region is between 1 and 4 million m^2. The mean residence time of the system is approximately 40 hours. The system has been in continuous circulation for over 3100 hours and no thermal drawdown has been observed.

Hydraulic analysis shows that there is a direct channeled flow path associated with a minimum amount of storage capacity within the flow zone itself. However, there is significant fluid stored in the overall structure. This appears to be stored at less than equilibrium temperature of the surrounding rock.

The resistance to flow of the current system (1 MPa/l/s, 10 psi/gpm) is still too high for an economically viable HDR operation.

The experiments continue with the immediate target of achieving a sustained production of 25 l/s at 80°C which will be the equivalent of 75 l/s at 200°C because of the significant reduction in viscosity at high temperature. It is hoped this flow will be attained before April 1986.

ACKNOWLEDGEMENTS

Obviously the results of this paper are the synthesis of the work of the Project team and not just the author. The entire Project staff (60 people) has been involved with each of the experiments in one form or another and the credit should go to them.

The work has been supported by Contract E/5A/CON/125/960 by the UK Department of Energy and Contract EN3 G/E1/019/GB of the EEC whose support is gratefully acknowledged.

NOMENCLATURE

k = permeability (m^2)

h = formation heights (m)

μ = viscosity (Pa.s)

c = compressibility (Pa^{-1})

ϕ = porosity

I = impedance to flow ($Pa/m^3/s$)

r = interwell distance (m)

r_w = wellbore radius

s_2 = skin factor at production well

q_1 = injection flow

q_2 = production flow

s_1 = skin at injection well

REFERENCES

Anon. (1984) Review of Batchelor A S, Baria R, Hearn K: Monitoring the effects of hydraulic stimulation by microseismic event location: a case study, in SPE-AIME 58th annual technical conference, San Francisco, Oct 1983. (SPE 12109).

Baria R, Hearn K, Batchelor A S. (1985) Induced seismicity during the hydraulic stimulation of the potential hot dry rock geothermal reservoir. In Pennsylvania State University 4th conference on acoustic emission/microseismic activity in geologic structures and materials, University Park, Pennsylvania, Oct 1985.

Batchelor A S. (1984) An overview of hot dry rock technology. In 4th international conference on energy options: the role of alternatives in the world energy scene. Institution of Electrical Engineers, London, Apr 1984.

Batchelor A S. (1983) Stimulation of a hot dry rock geothermal reservoir in the Cornubian granite, England. In 8th workshop on geothermal reservoir engineering, Stanford University, California, Dec 1982.

Batchelor A S, Baria R, Hearn K. (1983) Monitoring the effects of hydraulic stimulation by microseismic event location: a case study. In Institution of Mining and Metallurgy conference on Rockbursts: prediction and control, London, Oct 1983.

Camborne School of Mines Geothermal Energy Project. (1986) Drilling operations 1984 Volume 3: drilling and casing well RH15. Phase 2B report, 2B-6.

Lawton R. (1986) An analytical model of the hot dry rock reservoir. Camborne School of Mines Geothermal Energy Project Phase 2B report.

Pine R J. (1984) Pressure transient analysis for large scale hydraulic injections in the Carnmenellis granite, England. In 9th workshop on geothermal reservoir engineering, Stanford University, California, Dec 1983.

Pine R J, Batchelor A S. (1984) Downward migration of shearing in jointed rock during hydraulic injections. International Journal of Rock Mechanics Mining Sciences & Geomechanical Abstracts. Vol 21, No 5, pp 249-263.

Pine R J, Cundall P A. (1985) Applications of the Fluid-Rock Interaction Program (FRIP) to the modelling of hot dry rock geothermal energy systems. In Swedish National Group of the ISRM international symposium on the fundamentals of rock joints, Bjorkliden, Lapland, Sweden, Sep 1985.

Tester et al. (1986) Inert and reacting tracers for reservoir sizing in fractured, hot rock systems. In 11th workshop on geothermal reservoir engineering, Stanford University, California, Jan 1986.