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A MULTI-CELL DESIGN OF A HDR RESERVOIR

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ABSTRACT

Economic HDR reservoirs require both a good hydraulic performance (low water loss and impedance) and a good thermal performance. Experience at the Rosemanowes HDR test site in Cornwall, UK, suggests that there is a trade off between thermal performance and hydraulic performance. A good thermal performance requires the efficient circulation of a large rock volume which leads to poor hydraulic performance. Hydraulic stimulations in adjacent sections of a well at Rosemanowes at measured depths between 2200 and 2800 metres suggest that it is possible to create HDR reservoirs close to each other that have minimal hydraulic interaction. This has led to the multi-cell stimulation concept of an HDR reservoir in which a number of parallel HDR reservoirs, or cells, are created along a section of borehole. The total volume is sufficient to provided the required thermal performance. The flow rate in any one cell is small (<4 l/s), keeping the water losses low, and although the impedance of any one cell is significant (>1 MPa/l/s), with the cells in parallel the total impedance is also low.

INTRODUCTION

The development of a Hot Dry Rock (HDR) geothermal energy system requires the creation of a high permeability heat exchanger in a low permeability rock mass and the circulation of water between a minimum of one injection and one production well. The objective is to create a system with a good thermal performance with low water losses and low impedance (production flow rate divided by injection pressure); these are the performance parameters for a HDR system.

What constitutes good performance parameters is determined by economics. An HDR system must produce energy, whether it is hot water or electricity, at rates that are competitive with other methods. Tester and Herzog, (1990) have reviewed the results of a number of economic studies of HDR geothermal energy for electricity generation. Table 1 shows the different performance parameters assumed by these studies of HDR economics, together with more recent information on the UK from Harrison and Doherty (1991).

Table 1. Performance parameters from HDR systems.

	INITIAL PROD TEMP °C	**INJECTION FLOW RATE** l/s	**LIFE TIME YEARS**	**WATER LOSS** %	**IMPEDANCE** MPa/(l/s)
EPRI	160	75	30	5	-
LANL	230	46	10	5	0.09
Japan	280	74	15	13	0.14
Bechtel	275	120	30	10	0.08
UK	179	75	18	10	0.1

Although there are a number of HDR R&D projects around the world no HDR reservoirs with the performance parameters listed in Table 1 have been created. Nevertheless, significant progress has been made since research started in the 1970's in understanding the factors controlling the performance parameters. These are principally the fundamental and operational parameters.

The fundamental parameters are the in situ rock mass characteristics, the most important of which are the rock stresses and natural jointing. It is the manipulation of these fundamental parameters during hydraulic stimulation that is the means of creating the HDR reservoir. Gaining the best performance from any reservoir so created is then obtained by optimising the operational parameters, such as the separation of the wells, their orientation and deviation, and the injection flow rate or pressure.

Comparison of the HDR research sites around the world shows that no two sites have the same fundamental parameters. This being the case then no single stimulation strategy or set of operational parameters will be appropriate for each site. Despite this there are some common problems. Experimental work has shown that there is a trade off between thermal performance and hydraulic performance (water loss and impedance). This is no surprise.

A good thermal performance requires a large volume of rock for the heat exchanger suggesting a large separation between the injection and production wells. A large well separation implies long flow paths through the joints and the likelihood of a significant impedance and commensurate water loss.

This paper presents the results of experiments carried out at Rosemanowes HDR test site and suggests a multi-cell design for a HDR reservoir which seeks to optimise both the thermal and hydraulic performance. This design has a number of separate parallel reservoirs, or cells, along a borehole. Each cell only takes a relatively low flow rate which keeps the water losses low and although the impedance of each cell is relatively high the total system impedance is low because the cells act like electrical resistors in parallel.

ROSEMANOWES HDR TEST SITE

In the 1980's experiments have been carried out in three well at depths between 2000 and 2600 metres. At these depths there have been 5 major stimulations using low, medium and high viscosity fluids, with and without proppants and more than six years of circulation. Only one of the stimulations and part of the circulation experiments will be briefly described here. A more complete picture of the geological setting and the experimental programmes can be found in (CSM, 1990, 1992; Richards et al, 1991 and Parker, 1989).

The most important fundamental rock properties are the in situ stress and jointing. These are briefly described.

Stresses and jointing

Stress magnitudes and orientations have been determined from overcoring measurements at a depth of 790 metres in a local mine and by hydrofracture stress measurements (HFSM) at depths of 2000 to 250 metres. Indirect evidence has also been obtained from induced microseismicity. Pine et al, (1990) summarise these data. Measurement of the maximum horizontal stress and orientation of the stress has provided difficult. Nevertheless, from these measurements linear trends in stress magnitude versus depth have been determined as follows:

$$\sigma_H = 15 + 28d \text{ (MPa)}$$
$$\sigma_h = 6 + 12d \text{ (MPa)}$$
$$\sigma_v = 26d \text{ (MPa)}$$

where d = depth (km)

The average of a number of measurements of the maximum stress direction is 323°N (±12 1SD).

Surface mapping shows that the jointing is dominated by two subvertical joint sets striking approximately 320-345° and 240-270°. Horizontal joints appear throughout the granite. The joint spacing on the subvertical sets is approximately 1-5 metres on the surface and approximately 3-10 metres at 800 metres in local mines.

Borehole televiewer (BHTV) logs to a depth of 2600 metres show that the horizontal joints are absent at depth but that the pattern of vertical jointing is similar to that observed at the surface.

EARLY RESERVOIR DEVELOPMENT

In 1982 during Phase 2A two wells (RH11 and RH12) were drilled to depths of 2 km entirely through granite, deviated to the north-west at a deviation of about 35° in the lower section. Following stimulation of RH12 circulation between RH12 (injection) and RH11 (production) demonstrated a poor hydraulic performance with high water losses (31%) and impedance (1.8 MPa/(l/s) at an average injection flow rate of 24 l/s. There was, however, no thermal drawdown.

In 1984 during Phase 2B RH11 and RH12 were extended and a third well RH15 was drilled on a helical trajectory to a measured depth 2800 m with the bottom hole section deviated to the north east by 30°. RH15 was stimulated in 1985 by injecting 5500 m^3 of a 50 cp viscosity gel at 200 l/s into a 140 m long openhole section located directly below well RH12.

Circulation of this new reservoir (RH12/RH15) was started in August 1985. For the next two years the injection flow rate was varied between 5 l/s and 40 l/s. During this period it was discovered that the maximum injection flow rate that could be sustained without microseismic activity and rapidly increasing water loss was 24 l/s. At this optimum flow rate the injection pressure was 10 MPa, the water loss 20% and the impedance 0.5 MPa/(l/s). This was a considerable improvement of the hydraulic performance of the RH12/RH11 system.

Circulation continued through to 1989 at the optimum flow rate. Although the hydraulic performance was maintained, thermal drawdown of approximately 10°C per year was being observed. It appeared that the improvement in the hydraulic performance of the RH12/RH15 system over the RH12/RH11 system may have been at the expense of the thermal performance.

In 1989 proppants were placed in RH15 as apart of an experiment to assess the use of downhole pumps in the production well. It is not intended to discuss the results of this experiment here. However, whilst it improved the hydraulic performance yet again, it also had the effect of increasing the thermal drawdown.

A stimulation deeper in RH15 was proposed to improve the thermal performance. This stimulation and how it led to the multi-cell HDR reservoir design is now described.

LOW FLOW ZONE STIMULATION AND TEST

Examining the flow/temperature logs in RH15 (Figure 1) it was apparent that there was a small amount of flow into RH15, below the main flow entrance (2370-2420 metres) at depths of 2580 m and 2610 m. These formed what was know as the low flow zone. This zone was also close to the region of microseismicity induced during the stimulation of RH15 in 1985 which was believed to be a region of enhanced permeability connected to the injection well, RH12 (Figure 2).

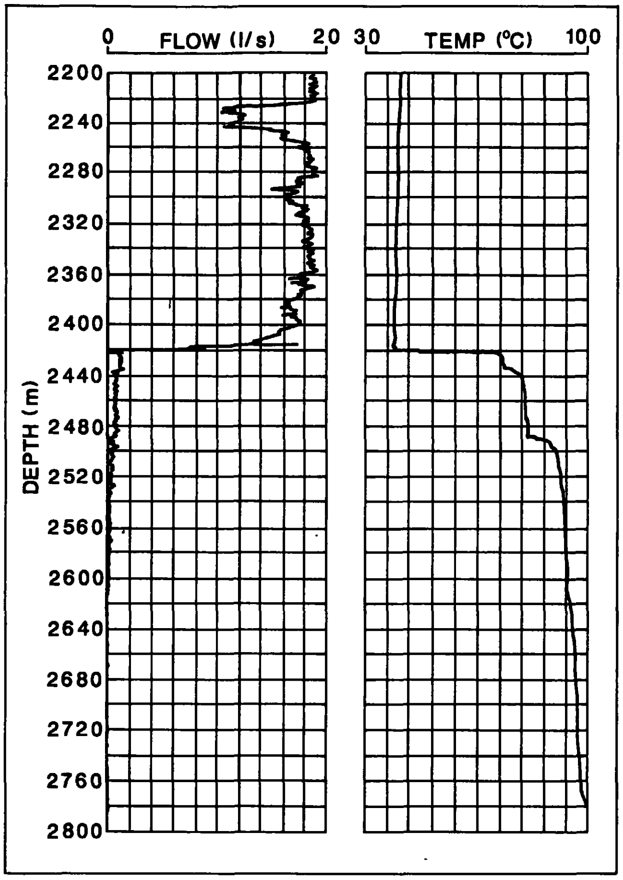

Figure 1. Flow and temperature logs in well RH15.

Stimulation objectives

It was proposed that if, by stimulation, the flow in the low flow zone could be increased by connecting into the microseismicity induced in the 1985 stimulation and the main flow zone higher up RH15 could be sealed, the thermal performance of the system would be significantly improved.

The stimulation design consisted of a 400 m^3 prepad of low viscosity (10 cp) fluid followed by a 40 m^3 pad of high viscosity (500 cp) gel and 20 m^3 of 500 cp slurry containing 11 tonnes of 20/40 scintered bauxite proppant. The high viscosity gel has a maximum working temperature of 85°C so the purpose of the prepad was to lower the fracture temperature within 50 m of the wellbore. The prepad was also designed to develop a lateral spread connection with the 1985 microseismic structure.

The bottom of RH15 was filled with sand to a depth of 2588 m and a double anchor packer assembly deployed at a depth of 2553 m with the muleshoe at 2555 m (Figure 3). This gave an openhole length of 35 m.

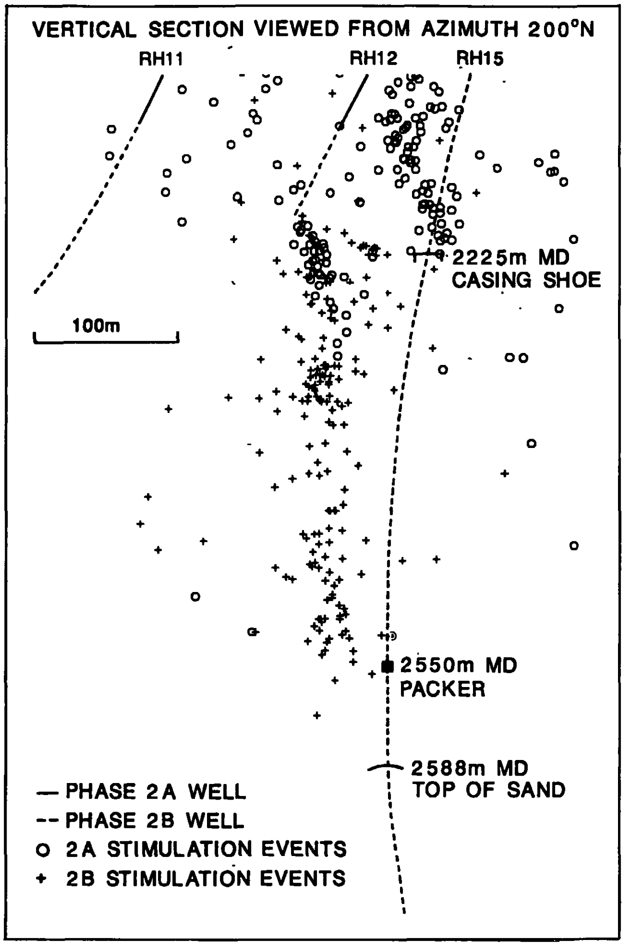

Figure 2. Microseismicity induced during the 1985 stimulation of well RH15.

Stimulation operation

The stimulation was carried out on the 16 June 1990. The full pumping schedule is shown in Table 2.

Table 2. Pumping schedule.

FLUID TYPE	END TIME	PROPPANT DENSITY (lb/gal)	FLOW RATE (l/s)	VOLUME STAGE (m^3)	PROPPANT SURFACE		
					CUM (m^3)	WEIGHT (kg)	PRESSURE (MPa)
Prepad	21:41	--	65.2	345	345	--	26.2
WF40 pad	22:46	--	71.5	21	366	--	26.9
Main pad	22:57	--	65.0	39	405	--	26.9
Slurry 1	22:58	1.0	61.0	6	411	803	26.9
Slurry 2	23:01	3.0	51.1	9	420	4045	26.9
Slurry 3	23:02	4.0	50.4	3	423	5090	26.9
Slurry 4	23:07	5.0	52.2	11	434	10900	24.8
Flush	23:12	--	65.2	24	458	--	26.2

The surface pressure was limited to 28 MPa, which meant that the injection flow rate was restricted to 70 l/s. This was due to the high friction losses in the in the 5 inch drillpipe of 12.5 MPa (5.1 MPa/km).

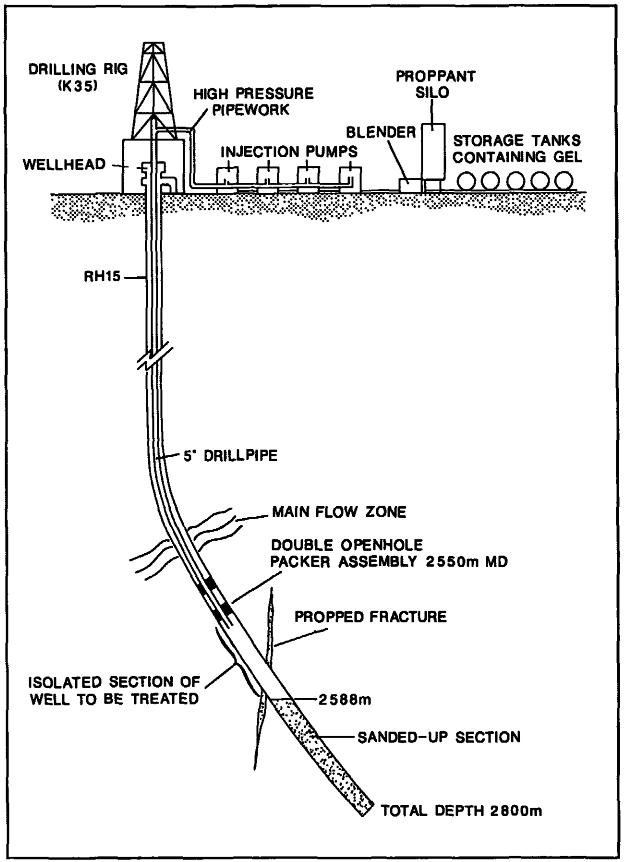

Figure 3. Location of stimulation in well RH15.

666 microseismic events were detected, of which 456 were located, during the stimulation. Although this microseismicity was in the region between RH15 and RH12 there was no evidence, on the basis of the pressure response in RH12 during the stimulation, of a connection between the two wells (Figure 4). Figures 5 and 6 show the locations of the microseismic events together with those induced during the 1985 stimulation of RH15.

The wells were left shut in for 33 hours to allow the gel to break. Laboratory samples confirmed that the gel had cross-linked to the correct viscosity and had broke after 30 hours. After the packer was removed the top of the sand was tagged at 2582 m, from which it was calculated that 96.5% of the proppant had entered the formation. On venting RH15 after the shut-in there was no evidence of unbroken gel or proppant being produced.

Production test

A production test was carried out with the packer reset at 2552 m. The sand was left in place to 2582 m giving an openhole interval of 30 m. The production test began at an injection flow rate of 14.5 l/s in RH12.

Once steady-state hydraulic conditions had been achieved, after about a month, it was evident that the stimulation had only improved the production by about 0.8 l/s. The injection flow profile in RH12 had not changed significantly.

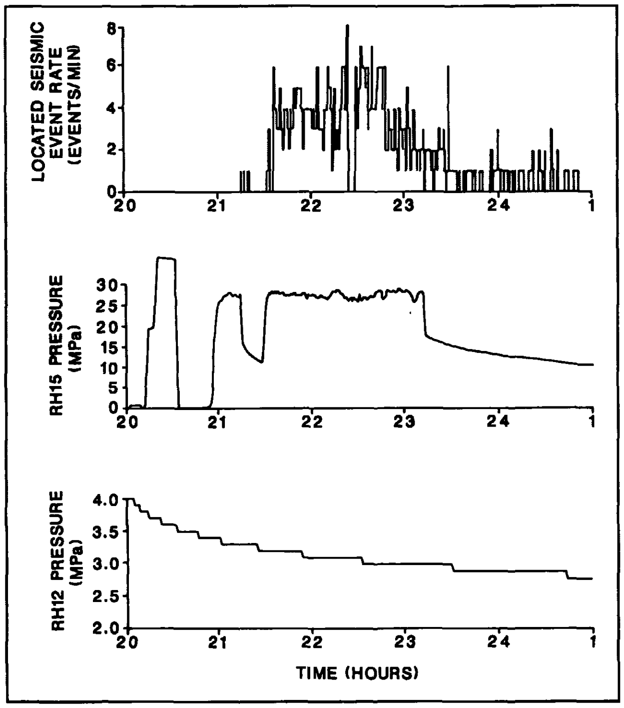

Figure 4. Microseismic and hydraulic data from the 1990 stimulation of well RH15.

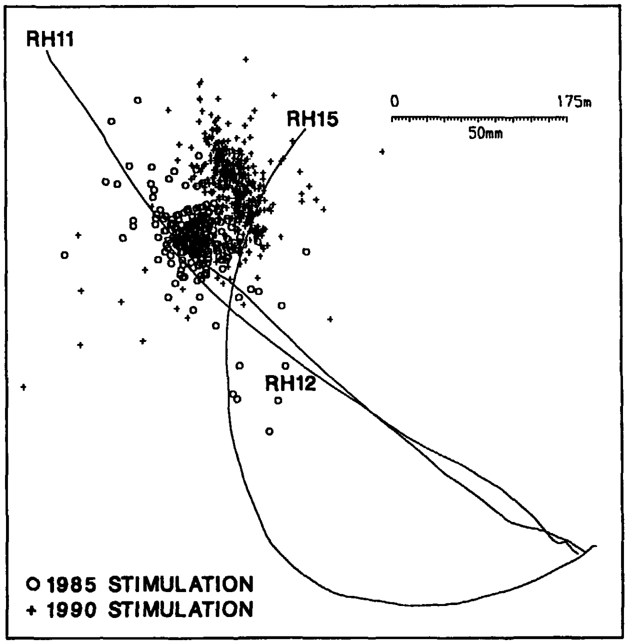

Figure 5. Plan view of microseismicity induced during both the 1985 and 1990 stimulations of well RH15.

Typical circulation data were:

RH12	Flow rate	14.5 l/s
RH12	Pressure	9.6 MPa
RH15	Drillpipe flow rate	3.3 l/s
RH15	Annulus pressure	6.5 MPa
RH11	Pressure	4.8 MPa
Recovery		22.8%

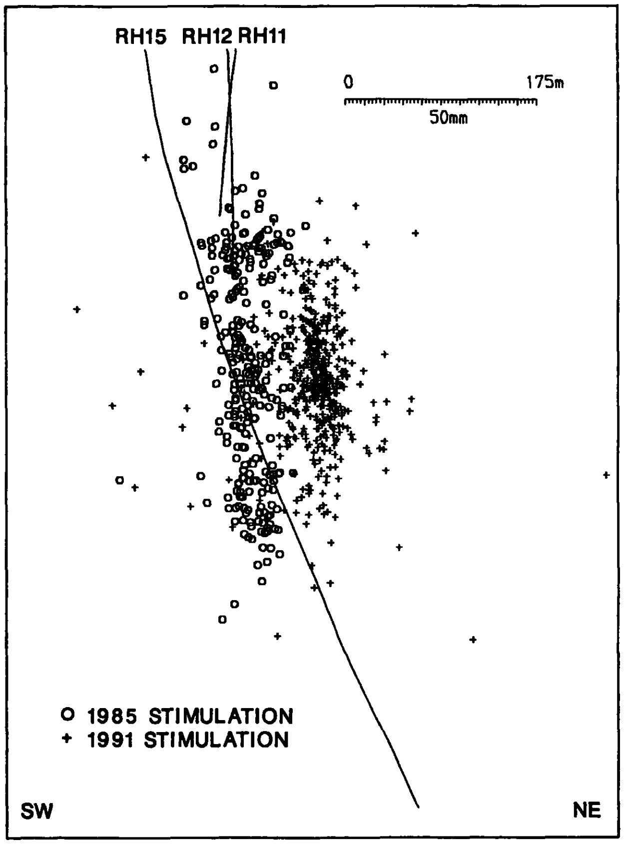

Figure 6. Side view of microseismicity induced during both the 1985 and 1990 stimulations of well RH15.

Despite the high water loss virtually no microseismic activity was detected during this production test.

Although the re-stimulation was operationally a success the connection with RH12/RH15 system created in 1985 was not achieved. The experiment did however raise a number of important questions regarding the pattern of growth namely:

* Poor connection to adjacent structures despite being separated by only a few tens of metres.

* A strong tendency for upward growth.

Examination of the microseismic locations alone from the 1985 and 1990 stimulations does not satisfactorily explain the poor connection. The two microseismic clouds, although largely separate do overlap to a small degree (Figures 5 and 6). There is however further information on the shear mechanism from the waveforms of the microseismicity.

The frequency of the microseismic signal is related to the surface area of the rupture. There are a number of models that quantify this relationship; the Brune (1970) model of the rupture surface as a circle being much used. Utilising the Brune model the source radii of the rupture surfaces for the located microseismicity of the 1990 stimulation are in the range 5-40 m.

In addition to a measure of the size of the rupture surface an estimate of its orientation and direction of shear can be obtained from recording whether the first motions at the seismic sensors are compressions or dilations. This fault-plane analysis indicates that the shear is most likely to be a result of shear failure on sub-vertical joints striking NW-N.

Figure 7 shows a random selection of events from the 1990 stimulation represented as planes. It is clear that if flow is along these shear planes then permeability enhancement will be anisotropic with the greatest increase in a vertical and north-west direction. Permeability enhancement in an orthogonal direction, towards the 1985 stimulation and well RH12 would be poor.

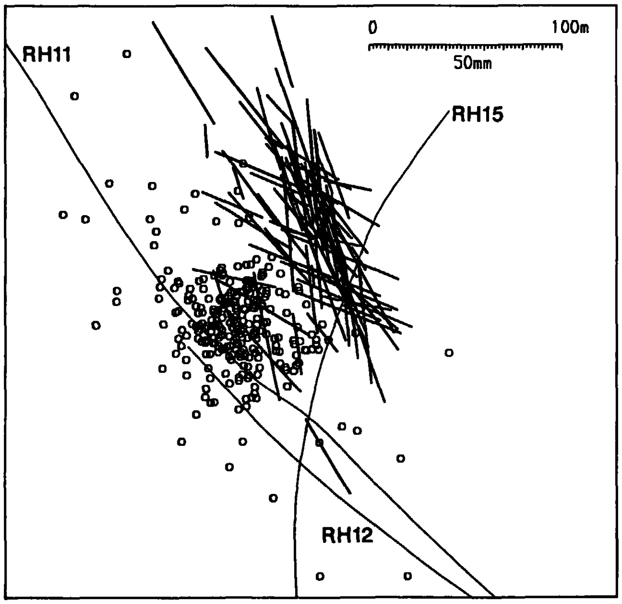

Figure 7. Microseismicity from the 1990 stimulation represented as planes.

Taking the measured in situ stresses and jointing and using a Mohr-Coulomb shear failure criterion, it is the vertical north-west striking joints that have the weakest shear strength and are the most susceptible to shearing at elevated joint pore pressure. This is consistent with the interpretation of the microseismicity presented in Figure 7.

The strong upwards growth of microseismicity observed during the 1990 stimulation of RH15 contrasts with the neutral growth during the viscous stimulation of RH15 during 1985. However, the effect of 4.5 years of circulation and thermal drawdown of the RH12/RH15 reservoir between the 1985 and 1990 stimulations is thought to be important. Calculations of the disturbance to the local stress field caused by cooling indicate reductions in the joint normal stress for vertical north-west striking joints by up to 6 MPa. This is sufficient to dictate that shearing during the 1990 stimulation would be parallel to the RH12/RH15 reservoir as indicated by the 1985 stimulation microseismicity. Modelling of the stimulation indicates that, in the absence of the cooling effect on the stress field, growth would have still been mainly upwards but less pronounced.

DISCUSSION

The objective of the secondary stimulation was to improve significantly the performance of the reservoir by connecting the low flow zone in RH15 to the region of microseismic activity located during the 1985 viscous stimulation and thereby extending the active volume of the reservoir. It is clear that this objective was not achieved because the stimulated zone, delineated by the microseismicity, grew directionally alongside but essentially unconnected with the stimulated zone from 1985. However, from this the following behaviour of significance was observed:

* strong planar growth during stimulation revealed by the microseismicity creating discrete units that are separated by a few tens of metres;

* asymmetric growth in the horizontal plane;

* preferential stimulation of one or two joints;

* very poor hydraulic connections between adjacent stimulated zones or cells.

The ability to create non interacting adjacent stimulated zones leads to the following concept for the creation of a HDR reservoir of sufficient rock volume for a good thermal performance whilst achieving a low water loss and impedance. Allowing for a combined sweep and flow efficiency of 33% the minimum volume for a heat exchanger for a 15 year life is 290 x 106 m^3. Assuming a well separation of 550 m this could be built from 20 zones or cells each containing a volume of 14.5 x 106 m^3 (Figure 8).

Each cell would be formed by the stimulation of a small number of joints. For a 20 cell system an injection flow rate of 70 l/s is proposed; 3.5 l/s per cell. Circulation of the RH12/RH15 system suggests a pressure drop of 3.9 MPa across each cell at this flow rate giving a impedance for each cell of 1.1 MPa/(l/s). The advantage of the multi-cell system is that cell impedances add like electrical resistors in parallel. For 20 cells the overall system impedance would therefore be approximately 0.05 MPa/(l/s).

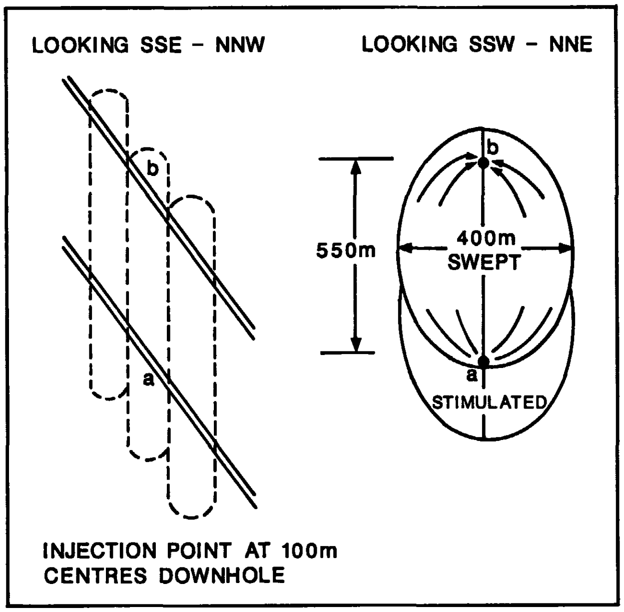

Figure 8. Design of a multi-cell HDR reservoir.

Whilst the specific design of a multi-cell HDR reservoir described above applies to the in situ conditions at Rosemanowes, it is believed that similar multi-cell systems are likely to be important for most HDR systems to meet the requirement of sweeping a large rock mass whilst maintaining a low water loss and impedance.

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