PROCEEDINGS, Thirteenth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 19-21, 1988
SGP-TR-113

TRACER MEASUREMENTS DURING LONG-TERM CIRCULATION OF THE ROSEMANOWES HDR GEOTHERMAL SYSTEM

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ABSTRACT

Circulation experiments have been in operation for over two years in the artificially stimulated hot dry rock (HDR) doublet of the Camborne School of Mines (CSM) research facility in Cornwall, England. During that period tracer tests have been run at intervals using inert and reactive compounds.

Initially, the results of the inert tracer investigations showed that the active volume (indicated by modal and median volumes) of the circulating system was dormant. Then, after a period of sustained oscillation, notable increases in active volume were observed which depended on both the subsequent flow rate changes and circulation time. These dynamic changes had almost reached optimum values when a downhole pump was introduced in the production well. The drawdown in the production well caused a reduction of the modal volume, whilst the median volume remained almost the same. Since then, the active volume has remained unchanged and irresponsive to circulation time and flow rate.

The results of the reactive tracer tests confirm increasing chemical reaction with increasing circulation time and correlate qualitatively with the opening of newer and hotter pathways within the reservoir. However, repeated production logs throughout the circulation have identified flow paths that have depleted thermally; a discrepancy that can be explained by the geometry of the system and the preferential downward reservoir growth.

INTRODUCTION

Research into the exploitation of HDR geothermal energy has been in progress at Rosemanowes quarry, the CSM research facility, for several years. A number of published papers describe the location and geology of the area (eg Pine et al, 1983) and progress of the research (eg Batchelor,1983,1984,1986; Pine et al, 1987).

Circulation of the current 2 km-deep system began in August 1985 and tracer testing, involving inert and chemically reactive compounds, has been used to determine the volumetric, flow and thermal characteristics of the reservoir.

The inert tracer, sodium fluorescein (NaFl), was used to determine the residence time distribution (RTD) of the bulk flow. Analysis of the RTD provided the breakthrough, modal and median volumes, and information about tracer dispersion (Johnson, 1984). Comparison of tests at different flow rates and circulation times, also enabled volumetric changes in the reservoir to be monitored.

The concept, theory and application of reactive tracer technology have been well documented (Robinson and Tester, 1984; Tester et al, 1986). It is being developed as a tool for estimating the productive life of a reservoir long before thermal breakthrough occurs at the production well. In the trial at CSM, ethyl acetate (EtAc), an ester sensitive to both temperature and pH, was used repeatedly. Although the material balance did not account for all the recoverable tracer in these experiments, the overall results yielded useful qualitative information.

This paper presents the results of 21 inert and 10 reactive tracer tests carried out during 28 months of continuous circulation of the Rosemanowes HDR reservoir.

BACKGROUND

HDR research at a depth of 2 km started in Phase 2A (1980-1983) with the drilling of wells RH12 (injection) and RH11 (production) in the Carnmenellis granite. The wells were orientated in the north-westerly direction, with RH11 above RH12 in vertical section, and later interlinked by sustained hydraulic stimulation of the naturally occurring joints, creating an artificial reservoir. The growth of the reservoir was predominantly downwards, below the open-hole sections of the two wells, and a diffusive hydraulic connection was achieved between them (CSM, 1984a; Pine and Batchelor, 1984).

In the subsequent circulations only 30% of the injected fluid was returned, and circulation had to be carried out for several weeks before steady conditions could be reached.

Three inert tracer experiments (test nos 1-3) were conducted during Phase 2A. Typically, the test durations were between 600 and 800 hours. The RTDs showed two characteristic peaks (bi-modal) and long diffusive tails. Modelling, using a source and sink in an equivalent uniformly porous medium (Webster et al, 1970), was successful and implied an extremely large, low permeability, system.

In Phase 2B (1983-1986) a third well, RH15, was drilled (to a true vertical depth of 2.6 km) to intersect the already stimulated region below Wells RH11 and RH12. Following a series of hydraulic activities in RH15, including a massive viscous fracturing operation (CSM, 1986a), significant improvement in the interwell connectivity was achieved and a long-term circulation of the RH12-RH15 system began. During this circulation RH11 has continuously produced about 10% of the injection flow, which is ignored in the tracer calculation.

CIRCULATION PROGRAMME

The circulation programme, still continuing in Phase 2C (1986-1988), has involved step changes in injection flow rate varying from 5 l/s to 38 l/s. The tracer tests were carried out between the injection (RH12) and production (RH15) wells, after hydraulically steady conditions had been reached at the wellheads. A summary of the flow rates of both wells, from the start of circulation, is presented in Figure 1. The numbers (4-24) identify the flow conditions at which NaFl tests were carried out. Circled numbers indicate where EtAc tests were also conducted. The Figure also shows that an oscillation experiment was carried out about 3000 hours into the circulation. In the test (CSM, 1986b), the interwell region was cyclically inflated (to pressures in the range 5-6 MPa) and deflated many times, at different periods (by opening and shutting-in RH15, whilst injecting at a steady 10 l/s into RH12).

For reasons to be made apparent, Figure 1 can be broadly divided into three main categories; pre-oscillation, post-oscillation, and the period beginning from the downhole pump test (DHP) as indicated. Apart from the DHP test, during which RH15 was drawn down by a maximum of 5 MPa, the well was fully open to the atmosphere (normal circulation).

INERT TRACER DEFINITIONS

1 The RTD, also known as the exit age distribution function, E(t), is the system response curve derived from the input (C_{in}) and the output (C_{out}) tracer data. These are related by the convolution integral (Levenspiel, 1972) given by:

$$C_{out}(t) = \int_0^t C_{in}(t-t') E(t') dt' \quad (1)$$

For convenience each RTD presented in this paper is the response to a pulse injection containing 2 kg of tracer. Where shortage of fresh water necessitated total or partial recirculation of the produced fluid, the above equation was used to determine the RTD.

2 The breakthrough time is the elapsed time between tracer injection at the top of RH12 and first detection at the top of RH15. The breakthrough volume is the total produced volume from the start of the test to breakthrough time. These parameters provide information about the most direct connection in the system.

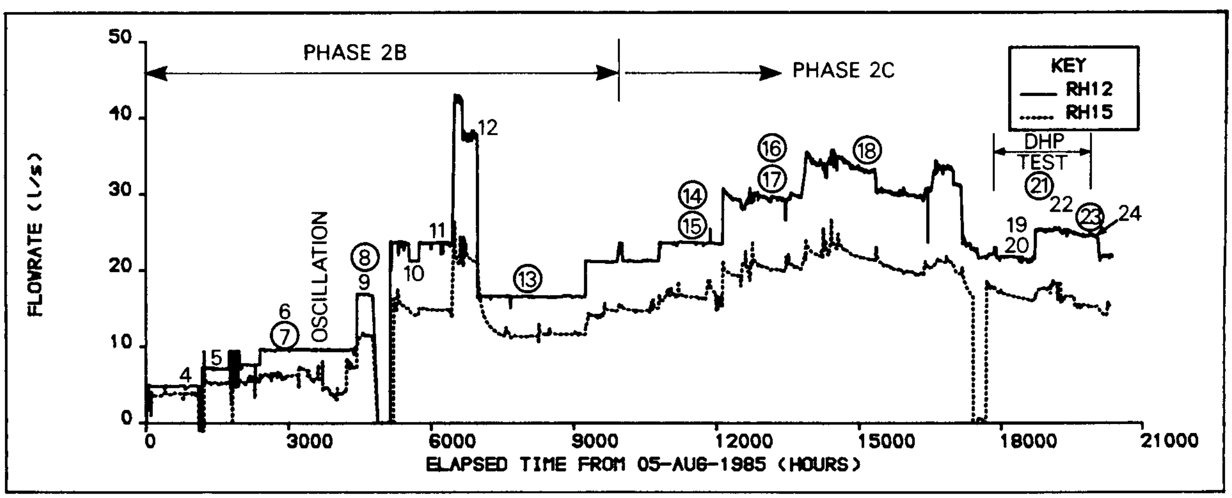

Figure 1. RH12 injection and RH15 production during Phases 2B and 2C circulation.

3 The modal volume is defined as the volume produced from RH15, from the start of the test until peak tracer concentration is reached, less the volumes of RH12 (85 m^3) and RH15 (90 m^3) wellbores. The modal volume is considered to represent the volume of the low impedance connections in the reservoir.

4 The median volume ([V]) is defined by the equation:

$$\int_0^{[V]} C_{out}dV = 0.5 \int_0^{\infty} C_{out}dV \qquad (2)$$

using the RTD (plotted as a concentration versus total produced volume). The median volume is considered as representative of the total volume of the major production paths (Tester et al, 1982).

Since all the tests presented here were carried out at steady state, and the RTDs are based on 2 kg of tracer, [V] can be redefined as the total produced volume containing 50% of the total recoverable tracer. Thus:

$$\int^{[V]} C_{out}dV = \text{Circulation Efficiency} \qquad (3)$$

where the circulation efficiency is defined as the percentage of injection fluid returned at RH15 during steady conditions. This definition avoids the extrapolation to infinite volume in equation 2. The median time, t_{50}, is the elapsed time corresponding to [V].

PROCEDURE

Similar experimental procedures were adopted for each of the tests. It was essential to pump each tracer very quickly into the injection stream (at the inlet to RH12) in order to conform to the assumption of pulse injection in the analyses. All the tracers were pumped individually into the injection stream, and at an identical flow rate (12 l/min). Prior to starting each experiment, it was ensured that the background tracer concentration in the reservoir was minimal. Where both inert and reactive tracers were introduced, the inert tracers were introduced first, followed by the reactive tracer. Sodium fluorescein injections lasted about 2.5 min and the times taken to inject the reactive tracers were typically 3-5 minutes.

Fluid samples were abstracted at the wellheads for analysis. The sampling programme was designed to ensure minimal ambiguity in the test results. RH15 samples were taken at 10-15 minute intervals from breakthrough until the peak tracer concentration was completed. Otherwise, the sampling intervals were between 30 minutes and 2 hours. Sampling frequency at RH12 depended on the type of circulation. Typically, samples were taken at 4- to 6-hour intervals on open-loop circulation. During closed-loop circulation, a sampling frequency identical to that for RH15 was used to provide sufficient input data for deconvoluting the system RTD.

A single-sided fluorimeter was used to determine the NaFl concentrations in the samples after they had been cooled to room temperature. A gas chromatograph was used to determine the concentrations of EtAc and ethyl alcohol (EtOH), one of the two reaction products, in the produced fluid. These enabled a mass balance of EtAc to be computed for comparison with NaFl. Laboratory studies showed that these chemicals and NaFl do not interact during analysis (Ferguson, 1985).

RESULTS AND INTERPRETATION

In the text that follows, the pre-qualifiers **total** and **net** are used to distinguish between volumetric parameters. The former refers to the gross volume produced at RH15 from the beginning of a test, and the latter implies that RH12 and RH15 wellbore volumes (estimated at 175 m^3) have been subtracted from the gross volume produced in RH15. Also by definition, the breakthrough and modal volumes are respectively **total** and **net** quantities. Furthermore, selected RTDs have been presented in this paper to illustrate clearly the trends of the volumetric behaviour. The omitted RTDs do not show any deviations from that depicted in this paper.

1 INERT TRACER TESTS

The RTDs are presented on identical horizontal axes in Figures 2 to 4. The steep decay exhibited by the NaFl RTDs after the peak, together with the high percentage tracer recovery (typically over 80%) at the end of

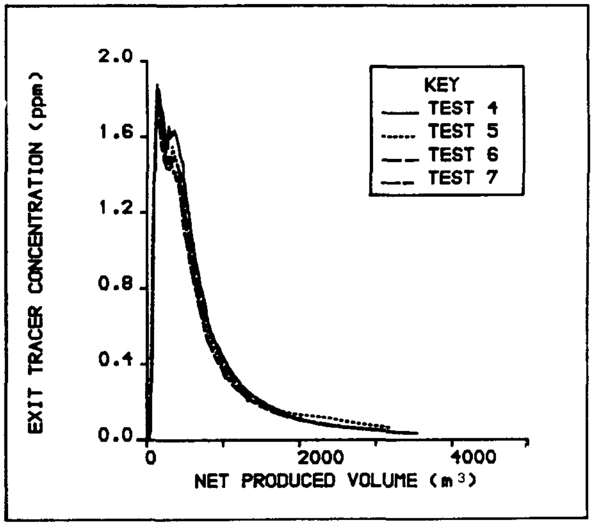

Figure 2. Pre-oscillation NaFl RTDs.

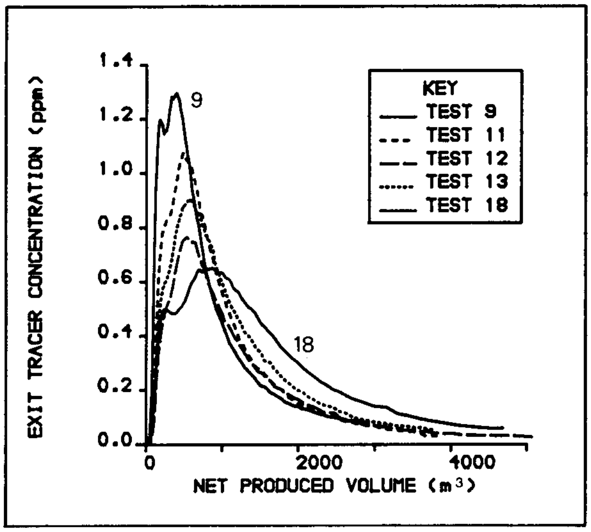

Figure 3. Post-oscillation NaFl RTDs.

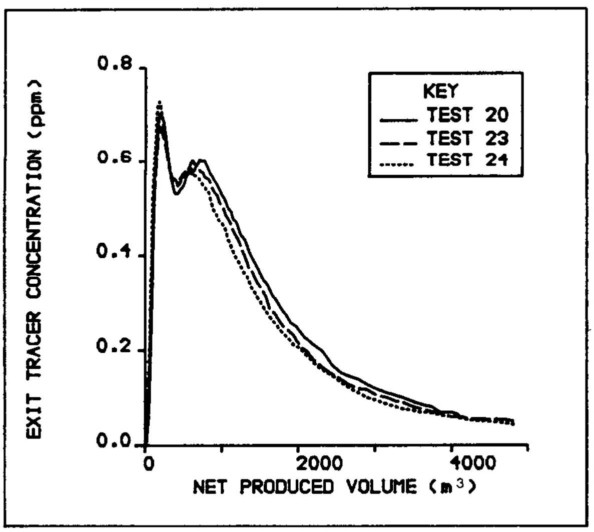

Figure 4. RTDs of NaFl tests during and after DHP.

each test, is indicative of minimal diffusivity and an absence of a 'retention-release' mechanism in the reservoir. These characteristics also imply that the system consists of discrete flow paths/features, and support the suggestion that the principal dispersion mechanism derives from fluid mixing owing to the different path lengths (Gardner, 1984; Breitenbach and Horne, 1982; Capuano et al, 1983). The non-reactive nature of NaFl was confirmed further by the excellent agreement obtained in a simultaneous experiment, using ammonium bromide as an inert tracer, during test 19 (Larkin, 1987).

Bi-modal RTDs, similar to those obtained in these tests, were also observed during Phase 2A. The Phase 2A hydraulic test results show that RH12 was strongly fractured with negligible wellbore impedance (CSM, 1984a). Also the bulk of the injection flow left RH12 near the bottom, and the remaining fluid exit points were almost uniformly distributed along the open section. These characteristics have remained unaltered in Phases 2B and 2C, although RH12 was not directly connected to RH11 in the case of Phase 2A. It was concluded then that the injection fluid left RH12 through large, open fractures and somehow diffused across to RH11.

The drilling of RH15 established a direct connection between RH12 and RH15. After the massive viscous stimulation of RH15, it was found that only the joints which had flowed previously flowed, but at a higher rate (Pine et al, 1987). Therefore, it can be inferred that the similar bi-modal peak displayed by both the current NaFl RTDs and the Phase 2A tests indicates that the dominant connections of the current system derive from the most permeable connections of Phase 2A. This also implies that the open features connected to RH12 continue to dominate behaviour of the current system. Maintenance of the characteristic profiles of the peak concentration regions also suggests that the tortuosity of the paths has not changed significantly.

Excellent linear correlations were obtained by plotting the injection and production flow rates against the reciprocal of the total breakthrough times. The latter indicated that the total volume produced (242±6 m^3) to breakthrough remained constant throughout the circulation. With the wellbore volumes estimated at 175 m^3, the above analyses also suggested that the volume of the breakthrough feature cannot be greater than 67 m^3.

Figure 5 shows a plot of modal volume against time. It is obvious from Figures 2 to 4 that the modal volume depended on which of the two modes showed the highest NaFl concentration. In the pre-oscillation period, the modal volumes were associated with the first mode and remained invariant at about 140 m^3. This was repeated during and after the DHP test, but at a higher modal volume of 210 m^3. Between the two periods (Figure 3), the modal volume was associated with the second mode and increased with increasing flow rate; from about 400 to 710 m^3. Clearly, since the breakthrough feature has remained unchanged throughout the circulation, it can be concluded that the pathways associated with the second mode have been responsible for the changes in modal volume.

A comparison of tests 9 and 13, carried out at similar injection flow rates (but separated by four months of circulation), indicated that the increases in the modal volume were irreversible during normal

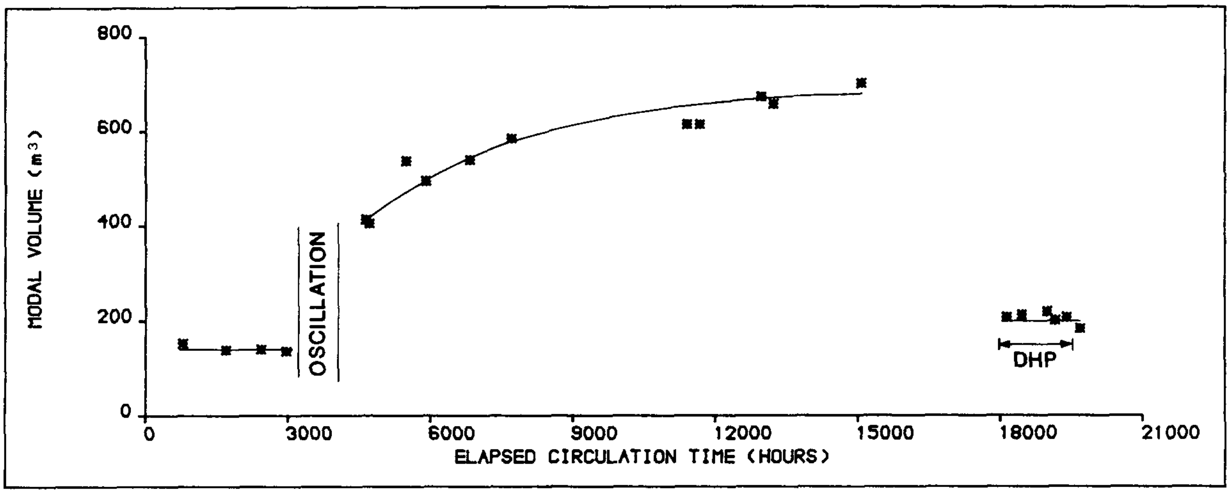

Figure 5. Modal volume trend during Phases 2B and 2C circulation.

circulation. This observation (confirmed by tests 11 and 15) has the implication of a reservoir whose optimum size has not yet been attained. Test 13 showed a slight improvement in the steady state impedance (0.74 compared with 0.77 MPa/l/s), a 44% increase in modal volume, and a 44% increase in median volume. It is believed that the increase in modal volume has not been the consequence of increases in the apertures of the low impedance features alone. (Note that for laminar flow in parallel-sided joints, the impedance reduces in proportion to the cube of the aperture increase). It is likely that the volumetric changes included increases in the swept areas of the original features, and enhancement of the permeabilities of some other, previously high impedance, features.

The median volume derived from the tests showed similar trends to that of modal volume, from the start of circulation to just before the DHP test. It was almost constant (750 m^3) initially, and increased with time/flow rate (from 940 to 1550 m^3) after the intensive oscillation. An even higher median volume of 1810 m^3 was recorded in test 18, during which continuous microseismic activity (indicative of reservoir growth) was recorded. The median volume peaked during the DHP test at 1920 m^3 (probably due to the production of stored fluid) and declined to some 1480 m^3 by the end of the DHP test. The latter value is in good agreement with the optimum value of 1550 m^3 obtained immediately prior to the microseismic activity, and is probably indicative of the end of reservoir development.

Simulation of the NaFl RTDs was carried out successfully with a multiple dipole model consisting of a parallel connection of hydraulically distinct homogeneous media (Webster et al, 1970; CSM, 1986c).

The results showed that a minimum of 3 parallel-connected dipoles could fit each of the NaFl RTDs, with average flow splits of 15%, 80% and 5%. The splits were similar to those used in a simplified thermal model involving three independent parallel plates (CSM, 1986). The derived Peclet numbers ranged between 1 and 5, further confirming that fluid dispersion, due to mixing, is high.

The simulation was not unique. However, it demonstrated clearly that the system was dominated by a finite number of flowing features and could not be simulated with one uniformly diffusive model, as was used in Phase 2A, (CSM, 1984).

2 REACTIVE TRACER TESTS

All the tests were terminated earlier than their corresponding NaFl experiments either due to a malfunction of the gas chromatograph, or because EtAc and EtOH (ethyl alcohol) could not be detected in the production fluid.

Good agreement between the breakthrough and modal volumes of reactive and inert tracer curves implied that the transit characteristics of both types of tracer were similar. A comparison of the quantities of unreacted EtAc recovered from RH15 (Figure 6) indicates that progressively less EtAc was produced as circulation continued. In the Figure, only the first three test results are shown. Subsequent tests followed a similar trend but are not presented, as the quantities were small.

Mass balances showed close agreement with the corresponding NaFl curves at early time only. Deviations after early time suggested loss of EtAc or EtOH. Losses were about 10% or less during the first three tests. In subsequent tests, over 40% of the total recoverable tracer was unaccounted for and there was no

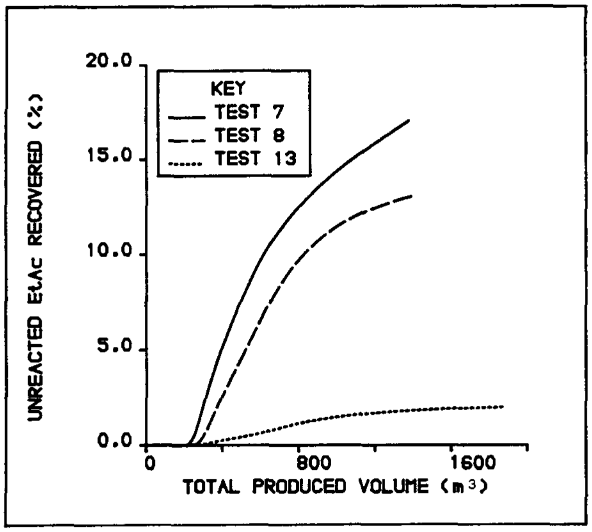

Figure 6. Reactive tracer test results.

detectable reactive tracer in the production fluid by the end of each test. Recent laboratory tests suggest that the losses in the latter tests may be due to the low sensitivity of the gas chromatograph. Further work on the analytical technique is still in progress.

The results of test 13, conducted at a similar flow regime to that of test 8, showed that less ethyl acetate was produced than previously.

These results suggest that the system was progressively more reactive as circulation continued; due to either increased temperature or pH. Since the first three tests were carried out in chemically similar injection conditions, it is believed that an increased temperature is the likely cause.

DISCUSSION

INERT TRACER TESTS

Clearly, the oscillation and DHP experiments have been instrumental in modifying the volumetric and flow behaviour of the current system. In a steady state circulation with RH15 fully venting, the highest system pressure is at RH12 and a steep pressure gradient exists in the reservoir. Hence, any volumetric readjustment is likely to be highest in the vicinity of RH12. An increase in the injection pressure would tend to predominantly stimulate RH12, increase wellbore storage, and probably increase losses.

In the oscillation test, a more gradual pressure gradient was imposed on the reservoir during the inflation half-cycle, causing the average reservoir pressure to increase significantly. However, since the duration was short, the increased pressure was localised (near RH15, and in the low impedance connections) and there was not time for the hydraulic pressure to reach the reservoir boundary to cause further stimulation. Therefore, the high pressure at the 'core' of the reservoir tends to enhance the interwell conductivity without appreciable losses. It appears that the large increases in the volumetric performance (CSM, 1986b) were achieved in this way, probably through joint block re-orientation, relaxation, and mechanical readjustment of flow fractions in the interwell region near RH15. An oscillation test, carried out subsequently at Los Alamos, yielded similar results (Hendron, 1987).

The reverse effect, to the massive oscillation, was probably achieved with the downhole pump. Reduction of the water level in the production well created an even steeper pressure gradient in the reservoir and also increased the effective stresses on the flowing features nearer RH15. These were probably sufficient to reverse some of the changes caused by the oscillation test. The common factor in the two operations is that similar absolute pressures (nominally 5 MPa) were sustained on RH15. This is in good agreement with the onset pressure for shearing along the most favourable joint set in the Rosemanowes granite (Pine and Batchelor, 1984) and is probably not a coincidence. It is likely that such absolute pressures are required to mechanically trigger the volumetric changes. Further work on this tentative interpretation continues.

It has been suggested that the small, unchanging, volume of the breakthrough feature may be responsible for the observed thermal decline in the system. However, routine temperature logs in RH15 show a more complicated distribution, and suggest that the observed effects may be geometry dependent. It is planned to embark on an intensive programme of downhole tracer injection with continuous sampling, at different locations in both wells in order to understand the interwell behaviour and, perhaps, establish the mechanism of the thermal decline.

REACTIVE TRACER TESTS

The reactive tracer results were encouraging. The concept is still in the developmental stage and requires further theoretical, laboratory and field work to improve the confidence in data and its interpretation. Apart from the high losses which are a major source of error, the use of only EtAc requires an estimate of the spatial pH distribution within the reservoir for complete interpretation. This was impossible to determine in these tests. However, the pH complication could perhaps be resolved by the simultaneous introduction of two or more different reactive tracers. Since these tracers access identical pH and temperature distribution, it should be possible to determine the reservoir temperature as a function of residence time.

The concept of using reactive tracers for predicting the productive life of the HDR system (Tester et al, 1986), was not proven in these tests. Whilst the reactive tracer tests progressively showed more reactivity, production temperature surveys (CSM, 1986d) showed that the temperature of the mixed wellbore fluid at the casing shoe was decreasing. This suggests that the water accesses hotter flow paths as the reservoir grows but on its return to RH15, it either mixes with colder fluid or accesses colder features. Until the reservoir size stabilises, it is unlikely that the reactive tracer would show evidence of thermal drawdown.

CONCEPTUAL RESERVOIR MODEL

A conceptual model which fits the inert tracer and reactive tracer results can be proposed. The open-hole section of RH12 lies along the strike of the dominant joint set (striking in the north-westerly direction). Hence it has a low-impedance access to a limited number of joints with high conductivity. This zone is surrounded by a secondary system of lesser permeability. Injections create pressure, first in the dominant joints, then enhance the conductivity of the secondary zone. By virtue of the high permeability contrast between the two zones, and the increasing stress anisotropy with depth (CSM, 1984b), fluid migration is predominantly downwards (Pine and Batchelor, 1984) to even hotter regions as the reservoir pressure increases. Therefore, the tortuosity of the circulation paths changes and the fluid penetrates deeper into the hotter regions before it rises into the production well through colder features. These zones are coupled to a breakthrough feature, probably located at the top of the structure, which is largely immune to pressure changes.

CONCLUSIONS

The results obtained so far from the long term circulation have demonstrated the importance of tracer testing as a diagnostic tool for characterising the volumetric flow and thermal behaviour of an HDR system early in its productive life. They lead to the following conclusions:

1 The current system derived from an enhancement of the most conductive features of the Phase 2A system, and demonstrates that irrespective of the extent and success of a stimulation, only the natural joints with connectivity would flow.

2 The interconnection is heterogeneous (compared to a uniformly diffusive medium) and the reservoir flow characteristics are dominated by the major features connected to the injection well.

3 Although the limiting breakthrough volume remained constant throughout the tests, all other tracer-determined volumetric parameters were responsive to flow rate changes. The modal volume rose from 140 m^3 to 710 m^3 after the oscillation, and dropped to 210 m^3 during and after the DHP. This has not recovered although the flow distribution in RH15 has not changed significantly since the oscillation.

However, the median volume increased from 750 m^3 to 1550 m^3 after the oscillation and has remained about the same after the DHP. This is consistent with the observed flow distribution in RH15 and suggests that the median volume (rather than the modal volume) is a better measure of gross volumetric and flow changes in the reservoir.

4 The available evidence indicates that substantial improvement in the system was achieved with the oscillation experiment. This, and the downhole pump test, must be further investigated for use as tools for HDR reservoir development.

5 Reactive tracers can be useful tools for diagnosing thermal changes in the interwell region. Their development must be continued.

ACKNOWLEDGEMENTS

During the period of work reported, the author was employed by the Camborne School of Mines and subsequently by GeoScience Limited. This work was carried out at Camborne School of Mines on a programme funded by the UK Department of Energy and the Commission of European Communities. The author wishes to thank the UK Department of Energy through the UK Atomic Energy Authority under contract number E/5A/CON/A37/1593 for permission to publish this paper. The support and encouragement of the staff of these organisations is gratefully acknowledged.

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