Hot Dry Rock Geothermal Energy Research at the Camborne School of Mines

by
ROGER PARKER, Project Director
Camborne School of Mines Geothermal Energy Project, Rosemanowes
Quarry, Herniss, Penryn, Cornwall, UK

Introduction

The Camborne School of Mines (CSM) Hot Dry Rock Geothermal Energy project in the period of 1977-89 has been concerned mainly with the technology of the development and characterisation of Hot Dry Rock (HDR) reservoirs in a jointed granite. There has been no attempt to demonstrate the exploitation of the energy extracted. The UK Department of Energy has been responsible for providing most of the funding, but the Commission of the European Communities provided significant support until 1986.

In Phase 1 (1977-1980), boreholes 300 m deep were drilled in the Carnmenellis granite at Rosemanowes Quarry, near Penryn in Cornwall. It was demonstrated that it was possible to connect the boreholes by hydraulic stimulation of natural joints in the granite, and to circulate water through these joints (Batchelor, 1982).

Phase 2 (1980-1988) was carried out in three parts at Rosemanowes, with the aim of investigating reservoir development at a depth of about 2 km, which was considered to provide conditions reasonably representative of those expected at the greater depths required for commercial exploitation. Hydraulic stimulations using water and a medium viscosity gel were used to create the reservoir, and long periods of circulation of the reservoir were used to establish its hydraulic and thermal characteristics.

Phase 3 began in 1988, having as its main objective the development in Cornwall of a prototype of a commercial system for generating electricity. For an acceptable lifetime, this prototype would require a reservoir 6 km deep occupying a rock volume of 300 million m^3, producing water at 200°C, at a rate of 75 l/s.

HDR Environment at Rosemanowes

Throughout the programme, the aim has been to produce a technology which is as widely applicable as possible. Return from investment in HDR exploitation is unlikely to be high enough to justify high exploration costs, and therefore the technology must be capable of adapting to the geological environment in which it is placed. If there is a need to incorporate specific localised geological structures in creating the reservoir, exploration costs (and the chances of a sterile operation) increase. Conversely, there is a need to avoid such structures in choosing the site, if they would tend to jeopardise the operation.

Rosemanowes Quarry was chosen because it was on the exposed Carnmenellis granite, and did not have a major geological feature (such as a fault) at the surface. The absence of sedimentary or metamorphic cover rock has made installation of the comprehensive microseismic network cheaper and more effective.

The rock is granite, with textures changing from porphyritic to equigranular at about 2 km. The base of the granite extends well below a depth of 9 km. In situ mechanical properties are:

Uni-axial compressive strength:
103 MPa + 32 MPa/km
Young's modulus: 54 GPa + 4 GPa/km
Poisson's ratio: 0.22-0.27
Density: 2640 kg/m^3

Two main vertical joint sets (northeast-southwest, parallel to the trend of tin/copper lode mineralisation, and northwest-southeast, parallel to post-granite extension and strike slip faults known as "cross-courses") have been identified from surface mapping. These joint sets (although with a broad range of strikes) have been identified on BHTV logs to a depth of 2.6 km, and microseismic data indicate their continuation to at least 3.5 km.

The relationship of stress distribution to depth has been measured at Rosemanowes in considerable detail to a depth of 2.5 km, and these measurements have been complemented by measurements in local tin mines. Pine and Batchelor (1984) summarised the relationship for in situ stresses (in MPa) in the Carmenellis granite with depth (z, in km):

$$\sigma_H = 15 + 28\,z$$
$$\sigma_h = 6 + 12\,z$$
$$\sigma_Y = 26\,z$$

Subsequent measurements at 2.5 km confirmed this relationship.

Three-dimensional heat flow models, based on extensive heat flow measurements and gravity surveys, indicate an almost linear dependence of temperature on depth in the upper 7 km of crust over large portions of the Cornubian granite batholith. With an average surface temperature of 10° C, this results in a relationship for regions close to Rosemanowes:

$$T = 10 + 35 z,$$

where T is the temperature in °C at a depth of z km (CSM, 1989).

In situ hydraulic properties have been measured at Rosemanowes at depths up to 2 km, before major hydraulic injections commenced. Low flow rate hydraulic tests at low injection pressures indicated permeabilities between 1 and 10 μ D at up to 0.7 MPa fluid overpressure. Then permeabilities rose to 60 μ D, prior to onset of significant discontinuous behaviour at over 5 MPa.

Phase 2: Reservoir Creation and Characterisation

In Phase 2A (1980-83), two wells (RH11 and RH12) were drilled to a depth of 2100 m entirely through granite, deviated to an angle of 30° from the vertical in the lower section. They were separated vertically by 300 m at full depth, where a bottom hole temperature of 79°C was recorded. Explosives were used to pre-treat the well to allow better water access from the borehole into the granite, but the joint stimulation was hydraulic, using 26,000 m^3 of water injected into the injection well (RH12) at flow rates up to 100 l/s, generating a wellhead pressure of 14 MPa (Batchelor, 1983; CSM, 1987).

This hydraulic stimulation established a poor connection between RH12 and RH11 and created a large stimulated region, below the two wells, whose predominantly downward growth persisted throughout the subsequent circulation of the reservoir during Phase 2A. The importance of the installation of a comprehensive microseismic sensing system in the monitoring of these stimulation and circulation developments cannot be overemphasised.

Circulation following the main stimulation gave an average water recovery of 31 percent at an average injection flow rate of 24 l/s. The highest injection flow rate was 32 l/s, at which the recovery was 26 percent. Impedance (pressure drop across the reservoir measured at the wellheads divided by the production flow rate) was high (1.8 MPa/kg/s average), but there was no measurable thermal drawdown in the production temperature (52°C at surface). Tracer tests using sodium fluorescein showed considerable dispersion with long breakthrough times, implying a very large system with low permeability. The overall envelope of the microseismic cloud located during Phase 2A contains a volume of about 800 million m^3 of rock, but it is clear that water flow through this volume was mainly lost, and an unacceptably low proportion was returning to the production well.

Pine and Batchelor (1984) have provided an explanation for this downward growth of the reservoir during hydraulic stimulation and circulation, and have related it to the changes of in situ stress anisotropy with depth in Cornwall.

A third well (RH15) was drilled in Phase 2B of the CSM project (1983-86), on a spiral trajectory to a depth of 2600 m, at which the bottom hole temperature was 100° C. The aim was to intersect the microseismic zones which had indicated downward growth of the reservoir from RH12 in Phase 2A. In order to achieve a good connection with the injection well (RH12), it was necessary to stimulate the system from RH15, which was to be the new production well. To reduce the tendency to leak-off and to increase the chance of jacking open the joints, rather than shear-slippage, 5500 m^3 of an intermediate viscosity gel (50 cp) was injected into RH15 at an average flow rate of 200 l/s. The injection wellhead pressure was 14 to 15 MPa. Microseismic activity was much lower, and was confined to a more restricted tube-shaped envelope extending vertically mainly between RH15 and RH12 (Parker, 1989a). The volume of this microseismic envelope was 1 million m^3, and subsequent experience with circulation of the reservoir created indicates that an effective reservoir rock volume of 5 to 10 million m^3 was produced by this viscous gel stimulation in 1985 (Figure 1).

The remaining part of Phase 2B (1985-86) and the whole of Phase 2C (1986-88) were concerned with a continuous circulation of the reservoir stimulated in 1985, using a number of diagnostic methods to characterise the reservoir. This work represents the longest continuous circulation of any HDR reservoir (Parker, 1989b).

This extended circulation programme can be divided into three stages:

I. A gradual increase in the injection flow rate, using periods of up to 6 weeks at each flow rate step increase, to allow approximately steady-state conditions to be achieved at each step (Figure 2). Water losses remained fairly constant throughout, at about 20 percent, and impedance reached a minimum of about 0.5 MPa/kg/s at the maximum injection flow rate of 35 l/s. At flow rates as high as this, requiring an injection pressure of 11.5 MPa, the rate of water loss increased and microseismic activity indicated downward reservoir growth similar to that experienced in Phase 2A. It appeared that the optimum performance of the reservoir was at an injection pressure of 10 MPa, producing an injection flow rate of 24 l/s and an impedance of 0.6 MPa/kg/s. Nevertheless, this was a much more satisfactory connection between the wells than had been achieved in Phase 2A.

II. A downhole pump was used to lower the pressure in the production well (RH15) by 4.5 MPa. This produced evidence of "pinching in" of joints close to RH15, resulting in a significant rise in impedance. Proppants placed in these joints might reduce this effect, and in Phase 3A (1989), a proppant placement has been used in connection with a downhole pump to test this proposition.

III. Thermal drawdown had been of the order of 1° C per month since 1986, and thermal modelling had indicated the possibility of a short circuit. In 1988, tracer runs were carried out involving fluorescein injection at specific points downhole in RH12 and continuous sampling downhole in RH15. This flowpath characterisation indicated a short circuit between the bottom of RH12 and the upper flowing zone of RH15. Plans are being made to attempt to seal this short circuit in Phase 3A (1988-90).

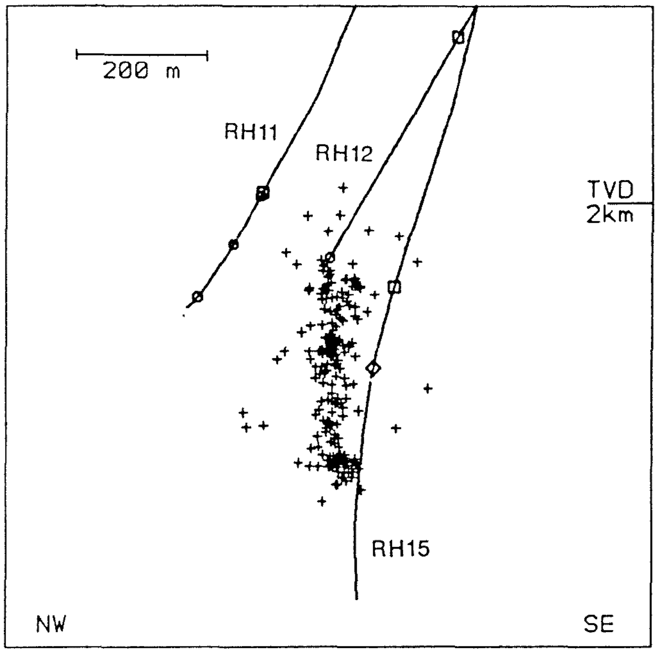

Figure 1. Vertical view of all the microseismic events during Phase B viscous stimulation of RH15.

In the characterisation of the HDR reservoir, a number of diagnostic techniques have been used, and developed significantly by the CSM team. These include hydraulic well testing, tracers, radon dissolution modelling, geochemical modelling, vertical seismic profiling and crosshole seismics, tracers and thermal modelling.

Instrument Development

Throughout the CSM project, it has been found unsatisfactory to rely totally on commercially available instrumentation for monitoring the creation and development of the HDR reservoir, and for its characterisation. In particular, microseismic instruments, production logging tools and, more recently, downhole tracer experimentation tools have been an important field of development in the research programme. Commercially available instruments and tools have been substantially modified, and completely new items designed and built.

The associated system software has been developed mainly in-house, and software for the interpretation of proprietary logging data (e.g. BHTV, FMS) has been developed by the project.

A set of production logging tools (to measure temperature, pressure and flow rate downhole) is available, with downhole electronics able to operate at ambient temperatures up to 125°C. Tracer tools capable of injecting and sampling downhole have been built, and a conductance tool and fluorimeter tool capable of sensing for tracer purposes have been purchased and modified.

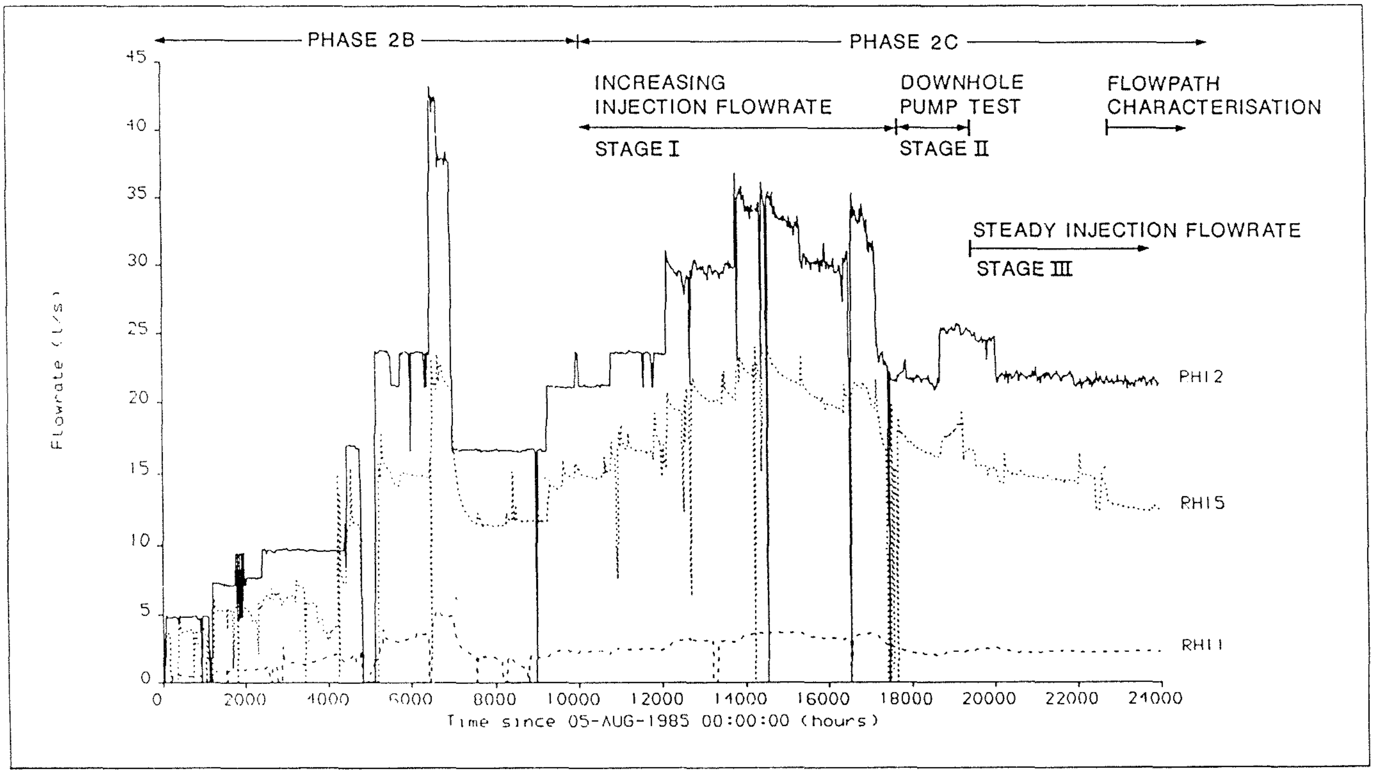

Figure 2. Flowrate since start of circulation (Phase 2B and 2C).

An earlier review of the borehole tool requirements for the project's future revealed the need for tools operating downhole at temperatures around 200°C and pressures about 140 MPa. Passive cooling using vacuum barrier flasks and low melting point eutectic materials to provide a negative heat store are adequate where equipment requires only a relatively short time in the well (e.g. production logging). Where a seismic tool is required for passive monitoring for long periods, active cooling devices will be necessary. Work on thermoelectric cooling has developed a system operable at an ambient temperature of 220° C, with a cooling differential of 40° C. A database has been built up on electronic components available and capable of operating at 180° C for over 3000 hours (CSM, 1988a).

A seismic source (sparker) is being designed, built and tested to produce a repeatable wide bandwidth source for use in deep boreholes in sedimentary and crystalline rocks. A commercial 3-axis microseismic tool was purchased and found to be severely affected by resonance. After exhaustive testing of this tool, it was decided to design and build a tool in-house. The aim is to have a tool capable of remaining long periods clamped downhole at up to 200° C, to provide accurate location of microseismic events where attenuation will decrease accuracy if sub-surface sondes are used on their own in a deep system used to develop a commercial prototype (CSM, 1988a).

Resource Assessment

In preparation for the development of a prototype commercial HDR system in Cornwall, it has been necessary to explore the structure and thermal characteristics of the 14 km-thick Cornish granite batholith, together with its metamorphic cover. This should provide data for the costing and site selection for the prototype. Gravity and heat flow studies have provided important data on the HDR resource in southwest England, and a model which will predict temperatures at depths of about 6 km with an accuracy of 8° C (one standard deviation) (Figure 3) has been produced (CSM, 1989). The geothermal gradient is nearly linear over the upper crust, 35° C/km typifying the granite batholith.

A seismic reflection survey found no evidence of reflectors within the Carnmenellis granite at depths of relevance to the development of HDR (CSM, 1988b). The survey was carried out along two lines crossing over at Rosemanowes Quarry, and having a total length of 72 km. In addition to heat flow and seismic reflection studies, a magnetotelluric survey has been carried out more recently by the British Geological Survey (CSM, 1988a).

In addition to geological studies, environmental and infrastructure restraints on potential HDR development have been studied in broad detail in Cornwall, and it is concluded that there are a large number of sites which could be investigated, should a decision be made to go ahead with development of a prototype deep system (CSM, 1988a).

Phase 3

Having completed an extensive study of the Rosemanowes reservoir created in Phase 2, the programme had reached the stage where decisions were needed on the future of the project. It has been shown that the reservoir characterised in Phase 2C is significantly smaller than that which would be required for a commercial application of the technology for electrical power generation. Further

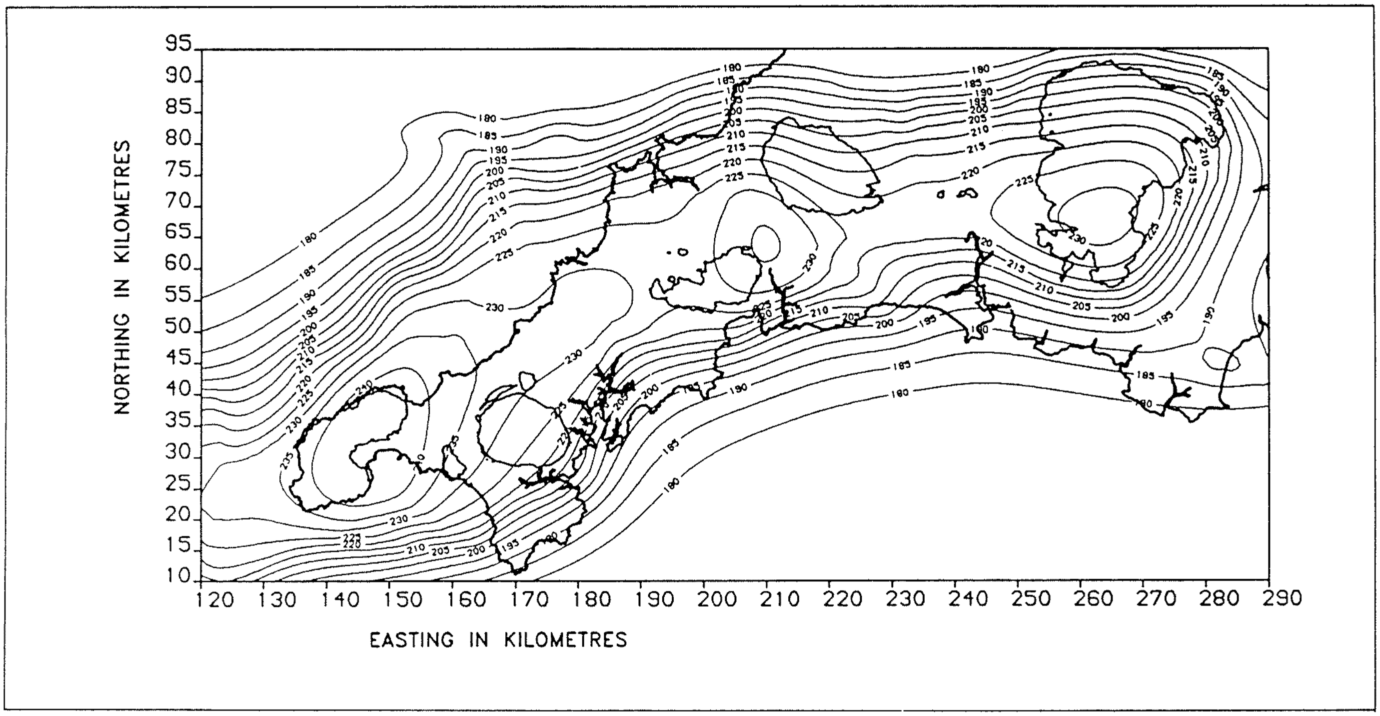

Figure 3. Model calculated temperature at 6 kms depth for Cornwall, England.

work on the assessment of the engineering problems in creating a deep system shows that a properly designed stimulation should develop a reservoir system larger in volume than that produced in Phase 2 at Rosemanowes. Nevertheless, it is believed that the design assumptions will require a commercial reservoir to be created by stimulation in several segments, which are connected in parallel to the injection and production wells (CSM, 1987). By this means, the increased volume can be created, while maintaining an acceptable reservoir impedance.

With this premise in mind, a Conceptual Design study has been commenced by RTZ Consultants Ltd., aiming to design a commercial HDR system, and a prototype of such a system which will demonstrate the feasibility and costs of HDR development in Cornwall. CSM is participating in this Conceptual Design study, which will be completed in 1990.

In order to provide further input data for the Conceptual Design, CSM has a Phase 3A (1988-1990) R&D programme which in addition to further instrument and microseismic system development, aims to examine techniques which may be used to manipulate a HDR reservoir to improve its performance. The most important treatment applied so far has been the placement for proppants in the joints flowing into a section of the production well. This work was carried out successfully in February 1989, and the results of the placement will be analysed following the use of a downhole pump to lower the pressure in the production well. If the rise in reservoir impedance is less than that experienced with a downhole pump in Phase 2C, it will have been demonstrated that proppants prevent "pinching in" of joints close to a production well in which the pressure has been lowered below hydrostatic.

The next stimulation treatment will aim to access part of the reservoir which has been located microseismically, but which is not connected to the production well. A limited "secondary stimulation" will be carried out lower in RH15 than the proppant placement, to increase the effective circulating volume of the reservoir.

It was shown in the reservoir characterisation in Phase 2C that there is an important short circuit in the reservoir, leading to excessive thermal drawdown. Plans are being made to seal the short circuit, thus improving the thermal performance of the reservoir.

An experiment to investigate the effect of major oscillations of reservoir pressure and flow rate has shown no significant improvement in performance of the system.

Conclusions

After twelve years of work at Rosemanowes, the CSM project has demonstrated that it is possible to create a large hot dry rock geothermal reservoir occupying a rock volume of 5 to 10 million m^3 in granite, at a depth which allows a significant understanding of the engineering problems associated with the creation, development and circulation of the reservoir. This understanding is vital for the next stage of the project, which it is hoped will apply the lessons learned to the development of a new reservoir at a depth representative of the requirements of a commercial system. The area which still requires considerably more experience than has been possible on this single site is the stimulation of the rock mass to create the reservoir. Modelling and design studies can only support practical experience in this field; they can never replace it. Once an experimental reservoir has been created, it is important to devote adequate effort to characterising it, otherwise the lessons to be learned for the future will be incomplete.

We believe that at Camborne School of Mines we have laid a firm foundation for future development of HDR technology, and look forward to a significant growth in experimental activity in this field. We have valued the cooperation and support we have received from HDR research teams in the USA, in France and Germany, in Japan and in Sweden. Cooperation is so essential to the development of a significant research effort in a field of this nature.

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