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THE UK GEOTHERMAL HOT DRY ROCK R&D PROGRAMME

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ABSTRACT

The UK hot dry rock research and development programme is funded by the Department of Energy and aims to demonstrate the feasibility of commercial exploitation of HDR in the UK. The philosophy of the UK programme has been to proceed to a full-scale prototype HDR power station via a number of stages:

- *Phase 1*
  Experiments at shallow depth (300 m) to assess the feasibility of enhancing the permeability of the rock.
- *Phase 2*
  Studies at intermediate depth (2500 m) to determine the feasibility of creating a viable HDR subsurface heat exchanger.
- *Phase 3*
  Establishment of an HDR prototype at commercial depth.

The programme has run over a 15 year period, and has been formally reviewed at stages throughout its progress. The 1987 review towards the end of Phase 2 identified a number of technical objectives for continuing research and proposed that the initial design stage of the deep HDR prototype should start.

Phase 3A is now complete. It addressed:

- the feasibility of creating an underground HDR heat exchanger suitable for commercial operation
- techniques for improving hydraulic performance and correcting short circuits in HDR systems
- modelling of the performance, resource size and economic aspects of HDR systems.

The work has been conducted by a number of contractors, including Camborne School of Mines, Sunderland and Sheffield City Polytechnics and RTZ Consultants Limited.

This paper focuses upon the experimental work at Rosemanowes in Cornwall and the recently completed conceptual design of a prototype HDR power station. The economics of HDR-generated electricity are also discussed and the conclusions of a 1990 programme review are presented. Details of the HDR programme to 1994, as announced by the UK Department of Energy in February 1991, are included.

INTRODUCTION

For nearly 20 years there has been interest in research and development aimed at extracting the heat from hot dry rock (HDR). The technology for extracting the heat involves pumping water down a borehole drilled from the surface, circulating it through artificially enlarged fissures in the hot rock and bringing it back to the surface via a second borehole(1). See Figure 1.

The UK programme has proceeded in 3 phases. The programme chronology and cumulative expenditure to April 1991 are shown in Figure 2.

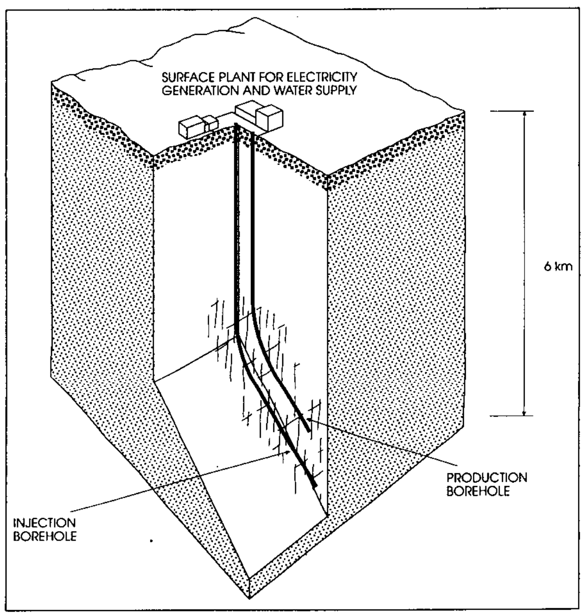

Figure 1 *Schematic representation of an HDR system in the UK*

1977–1980 PHASE 1

The major work under Phase 1 was a small-scale field trial at Rosemanowes, aimed at linking four 300 m deep boreholes over a horizontal distance of 40 m. Earlier work at Los Alamos in the United States had already shown that water could be circulated between two boreholes after hydraulic stimulation (at 3000 m), but the resistance to flow had been unacceptably high and it was

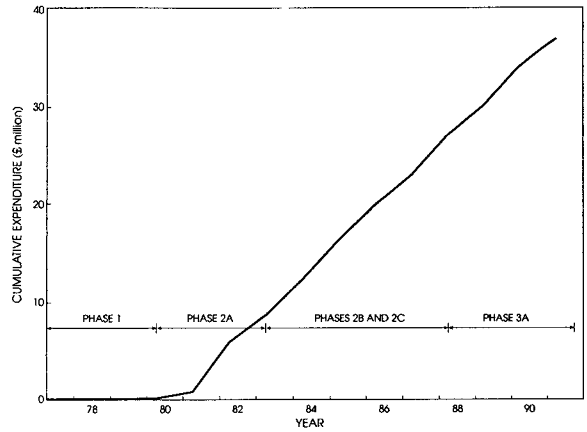

Figure 2 *Chronology of Phases 1 to 3A at Rosemanowes, and the cumulative expenditure by the UK Department of Energy to April 1991*

believed that much of the impedance was concentrated in the zones immediately surrounding the boreholes. One objective of Phase 1 of the CSM work was to show that the use of controlled explosions within the boreholes could improve the permeability of the rock adjacent to the wellbore and initiate new fractures, which might themselves be stimulated hydraulically to provide a low impedance path between the boreholes by way of the natural joint system.

During Phase 1, the combination of explosives and hydraulic fracturing followed by water circulation reduced the impedance of the system by a factor of 50 relative to that achieved previously (at Rosemanowes and at Los Alamos) by hydraulic fracturing alone. The lowest impedance achieved was close to 0.1 MPa per l/s, a value which was considered to be necessary for a commercial prototype.

In several senses, however, the conditions of this experiment were unrepresentative of those expected in a deeper system. At 300 m, the direction of minimum principal stress in the rock at Rosemanowes is vertical; consequently, the fractures that were opened were essentially in the horizontal plane. At depths greater than 400–500 m, the minimum principal stress will normally be horizontal and hence fractures will open preferentially in a vertical plane. It is now recognised that many aspects of the behaviour of shallow fractures (mode of opening, consequent water loss, etc) are different from those at depth. Nevertheless, at the time, the results of Phase 1 gave sufficient confidence in the experimental procedures to justify a second phase of investigation.

1980–1983 PHASE 2A

Phase 2 was an eight-year project in total, aimed at engineering a commercial-scale HDR heat exchanger. However, instead of drilling to the commercial depth of 6 km, it was decided to drill two boreholes to a depth of about 2 km. This reduced the drilling costs and meant that rocks at a temperature of about 80°C would be reached. Phase 2 aimed at engineering a subsurface system with the hope that, if successful, it might have relevance to conditions at 6 km. However, many of the temperature-dependent aspects of reservoir performance at 6 km, such as geochemical and thermal drawdown effects, could not be evaluated directly at 2 km. The rock jointing and stress régime at 6 km depth would eventually have to be determined.

The first part of Phase 2 (ie Phase 2A) lasted from 1980 to 1983 and was funded in part by the Commission of the European Communities. During this period, two boreholes deviated from the vertical by 30° were drilled, in the same plane and spaced 300 m apart at depth, to a depth of 2 km. Figure 3 shows the wellheads at Rosemanowes. Hydraulic fracturing was carried out with water from the lower borehole to try to open up the near-vertical joints rising to and intersecting the upper borehole. When circulation started, the system did not behave as predicted: water losses were excessive and the pumping pressures required for circulation were too high. It was not possible to get within a factor of ten of the target production flow rate of 75 l/s. Examination of the microseismic evidence during stimulation and circulation showed a large 'cloud' beneath each borehole but the pumping and tracer tests showed that inter-connection between the boreholes was poor. To try to improve this connection by further hydraulic stimulation could have risked even greater water losses.

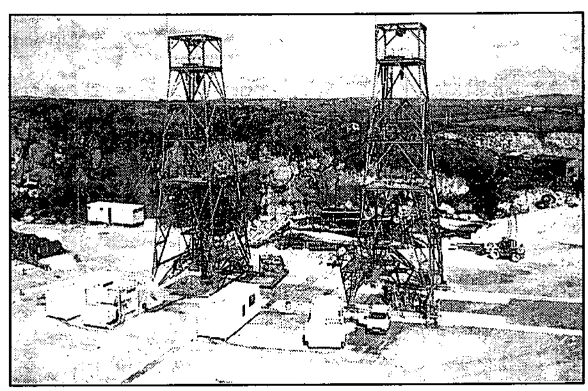

Figure 3 *Towers above production and injection boreholes at Rosemanowes Quarry, Cornwall, UK*
(Photo courtesy Camborne School of Mines)

The technical status of the work at Rosemanowes was reviewed early in 1984 by a group of outside consultants working with CSM staff. They concluded that a number of important technical issues were unresolved:

- how the geological structure (particularly the permeability and variability of rock joints) affects the development of a subsurface heat exchanger
- how the shear stresses affect the permeability of joints at depth
- the role of ambient reservoir pressure in hydraulic fracturing, and how it affects flow rates and water losses.

1983–1988 PHASES 2B AND 2C

Measurements made after the two boreholes (RH11 and RH12) had been drilled at Rosemanowes Quarry showed that the direction of the maximum principal stress in the ground was aligned almost exactly with the borehole deviation – the worst possible alignment for maximising the intersection of the boreholes with the most easily opened joints. Therefore a new borehole (RH15) was drilled at Rosemanowes at the end of 1984 to a depth of 2600 m and along a helical path crossing the microseismic 'cloud' at right angles to the vertical plane of the first two boreholes, to try to get the maximum number of intersections. The Phase 2B programme was started by using a medium-viscosity gel to try to open up the volume between this new borehole and the deeper of the original boreholes.

The circulation programme with the new arrangement at Rosemanowes represents the longest continuous circulation of any HDR system to date. The injection and production flow rates between 1985 and 1989 are illustrated in Figure 4. The results show that Phase 2B was dominated by a gradual increase in the injection flow rate. Measurements in Phase 2C established that impedance fell as the injection pressure and flow rate increased. The upper limit of injection pressure, above which the size of the envelope of microseismicity and water losses increased unsatisfactorily, was demonstrated to be 10 MPa above hydrostatic pressure. This suggested an optimum hydraulic performance at Rosemanowes of:

- injection flow rate 24 l/s
- impedance 0.6 MPa per l/s
- water loss 21%.

This hydraulic performance fell well short of the targets established in 1987 for a deep 'commercial' prototype. However, it was suggested[2] that a prototype might be engineered by combining a number of underground modules in parallel; in this way the system could have the required impedance without being limited to the volume of one module.

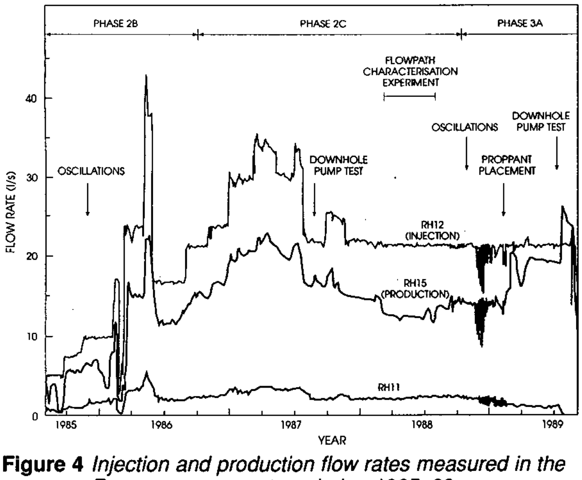

Figure 4 *Injection and production flow rates measured in the Rosemanowes system during 1985–89*

The circulation experiments showed that the new system at Rosemanowes had substantially lower impedance and lower water losses than its predecessor, but its better hydraulic performance had been achieved at the expense of thermal performance[3]. The temperature of water at the top of the production borehole dropped from 80°C to 55°C over a three year period from 1985 to 1988. Thermal modelling following a flow path characterisation experiment (using pulses of injected tracers) indicated the presence of a 'short circuit' between the boreholes. This short circuit through the system significantly reduced its effectiveness as a heat exchanger. The rock surrounding the short circuit had cooled more rapidly than the rest of the reservoir and had introduced colder water to the production borehole.

A review[2, 4] of the HDR R&D programme was started during 1987, towards the end of Phase 2. Its purpose was to consider the current status of the technology and to examine the case for proceeding further. The review was carried out for the Department of Energy by the Energy Technology Support Unit at Harwell and involved all the main contractors in the programme plus members of the Geothermal Energy Steering Committee. It concluded that significant uncertainties remained with the HDR concept, which should be viewed as being still at the experimental stage. A number of specific problems with HDR technology were identified:

- the effective size of the subsurface heat exchanger then available was almost two orders of magnitude smaller than required for a commercial system
- the thermal behaviour of the heat exchanger was unsatisfactory (because of excessive temperature drawdown and short circuiting) and water losses were too large
- the concept of engineering an underground HDR heat exchanger had not been validated
- a commercial system was likely to require the creation of several 'modules' in a multi-stimulation operation. This concept needed validation.

1988–1991 PHASE 3A

The experimental work was continued[5] in Phase 3A with further circulation and other tests at Rosemanowes Quarry. Phase 3 involved no further drilling.

In a downhole pump test in Phase 2C, lowering the pressure in the production well was thought to have closed the joint apertures close to the borehole and increased impedance. An experiment in Phase 3A to place a proppant material in the joints near the production borehole was designed to demonstrate that this effect might be remedied in a deep system. The sand used as proppant was carried into the reservoir as part of a secondary stimulation using a high viscosity (700 cP) gel. This stimulation significantly reduced the water losses and impedance but it also worsened the short circuiting and lowered the flow temperature into the production borehole still further. It was concluded that the proppant technique would need to be used with caution in any attempt to manipulate HDR systems.

An experiment was also carried out in Phase 3A to shut off the section of the production borehole that had been shown by the flow path characterisation experiment of Phase 2C to contain the exit from the short circuit. A temporary packer assembly was installed close to the bottom of the borehole to seal off all the upper parts of the wellbore and a production flow test carried out to measure the flow rate from the low flow zone at the bottom of the borehole under these conditions. The short circuit was sealed off but a very low flow rate was obtained, and a further stimulation carried out from the bottom of the borehole gave no significant increase in flow.

A subsequent interpretation of these results by CSM suggested(6) that the most recently stimulated zone was parallel to, but largely unconnected with, the previously stimulated zone alongside. It was suggested that this result could have a significant influence on HDR design, requiring as many as twenty parallel stimulations (or cells) rather than the five that had been proposed earlier.

Two other important studies were included in Phase 3A:

- RTZ Consultants Limited, assisted by CSM, carried out a conceptual design for a 6 km deep, commercial, HDR prototype power station.
- Sunderland Polytechnic, in association with Sheffield City Polytechnic, developed(7) an integrated spreadsheet model describing the costs and performance of an HDR power station.

The RTZC study and the conclusions from the cost modelling are discussed in the next sections.

CONCEPTUAL DESIGN OF AN HDR POWER STATION

RTZ Consultants Limited (RTZC) were commissioned in April 1989 to perform a conceptual design study for the construction of a deep HDR prototype and associated power generation station in the UK. The work included an assessment of the feasibility of creating an underground HDR heat exchanger suitable for commercial operation and the definition of a programme plan for the development of a deep HDR prototype. Early in this study it was concluded that it was not practical to design a system for a depth greater than 6 km, due mainly to drilling constraints. The RTZC final report(8) was published in 1991.

Geological conditions

RTZC examined the available data and CSM's predictions for the geological, geothermal and geomechanical conditions likely to be encountered at the 6 km depth of an HDR prototype. They concluded that:

- The geological environment at 6 km depth, particularly the characteristics of existing joints and fractures, was highly conjectural and would not be known until drilling to these depths was carried out.
- If technical viability were to be established, it could only be as a result of an extended research programme relevant to a deep HDR system. This would require exploration to, and experimental work at, 6 km depth.
- Even if the technology were demonstrated to be viable, each and every HDR system would, due to geological variations, individually carry significant risk of technical failure as distinct from the certain repeatability of successive units of a conventional generation programme.

Design of the underground heat exchanger

RTZC studied the various experiments carried out by CSM in their attempts to create a working HDR subsurface heat exchanger. They concluded that, even at this advanced stage in the UK's HDR investigations, there was an inadequate understanding of the principles governing underground stimulation and of the engineering techniques required to construct a working heat exchanger:

- Experiments in the granite in Cornwall at 2.5 km depth had shown that it was possible to increase the permeability of a rock mass containing joints and fractures by high pressure hydraulic injection – one form of stimulation. However, the increases so far achieved had not been sufficient to permit flow through the rock with an acceptable level of impedance and, consequently, pumping effort.
- There was a general assumption, implicit behind the use of microseismicity as a predictive tool, that hydraulic connections existed between the injection borehole and recorded seismic events, and consequently that clusters of events represented flow paths. This assumption was unproven and had not been confirmed by flow measurements.
- Flow through the underground system at Rosemanowes had been dominated by the effects of short circuits. These effects were an inevitable consequence of geological heterogeneity and therefore would be a feature of any stimulated rock mass. Successful operation of an HDR system would depend on exploitation and management of these short circuits.
- CSM had argued that the most promising way forward for reservoir creation was by smaller more numerous stimulations than previously proposed. RTZC acknowledged the logic of this but, in the absence of any demonstrable proof by circulation, had based their conceptual design of a deep prototype on five modules.

RTZC conclusions

The main conclusion of the RTZC study(8) was that generation of electrical power from hot dry rock was unlikely to be technically or commercially viable in Cornwall, or elsewhere in the UK, in the short or medium term.

Any expectation of private capital investment in the commercial development of HDR technology in the UK was unrealistic in the foreseeable future.

Plans to construct a deep prototype HDR system in the UK should be shelved indefinitely.

Short and medium term commercial development of HDR technology should be abandoned.

Any meaningful continuation of the UK HDR R&D programme would be costly, uncertain in outcome and therefore difficult to justify but should be directed towards the basic geotechnical aspects of HDR.

ECONOMICS, COSTS AND THE RESOURCE

Resource estimates

Several estimates of the geothermal HDR resource in the UK have been made since 1976, as illustrated in Figure 5. The early estimates were very optimistic and assumed that any technical difficulties would be solved in time. The 1976 calculations[9] predicted that south-west England could yield a total output of medium-grade heat from HDR (at about 200°C), equivalent to 8000 million tonnes of coal (ie about 60,000 TWh). Converted into electricity with an efficiency of 10%, this represented a resource of about 5000 TWh(e).

A strategic review undertaken by ETSU in 1982 indicated[10] that the HDR electricity resource might be between 2500 and 60,000 TWh for depths down to 8 or 9 km in the UK. (Annual electricity generation in the UK is about 250 TWh.)

In 1985, Newton estimated[11] that the UK geothermal HDR resource could provide 20,000 to 130,000 TWh, with a 'credible contribution' to electricity generation of up to 25 TWh/y (10% of present UK electricity demand) for about 800 years. Drilling to a depth of 9 km was then envisaged.

The latest estimate of accessible resource (ie the resource located within the practical limit of borehole drilling – currently set at 6 km) was prepared for the 1990 HDR programme review and is shown in Figure 6. The

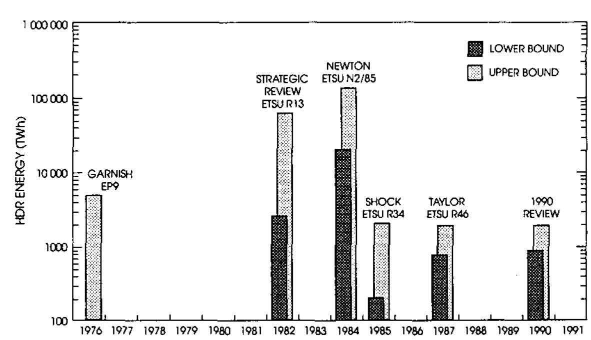

Figure 5 *Estimates of finite UK HDR geothermal resource (electrical equivalent)*

accessible resource is shown as a cumulative function of cost. The data were calculated from temperature distributions provided by CSM and the British Geological Survey and based on extraction using the Sunderland cost model with an 8% discount rate. From this evidence, the geothermal HDR accessible resource in the UK ranges from 900 TWh (for Cornwall alone) to 1880 TWh (for the whole of the UK).

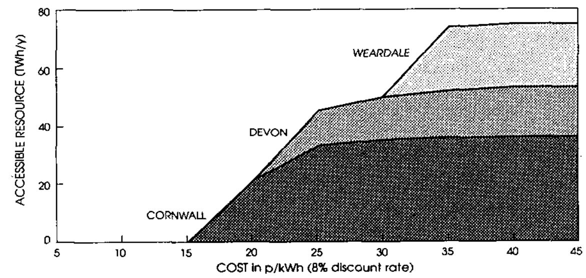

Figure 6 *The UK geothermal HDR accessible resource as a function of cost (1990 values)*

1990 cost estimates

The capital cost of an early post-prototype commercial HDR station was estimated by RTZC to be about £45 million. This is to be compared with the estimate of £35 million from the Sunderland cost model. The RTZC costs are greater due to differences in contingencies (15% rather than Sunderland's 5%), management (7.5% rather than 5%) and other special circumstances. RTZC assumed levels of cost consistent with normal industrial projects and appropriate to an early post-prototype system; Sunderland were more optimistic in this regard.

Sunderland estimated that the cheapest HDR-generated electricity in the UK (ie from south-west England) would cost between 12p/kWh and 19p/kWh (at 1990 prices and for discount rates of 2% and 10% respectively) assuming a plant lifetime of 18 years and a maximum drilling depth of 6 km. The Sunderland design produced 4.5 MW of output power, of which 0.8 MW was needed to pump the circulating water through the boreholes and underground heat exchanger.

The RTZC design produced 3.3 MW of output power and, for an 'optimistic' case, required 0.5 MW of this power for water circulation. For this optimistic case, the equivalent costs for generating electricity in the RTZC design are 19p/kWh and 34p/kWh. (Their lifetime of 20 years included 2.5 years for construction, making it almost equivalent to the 18 year operating lifetime of the Sunderland case.)

RTZC also considered a 'realistic' case, which assumed 1.5 MW to pump the circulating water and a higher impedance in the HDR system. In this case, the power costs became 25p/kWh and 53p/kWh for the 2% and 10% discount rates.

Part of the differences in costs between Sunderland and RTZC resulted from the differences in output power:

RTZC's proposal used currently available 'Ormat' type turbines, whereas Sunderland assumed that higher performance binary cycles would be developed and be available in the long term. Hence, RTZC's cost estimates are appropriate to the short term and Sunderland's results are based upon longer-term developments.

International comparison of costs

A recent study by Tester and Herzog[12] reviewed seven HDR cost studies and developed a generalised HDR economic model to calculate the break-even electricity price as a function of the thermal gradient. Their predictions for the case of today's technology (ie current drilling and completion costs) and for a reservoir performance which would be required for commercial operation are shown in Figure 7. These predictions have been converted to 1990 UK costs assuming a US inflation of 5% from 1989 to 1990 and an exchange rate of US$1.6 to the pound sterling. For comparison, the latest cost estimates by RTZC (their 'optimistic' case) and Sunderland for 10% discount rate and a lifetime of 18 years are included in this figure.

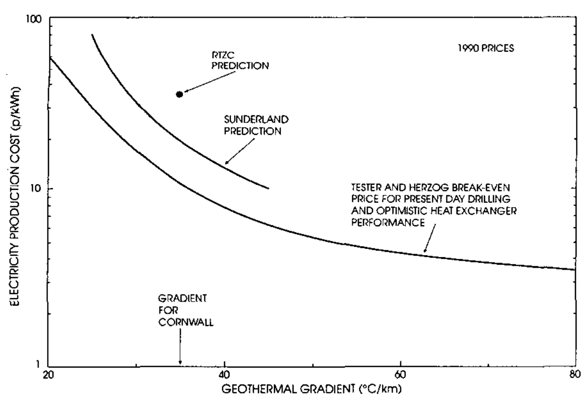

Figure 7 *Electricity production cost as a function of geothermal gradient (after Tester and Herzog)*
The costs predicted by Sunderland and RTZC (optimistic case) are also indicated for 10% discount rate and 18 year life span.

Figure 7 indicates that current forecasts of the costs of HDR electricity production are significantly higher than those made previously. Given the low thermal gradients which exist in the UK, it is now unlikely that HDR will provide an energy source with a wide application. Unless there is a significant technological break-through in an area that cannot currently be foreseen, the costs of generating electricity from HDR in the UK are likely to remain uncompetitive with conventional methods by a large margin.

THE FUTURE OF HDR IN THE UK

Review conclusions

The 1990 UK review of HDR reached the following conclusions:

- A satisfactory procedure for creating an underground HDR heat exchanger has not been demonstrated.
- A satisfactory method for sealing short circuits, other than by mechanical sealing of the production wellbore, has not yet been demonstrated.
- There is no reliable information available about the rock joints and stresses likely to be encountered at the 6 km depths needed in the UK for a commercial HDR system.
- Electricity from commercial HDR power stations is unlikely to be competitive with conventional means of generation in the short to medium term.
- Despite the early promise of the technology, HDR is still at an early stage of development. It is unlikely to attract private sector funding in the foreseeable future.
- Participation in a joint European programme offers the opportunity of resolving some of the technical uncertainties.

Future programme

In 1987 it was thought that, despite the considerable technical uncertainties facing HDR, it might still be possible to construct a 6 km deep prototype in Cornwall in the 1990s. The results of the 1990 HDR review indicate that this option is no longer a feasible proposition. Even assuming that there were successful technical developments in the long term, it is likely that the HDR resource will be much more expensive than other renewables, such as landfill gas, hydro and wind.

So far no country in the world, including the UK, has engineered an underground HDR heat exchanger which has operated successfully, with minimal temperature drawdown over a significant time period. Research into HDR technology requires complicated experimentation and is very expensive. It is therefore considered that a collaborative programme with Europe might be the best way of investigating this difficult problem over the next few years.

A decision was therefore announced by the UK Department of Energy on 1 February 1991 to direct future UK HDR work towards a collaborative research and development programme in a European partnership involving France, Germany and the European Commission. The Department of Energy is providing £3.3 million of further funding over the period 1 January 1992 to 31 March 1994 for the current phase of the UK HDR programme. Any decision on further major investment in an experimental prototype will be taken towards the end of this time, when feasibility studies of various possible sites in Europe have been completed.

The new UK R&D programme will have the following objectives:

- to improve the understanding of HDR technology in a collaborative European programme
- to further understand the costs, performance and resource size of HDR

- to carry out a programme of technology transfer
- to provide independent monitoring of seismic activity in south-west England.

An industrial consortium, which includes RTZC and French and German companies, has been formed to help co-ordinate the European programme. One of their first tasks is to evaluate the feasibility studies of the various European sites prior to any investment in a European HDR prototype.

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