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INTERNATIONAL CONFERENCE ON HOT DRY ROCK GEOTHERMAL ENERGY

Abstracts (with program)

DMR PUBLICATIONS COMPACTUS
(LENDING SECTION)

edited by
Doone Wyborn

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AUSTRALIAN GEOLOGICAL
SURVEY ORGANISATION

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International Conference on Hot Dry Rock Geothermal Energy

**Abstracts
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**edited by
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**Australian Geological Survey Organisation
Record 1993/72**



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DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

Minister for Resources: Hon. Michael Lee, MP

Secretary: Greg Taylor

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Executive Director: Harvey Jacka

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PROGRAM

INTERNATIONAL CONFERENCE ON HOT DRY ROCK GEOTHERMAL ENERGY

Tuesday 5th October

Chairman, Dr Larry Harrington

9.00AM **Opening:** Mr Harvey Jacka, Executive Director, Australian Geological Survey Organisation.

9.10AM **Dr R. B. Godfrey**, Managing Director, Energy Research & Development Corporation:
Energy research - a critical investment for the future.

9.50AM **Professor Paul Morgan**, Department of Geology, Northern Arizona University:
Geothermal processes and geothermal energy in the earth.

10.50AM **Morning tea**

11.10AM **Dr James A. Stimac**, Earth & Environmental Sciences, Los Alamos National Laboratory: The HDR concept, its resource base, and potential.

12.10PM **Mr R. C. Stewart**, Senior Seismologist, Rabaul Volcano Observatory, Rabaul, PNG:
HDR research in the UK and Europe.

12.50PM **Lunch**

Chairman, Professor Paul Morgan

2.00PM **Dr James A. Stimac**, Earth & Environmental Sciences, Los Alamos National Laboratory: Towards commercial HDR development: research in the USA.

3.00PM **Associate Professor J. P. Cull**, Department of Earth Sciences, Monash University:
Heat flow and geothermal energy in Australia.

3.40PM **Afternoon Tea**

4.00PM **Mr Stephen Kelemen**, Manager, Petroleum Development, Santos Ltd.: The Cooper Basin - characteristics and deep drilling.

4.30PM **Mr Colin Gatehouse, Senior Geologist, Department of Minerals and Energy, South Australia:**
Geological history of the Warburton Basin.

5.00PM **Dr Doone Wyborn, Senior Research Scientist, Australian Geological Survey**
Organisation: Geothermal gradients in the Cooper Basin area, and HDR potential.

Wednesday 6th October

Chairman, Dr Wally Johnson

9.00AM **Dr Prame Chopra**, Senior Research Scientist, Australian Geological Survey Organisation:
Hydraulic fracturing - a key technology in HDR.

9.30AM **Dr Michael Swift, Director/Senior Geophysicist, Applied GeothermEx Pty Ltd.:**
Fundamental reservoir modelling and production from geothermal reservoirs.

10.10AM **Professor Bruce Chappell**, Department of Geology, ANU: Heat producing elements in granites of southeastern Australia.

10.40AM **Morning Tea**

Chairman, Professor Bruce Chappell

11.00AM **Dr Robyn Johnston, Senior Research Scientist, Bureau of Resource Sciences:** Is there a radiation risk associated with generation of geothermal energy from a high heat producing granite?

11.30AM **Dr James A. Stimac**, Earth & Environmental Sciences, Los Alamos National Laboratory: The new US HDR project area, Clear Lake, Northern California.

12.30PM **Lunch**

Chairman, Dr Jim Stimac

2.00PM **Mr Ronald W. Wise, Chairman, Cape Range Ltd: Kalina Cycle power systems for geothermal hot rock applications.**

2.40PM **Discussion** - where to from here? CRC? pilot development?

HEAT PRODUCING ELEMENTS IN GRANITES OF SOUTHEASTERN AUSTRALIA

B.W. Chappell, Department of Geology, Australian National University

Granites comprise 30% of the area of the Lachlan Fold Belt (LFB) of southeastern Australia. The geochemistry of these rocks has been studied more intensively than that of similar rocks from any other region. Abundances of the heat-producing elements (HPE) have been determined on more than 2000 samples and these data provide an opportunity to study the behaviour of those elements during the evolution of granites and the chemical fractionation of the crust.

Granites of the LFB have been divided into two main types, those derived from the partial melting of igneous or infracrustal rocks, the I-types, and of sedimentary or supracrustal rocks, the S-types (Chappell & White, 1992). These two types are present in approximately equal amounts in the LFB. A-type granites, with distinctive abundances of some trace elements, make up a third minor group (<1%). The varying types of chemical fractionation shown by the two major groups provide a basis for studying the evolution of HPE abundances in granites.

Mean and maximum concentrations of K, Th and U for the I-, S- and A-type granites of the LFB are given in the following table.

| Number | All granites 2027 | | I-type 1109 | | S-type 716 | | A-type 56 | |
|--------|----------------------|------|----------------|------|---------------|------|--------------|------|
| | mean | max | mean | max | mean | max | mean | max |
| K % | 3.14 | 4.80 | 2.90 | 4.66 | 3.40 | 4.80 | 3.85 | 4.57 |
| Th ppm | 19.7 | 46 | 20.0 | 43 | 18.6 | 46 | 25.1 | 22 |
| U ppm | 5.0 | 122 | 4.6 | 122 | 5.1 | 43 | 5.3 | 39 |

A-type granites have the highest mean levels of the HPE because they are an intrinsically more felsic group of rocks. They are also the least variable type and the HPE never rise to the high values found in the other two types.

I- and S-type granites both show two distinct types of fractionation, which may occur sequentially within a single series of rocks. In one case, variation in composition is dominated by the separation of melt from unmelted source rock (restite) with neither component undergoing significant changes in composition during that process. This is exemplified by the S-type Bullenbalong Supersuite of the Canberra region and in such rocks the concentrations of HPE do not rise to high levels. In the other case, fractional crystallisation may lead to significant increases in the abundances of HPE. However, the I- and S-type granites show contrasting behaviour. In the former, the three HPE increase and such granites provide the best prospect for concentration of all three elements. In the S-types, Th decreases in amount with fractionation. In all cases, U concentrations may be extremely variable in the most fractionated rocks due to the effects of weathering and the observed U contents of a rock need not be a direct indication of the abundance of that element at deeper levels in the Earth. However, there are other chemical features that would enable such high U rocks to be identified with some confidence.

The fractionated S-type granites of Wagga Batholith show remarkable compositional similarities with the granites of the Cornubian Batholith and provide significant insights into the evolution of those other rocks, not locally available in a classic area of hot dry rock studies.

Chappell, B.W. & White, A.J.R., 1992. I-type and S-type granites in the Lachlan Fold Belt. *Trans R. Soc. Edinburgh: Earth Sciences* 83, 1-26.

HYDRAULIC FRACTURING - A KEY TECHNOLOGY IN HDR

Prame Chopra
Australian Geological Survey Organisation
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Hot Dry Rock (HDR) energy extraction schemes are generally premised on the creation of inter-connecting fractures between adjacent boreholes. These fractures provide a path for the fluid that is used to extract heat from the hot dry rock. They can be produced by a technique called hydraulic fracturing.

Hydraulic fracturing is extensively used in the petroleum industry to aid in the extraction of hydrocarbons from sedimentary rocks. The technique has also been used in scientific studies of rock stress in a wide variety of rocks, including granites. The rock stress studies on granites have direct applicability to HDR in areas beneath the Eromanga Basin as they illustrate that the orientation of fracture patterns can be readily predicted.

The hydraulic fracturing technique uses a special borehole tool composed of three parts: an upper and a lower sealing packer assembly and a central fracture interval. By inflating the two packers until they form tight seals on the borehole wall, the intervening section of borehole can be effectively isolated from the remainder of the hole. Fluid can then be injected into this isolated section causing the pressure to rise until a fracture or fractures are induced in the borehole wall.

In the absence of any pre-existing weaknesses in the rocks of the borehole wall, the orientation of the induced fractures will be controlled, in a well understood manner, by the state of stress in the rocks. Indeed this is the basis for using hydraulic fracture testing to determine the state of in-situ stress in rocks.

However, pre-existing features such as fractures, joints and shear zones can directly influence the orientation of induced fracturing if a propagating fracture encounters one. These features can also indirectly influence the propagation direction by perturbing the local stress field. Both these effects can be minimised by the judicious choice of the borehole interval to fracture. This can be done by examining any recovered core and by studying the rocks around the borehole using geophysical techniques (e.g. formation density, porosity, radar).

The hydraulic fracturing technique has been used selectively in this way to determine in-situ stress levels in a number of boreholes in granites in eastern Australia. In several cases, multiple tests have been performed at different depths in the same borehole. What has emerged from all these tests is a fairly consistent picture of the state of in-situ stress in the rocks of eastern Australia. This is another way of saying that the orientation of hydraulically-induced fractures in granite in eastern Australia can be predicted with some confidence when the rock has first been characterised.

HEAT FLOW AND GEOTHERMAL ENERGY IN AUSTRALIA

J.P. Cull, Monash University, Clayton, Vic 3168

Heat flow data were first obtained in Australia by Newstead and Beck (1953). Since then, data have been accumulated mainly as part of academic and ad-hoc programs concerned with regional tectonics. Compilations have been published by Sass et al (1976), Lilley et al (1978), and Cull (1982). Sass et al (1976) were able to define three principal domains centred on the Precambrian, the Central Shield, and the Cainozoic eastern margin. Cull and Denham (1979) were able to demonstrate additional regional correlations with other geophysical data.

Systematic trends are observed for Australia with heat flow values close to 40 mW/m^2 in Western Australia increasing beyond 100 mW/m^2 in the east. Most of this trend can be attributed to variations in erosion and the elimination of radiogenic fractions from the outer crust in each province. However more complex anomalies are suggested for the Cainozoic consistent with recent volcanism and residual heat associated with different mechanisms for crustal evolution. In particular some NS trends in the eastern province may be attributed to southwards younging of volcanism complicated by underplating of the crust (Cull et al., 1991).

There are few prospects for conventional high enthalpy geothermal energy systems in Australia. Variations in surface heat flow can be anticipated for areas subject to recent tectonism but the geothermal gradient in each province can be generally related to systematic trends in thermal conductivity. High geothermal gradients can be expected in many sedimentary basins particularly where there are significant coal measures acting as thermal insulators (Cull and Conley, 1983). These systems are normally considered to represent geothermal energy prospects of low enthalpy. Hot water can be extracted directly for applications in space heating and industry for processing of materials. One such system has been developed at Portland in Victoria.

At present there has been no extensive exploitation of deep aquifers in the major sedimentary basins. Boiling water is extracted and cooled for domestic use from 1000m bores near Quilpie in Queensland. However deeper aquifers are documented and temperatures exceeding 150°C are encountered in oil exploration wells. Consequently there may be no clear division between low enthalpy and high enthalpy resources other than final application. Low level generating systems have been trialed at Mulka in South Australia (Collins, 1987) and deeper systems capitalising on hot rock technology may be viable for major power stations.

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GEOLOGICAL HISTORY OF THE Warburton Basin

C. G. Gatehouse

Department of Mines and Energy, Parkside, SA 5063

The pericratonic early Palaeozoic Warburton Basin is known to contain early Middle Cambrian to Late Ordovician clastic sediments, carbonates and volcanics. They rest on Willyama Supergroup to the south and on the Arunta Block to the north. Mid Carboniferous granites, the Big Lake Suite, were emplaced at several locations.

Early Cambrian strata occur near Maria to the west and in the Arrowie Basin to the south; they have not yet been positively identified within the basin. The accompanying figure shows the stratigraphic units and lithotypes so far recognised.

The Mooracoochie Volcanics is the oldest known unit but the presence of siltstone in Coongie 1 beneath them suggests older sediments. One stratigraphic interpretation places clastics of the Pando Formation beneath the Mooracoochie Volcanics; another (see figure) places the 'Pando Sandstone' within the Early Ordovician. Alternatively, they may be separate units. Sedimentation of the Kalladeina Formation was predominantly in a shallow marine environment. Adjacent slope facies of organic rich muds with lithified limestone from the shallower shelf are present and are interbedded with basalt, tuff and ignimbrite. Carbonates predominated in the Late Cambrian.

The Ordovician is represented by a variety of siliciclastic lithotypes. Shallow-marine sandstone from the Gnaltia Shelf passes northward into green siltstone and black, pyritic shale in the Tilpree Trough. These sediments comprise the Dullingari Group. Red bed siltstone and sandstone of the Innamincka Formation border the Arunta Block in the north and pass southward into the Tilpree Trough via a major deltaic complex.

The structural style of Warburton Basin sediments, as depicted by the 'Z-Horizon' structure contour map, is strongly influenced by Late Devonian deformation (Alice Springs Orogeny) and mid-Carboniferous granite intrusion (Big Lake Suite). The arcuate NE trends of the Gidgealpa, Merrimelia and Innamincka Ridges, and the Dunoos and Murteree Ridges, are products of this structural overprint.

The direction of the Cambrian rift is not known with certainty, but is suggested to strike NW, parallel to - or as an extension of - the Koonenberry Fault Zone in western NSW. The sedimentary history of the Wonominta Block appears to be closely allied to that of the eastern Warburton Basin and warrants detailed comparative study.

ENERGY RESEARCH - A CRITICAL INVESTMENT FOR THE FUTURE

**Dr R Bruce Godfrey
Energy Research and Development Corporation**

The world is faced with a number of critical economic, social and environmental issues based on or derived from the delivery of energy. Energy underlies the quality of life of a nation's citizens, with higher quality of life generally being accompanied by increasing energy intensity.

For benefits to accrue to nations, it is now being recognised that there is a substantial requirement for additional effort which must be directed primarily towards ensuring the effective application of research results for social and economic benefit. While such considerations may appear obvious, it has not always been so.

Research - defined broadly as any activity in the concept to commercialisation continuum - is critical to the success of the present thrust for development of competitive Australian industries. It provides the key to maintenance of existing competitive advantages, and the development of new competitive advantages for and between Australian industry and social sectors, and in export markets.

Of course it is true that substantial funds are often expended on research with little, if any, resultant benefit to the funding entity - be they government or industry. This is the nature of research however, and no one should be surprised by this fact.

A goal for Australia should be, and increasingly is, to enhance the effectiveness of research. To be effective for Australia, research must deliver:

- timely solutions to priority problems;
- social, economic and/or environmental benefits; and
- appropriate products and services

which Australia can exploit to:

- maintain existing competitive advantages; and
- create new competitive advantages

To achieve the goal of increasing the effectiveness of energy R&D and to reduce the gap between research and adoption of the results of research projects, there is a need to pool government and industry resources and increase the degree of interaction between researchers and the potential end users. Research expenditure - whether by industry or government - is an investment which demands a return. It should not be a discretionary expense.

Uniting industries' needs with public and private sector researchers' skills is required to effect world-class quality product delivery to maximise economic and environmental benefits.

IS THERE A RADIATION RISK ASSOCIATED WITH GENERATION OF GEOTHERMAL ENERGY FROM HIGH HEAT PRODUCING GRANITES?

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Generation of geothermal energy from high heat producing granites uses heat generated by decay of radioactive elements U, Th and K. It is reasonable, then, to ask whether there is a radiation risk associated with the energy generation process, which involves pumping water through the hot dry rock (HDR) reservoir to absorb heat from the rock and extracting the thermal energy at the surface.

There are two potential mechanisms by which radioactive elements can enter circulating fluids and so be carried to the surface: release of radon gas; and dissolution of long-lived isotopes (particularly U, Th and Ra). Levels of radionuclides associated with granite HDR reservoirs are discussed here, with particular reference to potential levels from an HDR reservoir in the Cooper Basin, and compared to recommended maximum levels (Table 1).

Radon emissions

Of the three naturally occurring Rn isotopes, only ^{222}Rn (half-life = $t_{1/2} = 92$ h) is sufficiently long-lived to pose a problem in an HDR reservoir; ^{220}Rn ($t_{1/2} = 55$ s) and ^{219}Rn ($t_{1/2} = 4$ s) decay to negligible levels in less than 10 minutes after separation from their parent nuclides, and so have disappeared before circulating fluids reach the surface.

The concentration of Rn in fluids circulating through an HDR reservoir is controlled by: the flux of radon from fracture surfaces; the dimensions of the fractures; and the residence time of the fluid in the fractures (to account for in-growth of Rn). For any given fracture, the activity of Rn ($[\text{Rn}]$) in the fluid can be calculated by

$$[\text{Rn}] = [\text{Rn}]_0 e^{-\lambda t} + 2F(1 - e^{-\lambda t})/w \quad (\text{Bq m}^{-3})$$

where $[\text{Rn}]_0$ = initial Rn activity of the fluids (Bq m^{-3}); F = Rn flux ($\text{atoms m}^{-2} \text{s}^{-1}$); w = crack width (m); λ = decay constant for ^{222}Rn ($2.10 \times 10^{-6} \text{s}^{-1}$); t = transit time of fluids in the fracture (s) (Andrews *et al* 1986).

The flux of radon from fracture surfaces (F) depends both on the content and distribution of U and ^{226}Ra . The release of ^{222}Rn to groundwater occurs dominantly by alpha recoil from decay of ^{226}Ra . Enrichment of U and/or ^{226}Ra on fracture surfaces and grain boundaries due to remobilisation or alpha recoil processes can considerably enhance Rn emanation (Krishnaswami *et al* 1988; Torgersen *et al*, 1990). Experimental measurements of ^{222}Rn flux from granite surfaces support this: the average flux from the Cammenellis granite (average U content = 13.5 ppm) was measured as $30 \text{ atoms m}^{-2} \text{s}^{-1}$ (Andrews *et al*, 1986) compared to $1100 \text{ atoms m}^{-2} \text{s}^{-1}$ from the Stripa granite ($U = 44.5 \text{ ppm}$), where much of the U was present as uraninite in microfractures (Andrews 1982).

The surface area exposed for alpha recoil escape is controlled by fracture dimensions and geometry, specifically the ratio of fluid volume to surface area, which is inversely proportional to the average

fracture width (Torgersen *et al* 1990). Fractures in granites vary greatly, from microfractures to major joint planes, each defined by a characteristic width and transit time. Smaller fractures have both greater surface area to volume ratio and slower flow, resulting in higher activities of Rn in solution, however, microfractures may play little role in active circulation systems. Davis (1969) considered the probable minimum hydrologically conductive crack width to be 1 mm, but Richards *et al* (1992) calculated average crack width at the Rosemanowes HDR test site to be 0.5 mm.

The mean Rn content of return fluids from the total reservoir flow depends on average residence time of fluids, given by integration of the flow curves. Flow characteristics of the reservoir are entirely site-specific, and must be derived from tracer studies. A maximum value for Rn concentration is given by the equilibrium value

$$[\text{Rn}] = 2F/w$$

which is attained if the transit time is more than a few half-lives of Rn (90% of equilibrium concentration is attained in 3.3 half-lives=304 hours). Integral mean residence times at the Rosemanowes site in Cornwall are of the order of 150-240 hours (Richards *et al.* 1992).

Granites beneath the Cooper Basin have U contents around 15 ppm (D. Wyborn, pers. comm.), and it is reasonable to expect that the Rn flux (F) will be of the same order of magnitude as for the Carnmenellis granite from the Rosemanowes test site (say 50 atoms $\text{m}^{-2} \text{s}^{-1}$). Using a crack width of 0.5-1 mm, a reasonable maximum estimate for activity of ^{222}Rn in circulating fluids is 100-200 kBq m^{-3} , similar to measured levels of Rn in production fluids at the Rosemanowes HDR pilot project of 50-200 kBq m^{-3} (Richards *et al.* 1992).

The uncertainty involved in estimating Rn concentrations in groundwater is very high, since the variability is dominated by site-specific rock properties (Torgersen *et al.* 1990). Estimates of both flux rate and crack width can vary by up to two orders of magnitude, and resulting dissolved Rn activity could be much higher, particularly if microfractures are important in fluid transmission.

The rate of release of Rn gas at the surface (by venting of gases during extraction of heat from circulating fluids) is proportional to the flow rate, which depends on reservoir characteristics and pumping regimes. Flow rates for the Rosemanowes test site range from 5-38 l s^{-1} (Richards *et al.* 1992) and for Fenton Hill test site are 1-14 l s^{-1} (Duchane 1992). Assuming flow rates of 20 l s^{-1} ($0.02 \text{ m}^3 \text{s}^{-1}$), release rates of Rn gas from a test site are likely to be 1-2 kBq s^{-1} . Flow rates at a fully operational plant may be considerably greater, and Rn release rates will be proportionally higher. Whether this would result in concentrations greater than the recommended limit for ^{222}Rn in air of 740 kBq m^{-3} is crucially dependent on dispersion patterns, which are controlled by micrometeorological patterns. Leach and Chandler (1992) observe that in arid Australia, stable conditions resulting in nocturnal inversions are very common, resulting in a stagnant near-surface layer 5 to 10 m thick at night. Under these conditions, very high levels of Rn could accumulate, even from natural Rn emissions from soils. Thus, in designing vent systems it is important to ensure that the vent is placed above the level of the inversion.

Dissolution of long-lived isotopes

Circulation of hot fluids through a geothermal reservoir presents the possibility of dissolution of U and Th bearing minerals and release of radio-isotopes into the fluids. Sufficient dissolution of wall rock occurs in HDR pilot plants to measurably affect fluid chemistry (Richards *et al.* 1992; Pauwels *et al.* 1992). In this context it is the longer-lived isotopes which are of most concern, particularly U, Th, and

Ra isotopes. The extent of dissolution of these isotopes will depend on the mineralogy and distribution of U and Th bearing phases, the composition and temperature of the circulating fluids, and the ratio of fracture surface area to volume of fluid (related to crack width as above). Temperatures over 200°C are expected in a HDR facility in the Cooper Basin. The discussion of U, Th and Ra solubility given below uses data for reactions at 25° C; in general, increased temperature is likely to enhance dissolution processes.

It is difficult to predict the chemical composition of fluids circulating through a granite HDR reservoir. Injection waters for an HDR reservoir would generally be dilute, near-neutral and oxidised. After injection, fluids are modified both by mixing with indigenous groundwaters and by interaction with the rock. Groundwaters in granites are usually dilute, mildly alkaline (pH 7-8), Na-SiO₂-HCO₃ dominated, oxidising near the surface and reducing at depth (White *et al.* 1963), but concentrated Na-Ca-Cl brines with low pH (5-6) occur at depth in Canadian (Fritz and Frape 1982) and French granites (Pauwels *et al.* 1992). Observations at operating HDR pilot plants indicate that production fluids become enriched in Na, SiO₂, HCO₃, Cl and sometimes SO₄; pH varied from 8.5 at Rosemanowes to 6.5 at Fenton Hill (Rodrigues *et al.* 1992) and 5.7 at Soultz-sous-Forêts (Pauwels *et al.* 1992). Fluids with low pH and abundant complexing ligands may occur.

Enrichment of U-bearing phases along fracture surfaces and grain boundaries in granites, observed by Gascoyne *et al.* (1988) and Nelson *et al.* (1975), enhances release of daughter nuclides. In addition, significant amounts of U and Th daughters can be released without substantial dissolution of host minerals if alpha recoil processes are important. The ratio ²³⁴U/²³⁸U is often greater than 1 for groundwaters in granite terrains and may be as high as 10 (Andrews 1982, Gascoyne 1988) indicating that daughter products are more mobile than parent isotopes.

Thorium occurs in granites mainly in zircon and phosphate phases such as monazite and allanite. Solubility of these minerals in natural waters is extremely low and Th in solution tends to form the insoluble hydroxide, so concentrations of Th in solution are often below detection limits in natural waters. Complexing of Th by sulphate, fluoride, phosphate and organics increases Th solubility markedly below pH 8, but Th concentrations in natural waters rarely exceed 10⁻³ mg l⁻¹ (0.004 Bq m⁻³ ²³²Th) (Langmuir and Herman 1980). Very high concentrations of Th are reported from acid sulphate waters associated with uranium tailings (up to 38 mg L⁻¹ = 1.55 x 10⁵ Bq m⁻³; Moffet and Tellier 1978), exceeding the recommended maximum of 7.4 x 10⁴ Bq m⁻³, but it is unlikely that groundwaters in granite systems would reach the required pH (<2) and ²³²Th is not likely to pose a major problem. Because of their higher activity, the mass of ²³⁴Th, ²³⁰Th and ²²⁸Th required to reach safe limits is negligible (<10⁻⁵ mg l⁻¹), so release from host minerals, rather than solubility of Th, is the major control. The availability of ²³⁴Th and ²³⁰Th is determined by dissolution of U-bearing minerals, and may be enhanced by disequilibrium processes.

Uranium is present in granites mainly in zircon, monazite and allanite, and uraninite if U contents are high. Uranium solubility is strongly controlled by redox conditions: under oxidising conditions, the uranyl (U(VI)) species are stable, which are several orders of magnitude more soluble than U(IV). Solubility is enhanced by the formation of carbonate complexes at pH 7-10, phosphate complexes at pH 4-7.5, and various cationic and uncharged complexes below pH 4.5. Uranyl minerals are least soluble in the pH range 5-8, and sorption is also at a maximum in this range (Langmuir 1978). Although U concentrations in groundwaters are generally low, Gascoyne (1988) reports very high concentrations of U (up to 840 mg l⁻¹ = 10⁴ Bq m⁻³) in granite groundwaters in Manitoba under oxidising conditions with high HCO₃, and where U is preferentially enriched on fracture surfaces. This is comparable to the recommended maximum of 3.7 x 10⁴ Bq m⁻³. The possibility of significant dissolution of U cannot be ruled out, particularly as increased temperatures are likely to enhance dissolution, but high

concentrations were observed only in shallow groundwaters; deep groundwaters tend to be reducing with low U contents.

Radium-226 is sited with U but alpha recoil and other disequilibrium processes may concentrate ^{226}Ra along fractures and grain boundaries, enhancing its availability for solution. Radium concentrations in natural waters are low, since Ra is readily removed from solution by adsorption on clays and silicates, and by coprecipitation with insoluble sulphates. Radium appears to be stabilised in solution by high concentrations of Ca^{2+} , Mg^{2+} and Cl^- , concentration increasing with total dissolved solids (Langmuir and Melchior 1985). Andrews (1982) reports ^{226}Ra concentrations up to 26640 Bq m^{-3} in deep mine waters in Cornish granites and Gascoyne (1988) reports 38000 Bq m^{-3} in very saline deep groundwaters in granites in Manitoba, both significantly higher than limits set for ^{226}Ra in waters (370 Bq m^{-3}). If circulating fluids mix with highly saline groundwaters at depth or attain high salinities (with high Ca contents) by reaction with host rocks, sufficient ^{226}Ra may be taken into solution to pose a radiological hazard.

Conclusion

The likelihood that radionuclide levels in circulating fluids in a granite HDR reservoir will exceed recommended limits is not high, but the possibility does exist that ^{226}Ra and ^{222}Rn could approach recommended limits, particularly if U in the host rock has been preferentially redistributed along fracture surfaces. However, the importance of site-specific factors in determining nuclide behaviour precludes accurate predictions and it is important that the appropriate observations and tests be included in a pilot program.

Table 1: Maximum permissible concentrations in air inhaled and water ingested by a member of the public, from the Australian Code of Practice on Radiation Protection in the Mining and Milling of Radioactive Ores (Department of Home Affairs and Environment, 1980)

| Contaminant | Maximum permissible concentration (Bq m^{-3}) | |
|---|--|-------------------|
| | In water | In air |
| Uranium (^{238}U and ^{234}U) | 3.7×10^4 | |
| Thorium (^{232}Th and ^{230}Th) | 7.4×10^4 | |
| Thorium-230 | 7.4×10^4 | |
| Radium-228 | 1.5×10^3 | |
| Radium-226 | 3.7×10^2 | |
| Radon-222 | 7.4×10^5 | 3.7×10^3 |

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THE COOPER BASIN - CHARACTERISTICS AND DEEP DRILLING

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The Cooper Basin lies in the north-eastern corner of South Australia and the south western portion of Queensland. It covers an area of some 100,000 square kilometres and underlies the more extensive Eromanga Basin which covers some 1 million square kilometres in Central Australia. In the Cooper Basin area both the Cooper and Eromanga Basins are known for their oil and gas discoveries and production, with the Cooper Basin being predominantly gas and the Eromanga Basin predominantly oil.

The first discovery was gas in the Cooper Basin at Gidgealpa in 1963. This was followed by Moomba in 1966. Some 1350 wells have been drilled in the Cooper/Eromanga Basin with some 500 fields having been discovered and delineated. There is a significant gathering system network with oil and gas being produced from some 300 fields. In South Australia all oil and gas production is gathered through the Moomba processing plant which annually processes some 170 Bcf sales gas to Adelaide and Sydney and, 460 thousand tonnes LPG and 10 million barrels of crude and condensate which is piped to the coast. In Queensland the oil production of 5 million barrels annually is gathered through Jackson where it is transported by pipeline to Brisbane.

The Cooper Basin contains sediments of Permian-Triassic age comprising several cycles of fluvial sandstone, fluvio-deltaic coal measures and lacustrine shales. The basin generally overlies a granitic basement. The sandstone reservoirs are generally of low permeability and some 150 fracture stimulations have been carried out to enhance and improve recovery. The basin is also noted for its high geothermal gradient with temperatures in the producing fields ranging from 120°C to 175°C.

The Nappamerri Trough in the centre of the Cooper Basin is the hottest and deepest part of the basin. Five wells have been drilled in the Nappamerri Trough with the deepest being 4000m. The temperatures recorded in the Nappamerri Trough range up to in excess of 200°C.

KALINA CYCLE POWER SYSTEMS FOR GEOTHERMAL HOT ROCK APPLICATIONS

Hank Leibowitz, Vice President, Engineering, Exergy, Inc.
delivered by Ron Wise, Chairman, Cape Range Ltd.

Kalina cycle systems have been designed for all variations of geothermal resources. Ammonia-water mixtures are used in conjunction with novel, highly recuperative features to provide substantial improvement in efficiency and generation costs.

The designs can accommodate low temperature, liquid dominated resources in the 165°C range, as well as high temperature (above 200°C), steam/liquid streams. Geothermal fluid used in hot rock applications will more likely require utilisation of the high temperature design.

Liquid Dominated Sources

Kalina cycle system 11 (KCS11) has been developed for liquid dominated applications. A flow diagram is presented in Figure 1. The design is straight-forward, uncomplicated, but very effective. A working fluid consisting of approximately 80% ammonia and 20% water is evaporated and superheated in HE-3 and HE-5, respectively, by the geothermal brine. The brine is injected back to the resource at 80°C. Because the working fluid evaporates at variable temperature, it matches the brine cooling characteristic very closely.

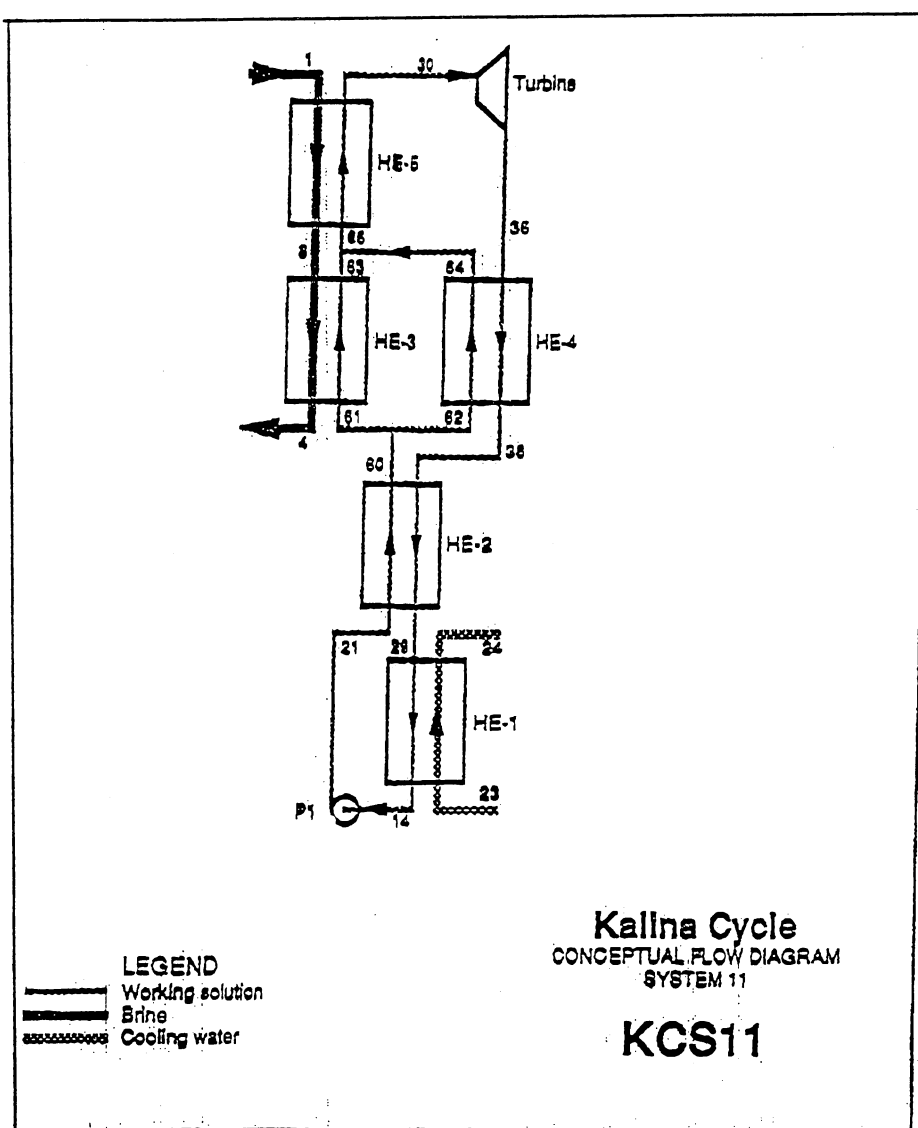


FIGURE 1

After being superheated to a temperature approximately 8°C below the incoming brine, the ammonia-water vapour is expanded through a conventional, axial steam turbine. The expansion rate is very modest, approximately 5:1, thereby keeping the number of turbine stages to a mere 3 or 4. No large diameter condensing stages are required because the back pressure is always above atmospheric. At a 24°C ambient, the exhaust is 10 bar. Furthermore, the similarity between the molecular weight of ammonia (17) and water (18) makes conventional steam turbines an excellent choice for ammonia-water operation.

After leaving the turbine near saturation, the vapour enters HE-4 where condensation begins. Within the heat exchanger tubes, there is ammonia-water liquid that is evaporated and then sent to HE-5 to complete vaporisation and superheating. The ability to recuperate heat from the turbine exhaust to vapourise part of the working fluid is unique. In conventional systems, the turbine exhaust can only be used to preheat liquid. This feature is achieved by the judicious use of mixtures at the proper composition. It is a patented feature of this system.

After leaving HE-4, the vapour continues to condense in HE-2, giving up its heat for liquid preheating. Complete condensation is effected in HE-1 where an ambient cooling source (air or water) is used. The amount of heat recuperated is HE-4 and HE-2 is about 40% of all the heat transferred to the working fluid. Therefore, only 60% needs to be delivered by the brine. The improvement in plant economics due to this feature is obvious; the cost of resource development is reduced significantly.

Performance

Using a 165°C source against a 24°C air sink, the brine utilisation is 149 lbs. per kW-hour, or 67.7 kg/kWh. This is based on output at the generator terminal but does not include parasitic loads associated with the resource gathering system. Compared to isobutane and isopentane Rankine cycles operating in the U.S., the KCS11 produces approximately 40% more output per unit of brine delivered to the plant. In the 25 MWe size, engineering studies conducted by Exergy and Calpine Corporation (a major geothermal developer in the U.S.) have concluded that KCS11 systems can be installed for (US)\$1400/kWe, not including the resource. We believe this to be 30-40 percent less than comparable hydrocarbon plants built in the U.S.

Reno Project

Exergy, Inc., the developer and licensor of the Kalina cycle technology, has recently embarked on the first Kalina geothermal plant. It will produce 24 MWe, net, and will be located just south of Reno, Nevada, in a region called Steamboat Hot Springs. The geothermal source is 156°C liquid. Exergy has been awarded a grant of \$7.2 million by the U.S. Department of Energy as a result of winning a competitive solicitation for advanced geothermal power schemes.

The plant will be designed and constructed by ABB Lummus Crest, Inc. on a commercial, lump sum turnkey basis. Performance, price and schedule are guaranteed. Commercial operation is scheduled to begin by December, 1995.

High Temperature (HDR) Applications

For high temperature, two phase streams, a different design, KCS13, is necessary. The utilisation of the flashed steam with the high temperature liquid fraction in an integrated manner is the main feature of KCS13. Instead of the steam and liquid being processed in separated plants, i.e., flash and binary, they are combined in a novel hybrid design. At this writing, the design is not yet available for public dissemination.

A comparison of KCS13 with a double flash plant reveals that KCS13 produces about 30-40 percent more output per unit of geofluid processed. For hot dry rock applications, the improvement should be even greater, because the geofluid will be cleaner than the brine found in natural formations. This will allow greater cooling of the geofluid to the benefit of KCS13.

GEOTHERMAL PROCESSES AND GEOTHERMAL ENERGY IN THE EARTH

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Geothermal processes, perhaps with a small contribution from gravitational energy release processes, are thought to be responsible for the basic energetic process of the solid earth. These energetic processes include earthquakes, volcanoes, plate tectonics, generation of mountain belts, and generation of the earth's magnetic field. An analysis of the magnitudes of these processes suggests that although the manifestations of geothermal processes are only obvious in relatively small areas of the surface of the earth, such as plate margins and intra-plate hot spots, by far the greatest loss of geothermal energy occurs by thermal conduction through the earth's lithosphere. Thus, the largest potential reservoir of geothermal energy is distributed throughout the terrestrial lithosphere as hot rock.

In most oceanic lithosphere, the thermal energy released through thermal conduction is primarily a function of the cooling of this lithosphere after its formation by sea-floor spreading at oceanic ridges. In continental lithosphere, however, energy released through thermal conduction originates both from heat transferred into the base of the lithosphere from the underlying mantle, and heat generated within the lithosphere by radioactive decay of natural unstable isotopes. The most important unstable isotopes for heat generation are isotopes of uranium, thorium and potassium which tend to be concentrated in the upper continental crust. There is also a large variation in the lateral concentrations of these isotopes and analyses of both heat flow and heat generation data suggest that they contribute from less than 5% of the surface heat flow in some basaltic terranes to greater than 65% of the surface heat flow in some granitic terranes. On average, they contribute approximately 40% of the surface heat flow. Thus, although the heat transferred into the base of continental lithosphere reflects underlying asthenospheric processes, heat flow from the surface is further complicated by crustal chemistry. Using this understanding of lithospheric heat flow, a strategy may be developed to identify the most favourable conditions under which near surface thermal reservoirs may be located.

HDR RESEARCH IN THE UK AND EUROPE

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European research into Hot Dry Rock Geothermal Energy has been spearheaded by Camborne School of Mines, Cornwall, UK and, since 1992, by CSM Associates Ltd.

Following initial results from the Los Alamos project, the UK's Department of Energy funded research at Camborne to explore the HDR potential of the high-heat-production granite that underlies SW England. In 1976, four shallow wells, 300 m deep, were drilled to establish that water circulation was possible. The Geothermal Energy Project was then established in 1980 to create a demonstration system that could be used to test techniques needed for full-scale HDR exploitation. Two, later three, wells were drilled to over 2 km depth where rock temperatures exceed 100°C. They were successfully linked using hydraulic stimulations and were circulated at injection rates of up to 35l/s for a period of over three years.

A large number of tests were carried out during the stimulations and circulation period. These led to pioneering work in stimulation design, seismic monitoring, borehole geophysics, tracer techniques and numerical modelling. Much of this research required custom-built borehole tools which were designed and built in-house.

During the 1980's, smaller-scale HDR projects were set up in Germany, France and Sweden. The results from these complement the results from Camborne and Los Alamos but also demonstrate that no two HDR projects are identical.

In the 1990's the focus in Europe has switched to a joint research effort between the UK, France and Germany. Most of the experimental work has been at the Soultz-sous-Forêts site in Alsace, France. Here, a hydrocarbon well has been extended to 2 km depth, 600 m into a granite. Four other wells have also been extended into the granite for the deployment of seismic sondes. A number of stimulation and injection tests have been carried out using this well, as well as active seismic experiments to characterise the rock-mass. There are, as yet, no plans to create a circulating system.

THE HDR CONCEPT, ITS RESOURCE BASE, AND POTENTIAL

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The Hot Dry Rock (HDR) concept was developed almost 20 years ago at Los Alamos National Laboratory, U.S. The basic idea is to extract, or mine thermal energy from rock that is hot, but does not contain sufficient natural fluids for conventional geothermal development. Engineering a HDR system entails: (1) drilling one or more injection wells into a region of hot, and relatively impermeable rock, (2) creating an artificial reservoir by hydraulic stimulation, and (3) connecting the reservoir to one or more production wells. A continuous flow loop is set up by injecting water into the system under high pressure. After heat is extracted from a working fluid that has traversed the reservoir, it is re-injected into the system, augmented by "make-up" water to offset losses to the reservoir. Research-oriented HDR systems have been engineered in the U.S. (Fenton Hill), Western Europe (Cornwall), and Japan (Hijiori, Ogachi, Iatate), but whether such systems can produce energy at competitive prices remains to be proven by further testing of these systems or their next generation.

Of all nonrenewable energy sources only HDR and nuclear fusion can potentially meet the world's projected long-term needs (Armstead and Tester, 1987, E.&F.N. Spon). The worldwide HDR resource base may be as great as 10^8 quads (1 quad equals 10^{15} BTU or about 10^{18} Joules or 3×10^{11} kWh), compared with a worldwide fossil fuel resource base of about 3.6×10^5 quads, and an annual worldwide consumption of about 300 quads. The HDR resource base can be divided into high- and low-grade depending on geothermal gradient, which in turn depends on crustal thickness, lithology, and heat and magma flux from the mantle. High-grade resources are most accessible by conventional drilling, whereas development of low-grade resources will await reduction in the cost of deep drilling. In regions of relatively high heat flow (about 16% of the continental land masses) only a very small fraction of the thermal energy is exploitable through conventional geothermal development, thus HDR resources exceed those of conventional geothermal by about three orders of magnitude. Tapping of this large resource potential currently awaits convincing evidence that HDR systems can be engineered and operated at a profit in today's competitive energy market. Factors which make HDR attractive include:

- (1) a very large and widely distributed resource base,
- (2) its potential as a source of domestic energy production (and jobs) in countries that lack large fossil fuel reserves, and
- (3) its low environmental impact (if properly designed and managed). These features will make HDR development increasingly attractive as the long-term environmental costs of fossil fuel energy production become more apparent.

TOWARDS COMMERCIAL HDR DEVELOPMENT- RESEARCH RESULTS IN THE U.S.

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Between 1974 and 1987, two successful HDR reservoirs (Phase I and II) were engineered and experimentally tested at Fenton Hill, NM by Los Alamos National Laboratory. The Phase II reservoir is centred at 3.6km depth and has a temperature of 220-240°C (430-460°F). The reservoir is connected by two wellbores about 100m apart and has a flow-connected volume of $16\text{-}20 \times 10^6 \text{m}^3$. During the period 1987-1991, a surface facility, built to power plant standards, and capable of extended operation was constructed. The plant, which was designed for reservoir testing rather than power generation, is completely automated and instrumented for detailed data collection. A series of recent flow tests of the system (1992-1993) included 112 and 56 day tests conducted under steady-state conditions. These tests were run at the highest injection pressure that could be sustained (27.6 MPa or 4000 psi) without significant reservoir growth and water loss. The tests indicate that: (1) thermal drawdown of the resource did not occur (production at 183°C), (2) access to hot rock appeared to increase as the test proceeded, (3) water loss was in the range 7-12% of the injected volume, (4) the circulating fluid contained little dissolved solids and entrained gases (TDS < 4000 ppm), and (5) thermal energy was produced at \$0.81/10⁶ BTUs (1.9-2.8 cents/kilowatt-hour electric).

Remaining uncertainties to commercialisation of HDR in the U.S. include: (1) can creation of larger and lower impedance reservoirs be achieved, (2) can energy be extracted from such reservoirs at a sustained and useful rate on a long-term basis (ie. 10-30 years), (3) can HDR technologies be customised for a variety of geologic settings and host rock types, and (4) can capital and operating costs be further reduced to make heat mining an economically competitive source of energy. New research and development efforts should focus on thorough resource evaluation, enhanced drilling and reservoir mapping technologies, staged development (eg. modular reservoirs), more efficient power plants and optimised reservoir operations, and the possibilities of hybrid systems (eg. mixed geothermal and HDR). Strategies for maximising reservoir performance might include pressure propping of fractures, multiple production wells, cyclic operations, high back pressures and combined techniques. Risks associated with site-specific unknowns, combined with large up-front capital expenditures remain the greatest impediments to commercial HDR development. These obstacles can be overcome by continued cooperation between governments and industry in a climate where the long-term environmental costs of energy production are considered. Therefore, the climate for HDR development should improve as the direct and long-term costs of fossil fuel use increase, and as the costs of HDR and deep drilling technologies decrease.

The HDR resource base of the U.S. has been estimated at >10⁶ quads, compared to an annual energy consumption of about 80 quads (Tester, 1992, GRC Bull., 21). Of this huge potential resource, 10% is considered high-grade (thermal gradients of >80°C/km), 30% is mid-grade, and 60% is low-grade. At present only high-grade HDR resources are economically recoverable in the U.S., restricting near-term development mainly to the western half of the country. Lower-grade resources should become economic if advanced drilling technologies are developed.

MAGMATIC AND THERMAL STRUCTURE OF THE CRUST IN THE CLEAR LAKE AREA, CALIFORNIA: IMPLICATIONS FOR HDR DEVELOPMENT

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With conductive thermal gradients ranging from 80-120°C/km over an area of 750 km², and the lack of convectional geothermal reservoirs, the Clear Lake area of California is one of the best prospects for hot dry rock (HDR) geothermal development in the U.S. This talk summarises what we know about the magmatic system at Clear Lake, and what implications this has for HDR site selection. Emphasis is placed on the distribution of volcanism through time, and the chemical, mineralogical, and textural features of Clear Lake magmatism. The nature of upper crustal magma bodies at Clear Lake is inferred from studying sequences of closely related silicic lava flows. These lavas tell a story of multi-stage mixing of silicic and mafic magma in clusters of small reservoirs. Some mafic to intermediate lavas at Clear Lake also contain crustal xenoliths which provide information about deeper levels of the magmatic system. The xenolith suite includes noritic to gabbroic cumulates as well as high-grade metamorphic rocks. Together, these rocks probably represents fragments of gabbroic intrusions and their contact aureoles. Preliminary thermobarometry on granulites yields temperature and depth estimates of ~800-900°C and 12-18 km. Metasedimentary xenoliths also exhibit partial melting textures, providing direct evidence for assimilation in the deep crust. The chemical and isotopic signatures of volcanic rocks also confirm that extensive mixing of mantle and crustal components was an important petrogenetic pathway to silicic magmas.

Thermal modelling based on petrologic and geophysical constraints provides a test of petrologic models, and yields insight into the relationships between observed thermal gradient and magma chamber size, abundance, and emplacement history. A user-interactive 2-D numerical model was developed to study conductive/convective heat flow in and around magma bodies, allowing for host rocks of various compositions and physical properties. Using the Mt. Konocti sequence as a test case, a number of conductive thermal models based on petrologic constraints were constructed. Conductive models that are broadly consistent with the petrologic history and observed thermal gradients of the Mt. Konocti area imply a combination of high background gradients, shallow silicic magma bodies (roofs at 4-5 km), and/or magma chamber volumes exceeding the "1:10 rule of thumb" of Smith and Shaw (1975, 1978, USGS Open-File Reps. 726 and 790). Models that allow convection in regions above magma bodies permit deeper emplacement, lower regional gradients, and smaller volumes, but gradients drop off abruptly at the edge of convective regions. Consideration of the Clear Lake magmatic and geothermal systems generally supports the view that: (1) mafic magmas were injected into the lower crust on a regional scale, (2) only a small fraction (<10%) of the silicic magma produced from the deeper, dominantly mafic system at Clear Lake has been erupted, and (3) hydrothermal convection is a minor contribution to the high regional thermal gradient and heat flow.

FUNDAMENTAL RESERVOIR MODELLING AND PRODUCTION FROM GEOTHERMAL RESERVOIRS

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The extraction of heat from a Hot Dry Rock (HDR) geothermal reservoir for economic exploitation is possible, but problematic. As the name suggests, the reservoir is dry - a characteristic which causes the greatest impediment to its exploitation. The extraction of heat is achieved by the introduction of cool water and its subsequent withdrawal at a higher temperature. This however alters the basic nature of the thermal reservoir. It can no longer be considered 'dry' and thermal depletion will eventually cool the thermal reservoir. The final outcome will inevitably be a cold wet rock which has little or no economic viability. The following discussion outlines the fundamental mathematics for the economic extraction of the heat. In its development, the discussion places some emphasis on the postulated HDR reservoirs from the Cooper Basin, central Australia.

The main requirement of production of heat from a HDR reservoir is that it is economically viable. The economics determine the rate at which heat is drawn from the HDR. A typical economic strategy for a HDR geothermal power plant is shown in Table 1 below. The fundamental assumption in the economics is that a 30 megawatt (MW) power station can be supported for a period of 30 years. The other economic assumptions are also outlined in Table 1. Monetary returns have been calculated for two cases; firstly if a return in excess of 8% is required and secondly if a return over 25% is required. The table shows that the project will gross 1.5 billion dollars and return 320 million dollars for the first case (a typical government utility scenario), but only 40 million dollars for the second case (a typical private enterprise investment scenario). The economics appear favourable, however this can only be said if the other assumptions in the table are correct. Variations upward in the CAPEX reduce the expected return markedly. Having now determined a viable economic strategy this discussion will now limit itself to the problem of drawing 30 MW from a HDR geothermal

reservoir for a period of 30 years.

| | | | | | |
|----------------------|---------|------------|-----------------------|---------|----------|
| Drilling cost | 5.00 | \$ million | Cumulative generation | 5475000 | MWhr |
| Completion cost | 0.25 | \$ million | Initial generation | 500 | MWhr/day |
| Connection cost | 0.10 | \$ million | Decline rate | 1 | |
| No of wells | 2 | | | | |
| Surface installation | 4.00 | \$ million | | | |
| Generating plant | 36.00 | \$ million | | | |
| Year of discovery | 1995 | | | | |
| Production commences | 1996 | | Electricity price | 0.12 | \$/KWhr |
| Plant life | 30 | years | Price escalation | 1.05 | |
| OPEX | 2.91 | \$/MWhr | OPEX escalation | 1.05 | |
| Royalty | | | | | |
| Dollars of the day | 1522.64 | \$ million | Start up cost | 490 | \$/MW |

CASE 1: TYPICAL GOVERNMENT UTILITY SCENARIO

| | | | | |
|---------------|--------|------------|------|--------------------|
| Discount rate | 8 | % | | |
| NPV | 320.22 | \$ million | 5.85 | Cents/million MWhr |

CASE 2: TYPICAL INVESTMENT SCENARIO

| | | | | |
|---------------|-------|------------|------|--------------------|
| Discount rate | 25 | % | | |
| NPV | 39.53 | \$ million | 0.72 | Cents/million MWhr |

TABLE 1 Economic analysis of HDR geothermal electricity power generation with 30 MW peak generation and income from 70% base load.

A 30 MW power station is by today's standards, a small power station. The power station generator would be turned by a steam turbine. The source of the heat to generate the steam would be from the heated water from the HDR geothermal reservoir. The energy budget that could be harnessed from the hot water is illustrated in Figure 1. This figure shows the heat content held by water for various temperatures and pressures. Steam turbines are most efficient when the steam is super heated, giving energy transfer efficiencies of up to 60%. To readily achieve this the temperature of the steam needs to be over 450°C. Such temperatures would only be expected between six and eight kilometres (Middleton, 1979, Gallagher 1987) in the Cooper Basin area. Therefore, it would seem appropriate to aim for a formation temperature of 250°C. Rocks at such a depth should lie at shallow enough depths (about 5 kilometres) to be easily and economically reached by drilling, with the savings from shallower drilling making up for reduced power generation.

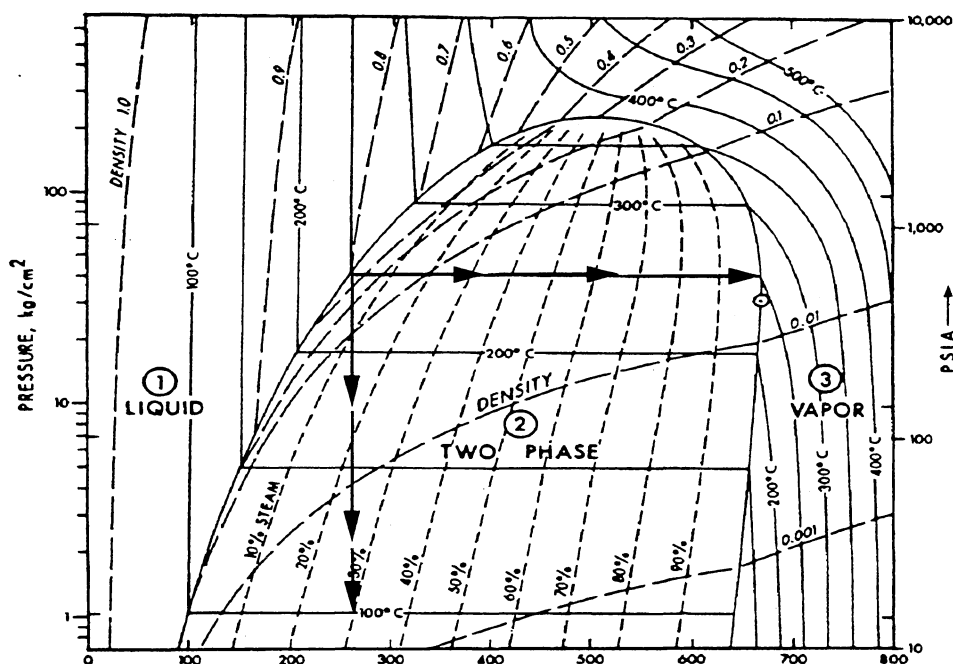


Figure 1 Heat content for pure water and steam. (Edwards et al, 1982). Bottom axis is enthalpy in calories per gram. 4.187 cal/gm is equivalent to 1000 Watt/seconds per kilogram.

With a supply of high pressure water at about 300 kg/cm² at a temperature of 250°C there are two ways of producing steam for use in a turbine, these are indicated in Figure 1. The first method is to flash to steam by reducing the pressure. This is indicated by the vertical line on the figure. Unfortunately for every 10 kilograms of hot water only three kilograms of steam will be produced. This in itself is of little concern with an unlimited amount of water. However as will be shown later there is a limit to the amount of water that can be drawn from a HDR reservoir without greatly effecting the exit temperature. The most deleterious effect of flashing is that the residual water and steam temperature

is reduced to about 100°C, this is far too low for efficient use in a turbine.

The alternative is to use a heat exchange, whereby the extracted hot water boils another body of water. This is indicated by the horizontal line in Figure 1. With a heat exchange system, super heated steam at a pressure of 40 kg/cm² and temperature of about 240°C can be produced for turbine use. Heat exchangers are very efficient, however it can be seen from Figure 1, and from the consideration of conservation of energy; for every 10 kilograms of water produced from the HDR thermal reservoir only four kilograms of steam will be produced. This is however better than flashing as there is the added advantage of having higher temperature steam. In summary, one kilogram per second of steam at 240 degrees will yield 825 kilowatts (kW) of power from which the turbine will deliver 60% or 495 kW. With a heat exchanger 2.5 kilograms of hot water is required to boil 1 kilogram of steam. Thus for a 30 MW power station a supply of 150 litres per second is required. The requirements that this flow rate places on the geothermal reservoir are discussed below.

The possible thermal reservoir exploitation strategies are shown in Figure 2. The basic requirement is for two wells to be drilled into the HDR. One well is used to inject cool water (usually the lower well), the second is used to extract the heated fluid. Between the wells the fluid is transferred under pressure along the fractures that are common to each well, being heated as it does so. The temperature that the fluid exits the system depends on a large number of factors. The mathematical equations which govern the heat transfer, and hence the final exit temperature of the fluid can be summarised as;

$$(\rho C) \delta_t T = \delta_x (K_x(x) \delta_x T) + \delta_z (K_z(z) \delta_z T) - \rho_f C_f U \phi \delta_x T - \rho_f C_f V \phi \delta_z T + S$$

$$U = - \left(\frac{k_x}{\mu} \right) (\delta_x P)$$

$$V = - \left(\frac{k_z}{\mu} \right) (\delta_z P + \rho_f g)$$

where ρ is composite rock-fluid density, the fluid density is denoted with a subscript f, C is the heat capacity of the rock-fluid composite, the fluid heat capacity is denoted with a subscript f, T is temperature, K is the thermal conductivity, k is the permeability, Φ is the porosity, S is the internal heat generation, x and z are the spatial dimensions (horizontal and vertical respectively), t is the time dimension, U is the fluid velocity in the horizontal direction, V is the fluid velocity in the vertical direction, μ is the fluid viscosity and g is the force due to gravity.

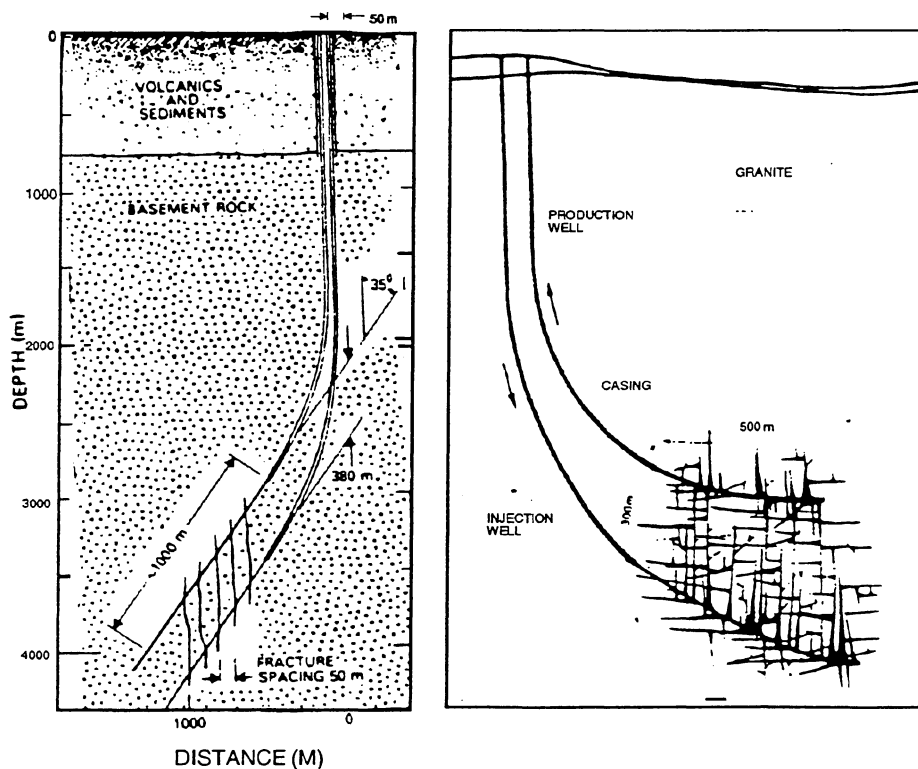


Figure 2 Concepts for HDR reservoir structures between two boreholes (Smith et al., 1985; Batchelor, 1982).

The solution of the equations stated above is very sensitive to the physical parameters that are characteristic to any one HDR geothermal reservoir. The primary aim of modelling the geothermal reservoir is to ascertain what the highest possible flow rate of hottest water can be sustained over a long period of time. However, some general comments on the sensitivity of the solutions can be made. First the system is wholly dependent on the permeability. If there is insufficient permeability fluid will not flow at the required rate or in the worst case there will be no flow. It can be stated unequivocally that the permeability is the most critical factor in extracting heat energy from HDR geothermal systems. As HDR reservoirs are normally granitic, they do not have sufficient natural permeability for fluid movement. If the HDR rock reservoir permeability cannot be increased then energy extraction will be impossible.

The heat transfer from rock to fluid is dominated by conduction. Fluid movement is needed only to extract the heated fluid from the reservoir. The heat exchange in the system will be controlled by the thermal diffusivity of the rock. The thermal diffusivity is defined as;

$$\kappa = \frac{K}{\rho C}$$

This relationship is fundamental in that it helps to quantify the temporal rate at which heat can be extracted from the thermal system without undue temperature loss (thermal drawdown). If temperature changes occur over a time τ , then these changes will propagate a distance of the order of $\sqrt{\kappa\tau}$. More importantly for geothermal exploitation a time l^2/κ is required for temperature changes to propagate a distance l . For example it takes a temperature change 12 days to travel one metre. Therefore in a period of 30 years it would only be possible to sample the heat within radius of about one kilometre. Given the time scale needed to extract all the heat, and the corresponding time scale for the heat to return, geothermal energy can be regarded as a non-renewable energy source within the volume of the sampled rock. The total available energy within the affected radius that is available is about 5×10^8 MW/hr, which is about 2 orders of magnitude above the requirement for the proposed 30 MW power

station with a total of 5×10^6 MW/hr over 30 years, see Table 1.

Not only does the volume of the rock from which the heat is being extracted need to be large, but similarly the total surface area exposed to the moving fluid needs to be maximised. This is due to the slow rate of heat transfer through the rock, which can only be overcome by decreasing the distance the heat needs to travel before it can be conducted into the convecting fluid. Per pair of wells, the area must effectively approach one million square metres for a power generation in the order of 30 MW (Tester et al, 1989). Returning to Figure 2, it is evident that the reservoir on the right has the largest fracture surface area due to the added presence of horizontal fractures. Consequently it represents a better geothermal reservoir, however horizontal fractures are usually only present in shallow granitic bodies. Kruger et al (1992) studied the thermal drawdown as a function of fracture spacing and showed that there is negligible thermal drawdown when mean fracture spacing is of the order of 25 to 50 metres or less. A reduced surface area will result in a rapid drawdown of the temperature for any given flow rate. As can be seen from Table 1 a reduction in the flow rate may not be possible for economic reasons, as less electrical power could be generated.

An advantage of HDR rock heat extraction is that the thermal reservoir can be enhanced. Higher temperatures can be reached simply by drilling deeper. Reservoir permeability can be improved by increased hydraulic fracturing. Wallroth (1992) reports the possibility of increased fracture permeability occurring during production from a HDR geothermal reservoir. The fracturing is a consequence of pumping in cold water under pressure through the injection well. A flow rate of 150 litres a second of water through a HDR geothermal reservoir is a moderate target if a sufficient permeability can be distributed evenly through a relatively small volume of rock.

Whilst it is possible to create a thermal reservoir with the configuration required to generate electrical power economically there are other factors that may positively influence the viability of HDR technology. These include; improved heat

extraction via the Kalina cycle, government subsidies or tax incentives that would improve project economics. In the case of the Cooper Basin, co-generation with a gas turbine or the utilisation of hot thermal waters from the Great Artesian Basin would increase the efficiency of the system. A system where water is pumped down through the rock from the uppermost well, should also increase the sustainable exit temperature of the fluid.

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GEOHERMAL GRADIENTS IN THE COOPER BASIN AND HDR POTENTIAL

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Since 1960 over 800 wells have been drilled into the South Australian section of the Cooper Basin. Their average depth has been 2.5 kilometres and the average geothermal gradient is 46°C/kilometre. The highest gradients occur in the central part of the Basin (Kantsler et al., 1983) in the Nappamerri Trough, where the depth to basement is 3 to 3.6 kilometres, and the basement contains a significant proportion of Carboniferous (Gatehouse et al., 1993) high heat producing (HHP) I-type granites. Gradients as high as 62°C/kilometre occur above these granites in the Burley 2 well, where a bottom hole temperature of 253°C was measured at 3707m depth. The few analyses of the granites (Middleton, 1979) indicate uranium contents around 15ppm, thorium 50ppm and K 5%, well within the range of high heat producing granites. Contour maps defining the geothermal gradients indicate that an area between Moomba and Innamincka forms a thermal anomaly measuring 60km by 35km. HHP granites have been intersected in wells on the margins of this anomaly, but the centre of the anomaly has not yet been tested. Relatively impermeable fluvio-deltaic coal measures and lacustrine shales in the overlying Cooper Basin provide the ideal insulating blanket for these granites. The blanket traps heat generated from both radioactive decay and from heat brought up from greater depths by the thermally conducting granites.

The HDR geothermal potential of the Cooper Basin area was first brought to public attention by Koch (1985), when he stated that "the Cooper Basin must be one of the most significant geothermal areas in the world". Economic exploitation of this energy source in order to generate electricity is favoured in this area by a number of factors over areas heated by young magmatic activity, such as the western United States. These factors include:

- 1) relatively inexpensive drilling to rocks with a temperature of 200°C in soft sedimentary formations.
- 2) a dispersed heat source which does not require expensive detailed subsurface exploration.
- 3) a simple granitic heat reservoir, the homogeneity of which allows controlled and predictive hydraulic fracturing.
- 4) uncomplicated faulting.
- 5) low seismic activity.

Two industries in the local area, the Moomba processing plant and the Olympic Dam Mine, require large amounts of electrical energy on a long term basis. These industries could directly benefit from the setting up of a pilot plant in the area, but much greater benefits would flow to the nation as a whole if such a plant was to prove successful.

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