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THERMAL MODELLING OF LONG TERM CIRCULATION OF MULTI-WELL DEVELOPMENT AT THE COOPER BASIN HOT FRACTURED ROCK (HFR) PROJECT AND CURRENT PROPOSED SCALE-UP PROGRAM.

Robert Vörös[1], Ralph Weidler[1], Lambertus de Graaf [2] and Doone Wyborn[3]

[1]Q-con GmbH, 76887 Bad Bergzabern, Germany
[2]Panax Geothermal Pty Ltd, Sherwood, Queensland 4075, Australia
[3]Geodynamics Limited, Milton, Queensland 4064, Australia
e-mail:voeroes@q-con.de

ABSTRACT

The remote location and extensive HFR resources of the Cooper Basin, Australia, require large scale multi-well exploitation as the optimal means of development. There is estimated more than 1,000 km^2 of granite with a temperature of greater than 250ºC at 4,400m. A combination of overthrust stress conditions and overpressured fractures has resulted in extensive stimulations in horizontally oriented fracture systems during fluid injection (hydraulic stimulation). Additionally fracture systems stacked on each other have been stimulated independently with low connectivity in the vertical plane. This leads to the possibility of developing stimulated fracture systems that extend over many square kilometres, with many injection and production wells operating within the fracture systems.

A conceptual model based on the current understanding of the geology and fracture hydraulics was implemented using the commercial finite element software package FEMLAB® and “in house” Q-con development of the package. In the model injection and production wells were spaced up to 1,000 m apart in triangular or square grid patterns. Flow in stimulated fracture zones in the depth range 4,200 m to 5,000 m was simulated for a triangular pattern of 43 wells and a square pattern of 41 wells with a total flow of 600 kg/second for the well field per fracture zone. With a 1,000 m well spacing the well field covers 31 km^2 for the triangular pattern and 32 km^2 for the square pattern. From the model were computed: pressure distribution, flow distribution pumping pressure, temperature decline over time, thermal power, and temperature distribution in the rock matrix. The modelling shows that for a 1,000 m well spacing the production well temperature decline will be approximately 12ºC over 20 years. and 40ºC over 50 years. The life of a power station would be greater than 50 years with this temperature decline**.**

On the basis of the model a scale-up program has been developed once the “proof of concept” Habanero doublet circulation testing has been completed. The initial scale-up will be a 7-well program producing 40 MWe.

INTRODUCTION

Geodynamics has been operating a hot fractured rock (HFR) project in the Cooper Basin since 2003. One of the main attractions of this site for large scale geothermal development lies in the great extent of known high temperature granitic basement rocks below 3km depth. These have been outlined by decades of oil and gas exploration in the cover rocks. However the location is remote from the electricity market being more than 400 km from a strong connection to the Australian electricity grid. It is likely that large scale development is required to satisfy connection to the electricity market.

To date two wells have been drilled (Habanero 1 and 2) into granite basement to 4,400 m and 4,350 m respectively. The rock temperature at this depth has been confirmed at 250°C. Hydraulic stimulation in the granite has been carried out in both wells, monitored by a network of eight three-component borehole seismometers covering an area of 42 km^2 (Baisch et al., 2006). The stimulations have been highly successful and have demonstrated that:

- Near-horizontal fracture systems are preferentially stimulated over steeper fractures.
- Repeated stimulation from the same location with a time break between stimulations both extends the reservoir and re-stimulates the existing reservoir.
- An aerial extent of more than 4 km^2 has been stimulated in what is known as the main fracture system.
- Fracture systems stacked vertically and only 150m apart behave almost independently implying very little vertical fluid flow in this thrust faulting stress regime.

These understandings from the fracture stimulations provide a basis for developing a multi-well thermal model which is necessary to justify continued expansion of the facility leading to electricity production and connection to the electricity grid.

NUMERICAL MODEL

The model was established to investigate both the hydraulic and thermal behaviour of a multi-well geothermal field under various geometrical and operational conditions.

To set up the simulator, first a geological model for a subsurface heat exchanger was required. The model is primarily based on the results of the seismic monitoring of hydraulic stimulations and the analysis of various hydraulic tests conducted in the Habanero wells. It is further supported by numerous pTS logging profiles. This model is not finally confirmed yet. Clear logging images of the fracture zone and a circulation test are still missing, which leaves remaining uncertainties. It is further unknown at which frequency similar structures will be found at greater depth. The latter is relevant for scaling up the results towards a multi-layer stacked reservoir.

The large scale field simulation was run with different well field patterns. Two simple base-modules were chosen and larger aerial patterns were built by lining up the base-modules in lateral directions. The well field patterns contain more than 40 wells and cover an area of 15 km^2 - 30 km^2.

A simulation of continuous fluid circulation over a time frame of at least two decades was required to investigate the long-term performance. The performance of the different models is compared with respect to the temperature decline of the produced fluid, the thermal power output and the pressure differences between production and injection wells.

Geological Model

A geological model for the reservoir (heat exchanger) has been constructed based on results of the analysis of hydraulic tests in 2003 and 2005, the seismic monitoring of the stimulations in 2003 and 2005 (Baisch et al., 2006) and various pTS logging profiles in the Habanero 1 and 2 wells. According to these results a slightly dipping planar structure with a well defined vertical extension could be identified at a depth of approximately 4.3 km. This structure forms a highly permeable hydraulic conduit connecting the two Habanero wells which are 500 m apart.

The geological model of a heat exchange layer forms the base element for all computations in this study. Assuming that stimulation treatments at different depth intervals allow the development of additional layers with similar properties (e.g. by applying diversion techniques or by drilling to greater depths), the results for a single layer can be simply scaled up by the amount of layers present in the final state of the reservoir. Doing so, the temperature gradient in the rock is to be considered, though. As temperature increases with depth, variable initial temperature differences between the fluid and the rock occur for different layers. In addition, a thermal interference between the layers must be excluded. Various simulations were run to estimate the minimum distance between the layers required to avoid a significant interference. For a 20 years operation we found that a separation of 100 m or more is sufficient to use this simple extrapolation approach.

Since our models were computed for a total layer thickness of 100 m, in principle the computational results with respect to the mean power output can be scaled up by a maximum factor of 9 based on nine layers each 100m apart. Based on observations in other HFR projects though, the number is not likely to exceed 2-4 layers within the given depth interval. In this case, the thickness of the individual layers might be larger than 100 m and our results can be regarded as a conservative estimate for the thermal behaviour since an increase in layer thickness would also tend to increase the thermal long-term performance.

Well Pattern

Economical and technical aspects

The selection of a suitable exploitation concept with respect to the geometrical well pattern is a multi-variable optimization problem. Several counteracting technical and economical aspects have to be reconciled. Ignoring any geological heterogeneity in the reservoir for the time being, the exploitation concept is essentially depending on the separation between the producers and the injectors and the geometrical shape of the well-field pattern. A key reservoir management challenge is to develop a geothermal field in such a way that the two following criteria are met:

- Minimization of the pressure difference between production and injection wells to minimize operational costs related to the pumping power.
- Minimization of the temperature decline of the working fluid over the lifetime of the reservoir to keep the system operational from an economical point of view.

Generation of the well-pattern

The approach chosen in this study is to consider two relatively simple geometries, a triangle and a square. The base module is created by placing wells at the corners and in the centre of these geometries. Subsequently, the final pattern of the well field is generated by aligning the base modules to allow a complete coverage of the exploitation area.

The first base-module is an equilateral triangle with a central injection well and 3 production wells at the apices. The model calculations use a distance R between the centre and the apices of 700 m and 1,000 m. For the 1,000 m case the triangle covers an area of 1.3 km^2 with a side length of 1.7 km.

The second base-module is a square, again with one central injection well but 4 production wells at the vertices. As in the case of the triangle, the distance R between the centre and the vertices is 700 m in one set of calculations and 1,000 m in a second set. For the 1,000 m case the resulting side length is 1.4 km and the total area covered by the square is 2.0 km^2.

The models needed to be set up in such a way that boundary effects could be considered effects of second order. These considerations finally resulted in a number of wells greater than 40 for each pattern and an aerial extension in the order of 15 – 30 km^2. The geometry of the final patterns reflects the shape of their accordant base-modules (Figure 1). These are

- A hexagonal pattern consisting of 24 triangular base modules.
- A square pattern consisting of 16 square base modules.

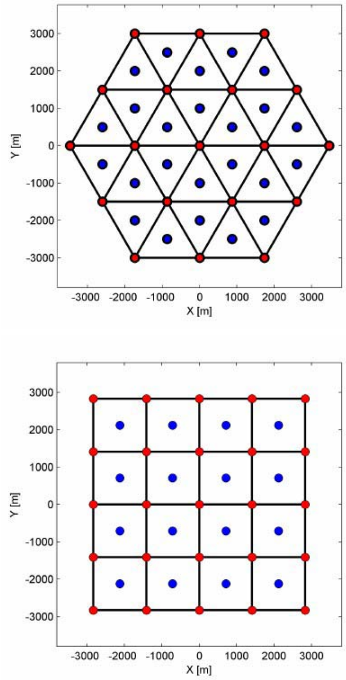

Figure 1: Hexagon pattern (top) and square pattern (bottom) for the 1,000 m well separation.. The ratio of injection (blue) to production (red) wells is 24/19 for the hexagon and 16/25 for the square.

The ratio of injection to production wells is 24/19 = 1.26 and 16/24 = 0.67 for the hexagon and the square, respectively. As this value differs quite significantly, also the inverse patterns were considered. These are generated by simply permuting injection and production wells. A summary of the geometrical parameters is given in Table 1.

Table 1: Geometrical Parameters

Parameter	Symbol	Value	Unit
Total width heat exchange layer	h1	100	m
Depth top layer	z1	4.2	km
Depth bottom layer	z2	5.0	km
Well distance small/large base-module	R	700/1000	m
Side length small/large equilateral triangle	a	1212/1732	m
Side length small/large square	a	990/1414	m
Area small/large equilateral triangle	A	0.6/1.3	km^2
Area small/large square	A	0.98/2.0	km^2
Total area small/large hexagonal pattern	A	15.3/31.2	km^2
Total area small/large square pattern	A	15.7/32.0	km^2
Number of injection wells hexagonal pattern	NI	24	-
Number of production wells hexagonal pattern	NP	19	-
Number of injection wells square pattern	NI	16	-
Number of production wells square pattern	NP	25	-

MODELLING PROCEDURE

Implementation of the model

The conceptual model was implemented with a commercial finite element software package (FEMLAB®) additionally utilizing a wide range of in-house developments by Q-con. The large number of wells (43 and 41, respectively) put a high demand on hardware and software capacities. Convergence tests had to be performed in order to ensure a correct and numerically stable computation of the model. Especially the areas surrounding the wells require a high computational resolution resulting in a large number of elements (Figure 2).

Hydraulic Modelling

An accurate pressure and flow field, first had to be computed to account for the complex flow pattern created in a multi-well system. The system is operated with a constant circulation rate (600 kg/second) to ensure a balanced flux for the complete model. The wells are implemented as point sources/sinks with either constant flux or constant pressure conditions (either flow or pressure controlled operation). In relation to the large time frame of 20 years under consideration, the flow field can be regarded instantaneously stationary. It is therefore sufficient to use the stationary hydraulic solution for computing the transient thermal performance of the system.

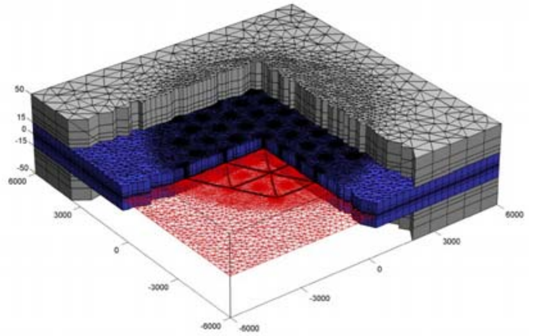

Figure 2: FE-Mesh for the large hexagonal pattern. The blue mesh represents the stimulated fracture zone whereas the red mesh represents the main fracture. The grey mesh corresponds to the rock matrix which is hydraulically tight. The positions of the wells are characterized by extremely dense FE-element meshes. The shape of the base modules is plotted on the fracture as black lines to get an overview of the extension of the pattern within the mesh. Note the different scaling for the horizontal and vertical directions (units in m).

The production and injection rates differ due to the different number of injection and production wells and the requirement of a balanced system. However, for the flow controlled systems the value for the flux is constant for all wells of the same type. This is not the case for the model with constant pressure conditions, where the flux rates at each well depends on the geometry and the pressure values. In order to make the models with different boundary conditions comparable, the pressure values at the respective well types with constant flux condition are averaged. These values are then taken as boundary values for the wells in the constant pressure models. This procedure ensures only slight deviations of the total flux rates for both types of models.

Thermal Modelling

For the investigation of the thermal performance of the system, i.e. the temporal behaviour of production temperatures and rock cooling, the transient thermal solution must be computed over the period of investigation (20 years). As already mentioned, only the stationary flow field is required to determine the advective heat transport in the model. Advective heat transport takes place primarily in the main fracture but also in the rock immediately surrounding the fracture (stimulated zone). The unstimulated rock matrix delivers additional heat through conductive transport processes, only.

Given the thermal parameters of the rock and the fluid, the temperature distributions can be computed for different time steps. It is assumed that at the initial state the reservoir temperature only changes with depth, as a result of the geothermal gradient in the vertical direction. Additionally, it is assumed that the re-injection temperature is constant at all injection wells. In order to assess the performance of layers at different depth levels, the top (T1) and bottom (T2) layers in the depth interval of 4.2 km to 5 km were computed serving as an upper and lower limit for the results to be expected.

RESULTS

Overview of computed models

In order to analyse the impact of varying well patterns and operation modes on the thermal and hydraulic behaviour of the geothermal system, the following models have been computed:

a) Large hexagon pattern with temperature differences T1 and T2 for the top and bottom layer in the depth interval between 4.2 km and 5 km, respectively (R = 1000 m)

b) Large square pattern, otherwise like a)

c) Both patterns with a smaller well separation (small hexagon and small square pattern, R = 700 m) and both temperatures

d) All models above with inverted wells, i.e. production and injection wells have been permuted

e) Large hexagon and square pattern with constant pressure operation instead of constant flow operation

The stationary pressure distribution within the main fracture layer for the large hexagon and square patterns is shown in Figure 3. The corresponding temperature distributions after 20 years of continuous circulation are shown in Figure 4.

Pumping pressures

For a quantitative prediction of pumping pressures, we used the hydraulic parameters derived from numerous well tests conducted in the Habanero wells. In the modeled scenario, the injection pressures vary from 3.3 MPa to 5.4 MPa, and the production drawdowns vary from 1.8 MPa to 5.6 MPa, depending on the location of well. The total pumping power required to operate the circulation at 600 kg/s would be in the order of 9 MW compared to a gross electrical power output of around 70 MW.

The remaining question relates to the degree of homogeneity at which such properties are provided by the reservoir, or can be achieved by stimulation, respectively. Should these properties be existent on a spacious scale, the results from the above simulation are very promising.

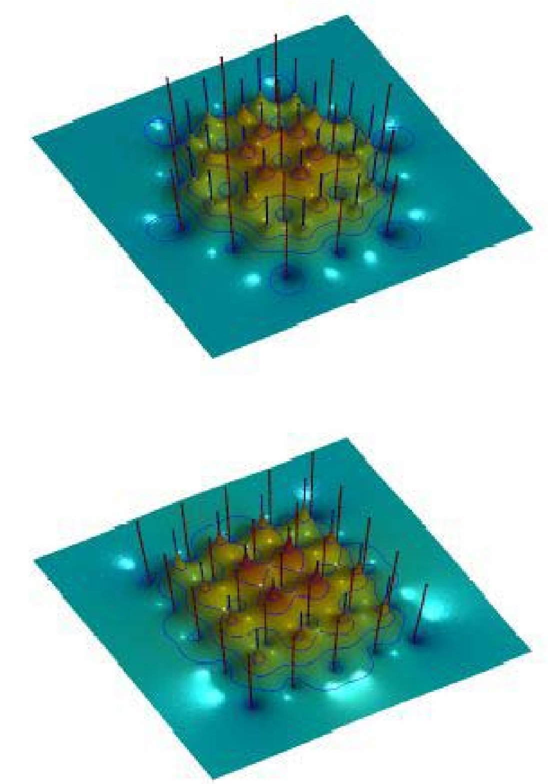

Figure 3: Pressure distribution within the main fracture layer for the large hexagonal pattern (top) and the square pattern (bottom). The wells are also shown in red colour for production wells and blue colour for injection wells. The blue contour lines represent isobars of the pressure distribution..

Temperature decline and thermal power

The relative thermal performance for the different geometrical models can be compared in both temperature decline of the produced fluid and the corresponding thermal power. The temperature is computed by averaging the values at all production wells, using the production rate as a weighting factor. In the case of constant production rate conditions, the amount of fluid is the same at each production well.

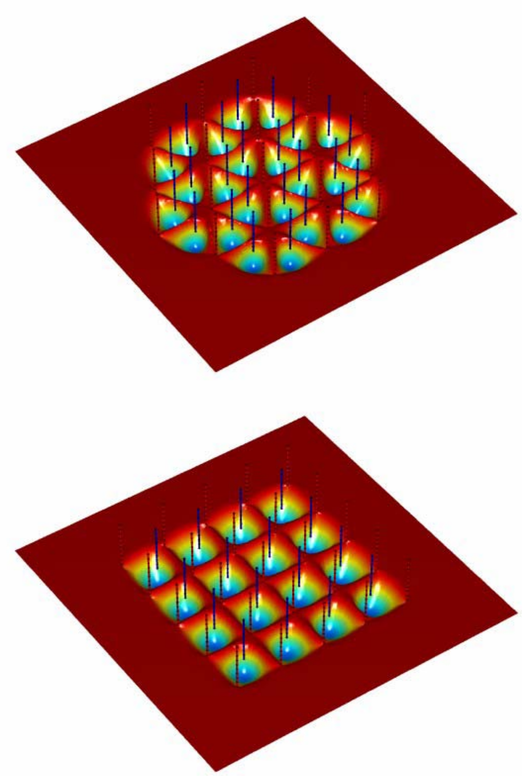

Figure 4: Temperature distribution after 20 years of continuous circulation for the hexagonal pattern (top) and the square pattern (bottom). Injection and production wells are displayed in blue and red, respectively.

The models with constant pressure conditions, however, result in deviating production rates. The corresponding thermal power can be computed from the thermal parameters, the production rates and, assuming a constant re-injection temperature, the temperature difference between injected and produced fluid. It has to be kept in mind that the temperature decline for the deeper layer (T2) is slightly higher because of the larger temperature difference between injected fluid and rock. This higher value, however, also results in a larger thermal power output, which linearly depends on the temperature difference.

Influence of well distance

The distance R between the central and the outer wells in the base-modules is the dominant parameter determining the thermal performance of the system. The difference in temperature drawdown between the small (700 m well spacing) and the large (1,000 m well spacing) pattern is quite significant (34°K for T1 and 40°K for T2, see Figure 5 and Figure 6). This corresponds to a decline of thermal power of 7% for the large pattern and 29 % for the small pattern after 20 years.

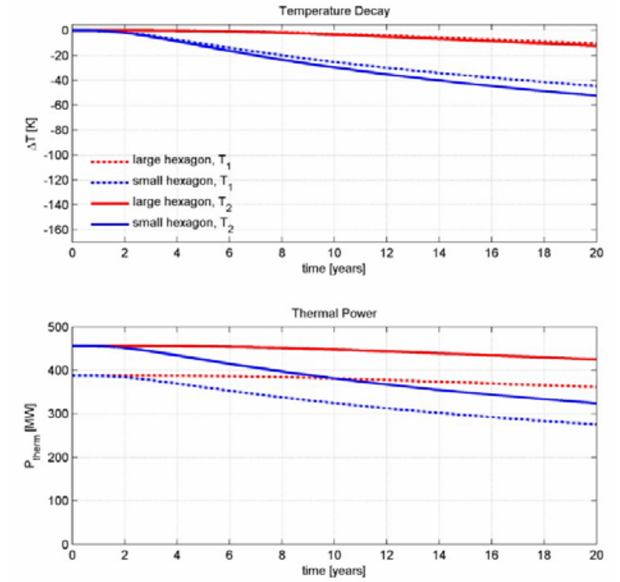

Figure 5: Temperature decline for the ***hexagon*** *patterns with different wellbore distances and initial subsurface temperatures.*

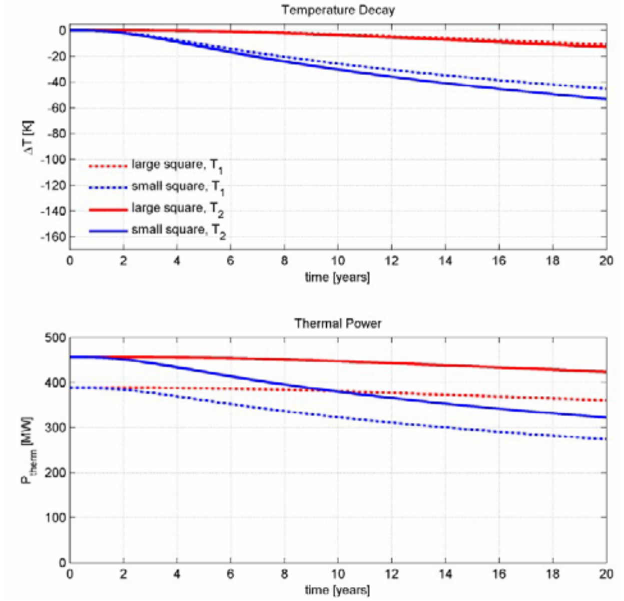

Figure 6: Temperature decline for the ***square*** *patterns with different wellbore distances and initial subsurface temperatures.*

Influence of geometrical pattern

The investigation of the two different geometrical patterns revealed no significant differences of the thermal performance curves. It appears that due to the high degree of symmetry in both the hexagon and the square pattern, the differences are rather marginal.

Influence of operation mode

For technical reasons, it is preferable to operate the system at fixed pressures as the produced fluids from the wells will flow into a joint pipeline before heat is extracted in the binary plant. The performance of the pressure controlled models tend to be slightly better than the ones operated with constant rates.

A more or less constant temperature and corresponding thermal power during the lifetime of a geothermal reservoir are prerequisite for an efficiently operating binary plant. This is approximately fulfilled for the patterns with 1,000 m well spacing. The temperature decline on average is around 11°K over the period of 20 years and the thermal power varies between 465 - 437 MW (bottom layer) and 400 - 376 MW (top layer).

The model was also implemented over a period of 50 years for a well spacing of 1,000 m with a resulting thermal decline of 40ºK. Such a decline would result in a net electrical output decline of almost 50% over this period. However the power station life would exceed 50 years as the annual return from a 50% output would still far exceed annual operating and maintenance costs at that time.

Temperature distribution in the rock matrix

The temperature distribution within the rock matrix is representatively shown for the large hexagonal pattern in Figure 7. The blue iso-surfaces visualize the migration of the cooling front, where the rock has been cooled down by ΔT = 100ºK.

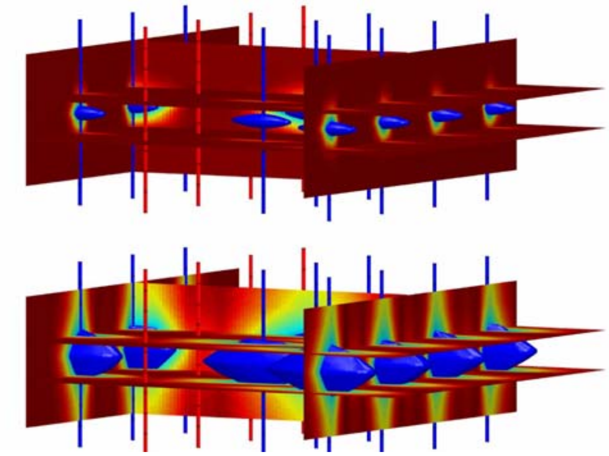

Figure 7: Propagation of the cooling front in the rock matrix after 2 years (top) and 20 years (bottom) for the large hexagonal pattern Note a different scaling for the horizontal and vertical directions.

Although the cooling front has already significantly propagated after 2 years, it has not fully reached the upper or lower boundary of the layer after 20 years (Figure 7). Instead, it mainly propagates in the horizontal direction which is the main flow direction of the fluid. Generally, the migration velocity of the cooling front slows down with time.

CONCLUSIONS FROM THE MODEL

1) The two geometrical shapes of the well patterns investigated in this study, i.e. the hexagonal and the square pattern did not show significant differences in the thermal behaviour of the system. It appears that this is a result of the high degree of symmetry inherent in both patterns.

2) The dominant parameter affecting the long-term thermal performance is the well separation R. For a total circulation rate of 600 kg/s per layer, the models with 700 m well spacing showed a temperature decay starting in the second year and declining at a rate of approx 2.0-2.5 ºK/year. The large model with a well separation of 1,000 m only showed a total decay of 11 ºK after 20 years.

3) The differences resulting from operating the field with pressure or with flow controlled conditions were minor, slightly favouring the pressure controlled operation. This is an important result since a pressure controlled operation seems more suitable from a technical point of view.

4) For the large models (1,000 m well separation), the heat extraction from the rock matrix was well confined within the layer of 100 m thickness. This provides important information for developing a heat mining concept.

5) The computation of pumping pressures with realistic reservoir and well properties revealed that highly favourable operating conditions may be achieved, even at well distances of 1,000 m, or greater. Taking density effects into account the boost pressure required to re-inject the fluid will be further reduced (buoyancy effect).

PROPOSED SCALE-UP PROGRAM

Using the geological and hydraulic properties applied in the model, a multi-well scale-up appears highly desireable. The main technical limitations of such a development relate to (a) the ability to stimulate multiple fracture layers and (b) the aerial extent and behaviour of each stimulated fracture layer.

To date two fracture layers have been independently stimulated and the main layer at 4,350 m depth has been stimulated over an area of more than 4 km^2. There is every indication that the main layer can easily be extended much further with additional high pressure fluid injection.

The actual scale-up currently proposed is constrained more by surface and commercial imperatives than underground technical limitations. On this basis the first module of 40 megawatts net electrical is derived from 3 injection wells and 4 production wells. It has been given the acronym HotRock40. A total of 41 wells in a square pattern would have the capacity to produce a total of 280 MWe net provided several layers could be equally utilised. An aerial photo showing the possible position of wells is shown in Figure 8.

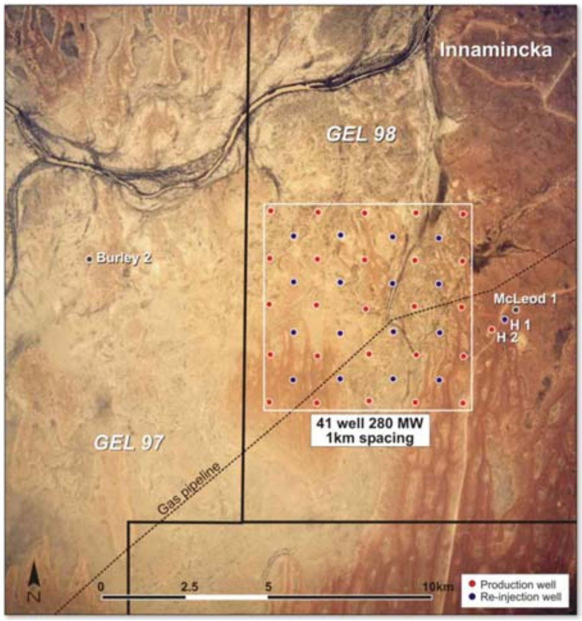

Figure 8. Location of existing wells including Habanero 1 and 2 (H1 and H2) and possible 280 megawatt scale-up wells superimposed on an aerial photo. GEL stands for Geothermal Exploration License.

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