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# INITIAL CALCULATIONS OF PERFORMANCE FOR AN AUSTRALIAN HOT DRY ROCK RESERVOIR

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**ABSTRACT**

Australia has the potential for a large Hot Dry Rock (HDR) geothermal resource. The large scale of the resource stems from the thermal blanketing of sedimentary basins and high heat-producing basement rocks. The crustal-shortening stress regime should result in favourable reservoir orientations (horizontal or sub-horizontal), at the expense of requiring high stimulation pressures. The ease of drilling through sedimentary basins and the anticipated reservoir orientation should reduce drilling costs. If favourable stimulation is achieved, the useful production life of repeating well cells should exceed 20 years.

## 1. INTRODUCTION

Geothermal energy manifests itself in spectacular fashion in many places on the Earth's surface. Volcanoes sporadically emit very large quantities of heat, but the extent of this heat is dwarfed by the cumulative magnitude of the heat that is liberated through the earth's surface by thermal conduction (Morgan, 1984). The overall global heat loss has been estimated at $4.42\times10^{13}$ $Js^{-1}$ (Pollack et al., 1993). Heat flow through the surface of the continental crust results from the conduction of heat through the crust from the upper mantle and from radiogenic heat produced within it, principally from the decay of isotopes of the elements potassium, thorium and uranium. In regions where the near-surface concentrations of these radiogenic elements are relatively high, heat flow is considerably enhanced. However this heat flow only translates into high near-surface temperatures if the heat producing region is overlain by rocks which have low thermal conductivities. When this fortuitous combination occurs in the upper crust, rock temperatures may be high enough to constitute an exploitable energy resource using Hot Dry Rock (HDR) geothermal energy technology.

The 3-dimensional distribution of temperature defines the scale of the potential HDR resource, but it is the particulars of the local stress field at depth and the complexity of the host rock's structure and pre-existing fracture systems which determine the practicality and the economics of exploitation. Unfortunately, these parameters can only be directly measured by drilling which is both very expensive and fundamentally limited in terms of sampling and 3D resolution. For these reasons, detailed modelling of the characteristics of a potential HDR prospect is a very important precursor to any HDR enterprise.

## 2. GEOLOGICAL SETTING FOR HDR IN AUSTRALIA

### 2.1 Temperature

Australia is situated wholly in an intraplate environment in the Indian-Australian Plate. Hot springs and hot artesian water are widely distributed in much of central Australia. The Great Artesian Basin (GAB) which is the best known of these artesian systems (Habermehl, 1980), underlies 1.7 million square kilometres of eastern central Australia (about 22% of the continent), and is currently producing around 1 million cubic metres of water per day from 3000 bores, much of it at temperatures as high as 90-100°C.

In significant parts of Australia, the estimated subsurface temperature at 5 kilometre depth is >250°C as shown in Figure 1. This figure was extrapolated from a database of temperatures recorded in 3291 wells which was compiled by Somerville et al. (1994). The deepest well in the database was drilled to a depth of 5594 metre while the average depth is 1669 metre. The high temperatures associated with the GAB represent the largest area of hot rock identified in Figure 1. However high sub-surface temperatures under a number of other Australian sedimentary basins are also possibly correlated with HHP granites in the basement. For example, two 700m wells drilled 4 km apart in the northern Sydney Basin (150.8°E, 32.4°S; label A in Figure 1) have geothermal gradients twice that of other wells in the region. Gravity measurements in this area define a surrounding gravity low which is about 10km by 15km in extent which is consistent with a buried granite. Extrapolation of the temperature data from the wells to the estimated basement depth in this area of 3.5km, suggests likely temperatures at that depth of >200°C. If this gravity low corresponds to a buried HHP granite, this area is a prime target for HDR development. It lies only 12 km from one of Australia's largest coal-fired power stations (2600 MWe), and is centrally located to major industry, population centres, water supply and the national electricity grid.

### 2.2 Stress

Experience already gained in HDR programs in other parts of the world (Europe, Gerard et al., 1997; Japan, Matsunaga, 1997; USA, Brown, 1995) has shown that the engineering of an HDR reservoir of interconnected fractures is strongly influenced by the contemporaneous stress field and by the character of the natural fracture system.

Most of the crust in Australia is subject to a crustal shortening stress field, in which the minimum principal stress direction is sub-vertical to vertical in orientation. This stress field geometry is defined at shallow depths (i.e. <200 metre) by direct measurements of the in-situ stress field (Denham et al., 1979; Chopra, 1989), at depths on the order of kilometres by borehole breakout analyses (Denham and Windsor, 1991), and at greater depths by the analysis of earthquake focal mechanisms (Denham et al., 1981).

Brown and Windsor (1990) have compiled a database of *in-situ* stress measurements made in tunnels, mines and on rock outcrops throughout Australia. Their data for the maximum horizontal stress ($\sigma_H$), the minimum horizontal stress ($\sigma_h$) and the vertical stress ($\sigma_v$) span the depth interval between the surface and 1200 metre. The data show a considerable scatter but do serve to define two important trends. First, the ratio of the average horizontal stress to the vertical stress [$(\sigma_h + \sigma_H)/2\sigma_v$] has a median value of ~2 and there is a tendency for this ratio to decrease with depth from values as high as 5 in the near-surface to ~2 at 800 - 1200 metre. Second, the ratio of the horizontal stresses ($\sigma_H / \sigma_h$) again has a median value of ~2 and shows a similar decrease to this value in the depth range 800 - 1200 metre from near-surface values as high as ~8.

The data of Chopra (1989) show similar trends over a much more restricted depth range (Table 1). These data were obtained at depths between 5 and 169 metre by the hydraulic fracturing technique (Haimson, 1978) in boreholes drilled into granite. These data are likely to be more accurate than most of the data of Brown and Windsor (1990) because of the technique used, the host rock selected and the depths of the measurements from any free surface. The stress ranges for $\sigma_1$ and $\sigma_2$ given in Table 1 encompass the results of several stress measurements at each depth. The data for Berrigan show a consistent decrease in both the $\sigma_1/\sigma_v$ and $\sigma_2/\sigma_v$ ratios with depth. The data for Eugowra are perturbed by the presence of fractures and illustrate how the long-range tectonic stress field can be disturbed by local influences.

The details of the stress field in an Australian HDR test under the GAB or in the Sydney Basin at depths of 3 - 4 km will obviously have to wait for *in-situ* measurements at those depths but some inferences can be drawn from the data presently available. First, all the available data on *in-situ* stress and the earthquake focal mechanism results suggest that a crustal shortening stress field is likely. In other words, the minimum principal stress ($\sigma_3$) is likely to be approximately vertical and as a result, the maximum and minimum horizontal stresses ($\sigma_H$ and $\sigma_h$) will approximate the maximum and intermediate principal stresses ($\sigma_1$ and $\sigma_2$) respectively. Second, the $\sigma_1/\sigma_2$ ratio is likely to be between 1 and 2 at depths greater than 1200 metre. The scatter in the available *in-situ* stress measurements prevent any rigorous extrapolation to 4 km depth but the earthquake focal mechanism data point strongly to the existence of horizontal stresses greater than the vertical stress down to appreciable depths (e.g. the 1989 Newcastle, NSW earthquake had a focal depth of 19 km and a focal mechanism consistent with a sub-horizontal orientation of the maximum compressive stress).

### 2.3 Implications of Stress Field

This crustal shortening environment will play a most important part in HDR reservoir engineering in Australia. The experience of HDR experiments performed elsewhere in the world to date indicates that an injection test carried out at a representative Australian site would stimulate a horizontal or sub-horizontal reservoir zone. The zone should have maximum elongation in a direction close to the maximum principal stress axis. Fractures most readily opened would be horizontal, and shear fractures most readily activated by release of tectonic strain would be inclined at about 30° to the horizontal. The zone would be expected to have a minimum extent in a vertical or sub-vertical direction.

The sub-horizontal reservoir geometry should allow vertical injection and production wells which are optimal in terms of ease of drilling and logging. Sub-horizontal reservoir geometry also has important implications for multi-cell reservoir design, which is acknowledged as necessary for the commercialization of HDR energy. In a crustal shortening stress regime, it should be possible to generate a vertically-layered group of sub-horizontal reservoirs from a single vertical injection well. Microseismic locations would serve as the diagnostic of reservoir geometry. Decisions on the siting of a production well, or wells, would be straightforward. Sub-horizontal reservoir geometry would provide scope for expanding the scale of an HDR facility virtually without limit by drilling additional vertical wells. Moreover, with sub-horizontal reservoir cells, there would be options for engineering additional cells in both vertical and horizontal directions.

The existence of a crustal shortening regime does however have an important consequence on the injection pressure that may be required to generate a reservoir. In crustal shortening regimes, the minimum principal stress is vertical, and equivalent in magnitude to the lithostatic pressure. In general, fluid pressures at least as high as this are required to open existing fractures in the rock. Thus, although shear failure may be induced at much lower pressures, provision must be made, when planning an injection experiment, for borehole pressures at least as high as the minimum principal stress. The lithostatic pressure at the depth of a typical HDR test in granite overlain by a thermal blanket of sediments is likely to be in the order of 100MPa corresponding to a depth of ~4 km. The hydrostatic head at this depth will be 40 to 45 MPa, so injection pressures of up to 60MPa will be required to overcome the minimum principal stress. Such pressures are higher than have been used in HDR testing to date but are not uncommon in oil-field fracturing operations.

In view of the above considerations of stress, we propose the following estimates for the stress state likely to be encountered at a depth of 4 km in an Australian HDR experiment: a minimum principal stress (lithostatic) of 100 MPa, an intermediate principal stress (sub-horizontal) of 115 MPa, and a maximum principal stress (sub-horizontal) of 130 MPa. The values for $\sigma_1$ and $\sigma_2$ are likely to represent conservative estimates since they correspond to values of the ratios $\sigma_1/\sigma_2$ and $(\sigma_h + \sigma_H)/2\sigma_v$ of only 1.1 and 1.2 respectively. These ratios are much lower than those reported for shallower depths by Brown and Windsor (1990) and are at the lower end of values still consistent with the focal mechanism solutions for earthquakes occurring at much greater depths.

In summary, HDR reservoir engineering in the Australian crustal shortening stress regime will differ from most HDR experiments to date in that higher injection pressures will be required, and the geometry of the reservoir generated by stimulation is expected to be sub-horizontal rather than sub-vertical. Qualitatively, a crustal shortening regime appears to be more favorable than other stress regimes, despite the need for higher injection pressure, because of advantages in reservoir geometry, drilling requirements and water containment.

## 3. RESERVOIR PERFORMANCE PREDICTIONS

### 3.1 Conceptual Reservoir

As discussed above, during stimulation, the reservoir should extend horizontally, normal to the minimum principal stress. This leads to the conceptual design shown in Figure 2. Ideally, the stimulation zone will extend with an elliptical shape in the horizontal plane. The objective will be to have the wells spaced approximately 500 m apart, with the dimensions of the fluid accessible rock being about 200 m in height and with a 200-400 m horizontal width (200 m assumed in these analyses). Since the stimulated regions will be horizontal, it is assumed that it will be possible to stack five stimulated zones in the reservoir.

Figure 2 also shows that the goal is to flow at a rate of 10 l/s through each region between the injection and production wells. The surface pumping pressure is to be 30 MPa. The temperature of the rock is 250°C and the injection temperature is 70°C.

### 3.2 Analysis

The goal is to predict the thermal performance of the reservoir during operation. Operating experience at Rosmanowes, Soultz and Hijiori appears to indicate that much of the flow will take place along dominant flow paths. This is also consistent with the experience at Fenton Hill, although Fenton Hill did tend to show increasing dispersion of the fluid with operation.

### 3.3 Simple Planar Fracture Calculations

A simple approach to analysis is to assume planar fractures between the injection and production wells. While idealised, such calculations can provide insight into the characteristics of reservoir performance.

Calculations were made for two cases: a pessimistic assumption of a single fracture between the injection and production wells and an optimistic case where 10 parallel fractures connect the wells. The distance between the injection and production points was 500m, with a horizontal width of 200m, a fracture opening of 0.25mm, initial temperature of 250°C, and an injection temperature of 70°C. The calculations were performed using Geocrack2D (Swenson, 1997), a fully coupled finite element model of fluid flow in fractured rock. In these calculations, the fracture opening was kept constant and no rock deformation allowed, leading to only a flow/thermal analysis. Typical properties for granite and water were used in the analysis.

The analyses were run for 7,300 days (20 years). Depending on the flow rate through the fracture, significant cooling of the fracture surfaces can occur early in life with a corresponding drop in production temperature. This is shown in Figure 3, which shows temperature contours at 7,300 days for the single fracture case with a flow of 10 l/s. Figure 4 shows the production temperatures for a range of flow rates and compares these to the analytic solution of Carslaw and Jeager, 1955 for a single fracture. Note that the excellent correspondence between the Geocrack2D modelling and the analytic solution and that reducing the fracture flow rate below 10 l/s significantly increases the useful production life.

For the multi-fracture case and fracture spacings of 20 m, the flow on each fracture is reduced and more evenly distributed through the reservoir. As a result, heat is removed much more uniformly from the reservoir and the production temperature remains higher much longer, Figure 4.

The planar fracture results emphasise the trade-offs that may occur in a fracture-dominated reservoir. Granite has a relatively low thermal conductivity. If flow rates are used that can remove more heat than can be delivered to the fracture surfaces by conduction, the production temperature will decline rapidly. However, if sufficient fractures can be involved in the overall flow regime then the flow rate on each one is reduced and the production temperature of the reservoir remains high.

### 3.4 Block Analysis

Geocrack2D was also used to analyse a more realistic case of a reservoir with a blocked arrangement of flow paths that should more closely simulate the actual reservoir. These calculations used the fully coupled deformation-hydraulic-thermal capabilities of Geocrack2D. The geometry represented a vertical slice of one stimulated region of the reservoir as shown in Figure 5. In this figure, the left boundary corresponds to the injection well and the production well is 500 m away (about 2/3 of the model) to the right. The extent of the model is 825 m (horizontal) by 500 m (vertical), with the inner blocked region being 675 m by 200 m.

The Geocrack2D model includes the effects of deformation of the rock blocks and contact between the blocks. At this time, there is little information on what the actual fracture behavior will be, so the Gangi model of fracture behavior was assumed. The Gangi equation is given by:

$$a = 0.25\left(1.0 - \left(\frac{\sigma}{150}\right)^{0.333}\right) \qquad (1)$$

where a is the fracture opening (mm) and $\sigma$ is the effective contact stress (MPa). The fracture will close at a contact stress of 150 MPa and has an opening of 0.25 mm at a contact stress of zero. For example, at an effective stress of 60 MPa (100 MPa vertical - 40 MPa hydrostatic), the fracture will be open 0.065 mm. In the analysis, the contact stress changes due to fluid pressure, so if the fluid pressure is increased by 30 MPa, the fracture effective stress will be reduced from 60 MPa to 30 Mpa, and the fracture opening will be 0.103 mm, or a change in opening of 0.038 mm due to pressure. This will then increase the flow through the fracture. Relatively small changes in opening can lead to significant changes in flow, since the cubic law is assumed to apply.

Three analyses were made using the block model. The first case had an injection pressure of 30 MPa (surface) and a production pressure of 5 MPa (surface). In this case, the predicted flow rate through the reservoir was less than the desired rate of 10 l/s for each wing of a stimulated region. Instead, the flow was approximately 3.3 l/s, with some increase as heat was mined and fractures opened due to thermal contraction.

In reality, the reservoir will be stimulated before being placed in operation. This stimulation will open fractures with high pressure water, causing shear displacement and permanent propping of the fractures. The amount of propping is poorly constrained at present because it will depend on the in-situ mechanical properties of the reservoir rock and the local stress field. We have assumed an opening due to propping of 0.1mm for the second block analysis. In this case the injection pressure was held constant, and the production flow rate was set at 10 l/s. The extra propping was sufficient to allow flow at the desired rate with an injection pressure of 30 MPa (surface) and a production pressure of 27.7 MPa surface (an optimistic result). Again, this illustrates the sensitivity to propping of the fractures.

The final calculation added one additional feature that has been found useful in matching test data at Fenton Hill. Instead of assuming that all the flow paths had a horizontal width of 200 m, the width of each fluid element in the model was randomly given a value of 50, 100, or 200 m, so that 1/3 of the fluid elements had a width of 50m, etc. This is a rough attempt to simulate the non-uniform flow paths expected between the wells. One effect in the model is to speed flow through the narrower fractures. A second effect is to increase the cooling rate of the reservoir, since the volume of the block cooled by the fluid is reduced.

Figure 6 shows cooling of the reservoir after 20 years for the final case. The production pressure remained at about 20 MPa, surface. This is still perhaps optimistic with respect to the pressure difference required to obtain the desired flow.

Of primary interest is the production temperatures for the different block cases. These results are given in Figure 7. For the most realistic case, the production temperatures remain above 200°C for about 17 years of production.

## 4. CONCLUSIONS

A large potential for Hot Dry Rock (HDR) geothermal energy exists in Australia. The crustal-shortening stress regime should result in favourable reservoir orientations. Preliminary calculations demonstrate the significant potential that exists for heat extraction using HDR technology. They also highlight the uncertainty as to the actual conditions that will be found as the reservoir is developed. However, experience with HDR reservoirs shows that, when reservoir development is approached with sufficient design flexibility to respond to whatever conditions are encountered, successful HDR reservoirs can be engineered.

Following are some of the issues that will need to be addressed as the reservoir is developed:

- The actual *in-situ* stresses will determine the orientation and extent of the reservoir and the required pressures to obtain the desired flow rates.

- The concept of stacking stimulated regions is attractive, but may be difficult to implement in practice. It is unlikely that all regions will accept flow equally, so some type of flow equalizing scheme will be needed.

- The amount of propping that will occur is critical to obtaining sufficient flow through the reservoir. These analyses highlight the importance of propping, but do not predict the actual amount that will be expected.

- Micro-seismic sensing should be used during stimulation to find the orientation and size of the stimulated zone. Extensive use of tracers then needs to be made to help understand the amount of dispersion of flow in the reservoir. The tracer data can then be used to decide on the flow rate that will result in optimal reservoir lifetime.

## 5. ACKNOWLEDGEMENTS

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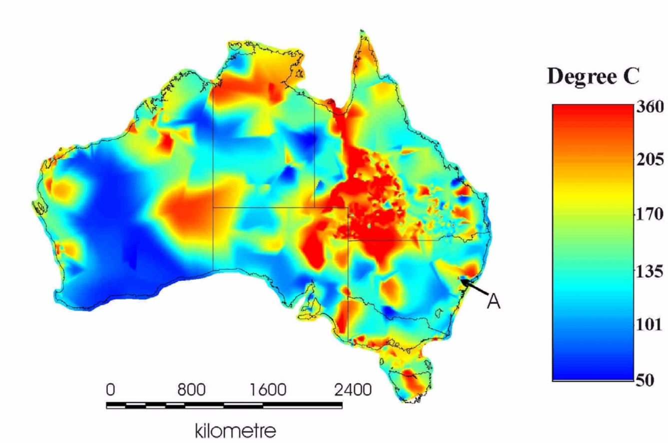


Figure 1: The estimated temperature at a depth of 5km in the Australian continental crust (calculated from the database of Somerville et al, 1994)

Table 1: Selected Results of Hydraulic Fracturing Stress Measurements in Granite

| Site | Depth (m) | $\sigma_v$ (MPa) | $\sigma_1/\sigma_v$ | $\sigma_2/\sigma_v$ |
|---|---|---|---|---|
| Berrigan | 4.5 | 0.11 | 101 | 51 |
| | 69.5 | 1.76 | 5.8 | 3.1 |
| | 125.5 | 3.17 | 3.4 | 2.0 |
| | 168.5 | 4.26 | 3.2 | 1.8 |
| Eugowra | 100.8 | 2.59 | 2.6 | 1.7 |
| | 108.2 | 2.78 | 3.8 | 2.3 |
| | 115.8 | 2.97 | 3.2 | 2.3 |
| | 148.4 | 3.81 | 3.7 | 2.8 |
| Oolong | 83.4 | 2.24 | 6.1 | 3.6 |

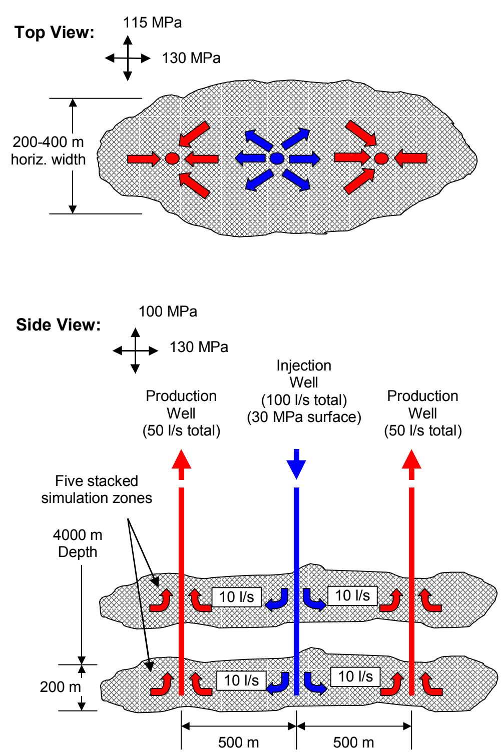


Figure 2: Schematic of reservoir

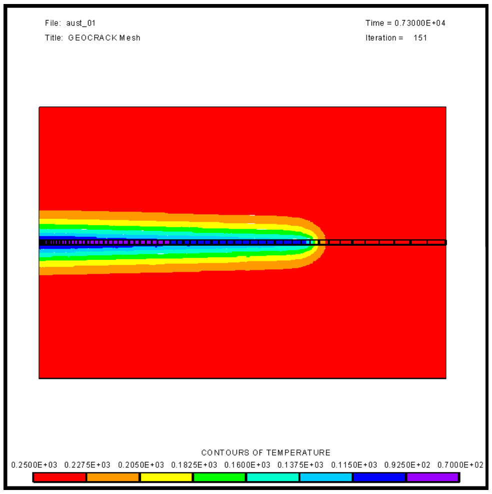


Figure 3: Temperature contours in a single fracture at 7,300 days (20 years)

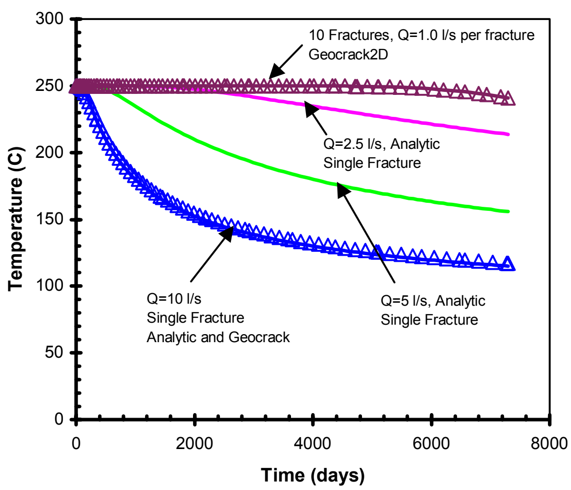


Figure 4: Planar fracture production temperatures

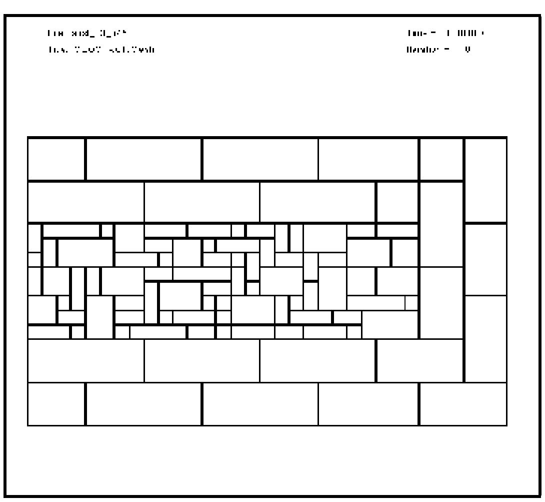

Figure 5: Blocks used in more realistic analysis

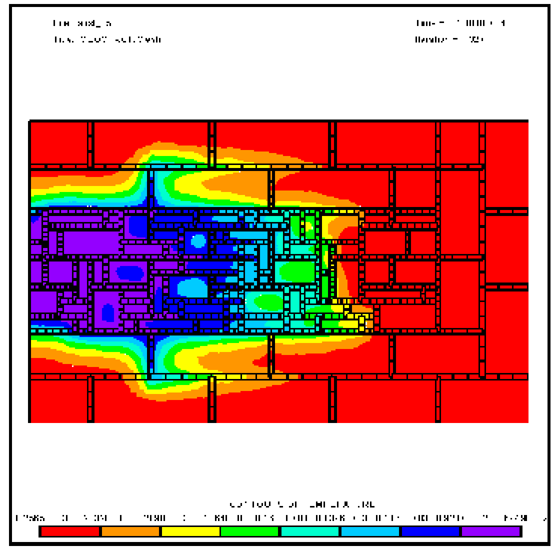

Figure 6: Temperature contours at 20 years

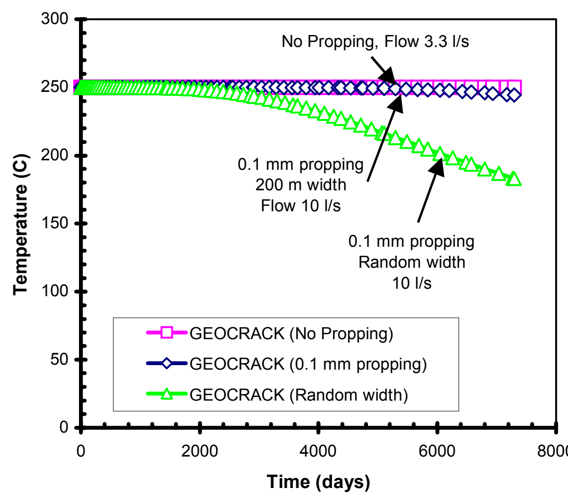


Figure 7: Production temperatures for block analysis