Aims of a Basic EGS Model for the Cooper Basin, Australia

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Geodynamics Limited is currently undertaking field development activities to support a proposal for Engineered Geothermal Systems (EGS) in the Cooper Basin, Australia. For feasibility assessment it is essential that the relationship between EGS design variables and both net electrical power and return on investment are understood. This paper presents key aims and concepts of a spreadsheet model that will help provide this information. The model, which is currently in development, is called the Basic EGS Model.

Incorporated into the Basic EGS Model are sub-models that quantify fluid pressures and temperatures at key locations in the system, including within the geothermal reservoir, within the wells, across the heat-exchanger (of the power plant) and across the circulation pump. The model will link the geothermal power result to a generalist sub-model for a range of power plant designs to estimate the net electrical power deliverable to market. The model will then link the net electrical power results to an economic sub-model for calculating financial performance.

The EGS design variables of major interest include (i) well spacing, (ii) well diameter, (iii) well layout, (iv) well depth, (v) well trajectory, and (vi) number and location of stimulated fracture zones. These design variables are discussed in context of their potential impact on geothermal power and economic performance.

Keywords: EGS, Australia, Cooper Basin, model, geothermal, economic, reservoir, fracture, power, sensitivity.

Project and Location

Geodynamics Limited is developing Engineered Geothermal Systems (EGS) near the small town of Innamincka in South Australia (Figure 1). Drilling and related field work began in 2003 and is currently contained within the company's Geothermal Retention Licenses (GRL) 3 to 12, totalling 985 km^2 (Figure 1).

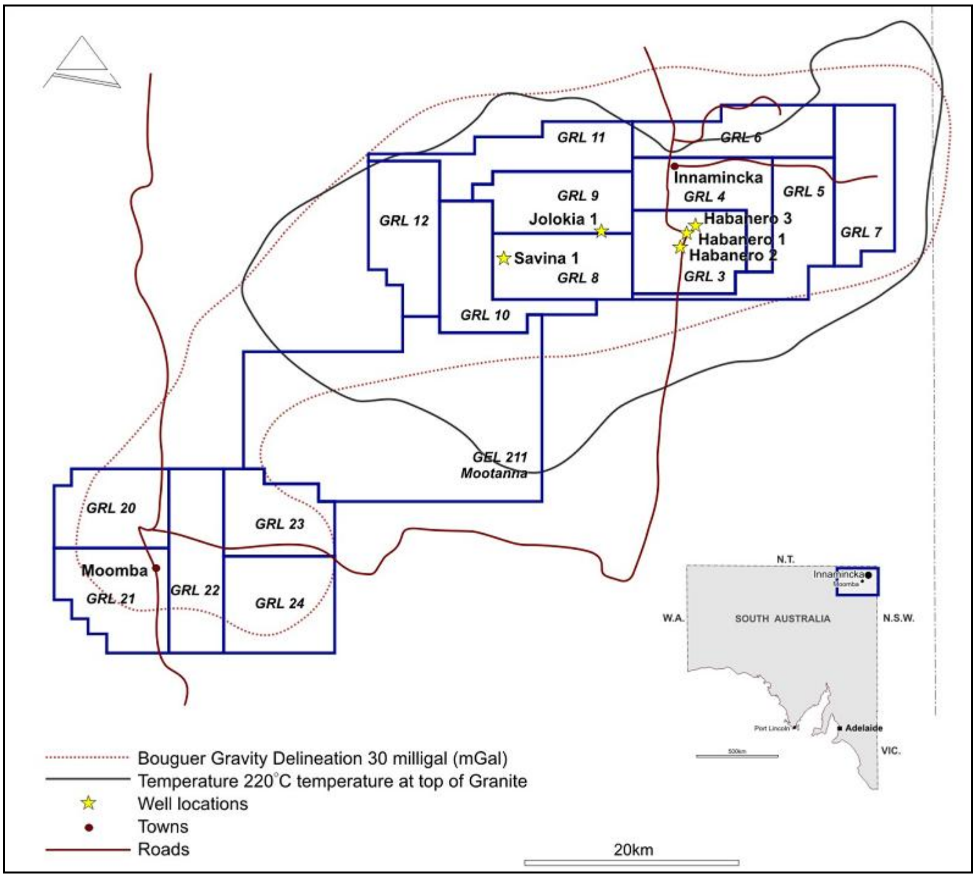

Figure 1. Site location map showing Innamincka and Moomba townships (dots) and the well bore locations (stars). Geodynamics Limited holds the geothermal retention licenses (GRL) and geothermal exploration licenses (GEL) shown. The location of the granite batholith is inferred from gravity and temperature contours.

The company initially aims to supply base-load electricity to a co-located consumer with a commercial demonstration plant (CDP), followed by the development of ten 50 MW_e EGS modules to supply 500 MW_e of electricity to the national grid. Each module will consist of about nine wells drilled to a maximum depth of 5 km, closed-loop pipeline, pump, heat exchanger, air-cooled condenser, and steam-turbine power plant. Multi-layered reservoir stimulation will be needed and the economic life of each module will be about 20 years.

Status of Wells

Five wells have been drilled to date, including: Habanero #1, #2 and #3, Jolokia #1, and Savina #1. At the time of writing the status of the wells were as follows:

- Habanero #1 (4,421 m TVD[1]) is an injection well for the 1 MW_e demonstration power plant.
- Habanero #2 (4,358 m TVD) is shut-in and available for a possible side-track.
- Habanero #3 (4,221 m TVD) was a production well for a 1 MW_e pilot plant until a well rupture on 24 April 2009. On 22 May 2009 the well was controlled and secured with two cement plugs. The precise cause of failure and the future of the well were not known at the time of writing.
- Savina #1 is temporarily suspended and secured with a cemented plug at 2,640 m TVD (100 m above a stuck pipe). The well is available for side-track drilling.
- Jolokia #1 (4,852 m TVD) is temporarily suspended whilst preparations are made for well completion and reservoir stimulation.

The drilling of Habanero #1, #2 and #3 into fractured granite, effective hydraulic stimulations, and subsequent closed-loop flow and tracer tests provided the basis of a proof-of-concept (Grove-White, 2009; Chen and Wyborn, 2009) that brought the company a major step closer to achieving its long-term goal of economically extracting energy from a non-volcanic geothermal resource. The proof-of-concept report was released to the Australian Stock Exchange (ASX) on 31 March 2009 and is available on the internet at http://www.geodynamics.com.au.

Geothermal Resource

The resource is a radiogenic granite (batholith) buried under ~3.7 km of layered sedimentary rock and it extends slightly beyond GRLs 3 to 12 (Figure 1). The company also holds adjacent Geothermal Exploration License (GEL) 211 and GRLs 20 to 24. The target interval for drilling is 3.7-5 km below ground where the granite temperature is approximately 227-284°C. The granite produces heat at a rate of 7-10 μW m^{-3}, and is comprised of 75% SiO_2 and >5% K_2O.

The granite has crystalline medium-to-coarse sized grains and is saturated with brine which is pressured to ~34.4 MPa above hydrostatic. Regional confinement is provided by sedimentary layers that have a very low porosity and low permeability. The granite was glacially eroded during the early-Permian ice age (circa 300 Ma ago) prior to burial. There is no evidence of major faulting in GRLs 3 to 12.

Rock stress at 4 km depth

In the project area the rock stresses at 4 km depth are characterized by: (i) a vertical minimum principal stress of ~90 MPa; (ii) a minor horizontal stress of ~110 MPa; (iii) a maximum horizontal stress of ~140 MPa; and (iv) a pore pressure of ~75 MPa. The maximum horizontal stress is orientated east-west due to present day tectonic compression of the Australian plate. Hydraulic stimulations in this stress field are effective at activating fractures that are orientated sub-horizontally (Grove-White, 2009). This sub-horizontal fracture orientation is considered ideal for heat extraction because it promises the development of vertically-stacked fracture zones within the granite.

The Basic EGS Model

Main Aims

The Basic EGS Model is an empirical-analytical thermo-hydraulic model for constant flow circulation conditions (on a mass per time basis). The term ‘Basic’ is used in recognition that the final EGS model may need to be better calibrated and refined and expanded in scope to include a combination of mechanical, thermal, hydraulic, and chemical processes in time and space (e.g. Hayashi et al., 1999).

The Basic EGS Model aims to predict the production temperature and pressure (average for all production wells), pump differential pressure, total geothermal power, and total net electrical power over ~20 years for various EGS designs. The Basic EGS Model is coded in a spreadsheet (Microsoft Office Excel 2007) to facilitate rapid development. After the model is reviewed and validated (a work in progress) it may then be used for economic sensitivity analysis.

EGS Design Variables

The EGS design variables of major interest are (i) well spacing, (ii) well diameter, (iii) well layout, (iv) well depth, (v) well trajectory, and (vi) number and location of stimulated fracture zones. Other important variables describe (vii) well cavity

[1] Total Vertical Depth (TVD)

completion (e.g. under-reaming or perforation jetting), (viii) pump efficiency, (ix) pump inlet/outlet pressure limits, (x) heat-exchanger discharge temperature, (xi) power plant geothermal-to-electrical efficiency, and (xii) power plant auxiliary power loads. The effect of well cavity completions may be employed in the future to reduce turbulent friction ('skin') near-field of the wells with the intention of improving well bore productivity and injectivity.

Reservoir Sub-Model

The reservoir sub-model describes the quasi-steady fluid pressure and transient fluid temperature distributions throughout the closed-loop (Figures 2 and 3). The model is limited to a steady circulation rate (mass per time) to simplify the analysis.

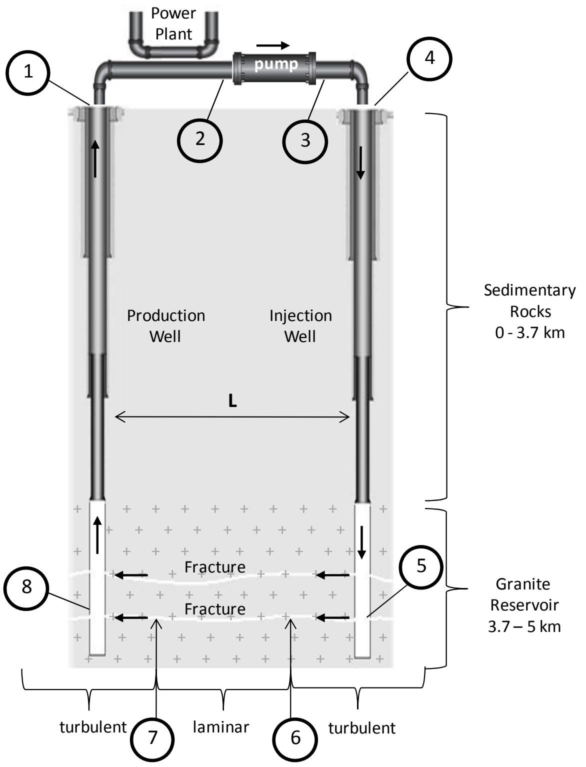

Figure 2: Conceptual fluid flow diagram for EGS based on a producer-injector pair or 'doublet'. The important thermo-hydraulic reference points are numbered.

Referring to Figure 2, the main processes that influence fluid temperature and pressure include: (1-2) pipe frictional pressure loss and temperature drop across the heat exchanger; (2-3) pressure rise forced by the pump; (3-4) pipe frictional pressure loss; (4-5) well bore and constricted[2] frictional pressure drops, hydrostatic pressure change with depth, and temperature rise due to conduction; (5-6) turbulent frictional pressure drop due to radial-diverging flow in fractures and temperature rise due to conduction; (6-7) laminar frictional pressure drop within the fracture network and temperature rise due to conduction; (7-8) turbulent frictional pressure drop due to radial-converging flow in fractures and temperature rise due to conduction; and (8-1) well bore and constricted frictional pressure drops, hydrostatic pressure change with depth, and falling temperatures due to conduction.

Turbulent radial flow near-field of the wells (5-6 and 7-8 in Figure 2) is believed to be responsible for most of the pressure drop in the fractured reservoir. A novel semi-analytical method for modelling pressures losses in the near-field of wells is currently in development. The method, called the Radial Pipe Flow Method (RPFM) (Chen, *in press*), is based on empirical formulae for laminar and turbulent losses in tubular pipes. Preliminary results using the RPFM are promising and the method appears suitable for use in the Basic EGS Model.

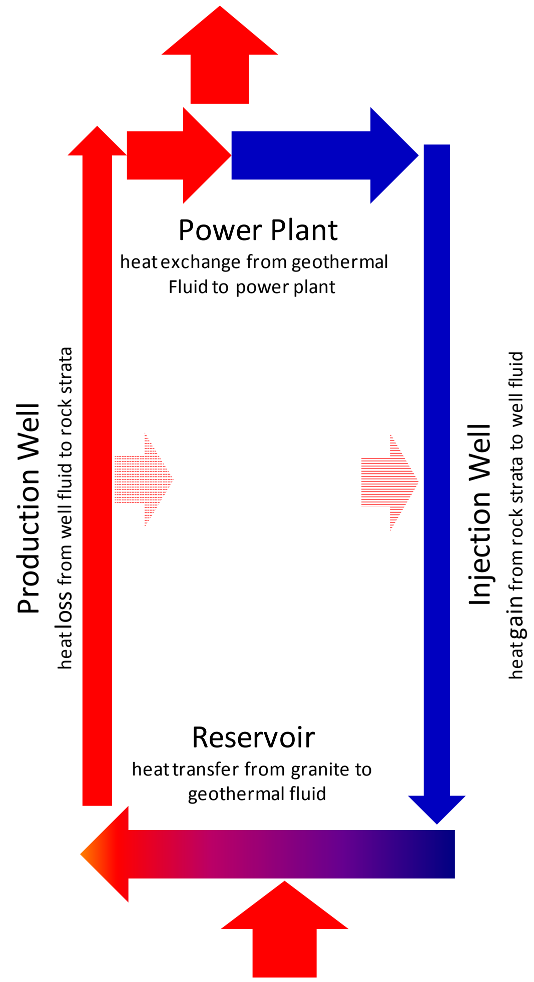

Figure 3: Conceptual heat flow diagram for a single producer-injector 'sweep zone'. The Basic EGS Model is comprised of a collection of 'sweep zones' as a means of approximating the total geothermal power output of multi-well systems. Each sweep zone is analysed individually using a combination of empirical, analytical and numerical methods. Red indicates relatively hot fluid and blue relatively cold fluid.

[2] Constrictions include changes in pipe internal diameter and *vena contracta* at the well-fracture interface.

At every location in the flow system, fluid viscosity and fluid density are influenced by temperature and pressure. Consequently there are physical feedback loops affecting fluid pressure. To address this inherent complexity, the fluid pressure profiles of the production and injection wells are solved iteratively. Furthermore, the pressures at all key reference points in the model (Figure 2) are also solved iteratively to determine the pressures that balance the entire system. A method has been developed for solving system pressures and the preliminary results are promising.

The most simple system diagram for heat flow involves four exchange processes (Figure 3): (i) heat losses to the power plant; (ii) heat gains/losses in the injection wells; (iii) heat gains in the reservoir; and (iv) heat losses in the production wells.

Extracting heat produces a three-dimensional cooling front in the rock that starts at the injection wells and grows towards the production wells (Vörös et al., 2007). Also, the heating and cooling of fluid in the well bores involves three-dimensional 'radial-type' heat flow patterns. These heat transfer processes are generally too complex to be modelled with just analytical methods. The current approach is to utilise the results of detailed numerical modelling studies (Vörös et al., 2007) in combination with analytical methods (Arpaci, 1966). This is achieved by representing numerical results with empirically adjusted analytical equations or 'black-box' empirical equations (a work in progress).

Well Layouts

The multi-well layouts produce spatially and temporally complex fluid flow and heat transport patterns (Vörös et al., 2007). They also need to be carefully designed to ensure sufficient sweep of the reservoir for achieving stated geothermal power targets. In this modelling study, a sweep zones is defined as the planar area of the reservoir that transfers appreciable fluid between neighbouring injection and production wells (Figure 4).

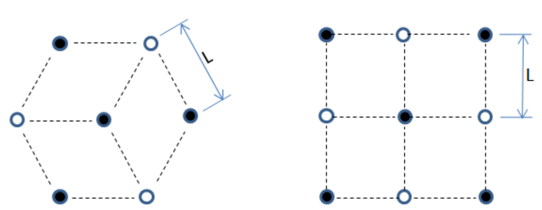

Figure 4: Two plausible EGS well layouts: (a) seven wells on a triangular grid with nine sweep zones, and (b) nine wells on a square grid with twelve sweep zones. Sweep zones are represented as dotted lines, producers as black dots, and injectors as white dots.

The total sweep area is principally controlled by (i) number of wells, (ii) well layout and spacing, and (iii) number of parallel fracture zones. The ratio of sweep zones to the number of wells give a basic indication of the efficacy of a well layout. The current model approximates multi-well heat extraction by representing the reservoir as collection of discrete sweep zones (a work in progress). Each sweep zone is defined by an approximately equivalent rectangular fluid-rock contact area. Preliminary results based on this method are promising.

Well Bore Averaging

The Basic EGS Model simplifies the flow hydraulic problem by representing the multi-well layout with one 'average producer' and one 'average injector' doublet (Figure 2). The averaging method involves spreading the total flow evenly amongst the producers and injectors and calculating the average geometry of the producers and injectors taking into account well design and directional drilling. This well bore averaging technique and the discrete sweep zone method (described above) greatly simplify the modelling task. Validation against a more accurate and proven modelling approach is required.

Power Sub-Model

The Basic EGS Model includes a power sub-model that will provide an estimate of power plant efficiency and auxiliary equipment power load for any plausible geothermal production flow, production temperature, and ambient air temperature.

The main aim of the sub-model is to estimate the main components of the EGS power balance, namely: (i) geothermal power output, (ii) steam turbine power output, (iii) pump power load, and (iv) auxiliary equipment power load. The auxiliaries will include air cooled condensers (as opposed to water cooled) because of water scarcity in the Cooper Basin (Figure 5).

Power plant designs should be tailored to production flow and temperature hence the Basic EGS Model requires a capacity to adapt the power plant design to a wide range of possible production outcomes. The design of power plants also requires specialised engineering skills and software (Thermoflow by Thermaflow, Inc. USA). To circumvent this inherent complexity, the current approach is to collate a range of suitable power plant designs and to develop empirical ('black-box') regression equations for plant gross power supply and auxiliary power load as a function of production flow, production temperature, and ambient air temperature.

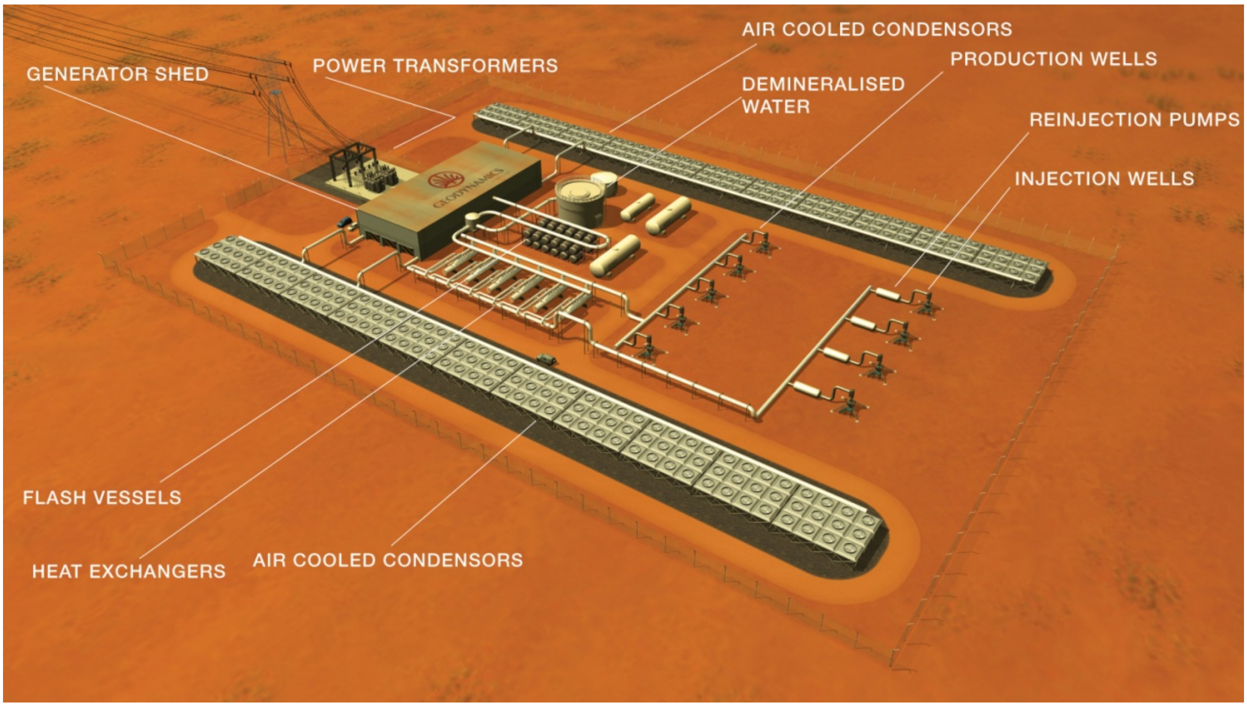

Figure 5: Artist's impression of a 50 MW EGS module comprising four injectors, five producers, steam turbine power plant, heat exchanger, and air cooled condensers.

Economic Sub-Model

The economic sub-model is based on discounted cash flow analysis and calculation of Internal Rate of Return (IRR) over 20-30 years. Of interest is the sensitivity of the IRR to the various EGS design variables. The following are the key economic inputs: (i) drilling cost expectations, (ii) cost of power station and other capital equipment, (iii) operation and maintenance costs, (iv) electricity revenue expectations, and (v) renewable energy certificate revenue expectations. The electricity price expectations are taken from an economic analysis by McLennan Magasanik Associates (2008) for the Australian government's Carbon Pollution Reduction Scheme. The renewable energy certificate revenue expectations are taken from market analysis by McLennan Magasanik Associates (2009).

Implications for EGS Design

The main benefit of the proposed modelling is the ability to rank Cooper Basin EGS designs in terms of revenue potential. The work completed to date has identified a number of optimal design points ('sweet spots'). Two key examples are:

- A peak net electrical power and IRR as a function of pump differential pressure; and
- A peak in IRR as a function of well spacing.

Summary

A basic thermo-hydraulic model for EGS in the Cooper Basin is currently being developed. It is called the 'Basic EGS Model'. It is comprised of sub-models for the reservoir, power plant, and expected economic conditions. Early model results are promising and suggest that the model components are valid and will be accurate enough for economic sensitivity analysis. Although the model is currently a work-in-progress, some preliminary results may be presented at the 2009 Australian Geothermal Conference in Brisbane.

References

Arpaci, V.S., 1966, Conduction Heat Transfer. Addison-Wesley, Reading, Massachusetts, 1966, 351 p.

Chen, D., in press, Concepts of a basic EGS model for the Cooper Basin, Australia, Proceedings of the World Geothermal Congress 2010, Bali, Indonesia, 25-30 April 2010.

Chen, D., and Wyborn, D., 2009, Habanero Field Tests in the Cooper Basin, Australia: A Proof-of-Concept for EGS, Proceedings of the GRC Annual Meeting, 4–7 October 2009, Reno, Nevada, USA.

Grove-White, G., 2009, ASX Announcement 31 March 2009: Stage 1 - Proof of Concept Complete, Geodynamics Ltd., 31 March 2009.

Hayashi, K., Willis-Richards, J., Hopkirk, R.J., and Niibori, Y., 1999, Numerical models of HDR geothermal reservoirs - a review of current thinking and progress, Geothermics, 28, p. 507-518.

McLennan Magasanik Associates, 2008, Impacts of the Carbon Pollution Reduction Scheme on

Australia's Electricity Markets - Report to Federal Treasury, 11 December 2008, Ref: J1565, 75 p.

McLennan Magasanik Associates, 2009, Benefits and Costs of the Expanded Renewable Energy Target – Report to Department of Climate Change, January 2009, 38 p.

Vörös, R., Weidler, R., de Graaf, L., and Wyborn, D., 2007, 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, Proceedings, Thirty-Second Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 22-24, 2007.

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