Some Recent Developments in Geothermal Reservoir Engineering in New Zealand

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NGAWHA — a fractured geothermal reservoir

Ngawha is different to other geothermal fields in New Zealand — it lies outside the Taupo Volcanic Zone (Figure 1). Reservoir material is predominantly fractured greywacke, heavily faulted, overlain by up to 500m of low permeability breccias. Fluid temperatures are typically 220–230°C (1000 kJ/kg) in the main permeable region, although temperatures above 300°C have been measured in the low permeability bottom of NG13, the deepest well in the field. Fluid is mostly single-phase liquid, with extensive and large gas upflow, up to 3% by weight.

It is perhaps not surprising then that pressure transients are not explained by homogeneous reservoir models. For example, consider the responses during October 1983 in NG8, NG9 and NG11 to production from NG13 and injection into NG3 (Figure 2).

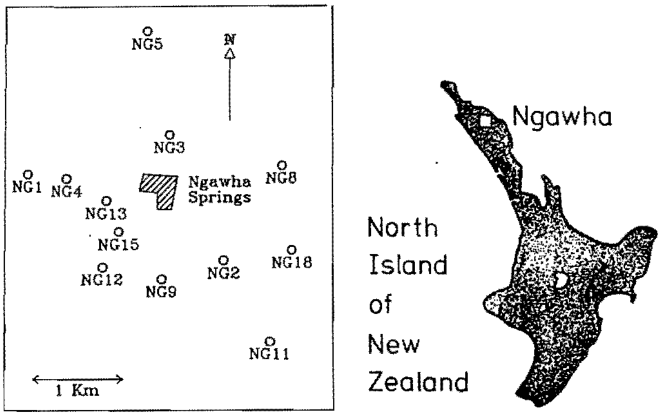


Figure 1. The Ngawha geothermal field — location and well sites

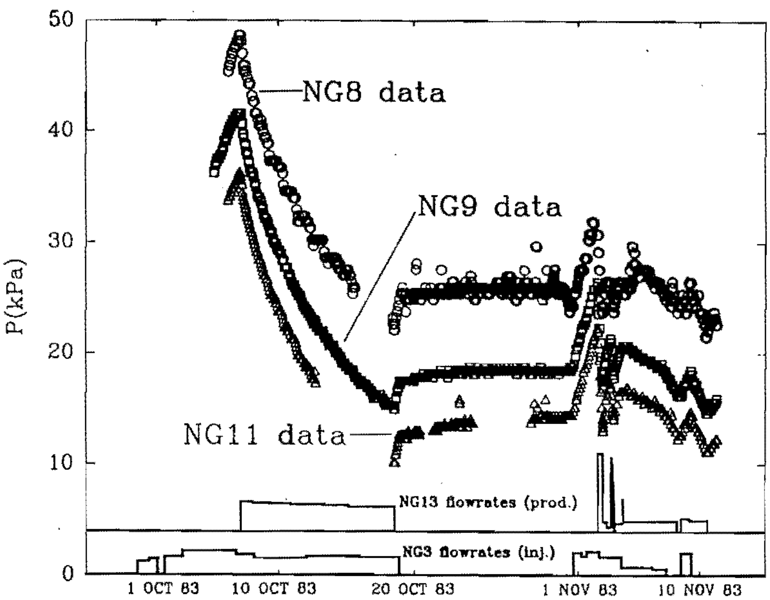


Figure 2. Pressure responses in NG8, NG9 and NG11. The production flowrates for NG13, up to 500 t/hr, are shown, together with injection flowrates for NG3 to the same scale. The pressure origin is arbitrary, and is chosen here for convenient presentation

Note the rapid and identical responses to both production and injection. This is not consistent with a homogeneous reservoir model, for which the solution depends on distance from the source wells. Indeed, a fit of the line-source solution (infinite homogeneous radial model) to the data from NG9, for example, is unsatisfactory (Figure 3).

These considerations have led to the development of a model for the pressure changes at Ngawha, which has a highly permeable fracture system, in contact everywhere with a low permeability rock matrix. Transient changes in the fracture system are ignored, and the reservoir is taken to be finite. Pressure changes in the fracture system are then controlled by the size of the fracture system and by flow between rock matrix and fractures. All wells accessing this fracture system will have almost identical responses to source wells.

Simple asymptotic approximations to the solution of such a model are put together, using the concept of an effective depth of penetration into the rock blocks for the pressure changes. This is done firstly for a single block, then extended to the case of many blocks which are of varying sizes. A natural choice is to consider an exponential distribution of block sizes. With this choice, and assuming the rock blocks are slabs, this approximate approach leads to the solution (McGuinness 1986)

$$p = -qt/V[\phi_f + \phi_m\{1 - \exp(-\sqrt{\pi t}/2\lambda d)\}]$$

where p is the change in pressure in the fracture system, q is the volume flowrate change at a source well, V is the total reservoir volume, ϕ_f is the porosity of the fracture system, ϕ_m is the porosity of the rock matrix, λ is $\phi_m \mu c/k_m$, k_m is the rock permeability and d is the average slab thickness.

If the rock matrix is assumed to be composed of spheres instead of slabs, a similar formula holds, with d replaced by r (average sphere radius) and ϕ_m multiplied by a factor of 6.

When this solution is fitted to the pressure data, much closer fits are obtained (Figure 4), and estimates are made of reservoir volume, fluid volume, percentage of fluid in the fractures, and a parameter involving average block size and rock permeability.

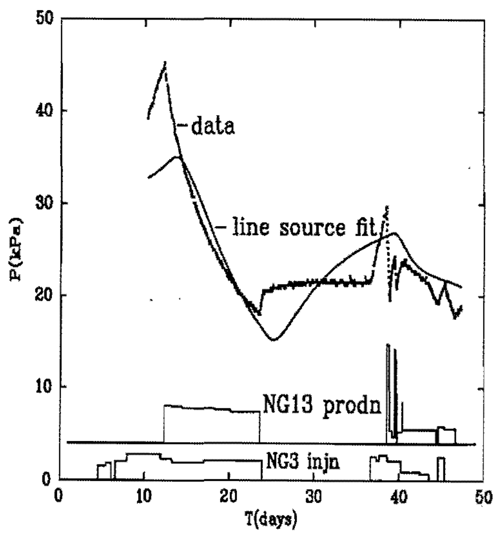


Figure 3. NG9 pressure data, and the best fit line-source solution. The fit is obtained by superposing flowrate changes and nonlinear regression on a computer.

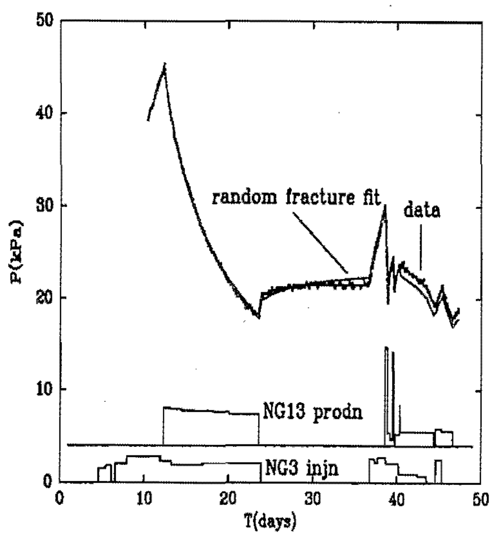


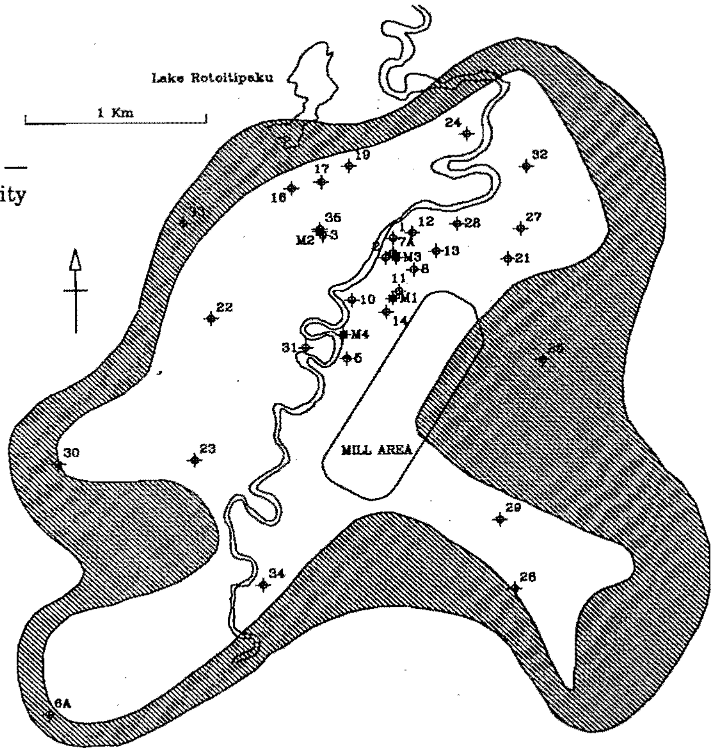
Figure 4. NG9 pressure data, and the best fit solution for a randomly fractured finite reservoir. Where the fit is not visible it almost coincides with the data

KAWERAU — a heat sweep model

Kawerau is more typical of New Zealand geothermal fields. Located in the Taupo Volcanic Zone (Figure 5), it consists of basement greywacke overlain by poorly correlated volcanic sequences. Currently about 270 t/hr of process steam is supplied to the Tasman Pulp and Paper Mill. Early wells lasted only 4 years before cooling occurred. Deeper wells have not cooled so rapidly. Pressures have dropped by less than 2 bars in the reservoir, suggesting good recharge.

The reservoir fluid is about 280°C at depth, and is mostly single-phase. Interference tests, lithology and chemistry suggest the importance of fracturing in this reservoir. High permeabilities and low storativities are evident. Feedpoints often coincide with andesite or greywacke formations, which are relatively hard and brittle. Gas and chloride chemistry suggest evaporation in a fracture system followed by local boiling.

Interference tests also suggest a two-reservoir structure, with a smallish shallow reservoir overlying a larger deep reservoir. A fairly ubiquitous mudstone formation forms a low permeability structure between the two regions. Pressure and tracer communication between them is poor.



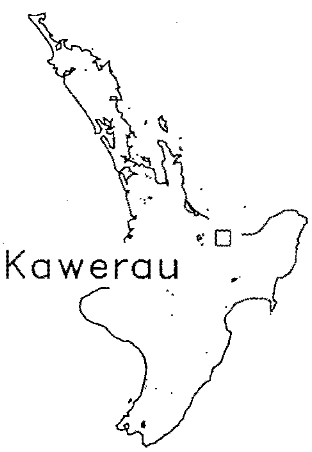


Figure 5. Kawerau geothermal field — location and well sites. The resistivity boundary is shown shaded

Earlier work by Grant (1977) models temperature changes at Kawerau as due to the drawing-down of cooler fluid from shallow regions. The modelling described here, done in collaboration with S. White (Division of Information Technology, DSIR), is intended to extend and improve upon Grant's analysis.

In view of the above comments, a heat-sweep computer model of the Kawerau geothermal field has been constructed. Fluid is taken to flow through a fracture system, exchanging heat with adjacent rock by conduction. A convecton-diffusion equation is obtained for the temperature in the fractures, with a source term allowing for the effect of conduction in nearby rock blocks. Blocks are approximated by equivalent spheres of some finite radius.

A three-dimensional finite difference scheme has been implemented with over 7,000 elements (Figure 6), in which fluid flows are obtained by solving a steady-state pressure equation. These flows are used in the subsequent solution of the temperature equation. Numerical techniques include Stone's Strongly Implicit method, operator splitting and flux correction.

Permeabilities and recharge rates are adjusted to match field pressures, and block sizes are adjusted to match well cooldown rates (Figure 7). The model is successful in improving on Grant's model, by taking recharge to be mainly from the sides of the reservoir instead of from above. In this way deep cooling rates are more accurately matched, as may be seen in Figure 7.

The computer model is useful for examining the thermal effects of various field management options, including extra production wells and the effects of shallow versus deep reinjection of separated fluid.

During this work it has also become clear that where older wells have been deepened at Kawerau, cooling problems are typically associated not with cooling in the actual reservoir, but with poor sealing off of cooler shallow feeds, allowing cool shallow waters to enter the well. As the deeper hotter feedpoint becomes more drawn-down, relatively more of the cooler feedpoint fluid enters the well, causing calciting problems as well as lowering production enthalpy and flowrate.

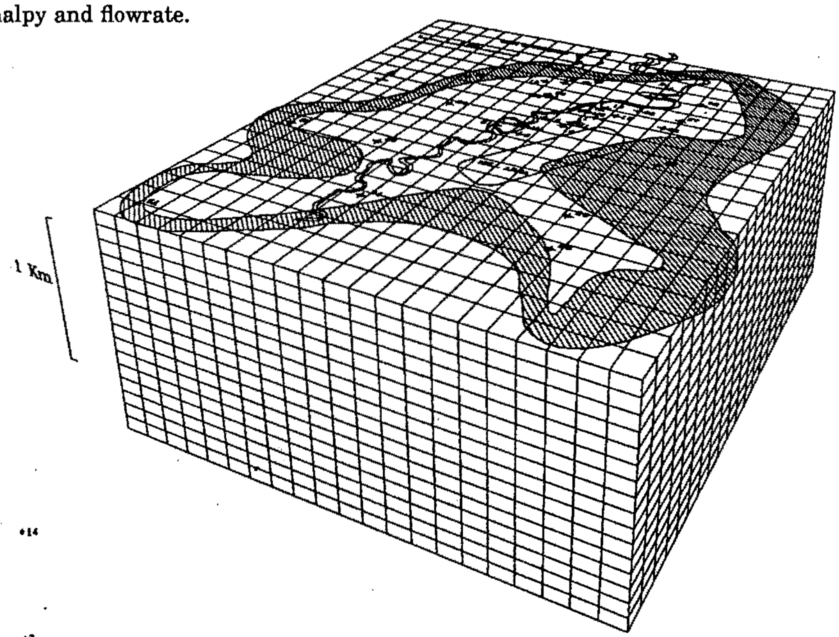


Figure 6. A 3D perspective view of the computational grid used in the Kawerau heat-sweep model

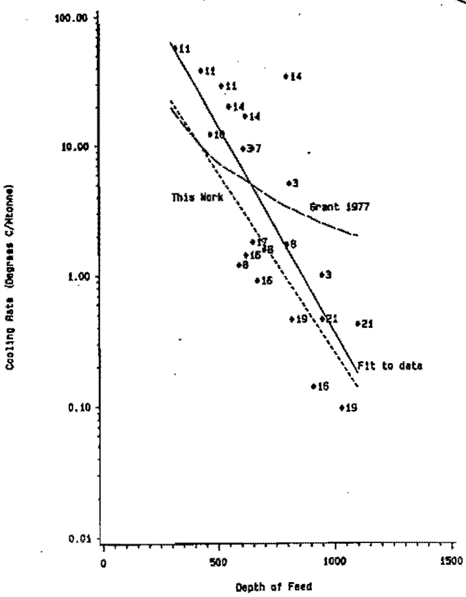


Figure 7. Cooling rate versus feed depth (m) for Kawerau wells. The short dashed line is the cooling rate for the heat-sweep model described here. The long dashed line is for Grant's model. The solid line is a least-squares fit straight line, for comparison purposes only

REFERENCES

Grant, M.A. (1977) *Temperature Patterns and Changes at Kawerau*, Geothermal Circular MAG16, Applied Math. Division, DSIR, Wellington.

McGuinness, M.J. (1986) *Pressure Transmission in a Bounded Randomly Fractured Reservoir of Single-Phase Fluid*, Transport in Porous Media 1, pp.371–397.