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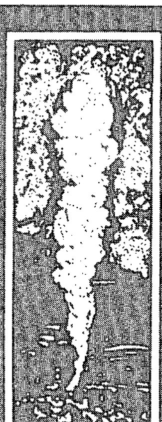

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RECENT DEVELOPMENTS IN RESERVOIR ENGINEERING IN NEW ZEALAND

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ABSTRACT

Over 1982-83 there have been substantial increases in the reservoir engineering contribution to the New Zealand geothermal programme. This has taken four forms:

- more extensive and detailed analysis of pre- and post-production performance, primarily at Broadlands;
- the extensive use of high-resolution pressure gauges to carry out interference tests at Rotorua, Ngawha and Broadlands;
- the installation of an extensive monitoring system at Rotorua;
- the commencement of detailed simulation of Broadlands.

Past modelling of Broadlands used a lumped-parameter model. More detailed data analysis has produced clearly-defined histories of the two productive areas of the field, and more detailed estimates of the amounts of recharge deriving from deep and shallow sources. Some interference tests at Broadlands show results which fit closely to the line source solution or the line source solution with barrier. An extensive monitoring system is being installed to record changes in the Ohaaki rhyolite, a shallow very permeable aquifer extending far beyond field boundaries.

Interference tests at Ngawha, using Paroscientific gauges mounted at wellhead or within the casing have shown responses over a distance of several kilometres, and transmissivities of several hundred darcy-metres. Similar tests at Rotorua over shorter distances have shown major structure or anisotropy within a very permeable aquifer, and anomalously large storativity.

Monitoring of reservoir pressures by water level or transducer at Rotorua has shown these to respond to barometric pressure, earth tides, fluctuations in domestic withdrawal and level of Lake Rotorua. Instrumentation of springs and geysers has just been completed.

Detailed numerical modelling of Broadlands has been started, initially with a model of the natural state. Results are expected to be used in detailed design of the reinjection system. Analysis of detailed chemical and enthalpy transients at BR21 demonstrate that the well produces from a fractured medium.

INTRODUCTION

Figure 1 shows the location of the fields referred to in the text. The geothermal program consists of maintenance work at Wairakei and Kawerau, development at Broadlands for the 102MW station to come on line in 1988, exploration work at Ngawha and Mokai, and at Rotorua the monitoring program.

ROTORUA

Rotorua field supports a major tourist attraction, the Whakarewarewa Thermal Reserve ("Whaka"), which contains some geysers and numerous springs and other surface manifestations. The field underlies part of Rotorua city and here it supports the discharge of over 400 domestic and industrial wells.

The development of the geothermal resource for such heat supply began significantly in the 1950's and has accelerated rapidly. Simultaneously, there has been an apparent decline in the surface activity of Rotorua, both in the Thermal Reserve and elsewhere. The present balance of discharge is a flow of about 100 kg/s from Whaka, and about 400 kg/s from the wells, most of which is reinjected into producing or shallower levels.

The inference that declining surface activity is caused by the increasing exploitation has led to the establishment of a monitoring programme for Rotorua. The object of this program is to more accurately define the structure of the field and the relation between exploitation and changes in surface activity, and hopefully to contribute to an ultimate management plan.

Past records at Rotorua are scarce and generally of poor quality. There are available good histories of neither surface activity nor wells. The lack of past data severely limits present attempts to model reservoir processes. The present monitoring program consists of series of monitor wells, of groundwater wells, of instruments on springs and of well discharge measurements. Figure 2 shows a map of the city and the resistivity boundary. The major surface discharge is now at Whaka and apparently also directly into Lake Rotorua. The monitor wells are drilled to depths typical of production wells, but differ from typical wells in that they have only a very short open interval, at a loss zone, to eliminate internal flows. The monitor wells are equipped with a float recorder, if they have a water level, or else a pressure gauge. The groundwater wells are shallow wells recording the local groundwater table. Two have float recorders and the remainder are measured two or three times weekly.

A number of springs,pools or geysers in Whakarewarewa are instrumented. Variables recorded are some of: water level, temperature, time in eruption and conductivity. Puarenga stream, which drains Whaka, also has gauging stations above and below at which flow rate and temperature are recorded. Chemical samples are taken from wells and springs at intervals.

Discharge and injection tests have been carried out on a number of wells, and five interference tests utilising pairs or groups of wells.

The monitoring system is not yet quite complete, and records are available so far from only part of the system. The interference tests with several observation wells have produced puzzling responses, with quite inconsistent results at the different observation wells. In general permeability is high and storativity often larger than for a liquid aquifer. The most interesting result so far is the interference test in which water level in the observation well fell in response to cold water injection in the source well. The source well penetrated boiling temperatures. Monitor well records have been analysed for correlation with barometric pressure, lake level, earth tides and demand fluctuations. All effects are

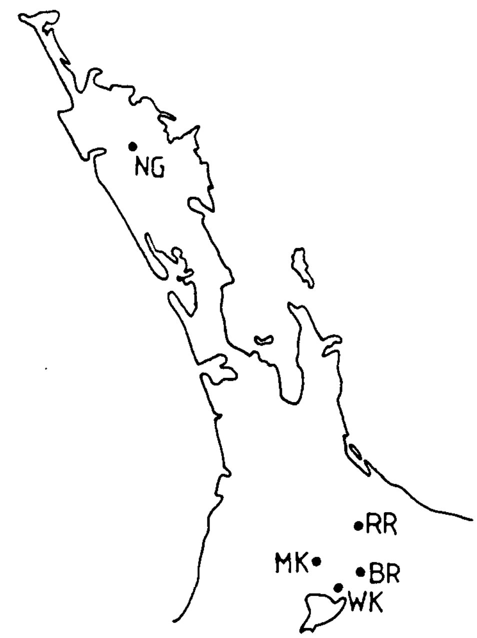

Figure 1. Northern part of North Island. Fields are labelled by their prefix: BR = Broadlands, MK = Mokai, RR = Rotorua, WK = Wairakei (all in the Central Volcanic Region) and NG = Ngawha in Northland.

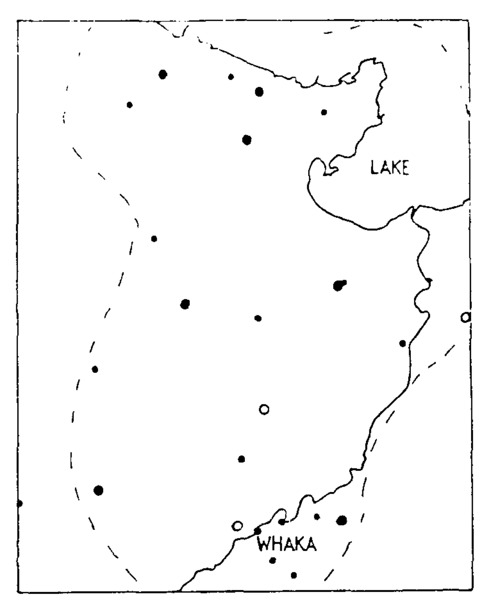

Figure 2. Rotorua field. Dashed line is approximate field boundary. Large circles are monitor wells (open circles undrilled) and small circles groundwater wells. After Grant and Bradford, 1983b.

present but not consistently. Some events are seen right across the field, confirming high permeability.

Since the monitoring program was first proposed in 1979, several more springs have failed, temporarily or permanently. Public concern over the last was such that the monitoring program's results have been partially anticipated: a task force has been established to provide technical assistance to well users to reduce flow rates. It is believed that the inefficiency of present use is so great that substantial reductions can be achieved at little cost to users, and the immediate aim of the task force is such reductions as can easily and cheaply be achieved. The longer management of the field is still unclear, and this remains the ultimate objective of the monitoring program.

WAIRAKEI

Recently work has been completed on a simple model of the Wairakei reservoir (see Blakeley and O'Sullivan, 1982). The model is rather idealised as radial symmetry is assumed and the discretisation is quite coarse. The block layout is shown in Figure 3.

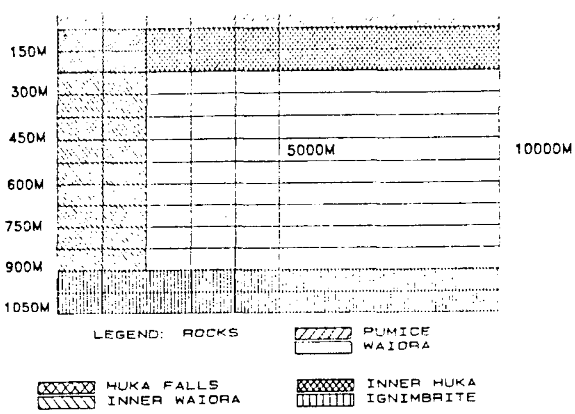

Figure 3. Wairakei field axisymmetric model.

The basic aim of the modelling study was to construct a simple model which was able to perform three tasks:

(i) reproduce a natural state similar to that observed at Wairakei before exploitation;
(ii) match the production history;
(iii) produce a plausible long-term future.

Also the model was designed to be independent of external assumptions as far as possible. Therefore a large total volume was considered so that the inevitable boundary conditions do not significantly affect the performance of the model over the simulation time of 70 years (1953-2023).

The results from the model were good. An excellent match to the pressure response was obtained (any two parameter model can achieve this) and a reasonable match to production enthalpy was obtained. A small number of parameters was used. As Figure 3 shows, different properties were used for each of the major material types (idealised here as uniform constant thickness layers), and in tuning the model to match the production history it was found to be necessary to have different permeabilities inside and outside the production zone. Further discussion of the model and the results are given by Blakeley and O'Sullivan (1982). Perhaps the most interesting results are the temperature and saturation distributions at various stages of exploitation shown in Figure 4.

They illustrate the stages of development of the Wairakei reservoir. First the two-phase zone expands as the pressure in the production zone drops rapidly. This stage continues until a quasi-equilibrium state is attained where the lateral inflow to the production zone matches the production rate. After this time the pressure drop slows and the production zone is gradually cooled by the cooler recharge water.

In fact, Wairakei is not radially symmetric or perfectly uniform, and the intrusion of cooler recharge water along faults to some parts of the production zone is already noticeable. The future predicted by the model should be regarded, therefore, as the "best possible" case.

NGAWHA

During 1983 a set of Paroscientific quartz pressure gauges and data logging equipment was purchased by Ministry of Works and Development for use on interference testing. These gauges have a resolution of 1-10 millibar depending on the individual gauge full scale range and the capabilities of the data logger.

At Ngawha we are fortunate that many of the well will stand shut with a liquid column to the wellhead and a stable pressure of 4-12 bars. So by simply attaching a high resolution gauge to the wellhead, interference observations can be made.

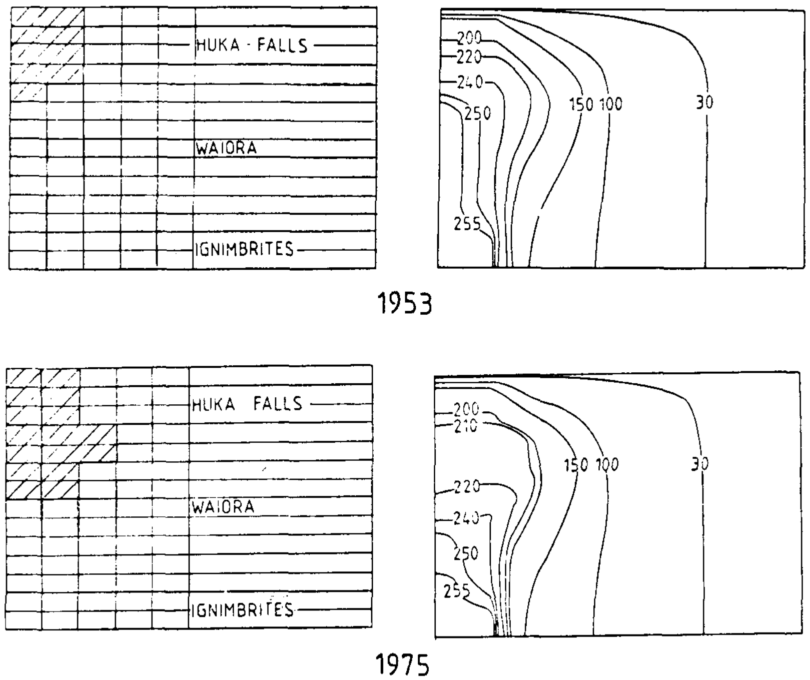

Figure 4. Wairakei model results at two times. Shaded area on left block is two-phase zone.

A section of the Ngawha field is shown on Figure 5, showing observation and production wells. In all wells except NG13 feed points are at 700-1000 m; in NG13 they are between 960-1600 m.

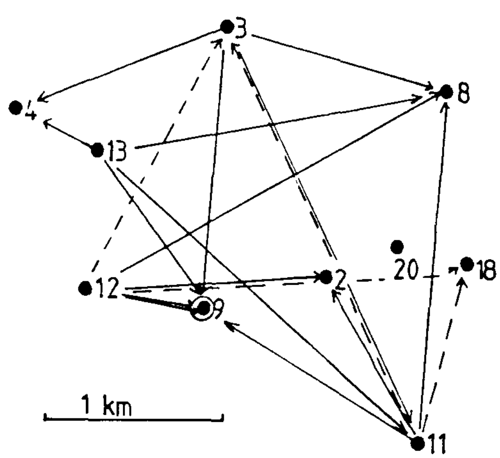

Figure 5. Ngawha field layout and interference tests. Solid lines indicate response, dashed lines no response. NG9 has a dual completion.

Ngawha reservoir is overlain by a caprock of breccia of very low permeability. The reservoir rock is fractured greywacke. Within this greywacke is a zone of very high permeability, containing liquid water at 220-230°C and 1-2%CO_2. Beneath the permeable layer temperatures rise rapidly.

Analysis of the interference test results has been difficult. There are significant instrumental problems, producing a drift in the recorded results that is difficult to correct for. Another instrumental problem is that cable coatings are palatable to cattle. There are also difficulties in the interpretation of the real data. This has been shown most strikingly in the response of NG9, 2 and 8, to NG12. Each observation well produces a result that fits well to the line source solution, but the three wells have nearly identical responses despite different distances. Work continues on a structural model.

MOKAI

Mokai field, located 25 km northwest of Taupo, is the most recent exploration target, and the most promising field yet drilled in New Zealand. The resistivity boundary contains 18 km^2 (Bibby et al., 1981). The six wells drilled so far have found that part is cool (150-220°C); part is very hot, at boiling point to above 320°C, and permeable.

The initial assessment of the reservoir has used detailed interpretation of the reservoir pressure distribution (Bixley and Grant, 1981) and the natural flow to determine that overall reservoir values are $k_h h \geq 100$ d-m, and $k_v A \cong 20$ md-km^2, where k_v and k_h are vertical and horizontal permeabilities and h and A are aquifer thickness and area. In an exploited reservoir at boiling point vertical fluxes are important. Simulations of vertical fluid distribution under exploitation (Figure 6), implemented using the Auckland University geothermal reservoir simulator (Zyvoloski and O'Sullivan, 1980), show that for $k_v > 10$ md no deep production wells will be required. By such simple modelling studies it is hoped to optimise development strategy.

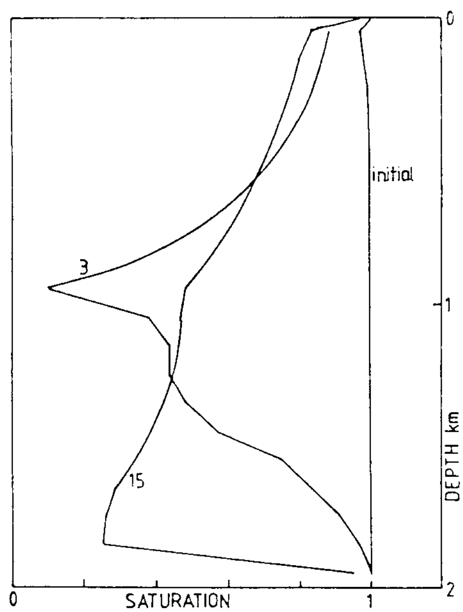

Figure 6. Mokai vertical scenarios. Sensitivity to vertical permeability. Figure shows saturation profile initially, and after 12 years withdrawal at 1000 kg/s, for k_v = 3 and 15 md. From Grant and Bradford, 1983b.

BROADLANDS

The greatest variety and depth of reservoir work has been done at Broadlands. This includes interference testing, detailed interpretation of pressure-temperature data and simulation.

Interference testing

Several of the investigation and production wells drilled at Broadlands will stand open with a stable water level, unless stimulated into production. Since 1979 most of these wells have been used to monitor interference effects from single well production or injection tests. Most of the wells are drilled to about 1200 m and have feed points at 800-1000 m. Nine interference tests were done, including one well pair where the observation and production wells were reversed, and later an injection test was performed. Results from most of these tests have been previously analysed using semi-log analysis methods and are reported by Grant, Donaldson and Bixley (1983).

In May 1983 Professor H.J. Ramey Jnr visited New Zealand and gave a series of lectures on well test analysis. As part of these lectures the Broadlands interference tests were re-evaluated using log-log matching to the line source solution. Examples of curve matching are shown in Figure 7.

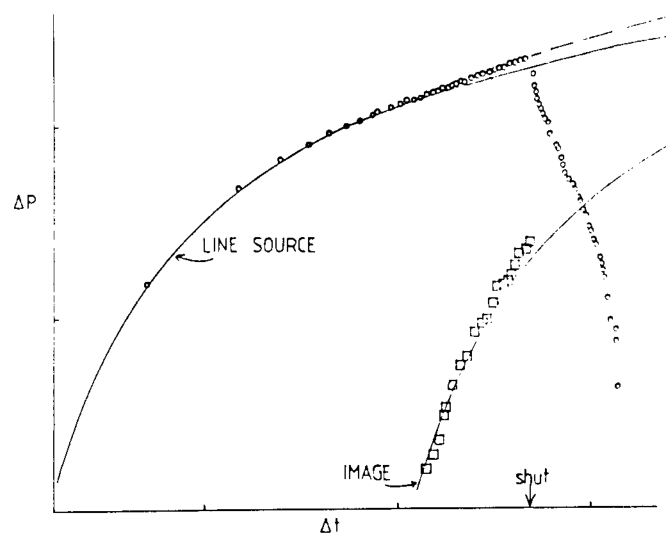

Figure 7. BR13 response to BR23 production, log-log plot. Boundary effect after 11 hrs production.

In general the observed data corrected for changes in atmosphere pressure - the water levels were 0-90 m below surface and were recorded with a resolution of 1-3 cm, i.e. 1-3 millibar - give very good matches with the line source solution, and display a range of characteristic responses. Figure 7 shows a boundary effect commencing during the production period.

Results are summarised in Table 1, together with those presented by Grant, Donaldson and Bixley, using semi-log analysis. Image distances obtained from the line source analysis are somewhat erratic, but permeability-thickness values are quite consistent showing an area with kh of 70-100 d-m in the known, hot, productive section of the reservoir and a more extensive area to the south with a lower permeability-

Obser-vation well	Prodn well	r m	SEMILOG ANALYSIS kh (d-m)	SEMILOG ANALYSIS ϕch (x 10^{-7} m/Pa)	LINE SOURCE ANALYSIS kh (d-m)	LINE SOURCE ANALYSIS ϕch (x 10^{-7} m/Pa)	LINE SOURCE ANALYSIS image (m)	LINE SOURCE ANALYSIS duration (hr)
13	23	280	90	7.8	93	0.7	2400	140
23	13*	"	120	3.1	72	1.3	3600	500
23	13(I)	"	95	2.8	68	2.1	900	50
23	19	360	80	5.6	93	3.1	1100	190
34	31	570	-	-	20	6.4	-	300
34	23	790	-	-	27	3.6	-	200
34	19	740	-	-	29	4.0	3400	500

TABLE 1. BROADLANDS INTERFERENCE TEST RESULTS

* For this test choosing the correct straight line is very difficult and the line source match is not as good as for other tests.

thickness of 20-30 d-m and cooler formation - say 200°C compared with 260-270°C in the productive reservoir.

Further testing

During December 1983 an extensive interference testing program will commence at Broadlands to determine reservoir parameters at the production level (600-1000 m) and in cooler aquifers overlying the production field. In this program up to 20 wells, of a range of depths from deep production wells (1200 m), through monitor wells (150-500 m) to groundwater holes (10 m), will be monitored continuously for response to production or injection at various levels of the system.

Reservoir interpretation

Past modelling of Broadlands relied upon a single average pressure history against which a lumped-parameter model was calibrated (Grant, 1977). There is in fact considerable detail in the pressure distribution, both in area and depth, over time. More detailed reservoir histories have been constructed. Figure 8 shows pressure drawdown in 1980-81. Two well-defined areas, W (West or Ohaaki) and E (Eastern) appear. Also shown is an anomalous zone in which pressures are consistently high, conjectured as the upflow region of the field.

Using pressure histories for Eastern and Western fields, and of shallow and deep zones of Ohaaki, more detailed mass and energy balances have been made. Of the 30 Mt discharged from Ohaaki 1968-71, it is estimated that 15 Mt was replaced from the East and 10 Mt by downflow from the rhyolites above the reservoir. Most of the 10 Mt loss from the rhyolite was in turn made up by return of water disposed at surface.

Figure 8. Isobars of drawdown, 1980-81. Pressure drop is marked in bars. Solid circles are productive wells and open circles non-productive. From Grant and Iles, 1981.

Simulation

The Broadlands geothermal reservoir presents a difficult modelling task because it contains significant quantities of carbon dioxide in the reservoir fluid. However, there are plenty of data available enabling approximate pressures, temperatures and chemical compositions to be deduced over a large part of the field. Also, a large discharge of the reservoir, with a resulting large pressure drop, was made during the period 1968-71. The behavior of the reservoir during this period and its subsequent recovery from 1971-74 and beyond was extensively monitored, thus providing an excellent data base for model calibration.

Work is proceeding on various modelling studies of the Broadlands geothermal field with the aim of setting up a model to assist with the planning of the development of the field.

Some related generic studies of the behavior of gas-rich geothermal reservoirs have been carried out in collaboration with scientists at Lawrence Berkeley Laboratory (O'Sullivan et al., 1983).

The most simple model of the Broadlands reservoir is a single block with a pressure-dependent recharge. Grant (1977) used such a model to produce a good fit to the production history at Broadlands from 1967-71 and the recovery from 1971-74.

Grant's results have been reproduced using reservoir simulators with the capability of modelling gas-rich reservoirs (Zyvoloski and O'Sullivan, 1983). The main problem with simple lumped parameter models of Broadlands is their long-term behavior depends on external recharge assumptions. In order to model the actual change of recharge properties with time, some spatial variation is required.

To further study the permeability structure of Broadlands several modelling studies are being carried out. The first of these involves a simple 1-D vertical model designed to assist with understanding the vertical permeability structure of Broadlands and to help explain the pressure, temperature and CO_2 distribution in the reservoir. The model produces a good match to the observed pressure and temperature distributions in the upflow zone in the Ohaaki section of the reservoir.

The model has also been used to simulate the reservoir behavior during the 1968-74 period. The vertical discretisation of this simple model results in a better match to production enthalpy and CO_2 content histories. However, lateral recharge is still represented only by pressure-dependent sources and therefore this model cannot be used for long-term predictions, a criticism which applies even more directly to the lumped-parameter model (Grant, 1983). Detailed results are given by Blakeley et al., 1983.

Some progress has been made on a 3-D model of the natural state of the

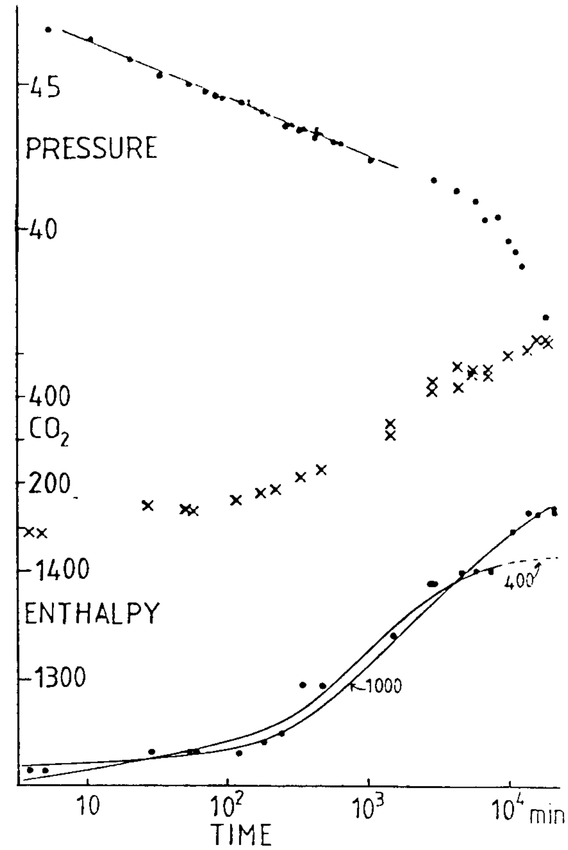

Figure 9. Changes during two weeks discharge of BR21. Pressure at principal feedpoint in bar; CO_2 content in mmol/100mol of total discharge and enthalpy in kJ/kg. From Grant and Glover (1984).

Broadlands reservoir. Also, work is proceeding on modelling the highly permeable Ohaaki rhyolite.

Other scientific work

In March-April 1982 BR21 was discharged for four weeks to obtain detailed measurements of the transient changes in enthalpy and gas and water chemistry of a two-phase well. The pressure transient results were presented at the previous workshop (Grant et al., 1982). Figure 9 shows some changes over two weeks flow at near-constant rate.

The enthalpy and chemical changes do not conform to flow in a homogeneous porous medium. Both took long to stabilise, and indeed probably did not attain stability within the test. This can be explained by modelling the reservoir as fractured, in which case the stabilisation time is increased to the block relaxation time. Correlations between chemical composition and enthalpy indicate a high residual saturation (≥80%), assuming fracture relative permeabilities. For more details see Grant and Glover (1984).

CONCLUSION

The reservoir engineering program in New Zealand, like those elsewhere, has expanded in scope and responsibility. The combination of increased experience, better instrumentation and simulation capability means that operators now expect predictions of future behavior rather than qualitative answers.

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