Paper presented to 6th New Zealand Geothermal Workshop 1984

# COPING WITH UNCERTAINTY IN GEOTHERMAL FIELD DEVELOPMENT

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## ABSTRACT

As with other energy forms, assessment of the capacity and cost of a geothermal field suffers from a number of major uncertainties. These include field extent and temperature, permeability, presence of gases and other dissolved chemicals, reinjection costs, steam deliverability per well, and recharge rate. This paper assesses the exploration histories of all New Zealand and some overseas fields.. Effective strategies for coping with uncertainty, and reducing risk, are discussed, based on this experience. Exploration drilling patterns conditional on the results from previously drilled wells, are recommended. More important, because some uncertainties, such as recharge, cannot be adequately determined, without some exploitation, a multi-staged construction of power stations is necessary to cope with the major economic risk of oversizing.

## 1. INTRODUCTION

The exploration of geothermal fields, as with oil and gas fields, starts with a very imprecise knowledge of the field. As money is spent, greater understanding of the field's performance, and its suitability for exploitation, results. A field that performs poorly may be discarded, while a really good field may be quickly and cheaply identified. Fields of intermediate performance require more care. Exploration and proving strategies that reduce the uncertainty as economically as possible, are desired.

In a similar way to oil and gas exploration, geophysics, geology and (for geothermal) geochemistry quickly and cheaply tell us something of the field's prospects [Grant et.al, 1982]. However, uncertainty is large until discovery drilling is carried out. This determines temperature, chemical composition, and initial estimates of per-

Table 1: Stages in Geothermal Development

| Stage | Description | Minimum Time | Approximate cost ($NZ million) | Purpose |
|---|---|---|---|---|
| 1. Identification | eg thermal measurement, resistivity anomaly | | negligible | Identification |
| 2. Resistivity Survey | Identifies low electrical resistivity area | 1-6 mths | 0.1 - 0.3 | Defines the major area of interest |
| 3. Discovery drilling | 1-3 wells and test. | 2-4 mths | 1 - 4 | Determine temperature chemistry, local permeability. |
| 4. Exploration drilling | 5-14 wells, interference tests, mathematical modelling | 1-2 yrs | 6 - 16 | Assess permeability across field, steam production, reinjection prospects |
| 5. Reinjection assessment | 1-3 wells, and assess field structure | 3-4 mths | 1 - 3 | Assess reinjection costs |
| 6. Decision to proceed | | | | |
| 7. Production drilling | Drill production and reinjection wells for first stage of power station | 1-3 yrs | 5 - 20 | Prove steam for station |
| 8. First stage | Build station. pipelines, etc. (in parallel with stage 7) | 2-3 yrs | 200 - 300 (for 100 MW) | Generate electricity with minimum risk of oversizing |
| 9. Operation | Operate first stage | 2-3 yrs | | Generate electricity. Assess field recharge, drawdown, etc. |
| 10. Subsequent stages (if appropriate) | Drill and build | 2-3 yrs each | as for stage 8 | Produce electricity with minimum risk of oversizing |

meability. Exploration drilling then delimits the permeable region, and gives estimates of the steam per well, that normally allow a decision on whether to proceed or not. The high cost stages, of production drilling, and staged station and pipeline construction, follow. The stages in field development are shown in Table 1.

Resistivity surveys have proved very useful in delimiting fields in Sew Zealand, where the terrain is easy and the fields are chloride dominated. However, overseas experience with resistivity surveys has been mised, eg in the Phillipines.

Drilling costs in New Zealand are about $NZ 1 million/well, and make up 10-20% of the capital cost [Barr et.al. 1984, P42]. Government projects in New Zealand.are supposed to earn a 10% real rate of return. This implies a need for fast development. and a consequent need to quickly reduce uncertainties and risks surrounding a field's capabilities.

## 2. RISKS AND UNCERTAINTIES

An uncertainty is a factor that is not completely understood or forecastable. A risk is a cost that would be incurred through this lack of understanding. Considerable literature has been written on coping with uncertainty [Hickling, 1974], [Raiffa, 1970]. The important conclusions are, firstly, that uncertainty should not be suppressed but should be investigated, and secondly. that strategies can be developed that can cope with uncertainty. Table 2 lists the major areas of uncertainty. and their associated risks, based on geothermal fields explored to date.

Temperature is one of the main determinants of the exploitability of a field. Megawatts per well is proportional to the cube of the temperature, other factors being equal [James, 1980]. High temperatures mean proportionately more steam, and less fluid to reinject. Low temperatures mean the reverse, a double penalty. In New Zealand, fields with a production temperature below 240°C are unlikely to be developed, for power generation. Permeability is the ability of fluid to flow through the field. Good permeability is reflected in high MW/well, relative to the maximum MW at that temperature.

It is now normal io reinject fluid in New Zealand fields. although there is as yet no long term history for reinjection. Reinjection can sometimes be difficult if wells are impermeable, or if there is a risk of quenching; hot parts of the field. Consequently, reinjection still poses considerable uncertainty in the longer term. Quenching of wells by cool inflow of groundwater is also possible, and is believed to occur at Kawerau.

Silica deposition can also be a problem, requiring the added expense of frequent redrilling e.g. Kawerau. Presence of carbon dioxide causes a field to run down more rapidly and reduces station efficiency e.g. Broadlands.

The major determinant of field rundown is a combination of the size of the permeable region from which fluid is drawn, and the recharge rate of this reservoir [Grant et.al, 1982]. To be accurately determined both these factors need discharge of the field.

Table 2: Uncertainties and Their Associated Risks

| Uncertainty | How reduced | Associated Risk |
|---|---|---|
| i) Field Extent, ie area for drilling | by resistivity survey determining the resistivity boundary. Very effective for NZ fields | Cold wells |
| ii) Temperature of reservoir | by discovery and exploration drilling | low temperature field uneconomic to exploit eg Ngawha |
| (iii) Permeability | by exploration drilling interference testing, and mathematical modelling | Impermeable or partly permeable eg Broadlands |
| (iv) Reinjection cost | by esploration well probing, and drilling specific wells, possibly outside the hot area | High cost. possible quenching |
| (v) Average Well steam production | by a good exploration well pattern, and interference testing, and modelling | Inadequate steam production by startup timc |
| (vi) Quenching, chemical clogging corrosion, gases etc | by assessment over time Gases found during discovery drilling eg Braodlands | Inadequate steam production, higher costs of steam. (Gas reduces the efficienc of use of the steam) |
| (vii) Field dynamics and Recharge | by assessment over time during field discharge with mathematical models. Staged construction of power stations eg Wairakei | Oversizing of station Fast rundown of field eg Tiwi, initial Broadlands prosposal |
| (viii) Other | New Uncertainties and risks not recognised are possible | |

Consequently. there is a **major** risk of over-sizing, if it is considered desirable to build a one-hit large power station before actually drawing down the field.

There is no reason to believe the uncertainties or risks associated with geothermal fields are any greater than those for othcr forms of electricity generation. There is now a large body of knowledge about geothermal exploration throughout the world and it is generally recognised as an economic and quick method of generation. from which most of the teething troubles have been eliminated [Budd, 1984: Barr et.al., 1984, Ch4]. A doubling in the cost of mining coal at Huntly, escalation of the cost of building the Clyde Dam, or the reconstruction costs of the Ruahihi and Wheao hydro electric schemes, are New Zealand examples of the suppressed or ignored **risks** of these other means'of generation. The risks of geothermal development are different, and need to be approached in the most appropriate way to minimise adverse outcomes.

## 3. ANALYSIS OF PAST DATA

The following analysis of field development data aims at assessing the most appropriate proving and assessment strategy, to reduce risk and uncertainty.

### 3.1 Comparison of fields

Table 3 compares the six New Zealand fields drilled so far and also gives available but dated data from some Phillipines. Iceland (Krafla) Mexican (Los Azufres) and US (Baca) fields. The Geysers (US) steam field has the greatest power production to date (930 MW in 1981) but little data is available. The table shows the great range of quality in geothermal Pields.

The most useful criteria of initial goodness are the mean initial output/well. On this criterion, Mokai is best with 3.7 MW/well, followed by Tongonan (6.7) Tiwi (5.4), Rotokawa (4.0). Kawerau (4.9), Mak Ban and Broadlands (4.2), Wairakui (3.0), Ngawha (2.8), Krafla (1.6) and Baca (0.8). Other factors are important, such as size of the field, field temperature, recharge etc. as discussed in Table 2. Tiwi, Mak Ban, Tongonan and Wairakei have all been successfully exploited.

Wairakei, which has a relatively low initial MW/well, is actually a very good field, because of its consistently high permeability.

A field in New Zealand is likely to be economically exploitable, subject to having appropriate recharge and reinjection characteristics, if the average yield per weli is 3 MW or above.

### 3.2 Consistency of Drilling Success

After the discovery and esploration phase, it is important to have an accurate estimate of what the likely future yield of steam per well will he. This will depend on understanding of the field. However, the records of the different fields are good estimators of the yield during the exploration phase.

Figure 1 shows the success rate (hits) of New Zealand wells drilled, as the number of wells drilled increases in a field. (A hit is a well producing 1 MW or inore.) One would expect that, as our understanding of the field improves, the success rate improves. This is partly, also, because the exploration phase aims to cover the field, rather than tap the maximum amount of stearn.

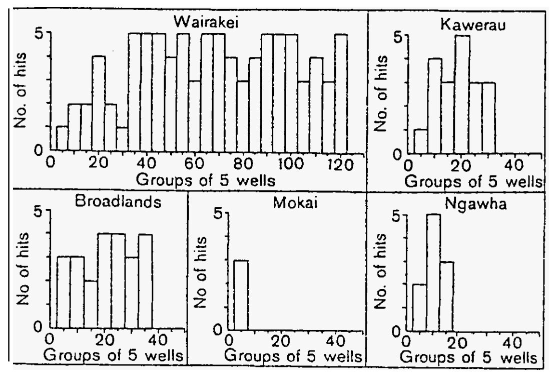


Figure 1: Well hit rate in Groups of 5 Wells

Another consideration is that the temperature of the Pield cubed and well diameter to the 2.5th power determine the maximum power that can be delivered (James, 1980).

Table 3: Comparison of Geothermal Fields

| Field | Size (sq.km) | Wells drilled | Temperature °C | Maximum Output per Well (MW) | Mean output per Well (MW) | Reinjection costs | Total output Proved (MW) | Production (MW) |
|---|---|---|---|---|---|---|---|---|
| New Zealand | | | | | | | | |
| Wairakei | 15 | 123 | 260 | 10 | 3.0 | unknown | 364 | 150 |
| Kawerau | 8 | 33 | 290 | 25 | 3.7 | unknown | 124** | 25 (steam) |
| Broadlands | 11 | 36 | 270 | 13.5 | 4.2 | high | 152 | 80 (proposed) |
| Mokai | 10 | 6 | 290 | 25 | 8.7 | low | 52 | - |
| Rotokawa | 10 | 5 | 300 | 10 | 4.0 | unknown | 20 | |
| Ngawha | 30-50 | 13 | 225 | 8 | 2.8 | high | 37 | - |
| Overseas* | | | | | | | | |
| Los Azufrcs (Mex) | n.a. | 22 | 220-320 | n.a. | 4.0 | n.a. | 71 | n.a. |
| Krafla (Iceland) | 30 | 22 | 350 | n.a. | 1.6 | n.a. | 35 | n.a. |
| Baca (USA) | 30 | 33 | 280 | n.a. | 0.8 | n.a. | 25 | abandoned |
| Tiwi (Phil) | n.a. | 95 | n.a. | n.a. | 5.4 | n.a. | 511 | 330 |
| Mak Ban (Phil) | n.a. | 83 | n.a. | n.a. | 4.2 | low | 352 | 220 |
| Tongonan (Phil) | n.a. | 50 | 300 | n.a. | 6.7 | low | 336 | 110 |

n.a.: not available
* Data may not be up-to-date.
** Initially 180 MW. 57 MW now lost by quenching.

One can graph the output of wells as a histogram. How nearly the distribution approaches the maximum possible is an indication of the permeability of the field. Good fields average one-third of this maximum. Histograms for the 4 most successful New Zealand fields are shown in Figure 2.

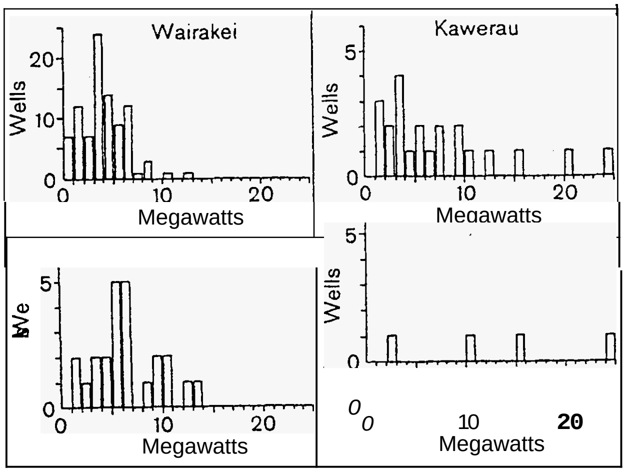


**Figure 2**: **Histograms of well** initial **output.**

It is important in planning the esploitation of a field to be able to proceed with construction at the same time that production drilling is being carried out. This speeds the station completion date. an important consideration at a 10% real discount rate. This is feasible if the likelihood of producing enough steam to run the station is virtually assured. That is, if there is consistency in the production from wells. Figure 3 graphs the cumulative initial MW from wells for a range of New Zealand and overseas fields. There is a measure of consistency in the graphs, with the slope remaining relatively constant for each field. Detailed data is not availabble for Tongonan, Tiwi, or Mak Ban, so only the average slopes are shown. With both Kawerau and Mokai, the largest producing well is 25 MW. There is greater uncertainty and bumpiness to the yield of steam, depending on when one of these very large wells is struck.

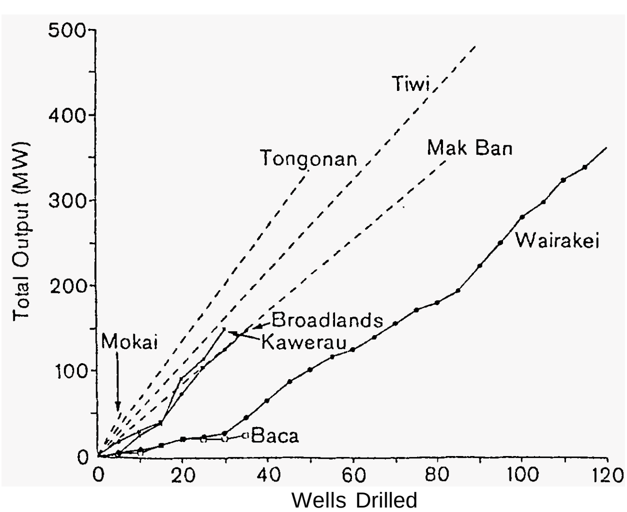


Figure 3: Cumulative Initial Well Outputs

**3.3** Wairakei

Wairakei, New Zealand's oldest exploited field, provides an interested case study (Figure 3). Yield from the first 30 shallow, narrow diameter wells. drilled in the early 1950's averaged only one MW, on a par with the abandoned Baca field. The next 50 wells averaged 3 MW each and the final wells have averaged a very healthy 4 MW. Wairakei is one of the more permeable fields in the world, and its wells are relatively cheap. It was the first New Zealand field to be exploited, and was planned in three stages. the first of 70 MW, and the second of 110 MW. A final stage was not proceeded with, because of the run-down in the field experienced through operation of the first two stages. Initial output of 180 MW has now dropped to 140 MW after over 22 years of operation. Over 1000 Gigawatt hours (Gwh) of electricity per year have been produced annually since 1963. Partly as a consequence of proving drilling for the third stage, very few new wells have been drilled since 1964. This is an expensive strategy, if one believes in a 10% real rate of return.

3.3 The Potential of New Zealand Fields

Three of the remaining four explored New Zealand fields look suitable for esploitation. Broadlands is already committed for 80 MW. Kawerau looks attractive, but the field has a pulp and paper mill on top of it, which may limit its use. Mokai looks one of the most attractive small fields in the world, with a very high yield per well drilled. to date, (i.e. good permeability). and good reinjection prospects. Electricity costs are of the order of 5c(NZ)/Kwh. These three fields, though all relatively small in extent, compare favourably, in terms of steam yield/well with the good overseas fields e.g. in the Phillipines (Figure 3, Table 3)

The fourth esplored New Zealand field, Ngawha, in contrast, although very permeable, suffers from low temperature, dissolved gases, and high reinjection costs.

The newest New Zealand field to be investigated. Rotokawa, has also shown promise, with the last well showing high temperatures and an initial 10 MW.

3.5 Purpose of Exploration Drilling

Exploration drilling has two purposes. Firstly it proves the permeability of the field. and gives an understanding of field structure and reinjection prospects. For this it is essential that the esploration drilling programme cover the field. and that effective use be made of interference testing and modelling, to probe the permeability near wells already drilled [Grant, et.al., 1982], [McGuinness, 1984]. A conditional drilling search process is called for which makes use of current. knowledge after each well, to determine the nest site that will yield maximum information on permeability or field structure. The second purpose of exploration is to prove steam. This should be a secondary, though important, consideration to exploring the field and proving its permeable region and reinjection areas.

In the past. drilling patterns that did not effectively cover the field. have been used. Broadlands is an example where the permeable region (Figure 4) covers less than half the area inside the resistivity boundary. This permeable region was not fully understood until near the end of production drilling. because of a tendency to drill near good wells. where good steam production was more likely. Over-estimation of the Broadlands field capacity (Figure 5) possibly resulted from the assumption that the per-

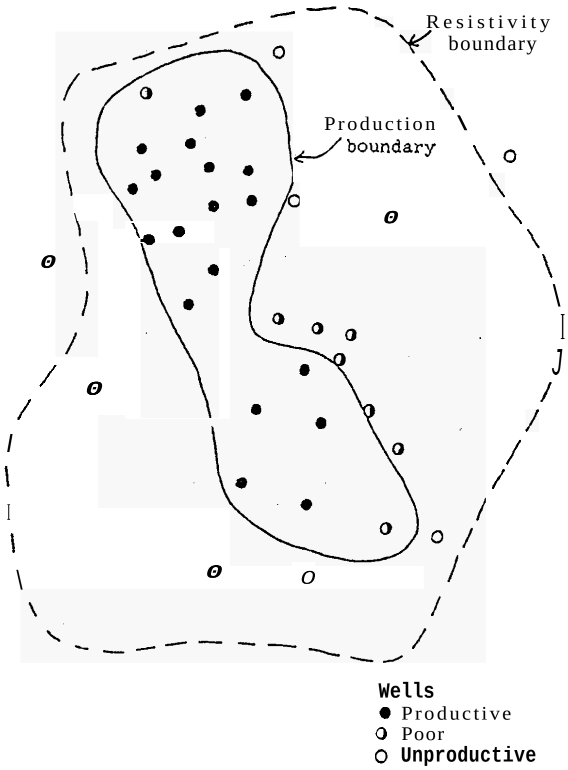


Figure 4: Broadlands productive area is much smaller than resistivity area.

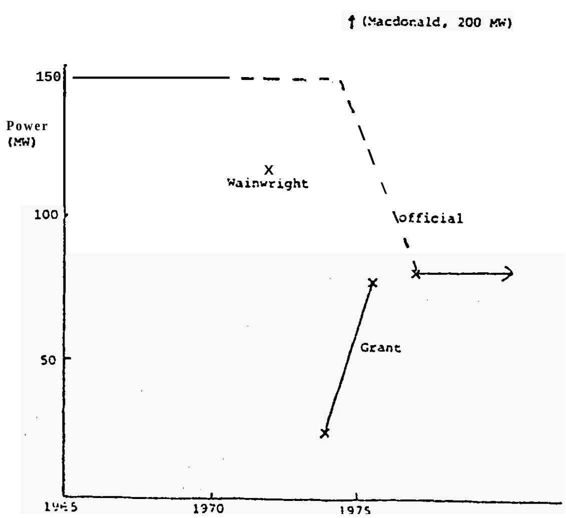


Figure 5: **Estimates** of **Broadlands Field size changed** with time.

meable area anti the resistivity area were the same. They are not. Presence of carbon dioxide also reduces field capacity.

### 3.6 Uncertainties Remaining after Exploration Drilling: Oversizing

Three major uncertainties concerning field production, remain after the exploration **phase.** These are, in order of importance, from Table **2**:

| | |
|---|---|
| (vii) | field dynamics, reinjection and recharge |
| (vi) | quenching, chemical clogging etc |
| (v) | average future well production |

The **major** risk associated with all three of these uncertainties is inability to supply sufficient steam to the power station.

Because (vi) and (v) can usually be overcome by greater drilling **or redrilling** activity they are not usually critical, Uncertainty **(vii) on** the **other** hand leads to oversizing of the station. If too large a station is built. This cannot be recovered **from.** Figure **6** indicates the variation **in** drawdown rates. and, implicitly, in recharge rate:;. It **shows** the uncertainty here is very real.

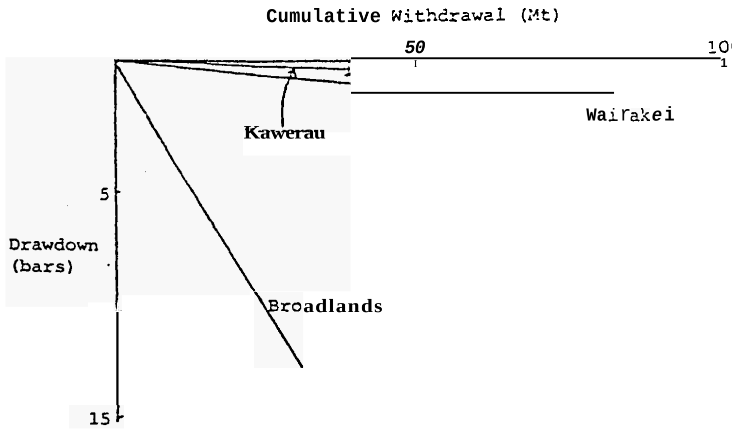


Figure 6: Drawdown of **3** Fields against Cumulative Discharge.

**The risk of** oversizing can be attacked in two alternative ways.

The first is to use the information from the exploration phase to estimate average field size, and then build a first stage *station* which is only 25–30% of this estimate. Even if things go ***wrong***, such **a** station is highly unlikely to be oversized. **As well** its unit capital cost **is** only slightly more than for a large station, as there appear to be few economies **of** scale in station construction [Barr. et.al., P46] **[Works.** 1984]. Engineering economies of scale for geothermal turbine:; larger than 50 MW seem to be negligible. Even on the large Geysers field, in California. 2 x 55 **MW** turbines is the accepted **station** size, **for** this reason, and because of the rate at which holes are drilled. **As** well, pipeline costs, which are often as large **as** drilling costs, increase rapidly with increasing station size. Consequently, the economic penalty of staged development is small *or* non-esistent. Operation of the first stage produces revenue while firming up uncertainties on field recharge. This is the strategy effectively followed at Wairakei, and followed in the **Geysers** and Phillipines fields. Because of the relatively small area of the New Zealand fields. **compared** with some of those **overseas**, it is most important to guard against oversizing in New Zealand. On a big field the **size of** a power station is usually determined **by** the **rate** of drilling and, as remarked. **is** usually about 100 MW.

The **second** strategy undertakes discharge of the field for **2-3** years to attempt to measure discharge and recharge rates before building an optimium sized station. It **wastes** a considerable portion of the energy of the field, and causes a considerable delay before income is received. It also still runs a high risk of oversizing. It is a most unattractive strategy. In spite of this. it was the strategy followed at Broadlands. The field was discharged at **50** MW for 3 years. after which a 150 MW power station was recommended (Figure 5). Further evidence **has** since shown 80 MW may **be** all that is sustainable. This is all that will be **built**, initially.

The long run performance of geothermal fields is very difficult to assess quickly by present methods. Consequently staged development is essential, if high rates of return are to be achieved, and if risks are to be minimised.

## 4. CONCLUSION - EXPLORATION STRATEGY

Based on esperience gained from development of geothermal fields to date, one can identify a number of uncertainties affecting the economics of development. An appropriate exploration strategy can delimit and reduce these uncertainties effectively. This allows an assessment of the field's worth for staged exploitation, and reduces the associated risk.

However. there are some uncertainties such as recharge that can only be reduced or understood through long term operation of 'the field. This situation makes it essential that exploitation is staged, to reduce the financial risk Prom adverse surprises. while still maintaining a high real rate of return [Barr, et.al., 1984, P47].

Specifically,

(1) a flexible exploration drilling strategy, conditional on all previous drilling results. should be followed, to effectively explore the field.

(2) Multi-staged development of the field is essential if high real rates of return are to be achieved, and if the risk of oversizing is to be minimised.

(3) Steam production per well, (which depends both on reservoir temperature, and field permeability), the extent of field permeability and reinjection costs are the major considerations in determining whether exploitation should proceed, after the esplorntion phase.

(4) Consistency of fields discovered to date would indicate that low risks are attached to a strategy of drilling production wells in parallel with initial construction of the first stage of the power station. The average and maximum number of wells required can be estimated. This strategy allows higher rates of return to be achieved.

(5) Mathematical models appear the only way to adequately describe field permeability, production performance, recharge and rundown.

(6) A long time is required to fully exploit a field past its first stage - some 10 years. There is also very great uncerta'inty surrounding the suitability of fields, prior to discovery drilling. Consequently it is essential that a discovery drilling programme in potentially esploitable fields, not considered valuable for tourist, cultural or scientific purposes, be continued, to firm up likely new stations. Drilling at Rotokawa, a consequence of this approach has recently been successful.

ACKNOWLEDGEMENTS

This work has been supported by the DSIR Geothermal Co-ordinacor. We are also grateful for information supplied by, and discussion with. sta'ff of New Zealand Electricity, Ministry of Works and Development, DSIR, and Ministry of Energy.

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