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# OPTIMISING FIELD PROVING AND DEVELOPMENT

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**ABSTRACT**

Mokai is a recently-explored geothermal field in New Zealand. After drilling 6 wells, it is clear that there exists an extremely productive reservoir. The future exploration and development options are evaluated to find the most economic path to a developed resource. The basic tradeoff considered is between additional proving effort, and the consequent expense and, more importantly, delay. For fields of the generally very productive type found in New Zealand, comparatively little proving appears justified.

## INTRODUCTION - MOKAI REVIEW

Figure 1 shows a map of Mokai field, including the resistivity boundary, the six drilled wells MK1-6 and sites MK7-11. Figure 2 shows the reservoir temperatures in the wells, and Table 1 lists permeability and performance data.

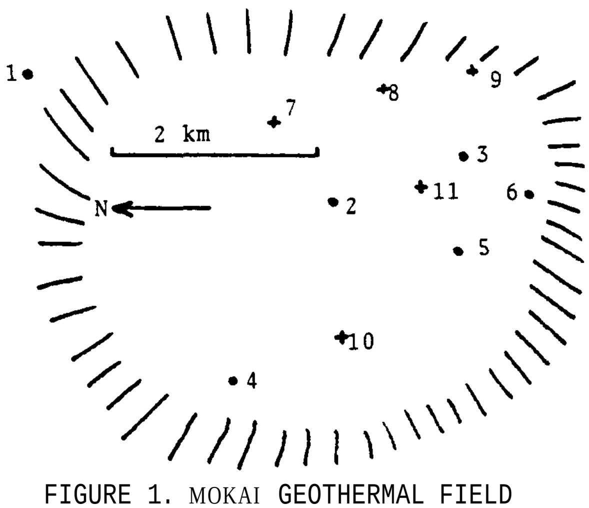


FIGURE 1. MOKAI GEOTHERMAL FIELD

Wells MK1 & 4 encounter temperature reversals. Although there is little surface activity within the field, warn springs emerge further north and an unknown amount of water enters the bed of the Waikato river 10km north. The total such outflow is 100-400 MW(th). Plotting reservoir pressures determined in the feedpoints of the different wells reveals no detectable horizontal gradient, despite a flow north; which implies that average reservoir kh is at least several tens of darcy-metres. There is a detectable vertical gradient difference fror hydrostatic, giving $k_vA$ = 10-20 md-km$^2$. Vertical permeability must be significantly less than horizontal.

On average there is thus implied to be good horizontal and moderate vertical permeability. The wells' performance confirms the good permeability and shows high temperature. Part of the field is indicated by MK4 to be of low temperature. The hot area includes MK2, 3, 5, 6 and presumably a larger area, say 6-8km$^2$. The reservoir water is an alkaline chloride water similar to Wairakei and gas content is low.

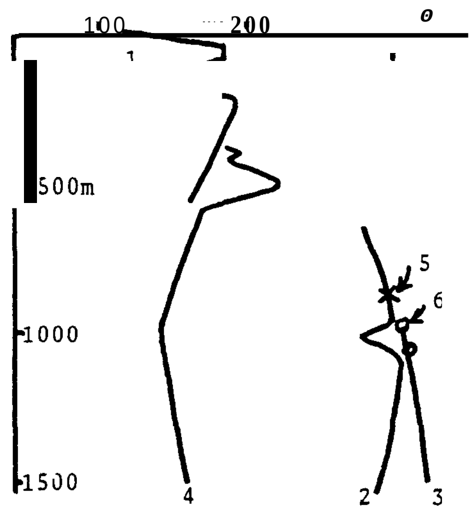


FIGURE 2. INTERPRETED RESERVOIR TEMPERATURES FOR MK1-6.

**TABLE 1. MOKAI WELLS**

| Well | MK1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Casing m | 228 | 650 | 644 | 652 | 799 | 845 |
| T.D. m | 606 | 1658 | 1679 | 518 | 2593 | 2220 |
| Feed: | | | | | | |
| Depth m | 350 | 980 | 1070 | 990 | 860 | 2105 |
| Temp °C | 164 | 290 | 305 | 160 | 290 | 300 |
| Inj kg/b.s | 5.3 | 10 | 10 | 7 | 30 | 6-14 |
| kh d-m | 9.5 | 10 | 2-10 | 8 | 30 | ? |
| Max Flow | | | | | | |
| Mass kg/s | 7.8 | 25 | 60 | - | 200 | 100 |
| Enth J/g | 720 | 1600 | 1840 | - | 1290 | 1350 |

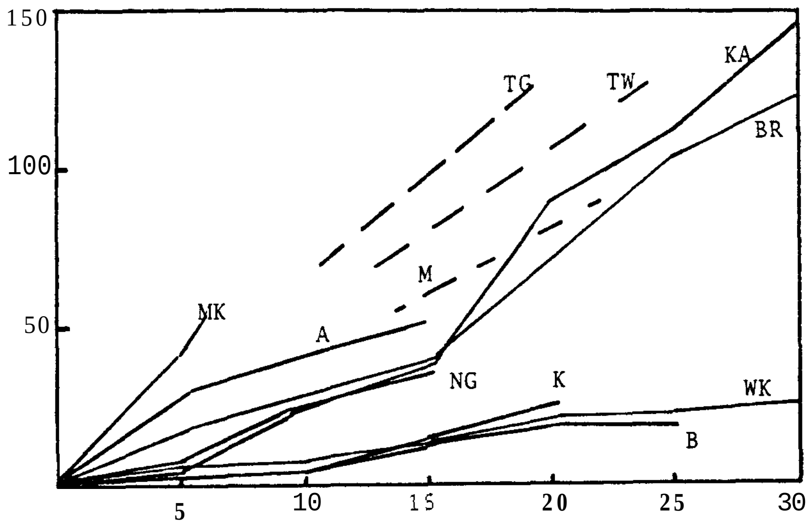


FIGURE 3. DRILLING SUCCESS, IN MW PROVEN AGAINST WELLS DRILLED. A= Los Azufres, B=Baca, BR=Broadlands, K=Krafla, KA=Kawerau, M=Mak-Ban, MK=Mokai, NG=Ngawha, TG=Tongonan, TW=Tiwi, WK=Wairakei.

Mokai is an excellent prospect. Figure 3 shows the cumulative MW(e) from drilling in a variety of fields. With 55WM after the first 6 wells, Mokai has by far the best results of exploratory drilling. In general, except that there exist larger fields, Mokai is the most productive geothermal field known to the authors, anywhere' in the world.

**PROVING PROCEDURE**

There appear to be a wide variety of proving criteria in use. At one stage an international criterion used was a requirement of 130% of needed steam supply available from drilled wells, before committal to development. Other criteria have been 35% of stored heat, used over a 30 year life.

The authors' reserve criteria in practice are equivalent to:

- a reservoir of several $km^2$ in area and several hundred m, thickness
- reservoir temperature $\geq 240°C$
- field kh $\geq$ 10 d-m: as measured by interference test or inference from natural state.

Then the reserve is 100% of the stored heat within a conservatively - defined productive interval and area, or 1/3 of the stored heat within a more generous volume: and half or 1/3 of the reserve is initially considered proven. Such an estimate can be made fairly early. One has been made for Mokai, with 5 wells drilled, was 200 MWe, on which basis 100 MWe was recommended. Some simple modelling was also done of stylised responses to exploitation.

The physical quantity actually desired to be proven is a steam flow, over a period of years. Thus the physical essential is a reservoir large enough (in some sense) and the ability to deliver from reservoir to turbine.

**DELIVERABILITY PROVING**

The process of proving deliverability is fairly straightforward. One drills wells and measures their output. Repeatable drilling success or inference from reservoir parameters of extensive permeability implies deliverability. In practice it takes 5-15 wells to hit opon typical well performance of a field. Barr & Grant (1984) summarise the drilling success at a number of fields within and without New Zealand, summarised in Figure 3. Each field has a typical average well size, with an initial exploration period in which less productive wells are drilled. This initial period lasts 5-15 wells.

Once a reasonable average deliverability is attained, there seems little point in additional drilling to prove additional steam flow. In the case of Mokai. drilling another well alongside MK5 would increase the average well flow, but do nothing to prove the field.

The additional information needed is about reservoir size. The point may seem obvious but there are excess wells drilled at Broadlands, Krafla, Olkaria and Tiwi.

**RESERVOIR PROVING**

Given a party-explored geothermal reservoir, there is within the current knowledge some estimate, with sone uncertainty, of the field capacity. For simplicity I regard this as being expressed as M megawatts. The choice at any stage is to collect more information, or to commit immediately to some size of station.

Figure 4 sketches the flow path. After committal and construction, the chosen power station may turn out to be too small: in which case an increment is later constructed: or too large: in which case it is not fully loaded.

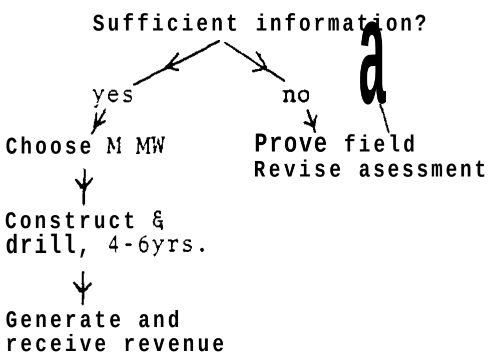


**FIGURE 4. FIELD PROVING.**

Given a probability distribution of field capacity, costs of construction and revenue from generation, it is possible to optimise the initial station size. The optimisation balances the risk of oversizing, with excess capital expenditure, against the risk of undersizing. with delayed revenue. A simple criterion emerges (A8) which sets the optimal station size at a level of the probability distribution determined by the cost data.

For a range of costs, this lay at the 10-203 level of the cumulative distribution. That is, the optimal size station to build was one such that there is 10-20% probability of station oversizing, and 80-90% probability of undersizing and the later construction of an increment.

For the case of Mokai. a triangular distribution my be assumed. (Fig 5) over a range 50-250 MW. The cost data assumed give an optimum at $F(M_0) = 0.18$, which is attained at $M_0 = 110$ MW. There is an 18% chance of oversizing and an 82% chance of constructing an eventual increment. A station of 110 MW has at comaittal a present value of $68m. However the expected value of Mokai, with the initial choice of 110MW, is $72m, the delayed benefit of the probable increment somewhat out weighing the less probably oversizing.

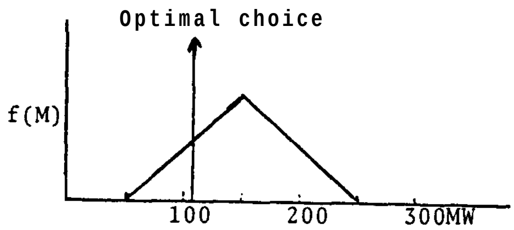


**FIGURE 5. TRIANGULAR PROBABILITY DISTRIBUTION FOR** MOKAI.

Note that the strategy of being certain is poor. This entails committing 50 MW to Mokai and later building an increment of expected size 100 MW. This strategy has a present value of $58m, because of the delayed large increment. This specific example points up the general observation that information costs money and it cannot be optimal to seek perfect information.

**VALUE OF IMPROVED RESERVOIR DEFINITION**

Given an expected value of the reservoir, one can then determine the change in this expected value created by better reservoir information. Suppose that further exploration drilling or testing will halve the uncertainty in reservoir size. What is this worth? This gives a rough yardstick against which to judge the cost of collecting the information.

There is at present the distribution $f_1$ of Figure 5. The result of better infornation will be a new, tighter, distribution, lying anywhere within the range of $f_1$. I assume there are three possible outcomes. shown in fig 6. (The possible outcomes must add up to the original distribution. Specifically, given possible outcomes $f_\alpha$. with distribution $f'(\alpha)$ some parameter $\alpha$, we need $f_1 = \int f_\alpha f'(\alpha) d\alpha$).
The new possibilities are:

a) with 25% probability: triangular distribution over 50-100 MW
b) with 50% probability: triangular distribution over 100-200 MW
c) with 25% probability: triangular distribution over 150-250 MW

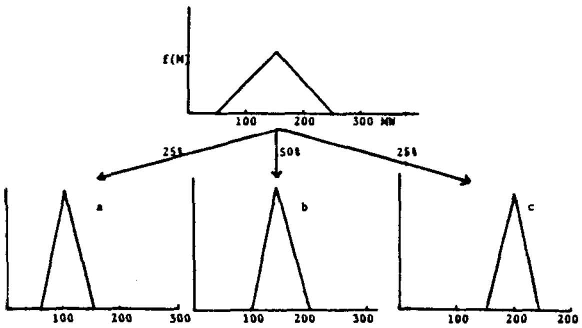


**FIGURE 6. POSSIBLE REVISED PROBABILITY DISTRIBUTIONS AFTER TESTING.**

This means that the effect of the additional information is to narrow the range of uncertainty. Then under outcome 1), one would construct a station at the 18% level. which is 80 MW. Similarly under b) one would choose 130 MW, and under c) 180 MW. The expected size of the power station would be 130 MW, and, again allowing for eventual increments/oversizing, the present value $81m.

The information that halves the uncertainty in reservoir size is worth $13m. But note that in any program to collect such information, the cost would be both the direct cost and the cost of delaying committal. If there is one year's delay, at 10% discount rate the reduces the present value by $8m.

We can now consider possible options at Mokai.

**MOKAI - RESERVOIR TESTING**

A major testing program was drawn up for Mokai, using the existing wells, plus another injector, and shallow monitor wells. Then a discharge-injection test sketched in Figure 7 would provide an interference test to measure both vertical and horizontal permeability over an extensive area, and measure changes in well characteristics over a period of months. An extensive area of the reservoir would thus be probed. There would also be gained information about possible enhanced surface steam discharge, and the possibility of relying on shallow production.

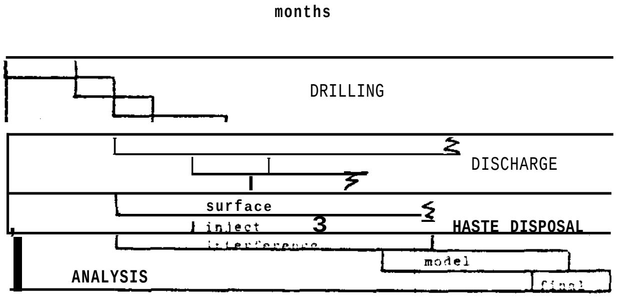


FIGURE 7. MOKAI PROVING PROGRAM

Excluding the drilling costs, or the cost of the wasted steam, this test would cost of the order of $1m, and would take 1½ years to final report. Comparing this with the preceding section it is immediately apparent that time is the major consideration. If decisions wait upon this or similar testing, the test is of doubtful value. If the test does not create delay, it is very valuable. Indeed, one can observe with more generality, comparing the value of improved reservoir definition with the cost of a major simulation exercise or a few scientist - years, that reservoir analysis that does lead to improved definition is very valuable. A profit-maximising operation would probably spend more than present practice on reservoir engineering, provided that such work does not delay development.

**MOKAI - POSSIBLE DRILLING**

Additional drilling does not do much to narrow the uncertainty in reservoir size, since much of the uncertainty involves issues like recharge and cold water incursion that need drawdown to test them. What drilling can do is to change the expected size of the reservoir.

Sites MK7-9 are on geological and geophysical grounds expected to be productive. There is therefore less point in drilling them as exploration wells. as opposed to sites will less certain outcome. MK11 is a production well site. MK10 is uncertain as given the disparate nature of MK4 and 5 it could be very hot, or cold. It has greatest leverage over future possibilities. We consider there are three possible outcomes, all assigned 1/3 probability:

a) MK10 is like MK5 - hot and peraeable
b) MK10 is like MK2 - hot but not very perneab
c) MK10 is like MK4 - cool.

Alternative a would increase the present 6km$^2$ area by 1.8km$^2$. Alternative b adds 0.8km$^2$ and c makes no change.

Figure 8 shows a flow chart. It compares the options of immediate committal; and drilling MK10, followed by committal. It is assumed that immediate committal would be to 100MW, with a 50% chance of a 50MW extension after three year's operation of the initial stage. Figure 9 shows the expectation values of the two paths. If MK10 is not drilled, there is immediate committal to 100MW followed by 49MW 8 years later. If MK10 is drilled, there is the cost of drilling, and delay to evaluate: followed by 115MW and eight years later 34MW.

Choosing between the two paths is economic, depending on construction costs, electricity price and discount rate. New Zealand costs are not quoted as they are pecular to local conditions. However under most scenarios the principal cost of drilling MK10 is not the cost of the well itself but the delay imposed on station construction and subsequent revenue. It is also, the case that under most cost scenarios drilling MK10 is not jusitified. Using the assumptions of Appendix 2, drilling MK10 has a benefit of S4n if it imposes no delay, but a cost of *53m* if it causes 9 months' delay: plus the drilling cost.

**CONCLUSION**

Six wells have been drilled at Mokai. The analysis of this paper reaches the possibly surprising conclusion that little if any further exploration drilling or testing is justified, in advance of a decision to commit to development. Both drilling, extensive testing and reservoir analysis are well justified if they do not delay coamittal. ie if delay is imposed by external (ie planning) procedures or if they can proceed in parallel with the initial developaent work.

Although Mokai is a very promising field and hence gives an atypically high level of initial confidence, comparing these results with actual development and proving undertaken in many fields suggests that there is much unnecessary delay being incurred in seeking unprofitably high levels of confidence in reservoir capacity.

**REFERENCE**

Barr, H., & Grant, M.A., 1984 "Coping with uncertainty in geothermal field development" NZ Geothermal Workshop, Auckland University.

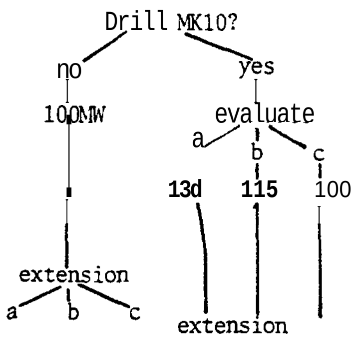


FIGURE 8. DECISION TREE FOR MK10

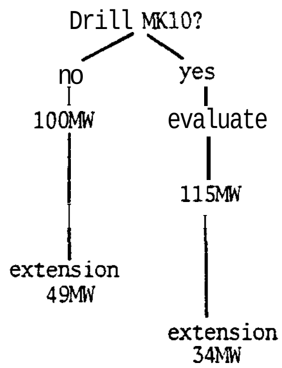


FIGURE 9. DECISION TREE - EXPECTATION VALUES

## APPENDIX 1. OPTIMAL SIZING

Assume a distribution $f(M)$ in reservoir capacity, expressed in megawatts M. The cumulative distribution is $F(M) = \int^M f(M')dM'$. Assume the following cost criteria: discount rate r, cost \$C per MW per year for n years of drilling and construction, followed by 30 years of revenue \$R per year. All costs are discounted back to the time of initiating construction. Then the construction cost is

$$P_c = C\{1-(1-r)^n\}/r \qquad \text{.. A1}$$

and the revenue benefit

$$P_R = R(1-r)^n\{1-(1-r)^{30}\}/r \qquad \text{.. A2}$$

and the present value of 1 MW is

$$P_1 = P_R - P_C \qquad \text{.. A3}$$

Given the distribution in field size $f(M)$, suppose that an initial station of size Mo is constructed. Then, if the actual size M is less, revenue is collected only for this power, so the present value is

$$PV_1 = -M_0 P_c + M P_R \quad (M<M_0) \qquad \text{.. A4}$$

If the actual size M is greater, an increment in station size M - Mo is commenced after p years of field operation.

$$PV_2 = \{M_0 + (1-r)^{n+p}(M-M_0)\}P_1 \quad (M>M_0) \qquad \text{.. A5}$$

The expected present value is

$$E(PV) = \int PV f(M) dM \qquad \text{.. A6}$$

The optimum initial choice is found by setting

$$\frac{\partial}{\partial M_0} E(PV) = 0$$

As $PV_1 = PV_2$ at M = Mo. this reduces to

$$0 = \int \frac{\partial (PV)}{\partial M_0} f(M) dM \qquad \text{.. A/}$$

and then

$$F(M_0) = \frac{\{1-(1-r)^{n+p}\}P_1}{\{1-(1-r)^{n+p}\}P_1 + P_c} \qquad \text{.. A8}$$

That is. the optimal size of the initial station lies at a level of the probability distribution determined by construction costs. discount rate and potential revenue.

For the synthetic costs this comes to about F(Mo) = 18%. For the triangular distribution assumed for Mokai. this lies about halfway between the lower limit and the maximum, at 110MW.

Note that this result explicilty confirms the obvious, that the optimum size is not the minimum proven one. One must take some risk of oversizing. to balance the risk of undersizing and consequently delaying revenue.

## APPENDIX 2. EXAMPLE COSTINGS

New Zealand energy pricing involves a number of artificialities. The following synthetic costs have been used in example calculations: (\$1NZ = 0.504 US)

| | | |
|---|---|---|
| discount rate 10% | | |
| construction cost | C = \$0.4m | for 5 years |
| revenue | R = \$0.4 | |
| evaluation time | p = 3 years | |
| drilling cost | = \$1m | |

These costings may be unrealistic. The discount rate r strongly affects the tradeoff between present costs and future benefits and at a lowed rate the cost of time spent proving a field is proportionately reduced.