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OPTIMUM DESIGN PARAMETERS FOR GEOTHERMAL POWER IN THE FACE OF DECLINING WELL DISCHARGES

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SUMMARY - A project based on one well puts in *sharp* focus two problems of geothermal exploitation which are (a) declining discharges; (b) failure in drilling make-up wells. To overcome these adverse features, it is recommended that discharge is throttled to 2/3 its maximum horizontal value and relieved over early years of production to sustain a constant discharge. This eventually gives way to flow reduction at a decreased rate of fall. An original decline curve is employed with its effect on project economics of different rates of fall. The design is self-contained and should reduce the financial risk in funding geothermal projects.

1. INTRODUCTION

The basic instrument of geothermal power is, of course, the borehole, and whether it is just one supplying a small project or hundreds discharging to a substantial development, the rate of decline of the power potential is as important as the initial output. But here we have a problem as, although the latter parameter *can* be measured in some detail, the former is to a large extent unknown, as it would take a few years of production to determine with confidence the drop in discharge, to be able to extrapolate over a decade (which is the length of time necessary to repay the invested capital).

The problem of economic development is brought into sharp focus when considering the small one-well project generating 5 to 15 MWe, as usually this is the most economic exploitation - at least initially - as economics of size do not apply to geothermal as they do for nuclear and fossil-fuel power plants.

The reason a hypothetical project may be only initially economic is that by its very nature such projects represent a declining asset with the discharge falling rapidly to start with and less rapidly as time and discharge progresses over the duration of the project; this places a great difficulty on efficient design, as within a few years the plant may be substantially over-sized for the now smaller steam flow to the turbine. And if drilling a new well has to be factored-in, there is no surety that it will be a commercial success - it is just as likely to be a dud. Hence the best strategy for the future expansion of geothermal energy is to design projects so that they do not depend on future drilling to sustain output, or if this cannot be guaranteed to at least minimise the likelihood of having to do so.

2. DESIGN FOR DECLINE

The principal design features to sustain production in the face of declining well discharges are shown in Figure 1,

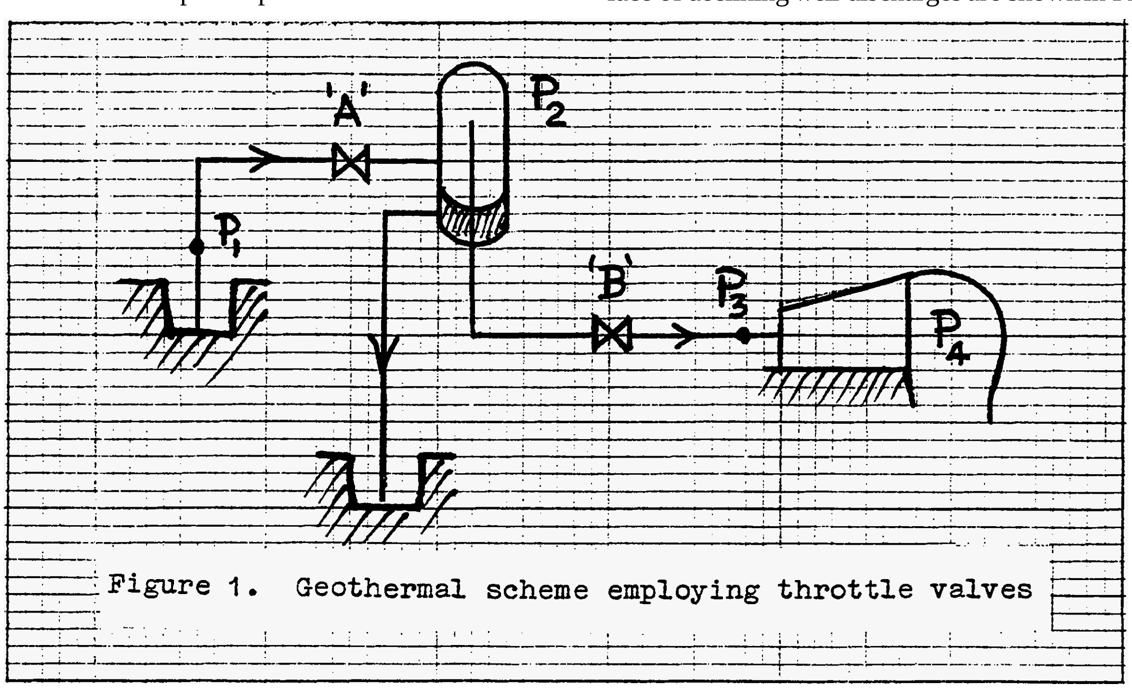

Figure 1. Geothermal scheme employing throttle valves

where pressures P,, P_2, P_3 and P_4 are respectively wellhead, separator, turbine entry and turbine outlet to the condenser. Throttle valve "A" is between wellhead and separator and throttle valve "B" is between separator and turbine. We arbitrarily assume an aquifer of **250°C,** a wellhead pressure at **22.25** ba (= bar abs), flow-rate of **231** t/h throttled by valve "A" to keep the separator pressure at ***5.5*** ba fiom which a steam flow of **47.6** t/h enters the turbine at **4.5** ba and exits at **0.15** ba. It is clear that there is an in-hand pressure-drop of **22.25 - 5.5** = **16.75** bar-difference across the throttle which ***can*** be relieved over years of decline until the wellhead pressure has fallen to **near** ***5.5*** ba at which point valve "A" is fully open. During **this** time, the wellhead pressure reduces progressively at constant discharge **so** that the ***steam*** flow to the turbine is also constant and generates ***5*** **MWe.** If the separator pressure has to be held at ***5.5*** ba or higher to inhibit chemical scaling of the injection water line, then **this** is accomplished after valve "A" is wide-open by throttling valve "B" in which **case** the **steam** to the turbine will decrease in harmony with the well output, leading to a continuous fall in power. However, if the brine chemistry is not a controlling feature, the separator pressure ***can*** be allowed to fall with increased steam flow to the turbine and a fractional increase in power. We shall, in **this** study, conservatively assume a fixed separator pressure.

3. TURBINE FLOW

Turbine design is controlled by the exit wetness which should not exceed **12.5%** otherwise severe blade erosion will result. For *dry* saturated steam entering a turbine at **4.5** ba, **an** exit pressure of **0.15** ba is mandatory **as** it limits final wetness to **this** value (if an exit pressure of 0.085 ba was employed, wetness would exceed **14%).**

There is also a significant advantage in high condenser pressure, **as** an optimisation study (James, **1970)** showed that minimum generating costs occurred in the range **0.15** to **0.17** ba. **This** is because smaller and cheaper plant is required, such **as** turbines, condensers and cooling towers with less fan and water pumping power. ***Also*** a single-stage steam-jet ejector without intercoolers is **all** that would be required to remove non-condensible gases **from** the condenser. Another (minor) advantage is that the higher temperature cooling water at **54°C** would probably inhibit the growth of bacteria in the cooling tower which thrives at the lower temperatures of **35** to **40°C** and has proved troublesome to remove.

4. WELL OUTPUT CURVE

Figure **2** gives the output curve of a geothermal well coordinating discharge fraction W/W_o with wellhead-pressure fraction P/P_o where the zero suffix represents

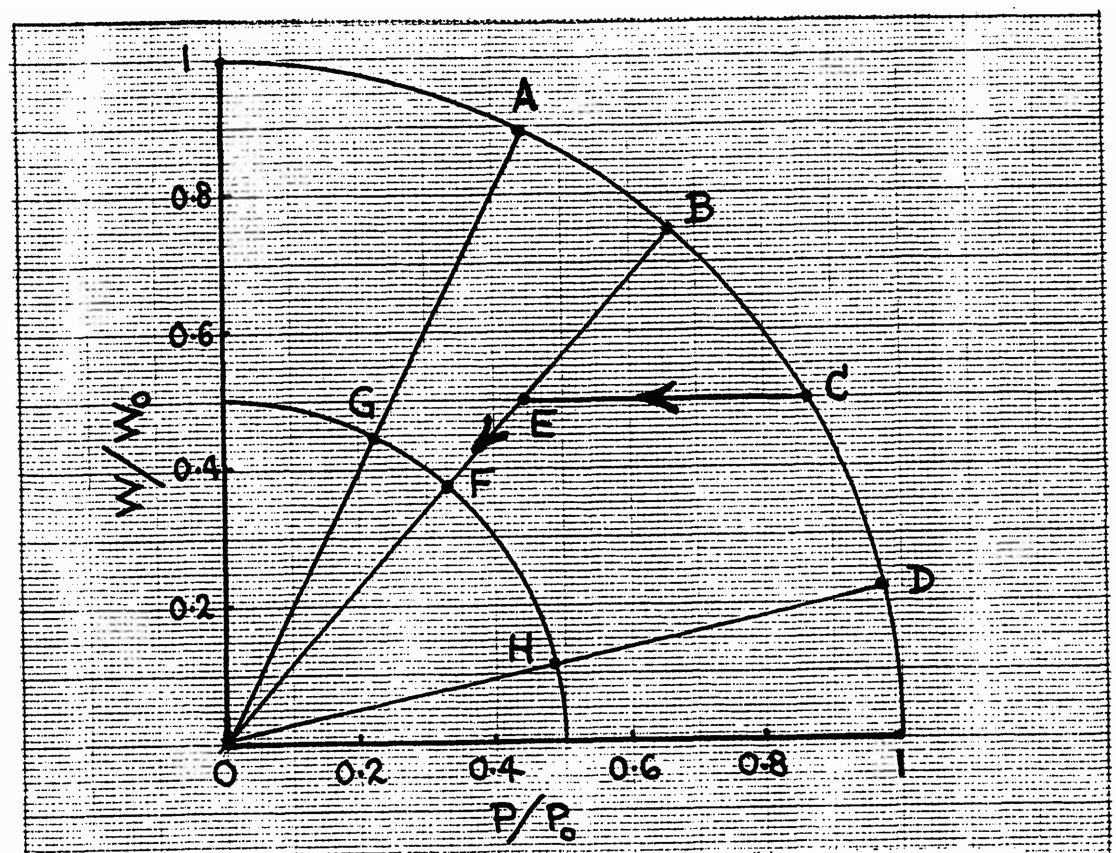

Figure 2. Output curve of a geothermal well coordin--ating discharge fraction W/W_o with well-head pressure fraction P/P_o

maximum conditions. The measurable part of the curve is AD where point A is the highest flow with wide-open vertical discharge. Point B is wide-open horizontal discharge suitable for maximum electric power. Point D is the condition of Maximum Discharging-Pressure (MDP) and gives the greatest wellhead pressure under flowing conditions (not bleeding). With years of production, curve ABCD **shrinks towards** the origin **so** that when flow and pressure have halved, the output curve **has** reduced to GFH. It is important to note that geothermal system paths usually follow radial BO, with both discharge and power directly proportional to MDP. Experience with powerful wells indicates that point B is roughly located where $W/W_o = 0.75$ and if **this** represents, say, **7.5** W e , it will decline along BO over the years to half its original value **(3.75**MWe) at point F.

Point C is for the throttled condition where discharge is held constant at $W/W_o = 0.5$ generating therefore **5** MWe **until** point E is intersected. The locus CE cannot be extended horizontally because the radial BO is for all valves wide-open, hence the locus has now to continue along the radial EO for the remainder of its productive life, with flow, wellhead pressure, MDP and power all decreasing together. Point C has **an** initial wellhead pressure of:

$$P/P_o = (1 - 0.5^2)^{0.5} = 0.866 \qquad (1)$$

Hence for a pristine hot water reservoir at **250°C** with a MDP = **25.7** ba P = **0.866 (25.7)** = **22.25** ba which is the wellhead pressure at the **start** of production in the example of Figure **1.**

So we either operate the well wide-open at an initial **7.5** W e which declines **fairly** rapidly during the early years and where the plant is soon over-sized and dependent on new drilling or we throttle flow to **2/3**the above discharge for a smaller plant of **5** MWe of constant power over a period of time dependent on the decline characteristics of the reservoir.

5. DECLINE CURVE

Experience dictates that no matter how big the reservoir, how large the discharge and how few the wells, they will **start** to decrease in output from the beginning of production. In a study of seven powerful Wairakei wells tapping the same reservoir (James, **1995),** it was found that all fell to half their original MDP in times varying **from 12.4** years to **23.5** years with an average "half-life" of **16.67** years. For each well a plot of $(P_o/P)^2$ versus t, the time in years from the **start** of production, gave a straight line correlation **so** that:

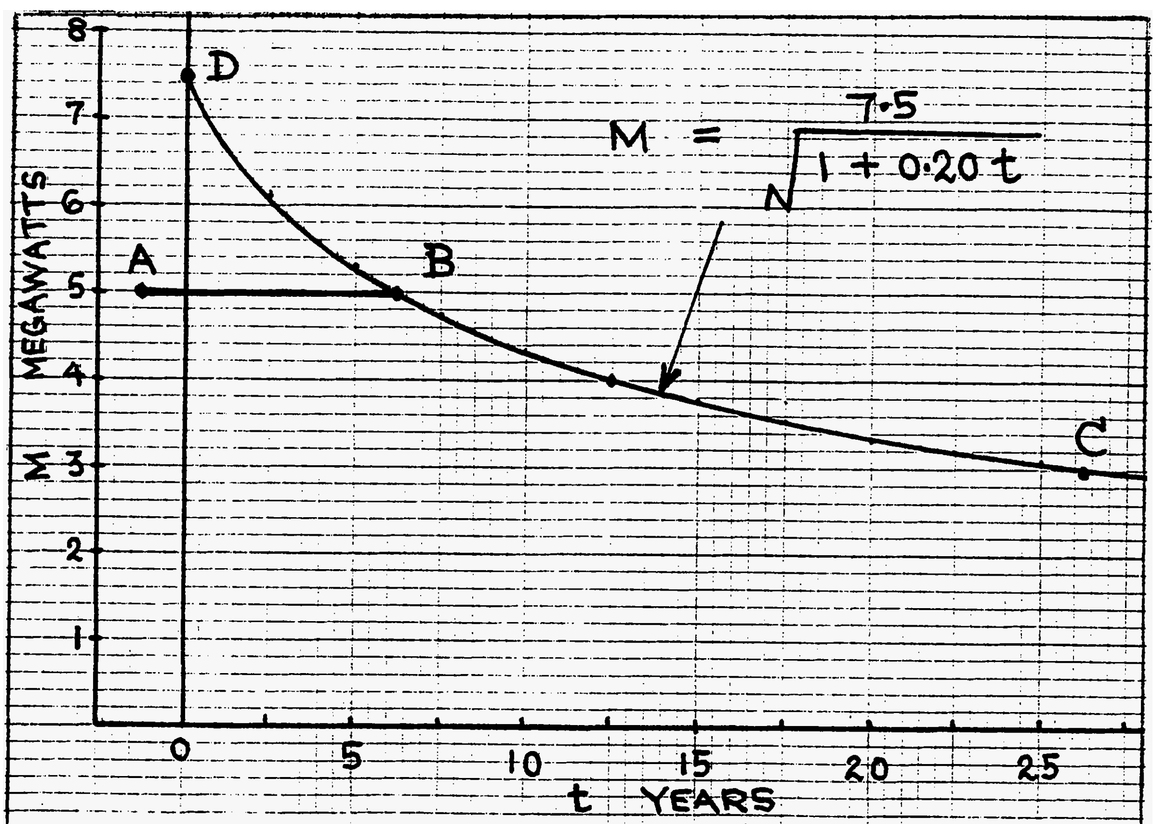

Figure 3. Geothermal well decline-curve with half-life of 15 years.

$$(P_o/P)^2 = 1 + kt \quad (2)$$

In order to make a guess at the likely decline for an untested well being considered for power harnessing, a slightly conservative half-life of **15** years is here **assumed** so that $(2/1)^2 = 1 + k\,15$ giving $k = 0.20$ **and** the applicable formula becomes:

$$(P_o/P)^2 = 1 + 0.20\,t \quad (3)$$

For radial flow, power is proportional to MDP and wellhead pressure, so we can substitute M megawatts in the above equation, and in the reversed form to obtain:

$$M/M_o = (1 + 0.20\,t)^{-0.5} \quad (4)$$

This equation is shown plotted on Figure **3** for M, = **7.5** MWe giving curve DBC (following the locus BO of Fig. **2)** where it is **seen** that the time to fall from **7.5** to **5** MWe is **6.25** years. The area under DB is calculated as **37.5 MWY** (megawatt-years) and therefore the time for the throttled flow at a constant **5** MWe **as** portrayed by line AB of Figure **3** equals **37.5/5** = **7.5** years from the **start** of production.

It should be noted that the area under the curve DBC is identical to that under ABC hence throttling the well to **5** MWe over the first **7.5** years of production has not reduced the equivalent electric energy **drawn** from the reservoir but **has** accomplished **this** at a cheaper cost - a **5** MWe plant versus one of **7.5** W e . After **7.5** years at a constant **5 MWe,** the output now **falls** along the curve BC dropping to **4 MWe** by **13.8** years from the beginning at point A, and to **3 MWe** by **27.5** years from A.

If the half-life of the decline curve **had** been **20** years instead of the **15** assumed, the time of throttling would have increased from **7.5** to **10** years **as** the two factors are in direct proportion. Likewise, a shorter half-life of **10** years would result in AB of Figure **3** being reduced to **5** years. Also, by reducing the turbine to less **than** ***5*** MWe the time of throttling would be **increased** (a **4.63 MWe** turbine would give **10** years **instead** of the **7.5** years at **5** W e) . However, a size smaller **than** ***5*** MWe is unlikely to be considered for most single-well projects utilising condenser sets.

6. DECREASING POWER

After horizontally attaining point E of Figure **2,** wellhead pressure and discharge now decrease together **as** they follow the radial EO. ***As*** throttle valve "A" is now wide-open, throttle "B" has now to be gradually closed over time in order to **keep** the separator pressure constant. For a fixed well enthalpy the steam to turbine **also** decreases, and therefore the turbine inlet and exit pressures **will** also fall, and all these variables, wellhead pressure, total discharge, separated **steam** flow, turbine inlet pressure and condenser pressure will be in direct proportion to one another. The effect of these composite declines, is that the electric power **will also** fall in the same proportion, **so** that if the wellhead pressure decreases by 50% **so** will the total discharge, the **steam** flow and the power output to **2.5** MWe. The turbine entry pressure **will** now be **2.25** ba and the condenser pressure will have fallen to **0.075** ba. The overall result of the turbine pressures (inlet and exit) being halved with double specific volumes at half the flow-rate, means that the volumetric throughput (metre^3/sec) remains the Same for the **original** design at **4.5** ba and **0.15** ba. Therefore **no** modification to the turbine will be required, such **as** removing the first row of blades **as** pressures fall.

With the separator at ***5.5*** ba and close in distance to the turbine, entry **steam will** have **4** degrees of superheat, giving an improved exhaust wetness of **12.25%** compared with **12.5%** for *dry* **saturated** steam entry. And when the **steam** flow has halved and the entry pressure fallen to **2.25** ba, the superheat **will** increase to **19** degrees, giving a significant reduction in the exit wetness to **11%** at **0.075** ba, hence reducing blade erosion.

7. COSTS

Geothermal capital **costs** from unpublished tenders, are about **NZ$2000/kW (US$1360)** but the present scheme with **all** plant situated at one wellhead and a high condenser pressure **will** be cheaper and is taken here **as NZ$1800/kW.** Repayment of capital and **12%** interest over **7.5** years gives capital charges calculated **as 21.83%.** If we add **3.17%** for operation and maintenance etc, the total **annual** charges are **25%,** and generating cost for **7500** hours/year **(0.856** load factor) is derived from:

1800 (25)/7500 = **6** cents/kWh **(US 4.08** cents)

During the first **7.5** years of production the money borrowed is completely paid back with interest, and over the following **20** years the power decreases from **5** to **3** MWe along the curve BC of Figure **3** with a loan-free gross income of **$2.25** million falling to **$1.35** million, when electric **units** are sold at the above **6 cents.**

Steeper decline curves with shorter half-lives such **as 10, 7.5** and **5** years result in higher generating costs of **7.52, 9.08** and **12.43** cents/kWh respectively, but these *can* be reduced if loan repayments are spread over the years where power reduces from **5** to **3** MWe, or even lower.

8. CONCLUSIONS

The **initial** discharge of a geothermal well is no indicator of its subsequent rate of decline except to be ***sure*** that it will be at its most severe during the first few years of production. For example, on Figure **3** it is **seen** that discharge and power fall to **70%** over the first ***5*** years. This **was** for a half-life of **15** years; for a half-life of ***5*** years it would, of course, decrease to 50% in that time. Obviously, without knowing precisely the steepness of the decline curve, it would be impossible to predict the economic viability of a project, and hence financial backing in these circumstances will prove difficult with interest rates significantly **raised** to compensate for the **risk.** As it is not possible to discharge to the atmosphere for long periods to establish the rate of decline with reasonable confidence in predictability, it is essential that a well (or wells) be throttled to a high wellhead pressure to avoid the fast **fall** in discharge of the early years and to gain the advantage of the eventual slower rate of **fall** - rather like buying a second-hand car when it is **3** to **5** years old.

The benefit of a Smaller turbine is that the amount of electric energy generated is the same, except it is over a slightly'longer time. For example, it is seen on Figure **3** that a **7.5** MWe project will decrease to **3.75** **MWe** in **15** years, whereas a ***5*** **MWe** project will decrease to **3.75** MWe in **16.25** years, with the first **7.5** years at a constant value of ***5*** MWe. The economic advantage of the latter is manifest, with a smaller turbo-generator-condenser and cooling tower, **as** well **as** of minor items. Also a slower rate of draw-off may extend the relaxation time, and hence increase inflow and pressure equilibrium within the reservoir, with ultimate beneficial effects on field longevity.

With privatisation influencing geothermal development it is increasingly important to reduce costs and to retard the **fall** in turbine power that seem associated with many projects.

9. REFERENCES

James, R. **1970.** Power **station** strategy. ***UN Symp. Development and utilisation of Geothermal resources, Pisa, Italy, Vol. 2 Pt 2:*** **1676-1687.**

James, R. **1995.** Maximum Discharging-Pressure (MDP); decline under production. ***Proc. World Geothermal Congress, Florence, Italy, International Geothermal Association,*** Vol.3: **1831-1834.**