PROCEEDINGS, Fourteenth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 24-26, 1989
SGP-TR-122

ONE CURVE FITS ALL

RUSSELL JAMES

GEOTHERMAL RESEARCH CENTRE,
WAIRAKEI, TAUPO, NEW ZEALAND

ABSTRACT

Characteristic curves of geothermal wells coordinate mass flow with wellhead pressure, and although differing from one another, plots of good commercial producers are roughly elliptical in appearance. This occurs whether the flow originates as dry saturated steam or as pressurized hot water.

All ellipses when tilted can be changed to a circle, hence by plotting (W/W_{max}) versus (P/P_{max}) where W is flowrate and P is wellhead pressure, we can obtain a circle when: $(W/W_{max})^2 + (P/P_{max})^2 = 1.0$

Ten geothermal wells - of which half emit dry saturated steam - are plotted employing the above parameters and give surprisingly close approximations to a circle considering the variety of wells tested.

The relationship permits optimization of turbine entry pressures which are found to be proportional to maximum operating wellhead pressures for both dry-steam and wet-steam wells.

Besides giving a sense of unity, this approach can be used to predict the whole output curve for differing discharge pipe diameters from limited field results; an example of this ability is presented with useful economic consequences for a new well under test.

INTRODUCTION

One of the fundamentals of geothermal power is the characteristic curve (also known as the output curve) which correlates wellhead pressure and mass flow-rate. Although there are numerous exceptions, the shape of the curve is elliptical in appearance and this applies both for dry steam wells (saturated steam or slightly superheated) and also for wells discharging mixtures of steam-water. These latter usually derive their flows from a feed of hot water either at boiling point or pressurized above it.

Six examples of the characteristic curves of wells discharging steam-water mixtures from the Cerro Prieto field in Mexico are given in a recent work by Lippman and Manon (1987).

An earlier seminal study by Rumi (1972) compares six dry steam wells of the Larderello field of Italy with modified ellipse equations to give good agreement with the experimentally plotted output curves.

A powerful steam-water well of New Zealand was studied by James (1984) and a similar equation gave good agreement with later output measurements.

No two geothermal wells have the same output characteristics with identical flows and wellhead pressures, hence all such curves are highly individualistic and generally are plotted on their own test result sheets. Under production discharge, both flow and wellhead pressure also decline with time although usually they remain geometrically similar and elliptical in shape. The relationship between flow and wellhead pressure in which both decline in harmony when the well discharges against a constant resistance such as is exerted by a fixed choke or an untouched control valve setting, is an important one and can permit future flow estimates when wellhead pressure trends are known, James (1983).

Various attempts have been made in the past to transform the well output relationship into a visually linear one by means of plotting versions on different types of graph paper, such as log-log and log-linear. As this has not been successful, the present attempt is to plot directly on the quadrant of a circle which should be suitable for all geothermal well outputs including ones taken from the same well at different periods under production discharge. To implement this approach, it is necessary to be aware that ellipses when tilted become circles.

Quadrant Plot

To plot well discharge parameters so that they fall on a circle, the following equation is employed:

$$(W/W_{max})^2 + (P/P_{max})^2 = 1.0 \qquad (1)$$

As this is a non-dimensional formula, consistent units can be used in which discharge ratios can be plotted against pressure ratios where W and P are spot values; W_{max} and P_{max} are theoretical maximum values taken where P = 0 and W = 0 respectively.

The reason for the term 'theoretical' is because even when a commercially sized well is discharging wide-open, there is a significant wellhead pressure for steam-water wells and to a lesser extent for wells discharging dry saturated or superheated steam. Also for steam-water wells the discharge is usually not zero but a substantial quantity at the highest operating wellhead pressure (known as the MDP or Maximum Discharge-Pressure). For example, at Wairakei flows do not fall much below about 100 t/h for 0.2 m diameter wells when the wellhead pressure is at a maximum (originally about 26 bar). Closing completely the wellhead valve results in the flow dropping to zero while the wellhead pressure can remain at MDP or start slowly to vary from this as explained in James (1980a) taking days or weeks to stabilise. In the case of dry steam wells, the phenomenon of MDP does not exist and hence the discharge truly is zero at the maximum wellhead pressure.

With bleeding of steam-water wells, a change of the relationship between wellhead pressure and flow-rate often takes place in which these parameters now increase (and decrease) together, but this is for non-commercial flows of the order of 1 t/h and has been pursued elsewhere, James and Gould (1987), and is not applicable here.

Plotting Procedure Examples

Taking data from the steam-water well M-102 described by Lippman and Manon (1987) where a wide-open flow of 225 t/h is obtained at a wellhead pressure of 11.5 bar, together with a flow of 75 t/h at 81 bar, we may calculate the theoretical maximum flow and maximum wellhead pressure as follows:

From equation (1), $$W_{max} = \frac{W}{\sqrt{1-\left(\frac{P}{P_{max}}\right)^2}} \quad (2)$$

Hence $$W_{max} = \frac{225}{\sqrt{1-\left(\frac{11.5}{P_{max}}\right)^2}} = \frac{75}{\sqrt{1-\left(\frac{81}{P_{max}}\right)^2}} \quad (3)$$

Solving gives $P_{max} = 85.817$ and $W_{max} = 227.047$

Discharges may now be calculated for various values of wellhead pressure from the following equation and compared with test results on Table 1.

$$W = 227.047\sqrt{1-\left(\frac{P}{85.817}\right)^2} \quad (4)$$

Table 1. Calculated discharges from equation (4) compared with test results on well M-102 from Lippman and Manon (1987).

P bar	$\frac{P}{P_{max}}$	W(calculated) t/h	W_t(test)	$\frac{W_t}{W_{max}}$
11.5	0.134	225	225	0.991
21	0.245	220.1	220	0.969
31	0.361	211.7	215	0.947
41	0.478	199.5	200	0.881
51	0.594	182.6	180	0.793
61	0.711	159.7	165	0.727
71	0.827	127.5	130	0.573
81	0.944	75	75	0.330

Taking as a further example a dry steam well of Larderello, Gabbo 1 as described by Rumi (1972) where a wide-open flow of 116 t/h is obtained at a wellhead pressure of 4 bar together with a flow of 20 t/h at 29.8 bar, we determine maximum theoretical flow and maximum wellhead pressure from the following relationship :

$$W_{max} = \frac{116}{\sqrt{1-\left(\frac{4}{P_{max}}\right)^2}} = \frac{20}{\sqrt{1-\left(\frac{29.8}{P_{max}}\right)^2}} \quad (5)$$

Solving gives $P_{max} = 30.245$ and $W_{max} = 117.028$

Discharges may now be calculated as before at different wellhead pressures from equation (6) following, and compared with test results shown on Table 2.

$$W = 117.028\sqrt{1-\left(\frac{P}{30.245}\right)^2} \quad (6)$$

Table 2. Calculated discharges from equation (6) compared with test results on well Gabbro 1 from Rumi (1972).

P bar	$\frac{P}{P_{max}}$	W(calculated) t/h	W_t (test)	$\frac{Wt}{W_{max}}$
4	0.132	116	116	0.991
6.9	0.228	113.94	112	0.957
9.9	0.327	110.58	108.1	0.924
12.8	0.423	106.03	102.5	0.876
15.9	0.526	99.55	97	0.829
18.2	0.602	93.47	89	0.761
25.6	0.846	62.32	56.5	0.483
29.8	0.985	20	20	0.171

Values of $\frac{P}{P_{max}}$ are plotted against $\frac{W}{W_{max}}$ on Figure 1 and taken from Tables 1 and 2. Three other dry steam wells are also plotted, namely VC-10, Scarzai 3 and La Selvaccia with two plots for the latter taken for the years 1958 and 1964 during which severe decline in discharge had occurred. Also plotted is a 'typical' steam well for the Geysers field as presented by Budd (1973).

In the case of steam-water wells, a total of 5 are plotted (including M-102) which are, E-2 and M-110 of Mexico, with MK-5 and KA-21 of New Zealand. It should be mentioned that for wells which have outputs which should not be divulged for commercial reasons, the plots of Figure 1 give no information in the way of enthalpy, discharge or wellhead pressure. The importance of these plots is the significance of the relationship between the parameters, and the result indicates a reasonably good correlation with the arc of a circle. Although any one test measurement point may be unreliable due to a variety of causes, overall there seems little difference attributable to the type of well, powerful or moderate, wet or dry. Causes of unreliability may be lack of stabilizing time, discharge fluctuations or errors caused by instrument fatigue, especially due to vibration inherent in two-phase flow.

Optimization of turbine entry pressure

As the output curves of geothermal wells approximate to the quadrant of a circle as shown in Figure 1, it should not be difficult to determine the turbine entry pressure which generates the maximum amount of electric energy both for steam-water and dry steam wells.
To obtain a practical grasp of the procedure, the quadrant of Figure 2 has the arbitrary values of 30 bar maximum wellhead pressure and 100 t/h maximum discharge. Although the latter figure is low for a commercial steam-water well (but realistic for a dry steam well), the power developed can be factored upwards in proportion to the actual maximum discharge.

Steam-Water well optimum

Assuming that Figure 2 is for a well which is fed from an all-liquid reservoir with Boiling-Point-with Depth applying, we may calculate the feed temperature from the Maximum Discharge-Pressure which in this case is considered as effectively 30 bar. The formula from James (1988) is:

$$C = 99.75\ P_m^{0.283} \quad \text{for } 8 < P_m < 80 \qquad (7)$$

where C is the feed temperature in degrees Celcius, and P_m is the Maximum Discharge-Pressure in bar. For the present example where $P_m = 30$, the feed water temperature is 261.2° which from steam tables gives a liquid water enthalpy of 1140 J/kg and taken here as constant over the whole output curve. Hence at any selected wellhead pressure, the steam fraction can be estimated (and the water fraction if secondary flash is considered). Taking a condenser pressure of 0.15 bar and steam rates from James and Meidav (1977), the power in megawatts of electricity can be estimated for both single-stage flash and double flash (respectively one and two separators). The case is also considered where single-stage flash is associated with an atomospheric-exhaust turbine venting to a pressure of 1 bar. The results are shown on figure 3 where curves 'A', 'B' and 'C' are for double flash, single-stage flash and atmospheric-exhaust with power potentials of 3, 2.5 and 1.3 MWe at optimum pressures of 1/3, 1/6 and 1/4 of the maximum wellhead pressure. Identical fractions were also found where the maximum wellhead pressure was raised to 60 bar and also when reduced to 15 bar so that if a steam-water well is considered with a maximum wellhead pressure of, say, 42 bar for exploitation by single-stage flash, then the optimum pressure would be 42/6 = 7 bar. It should be noted, however, that this value does not distinguish between wellhead pressure, separator pressure and turbine entry pressure which in this study are considered the same but which in an actual field development would not necessarily be identical. Also, of course, all fields under exploitation result in a shrinkage of the curve of Figure 2 towards the origin whatever the original values of discharge and wellhead pressure. Hence the maximum discharge-pressure diminishes with time and so does the value of $P_m/6$ in the case of single-stage flash, for example.

The optimum values should therefore be considered as maxima and it would be preferable to reduce them somewhat in the initial design when account is taken of discharge and wellhead pressures simultaneously reducing over years of exploitation. With reinjection of separated brine an inherent part of modern geothermal fields where hot water reservoirs are developed, design is moving in the direction of single-stage flash in order to avoid mineral scaling of overland pipes and disposal wells.

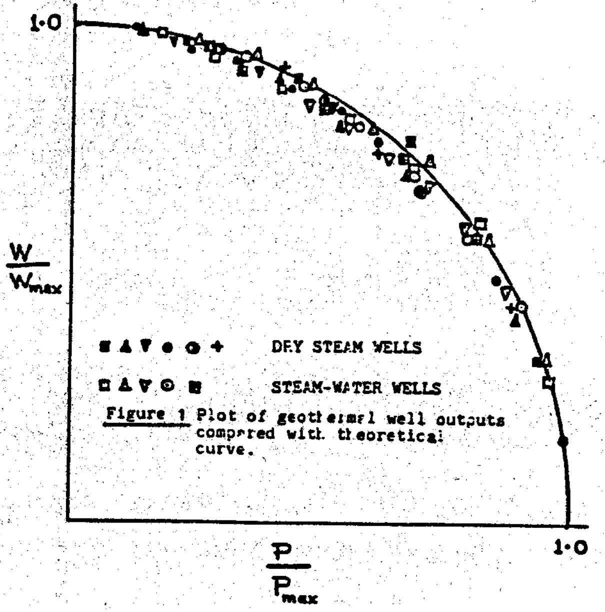


Figure 1 Plot of geothermal well outputs compared with theoretical curve.

Dry Steam Wells

Taking Figure 2 as the curve of a dry steam well, the discharge is known for each value of wellhead pressure and may be used to determine the electric power potential when using turbine steam rates as presented by James and Meidav (1977). This has been accomplished both for condensing sets with a back-pressure of 0.15 bar and for atmospheric-exhaust sets with a back-pressure of 1 bar. The results are shown on Figure 4 where it is seen that condensing sets generate about 50% more power than atmospheric-exhaust sets when designed at their optimum pressures of 12 bar and 15 bar respectively.

These optima are equal to 0.4 P_m and 0.5 P_m and are therefore higher ratios than those for steam-water wells. However, the same caveat applies with both discharge and maximum wellhead pressure declining with exploitation, so that they represent maximum values which would have to be reduced in practice to take into account an estimated maximum wellhead pressure at the end of the economic field-life.

The same ratios are found to apply when a curve similar to Figure 2 for dry saturated steam is considered but where the maximum wellhead pressure is 15 bar instead of 30 bar so can be considered as widely applicable. For theoretical reasons, James (1968), an exploitable steam reservoir with a pressure significantly in excess of 30 to 40 bar is not to be expected, hence calculations based on a maximum wellhead pressure of 60 bar (as for steam-water wells) is not undertaken here.

Predicting whole output curve

A geothermal well which produced large flows of dry saturated steam was tested in New Zealand. Employing a 12 inch production casing, it had a closed-in wellhead pressure of 24.5 bar and when discharged vertically wide-open produced a flow of 174.8 t/h at a wellhead pressure of 19.3 bar. The discharge pipe erected at the wellhead was rather small in diameter at 0.1524 m compared with the internal casing diameter of 0.315 m and was obviously restricting the discharge to a value much smaller than what the well was capable. With no restriction at the wellhead, the characteristic well curve was calculated as follows:

From equation (1), $\left(\frac{174.8}{W_{max}}\right)^2 + \left(\frac{19.3}{24.5}\right)^2 = 1$

Hence $W_{max} = 283.77$ t/h

Discharges may now be determined from various substituted values of wellhead pressure in the following formula:-

$$\left(\frac{W}{283.77}\right)^2 + \left(\frac{P}{24.5}\right)^2 = 1$$

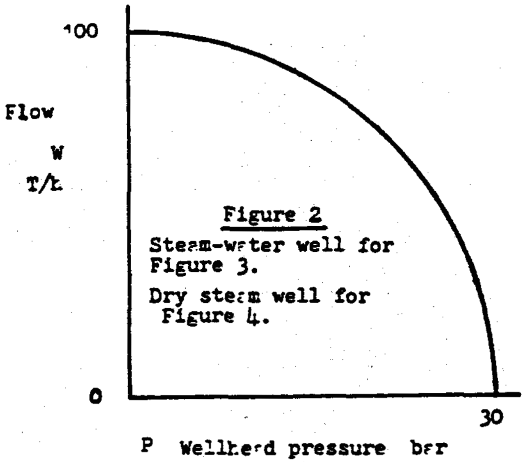
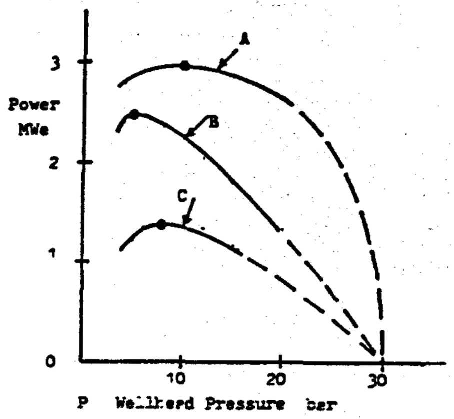
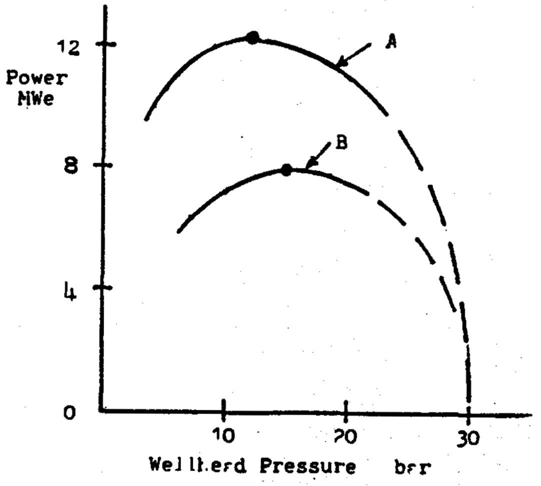


Figure 2
Steam-water well for Figure 3.
Dry steam well for Figure 4.



Curve A Double flash } Condenser pressure = 0.15 bar
Curve B Single flash }
Curve C Atmospheric exhaust at 1 bar

Figure 3 Power output of steam-water well of Figure 2



Curve A Condenser set at 0.15 bar
Curve B Atmospheric exhaust at 1.0 bar

Figure 4 Power output of dry steam well of Figure 2

The theoretical curve is shown on Figure 5 together with a few test results employing the 0.1524m diameter discharge pipe which could only cover a limited range of wellhead pressures from 24.5 to 19.3 bar. The line 'A' crosses the location where the minimum wellhead pressure is attained with the 0.1524m diameter discharge pipe. Lines 'B', 'C' and 'D' are shown intercepting the curve at the lowest wellhead pressures attainable when discharging wide-open vertically through 0.2032 m, 0.254 m and 0.3048 m diameter discharge pipes. It was only possible to confirm these estimates by replacing the 0.1524 m dia. by a 0.2032 m pipe and re-testing the well from closed-in to wide-open vertically. The results shown on Figure 5 follow the theoretical curve and nearly reach the estimated lower limit of wellhead pressure crossed by line 'B', hence the calculated curve is considered as a realistic first estimate of discharges attainable at lower wellhead pressures. With suitably large branch lines, it is believed that this well should be capable of a steam flow of 260 t/h at a wellhead pressure of 10.0 bar which is equivalent to an electric power output of about 30 MWe.

Measurement of the mass flow from geothermal wells under conditions of maximum vertical discharge employing the lip pressure technique (critical discharge pressure at sonic velocity) has been described elsewhere, James (1980b) and will not be followed here.

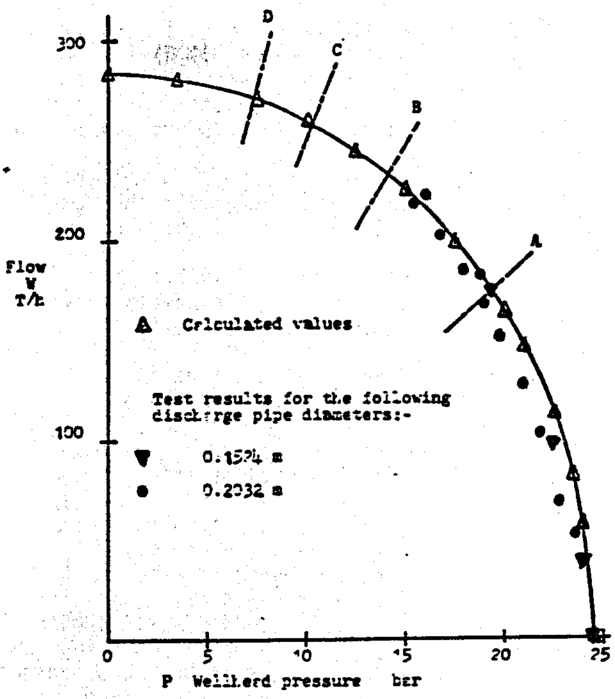


Figure 5 Output curve of powerful dry steam well for different discharge pipe diameters.

CONCLUSIONS

The power generated by geothermal wells is of course, dependant on discharge. However, the optimum turbine entry pressure is independent of flow and is proportional only to the instantaneous closed-in wellhead pressure for dry saturated steam wells and to the Maximum Discharge-Pressure (MDP) of steam-water wells. The elliptical-shaped characteristic curve which correlates discharge with wellhead pressure is an integral part of such optimizations and is basic to all such studies. As such curves shrink towards the origin with exploitation of a geothermal field, the MDP similarly declines with time (also the closed-in wellhead pressure of dry steam wells). Hence the optimum turbine entry pressure declines pro rata; because of this fact, such optima should emphatically be considered as maximum values and should be reduced somewhat in the original design of a project. Capital costs increase with low turbine pressures, however, and to ameliorate this effect a condenser pressure of 0.15 bar is assumed in the present study to provide a balanced trade-off between such costs and the overall thermal efficiency of utilization.

Although double-flash has been in vogue up to the present, it seems likely that single-stage flash will be increasingly common with re-injection becoming an intrinsic part of future projects. The spread of deeper drilling to 2km or more has also resulted in higher temperature wells with concomitant higher mineral content of the water phase; this requires water at increased temperatures (and pressures) to be transmitted to disposal wells, in order to avoid chemical scaling of plant.

A well's characteristic curve can be estimated (with reasonable approximation to reality) by taking only two sets of test values. Preferably these should be at maximum Discharging-Pressure (MDP) and at Maximum Vertical discharge (MVD) which provide the widest attainable difference of wellhead pressures and lip pressures. Interpolation between these points and extrapolation beyond, permits the full sweep of the output curve to be plotted.

REFERENCES

Budd, C.F. (1973:Steam Production at the Geysers Geothermal Field. In Geothermal Energy, Edited by Kruger, P and Otte, C. Stanford Univ. Press, Stanford, Calif. USA

James, R. (1968): Wairakei and Larderello: Geothermal Power Systems Compared. N.Z.J.Sc., 11,4, 706

James, R. and Meidav, T. (1977): Thermal Efficiency of Geothermal Power. Geo.Energy, 5, 4, 8.

James, R. (1980a): Deductions of the Character of Steam-Water Wells from the shape of the Output Curve. Proc.N.Z.Workshop, Univ.of Auckland, New Zealand

James, R. (1980b): Estimating Maximum Discharge of Geothermal Wells. Proc.6th Workshop Geothermal Reservoir Engineering, Stanford Univ., Stanford, Calif. USA

James, R. (1983): Locus of Wellhead Pressure with Time under Production Discharge. Proc.N.Z.Workshop, Univ. of Auckland, New Zealand

James, R. (1984): Successful Prediction of Mokai 5 Discharge. Geo.Energy, 12, 2, 7.

James, R. and Gould, T, (1987): Bleeding Characteristics of Geothermal Wells. Proc. NZ Workshop, Univ. of Auckland, New Zealand

James, R. (1988): Depth of Feed Water Influences Maximum Discharge-Pressure of Hot Water Geothermal Wells. Proc. 13th workshop Geothermal Reservoir Engineering, Stanford Univ. Calif. USA

Lippman, M.J. and Manon, A (1987): The Cerro Prieto Geothermal Field. Geo.Sc. and Techn. 1, 1, 1.

Rumi, O. 91972): Some Considerations on the Flow-rate/Pressure Curve of the Steam Wells of Larderello. Geothermics 1, 1, 13.