The Influence of Decline Rates and Pressure Interference Effects on the Economic Viability of Vapor-Phase Geothermal Reservoir Development.

Richard J. Miller

Pacific Resources Management, Inc.

ABSTRACT

The sensitivity of the economic feasibility of development of geothermal reservoirs for electric power generation to decline rate and intra-reservoir pressure interference effects in vapor dominated reservoirs are examined. Decline rate can be shown to be the primary controlling factor in determining economic viability due to the sensitivity of infill drill requirements to variance in decline rate over long-term (30 year) production. The additional influence of intra-reservoir pressure interference between wells and well-groups is examined to establish:

a) The initial impacts of multi-well production groups on individual well and well-group performance.

b) The long-term influence of inter-well inference from original well groups and infill drilling;

THE DEVELOPMENT OF GEOTHERMAL ENERGY PROJECTS

The development of a geothermal project can be described as having four phases: (1) An exploration phase wherein the resource is located and identified by geophysical and geologic methods; (2) A testing phase wherein one of more wells are drilled to verify the exploration work and determine the extent and nature of the resource; (3) A field expansion phase wherein the wells necessary to provide initial production of steam to a power plant are drilled, tested, and placed on production; *(4)* And an exploitation phase which encompasses the drilling and remedial work necessary to sustain the required level of production.

For the purpose of this study we will concentrate on the field expansion and exploitation phases of the project.

ECONOMICS OF GEOTHERMAL PROJECTS

The decision to develop the resource and build an electric generation plant is made following the completion of the exploration and testing phases. This decision is based on the results of the geologic and reservoir engineering information obtained in earlier stages, and on the apparent economic feasibility of the project which rests on major economic considerations:

(1) Cost of Power Plant construction.
(2) Steam or electric power sales price.
(3) Initial well drilling cost.
(4) Cost of infill (make-up) wells.

The cost of power plant construction is not within the bounds of this study and the steam or electric sales price is assumed to be uneffected by production rates.

Apart from major changes in the product sales price the primary influence on project feasibility in the field expansion and exploitation phases are the cost of drilling initial production and make-up wells. The term "make-up" wells is applied to all wells drilled after plant startup. The timing of the drilling of make-up wells and the ultimate number of those wells can make the difference between project economic success or failure. If Project A requires that 20 make-up wells be drilled over the 30-year life of the project and that drilling must start in year 5 the project may demonstrate that it is less economically feasible than Project B that requires only 12 wells starting in year 10. The combined cost of 12 wells versus 20 wells when drilling costs are equal directly impacts the project cash flow by that amount while the timing carries a direct impact on present worth cash flow which may effect project rate-of-return. Both these occurances could serve to reduce the economic feasibility of the project on an absolute basis as well as on a relative basis regarding other projects competing for the same funds.

The requirement for make-up wells and the timing of drilling is directly dependent on production rate behavior.

PRODUCTION RATE BEHAVIOR

A geothermal power plant is built to generate a specific output of electricity which requires the supply of a minimum volume of steam. The generation of 110 MW may require, depending on the plant design, steam volume of from 18000 to

20000 lb/Hr/MW on a constant basis. A reduction in steam supply to below those volumes would cause a reduction in plant output and efficiency. Continued reduced output would diminish the economic value of the project by reducing the revenue from electric power and/or steam sales. Many steam or electric power sales contracts have provisions that require direct economic consequences occur to the steam producer should the steam rate fall too far below the design capacity minimum.

The rate of steam supply to the plant is a function of the ability of the steam wells and the reservoir to perform as needed to maintain the required minimum rate of steam flow. In the context of a 30-year project with a large initial investment it may be critically important that the economic impact of the behavior of the production tate be considered in planning the project.

Production rate behavior is defined by the absolute flow rate and the production decline rate. The absolute flow rate is the instantaneous rate of flow of steam from one or more wells in the project. The decline rate is the percentage change in flow rate over a given period of time for a well or wells. Absolute flow rate and measurement of decline rate, for this study, are expressed as average flow in lbs/Hr per well on a monthly basis. The use of lbs/Hr per well reduce those aberrations in the data stream caused by the addition or deletion of wells during the period or by flow periods of less than full month.

The decline rate has major impacts on the project performance. The initial decline rate in the first few days and weeks of a project operation will determine the degree to which the initial spare capacity will be absorbed in the early life of the project. This will determine the point at which make-up well drilling will have to begin in order to keep the plant supplied and still maintain spare capacity for use during periods when one or more wells may be shut-in.

The decline rate over the life of the project will determine the rate at which make-up wells will have to be drilled in order to maintain minimum flow rates. This rate of drilling will depend on the rate of decline of the flow rate from the combined wells in the project and the acceleration of that rate due to the increased number of wells.

Empirical knowledge of the performance of geothermal reservoirs seems to indicate that, particularly in vapor phase systems, two production decline events occur. In single plant well groups the initial flow rate of both the well group and of the individual wells experience an immediate drop in production to a rate somewhat below that of the flor rates obtained from tests prior to start of production. The event seems to occur over a very short time immediately after the start of flow of the well group to the plant and is most detectable when monitored on a daily or hourly basis. If the tested rates are in fact representative of reservoir and well bore condition the initial decline can be measured as a daily decline from the test rate to a progressively lower rate of flow. The absolute amount of the production rate decline and time duration of the decline seems to vary on a well to well basis which indicates that there may be a number of factors influencing the event. After a period of time ranging from a few hours up to several days the decline subsides and a stable rate of flow is achieved. From this point the wells and the well group exhibit the actual initial flow rate of the project.

The second event generally occurs after the well group has reached stable flow and has established an overall decline rate. The addition of individual wells but more particularly the addition of other plant grcups creates a decline in the group flow rate which is similar to the initial production rate decline. This effect is documented by Lipman, Strobe1 et al. (1) The impact most clearly noted in well group production rates and occurs over a period measurable in weeks and months. The effect is more noticeable in some well groups than others and in some individual wells more than others. The result is a transitory steepening of the decline rate in the effected well group during which the absolute flow rate is reduced and following which the well group achieves a new stable flow rate and returns to the previously established decline rate. The influence is due to interference effects between the wells or well groups.

Both these events seem to support the concept in vapor-phase systems that increased withdrawals result in reduction in flow rate from other wells and the creation of an overall lower flow rate for the combination of old and new wells.

ECONOMIC EFECTS

The combined impacts of initial production decline, stabilized production decline, and interference effects bring about reductions in the absolute steam flow rate available to a plant which could result in the flow rate falling below the required minimum rate.

In order to maintain the necessary flow rate to the plant, the project will have to:

(1) Drill sufficient wells during the field expansion phase of the project to insure that the required steam volume is always available to the plant, and

(2) Plan to drill enough wells during the course of the project to sustain the required steam flow.

Assume for discussion that the geothermal system is required to provide sufficient steam for a 110 MW generating plant with a requirement for a constant minimum of 1,980,000 lb/Hr of dry steam at a given inlet pressure. Assume that all wells produce from the same reservoir interval with similar initial flow rate; that the flow rates from all wells are equal; and that flow rates decline uniformly in all wells.

For the purpose of this study assume also a vapor-dominated geothermal system with no water component where the fluid is at saturated conditions throughout the productive life of the reservoir. Assume that the reservoir storage and flow path is entirely in fractures and that there is no secondary porosity for storage. Finally, assume that the reservoir is essentially closed so that there is (a) no external inflow or recharge, (b) no communication to other reservoirs, and (c) no undeveloped storage areas.

In such a system the economic effect of small changes in decline rates can be substantial.

As an example assume a system where initial decline is 10% from tested rates and the settled decline is 4%. From combined well tests the expected production is 2,208,600 lbs/Hr from 16 wells which allows a spare capacity of 15% or 228,699 lbs/Hr after initial decline. Over the 30 year project life at 4% decline the project . will have to drill 20 make-up wells in order to maintain minimum production and 20% space capacity.

If the settled rate had been 6% the number of make-up wells would have increased to 29 and drilling would have had to start in the fifth year of the project. Similarly, if the decline was 8% or 10% the number of wells would increase and the time of the start of make-up wells drilling would become earlier.

If the initial decline is 30% the project would immediately fall below the required minimum production so that make-up drilling would have to begin right away.

The obvious economic impact on the project in terms of absolute costs for wells and the reduction in present worth value can be substantial and could be fatal if decline rates are excessive or are found to be higher than expected.

The questions that immediately arise in this circumstance are:

How to determine the initial decline and the necessary sufficient spare capacity?

How to determine the production decline rate and the timing of make-up well drilling?

INITIAL DECLINE RATE

Detailed analysis of production rates of wells and well groups in the period immediately following the start of production of the wells indicates that all the wells, to varying degrees, experience a decline in production rate prior to reaching a stable rate of flow. It is of interest to note that:

(a) The initial flow rate and settled rate is always less than the "tested" rate.

(b) The degree of decline varies from well to well.

(c) The wells tend to establish stable rate at nearly the same time.

In most projects the wells are tested following completion and/or during a planned testing program. The wells may be flowed at one or more rates for several hours while pressure drawdown data is obtained and flow characteristics are monitored. Generally however, the flow periods are short, constrained by regulatory or environmental considerations, and the tests are done one well at a time. The well is assigned a "deliverability" based on the tested rate at the required wellhead pressure. Often these rates are used to determine the combined capacity of the well group with the excess of the total capacity over the required plant minimum being the "spare" capacity.

When all the wells are put on production to supply the plant the combined withdrawal of steam from the reservoir creates an immediate pressure drawdown in the reservoir. The drawdown is the same as that which occurs when the individual well is produced but the combined effect is to reduce the reservoir pressure to an average of all the individual well drawdowns. To the extent that the wells have differing flow rates and well conditions vary the drawdowns will vary and the average pressure will reflect a tendency toward the highest rate and greatest drawdown. In addition, the combined flow in a closed system causes the drainage areas of each well to be reduced so that the reservoir is divided among the wells.

In single well tests the high pressure transmissibility of the vapor-phase allows the well to draw on the total reservoir or a much larger drainage area than when other wells are producing. The result is that when the well group is put on production the available reservoir volume for each well is reduced so that the production rate of the individual wells and the well group is reduced below the combined rates based on individual well tests.

The extent of the decline in initial rates can be determined by two methods:

A. Conducting combined well flow tests to measure the multi-well flow rate, or

B. Calculate approximate flow rates for each well based on demonstrated reservoir properties and estimated drainage areas.

The direct approach of conducting multi-well long term flow tests is the most desirable solution but may not be attainable due to time and/or well flow rates and group flow rates based on restricted drainage volumes. Any such approach depends on a knowledge of:

1. Reservoir drainage (storage) volume.

2. Individual well effective drainage areas.

3. Effective flow rates and wellbore conditions in each well at the expected delivery wellhead pressure, and

4. A well planned and competently done testing program to obtain the necessary data.

In fracture systems the storage volume in the reservoir can be defined by use of the evaluation-techniques of Pollard-Pirson (2)(3)(4) and Warren-Root-Kazemi (5)(6)(7) with appropriate consideration for those conditions endemic in geothermal evaluation. When computed on an individual well basis the reservoir volume defined will be that or the drainage volume available to the well at the time of the test so that there would be some overlapping of drainage volumes when all the wells are considered. Assuming a generally uniform reservoir the drainage volumes could be apportioned to each well on the basis of demonstrated flow rate and apparent reservoir volume.

Using radial flow equations or modifications thereof as necessary the apportioned limited drainage volumes could then be used to calculate the effective flow rate of the well at that limited volume. These adjusted rates should reflect the interference between wells that would occur when all wells are placed on production simultaneously. The total of these rates would be the settled flow rate that would occur following the initial decline.

The necessary amount of spare capacity should be *20-30%* of the required plant capacity. To the extent that the initial decline reduces actual flow rate below tested rates additional capacity will have to be added to ensure sufficient spare capacity.

PROJECT LIFE

The most direct approach to determination or estimation of long-term decline rate is through comparison of the reservoir conditions of the project reservoir with similar projects and the application the decline rates experienced in those fields to the project.

Unfortunately few geothermal fields are developed to the point that there is enough production history to establish a decline rate and in certain of those cases the data regarding production and decline are held as proprietary.

The alternative again is to attempt to calculate expected decline rates. Assuming that a reasonably reliable initial production rate has been determined for the project the future production can be estimated by use of the material balance modified for vapor phase geothermal fluids, (8)(9) known as the P/Z vs. Cumulative relation. The use of P/Z does not estimate decline rate directly but can be used to estimate future production which can then be converted to decline rates or used directly to determine drilling requirements.

Based on work to determine fracture volume and reservoir volume the original amount of steam in place, Ns can be estimated while the original reservoir pressure Pi/Z is known. Using the expected initial flow rate for an initial production period of 6 months a cumulative production is calculated. The reduced volume brings about a reduction in pressure which can then be used to calculate a new production rate for the well group. Repetition of this process would result in the calculation of periodically reducing production rates and pressures which would describe a decline curve. The curve would tend to be pessimistic if long flow periods are used but within the context of a 30-year project 3-6 month periods should be short enough.

Projecting future production defined in this manner to the minimum or spare capacity level the timing of the start of make-up well drilling can be defined. As a first approximation the new wells could be assumed to begin production at the then current average rate of the well group. In a closed system however, the addition of new wells would decrease the respective drainage volumes of all wells thereby reducing the individual flow rates by some fraction below the combined rates of original and new wells. The actual rate could be estimated by assuming the reduction of some drainage volumes and calculating actual reduced flow rates in the effected wells. The future production would be projected from the actual rate at the previously determined decline until the minimum production level is intersected. The estimation process is then repeated.

In a closed system the continual addition of new wells will eventually cause the decline rate to increase as production withdrawals increase and reservoir volume per well decreases. The result will be that at some point new wells will only maintain production rate and not provide any temporary increase and, further, the number of wells necessary to maintain production rate will increase with time.

A closed system as described earlier is a severely limited case and is not common, particularly in the early stages of a geothermal field development. In such cases the well group has the entire field volume to draw from and the flow of fluid within the field is unrestricted by production development.

Apart from the very unique case of a small, geologically closed geothermal system that could be developed by one or two well groups, the closed system can be approximated by systems where;

a. Geologic barriers, field edges, and/or earlier field development restrict fluid drainage,

b. The project area is surrounded by other development,

c. The project area is isolated from the geothermal system source of recharge by other development or geologic conditions.

Where the reservoir can be considered to be open or where restrictions to drainage volume are minimal the effects of initial decline will be minimized and the interference effects on decline rate can be generally discounted so that decline is essentially constant. Where the project area occupies a relatively small part of a very large reservoir the well group can be treated as a single drainage point with no real interference effects.

LIQUID PHASE SYSTEM

The basic principle that apply to vapor-phase systems can be applied to liquid phase systems with the condition that pressure interference respcrses are controlled by the fluid properties of the liquid system so that in most cases the effects of both initial decline and long term decline can be difficult to define and measure.

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