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Forty Years of Production History at The Geysers Geothermal Field, California – The Lessons Learned

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ABSTRACT

There is a persistent perception worldwide that The Geysers field is a classic example of everything that could go wrong with geothermal power development. This presentation analyzes the history of The Geysers to dispel that perception. It concludes that this field has proven to be the most productive geothermal field discovered yet, and that it provides the best example to date of maintaining commercial viability of geothermal power generation through ingenious field management. The analysis considers both the resource behavior and the socio-economic forces at play at this field. The presentation also forecasts the performance of this field over the next two decades and considers the lessons learned from its forty-year history.

Introduction

This presentation is essentially a personal perspective. The author feels privileged to have been associated with The Geysers for the past 32 years, and at one time or another, to have assisted each one of the nearly two dozen developers and utilities that have had any involvement with this field. Because the author has been privy to a vast amount of proprietary information concerning this field, to avoid infringing on the confidentiality of any party, this presentation is based exclusively on publicly available information.

The author was introduced to The Geysers by his mentor, the late Professor Henry J. Ramey, who conducted the first reservoir engineering analysis of the field more than three decades ago. This presentation is dedicated to his memory.

The History

From Slow Growth to Geothermal Rush

Electric power generation started at The Geysers in 1960 with a 12 MW (gross) plant. During the 1960s and 1970s, net generation grew slowly to about 500 MW, with only two operators active in either field development or power generation (figure 1). Following the "energy crisis" of 1973, oil and natural gas prices skyrocketed, boosting the price of geothermal power which was based to a large extent on the price of fossil fuels. By 1981 the oil price reached its all-time peak, followed by the natural gas price in 1984 (figure 2). This caused a major spurt in the rate of growth in installed generation capacity at The Geysers (figure 1).

In addition, during the early 1980s several incentives for developing geothermal power became available simultaneously from the Federal and State Governments. The first incentive was the Public Utilities Regulatory Powers Act ("PURPA"), which required a utility to purchase power from any facility of 80 MW or less developed by an Independent Power Producer (IPP) at the "avoided cost" of the utility; this cracked the monopoly of the large utilities and guaranteed a market for the IPP. The availability of a 10% Business Investment Tax Credit and another 15% Alternative Energy Tax Credit during this period allowed up to 25% savings in the capital needed for a new geothermal project. Also during this period, the U.S. Department of Energy introduced a Geothermal Loan Guaranty Program under which up to 75% of a developer's bank loan for a geothermal project could be guaranteed by the Federal Government. The combination of the Loan Guaranty, Business Investment Tax Credit and Alternative Energy Tax Credit allowed a developer to finance the development of a new geothermal project without any long-term equity investment, while PURPA ensured the developer a market for its power. The wholesale power price offered under PURPA was also on the upswing during this period (figure 3). Such an enticing combination of financial incentives in a free-market economy had rarely existed before or since the early 1980s.

This combination of an explosive rise in petroleum price, an exceptionally lucrative financial incentive package offered by the government and a guaranteed market drew a whole host of new developers to The Geysers. These included large energy companies capable of bankrolling their projects themselves and municipal utilities issuing tax-exempt Public Power Revenue Bonds, or IPPs securing non-recourse loans or selling corporate bonds to fund their developments. Hence the rush for rapid development of new capacity at The Geysers starting in 1979. Figure 3 shows the number of operators active at The Geysers at various times.

The Field Gets Overdeveloped

The rush lasted a decade, quadrupling the gross installed capacity (from 500 MW in 1979 to 2043 MW in 1989). Some dozen operators developed this new capacity on a strictly competitive, and largely confidential, basis without significant exchange of resource information among them. For some projects the field developer and the utility were two different—and typically adversarial—entities. There was no one standard steam or power sales contract during this period. Some utilities paid the field developer for steam supply by the pound while others paid the developer for steam supply by the kilowatt-hour generated from that steam. Some developers also operated power plants and sold power to the utility based on various pricing formulas. This diversity of contractual agreements reflected the innovative and fractious climate of the era. This competitive and, of necessity, secretive spirit of development was precipitated by the checkerboard nature of the myriad Federal, State and private lease blocks that comprised The Geysers field, and the need to win the geothermal development right through competitive bidding for Federal or State leases or through negotiations, often involving hard bargaining, with private land owners. Figure 4 shows the project areas currently dedicated to the various plants.

In this headlong rush, some unpromising, fringe areas of The Geysers got developed, and the plants built on them could not be sustained for long. New developers flocking to The Geysers in this period had little knowledge of the reservoir behavior being encountered by the developers who had preceded them. Therefore, in their optimism, each new developer tended to dedicate less area per MW than the one before. By the end of the 1980s in some parts of the field, the area dedicated per MW capacity became alarmingly small. Yet, at least 10 square kilometers of potentially productive area within the field remained undeveloped. Unlike most petroleum or geothermal fields shared by multiple field developers, The Geysers was not unitized; that is, the field developers did not elect one among them to operate the field with full access to the resource information available to all the others. This proliferation of information barriers and paucity of co-operation among the operators soon led to overdevelopment of the field, as evidenced by rapid declines in reservoir pressure and well productivity, and development of superheat, in the reservoir by 1987-1988. Figure 5 shows the rapid declines in reservoir pressure and well productivity experienced in a portion of the field during this period.

To maintain generation capacity in the face of rapid productivity decline, too many make-up wells were drilled in some parts of the field, which caused excessive interference among wells, further reducing well productivity. This fact plus the unexpected collapse of oil and natural gas prices after 1985 (figure 2) made make-up well drilling uneconomic by 1988. By 1989, the discounted cash flow rate of return for maintaining generation by make-up well drilling was estimated to be lower than that for the case of no make-up well drilling. Therefore, the net generation capacity was allowed to decline from this period on (figure 1).

Figure 1 shows many sharp temporary drops in generation. These drops were due to the utility forcing the field developer to curtail geothermal power generation because cheaper hydroelectric or other types of power were available to the utility. The utility's right to curtailment was included in many power sales contracts.

It should be noted that during the peak generation years of 1986-1988, the installed capacity was about 1,830 MW (gross) or about 1,640 MW (net) while generation was in the range of 1,500 to 1,600 MW; that is, the plant capacity factor was maintained at 91 to 97% in spite of forced curtailments. Once the power price dropped and make-up well drilling stopped, the net generation declined from a peak of 1,600 MW to 1,000 MW by 2000. This decline over the last 12 years implies a "harmonic" decline rate of only 5% per year.

Even though the first ominous signs of overdevelopment started appearing by the mid-1980s and the petroleum price as well as the "avoided cost" of power offered under PURPA had declined precipitously by then (figures 2 and 3), another 500 MW of capacity was installed before the decade ended (figure 1). There were several reasons behind this apparent paradox: (a) some of these late developments had secured unusually lucrative power sales contracts (known as the Standard Offer 4 contracts in California), which guaranteed levelized power rates for a period of 10 years; (b) most of these projects were too far along to be reconsidered; and (c) Ronald Reagan's presidency had turned around the economic stagnation of the previous decade and ushered in an era of unbridled optimism. For example, between 1980-1983, the inflation rate nose-dived from nearly 15% to 3% and stabilized at that level (figure 6). The interest rate plummeted from over 20% in 1982 to 7.5% by 1987 (figure 6). And after 1982, the stock market took off for the first time in a generation; the Dow Jones Industrial Average doubled during Reagan's presidency (figure 6). This optimism made project financing easier than ever before.

By the end of the 1980s, signs were unmistakable that the then drilled area of the field was overdeveloped, perhaps to the extent of the last 500 MW additional capacity; in other words, the drilled part of the field was overdeveloped by some 25%. In retrospect, there was a twist of irony: while most parts of the field became overdeveloped, some of the last projects to go on line proved the most sustainable and profitable.

Operational Innovations Come to the Rescue

By 1992 the decline in generation at The Geysers had attracted the attention of the California Energy Commission, which funded a numerical simulation and engineering study of the field to investigate the options available to mitigate the generation decline. The investigation, conducted with the support of the operators, concluded that augmenting injection into the reservoir was the most effective antidote to productivity decline.

Individual operators on their own had also arrived at the same conclusion nearly a decade earlier. However, injection augmentation was a major challenge. Since it was not cost-effective to capture the 75% of the steam that is lost in the cooling tower, a maximum of 25% of production was available for recovery as cooling tower blow-down for injection. Any augmentation of injection beyond 25% of production, therefore, called for significant operational innovation.

By 1982, injection augmentation had begun. The operators started increasing injection by capturing surface run-off during the rainy season and tapping local creeks or aquifers to the maximum extent permitted by the local government. Assuming 25% of the produced steam to be available for injection—plus an annual amount (W) of injection water available from surface run-off, creeks or aquifers—the annual injected rate as a fraction of the annual production rate (Q) is given by:

Injected Fraction $= 0.25 + W/Q$

Therefore when there is curtailment, the injection fraction increases. Figure 7 shows the fraction of production injected as well as the amount of injection augmentation (beyond 25% of production) over the years; it shows that the injection fraction rose from about 23% to about 27% after 1982. During 1993-1997, the injection fraction rose rapidly because of forced curtailment as well as injection augmentation. Finally in 1997, the injection fraction increased sharply through the initiation of injection of water from a lake (Clear Lake) and treated municipal waste water from the City of Clearlake, both piped in from 48 kilometers away. By 1999 the injection fraction had exceeded 60%, compared to 27% prevalent before 1993 (figure 7).

It is shown in the Appendix that if there is no significant water saturation or natural recharge, which is the case at The Geysers at present, the sustainable generation capacity (E), ignoring any socio-economic constraint, is given by:

$$E = C \cdot \left[\frac{p}{z} - \frac{(\Delta p + p_{ti})}{z_a} \right] / (1 - I) / u ,$$

where C = a constant depending the units used, reservoir pore volume and reservoir temperature,
p = current reservoir pressure,
Δp = steam pressure drop between reservoir and turbine inlet,
p_{ti} = turbine inlet pressure,
z = real gas deviation factor for steam at current reservoir pressure,
z_a = real gas deviation factor for steam when reservoir pressure becomes too low to supply steam at the turbine inlet pressure,
I = effective fraction of production injected, and
u = steam consumption per MW-hour at the plants.

This formula indicates that there are only four resource-related variables that would determine the sustainable capacity at The Geysers at this time: (a) pressure drop between the reservoir and the turbine inlet, (b) turbine inlet pressure, (c) plant steam consumption per MW-hour, and (d) effective injection fraction. However, the variables p_{ti} and u are inversely related, both being functions of plant design. Therefore, effectively, there are 3 variables that would determine the sustainable power capacity at The Geysers: pipeline and gathering system design, plant design and injection strategy. Throughout the past decade, the operators have been striving to reduce pressure drop between the reservoir and the turbine inlet by optimizing the pipeline and gathering system, to reduce the turbine inlet pressure and steam consumption rate by modifying power plants and to increase the effective injection fraction.

The fraction of injected water recovered as steam today is 60% to 80% as deduced from isotopic and gas content analyses and numerical simulation. Figure 7 indicates that some 50% to 70% of production is being injected today, of which 60% to 80% is produced as steam. Therefore, I has a value of about 0.4 today. For this I value, as per the above formula, the relative sustainable capacity (compared to the no injection case) is about 1.6 at this time. Before injection augmentation started in 1982, an average of 23% of production was being injected; assuming 70% to 80% of this water was recovered as steam, I had a value of 0.17, for which the relative sustainable capacity, from the above formula, is 1.2. Therefore, augmented injection since 1982 has increased the relative sustainable capacity from 1.2 to 1.6—that is, by about one-third.

The numerical simulation effort of 1992, funded by the California Energy Commission and conducted by GeothermEx in collaboration with the operators, indicated that without injection augmentation or any forced curtailment, generation would continue to decline at a harmonic rate of 9% per year starting in 1988 (Pham and Menzies, 1993). This forecast was based on calibration of the numerical model against the production history of over 600 wells spanning 31 years (1960-1991); therefore, the model was considered a reasonable representation of the reservoir. The model forecast implied a harmonic decline rate in generation of 4.3% by the year 2000. In actuality, the decline rate in well productivity today is about 3%. This lower decline rate of today has been achieved by augmenting and optimizing injection, improving the pipelines, gathering system and plants, and aided by the curtailment in generation during 1993-1997. Buoyed by this success, an even more ambitious plan for piping in treated waste water from yet another city, larger and farther away (Santa Rosa) is in the final stages.

Other Positive Developments

In addition to the injection and curtailment issues, the operators at The Geysers have faced numerous other developmental and operational challenges over the decades; for example, air drilling to depths exceeding 4 kilometers, drilling multi-leg wells to reduce drilling cost per MW, mitigation of silica scaling associated with superheatıd steam, handling corrosive steam, utilization of gassy steam, and so on. All these problems have been solved through technical and managerial innovation. For example, operators gradually adopted "load following" rather than "baseload" operation to reduce depletion. Guaranteed power sales contracts gave way in many cases to competition in a deregulated power market; the operators quickly adjusted to this market risk and focussed on maintaining the "peaking capacity" by reducing the "baseload capacity." In today's deregulated power market, a plant is much more profitable if it is operated at the peak capacity for the few hours in the day when power price spikes, the generation being sharply curtailed during the remainder of the day. Therefore, the annual plant capacity factor is no longer a useful measure of the profitability of a project. Many such technical and managerial innovations pioneered at The Geysers are commonplace throughout the geothermal industry today.

A particularly positive development at The Geysers in the 1990s has been the gradual increase in information exchange and co-operation among the operators. For example, Calpine Corporation, Unocal and the Northern California Power Agency jointly implemented some of the injection augmentation strategies developed during this period. This trend, contemporaneous with the rapid changes in the then Soviet Union, was aptly described by Tom Box of Calpine Corporation as the "Geysers glasnost". Not surprisingly, "perestroika" (restructuring) followed "glasnost" (openness) at The Geysers as in the Soviet Union. A series of acquisitions allowed consolidation of field operation in the hands of fewer and fewer operators (figure 3); by the end of the 1990s, there were only two (Calpine Corporation and Northern California Power Agency). This consolidation has finally begun to allow optimization and complete integration of field management and power generation, thus increasing net generation while reducing operating costs.

Summary

In summary, there are several singularly impressive facets of the forty-year history of The Geysers. First, the field has produced 26,000 MW-years in 40 years (figure 1), equivalent to a net capacity of 867 MW for 30 years; this is by far the largest amount of electric energy produced from any geothermal field to date. Second, throughout the past 25 years The Geysers field has maintained a higher net generation capacity than any other field in the world. Third, the operators at The Geysers have ridden the waves of vicissitudes of socio-economic forces and idiosyncrasies of the resource with utmost resilience and admirable ingenuity. Finally, The Geysers has provided employment for thousands of Californians for decades and has been a significant source of royalties and tax revenue for the Federal, State and local governments—the retail gross value of the power sales from The Geysers exceeded one billion dollars a year during the peak generation years.

The Future

The productivity decline rate at The Geysers today is on the order of 3%. At this rate, by 2020, when the newest of the existing plants exceeds its 30-year design life, net generation will have declined from 1000 MW today to 625 MW; this estimate is based on conservative assumptions of no make-up well drilling, no further improvement in the pipeline, gathering system or plants, and no further augmentation or optimization of injection. Given this scenario, two decades hence The Geysers will have generated a total of 41,000 MW-years in 60 years, equivalent to a 1,367 MW net capacity for 30 years. This would be an unparalleled feat against any bench-mark of geothermal field performance.

It should be noted that the decline rate in well productivity today has stabilized at the same modest level of 3% as seen before 1975, and the power price today in constant dollars is not much lower than what it was then. Then why should make-up well drilling be not resumed? Because it still remains uneconomic, as explained below. The reservoir pressure today averages about 230 psia, compared to 450 psia in 1975. Given this fact, it can be shown that a make-up well would produce about 20% of what it would have in 1975. Therefore, even with the same decline rate in well productivity, 5 times as many make-up wells as in 1975 would be required today to maintain generation. Therefore, unless the power price were to increase five fold, make-up well drilling would not be as cost-effective today as it was in 1975.

At present, the depletion rate at The Geysers (that is, production rate minus injection rate, there being no significant natural recharge) has declined to the level of 1975 (22 billion kilograms per year), which has lowered the productivity decline rate to the level prevalent before that period (figure 8). Yet, net generation is double what it was in 1975 (1000 MW compared to 500 MW), due largely to injection augmentation (figure 1).

It is worthwhile considering the additional benefits to be derived in the future from the improvements in the pipeline, gathering system and plants, injection augmentation and significant curtailment experienced since the mid 1990s. As already stated, the decline rate in well productivity today is 3% harmonic compared to a 4.3% harmonic rate forecast by numerical simulation in 1992 assuming no forced curtailment or injection augmentation. In addition, the simulation study in 1992 predicted a generation level of 725 MW by 2000 (Pham and Menzies, 1993). Therefore, over the next two decades energy recovery will be considerably higher than forecast only 8 years ago, this extra amount of energy being given by:

$$1000\int_0^{20} \frac{dt}{1+.03t} - 725\int_0^{20} \frac{dt}{1+.043t}$$

This extra generation amounts to 5,200 MW-years, equivalent to 260 MW (net) capacity for the next 20 years. In other words, the positive field management steps taken since 1992 have already ensured an equivalent extra capacity of 260 MW for 20 years. Even at a conservative power price of 3 cents/kilowatt-hour, this generation represents an extra revenue of $68 million per year for the next 20 years.

In the foreseeable future, optimization of injection, steam gathering and power plant operation will be the resource management tools, rather than make-up well drilling. The operator will confront three major challenges in the future: (a) utilization of progressively lower pressure, superheated, and possibly gassier, steam, (b) further injection augmentation and improvement in injection fluid recovery without causing enthalpy or productivity loss in wells; and (c) maintaining the highest possible "peaking capacity" and taking advantage of spikes in power price on a daily basis.

In case another energy crisis arises in the future, it is likely that additional new plant capacity would be installed at The Geysers. This seeming paradox has a rational explanation. The northwestern boundary of The Geysers reservoir has not yet been reached by development to date, and there are some yet undeveloped lease blocks with relatively high pressure within and around the currently exploited wellfield. The steam from these far-flung lease blocks cannot be transported economically to the existing plants; but suitably located new plants should be able to use this steam, if the power price is high enough. Hence another energy crisis may trigger another round of new developments at The Geysers.

Finally, after sixty years of supporting conventional power generation, The Geysers will become available for exploitation as the world's largest "hot, dry rock" reservoir (otherwise known as an "enhanced geothermal system")! By then, enhanced geothermal systems should have become a strategic source of energy in the U.S.

The Lessons Learned

The following important lessons have been learned from the long history of The Geysers field:

- Unitization, or reasonably open exchange of information between operators, is essential when multiple operators exploit the same geothermal field.
- Sustainable generation capacity is difficult to define; it is determined as much by socio-economic forces as by resource characteristics, design of surface facilities or field management strategy.
- Resilience and ingenuity of the operator can overcome the vagaries of resource behavior and socio-economic conditions.
- For steam fields, injection is the most effective reservoir management tool.

Acknowledgements

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References

Pham, M. and A. J. Menzies, "Results from a Field-wide Numerical Model of The Geysers Geothermal Field, California," Transactions of the Geothermal Resources Council, San Francisco, California, October, 1993

Appendix

Assumptions: (1) socio-economic factors ignored;
(2) no significant water saturation in the reservoir; and
(3) no significant natural recharge to the reservoir.

If M is the mass of steam (at pressure p) in the reservoir at present and M_a is the mass of steam left in the reservoir when the reservoir pressure reaches the level (p_a) at which steam can no longer be supplied to the turbine at the turbine inlet pressure (p_{ti}), then total available steam mass from the reservoir (ΔM) is:

$$\Delta M = M - M_a$$

If V is the pore volume of the reservoir, and v and v_a are the specific volumes of steam at p and p_a, respectively, then

$$\Delta M = \frac{V}{v} - \frac{V}{v_a}$$

From the Real Gas Law

$$v = \frac{zRT}{pM},$$

where

z = real gas deviation factor,
R = Universal Gas Constant,
T = absolute reservoir temperature,
p = reservoir pressure, and
M = molecular weight of the fluid.

Therefore,

$$\Delta M = \frac{VM}{RT}(p/z - p_a/z_a)$$

If Q is cumulative mass production and I is the effective fraction of production that is injected,

$$\Delta M = Q(1 - I)$$

If E is the average sustainable MW capacity over an assumed plant life of L hours, and u is steam consumption per MW-hour, then

$$E = \frac{Q}{u \cdot L}$$

$$= \frac{\Delta M}{u \cdot L(1-I)}$$

$$= \left(\frac{VM}{RTL}\right)(p/z - p_a/z_a)/(1-I)/u$$

If Δp is the steam pressure loss between the reservoir and the turbine inlet, then

$$p_a - \Delta p = p_{ti}$$

Therefore,

$$E = \left(\frac{VM}{RTL}\right)\left[\frac{p}{z} - \frac{(\Delta p + p_{ti})}{z_a}\right]/(1-I)/u$$

In the above equation, the first term within the parentheses is constant, and only 4 variables can affect the sustainable MW capacity, namely:

1. pressure drop between the reservoir and the turbine inlet *(Δp)*;
2. turbine inlet pressure *(p_{ti})*;
3. steam consumption per MW-hour (*u*); and
4. effective injection fraction (*I*).

It should be noted that the above formula, and indeed the concept of sustainable capacity, is valid only if *I* is less than 1, that is, injection does not exceed production.

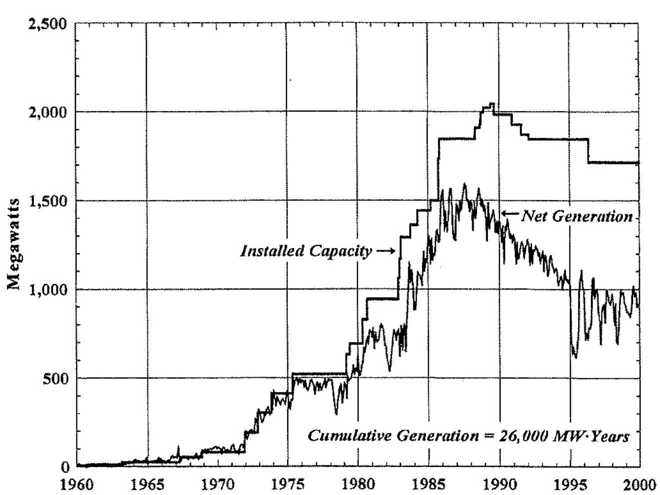

Figure 1. MW Capacity History at The Geysers.

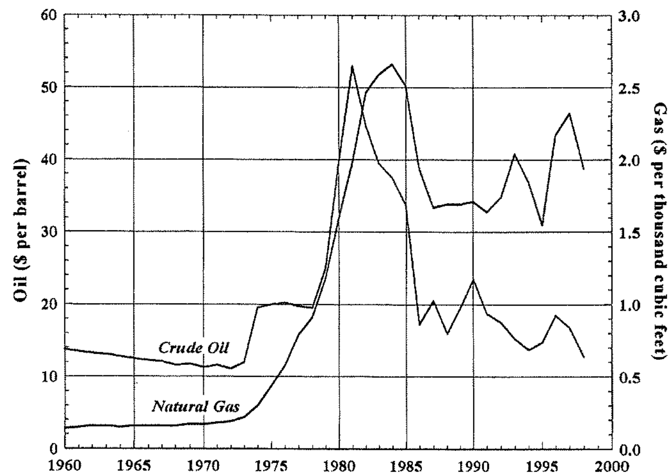

Figure 2. Crude Oil and Natural Gas Prices.

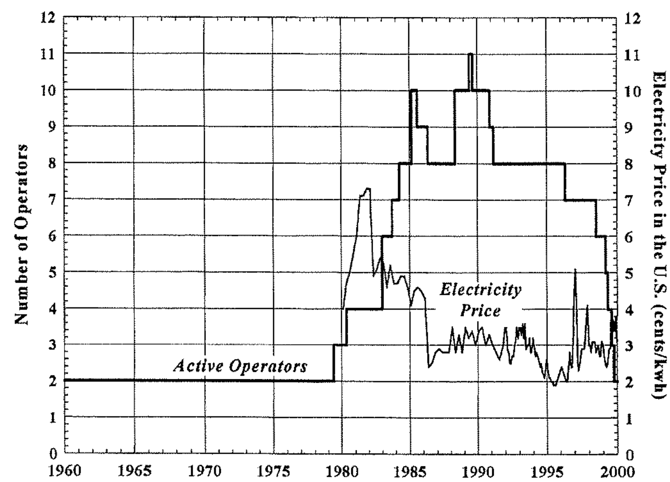

Figure 3. Number of Active Operators at The Geysers and U. S. Electricity Price History.

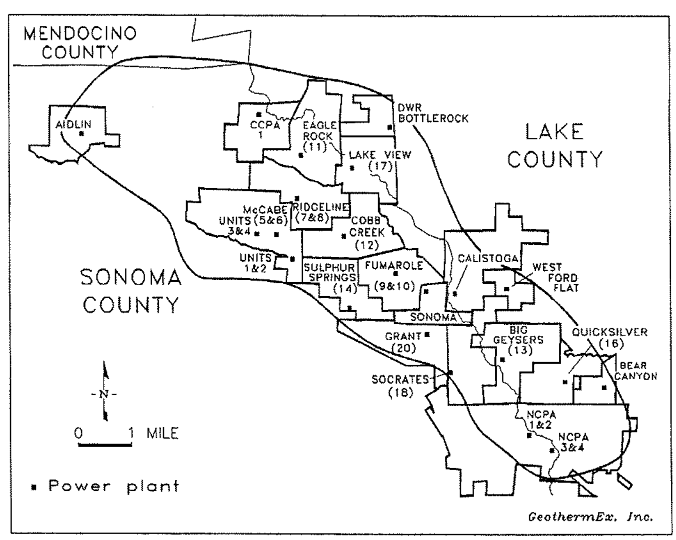

Figure 4. Location of Power Plants and Unit Areas at The Geysers.

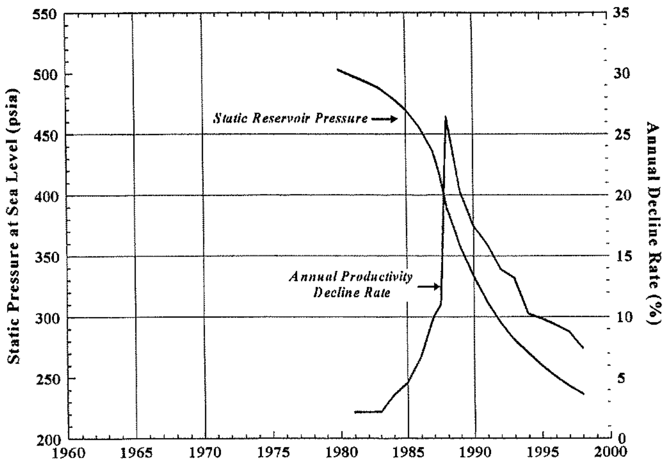

Figure 5. Static Pressure and Productivity Decline History in a Portion of The Geysers Field.

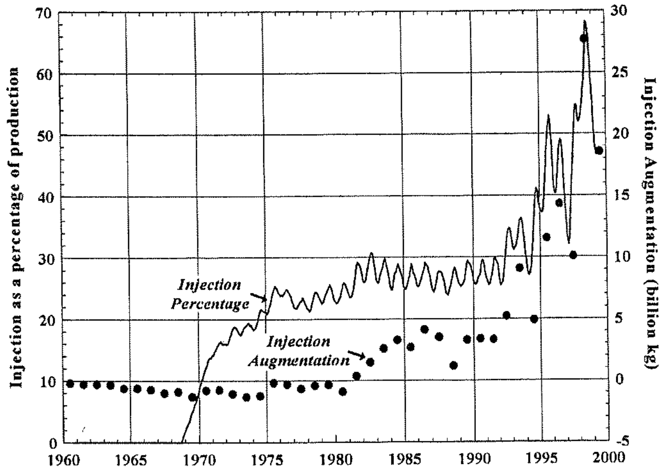

Figure 7. Injection History at The Geysers.

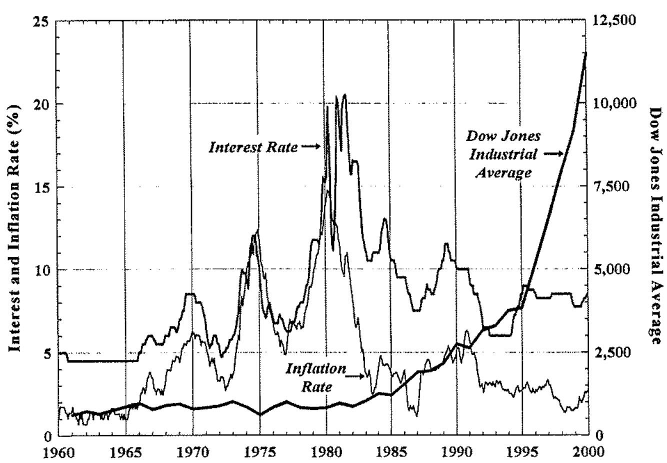

Figure 6. Interest and Inflation Rate and Dow Jones Average.

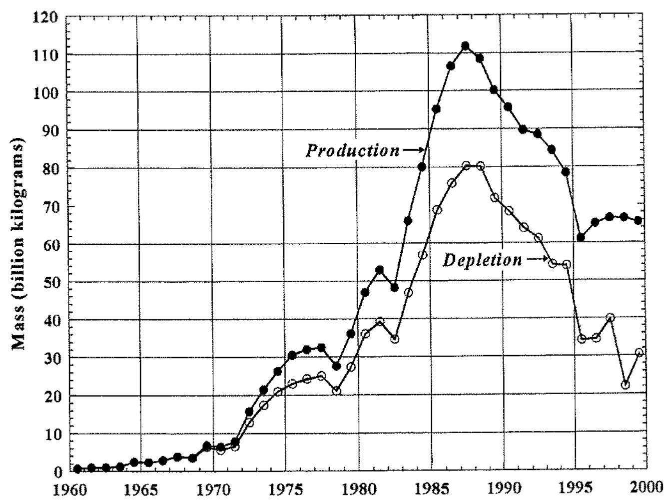

Figure 8. Annual Production and Depletion at The Geysers.