PROCEEDINGS, Thirty-Sixth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 31 - February 2, 2011
SGP-TR-191

FIFTY YEARS OF POWER GENERATION AT THE GEYSERS GEOTHERMAL FIELD, CALIFORNIA – THE LESSONS LEARNED

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ABSTRACT

This paper analyzes the fifty-year history of commercial power generation at The Geysers geothermal field in California as six distinct and consecutive periods (1960-1969, 1969-1979, 1979-1986, 1986-1995, 1995-1998, 1998-2004 and 2004-2010) reflecting the intricate interrelationship between the prevailing socio-economic forces, field development and management practices, and consequent reservoir response. It is shown that this field has proven to be by far the largest source of commercial geothermal power tapped to date in the world, and its history presents a singularly pioneering case of ingenious field management in the face of unpredictable socio-economic forces and challenging reservoir behavior. The most important innovation in this regard has been the augmentation of injection into the reservoir by piping in treated municipal effluents from long distances outside the field.

It is shown that (a) this field by now has produced electricity equivalent to a 1,033 MW plant producing at 90% capacity factor over a typical project life of 30 years; and (b) innovations in field management have led to a 33% higher generation level today than forecast two decades ago. This paper also attempts to forecast the future of this field. We believe the present generation capacity of about 850 MW will have declined to about 700 MW over the next two decades, taking into account the planned addition of at least 100 MW new capacity in the near future. A century since its exploitation began, this field would still be exploited by continued injection into the relatively pressure depleted reservoir, or possibly topping the yet-unexploited ultra-high temperature zones known to exist below the exploited system. Finally, we point out the lessons learned by the geothermal industry from the history of this unique field.

INTRODUCTION

The Geysers geothermal field in California has been supplying commercial electric power continuously for the last half century (1960 to present). Only two other geothermal fields in the world have had a longer history of power generation, namely, Lardarello in Italy (continuously producing since 1948) and Wairakei in New Zealand (continuously producing since 1958). Since the 1970s, the level of power generation at The Geysers has been consistently higher than at either Lardarello or Wairakei, or at any other geothermal field in the world. As discussed below, The Geysers field is expected to be capable of supplying several hundred megawatts of power even another five decades from now, when the field will have completed a century of commercial power generation. This long production history and the high level of power generation makes this field unique in the geothermal world.

BACKGROUND

The Geysers is a steam field, that is, it produces saturated steam rather than water or a steam-water mixture. Furthermore, this field represents an essentially closed system rather than the usual situation of an open geothermal system receiving natural recharge of hot or cold water from outside the reservoir. Steam fields are relatively rare, there being only half a dozen commercially exploited steam fields in the world compared to the numerous geothermal fields producing hot water or two-phase fluids (steam-water mixture). Figure 1 shows a map of this field showing the boundary of the known steam production area, the locations of the power plants and the “unit area” dedicated to each power plant. This field is the largest geothermal field in the world in terms of the areal extent (at least 100 square kilometers) and has more than 400 active wells at present. There are 18 operating power plants, generating about 850 MW at present in this field.

Figure 2 presents the historical production and injection data from the field during the past five decades. Figure 2 shows the monthly production (uppermost plot) and monthly injection (middle plot) in billion kg, and the percent of the produced mass injected each month (lowermost plot) as a function of time.

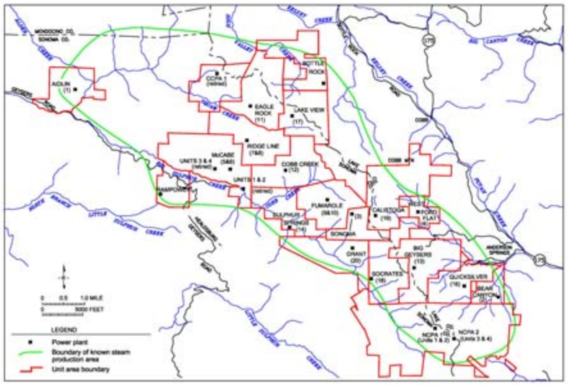

Figure 1: Location of power plants and unit areas at The Geysers geothermal field.

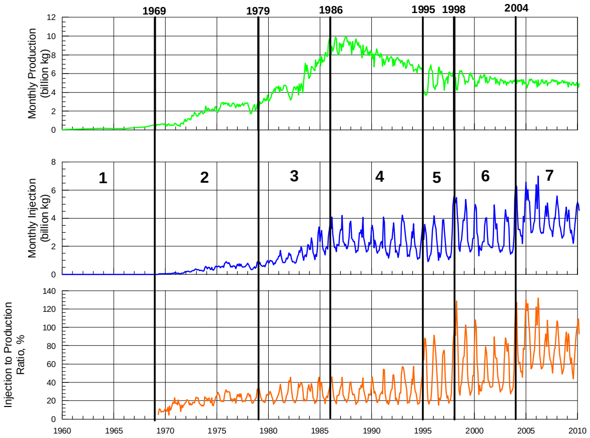

Figure 2: Historical production and injection data for The Geysers.

As attempted in this paper, the fifty-year history of the field can be best described as seven distinct periods of 3 to 10 years' duration both in terms of field and well behavior as well as the prevailing socio-economic forces; these periods are indicated in Figure 2.

Figure 3 presents the cumulative production, injection and depletion (that is, production minus injection) history of this field (in trillion kg), while Figure 4 shows the annual steam depletion (billion kg) and the power capacity (MW) versus time. Figures 2 and 4 show that this field had increasing steam production between 1960 and 1987, when it peaked at 10 billion kg per month, equivalent to about 1,600 MW (net). The installed generation capacity in this field peaked at about 2,000 MW (net) in 1989. Subsequently, steam production and power generation in the field declined continuously for the next 7 to 9 years, reaching stability after 1995. Between 1995 and present both steam production and power generation have seen relatively modest declines with time.

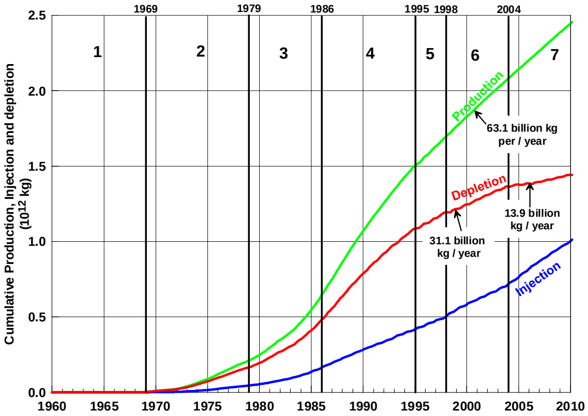

Figure 3: Cumulative production, injection and depletion data for The Geysers.

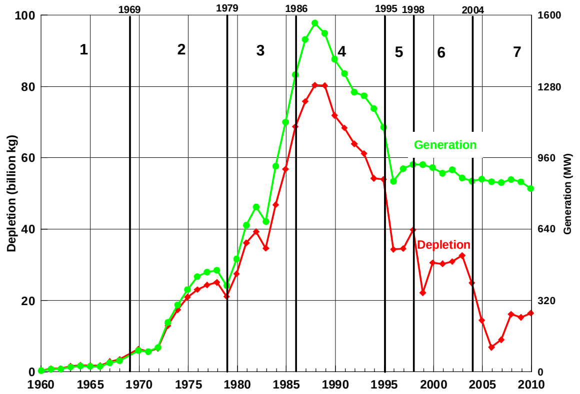

Figure 4: Annual depletion data for The Geysers.

Figure 5 presents the monthly steam production rate (thousand kg/month) from the field (on log scale) versus time to establish the productivity decline trend in the field since 1987. Figure 6 presents a similar plot of the steam production rate in kilopounds per hour (on log scale) versus time since 1980 for a typical well (GDC-12) to illustrate the changes in the productivity decline trend of individual wells.

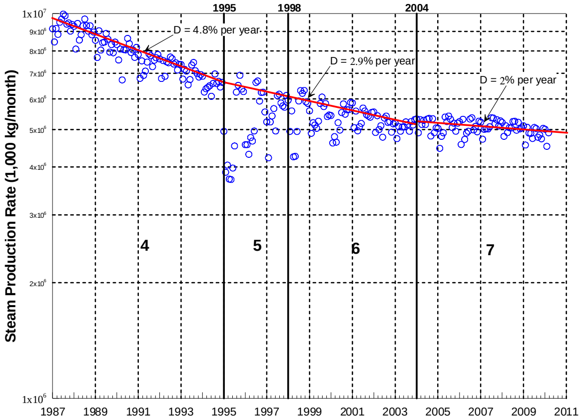

Figure 5: Total steam production rate from The Geysers field versus time.

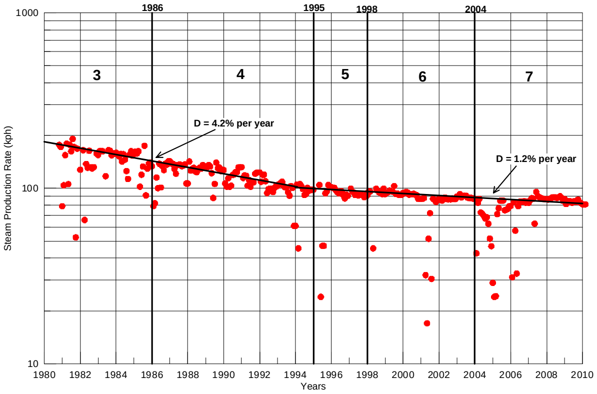

Figure 6: Steam production rate of well GDC-12 versus time.

We believe the long history of this field exemplifies the intricate inter-relationship between the socio-economic forces at play, field development and management practices, and consequent reservoir response. Therefore, in Figures 7 through 9 we present the histories of some indicators of the prevailing socio-economic forces in the United States over the last half century. Figure 7 shows the history of crude oil and natural gas prices, Figure 8 presents the history of the ratio of inflation rate to interest rate, and Figure 9 presents the history of two leading stock market indicators (Dow Jones Industrial Average and Standard & Poor 500). We will refer to the field behavior trends shown in Figures 2 through 5, an individual well behavior trend shown in Figure 6, and the trends in the socio-economic forces shown in Figures 7 through 9, in the remainder of this paper. In light of the above-discussed background, we analyze below the history of this field through each of the seven successive periods.

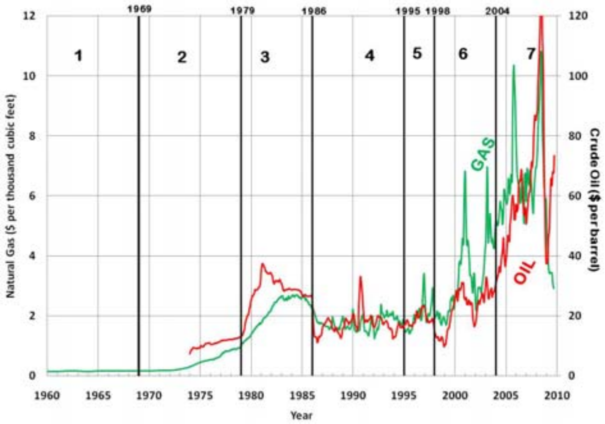

Figure 7: Crude oil and Natural Gas Prices.

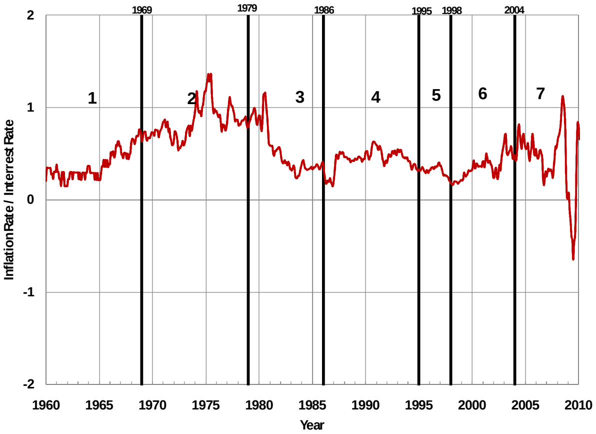

Figure 8: History of U.S. inflation rate to interest rate ratio.

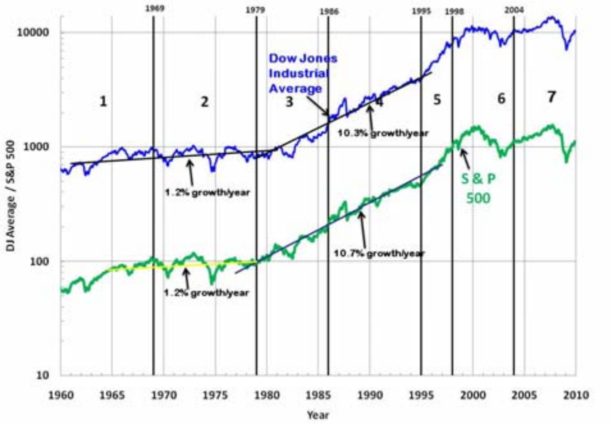

Figure 9: Leading stock market indicators.

THE FLEDGLING YEARS (PERIOD 1)

Electric power generation started at The Geysers with the installation of a 12 MW (gross) plant in 1960. During Period 1 (1960-1969), the installed capacity grew very slowly to above 100 MW (Figures 2 and 4). During this period the produced steam was vented to the atmosphere, the steam condensate was disposed of at the surface and there was no injection. Given the relatively minor rate of production compared to the vast size of the field, the decline rate in well productivity was modest (on the order of 1% per year). In this period, an oil company (Union Oil Company) developed and operated the field. The produced steam was sold to an investor-owned utility (Pacific Gas & Electric Company) who generated power.

GEOTHERMAL COMES OF AGE (PERIOD 2)

During this period (1969-1979), generation steadily grew to about 500 MW and injection of the condensed steam (amounting to about 25% of the mass produced) became a practice. The productivity decline trend in wells still remained modest (a few percent per year).

Crude oil and natural gas prices increased slowly (Figure 7) during this period. While the stock market showed modest growth (Figure 9), it was a strongly inflationary environment (Figure 8). The 1973 “oil crisis” causing concerns about future energy supply and the two decades of successful operations by the end of this period began to attract various municipal utilities and independent power producers (IPPs), in addition to oil companies and an investor-owned utility, to the opportunity for development and operation and/or power generation at The Geysers.

THE GEOTHERMAL RUSH (PERIOD 3)

This period lasted from 1979 to 1986, during which oil and natural gas prices skyrocketed, boosting the price of geothermal power, which was then based to a large extent on the price of fossil fuels. By 1981 the oil price reached its peak, followed by the natural gas price in 1984 (Figure 7). This caused a major spurt in the rate of growth in production and installed generation capacity at The Geysers (Figure 4).

During the early 1980s several incentives for developing geothermal power in the United States became available 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 IPP at the "avoided cost" for the utility. This ended the near-monopoly of the large investor-owned utilities and provided a guaranteed market for the IPP. The availability of a 10% Business Investment Tax Credit and another 15% Alternative Energy Tax Credit from the Federal Government 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 with a minimal 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. In California, the utilities began to offer particularly lucrative power purchase contracts, known as Standard Offer 4, under PURPA.

This combination of an explosive rise in petroleum price, an exceptionally attractive financial incentive package offered by the government and a guaranteed and lucrative power 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, and 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.

The decline rate in reservoir pressure and well productivity began accelerating during this period. This led the operators to augment injection into the reservoir. By 1982 the operators started augmenting injection, beyond that of condensed steam only, by capturing surface run-off during the rainy season and tapping local creeks or aquifers to the maximum extent permitted by the local government.

THE TROUBLED ERA (PERIOD 4)

This 9-year period (1986-1995) stands out as the troubled era in the half century history of The Geysers as production started a steady and steep decline. We discuss below the causes of this unexpected development as presented in Sanyal (2000).

Some dozen operators had developed the power capacity in this field 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 the mass of steam supplied 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. The pricing formula in which the utility paid the field operator by the kW-hour power generation (rather than steam supplied) provided little incentive for the utility to improve power plant efficiency. As such, power generation efficiency varied widely between plants, many being highly inefficient. 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 rights through competitive bidding for Federal or State leases or through negotiations, often involving hard bargaining, with private land owners.

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 and operators who had preceded them. Therefore, in their optimism, each new developer tended to dedicate less area per MW than the ones 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 superheated steam in some parts of the field (implying local drying out of the reservoir) by 1987-1988.

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 pressure interference among wells, further reducing well productivity. This fact plus the unexpected collapse of oil and natural gas prices, and its impact on the steam price for most projects, after 1985 (Figure 7) made make-up well drilling uneconomic by1989. The discounted cash flow rate of return for maintaining generation by make-up well drilling became lower than if no make-up wells were drilled. Therefore, the net generation capacity was allowed to decline from this period on (Figure 4).

During the peak generation year of 1987, 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 steadily from a peak of 1,600 MW in 1987 to less than 900 MW by 1995.

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, another 500 MW of capacity was installed by 1989. There were several reasons behind this apparent paradox: (a) some of these late developments had secured unusually lucrative Standard Offer 4 power sales contracts, 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 and 1983 the inflation rate nose-dived from nearly 15% to 3% and stabilized at that level. The interest rate plummeted from over 20% in 1982 to 7.5% by 1987. And after 1982, the stock market took off for the first time in a generation; the Dow Jones Industrial Average doubled during 1982-1988 (Figure 9). This socioeconomic 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 had been overdeveloped, perhaps to the extent of the last 500 MW of 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.

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 given the closed nature of the field, augmenting injection into the reservoir was the most effective antidote to pressure and productivity decline. Individual operators had also arrived at the same conclusion several years earlier on their own. However, injection augmentation was a major challenge. By 1995, the percentage of the produced mass injected (condensed steam plus surface run-off) had reached a practical limit of about 35% (Barker, et al, 1995). Any augmentation of injection beyond 35% of production, therefore, called for significant operational innovation and capital investment.

It became clear by this time that three critical variables determined the sustainable power capacity at The Geysers: pipeline and gathering system design, plant design, and injection strategy. Throughout this period, the operators had 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 numerical simulation effort funded by the California Energy Commission and conducted by GeothermEx, on behalf of and in collaboration with the operators (Pham and Menzies, 1993), indicated that without further injection augmentation or forced curtailment, generation would continue to decline at a harmonic rate of 9% per year (starting in 1988), which appeared economically unsustainable. 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.

A particularly positive development at The Geysers in this period was the gradual increase in information exchange and co-operation among the operators. For example, Calpine Corporation, Unocal (formerly Union Oil Company) and the Northern California Power Agency jointly implemented some of the injection augmentation strategies developed during this period. A series of acquisitions allowed consolidation of field operation in the hands of fewer and fewer operators; this consolidation finally began to allow optimization and integration of field management and power generation, thus increasing net generation while reducing operating costs.

THE WATERSHED YEARS (PERIOD 5)

During this period (1995-1998), the problems at The Geysers eased sharply and unexpectedly because of the cut-back in generation forced by the availability of cheaper hydroelectric power and the sharp increase in injection of the surface run-off (reaching up to 50% of the produced mass), both caused by the unusually high rain fall in this period. This production cut-back and increased injection further slowed the depletion rate (Figure 3); this, in turn, reduced the decline rate in well productivity sharply (Figures 5 and 6); see Goyal et al (2002) for the details.

During this period, oil and gas prices as well the inflation rate continued to remain low but a bull market in stocks ensued. By the beginning of this period planning began for further injection augmentation by piping in and injecting treated municipal effluent from the community of Clear Lake into the reservoir. A 46 km long pipeline from Clear Lake was constructed and 7.8 million gallons per day of effluent injection started by late 1997. The decline rate in well productivity eased further within a year from the start of this effluent injection. The doldrums at The Geysers seemed to be over.

STABILITY AT LAST (PERIOD 6)

This period (1998-2004) confirmed beyond doubt the remarkable stability achieved in this field. By 1998, the injection rate had increased to 60% of the produced mass due to effluent injection even as the production rate remained nearly the same as in the previous period (63.1 billion kg per year); this further reduced the reservoir depletion rate to 31.1 billion kg per year (Figure 3). This reduced depletion rate moderated the well productivity decline to less than 3% per year (Figures 5 and 6). In 2003, the Clear Lake pipeline was lengthened to 85 km to connect it to alternative sources of municipal effluent.

Field operation and power generation during this period was consolidated with only two remaining operators and power producers left in the field: an IPP (Calpine Corporation) and a municipal utility (Northern California Power Agency). This consolidation of operation allowed considerable optimization of field operation and power generation, further easing the generation decline rate to about 2% per year (Figure 4).

While the rate of inflation remained low during this period, oil and gas prices started climbing again and the stock market became volatile. Encouraged by the manifest benefit of effluent injection, planning started for installing a larger capacity pipeline for bringing in another 11 million gallons per day of treated effluents from the City of Santa Rosa through a 66 km pipeline to further reduce the reservoir decline rate. This pipeline was completed and put in operation by the end of 2003, thus increasing the effluent injection by 24%.

The model forecast of Pham and Menzies (1993), shown in Figure 10, forecast a production rate of about 11 million lb/hour by the end of this period. In actuality, the production rate by 2004 was about 16 million lb/hour. This lower decline rate was achieved by augmenting and optimizing injection, improving the pipelines, gathering system and plants, and aided by the curtailment in generation adopted during 1995-1998; see Goyal and Conant (2010), Butler and Enedy (2009) and Enedy and Butler (2010) for more details.

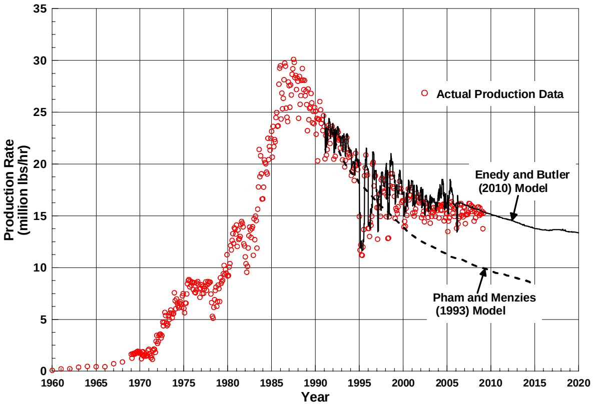

Figure 10: Production at The Geysers field – History and future (after Enedy and Butler, 2010).

RENEWED OPTIMISM (PERIOD 7)

During this period (2004 to present), the injection rate climbed to about 80% of the produced mass as the effluent import from Santa Rosa was increased further to 12.6 million gallons per day, even as production remained the same as in the previous period. The depletion rate was reduced sharply from 31.1 billion per year in the previous period to 13.9 billion kg per year (Figure 3). The decline rate in well productivity as well as generation eased to about 1% to 2% per year (Figures 4, 5 and 6). Furthermore, in many parts of The Geysers augmented injection had diluted the non-condensible gases in produced steam (Beall et al, 2007 and Pruess et al, 2007), which improved generation efficiency and reduced the discharge of greenhouse and noxious gases.

The oil price increased sharply in this period as did the gas price, but towards the end of this period the natural gas price declined sharply. The stock market was volatile and the U.S. economy suffered a major downturn towards the end of this period. However, these economic uncertainties of the period were largely mitigated in the geothermal industry by a set of already existing and new incentives offered by the Federal and State governments as well as the utilities. These incentives, some of which have only indirectly benefited the operators at The Geysers, consisted of the following:

(a) Renewable Portfolio Standard (RPS) enacted by the various States requiring a utility to generate a minimum percentage (20% by 2010 in California) of their power from renewable resources, including geothermal.

(b) Production Tax Credit (PTC), on the order of 2.1¢ per kilowatt-hour for 10 years, offered by the Federal Government on plants put into service before 2013.

(c) In lieu of the PTC, the option of choosing a Federal Investment Tax Credit (ITC) of 30% of the initial investment for a geothermal project, once power generation started.

(d) Rapid increases in the power price offered for renewable power by the utilities to fulfill their RPS obligation.

(e) Geothermal Loan Guaranty offered by the Federal Government.

(f) Development of a market for Renewable Energy Credit (REC) and the possibility of availing of a Carbon Credit in the future.

(g) A round of “stimulus funding” offered by the Federal Government in 2009 to encourage the development and demonstration of various geothermal technologies.

(h) More frequent and extensive geothermal lease sales by competitive bidding offered by the U.S. Bureau of Land Management as well as the California Bureau of Land Management to encourage further geothermal development on government lands.

In consequence of the economic incentives as well as the demonstrated stability and the minimal rate of well productivity decline established at The Geysers, planning began for new growth in installed power capacity and two new developers, both IPPs, entered the field (Ram Power Company and U.S. Renewables).

THE FUTURE

Two major issues characterize the uniqueness of the remarkable history of The Geysers:

(a) Figure 3 shows that in 50 years, cumulative steam production has amounted to 2.43 trillion kg, equivalent to 32,000 MW years of electricity. This cumulative generation is equivalent to 1,333 MW generation capacity for a typical power plant life of 30 years and a typical plant capacity factor of 90%. No other geothermal field in the world has proven to be so prolific.

(b) Figure 10 shows that as of 2010, total steam production rate from this field has been 5.3 million lbs/hour higher than predicted by Pham and Menzies (1993) before the various operational innovations (such as injection augmentation) were introduced. This higher rate implies that the innovations implemented resulted in 280 MW higher power capacity, or nearly 33% of the current power generation level of 850 MW.

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. Make-up well drilling is still not attractive because even though the decline rate in well productivity is now minimal, the typical production rate per well is too low (2 to 3 MW) and the pressure interference between wells too intense to justify the drilling cost. The operator will confront two major challenges in the future: (a) utilization of progressively lower pressure, superheated, and possibly gassier, steam, and (b) further injection augmentation and improvement in injection fluid recovery without causing enthalpy or productivity loss in wells.

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 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. Another source of production for new power capacity could be the deeper brine reservoir or ultra-hot rock (approaching the critical point for water in temperature) identified in several parts of the field (Beall and Wright, 2010), which have not yet been possible to exploit. Hence another energy crisis may trigger another round of new developments at The Geysers. In fact, the IPP U.S. Renewables has already restarted a previously shut power plant (Snedaker, 2007) and has plans for adding new capacity. Another IPP Ram Power, has plans to develop a new plant at a site originally developed by Western GeoPower Company (Sanyal et al, 2010). Calpine Corporation is also expected to add significant new capacity in the currently undeveloped north western part of the field. These new installations could add approximately 100 MW in the near future.

Finally, after a century of supporting conventional power generation, The Geysers may become available for exploitation as the world's largest “enhanced geothermal system”! By then, enhanced geothermal systems could become a strategic source of energy in the U.S.

LESSONS LEARNED

In addition to the injection, steam gathering system and corresponding power plant optimization, and curtailment issues discussed above, 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 superheated steam, handling corrosive steam, utilization of gassy steam, and so on. All these problems have been solved through technical and managerial innovation. For example, some operators gradually adopted effectively “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 focused on maintaining the “peaking capacity” by reducing the “baseload capacity.” In a 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 ceased to be a useful measure of the profitability of a project. Many such technical and managerial innovations pioneered at The Geysers are now commonplace in the geothermal industry.

Most important lessons learned from the case history of The Geysers are the following:

- Reasonably open exchange of information between field developers and operators is essential when multiple developers and operators exploit the same geothermal field.
- Sustainable generation capacity 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 unexpected changes in resource behavior and socio-economic conditions.
- For steam fields, injection is the most powerful reservoir management tool.
- Augmenting injection by bringing in water from outside the field can be both technically and economically feasible.
- Injection of treated municipal effluents in a steam field offers multiple benefits to society; environmental impact of sewage disposal can be replaced by the generation of relatively cheap renewable energy and reducing the discharge of greenhouse and noxious gases.

ACKNOWLEDGEMENTS

The authors owe a debt of gratitude to numerous individuals, involved with The Geysers at various times, for sharing their views with them. Of these individuals, Karl Urbank, and Keshav Goyal of Calpine, and Steven Butler of GeothermEx are singled out for their invaluable contribution to the development of the perspective presented here. The authors wish to thank Mr. Ali Khan of the California Department of Oil, Gas and Geothermal Resources for providing the production and injection database on which this assessment is based, Amber Falconer of GeothermEx for conducting literature search in preparation of this paper, and Keshav Goyal for reviewing the manuscript.

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