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# GEYSERS RESERVOIR PERFORMANCE

B.J. Barker, M.S. Gulati, M.A. Bryan, K.L. Riedel

*Unocal Geothermal Division*
*P.O. Box 6854, Santa Rosa, California 95406*

## ABSTRACT

Exploitation of The Geysers began about 140 years ago with the construction of a resort hotel. Electric generation commenced in the 1920s upon the completion of several shallow steam wells. A steam-engine-driven generator supplied roughly a kilowatt to electrify the resort through the 1930s.

The current large-scale development began with drilling in 1955 and the first 12 MW plant in 1960. Additions in the 1960s brought field capacity to 82 MW. The sustained development started in 1972, with an average of 67 MW/year installed through 1981. Growth accelerated to 150 MW/year in the latest phase (1982-89).

This latest phase of expansion has been accompanied by 100 to 200 percent increases in reservoir pressure decline and production decline rates. Steam deliverability fieldwide has peaked, and substantial declines have been experienced. The reservoir response indicates the field is fully developed. Performance forecasts have been made using both numerical models and direct extrapolation of pressure and flow rate trends. Both methods suggest that field life will exceed 50 years. However, Unocal-NEC-Thermal production will probably decline from 16 million pounds per hour to 8 million 1b/hr in the next 10 years.

## DEVELOPMENT HISTORY

Hot springs and fumaroles were known to exist at The Geysers as early as 1847, but except for two small reciprocating steam-engine driven generators installed for lighting a resort (Matthew, 1975), no attempts were made to harness this geothermal energy until recent times. The resort, located on the south side of Big Sulphur Creek, used steam from wells drilled in the 1920s on the north side (Allen and Day, 1925).

In 1955 the Magma Power Company obtained leases mostly on the north side of Big Sulphur Creek and initiated a drilling program along with Thermal Power Company. By 1958, sufficient wells had been drilled to provide steam for a small unit and PG&E signed a contract with Magma-Thermal to purchase steam for its 12 MW Unit No. 1, installed in 1960.

In 1967, Union Oil Company of California and Magma-Thermal merged their holdings, forming a joint venture (U-M-T) with Union as the operating partner. Magma Power Company was sold to Natomas as NEC Company in 1981. Unocal acquired NEC in 1985. The Unocal-NEC-Thermal (U-N-T) joint venture is now responsible for supplying steam to 1,103 MW of installed generating capacity built by PG&E.

In this paper, U-M-T is used to designate holdings or operations prior to 1981, and as U-N-T thereafter. In referring to operations in both periods, the terms may be used interchangeably.

U-M-T and PG&E's successful operations at The Geysers encouraged development efforts by other operators. The first non-U-M-T development reached fruition in 1979 when Pacific Energy Corporation started supplying steam to PG&E's Unit 15.

Besides PG&E, other utilities in The Geysers are: Northern California Power Agency (NCPA), California Department of Water Resources (DWR), Central California Power Agency (CCPA) and Sacramento Municipal Utility District (SMUD). The CCPA and SMUD plants are supplied, respectively, by GEO Operator Corporation (GEO) and

Geysers Geothermal Corporation (GGC), a division of Freeport McMoRan.

Some developers built their own power plants. They are: Santa Fe International, Freeport McMoRan (Bear Canyon and West Ford Flat plants) and Geothermal Energy Partners (GEP-Aidlin plant).

The growth of generation capacity at The Geysers did not follow a predetermined schedule, but can be conveniently described as occurring in three phases:

| Phase. | Period | New Capacity | Average MW/Yr |
|---|---|---|---|
| I | 82 MW | 1960-1968 | 10 |
| II | 861 MW | 1969-1981 | 67 |
| III | 1100 MW | 1982-1988 | 150 |

Figure 1 shows the growth in generating capacity at The Geysers. The locations of the plants are shown in Figure 2. Table 1 lists the power plants currently on line at The Geysers.

## RESERVOIR PRESSURE HISTORY

The heterogeneity of The Geysers reservoir made determining the initial pressure quite difficult. Allen and Day were able to measure 276 psig at a depth of 416 feet in 1925. In the 1960s, wellhead pressures over 300 psig were common in the Magma-Thermal wells drilled to 1,000 feet in the Sulphur Bank area (Ramey, 1968). The deeper wells reached static pressures over 500 psia, and eventually a value of 514 psia was determined to be the pre-exploitation pressure at a sea level datum within the U-N-T area (Lipman, Strobel and Gulati, 1978). Pressure in the great majority of U-N-T wells drilled into undepleted reservoir were within 15 psi of this value.

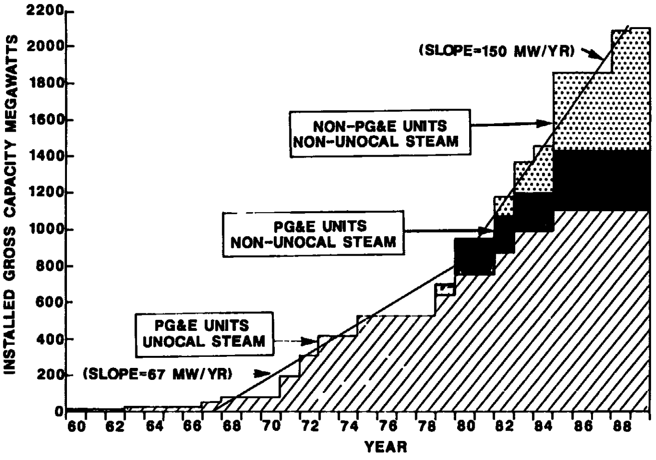

**Figure 1.** Geysers installed capacity.

**Table 1.** Geysers power plants.

| Unit | Start-up Date | Capacity (Gross MW) | Cumulative Capacity (MW) |
|---|---|---|---|
| PG&E-1 | 9-60 | 12 | 12 |
| PG&E-2 | 3-63 | 14 | 26 |
| PG&E-3 | 4-67 | 28 | 54 |
| PG&E-4 | 11-68 | 28 | 82 |
| PG&E-5&6 | 12-71 | 110 | 192 |
| PG&E-7&8 | 11-72 | 110 | 302 |
| PG&E-9&10 | 11-73 | 110 | 412 |
| PG&E-11 | 5-75 | 110 | 522 |
| PG&E-12 | 3-79 | 110 | 632 |
| PG&E-15 | 6-79 | 60 | 692 |
| PG&E-13 | 5-80 | 137 | 829 |
| PG&E-14 | 9-80 | 114 | 943 |
| PG&E-17 | 12-82 | 119 | 1062 |
| NCPA-1 | 1-83 | 110 | 1172 |
| PG&E-18 | 2-83 | 119 | 1291 |
| SMUDGEO-1 | 10-83 | 72 | 1363 |
| Santa Fe | 4-84 | 80 | 1443 |
| DWR-Bottle rock | 3-85 | 55 | 1498 |
| PG&E-16 | 10-85 | 119 | 1617 |
| PG&E-20 | 10-85 | 119 | 1736 |
| NCPA-2 | 11-85 | 110 | 1846 |
| CCPA-1 | 5-88 | 65 | 1911 |
| CCPA-2 | 10-88 | 65 | 1976 |
| Bear Canyon Creek | 9-88 | 20 | 1996 |
| West Ford Flat | 12-88 | 27 | 2023 |
| Aidlin | 6-89 | 20 | 2043 |

The uniform initial pressure indicated a high horizontal permeability, and this was borne out by the subsequent pressure decline. Figure 3 shows the 1988 static pressure distribution on U-N-T leases. These pressures were determined by buildup tests run on selected wells with normal production from the surrounding areas. Large areas are within 250 psig contours, with higher pressures only near the edges of the field.

The pressure sinks centered in Units 1-8 and in Units 9, 10 and 14 developed the broad minima associated with good lateral communication early in their history. This is illustrated by looking at the time history of pressure along the traces of A-A′ and B-B′ in Figure 3. The line A-A′ trends southeast for about 8 miles more or less parallel to Big Sulphur Creek. B-B′ runs northeasterly through the Units

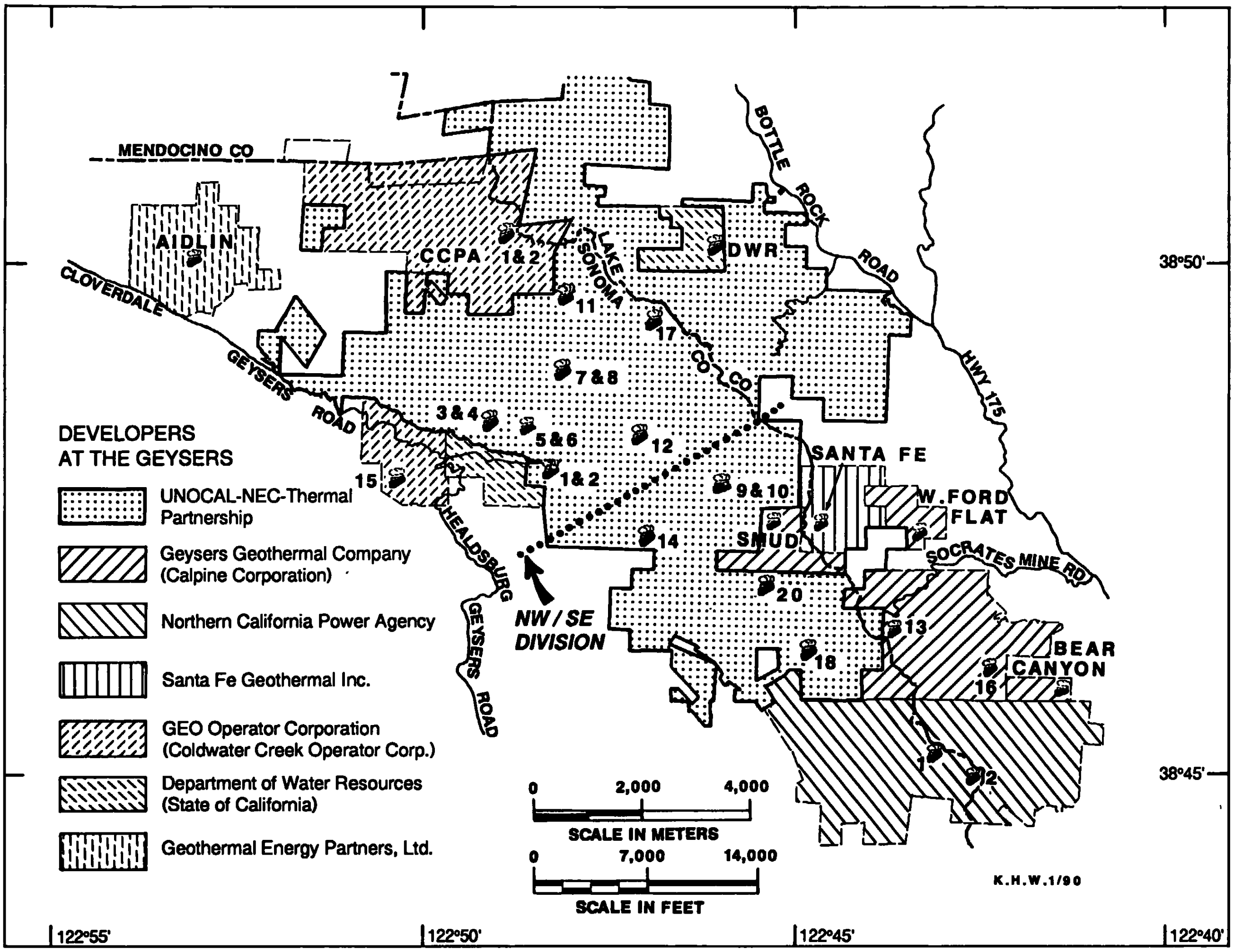

**Figure 2.** Geysers development map.

1-8 and 17 areas. Pressures along these lines from 1966 on are shown in Figures 4 and 5.

The finding of good lateral connectivity has important implications for field development and reservoir modelling. Unocal and others have used tracers such as tritium to test fluid movement across the reservoir (Gulati, Lipman and Strobel, 1978). Figure 6 is a map showing the recovery sites of flashed tritiated water in the oldest pressure sink area. The injection point was GDC 53A-13, near the intersection of the cross-section lines in Figures 4 and 5.

Comparing Figure 6 with Figures 4 and 5, it may be seen that tracer was recovered at locations with higher vapor-phase pressure than near the injection point. This suggests that the tritium traveled as liquid some distance before boiling, which is consistent with a large convection cell.

A parameter commonly used in volumetric natural gas reservoirs to track performance is pressure divided by real gas deviation factor, Z. Although The Geysers is not a single-phase gas reservoir, P/Z is useful for displaying historical depletion effects.

An estimated history of average P/Z for the entire Geysers field is shown in Figure 7. The trend shown here was determined by reservoir simulation, using a model which included non-U-N-T production. Block temperatures and pressures, corresponding to those of static observation wells in the producing field were used to compute the area averaged P/Z. The acceleration of pressure decline after 1981 is readily apparent.

## PRODUCTION HISTORY

From 1960 through 1978 Geysers production was almost entirely from the U-M-T leases. Yearly production and generation for the U-M-T/U-N-T area through 1988 is shown in Figure 8. Unit 1 began commercial operation on September 25, 1960, using approximately 225 kilopounds/hr (kph). By November 1968 Unit 4 brought field production to about 1,600 kph. Deliveries then remained flat through mid-1971.

The first plant (two units) in the second development phase began operation in 1971. From 1971 to 1981, 12 units

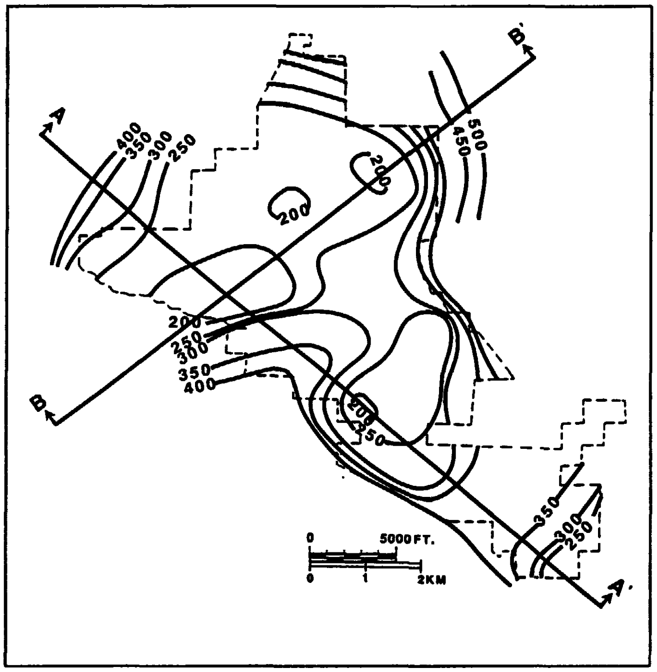

**Figure 3.** Isobaric map, values in psia at sea level.

were brought on line, with a capacity of 874 MW. Mass withdrawal from the field increased at a rate of 1.173 kph per year, to about 14,500 kph. This change in trend can be seen in Figure 9, which shows approximate total annual Geysers production from 1960 through 1988.

Fourteen units were installed in the third phase of development, which began in 1982. Total field deliverability peaked in mid-1987 at an estimated 30,000 kps, including 18,500 kph from U-N-T leases. Between 1982 and 1987 the mass withdrawals from the field increased at about 2,550 kps per year, more than twice the rate of development that had occurred during the previous 11 years. This was accompanied by substantial pressure and flow rate declines. The relationship is shown in Figure 10, which is a cross-plot of pressure decline and field withdrawal rate.

The heaviest development after 1981 occurred in the southeastern part of the field. Wells that existed in this part of the field prior to 1981 experienced as much as a threefold increase in production-decline rate, while wells in the northwestern part of the field generally experienced smaller increases. To compare the intensity of development in the two area, the U-N-T leases were divided into northwest (Units 1-8,11,12,17) and southeast (Units 9,10,14,18,20) sections as shown on Figure 2. When the withdrawal rate from the field peaked in mid-1987, the withdrawal rate per acre from the northwest part was 1.5 kph per acre, compared to 2.0 kph per acre for the southeast part.

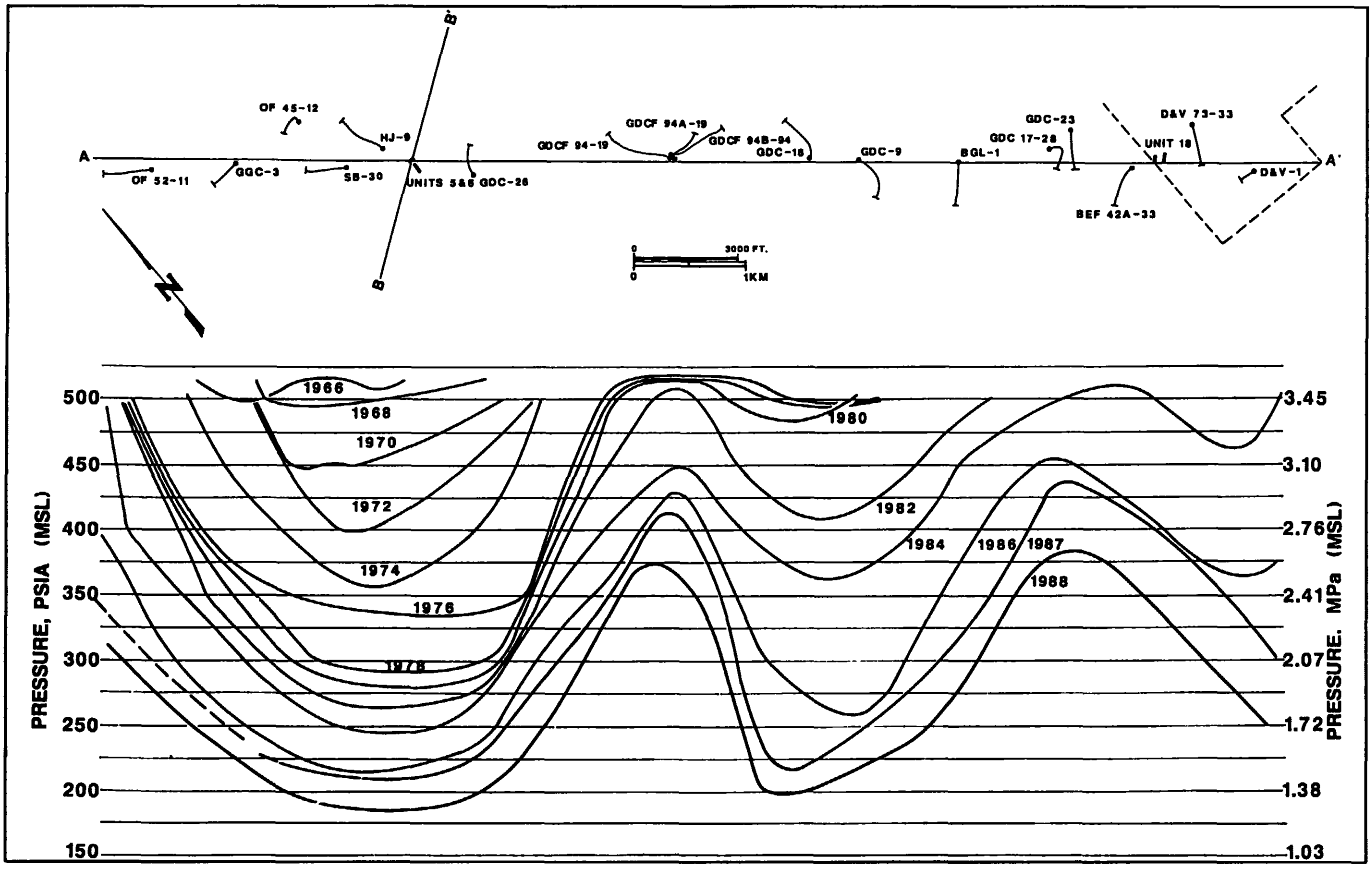

**Figure 4.** Change in pressure level at The Geysers from 1966 through 1989.

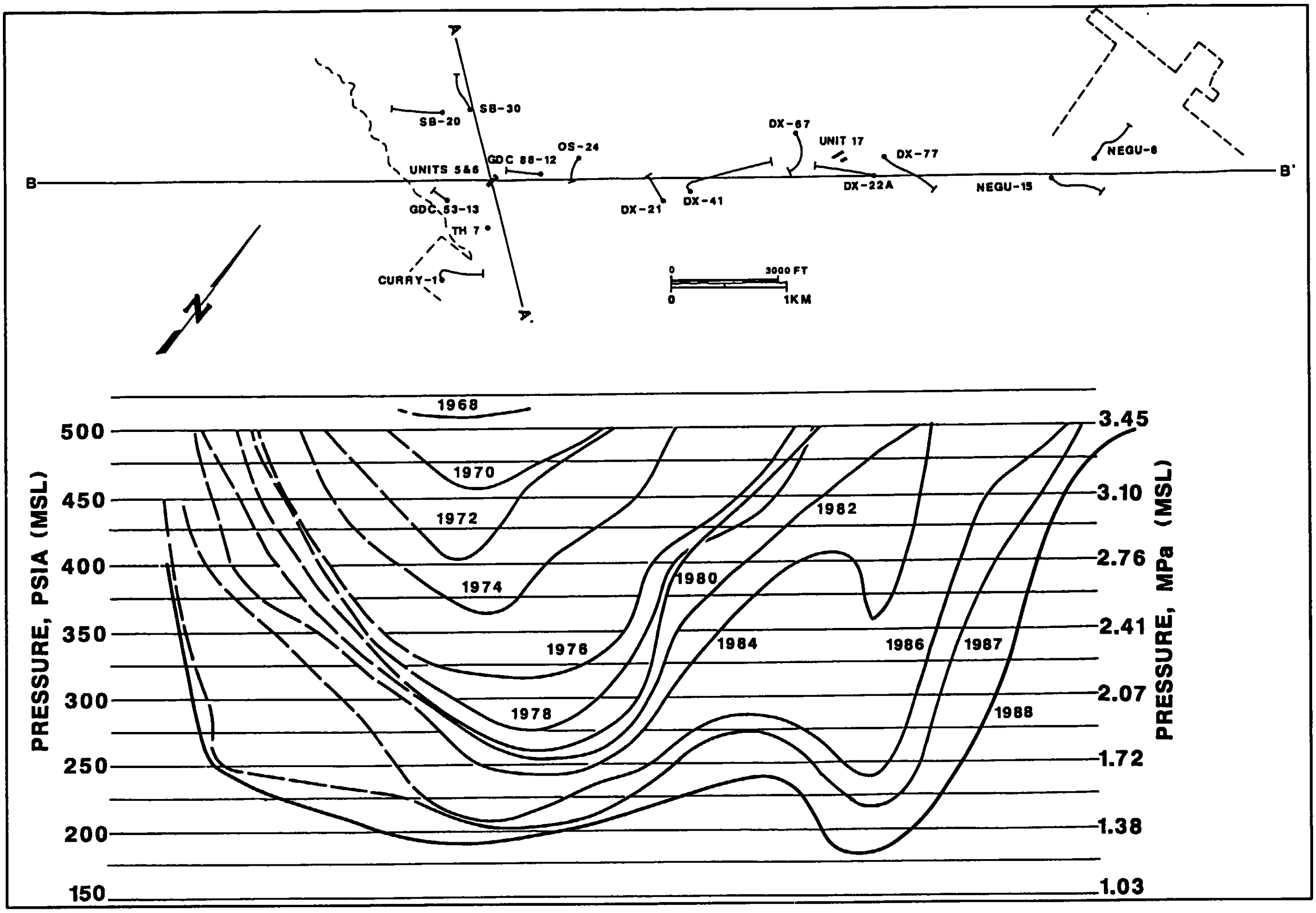

**Figure 5.** Change in pressure level at The Geysers from 1968 through 1989.

Figure 11 shows the monthly deliverability for U-N-T leases in each of these areas. The equivalent flow rate shown is the monthly mass produced divided by production rate-weighted average hours in service of the wells.

The exponential decline rate for U-N-T's northwestern leases is approximately 7 percent per year compared to 15 percent per year for the southeastern leases. The overall decline rate for U-N-T leases has been about 11 percent per year since mid-1987.

The impact of the rapid development that occurred in the southeast part of the field is evident in the flowrate history of LF-6. This was a start-up well for Units 9 and 10

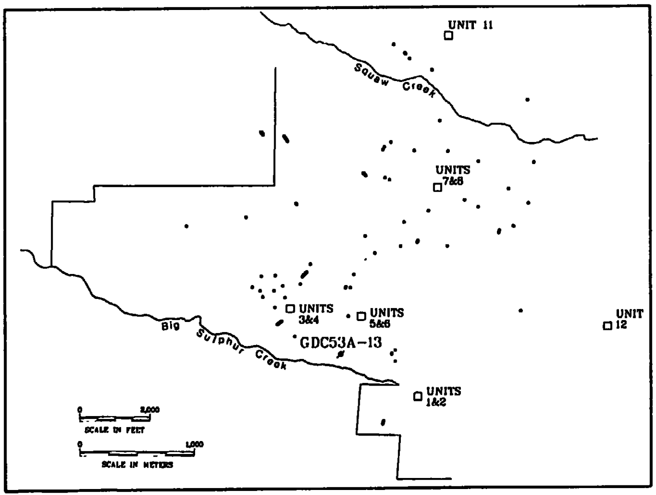

**Figure 6.** Recovery sites of tritium from GDC 53A-13.

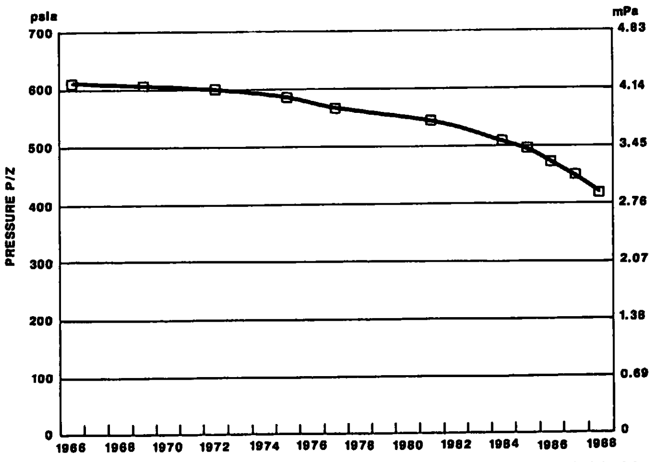

**Figure 7.** Geysers average reservoir pressure P/Z. Fieldwide simulation results, sea level static, areal average.

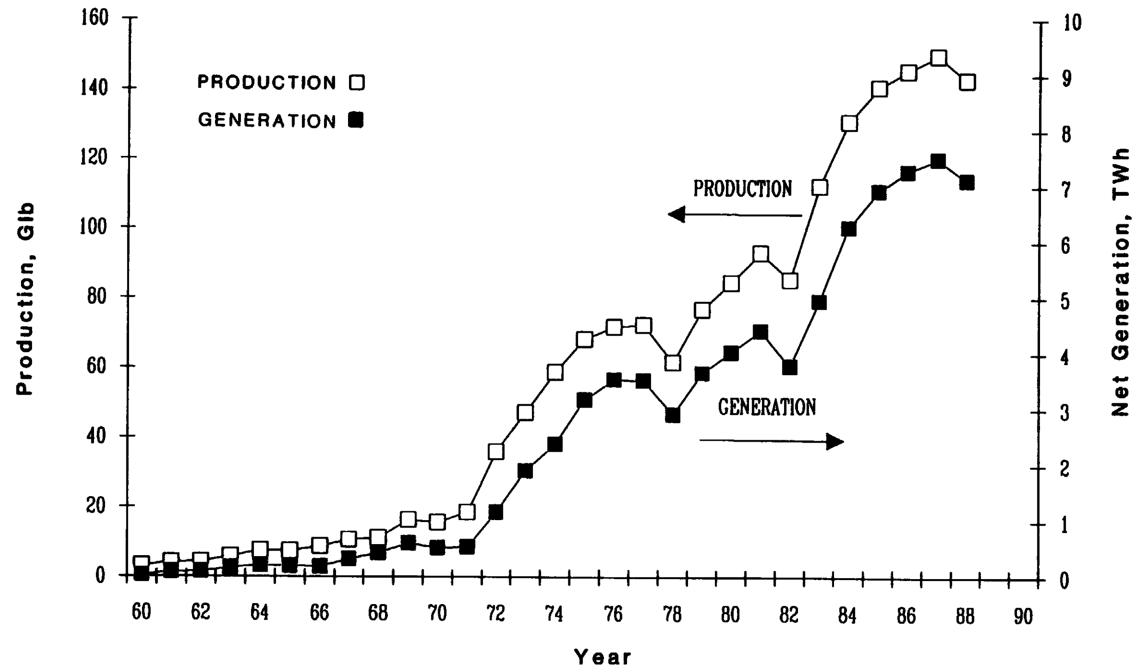

**Figure 8.** Union-Magma-Thermal production and generation annual total, 1960 - 1988.

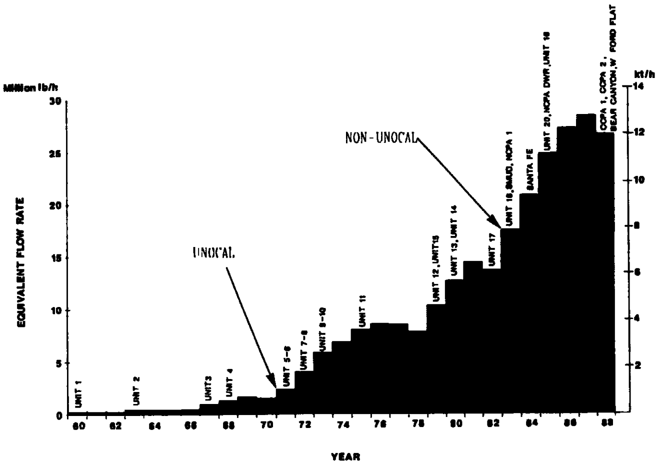

**Figure 9.** Geysers production history. Estimated annual production, expressed as hourly rate.

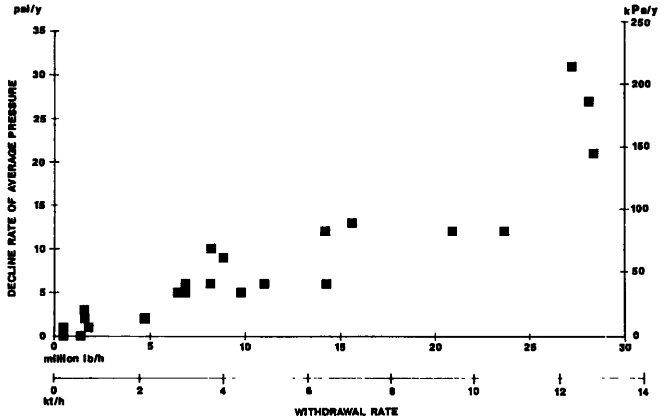

**Figure 10.** Reservoir pressure decline as a function of mass withdrawal rate, estimated fieldwide.

and is located 2,000 feet northeast of well GDC-9, which is on cross-section line A-A' in Figures 3 and 4. Figure 12 shows the monthly instantaneous flow rate measured at LF-6. LF-6 began producing at the end of 1972 at approximately 200 kph. Its current flow rate is approximately 23 kph. The well declined at an exponential rate of approximately 6 percent per year through mid-1984, after some initial scatter.

The decline steepened in late 1984 to about 30 percent per year and continues at that rate. This performance is typical of wells in the vicinity of Units 9-10. Similarly, decline rates between 15 and 25 percent per year are common around Units 14, 18 and 20.

## OUTLOOK FOR THE FUTURE

We believe that The Geysers reservoir is fully developed. Deliverability has been declining since 1987. The challenge now is to maximize power generation and energy recovery from the resource. In this section we will comment on our experience with forecasting, and discuss the probable impact of infill drilling, turbine inlet pressure changes, steam conservation and water injection.

Unocal has used a variety of techniques to study the future performance of the field. Decline curve analysis is useful for making short-term predictions whereas numerical modelling (reservoir simulation) is preferable for long-term forecasts and for studying different operating plans.

## Decline Curve Forecasting

Decline curve analysis is used extensively in the industry for predicting the performance of petroleum and geothermal wells. The method is strictly empirical and does not account for boiling or injection of water. Its application at The Geysers is further complicated by the effects of offset development, infill drilling, and changes in wellhead pressure. However, due to its ease of use, and the availability of accurate production data, decline curve analysis can be a useful forecasting tool.

Figure 13 shows U-N-T's total steam deliverability at The Geysers from 1987 through 1989. These data have a best-fit decline rate of 10.5 percent per year, using either exponential or harmonic formulae. The lower curve shows the exponential-decline extrapolation, while the upper shows a harmonic decline. Although the 1987-89 data are fit equally well by both techniques, they differ greatly in long-range predictions. A 20-year forecast of U-N-T's field-wide deliverability, which was made using the numerical model described below, was found to fit very well with the 10.5 percent harmonic decline. This suggests that if simple decline curve analysis must be used for long-term predictions, harmonic decline may be appropriate.

## Reservoir Simulation Forecasting

Unocal has pursued numerical simulation of The Geysers reservoir since the early 1970s. The most recent and sophisticated model was completed in 1987, and history-matched using production data since 1960. We have used this model extensively for forecasting long-term field performance. The model covers approximately 44,000 acres and includes all producing land at The Geysers. The model is constructed with a uniform cartesian grid consisting of 32 x 15 x 6 cells, each 2,000 feet on a side. A dual porosity formulation is used. The bottom two layers of the model, 8,000 and 12,000 feet subsea, are initially superheated. Other reservoir properties incorporated in the model were derived from physical measurements or the matching of historical pressure trends. The range of values is shown in Table 2. All U-N-T wells are represented individually, as are wells on the DWR-Bottle rock lease. Remaining non-U-N-T wells are lumped together within grid blocks.

Throughout forecasting, 28 percent of the steam produced from U-N-T acreage is reinjected as condensate. Injection on non-U-N-T property is maintained at estimated 1987 levels.

This model of The Geysers reservoir can be used in long-range planning aimed at increasing the value of the resource. Two applications of this model are to evaluate infill drilling and reduced turbine inlet pressure as methods of increasing the longevity of The Geysers.

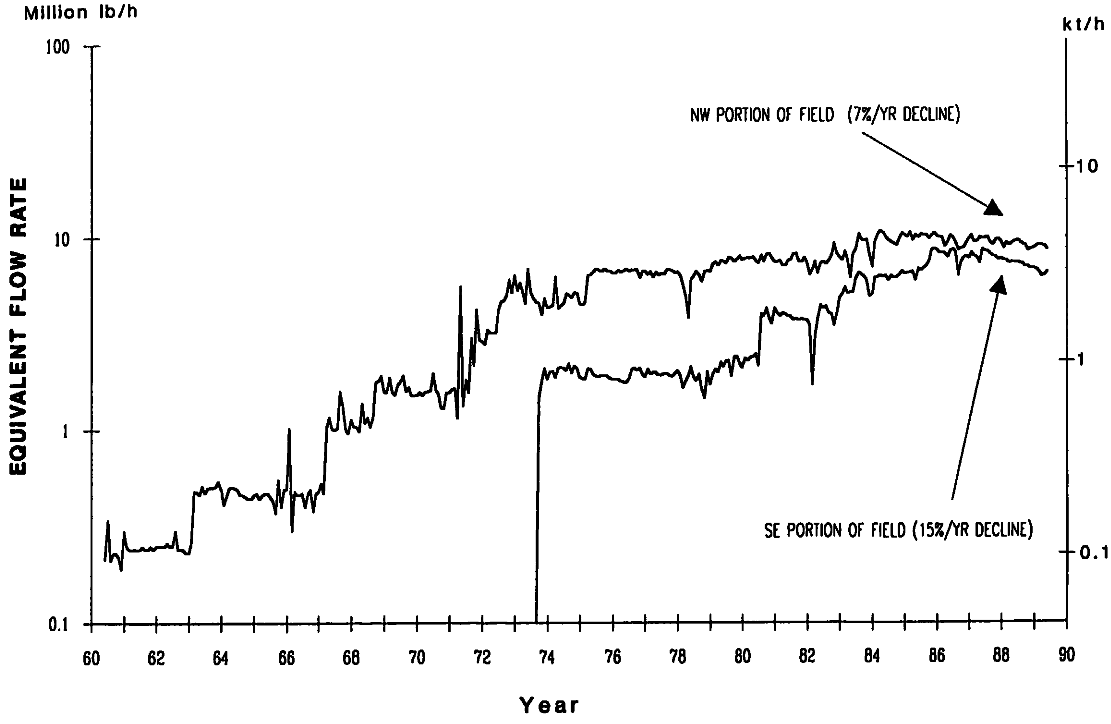

**Figure 11.** Monthly average production of Union-Magma-Thermal leases.

**Table 2.** Geysers model parameters.

| | |
|---|---|
| Initial Mass in Place | 11,100 Glb |
| Fracture Permeability | 10-180 md |
| Fracture Porosity | 1-2% |
| Fracture Liquid Saturation | 1-25% |
| Fracture Spacing | 180-700 ft |
| Matrix Permeability | 0.005-0.120 md |
| Matrix Porosity | 2-4% |
| Matrix Liquid Saturation | 82% |
| Thermal Conductivity | 29 BTU//Day ft F |
| Specific Heat of Rock | 37 BTU/cu ft F |

## Infill Drilling

To test the potential of additional infill drilling to increase deliverability, 130 well targets were identified in already-developed areas. These potential makeup wells were incorporated into The Geysers model and were individually calibrated to match the expected deliverability under present reservoir conditions. A steam supply forecast which shows the effect of drilling these 130 infill wells between 1989 and 1993 is shown in Figure 14, along with a forecast in which no wells are drilled after July 1989. By 1993 the net production increase from drilling is 920 kph over the no-drilling scenario, an average of only 7 kph per new well. This compares with typical commercial rates of 100 to 150 kph during field development. The additional production over 20 years is 82 gigapounds (Glbs). At a present cost of more than $1.5 million per well, this not a feasible option.

## Reducing Turbine Inlet Pressures

Steam deliverability is ultimately controlled by the difference between reservoir pressure and the back pressure imposed at the wellhead. At a number of PG&E plants steam is throttled upstream of the turbine in order to provide high pressure steam to the gas ejectors. If the ejectors at these plants were replaced with either compressors or ejectors designed to operate at a lower steam pressure, the throttle valves could be fully opened.

This would result in lower wellhead pressures which would increase the total steam deliverability. It would also increase the ultimate recoverable reserves from the reservoir by lowering the abandonment pressure. Figure 15 shows a steam supply forecast for ejector-equipped units which includes the effect of gradually lowering turbine inlet pressures by approximately 40 psi between 1989 and 1997. Shown for comparison is a forecast in which inlet pressures are fixed at 100 psig.

Reducing the inlet pressures results in an increase in deliverability of 1,070 kph by 1997 and an additional 158 Glbs of production over 20 years. This is nearly twice as effective as massive drilling, and may be economically attractive.

## Steam Conservation in Operations

From the early 1960s until 1986 steam from U-N-T leases was vented to the atmosphere when power plants tripped off line or were curtailed significantly. During those times, surplus steam in the piping system was vented to atmosphere while wells were manually cut back.

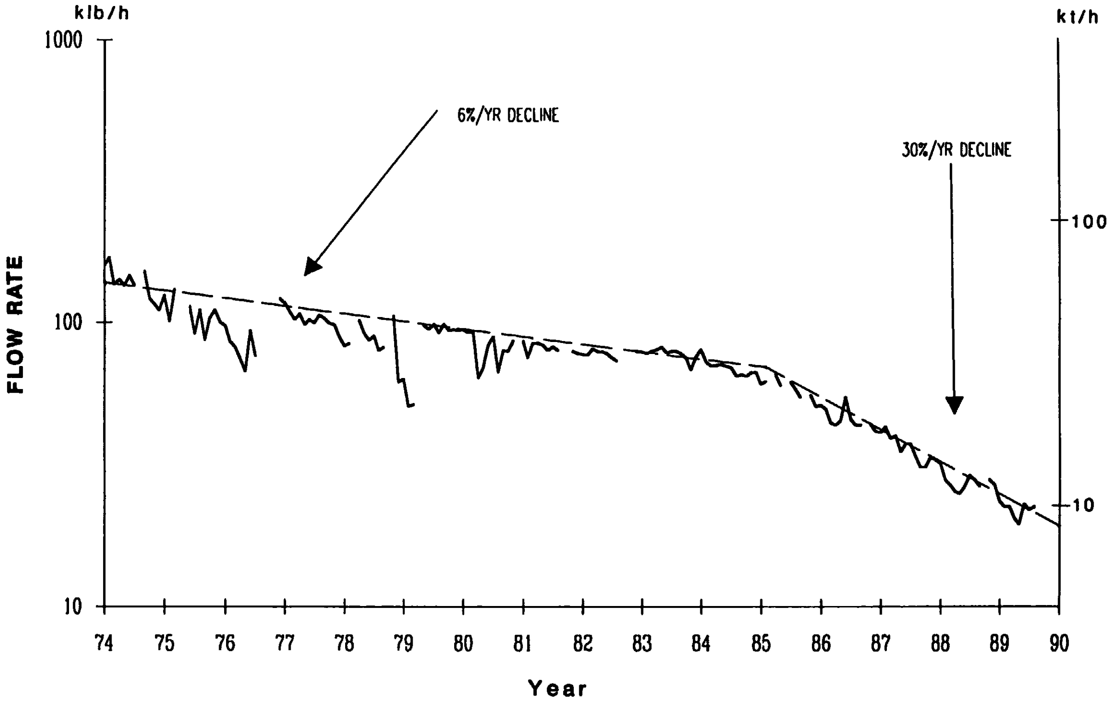

**Figure 12.** LF 6 monthly flow rate history.

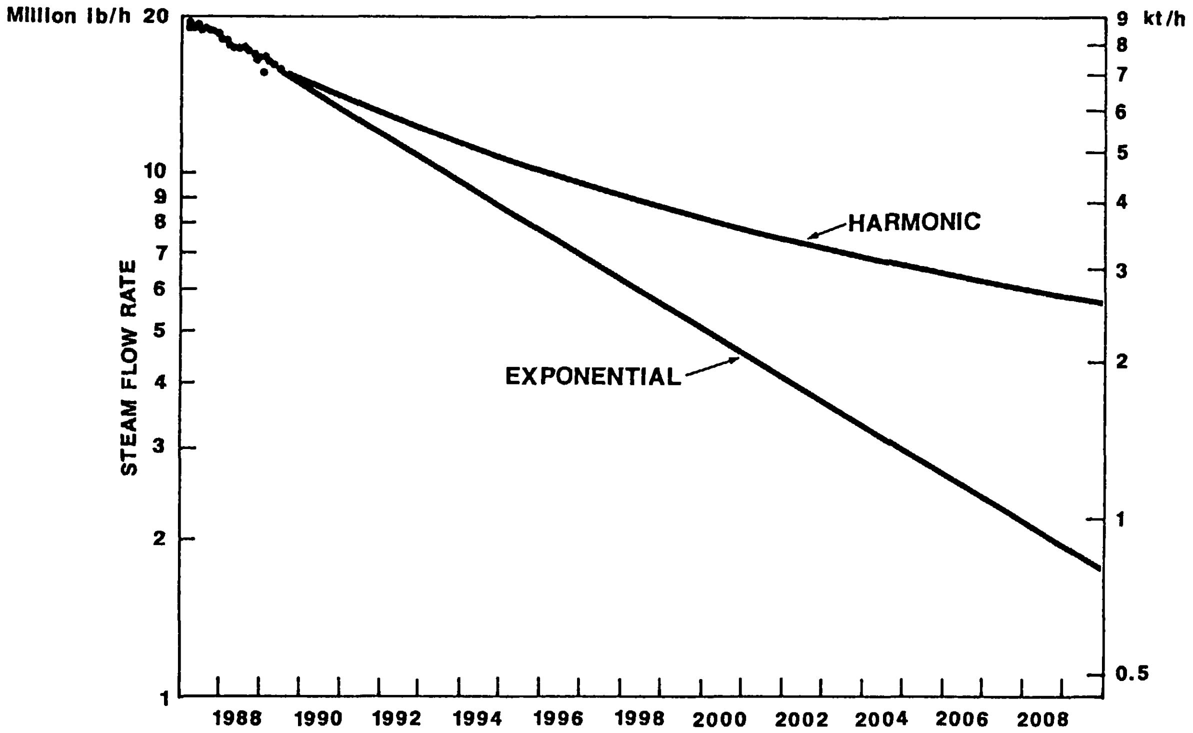

**Figure 13.** Exponential and harmonic decline forecasts, Unocal-NEC-Thermal production.

In 1980 U-N-T began installing a supervisory control system which allowed for automated ramping of throttling valves, greatly reducing the time required to cut production rates. The retrofit of Units 1 through 12 and 14 was completed in 1986. Wells supplying steam to Units 17, 18 and 20 came on line with supervisory control equipment already installed.

The supervisory control system and crossover pipeline network have greatly reduced the amount of steam vented. Figure 16 shows the percentage of total steam vented for the years 1980 through 1989. In 1980 roughly 2 percent or 1.7 Glb of produced steam was vented. This increased to approximately 4.5 percent in 1983, a year in which PG&E frequently changed power plant loads. By 1986,

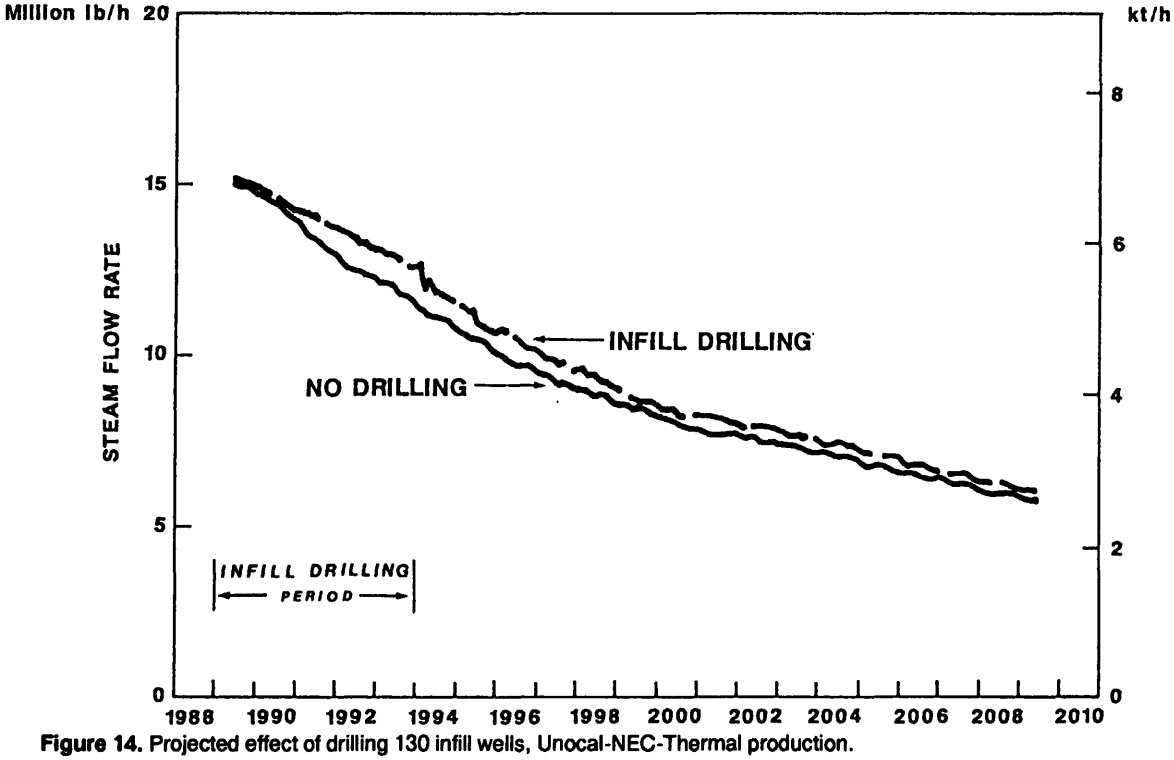

**Figure 14.** Projected effect of drilling 130 infill wells, Unocal-NEC-Thermal production.

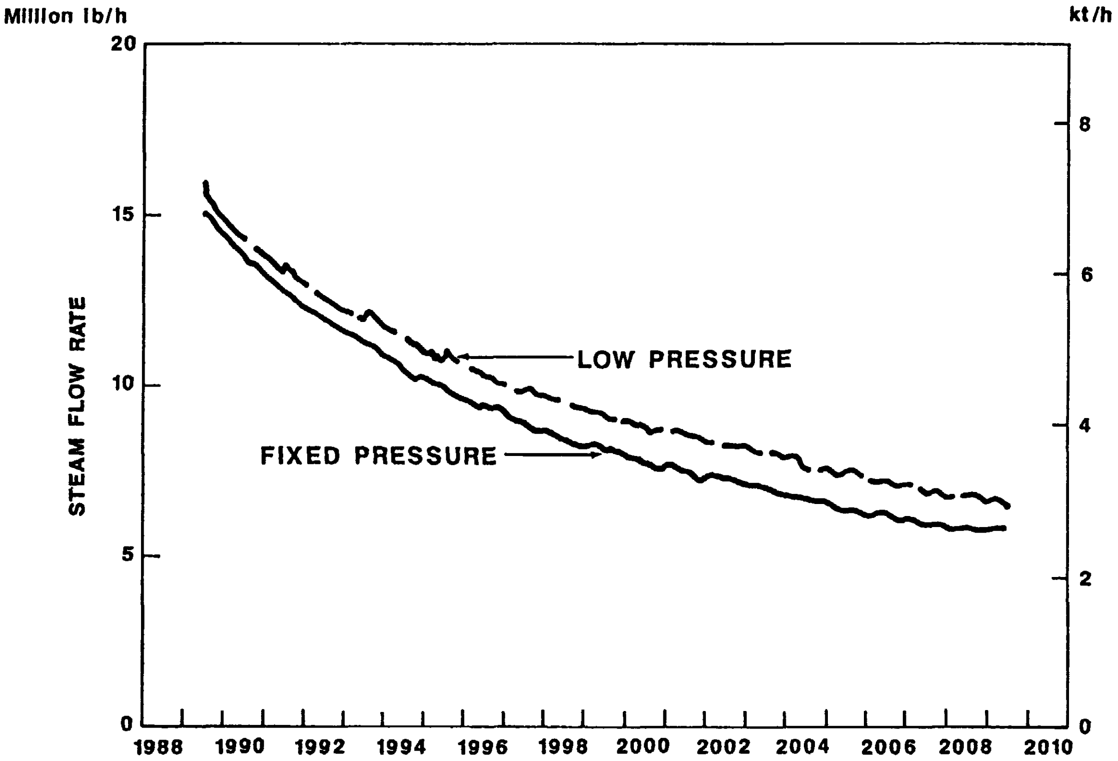

**Figure 15.** Projected effect of reducing turbine inlet pressures, Unocal-NEC-Thermal production.

when the supervisory control system was completed, the amount of vented steam dropped to less than four-tenths of a percent of the total U-N-T produced steam. During the first 6 months of 1989 the total steam vented was almost negligible at 105 klb.

The other operators at The Geysers have similarly efficient operations, leaving little room for generation improvement through reduced venting. Any major contribution from conservation will apparently require changing the basic conversion efficiency of the power plants.

### Water Injection

Fluid injection has helped replace mass withdrawals at The Geysers since disposal of steam condensate into the reservoir began in 1969. Unocal began injecting fresh water from Big Sulphur Creek in 1980. Since then, mass replacement by Unocal has averaged 28 percent of withdrawals.

Because most heat in the reservoir is initially stored in the rock rather than the water, depletion appears first as a problem of loss of working fluid. The low heat transfer rate of the rock, compared with commercial production rates, makes cooling of the rock surfaces which contact the water a factor limiting the extraction of stored heat. Injection can increase long-term heat recovery from The Geysers if it is done in such a way as to avoid quenching the rock surface temperatures and damaging short-term production.

Much effort has been expended to discern the effects of injection on production rates, but it is still not possible to quantify the gain in production that may be derived from flashed injectate. The case of a Unit 17 injector which was closely monitored from start-up is illustrative. Four neighboring wells showed increased production which was attributed to injection because isotope data indicated that these wells produced steam made up mostly of flashed condensate. The production increase amounted to less than 7 percent of the water injected, however. This was one of the U-N-T's most favorable experiences with injection. On the other hand, U-N-T has found several cases in which liquid reached producers, so it is unwise to assume that all injection recovery rates will be this high.

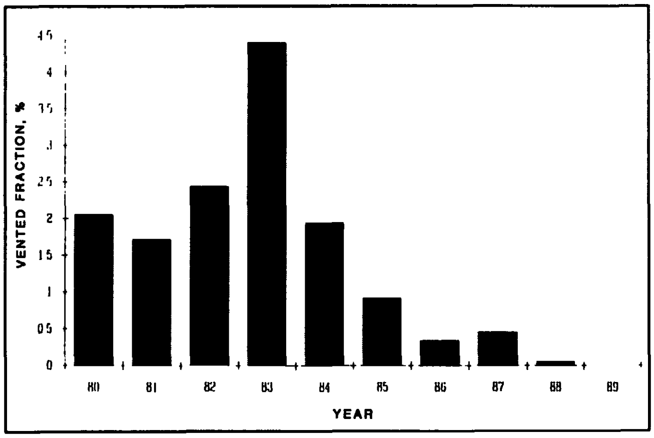

**Figure 16.** Vented steam as a fraction of production, Unocal-NEC-Thermal yearly total.

Problems in measuring the benefits from current injection practice along with the lack of a model which is well calibrated for injection make it technically challenging to predict the future effects of injection. A limiting factor in any enhanced injection program will be the availability of water. A large potential source of water would appear to be from a dam on Big Sulphur Creek, downstream of The Geysers. It is estimated that such a dam could increase the fresh water available for injection to a total of up to 50,000 acre-feet of water annually (Harding-Lawson, 1981). This is equivalent to 15,500 kph, which is almost four times U-N-T's average injection rate for 1988.

It is uncertain how recharge of this magnitude would affect the reservoir. If the same success ratio achieved at Unit 17 were applied throughout the field, a net gain in deliverability of less than 1,000 kph would result.

Unocal is developing a detailed numerical model for water injection which will be calibrated against tritium tracer data from The Geysers. This model should aid greatly in answering questions about injection. However, we believe benefits from injection will be moderate and long-term.

## CONCLUSIONS

1. Development at The Geysers accelerated in the early 1980s to more than double its prior growth rate. There is now an installed capacity of 2,043 MW.
2. Field performance peaked in 1987 and the subsequent decline is characteristic of a mature, fully developed field. The peak rates will not be achieved again from the current production areas.
3. The pressure distribution in the field indicates that the reservoir is being effectively drained by existing wells. Additional drilling may accelerate production only marginally and add little to total recovery.
4. Water injection has good potential to recover additional heat from the reservoir rock. Injection will not greatly increase deliverability in the short term, and must be done carefully to avoid damaging production.
5. Cooperation between steam field and power plant operators is necessary to improve steam usage and maximize energy recovery.

## ACKNOWLEDGEMENTS

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