Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

The Santa Rosa -- Geysers Recharge Project, Geysers Geothermal Field, California, USA

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Keywords: Geysers, enhanced geothermal, injection, pipeline, earthquakes, seismic, tracer, geochemistry generation, production, recovery, sustainment.

ABSTRACT

The Santa Rosa – Geysers Recharge Project (SRGRP) is a public-private collaboration that is bringing 42,000 m^3 per day of tertiary-treated municipal wastewater via a 65-km pipeline for injection at the 750-mw Calpine portion of the Geysers geothermal field. Since start-up in November 2003, over 11 million m^3 have been delivered and injected, as of August 31, 2004. This amounts to a 40% increase over pre-SRGRP injection rates. Reservoir modeling and experience with previous injection suggest that incremental steam production derived from the SRGRP injection will gradually increase and peak after three years at approximately 42% of the mass injection rate, yielding 85 gross mw, or 76 mw net of the 9 mw used to pump the wastewater to the injection wells. The benefit is calculated relative to the declining fieldwide production trend that would be expected without SRGRP. Early results are consistent with this projection, indicating a net benefit of approximately 16 mw after eight months of SRGRP injection (relative to the projected generation trend without SRGRP). Initial results from a tracer study showed recovery of 10% of the injected tritium slug within an eleven-week sample window. Analyses of non-condensible gases (NCG) in produced steam shows concentrations decreasing by as much as 70% in production wells in the high-NCG northwestern portion of the field. The project Environmental Impact Report (EIR) studied the possibility of increased seismicity induced by the increased injection. The study concluded that the effects on nearby residents would be “less than significant”, because the induced seismicity is almost entirely in the form of microearthquakes that are detected by seismological instruments but not felt by people. After ten months of SRGRP operation, the results have been consistent with the EIR projections. Activity in the magnitude range 1.5 to 3.0 is up 29% compared with pre-SRGRP seismicity, but there has actually been a slight decrease in the occurrence rates of earthquakes of magnitude 3.0 and greater.

1. INTRODUCTION

The Geysers geothermal field is a vapor-dominated resource located in the Mayacamas Mountains of Sonoma and Lake Counties, California (Figure 1, full-page at end of this paper). Commercial production (Figure 2) commenced in 1960, and today, after 44 years, it is still the world’s largest field, with a capacity of 890 mw from 16 Calpine-operated plants and two NCPA-operated plants. However, that represents a significant decline since the mid-1980’s when the field produced about 1600 mw. Steep declines began in the late 1980’s and were due to declining reservoir pressure. The root cause was a combination of overdevelopment, lack of natural recharge, and low artificial recharge. Barker et al (1995) calculated that without recharge only 22% to 43% of the potentially recoverable electrical energy would actually be produced (depending on reservoir porosity), leaving the remaining 78% to 57% in the reservoir as unexploited heat. Through the 1970’s the main source of injected water was plant condensate. As shown in Figure 2, that amounted to about 20% mass replacement of steam production. In the 1980’s, geothermal operators, acutely aware of the declining steam production, harnessed additional local sources of water and experimented with enhanced injection strategies. These actions, combined with economic curtailments of generation due to low power prices, resulted in greatly moderated decline rates starting in 1995.

The first significant external source of water was the Southeast Geysers Effluent Project (SEGEP), a 42-km pipeline delivering 35,000 m^3 per day of secondary-treated wastewater from Lake County to the southeastern portion of the Geysers field (Figure 1). SEGEP started operation in 1997 and quickly demonstrated success both in terms of helping Lake County meet state-mandated discharge limits, and enhancing Geysers generation (Goyal, 1999; Enedy, 1999). With SEGEP, the fieldwide mass replacement rate increased to about 55% of produced steam, and operators have continued to enjoy moderate production declines in spite of virtually uncurtailed production since 1999.

During the 1980’s, the City of Santa Rosa faced a similar requirement to upgrade its sewage treatment and discharge procedures. Geysers operators collaborated with the City, the California Energy Commission, and the US Department of Energy on the SRGRP proposal, which was eventually adopted as the best disposal option for the City. Construction began in 2001 and was essentially complete by September 2003 (Brauner and Carlson, 2003). South of the Termination Tank (Figure 1), in the portion owned and operated by the City of Santa Rosa, the main project components are: a pump station at the tertiary treatment facility in Santa Rosa; the 65-km mostly underground pipeline, 76 to 122 cm in diameter; and three pump stations that lift the water 850m from the valley floor near Healdsburg to the Termination Tank. Calpine provides the 8 mw of electrical power needed to operate the pumps, via 16 km of 21 kV line from Geysers Unit 18 to the pump stations. SRGRP facilities north of the Termination Tank are owned and operated by Calpine and include (Figure 1) 22 km of pipelines (diameter 20 to 76 cm), one pump station, two tanks, and nine injection wells. Using an additional 1 mw of power, SRGRP water is distributed, around the field, primarily to areas not previously supplied with freshwater or SEGEP water.

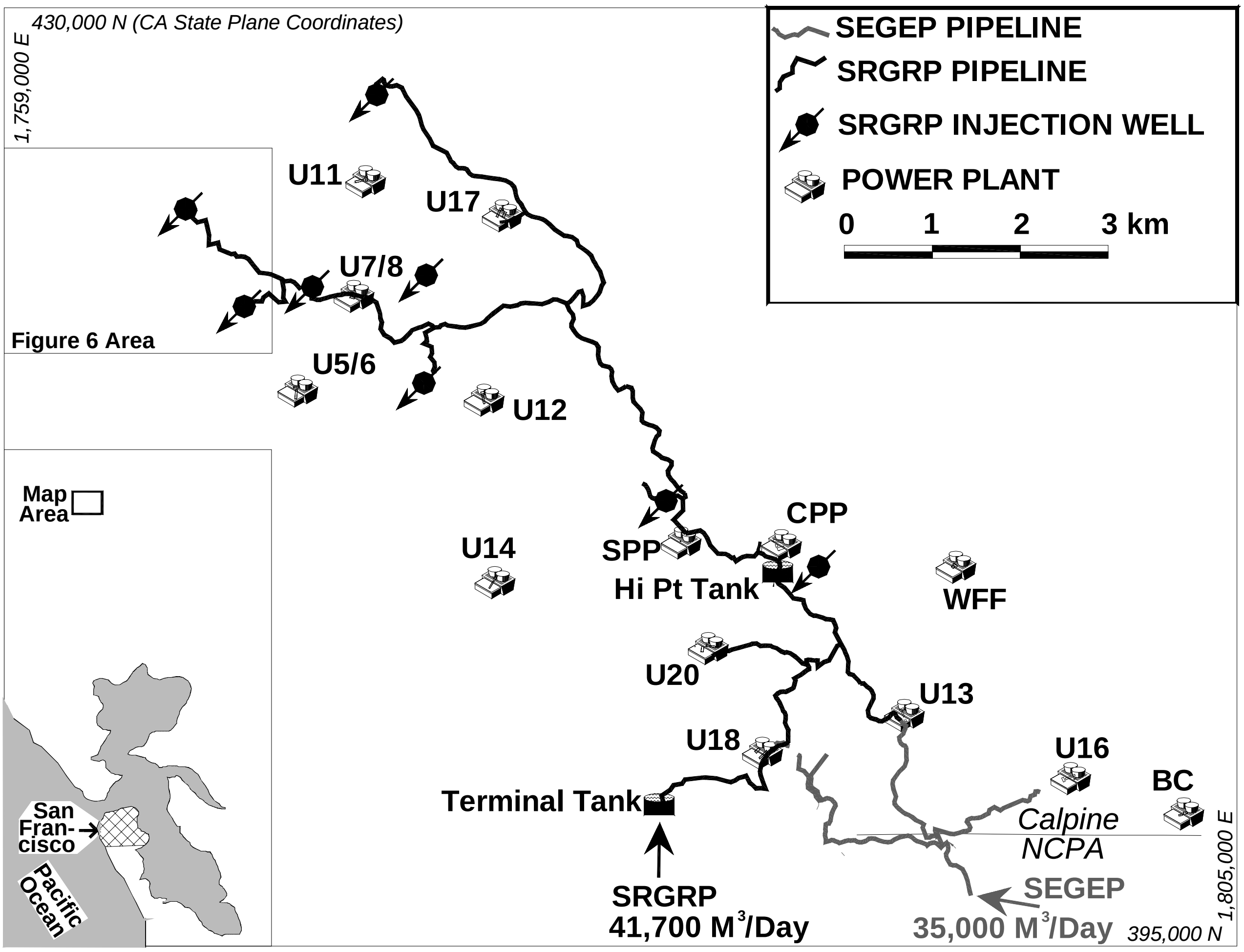

Figure 1: Geysers field map, showing Calpine plant locations and the injection distribution systems for the Southeast Geysers Effluent Project (SEGEP), operating since November 1997, and the Santa Rosa – Geysers Recharge Project (SRGRP), operating since Novermber 2003.

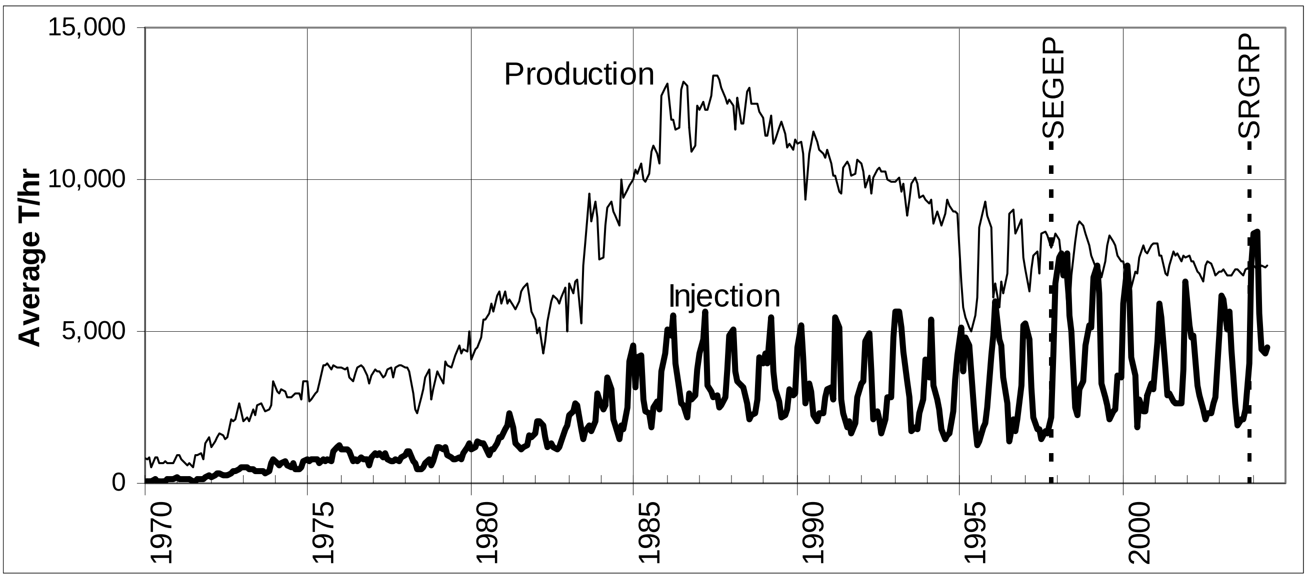

Figure 2: History of Geysers fieldwide monthly steam production and water injection, 1970 – 2004. Dashed lines indicate startup dates for the SEGEP and SRGRP injection projects.

Since starting up in November 2003, the project has operated with few problems or interruptions through August 2004. Through May, 2004, SRGRP water deliveries averaged about 42,000 m^3 per day, as anticipated. This brought the mass replacement rate up to 80%. An unusually dry spring season limited summertime deliveries to 30,000 m^3 per day, in order to allow the City to meet commitments to agricultural users. Those shortfalls were to be made up by extra deliveries during the autumn months.

2. EXPECTED BENEFITS OF SRGRP

For the geothermal operating companies, both the SEGEP and SRGRP projects entailed high capital costs and long-term commitments to accept wastewater. Therefore it was of critical importance to anticipate the project benefits, in terms of improved production and sustainability. The forecasts relied upon several different methods, each of which had its shortcomings, but collectively provided a sufficient basis to undertake these projects.

At the time that SRGRP was conceived, the expected benefits were based primarily on previous experience with Geysers injection (Gambill, 1992; Beall et al, 1992). Measuring those benefits is a difficult endeavor. One problem is that after the startup of injection in a given area, production of injection derived steam (IDS) tends to increase over a period of years. In the context of a declining resource it becomes increasingly difficult to compare actual production with what would have been produced without the injection.

Tracer studies, using injected slugs of tritium or hydrofluorocarbons, provide a measurement of the quantity and speed of IDS recovery (Beall et al, 2001; Shook, 2001). But determination of the effect of IDS production on total steam production is not obtained by tracer calculations. The effect of injection on steam production must be based on a comparison of projected production curves without injection and the actual injection-influenced production curves. The actual benefits of injection, in terms of increased production, are always less than the tracer recovery. Newly generated IDS in the steam reservoir creates a pressure cell which displaces the pre-existing steam. Consequently the IDS flows preferentially to the production wells (Barker et al, 1995).

Passive geochemical methods take advantage of natural contrasts in stable isotope and NCG compositions between IDS and normal reservoir steam (Gambill, 1992; Beall et al, 1992). These methods provide long-term data on IDS production but, in terms of evaluating the effect of IDS production on total steam production, are limited in the same manner as artificial tracers, as noted above.

In theory, numerical reservoir simulation can surmount these problems and provide a quantitative forecast of production trends with and without a given injection project. As a practical matter, this application challenges the precision of the simulation schemes (Pruess, 1995). These problems are magnified when taking the difference between two large numbers (fieldwide production with and without injection) to determine a smaller number (the injection benefit). Published Geysers simulations (Williamson, 1992; Antunez et al, 1994; Pham and Menzies, 1993) provided overall forecasts but did not address the effects of different development scenarios such as enhanced injection. Improved hardware and simulation schemes (Pruess, 1995) enable modelers to analyze and compare different development scenarios. Figure 3 shows results from an updated version of Williamson's model, showing generation forecasts with and without SRGRP. The curves diverge strongly during the first few years, predicting a maximum SRGRP benefit of about 80 mw during the third year. During subsequent years the curves slowly converge, indicating declining project benefits as boiling efficiency gradually degrades due to reservoir cooling.

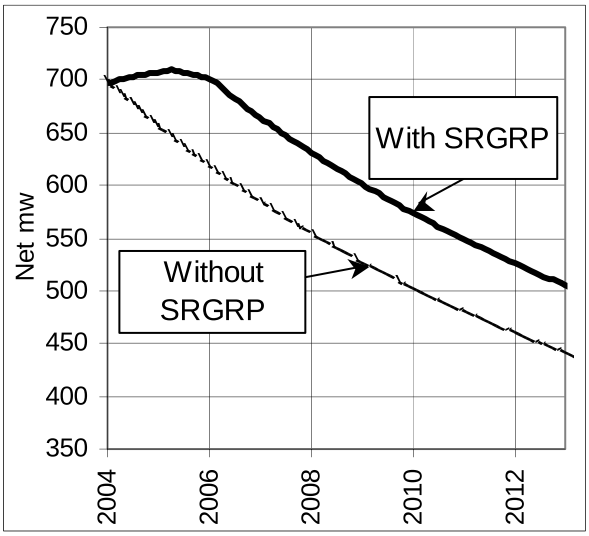

Figure 3: Geysers reservoir simulation forecast with and without SRGRP. Both curves show total net generation for the Calpine plants, assuming baseload conditions and no future plant improvements or other operational changes. Both curves are smoothed assuming harmonic decline trends. The "with SRGRP" curve assumes full time operation of SRGRP at 41,700 m^3 per day, distributed into ten injection wells. Model is an updated version of Williamson (1992).

2.1 Expected Steam Production Benefit

Barker et al (1995) studied all the above indications of injection benefit and established a simple, general model for recovery. Assuming a steady injection rate of 5,450 m^3 per day per injection well, the model predicts a steam mass flowrate benefit of 14% of the injection rate the first year, 28% the second year, and a peak benefit of 42% the third year. In subsequent years the modeled benefit slowly declines. This formulation is clearly a gross simplification, but for most forecasting purposes we still rely upon it, lacking both evidence to the contrary and a demonstrably superior model. Thus, for the SRGRP, we expect to see steam flow and generation increases as follows:

Table 1: Expected benefits from SRGRP injection, assuming 41,700 m^3 per day injected

Year	Steam flow increase (T/hr)	Generation Increase (mw) Gross[1]	Net[2]
1	243	28.3	19.3
2	485	56.5	47.5
3	729	84.8	75.8

[1] Assuming 8.6 T/mw-hr [2] Net of 9 mw pumping power

2.2 Expected Steam Usage Benefit

Turbines at the Geysers were designed and built for optimum steam usage at full capacity. Most are currently operating at about 50% of capacity and at inlet pressures lower than design, leading to sub-optimal steam usage. This has been partially mitigated by plant retirements and steam path re-engineering in the remaining plants. Increasing steam flow, or at least mitigating decline, should yield better steam usage than would be expected otherwise.

2.3 Expected NCG Benefit

Whereas most Geysers production wells have NCG concentrations of less than 0.1% by weight, in the northwest Geysers concentrations of 1% wt or higher are commonplace, leading to higher condenser backpressure and steam consumption per mw, particularly in Unit 7. There are a few wells that are so rich in NCGs that they cannot be used, and other wells that must be diverted to plants that are equipped to handle their NCG content. IDS has much lower NCG concentrations, and (as discussed above) tends to be produced preferentially, compared with normal reservoir steam. Therefore increased injection can lower NCG concentrations substantially beyond what would be expected from simple dilution (e.g. Stark and Koenig, 2001), so we expect to see significant drops in NCG in these wells, and correspondingly significant improvements in steam distribution and consumption.

3. OBSERVED BENEFITS OF SRGRP

After only ten months since startup, any measurements of SRGRP benefit must be regarded as preliminary and subject to revision. Nevertheless, we believe that the project is performing roughly as anticipated, based on the following early indications:

3.1 Steam Flow

Figure 4 shows the total steam flowrate for the Calpine Geysers plants from January 2002 through July 2004. The data shown are end-of-month "snapshot" points and are affected by a number of operational factors. Ignoring the short-term variations, the pre-SRGRP data are consistent with a harmonic decline rate of 4%. Extrapolating from this trend suggests that as of July 2004, steam flow is approximately 200 T/hr higher than it would have been without SRGRP.

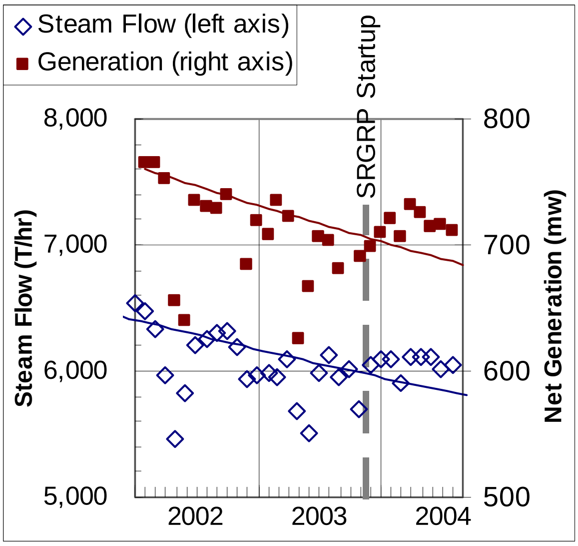

Figure 4: Monthly snapshot steam flow and net generation for Calpine Geysers plants, January 2002 – July 2004. Solid lines show harmonic decline trends interpreted for pre-SRGRP data.

3.2 Generation

Figure 4 also shows total net daily generation for the Calpine Geysers plants from January 2002 through July 2004. The generation data are similarly affected by operational factors. Extrapolating from the pre-SRGRP trend, we estimate a SRGRP benefit of approximately 24 mw as of July 2004. However, the SRGRP pumping load is 9 mw, leaving a net generation benefit of 15 mw.

3.3 Tracer Study

On July 7, 2004, 300 Ci of tritium was introduced at the SR1 pump station, from which point it was distributed to eight of the nine SRGRP injection wells (one well was shut-in due to mechanical problems). Shortly thereafter began a program of sampling at each of 13 main steam inlets where steam derived from SRGRP water might possibly appear. The results after 11 weeks of sampling are shown in Figure 5. Tracer was detected at all 13 points sampled, including six turbines – WFF, U5, U6, U14, U18 and U20 – with no SRGRP injection wells in their production well areas. Overall, approximately 10% of the injected tracer was recovered after two months, in line with experience from previous tracer experiments (e.g. Beall et al, 2001). As discussed above, this result reflects the recovery of IDS but does not mean that production has increased by 10% of the mass injected.

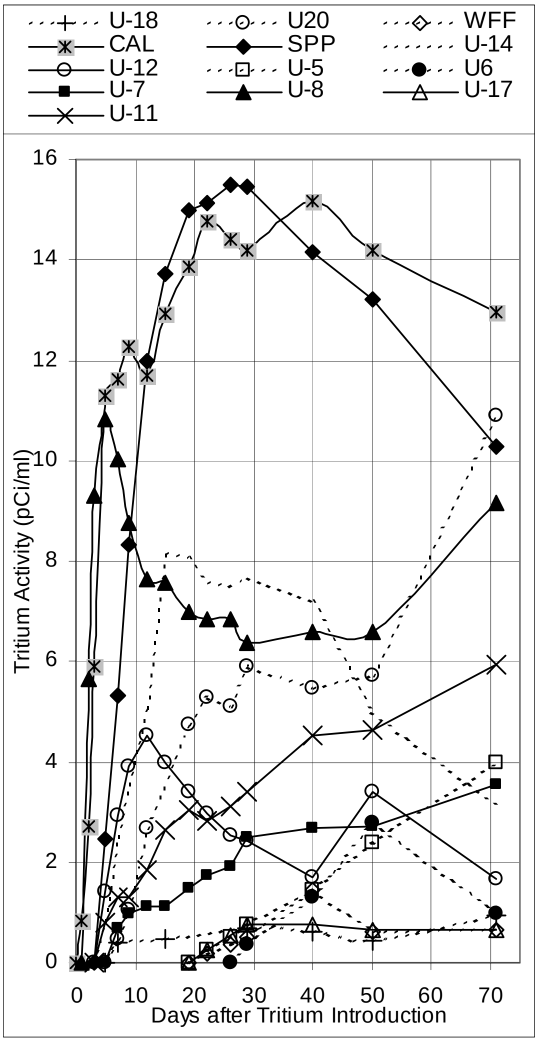

Figure 5: Tritium tracer activity during the first 11 weeks after introduction of the tracer. Samples were taken at the main steam inlets of 13 plants. Plant locations are shown in Figure 1.

The distribution of tracer returns reflects not only the movement and boiling of injected water in the reservoir, but also how the tracer was apportioned among the injection wells and how the produced steam is distributed to the plants. As sampling continues we expect to see much more of the tracer recovered in the months to come. More in-depth analysis of the results will be undertaken after a larger fraction of the tracer has been produced. At this time, the tracer results suffice to demonstrate that SRGRP water is being distributed to widespread areas of the reservoir, and is boiling and producing IDS at rates consistent with expectations.

3.4 NCG in Production Wells

At The Geysers, all production wells are sampled annually for total NCG content and constituent NCG concentrations. After the startup of SRGRP injection, extra samples were acquired and analyzed in a high-NCG area in the northwestern past of the field, where there had been little injection previously. After only five months of SRGRP injection, dramatic decreases of NCG concentrations, ranging up to 70%, have been observed in steam produced from the wells in the vicinity of the two SRGRP injectors in this area (Figure 6). Further from the SRGRP injectors, a few wells show slight increases in NCG's. This is evidently due to the IDS pushing NCG-rich reservoir steam outwards, temporarily raising NCG concentrations in the marginal wells, an effect that was predicted and modeled by Bloomfield et al (2003).

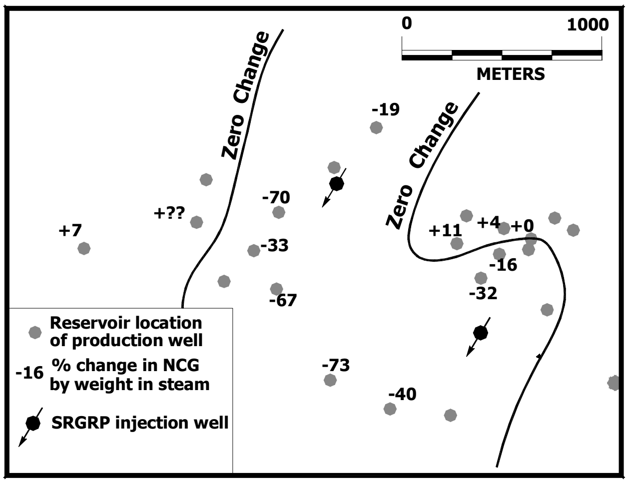

Figure 6: Percent change in NCG concentration by weight in produced steam between August 2003 (prior to SRGRP injection) and April 2004 (after five months of SRGRP injection). Map area (shown in Figure 1) includes many of the highest-NCG wells.

4. INDUCED SEISMICITY

The United States Geologic Survey (USGS) has recorded Geysers seismicity on its regional network since the 1970's. Geothermal operators have maintained a 22-station fieldwide array since 1989. Both data sets are made available to the public. The Geysers is very active seismically, with thousands of microearthquakes recorded annually fieldwide. Only a tiny percentage of these are large enough to be felt, and the largest have ranged in magnitude as high as 4.6. The Geysers lies within the seismically active boundary region between the North American and Pacific plates, so some of the earthquakes may be tectonic in origin. However, there is scientific consensus that most of the quakes are induced. Eberhart-Phillips and Oppenheimer (1984) discussed the occurrence and possible mechanisms of seismicity triggered by Geysers steam production and water injection. Stark (1992) identified microearthquake clusters around injection wells.

The Environmental Impact Report (EIR) prepared for SRGRP included a thorough study of the potential for increased seismicity induced by the increased injection (Greensfelder, 1996). The study focused on how the seismicity would affect exposure to shaking in nearby Lake County communities. Based on past examples of injection-induced seismicity at The Geysers, and a model of seismic shaking as a function of earthquake distance and magnitude, the study predicted an increase in felt earthquakes, but little or no increased exposure to potentially damaging shaking. A major reason for the "less than significant" impact is that injection-induced seismicity at The Geysers is typically dominated by microearthquakes with magnitudes lower than 3.0 (Barker et al, 1995; Beall et al, 1999; Smith et al, 2000).

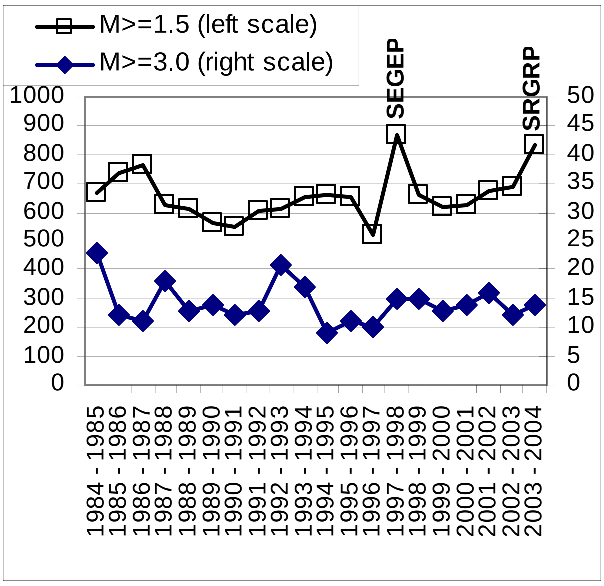

Figure 7: Fieldwide earthquake counts, 1984 – 2004, USGS data. Seasonal totals for November through August are presented, to provide a fair comparison with available data since SRGRP startup in November 2003. Startup years for SEGEP and SRGRP injection projects are shown. Both projects correlated with increases in smaller-magnitude seismicity, but no significant increase in earthquakes of magnitude 3.0 or greater.

Figure 7 shows that results to date have been consistent with this prediction. For a fair comparison, earthquake counts are plotted on a seasonal basis from November of each year (corresponding with SRGRP startup) through August of the succeeding year (the most recent month at the time this paper was submitted). The plot shows a stable overall trend for the past 20 years, but microearthquake activity of magnitudes $\geq$1.5 increased during the startups of both the SEGEP project in 1997 – 98 and the SRGRP project in 2003 – 04. Compared with the average rates for previous 19 seasons, activity in this magnitude range is up by 29% since SRGRP startup. By contrast, for earthquakes of magnitude $\geq$3.0 no such increase is evident; in fact, the total of 14 events recorded in 2003 -- 04 is slightly lower than the average of 14.2 registered during the previous 19 seasons.

5. CONCLUSIONS

After 10 months of reliable operation, the SRGRP project appears to be performing as expected. Preliminary data suggest improved trends in steam flow and generation, as well as decreases in NCG concentrations, that are attributed to the augmented injection. There has evidently been an increase in induced seismicity, but it has been restricted to low-magnitude microearthquakes, as foreseen in the EIR.

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