Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

DEVELOPMENT OF AN INJECTION AUGMENTATION PROGRAM AT THE DIXIE VALLEY, NEVADA GEOTHERMAL FIELD

Dick Benoit
Stuart Johnson
Mark Kumataka
Oxbow Power Services, Inc.
9790 Gateway Drive, Suite 220 Reno, Nevada 89511

Key Words: injection, injection strategy, augmentation, groundwater, case history, Dixie Valley geothermal field

ABSTRACT

Evaporative cooling at geothermal power plants generally reduces reservoir pressures even if all available geothermal liquids are reinjected. Controlled programs of injecting non-geothermal waters directly into reservoirs have been tested or implemented at only four fields, three of them being vapor dominated. At the liquid-dominated Dixie Valley geothermal field an unsuccessful search for a large volume source of warm, chemically desirable fluid for augmentation was conducted. After determining water treatment was uneconomical, an augmentation program utilizing cold shallow groundwater rich in Ca and Mg was implemented in mid 1997. This required extensive bench testing of various waters for scaling potential, obtaining water rights, rehabilitating an irrigation well, and constructing a polyethylene pipeline to a dedicated injector. During the first two years of this program four different injectors have been utilized and tested.

An injection augmentation rate of approximately 30 kg/sec is capable of stabilizing the Dixie Valley reservoir pressure. Higher rates result in increasing reservoir pressure. This program has not resulted in decreased injectivity of the dedicated injectors. One injection well showed a greatly increased injectivity. Monitoring of production chemistry has demonstrated that most, if not all, of the calcium and magnesium injected with the shallow groundwater is precipitating between the injection and production wells. Monitoring of the shallow groundwater aquifer has demonstrated that this aquifer is very large and is capable of supplying water indefinitely. Small drawdowns of this aquifer indicate subsidence is unlikely to be a problem.

1. INTRODUCTION

Evaporative cooling of geothermal power plants results in a fluid loss on the order of 100-120 kg/sec for a 50 to 60 MW geothermal power plant. When this withdrawal is not closely balanced by hot natural recharge to the reservoir a need for long-term injection augmentation arises to mitigate reservoir pressure decline. Developing an augmentation program requires consideration of many variables; injection strategy, production and injection chemistry, nongeothermal water availability and acquisition, possible water treatment and waste disposal, potential reservoir cooling, tracer testing, and improved temperature and pressure monitoring.

Injection augmentation crosses the line from passive reservoir management, where one simply accepts what the reservoir will naturally produce in its current condition, to actively stimulating the reservoir to produce more in the short term and hopefully also more in the long term.

2. PREVIOUS EXPERIENCE

To date, augmentation programs with nongeothermal water have been implemented or tested at only four reservoirs, The Geysers, Lardarello, Olkaria, and Dixie Valley, Nevada. Implementation of large scale injection augmentation systems at many geothermal fields will be a difficult and expensive process as many geothermal fields are located either in dry and/or mountainous terrains with relatively difficult access to large quantities of good quality water.

2.1 The Geysers

The Geysers reservoir is located in steep mountains with a highly seasonal rainfall pattern. Summer precipitation is virtually nonexistent. Some winters have very little rainfall while others have produced repeated flooding. There are no significant local sources of groundwater. Mass withdrawal has reduced the average reservoir pressure from over 34 bars to less than 13 bars. This decline has resulted in a 1989 installed capacity base of 1967 MW being able to produce only 1,100 MW (Atkinson, 1998). Wells which initially produced over 32 kg/sec of steam now produce less than 4 kg/sec at greatly reduced wellhead pressures. Turbine inlet pressures have been reduced to as low as 4 bars in most of the operating plants at substantial capital cost.

Condensate injection became a regulatory requirement in 1969, a decade after production commenced. Prior to 1969 condensate was discharged into streams. Supplemental fresh water injection has been used for augmented heat recovery in pressure depleted areas since 1980 when Unocal built the first of three seasonal pump stations on Big Sulphur Creek (Barker, and Pingol, 1997). These activities, along with numerous other smaller scale surface water catchment projects, boosted the yearly mass replacement fraction from less than 0.1 to about 0.3. In 1995 and 1996 the mass replacement fraction exceeded 0.57 due to extensive production curtailments.

In September 1997 the greatest experiment yet conducted in injection augmentation commenced with the startup of the $45 million, 46.7 km long, 50.8 cm diameter, Southeast Geysers Effluent Pipeline (SEGEP) which pumps about 400 l/sec of treated wastewater and lake water to numerous individual injection wells supporting six power plants with 714 MW of installed capacity (Dellinger, 1997). As of July 1999 SEGEP had delivered over 17 x 10^9 kilograms of fluid to The Geysers. During the early months of 1998 SEGEP actually increased the mass replacement fraction above 1.0 for the six plant area served by the pipeline.

An early indication of the success of SEGEP is the fact that the six power plants in early 1999 were generating an additional 9 megawatts of electricity compared to early 1998. These plant outputs were declining 25 to 30 MW/yr prior to the startup of the pipeline project (Steve Enedy, comments at 1999 Dept. of Energy Program Review). Therefore, these power plants were actually generating an additional 34 to 39 megawatts from SEGEP-derived steam in early 1999. An added benefit has been an 18% decline in the H_2S content of the produced steam.

A larger (61-76 cm) pipeline, known as the Santa Rosa wastewater disposal pipeline, is now in the advanced planning stages to bring treated wastewater to the western part of The Geysers.

2.2 Lardarello-Valle Secolo

The climate and experience at the dry steam Valle-Secolo field closely resembles that at The Geysers. The first injection experiments with condensate began in 1979. The success of this simple injection in increasing reservoir pressure, plant outputs, and lowering noncondensable gas contents led to the start of artificial field recharge with injection of 65-75 l/s of condensate pumped from remote geothermal plants and an aquifer bordering the Larderello field in 1993 (Capetti et al., 1995).

2.3 Olkaria

The Olkaria, Kenya geothermal field is located in the bottom of the east African rift valley just south of Lake Naivasha. Like The Geysers, the climate is generally dry with a rainy season.

Fifteen years of production has resulted in a steady decline in the total mass output. This has resulted in the implementation of both hot and cold injection programs in the center of the field (Simiyu and Malin, 2000). Unfortunately, nothing has been published on the Olkaria injection augmentation efforts. Injection augmentation efforts began in 1996 utilizing water from Lake Naivasha which has been pumped a few kilometers to the vicinity of the Olkaria I power plant (Simiyu, pers comm 1999).

3. DIXIE VALLEY EXPERIENCE

From 1985 through 1998 reservoir testing and routine operations at the 62 MW (gross) dual flash power plant have resulted in the loss of 69.5 x 10^9 kg of fluid from the Dixie Valley geothermal reservoir. This represents approximately 31% of the total fluid produced and caused a substantial decline in the reservoir pressure which in turn reduced the production well flow rates. Over the first 9 years of the project, the reaction to this decline was to drill five make-up production wells. As the net megawatt output of the makeup wells progressively decreased over time, With the lack of success in finding the ideal source, the Goerenger well, an idle 79 m deep irrigation well capable of it became apparent that this strategy would soon be uneconomic. A lower cost strategy was to utilize an excess of injection capacity by injection of nongeothermal fluids to reduce or even reverse the rate of reservoir pressure decline. As reservoir pressures decline injection capacity should increase in most geothermal fields. This increased injection capacity should be available for augmentation experiments within a few years of commencement of operations. An injection augmentation program was first conceptualized at Dixie Valley in late 1995 and was inaugurated on a test basis in mid 1997.

3.1 Water Source and Requirements

The Dixie Valley power plant has a 7 cell counterflow cooling tower. During the first several years of operation the cooling tower and, in hindsight, less than optimal spent fluids handling resulted in net mass removal from the reservoir of over 4.5 x 10^9 kg/year. Improvements to the cooling tower and a change in plant operations reduced this loss to about 3 x 10^9 kg/yr. However, even at this reduced rate periodic reservoir pressure measurements still indicated an overall reservoir pressure decline of about 2.7 bars/yr. To fully compensate for the cooling tower losses would require on the order of 100 kg/sec (3 x 10^9 kg/yr) of augmentation. This amount would be reduced by the unknown amount of hot natural recharge into the reservoir.

Maintaining up to 100 kg/sec throughout the year requires a very large water source, especially considering that Dixie Valley may have the least rainfall of anyplace in the United States, 7 to 10 cm/yr and is located far from any possible wastewater sources. However, Dixie Valley is the lowest of an interconnected system of seven valleys with an area of 6164 km^2. Groundwater can be found as shallow 3-6 meters below the surface at the plant site. The estimated groundwater recharge to Dixie Valley is huge at 28.4 x 10^9 l/yr. Lastly the valley had recently been depopulated as it was incorporated into a military supersonic warfare training area. This meant the previous agricultural water use in the area (alfalfa) had ceased and water rights were available.

The ideal augmentation fluid is chemically compatible with the reservoir fluid and just below the boiling point in temperature. Temperatures above boiling would further minimize potential cooling of the reservoir but would also require much more expensive pumps and surface facilities to deal with higher pressures and possible two phase conditions and scaling. An extensive field search was conducted for such a fluid. All existing wells in the area were evaluated and ultimately four exploratory water wells were drilled up to depths of 548 m to try to locate a large volume of water with temperatures near 100 ^{0}C and low Ca and Mg contents. Only very limited volumes of such water were found. Apparently the warming of the shallow groundwater with depth in the alluvium of Dixie Valley results in precipitation of the Ca and Mg which drastically reduces the formation's porosity and permeability. Two wells encountered steam in a previously unknown shallow outflow plume from the reservoir. One of these wells, 27-32, has since been placed in service as a test injection well for augmentation water (Figure 1).

pumping 125 l/sec of 25 ^{0}C water, conveniently located a short distance from the power plant, was evaluated as a water source

(Figure 1). A 9 hour step-drawdown aquifer pumping test at rates of 63 to 126 l/sec gave specific capacities of 11.7 l/sec/m to 7.7 l/sec/m, confirming high productivity. After pump testing, the well was caliper logged and the 40.64 cm casing was determined to be in poor condition. A new 30.5 cm partially slotted liner was installed and a new electrical powered pump was installed in the well. The well has sustained pumping at rates as high as 133 l/sec.

3.2 Fluid Chemistry

The geothermal fluid produces calcium carbonate scale when boiled and currently has exceptionally low preflash calcium contents of about 6 mg/l. The 25 ^{0}C augmentation fluid contains approximately 50 mg/l of Ca and 50 mg/l of Mg. Concerns about creation of calcium carbonate and magnesium silicates upon mixing of this water with 110 ^{0}C flashed brine led to extensive field tests which confirmed scaling would be a problem. These tests demonstrated that it was possible to mix the 40 ^{0}C cooling tower overflow (steam condensate) with the augmentation fluid without creating scales.

The field testing confirmed that a dedicated injection well would be required for the augmentation water. This required the construction of a new low temperature pipeline. Due to the experimental nature of the augmentation program, a low cost, uninsulated high density 25.4 cm polyethylene pipe rated to 7 bars was selected. It was simply laid on the ground to supply the Section 18 injectors at the south end of the field. This line has operated through one winter with no freezing problems. A 30.5 cm line was constructed in mid 1999 to deliver fluid to the injectors in Section 5 (Figure 1).

Recommendations were requested from water treatment companies for possible removal of calcium and magnesium from the ground water. As the system is Aonce through≅, anticipated treatment costs turned out to be unacceptably high. Also, permitting disposal of a concentrated waste stream resulting from the treatment appeared to be an expensive and time consuming effort. Ultimately, it was decided that untreated augmentation water would be used on a test basis in one more or less expendable injection well to determine if treatment really was necessary.

3.3 Injection Capacity

All eight injection wells were step-rate tested to determine their individual and combined capacity to accept additional fluid. Dedicating one injector to cold water injection requires that the remaining seven wells be able to accept all the hot injectate and cooling tower overflow. This testing showed that multiple injection wells had capacity to implement the program. However, existing pipeline and/or pump limitations were identified which meant certain individual wells or combinations of wells could not be dedicated solely to injection augmentation fluid. Tracer test results provided additional guidance in selecting the most desirable wells for cold water injection within the constraints of the surface facilities.

4. MONITORING

Monitoring systems should be an important part of any injection augmentation program. At Dixie Valley the near-term issues of concern are ground subsidence in the vicinity of the groundwater well, plugging of the dedicated injection wells, depletion of the shallow groundwater resource, and most importantly documentation of changes in pressure trends in the geothermal reservoir. Longer-term issues of concern are potential cooling of the geothermal reservoir and increased scaling potential of production wells that recycle the augmentation fluid. Tracer testing is very important and can be viewed as a discontinuous form of monitoring the flow paths of augmentation fluid.

4.1 Subsidence

The groundwater is pumped from unconsolidated alluvium immediately adjacent to the power plant. Therefore, a network of benchmarks capable of accurately determining the onset of any subsidence was installed prior to commencement of pumping. One and a half years after augmentation commenced a repeat survey has shown little or no subsidence in the immediate vicinity of the well and power plant.

A network of microgravity stations was installed in June 1999 in part to more completely monitor the shallow groundwater system and the movement of injectate (Allis, et al. 1999).

4.2 Shallow Water Levels

Two small diameter wells were drilled to similar depths as the augmentation well to monitor impacts of the pumping on the shallow groundwater aquifer. A third preexisting well is also utilized. All are about 300 m away from the injection augmentation well in orthogonal directions. Water levels are measured every few weeks and show reversible drawdowns of 3 m at pumping rates up to 60 l/sec, and approximately 6 meters at 133 l/sec indicating a large shallow groundwater resource is available. This small drawdown should also serve to limit any land subsidence.

4.3 Chemical

Samples of the augmentation fluid are collected quarterly for a standard water analysis, as are brine samples from the production wells. Calcium contents of the production wells are measured weekly to monitor the carbonate scale inhibition program and also now to monitor in the short term for any anomalous trends of increasing calcium. Tracer tests have shown which production wells produce the most augmentation fluid. Close inspection of calcium trends in these production wells shows no abnormal increase in calcium contents (above long-term background trends). Therefore, it is concluded that the calcium contained in the augmentation fluid is being precipitated in the fractures between the injection and production wells. There has been no measurable increase in magnesium content in any of the production wells.

The groundwater has about half the chloride content of the production wells, therefore a recent reduction in chloride contents in some production wells is regarded as evidence that the augmentation fluid is returning to the production wells in quantities large enough to impact the overall chemistry of the geothermal fluid.

4.4 Pressure

Reservoir pressure monitoring efforts have been increased throughout the reservoir to monitor the effectiveness of the augmentation program. Downhole pressure bombs were installed on 3 hangdown strings to give continuous downhole flowing pressures (Benoit et al., 1999). Also standard pressure bombs have been installed in two idle production wells.

4.5 Injection Well

The injection well flow rates and operating wellhead pressures are monitored daily for evidence of possible reduced permeability due to scale formation around the wellbore. So far there has been no evidence of this. One well, 65-18, actually had a doubling of injectivity when used for cold water injection.

4.6 Temperature

At some time, fluid-entry temperatures in all geothermal reservoirs which recycle injectate can be expected to start to decline. At Dixie Valley it requires twice as many calories to heat the augmentation fluid to reservoir temperatures as it does to reheat the spent brine. This places a larger heat mining load on the reservoir. As geothermal fields have a very large mass it generally takes considerable time for cooling to become measurable and similarly it also takes considerable time to stop an established cooling trend. A program of measuring temperatures with precisely calibrated conventional logging tools in selected production wells has been implemented. Also experimental thermocouples have been installed below the flash point in three wells to provide continuous downhole temperature monitoring (Benoit et al., 1999).

4.7 Tracer Tests

When fluid streams with differing temperatures are injected into a geothermal field it is intuitively obvious that the coolest fluid should be injected into an injector which it will provide the longest possible time to reheat prior to reaching the production wells. This can be most definitively recognized through tracer testing. In the past three years six tracer tests have been completed at Dixie Valley to map flow paths (Rose et al., 1998, 2000). Two other tests are in progress. Tracer tests have been conducted in all four injectors which have received augmentation fluid. Results of these tests have led to changes in the choice of injector(s) for the augmentation fluid as return times from more injectors become known.

5. INJECTION AUGMENTATION PERFORMANCE RESULTS

Injection augmentation commenced into the relatively shallow SWL-1 well (Benoit, 1992) in July 1997. A downhole seismometer in the nearest well (32-18) did not record any seismic events that might be related to thermal cracking of rocks during the first 2 2 days of cold water injection. Fluorescein tracer was injected into SWL-1 three days later (Rose et al., 1998) and first reappeared in production wells 25 days later. The injectivity of the SWL-1 well increased slightly as expected due to the density difference between 25 ^{0}C and 110 ^{0}C water. Between July 12 and October 20, 1997 a total of 4.0 x 10^{8} liters of augmentation water was pumped into the reservoir at an average rate of 45 l/sec. Quarterly pressure monitoring indicated this boosted the reservoir pressure in the south part of the field by about two bars and resulted in a gradual megawatt output increase of 1 to 2 MW over a two month period. As the Dixie Valley reservoir is a single phase liquid, the augmentation program had an immediate impact on reservoir pressure and megawatt output. This contrasts with the vapor dominated The Geysers field where it takes a couple of months to confirm increased outputs due to injection augmentation (Joe Beall, pers. comm.). The amount of fluid required to stabilize reservoir pressure was far below the 100 l/sec cooling tower loss. This indicated that the natural recharge into the geothermal reservoir is greater than 55 l/sec.

There was no apparent reduction in the injectivity of well SWL-1 and there was no measurable increase in calcium content in the production wells with the most fluorescein returning from well SWL-1. The injection augmentation system was temporarily shut down on October 20, 1997 so that the augmentation fluid could be diverted to the 65-18 injection well which had recently been discovered to have a longer tracer first return time of 75 - 79 days (Rose et al., 2000).

Injection augmentation resumed on March 27, 1998 into well 65-18. One unexpected benefit of this was that over a period of a few weeks the injectivity of well 65-18 doubled. Unlike the SWL-1 openhole completion, well 65-18 has a slotted liner in place through the injection zone. This completion prohibits the running of logs to try to determine the details of the injectivity improvement.

On June 29, 1999 the augmentation fluid was shifted to well 45-5 for two reasons. First, this well had a longer tracer first return time of over 90 days (Rose et al., 1998) as compared to the 70 – 79 days for well 65-18. Second, injection into well 45-5 allowed reduced injection into the Section 18 portion of the field with relatively rapid tracer returns. Injection into well 45-5 at rates up to 125 l/sec has shown overall reservoir pressure increases of up to 6 kPa/day in the idle 45-33 well and up to 19 kPa/day in the active 74-7 production well.

Once a dedicated polyethylene injection line was in place to well 45-5 it was easily extended to a recently discovered shallow injection area. Injection testing into the shallow 27-32 well has proven to be successful with the well accepting up to 90 l/sec and providing reservoir pressure support. In fact, the injection augmentation system allowed this new injection area to be tested and evaluated with cold water at a small fraction of the cost (and risk) that hot injection would have required.

6. CONCLUSIONS

The Dixie Valley geothermal power plant is fortuitously located above a shallow, large, and unutilized groundwater resource. This allowed the startup of an injection augmentation program 1 2 years after it was first conceptualized and at substantially less than half the $ 2 million cost of drilling a production well or a new deep injection well.

An extensive search for large volumes of high quality (low Ca and Mg) augmentation water with a temperature near 100 ^{0}C was unsuccessful. Field testing demonstrated that the shallow groundwater could not be mixed with the geothermal fluid without precipitating unacceptably large quantities of scale, but it could be mixed with the cooling tower overflow. Injection of untreated shallow groundwater relatively rich in calcium and magnesium into dedicated injectors has not led to reduced injectivity. Chemical monitoring demonstrates that the Ca and Mg must be precipitating in the fractures between injection and production wells.

With injection augmentation the reservoir pressure is now controlled by field operations. About 30 l/sec is all that is required to maintain the reservoir pressure. This means that the natural recharge to the reservoir is on the order of 70 l/sec, given a 100 l/sec loss through the cooling tower. Injection augmentation rates above 30 l/sec result in immediate increases in reservoir pressure, production well flow rates, and megawatt output.

Subsidence surveys indicate no measurable subsidence to date. Augmentation with cold water can provide a low cost opportunity for testing new injection wells or injection areas.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Oxbow Power Services Inc. for permission and support in preparing this paper and in providing the opportunity to work on such an interesting project.

REFERENCES

Allis, R.G., Johnson, S., Nash, G.D., and Benoit, D., 1999, A model for the shallow thermal regime at Dixie Valley Geothermal Field, *Geothermal Resources Council Transactions,* Vol. 23, pp. 493-498.

Atkinson, P., 1998 A continuing evolution, *Geothermal Resources Council Bulletin,* Vol. 27, No. 6, pp. 163-166.

Barker, B.J., and Pingol, A.S., 1997, Geysers reservoir performance - an update, *Proceedings, Twenty-Second Workshop on Geothermal Reservoir Engineering,* Stanford University, Stanford, California, pp. 55-62.

Benoit, D., 1992, A case history of injection through 1991 at Dixie Valley, Nevada, *Geothermal Resources Council Transactions,* Vol. 16, pp. 611-620.

Benoit, D., Norman, R., Smithpeter, C., Thompson, S., and Blackwell, D., 1999, Design, fabrication, installation, and testing of an advanced wellbore/reservoir monitoring system at the Dixie Valley, Nevada geothermal field., *Proceedings, Twenty-Fourth Workshop on Geothermal Reservoir Engineering,* Stanford University, Stanford, California, pp. 319-324.

Capetti, G., Parisi, L., Ridolfi, A., and Stefani, G., 1995, Fifteen years of reinjection in the Larderello-Valle Secolo area: analysis of the production data, *Proceedings of World Geothermal Congress, 1995,* Vol 3, pp. 1997-2000.

Dellinger, M., 1997, The Lake County Geysers effluent pipeline & injection project, *Geothermal Resources Council Bulletin,* Vol. 26, No. 9, pp. 218-223.

Rose, P.E., Benoit, W.R., and Adams, M.C., 1998, Tracer testing at Dixie Valley, Nevada, using pyrene tetrasulfonate, amino G, and fluorescein, *Geothermal Resources Council Transactions,* Vol. 22, pp. 583-587.

Rose, P. E., Benoit, D., Lee, S. G., Tandia, B., and Kilbourn, P., 2000, Testing the naphthalene sulfonates as geothermal tracers: field studies at Dixie Valley, Ohaaki, and Awibengkok, *Proceedings, Twenty-Fifth Workshop on Geothermal Reservoir Engineering,* Stanford University, Stanford, California

Simiyu, S.M., and Malin, P.E., 2000, Micro-seismic applications to geothermal exploration and reservoir monitoring: Olkaria, Kenya and Casa Diable, USA, *Proceedings of World Geothermal Congress, 2000.*

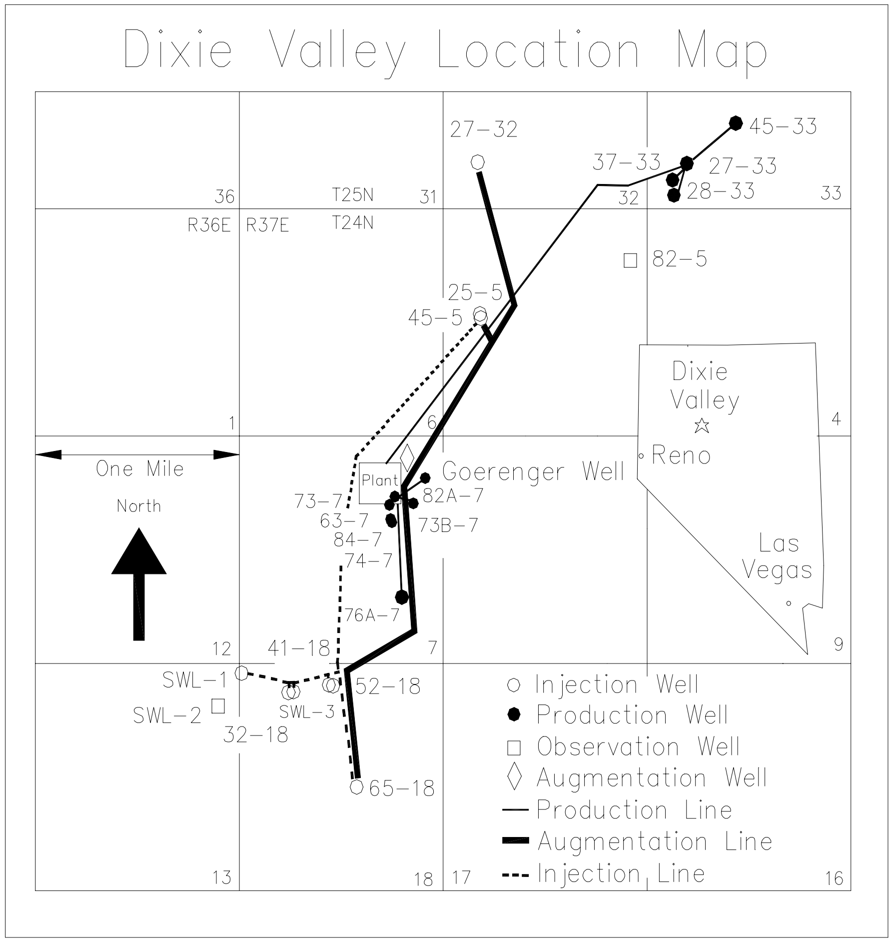

Figure 1 - Dixie Valley Location Map