A Case History of the Dixie Valley Geothermal Field, 1963–2014

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Keywords

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ABSTRACT

The 56 MW net Dixie Valley geothermal power project has now operated at more or less full output for 27 years. This success was primarily due to three companies with very different character and strengths being involved during the development phase between 1974 and 1988. The wide spacing of exploration wells early in the project history greatly reduced dry hole or step-out risk during the field development phase. The large horizontal and vertical separation between producers and injectors has been successful in allowing modest production fluid temperature declines. The project evolved over its initial 9 years of production from a 49.8 MW net project with a projected long-term production well makeup schedule to a 56 MW net project supported by a cold groundwater injection augmentation program that stabilized the reservoir pressure and eliminated the need for future makeup production wells. The timing of this fairly intense and costly activity coincided with a period of high electricity prices in the Standard Offer #4 contract that allowed significant ongoing field development expenditures. Since 2000 project improvements have shifted from the wellfield to power plant modifications. The turbine was modified to enable the power plant to operate at lower pressures and a 5 MW net binary plant was installed on the injection line.

Introduction

The Dixie Valley geothermal field, located in west-central Nevada, has been the most thoroughly studied Basin and Range geothermal field in the past 2 - 3 decades (Figure 1). The 62 MW gross project was the largest dual flash geothermal power plant in the world during its first few years of operations and remains the largest single turbine geothermal power plant in the Basin and Range Province since it began operating in July 1988. Many technical papers have been written on the resource (Blackwell et al., 2007, SMU, 2014) and scientific work on Dixie Valley geothermal resources is ongoing (Peiffer et al., 2014). No case history of the project has been published to document the overall field development history and preserve some of the stories and lessons learned along the way. The most recent, and by far the most extensive, publication on the Dixie Valley geology, geophysics and geochemistry (SMU, 2014) contains the most comprehensive bibliography.

Early Exploration and Activities (1963 – 1974)

The earliest documented recognition of geothermal power production potential in Dixie Valley occurred in 1963 during a mercury exploration program by the Cordero Mining Company (Berry, 1963). Several thermal springs are located within Dixie Valley but none of these springs provided classical chemical geothermometry close to temperatures required for a flash power plant (Peiffer et al., 2014). Along the Stillwater Mountains range front three active fumarole areas are present. The Senator Fumarole associated with the operating field was so weak prior to the field development that it was difficult to locate on a hot summer day. A discouraging factor for development was the remoteness of Dixie Valley, which had no power transmission lines and a primitive road network that was often inaccessible in winter or following flooding. There were only tiny parcels of privately held land within Dixie Valley surrounded by a vast acreage of Federal land managed by the Bureau of Land Management. Until the Geothermal Steam Act of 1970 was implemented in 1974 there was no mechanism to obtain the right to produce geothermal fluids from the Federal lands.

Dixie Valley was not recognized as a first rate geothermal prospect in the early 1970s (Garside and Shilling, 1979). None of the original 13 Known Geothermal Resource Areas (KGRAs) in Nevada defined by the U. S. Geological Survey (Godwin, et al., 1971) were located within Dixie Valley. Geothermal leasing of non KGRA lands commenced in 1974. Overlapping lease applications in the calendar month when applications were first accepted resulted in the creation of a new Dixie Valley KGRA, requiring competitive bidding for these Federal lands. The first competitive lease sale occurred in May 1976. Companies such as Sunoco Energy Development Company (SUNEDCO), Republic Geothermal Company, Southland Royalty Company, the Hughes-Clay-Knowles Group, Dow Chemical Company and the Millican Oil Company either performed exploration and/or obtained Federal geothermal leases in the mid 1970s. Chevron Oil Company and SUNEDCO leased the ½ square mile of private land, the Lamb Ranch, overlying part of the Dixie Valley geothermal field. Dixie Valley was the most competitively leased geothermal area in Nevada from the mid 1970s to the mid 1980s but none of the more dominant active developers in Nevada such as Unocal, Phillips, or Chevron made any significant exploratory commitment to Dixie Valley.

SUNEDCO Exploration (1974 – 1985)

Between 1974 and 1978 preliminary exploration activities were undertaken by several companies (SMU, 2014). Most importantly, SUNEDCO drilled 45 temperature-gradient holes up to 1500 feet deep and conducted a resistivity survey, a seismic emission study, a ground noise survey, two magnetotelluric surveys, a hydrology study, and a surface geology survey (Parchman and Knox, 1981a and 1981b). However, none of these surveys, other than the temperature data, have made it into the public literature, nor do they appear to have survived in unpublished form. The only public synthesis of the SUNEDCO effort by SUNEDCO personnel (Parchman and Knox, 1981b) present previously public regional geologic information and vaguely describe an elongated thermal anomaly with temperature gradients > 5.5 ^{o}C/100 ft that closely follows the curvature of the Stillwater Range. Other unspecified geophysical data were mentioned as anomalies tending to overlap the thermal anomaly in the vicinity of the private Lamb or Boyer (a prior name for the Lamb ranch) ranch lands but these interpretations have only briefly been elaborated on by Waibel (1987). There were a large amount of seismic reflection data in Dixie Valley, largely shot by AMOCO, that were also utilized to target specific structures. Initial exploration efforts at Dixie Valley were more heavily dependent upon seismic reflection data than at any other Basin and Range geothermal prospect. It is unfortunate that no reports appear to survive documenting this initial exploration effort.

In November 1978 SUNEDCO completed the #1 S. W. Lamb well (now known as SWL-1) as a geothermal producer at a depth of 7255 feet in Miocene basaltic lava flows (Figure 1). Extensive permeability was encountered at 7191 feet and temperatures near 430 ^{o}F were measured but remained a closely guarded secret for years. The SWL-1 well is located within the southern part of the 0.5 square miles of private land overlying the geothermal field. It was sited to intersect steeply dipping seismic line structure(s) interpreted as rhombograben margins (Waibel, 1987) that also happened to be close to or beneath the private acreage. SUNEDCO made no secret of their desire to avoid the Federal permitting process for drilling deep wells. The SWL-1 well is recognized as the discovery well and set off frenzy among the other leaseholders in the area with rumors of it producing dry steam. When this rumor was obviously disproven during extensive flow testing, visible to anyone who bothered to make the drive out to the site, the next erroneous rumor had dry steam beneath the liquid zone. Flow testing of the SWL-1 well represented the first time that fluid from the reservoir could be analyzed

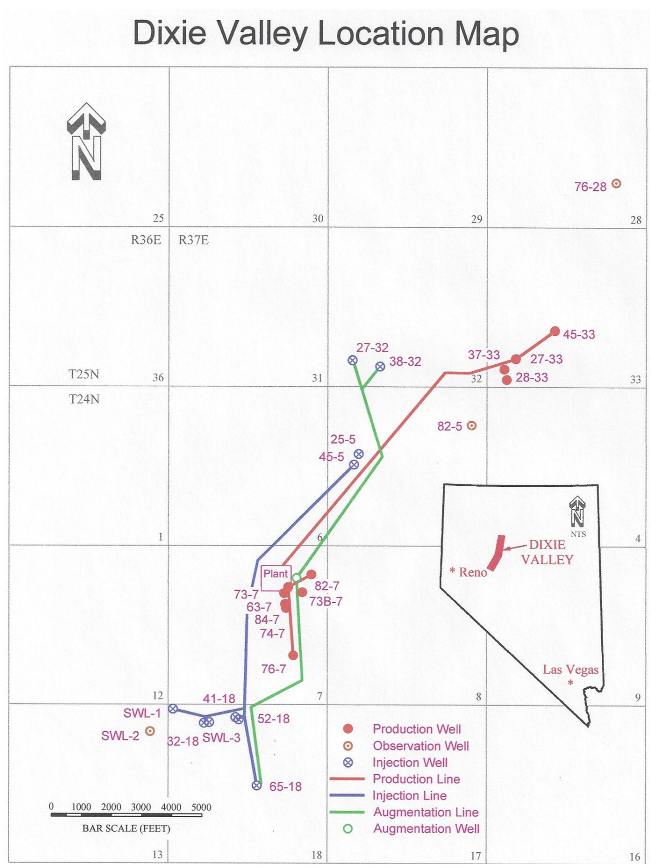

Figure 1. Location map of the Dixie Valley geothermal field.

and it is substantially different from all of the other thermal spring chemistries in the Dixie Valley region. Permeability in the SWL-1 well has since been interpreted as being a basaltic stratigraphic aquifer, rather than due to normal faulting. The SWL-1 well was approximately twice as deep as wells being drilled in most of the other geothermal prospects being explored in the Basin and Range in the 1970s. It has been utilized as a modest-volume long-term injection well.

In mid 1979, SUNEDCO drilled the #2 S. W. Lamb well (SWL-2) about 1000 feet southwest of the discovery well. The SWL-2 well failed to encounter permeability and was then redrilled as the #2B S. W. Lamb well to a depth of 8588 feet. This leg also failed to encounter commercial permeability. It did penetrate into granodiorite below a depth of 8350 feet becoming the first deep well in the field to penetrate the Stillwater Fault Zone, although it is unclear as to exactly when this was recognized. The SWL-2 well has occasionally been utilized as a low volume injector and to date has delineated the southwestern boundary of the reservoir along the Stillwater Fault Zone.

Immediately after the SWL-2 well was completed SUNEDCO drilled the #3 S. W. Lamb well (SWL-3) about 1000 feet east of the discovery well. The SWL-3 well reached a depth of 9126 feet and also penetrated into granitic rock but the fault gouge was tight and had never hosted geothermal fluid flow. Modest permeability was encountered in the Miocene basalt during drilling and was later accessed via perforations through a liner. The SWL-3 well has been utilized as a long-term injector.

Also in 1979 Thermal Power Company, in a farm-in arrangement with other lease holders, drilled two deep wells, 45-14 and 66-21 much further southwest along the western margin of Dixie Valley. Neither well encountered a commercial geothermal resource but did document temperatures of 389 and 426 ^{o}F. They produced small volumes of water with chemistries much different from the SUNEDCO wells. This was the first indication that geothermal resources along the Stillwater Fault Zone in Dixie Valley might not be easy to locate.

In early 1980 SUNEDCO began drilling a series of five wells that continued into mid 1982. The 52-18 well was the fourth well and was also located on what was believed to be private acreage but water rights surveys later identified a decades old surveying error had misplaced the private land boundary by about 1200 feet and the well ended up being on Federal land. The 52-18 well was about 1000 feet east of the SWL-3 well, a common 1970s spacing based on a 40 acre program. This spacing had much more in common with oilfield drilling tactics than geothermal geology. The 52-18 well was the deepest SUNEDCO well to date at 9691 feet but encountered only modest permeability in Mesozoic metavolcanic rocks beneath the Miocene basalt. The 52-18 well has been utilized as a modest volume long-term injector.

In late 1980 the fifth well, 62-21, was completed as the deepest geothermal well in Dixie Valley (and Nevada) at 12,500 feet in the middle of the valley. It represented SUNEDCO’s first major step out into their extensive Federal lease position and was intended to test the permeability of lower angled structures along the eastern edge of the pull-apart structure identified from the seismic reflection data (Waibel, 1987). The 62-21 well encountered very limited permeability and what are now interpreted as regional background temperatures. It was SUNEDCO’s most aggressive attempt to prove the Dixie Valley geothermal reservoir was aerially extensive.

In January 1981 the sixth well, 84-7, was completed as an important step out about 4200 feet north of the 52-18 well. Well 84-7 reached a depth of 8353 feet and was the first well to produce truly commercial amounts of fluid from the coarse grained gabbroic rocks of the Humboldt Lopolith, or ophiolite sequence. It was the first well SUNEDCO drilled to encounter the main reservoir temperatures near 480 ^{o}F and the only SUNEDCO well to be utilized for production. This well was sited at the northern edge of the private land with the intent of encountering a high angle permeable structure along the western edge of the rhombograben.

In early 1982 the seventh well, 65-18, was drilled to a depth of 9466 feet. It was located on Federal land about ½ mile south of the 52-18 well. This well was capable of modest production flows but was never used for production. In 1982 SUNEDCO performed the first injection testing in Dixie Valley by injecting some fluid into well 65-18 utilizing a Monoblock power unit with the turbine driving a pump, rather than a generator. A tracer test failed to return the sulfur hexafluoride tracer to the nearby producing wells in a detectable quantity.

In mid 1982 SUNEDCO drilled its eighth, and last, well at Dixie Valley, 45-5, to a depth of 8261 feet. This well was drilled over 1000 feet into granitic rocks making it the well drilled furthest into the footwall of the Stillwater Fault Zone. This well crossed the range-front at relatively shallow depths of 6200 – 6300 feet where the temperatures are near 400 ^{o}F. The 45-5 well has been in service as an important long-term injector. The 45-5 well-pad was sited to the west of the most desired surface location due to archaeological concerns about the original location.

During the 1982 drilling SUNEDCO also tried to obtain a power sales agreement. Extensive discussions with a utility consortium known as NORNEV ultimately failed to lead to the construction of a small demonstration power plant (Keilman, 1982). SUNEDCO did obtain a 9.6 MW Standard Offer #4 power sales contract from Southern California Edison but a steep decline in oil prices in the mid 1980s and the 1980 acquisition of the Texas Pacific Oil Company by SUNEDCOs parent company ended up requiring SUNEDCO to sell the Dixie Valley prospect.

The primary contribution of SUNEDCO to the development of the Dixie Valley project was the drilling of 8 deep and expensive (for that time period) exploratory wells. This drilling was self financed and done in a very remote area without having a power sales agreement in place. On the negative side one could view SUNEDCOs effort as not being particularly successful in that only one of their eight wells has been utilized as a production well but this well did discover the Section 7 production area that has supplied about 2/3 of the long-term production. More correctly, SUNEDCOs effort should be viewed as being highly successful in that only one of the eight wells, 62-21, was never attached to the gathering or injection system and one other well (SWL-2) has seen only very limited service. Five of the eight SUNEDCO wells have been utilized as long-term injection wells and these wells discovered three of the four geologic settings (basalt aquifer, shallow range front fault, and deep range front fault) (Benoit, 1992) that have successfully supported the production wells for 27 years. It can take years after a geothermal plant has commenced operations to truly understand and appreciate the value of good injection wells completed in a variety of locations and multiple geologic settings.

Trans Pacific Geothermal and Monterrey Energy Drilling (1983 – 1985)

Following the completion of the SUNEDCO drilling efforts, Trans Pacific Geothermal, with funding from the Swiss Reinsurance Corp, drilled two wells in late 1983. There was no cooperation between SUNEDCO and Trans Pacific Geothermal. The first well, 27-33, was located two miles northeast of the 84-7 well and over one mile from the closest SUNEDCO well, 45-5. It was a major step out targeted to be a similar distance from the Stillwater range front as the SUNEDCO wells and specifically targeted to cross the Stillwater Fault Zone. Fortunately for the Dixie Valley project, the 27-33 well encountered the 480 ºF resource as well as the highest permeability yet intersected at a depth of 8886'. This well was the first to produce from the Mesozoic quartzite of the Boyer Ranch Formation. This represented the most significant increase in the known productive length of the reservoir of any individual well.

Trans-Pacific immediately drilled a second well about 1000 feet further to the northeast, well 45-33. However, this vertical well was unsuccessful in locating permeability associated with the range front. It was immediately plugged back and redrilled to cross the range front to the west at a slightly shallower depth. This second leg was also impermeable. In a desperate move, the 45-33 well was again plugged back and highly directionally drilled beneath the 27-33 well where it finally encountered high permeability. The first two legs of the 45-33 well have defined the northeastern margin of the known reservoir. Both of the Trans-Pacific wells have been utilized as producers and extended the total length of the proven field to about 3.25 miles along the Stillwater Fault Zone.

Trans-Pacific Geothermal had the foresight to obtain 40 MW of Standard Offer #4 power sales agreements from Southern California Edison in late 1983. This agreement was every bit as important as the SUNEDCO drilling in moving the project toward development as SUNEDCO only obtained a 9.8 MW contract. It was also fortunate that the cost of obtaining the Standard Offer #4 contracts was low enough that a small company like Trans-Pacific Geothermal could afford to do so and that both contracts were with the same utility.

In 1984 Monterrey Energy drilled the 76-28 well one mile NNE of the 45-33 well to a depth of 10,419 feet but this well and a redrill failed to find permeability and the temperatures are significantly lower than those in the Section 33 wells, further confirming the northeastern boundary of the reservoir. However, this well does have a modest and delayed pressure connection to the geothermal reservoir.

Oxbow Geothermal Corporation (1985 – 1988)

In early 1985 Oxbow Geothermal Corporation was created specifically to acquire and merge the geothermal assets of SUNEDCO and Trans-Pacific Geothermal. Trans-Pacific Geothermal initiated discussions with Oxbow due to a chance meeting of two people on an airplane. Trans-Pacific Geothermal lacked the financial capability to take the Dixie Valley development beyond the drilling of its second well and SUNEDCO was forced to retrench due to the oil price decline of the mid 1980s. Oxbow initially viewed Trans-Pacific as primarily having the power sales agreement and SUNEDCO primarily having the production wells to make a combined project viable. Prior to the Oxbow entry, Trans-Pacific and SUNEDCO were uncooperative competitors who ultimately realized they could not independently develop a successful project at Dixie Valley, especially with the local utility showing no interest in purchasing the power at an economically viable price.

Once Oxbow obtained total control of the project in mid 1985 it was able to move very quickly to develop a 49.8 MW project within the time constraints of the power sales agreements. A nearly completed turbine generator set from the failed Parsons project in the Imperial Valley was quickly purchased and slightly modified. Oxbow began permitting work on the transmission line and sited what was believed to be a low risk infill well, 82-5, about ½ mile southwest of the successful 27-33 well. The 82-5 well proved to be impermeable, even with three redrills. This was unsettling enough that Oxbow began hiring in house geothermal expertise to develop the resource. Prior to the 82-5 experience Oxbow hoped to develop the project primarily with consultants and ultimately have a permanent staff of only 2 or 3 people in Reno to manage the project. Ultimately Oxbow acquired a permanent staff of about 10-15 people to manage the resource, power plant, and other business aspects of the project.

Immediately following the eye opening 82-5 experience, Oxbow brought three more drilling rigs into Dixie Valley and shifted its drilling focus to the vicinity of the SUNEDCO wells in Section 7 to obtain adequate production for the proposed power plant. Oxbow upper management also issued the decree that all future wells must be sited within 500 feet of an existing well, meaning that all the future Oxbow-drilled wells at Dixie Valley were essentially infill in nature. While this edict was viewed with some concern as unnecessary meddling by the technical staff at the time, it did not hamper the success of the project. Due to the very high permeability of the production areas the spacing between production wells turned out to be far less important than the separation between the production and injection wells which was already fixed, even if it wasn't recognized at that time. Oxbow began drilling wells with 13 3/8" production casing, which has double the cross sectional area of all of the previous 9 5/8" wells. Oxbow also retested and workover most of the existing wells.

In 1986 Oxbow completed four successful new 13 3/8" production wells. The 74-7 well and 76-7 wells were the most spectacular of them, being capable of producing 15 – 20 MW. Well 76-7 had the highest initial flow rate ever measured at Dixie Valley, 4000 gallons per minute, requiring a 14" diameter James tube to produce the full capability of the well.

During latest 1985 and early 1986 Oxbow also performed a modest scale reservoir test, flowing the 84-7 and 27-33 wells simultaneously and obtaining pressure interference information across the entire known field. This test, which surface discharged all the fluid, showed a significant reservoir pressure drawdown. When these test data were numerically modeled to predict various field operating scenarios, it became evident that injection of spent brine would probably be required to support the reservoir pressures for the 30 year length of the power sales agreement. Prior to this modeling, Oxbow management had hoped that the project would not require injection of the spent brine back into the reservoir so that all the existing wells could be counted as producers for financing reasons.

Oxbow performed considerable analytical work on the geothermal fluid, including fabricating a skid to mimic the proposed dual-flash process, to verify the fluid was compatible with the dual-flash process (Benoit and Hirtz, 1994). The Dixie Valley geothermal fluid is exceptionally low in total dissolved solids and has an abnormally high pH of $\pm$9 after the first flash (Goff et al., 2002). It is this high pH that allowed the plant to be dual flash without depositing silica scale in the gathering and injection systems. Extensive caliper logging was also performed to develop a better understanding of the carbonate scaling issue (Benoit, 1987).

To further test the initial numerical modeling results, which were required for the $100 million bank financing of the project, Oxbow conducted a six well flow test for a period of 74 days in mid 1986 producing a total of 7.2 billion pounds of fluid at rates as high as 5.9 million pounds per hour, again with field wide pressure monitoring (Desormier, 1987). This was the largest volume geothermal flow test ever performed in Nevada and perhaps in the United States. This testing and modeling conclusively demonstrated that injection of most of the spent brine was mandatory for the field to produce at full output for 30 years. This six well test truly defined the beginning of the injection program which ultimately required that most of the SUNEDCO wells be utilized as injectors, rather than as producers. Fortunately, the new 13 3/8 inch diameter production wells drilled by Oxbow were so prolific that the project economics and construction schedule were not significantly impacted by this major change.

An intensive program of short-term testing the injectivity of the lower productivity and lower enthalpy SUNEDCO wells was performed in 1987 and four widely spaced wells with differing injection depths were selected as the initial injectors (Benoit, 1991). A buried injection line was built to these injectors at a large cost saving compared to an above ground supported and insulated line.

The 60.5 MW (gross) dual inlet turbine and 67.23kVA generator, the largest dual flash plant in the world at that time, began operating on July 4, 1988 with the intent of delivering 49.8 MW to Bishop California via the longest privately owned transmission line in the United States. Permitting and construction of this line was a $35 million dollar effort that was accomplished in two years, in large part due to an absence of private lands along the route (Orser, 1988). The power plant and field development costs were $135 million or $2,455/kW. At startup the plant was supported by six production wells and four injectors. Three of the producers were completed with 9 5/8 inch diameter production casing and three had 13 3/8 inch diameter casing. These production wells supplied 4 high pressure separators scattered through the field and two low pressure separators adjacent to the turbine. The injection system was not placed in service until the plant had passed its performance test two months after the initial startup.

Oxbow 1989 – 2000

Once the power plant began operating with six production wells averaging over 8 MW net/well and four injectors it became clear that Southern California Edison would accept more power than the 49.8 MW the contracts specified and that the turbine and generator could produce up to 67.6 gross MW or 62 net MW. Although it was not recognized at the time, Oxbow almost immediately began an 8 year series of field improvements starting in 1989 involving both production and injection that would increase the plant output to a steady 56 megawatts delivered to Southern California Edison at the Bishop California substation. This required generating 62 gross MW. These improvements were fortunately completed by the end of the first ten years of power sales when the power prices were high enough to easily fund the additional drilling and construction.

Between 1989 and 1997 Oxbow drilled 2 new injection wells, placed two other SUNEDCO wells in injection service, drilled 5 new 13 3/8" production wells, and deepened the 76-7 well so that it produced higher-temperature fluid from the Stillwater Fault Zone (Benoit, 1992). One of the new injectors, well 25-5 accepted so much fluid that it effectively became the most important single well in the field. This amount of drilling might indicate that the field was underdeveloped at plant startup. However, during the first ten years of service all three of the original 9 5/8 inch production wells were taken out of service as they gradually became unable to maintain the required wellhead pressure to get into the gathering system dominated by the stronger 13 3/8 inch wells. As the reservoir pressure declined the 13 3/8 inch diameter wells had slower wellhead pressure declines and would back flow down the lower pressure 9 5/8 inch production wells. A significant portion of the 5 new production wells simply went into replacing the older smaller diameter wells which were still potentially viable producers, just at wellhead pressures slightly too low to continuously enter the high pressure separators. The additional production wells required one new high pressure separator to be installed in the gathering system to account for the 6 MW increase in desired plant output.

All of the Dixie Valley production wells precipitate calcium carbonate (Benoit, 1989). Immediately after plant startup Oxbow began developing a carbonate scale inhibition program (Benoit 1990). Without the scale inhibition program the project could have required 20 mechanical or acid carbonate scale cleanouts per year, with attendant risk of casing damage and loss of wells. Oxbow worked extensively with Pruett Industries and the Sandia National Laboratory to improve the scale inhibition hardware and incorporate long-term reservoir pressure and temperature monitoring capabilities into that hardware (Benoit, 1999, Benoit et al., 1999, Smithpeter et al., 1999). The scale inhibition program ultimately evolved to utilizing 1.9 inch hang down strings to protect the stainless steel capillary tubings from mechanical damage. These hang down strings were hung from the tops of the wellheads, making the master valves on the wellhead unusable hardware with the additional disadvantage of an unnecessary pressure drop through the master valves. The new production wells were completed with long radius sweeping elbows on the top of the wellhead to reduce the pressure drop. The wing valves became the master valves. This did not create any well control issues as once the Dixie Valley production wells are shut-in the wellhead pressure quickly drops to zero and the wells must be stimulated to resume flow. The scale inhibition program eventually eliminated the need for routine or regular scale cleanouts and as a nice bonus, provided a low cost method for stimulating the wells with an air compressor, instead of a coiled tubing unit.

In 1989 the second tracer testing effort at Dixie Valley consisted of injecting organic tracers into three different injectors (Adams et al., 1989). Numerical model predictions were made of the hoped for returns but only one pair of tracers was ever detected in the produced fluid, between injector 32-18 and the 76-7 producer. This disappointing lack of returns was due to the relatively high detection limits for the available tracers.

In mid 1996 tracer testing resumed at Dixie Valley with the initial field testing of polyaromatic sulfonate tracers with analytical detection limits in the part per trillion range (Rose et al., 1998). By 2002 seven different high-temperature polyaromatic sulfonate tracers had been injected into seven different injectors at Dixie Valley and successfully recovered (Rose et al., 2001, 2002). First arrival times varied from 30 to 150 days and peak arrivals as long as one year were defined. These were the longest return times yet documented in any geothermal field in the United States and provided confidence that injection caused cooling should not be a major short-term problem at Dixie Valley.

By the end of 1997 the field consisted of a total of 11 available production wells with eight 13 3/8 inch diameter wells actually in service and 8 active injection wells. During the addition of the new production wells each new production well resulted in progressively smaller net MW increases. The most recent production well, 37-33 drilled in 1997, resulted in only 1-2 MW net improvement in plant output, even though as a standalone well it was capable of producing over 10 MW. A different strategy was needed to economically maintain the field output and the preferable strategy was one that would benefit all of the existing production wells. This strategy, through a combination of fortuitous circumstances and timing, was to augment the injection with cold shallow groundwater via a dedicated cold water injection system (Benoit et al., 2000). The U. S Navy had water rights in Dixie Valley which needed to be quickly put to beneficial use (under Nevada State water regulations) so an agreement was quickly negotiated to lease these water rights. The extensive tracer testing provided the confidence that the reservoir could handle the additional load of heating up the cold augmentation fluid.

As the reservoir pressures declined due to continuous cooling tower evaporation losses of 1600 gallons per minute the injectivity of the injectors increased. By 1997 there was excess injection capacity to allow a couple of existing injectors to be dedicated to cold water injection. Dedicated cold injectors were required due scale precipitation when the hot geothermal fluid and cold groundwater were mixed (Benoit et al., 2000). Injection augmentation began with about 500 gpm of cold water from an existing shallow irrigation well and increasing reservoir pressure was measured with days in the idle 45-33 well. The augmentation system has been in more or less continuous operation since 1997 at rates as high as 2000 gallons per minute with the benefit of no new production wells being drilled in the past 18 years. This makes the shallow groundwater well now credibly the most important single well at Dixie Valley. Reservoir pressure monitoring at varying augmentation rates showed a stable reservoir pressure with an augmentation rate of about 500 gpm, meaning that the natural recharge into the Dixie Valley reservoir is about 1100 gpm (Benoit et al., 2000).

The only significant improvements Oxbow made to the power plant itself were the installation of vacuum pumps to reduce the amount of high pressure steam needed to remove the noncondensible gases from the condenser and some cooling tower modifications. Oxbow's improvements were focused on the wellfield and gathering system.

Caithness 2000 – 2007

In 1993 and 1994 Dixie Valley Power Partners, Caithness and Florida Power and Light, drilled the deep 62-23 and 36-14 wells a few miles southwest of the operating project with the intent of developing a project to sell power to Southern California Edison under one of the last Standard Offer #4 contracts available. Ultimately that contract was sold back to Southern California Edison and no plant was built.

Oxbow sold its Dixie Valley interests to Caithness in mid 2000. The only significant changes to the field during the time Caithness operated the project was the loss of the 82A-7 production well during a workover and the deepening and successful completion of the 38-32 injection well which was the first well to return injectate to the Section 33 production area (Johnson and Hulen, 2002, Rose, 2002). Previously all injectate returned to the Section 7 wells. In 2004 Caithness made a major modification to the turbine to operate at a lower inlet pressure which restored the plant to its desired output (Figure 2).

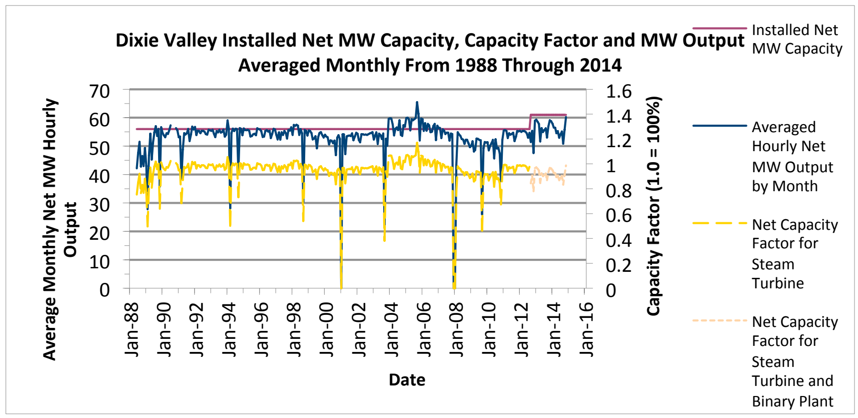

Figure 2. Dixie Valley average monthly production figures from the Nevada Division of Minerals.

Terra Gen Power Corp 2007 – 2015

Terra Gen Power Corp purchased the project from Caithness in 2007 and is the current owner. In 2012 Terra Gen installed a 6.2 MW (gross) binary power plant on the injection line to increase the total installed capacity to about 61 MW (net). Terra Gen has also installed a third low pressure separator near the turbine with the intent of increasing the amount of low pressure steam that can be supplied to the turbine. Terra Gen performed additional deep drilling in their Coyote Canyon prospect located a couple miles southwest of the operating project (in the vicinity of the 62-23 well) but in 2012 PG&E Corp cancelled the power sales agreement for this project.

Production History

Between coming on line in mid 1988 and mid 1989 the Dixie Valley power plant ramped up from an initial intended 49.8 MW net output to 56 MW (Figure 2). The first two years had more irregular outputs as the scale inhibition program was being developed and wells needed mechanical cleanouts. Since 1990 the project has maintained a remarkably consistent output, marred primarily by two major incidents involving the transmission line, a helicopter crash and an ice storm. Major scheduled plant maintenance outages have declined

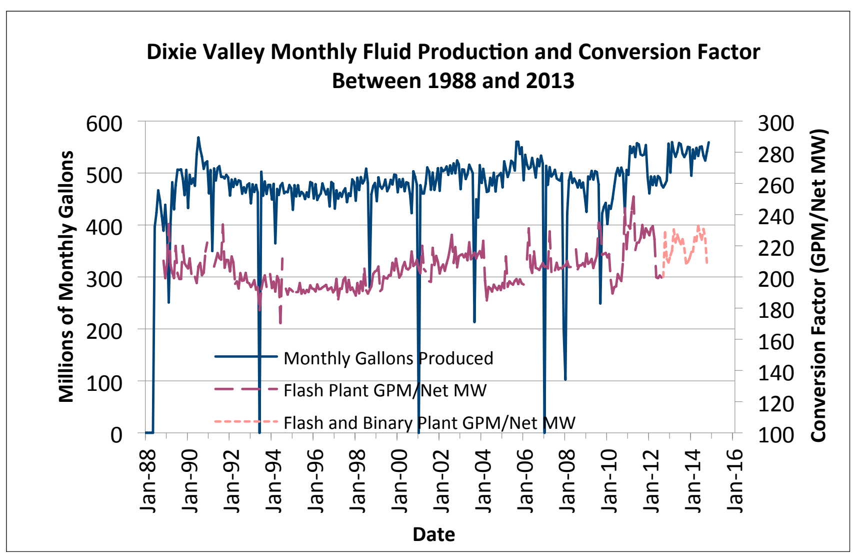

Figure 3. Dixie Valley average monthly fluid production and the amount of fluid required to generate one net megawatt of power. Values for the monthly gallons are from the Nevada Division of Minerals.

from every other year to once every six years. The 5 MW net binary plant which came on line in 2012 has not yet resulted in a comparable steady net output with only intermittent monthly average outputs above the background of 56 net MW. The binary plant has been the source of the irregular output (Mines and Williams, 2015).

Since the mid 1990s the Dixie Valley resource has shown modest resource cooling as the amount of fluid supplied to the plant has increased (Figure 3). The amount of fluid required to make a megawatt has increased from a low of about 190 gpm to about 230 gpm (Figure 3) (Benoit, 2013).

Through 2014 the Dixie Valley power plant has produced about 12 million megawatt hours of power at an average rate a little under half a million megawatt hours/year. To do this has required producing about 4500 acre feet of water per year and a cumulative volume of about 450,000 acre feet of geothermal fluid. This is enough water to cover about 700 square miles one foot deep, or about 0.13 cubic mile of water. A general idea of the overall times the geothermal fluid has been recycled through the reservoir is available from all the tracer tests. On the rapid side, a first return time of 30 days permits a few water molecules to have made up to 750 or 800 passes through the reservoir. On the slow side with a peak return time of 150 days over 27 years gives 66 passes through the reservoir. A weighted average should be somewhere between these two extreme values probably somewhere between 100 and 200 times.

In 2014 the power plant was supplied by 8 producing wells averaging about 7 net MW/well, a modest decline from the original 9 net MW/well average for the 6 wells in service at startup in 1988. In 2014 the plant utilized 11 injection wells as compared to 4 at startup. This last statistic emphasizes the importance of injection in achieving the overall project success.

Conclusions

Dixie Valley has been a very successful project producing at more or less its desired output for over 27 years (Benoit, 2013). This is primarily due to six factors. First, the resource has proven to be large enough to support the 56 MW net dual flash power plant and the benign resource chemistry has presented no serious production problems. Second, the fairly wide spacing of the exploratory wells in all three dimensions during the SUNEDCO and Trans-Pacific exploration phase of the project was adequate to allow the injection of up to 11,000 gallons per minute without rapid cooling of the production wells. This wide spacing at an early development stage greatly reduced the dry hole/step-out risk later in the project development when there was a potentially serious time constraint in the initial power delivery date. Third, the Standard Offer #4 power sales agreement provided adequate income during the first several years of plant operations to fund the drilling of several new wells to expand the field development to 56 MW net rather than the initial planned 49.8 MW net level. Fourth, the low cost availability of abundant shallow groundwater in the immediate vicinity of the power plant allowed the implementation of an injection augmentation program that reversed the reservoir pressure decline of the first decade of operations, eliminating the need for additional makeup wells. No new production wells have been drilled in the past 18 years. Fifth, there was no rush into a major megawatt output increase shortly after the plant started up. It took several years to fully realize that the plant and resource were well paired in terms of size for a 30 year life expectancy. Sixth, the operating project has been controlled by one owner at a time. This has eliminated conflicts between the field and plant operators and allowed decisions to be rapidly made and implemented.

The southwestern margin of the reservoir along the Stillwater Fault Zone has been defined by the SWL-2 well. The northeastern margin of the reservoir has similarly been defined by the 45-33 and 76-28 wells and their redrills. Boundaries not yet been tested or defined by drilling are along the Stillwater Fault zone in the presumably shallower northwest direction and the deeper southeast direction.

Development of the Dixie Valley project required widely differing skills and mindsets. This is reflected in the makeup and personalities of the three key companies that were required to complete the project, along with some fortunate timing. The patience, tenacity, and deep pockets of SUNEDCO, along with a period of high oil prices, were needed to drill enough exploration wells to ultimately define various parts of the reservoir. The chutzpah and foresight of Trans-Pacific Geothermal was needed to drill risky step out wells that doubled the known size or length of the resource and to obtain the 40 MW of Standard Offer #4 power sales agreement that was critical for the project to reach financial viability. The financial capabilities, determination, flexibility, and power generation savvy of Oxbow Geothermal Corp. were necessary to combine the resource with the power sales agreements, get the project built to meet the contract deadline, and then modify the initial field design to make it sustainable for decades of operation.

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