Reservoir Testing and Analysis at the Patua Geothermal Federal Unit, Northwestern Nevada

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ABSTRACT

To better understand the geothermal reservoir underlying the Gradient Resources Inc. (GRI) leases at the Patua Federal Geothermal Unit and better define the geothermal fluids to be used as fuel to generate electricity, GRI has undertaken an extensive exploration program consisting of geological, geochemical, and geophysical surveys, core hole drilling, well drilling, well discharge testing and finally a 30-day flow and injection test. Based on the data obtained from the well drilling and testing, a conceptual model of the Patua Geothermal Reservoir has been developed. The subsurface stratigraphy consists of a sequence of volcanic rocks overlying naturally-fractured granitic rocks of the basement. The geothermal reservoir consists of naturally-fractured granitic rocks with high-permeability stress induced fractures striking along northeastern and orthogonal northwestern trends. Pressure interference data recorded by monitoring coreholes and wells during ongoing discharge testing supports the concept of the lack of interconnection between coreholes completed in the volcanic rocks and production wells completed in the underlying geothermal reservoir. Pressure interference data indicates the geothermal reservoir extends to at least ten (10) square miles. Based on the results and analysis of the extensive exploration program, in addition to well discharge and pressure interference testing while using the USGS “heat in place” with Monte Carlo simulation methodology, there is a 90% probability (P90) that the gross power generation capacity of the Patua Geothermal Reservoir is at least 207 MW_{gross}, and a 50% probability (P50) it is more than 320 MW_{gross}.

Introduction

The GRI Patua Federal Geothermal Unit (Patua Unit Area) in Lyon and Churchill counties is near the town of Hazen, NV. The project area is approximately 10 miles east of Fernley, NV and about 40 miles east of Reno, NV. The Patua Unit Area primarily consists of Sections 7, 8, 9, 10, 15, 16, 17, 18, 19, 20, 21, 22, 27, 28, 29, and 30 of Township 20N, Range 26E, MDM (see Figure 1).

Based on the subsurface temperature data from the completed and discharged wells, GRI has focused its drilling program in the southern part of the Patua lease area (see Figure 1). Six coreholes (21A-19, 23A-17, 27-29, 45-9, 36-15, and 45-27; depth ranges of ~5,000 to ~7,000 ft), as well as thirteen slim- and large-diameter production wells (16-29ST2, 24-29, 58-29, 77-19, 77A-19, 21-19, 44-19, 85-19, 88-19, 37-17ST1, 23-17, 44-21, and 36A-15; depth ranges of ~8,400 to ~11,900 ft) have been completed. Exploration and production well drilling targets have been concentrated on intercepting faults noted in the 2-D seismic reflection data. Targeting has been successful with numerous faults encountered in the subsurface. At depth, these faults zones manifest themselves as

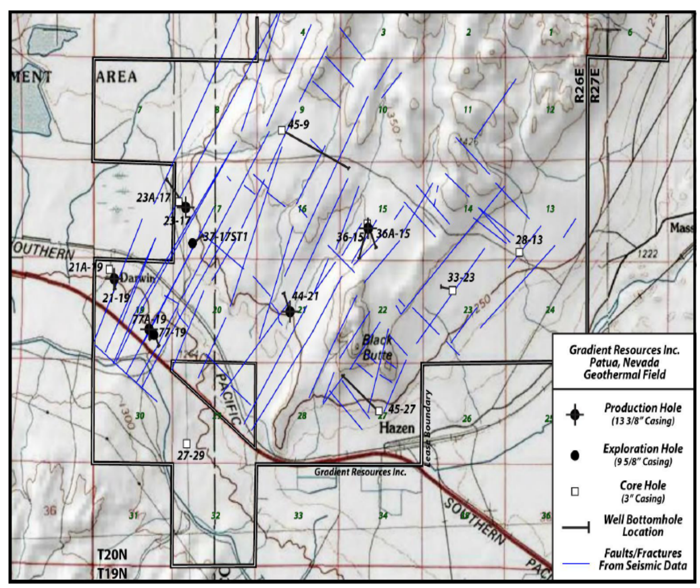

Figure 1. Patua Unit Area with well locations. Faults are from 2D seismic correlation (at ~4,000 feet MSL elevation). Figure from Garg and Goranson (2010).

Loss of Circulation Zones and drilling breaks with high (>30-ft/hr) rock penetration rates.

Subsurface Geology

The stratigraphy observed in the Patua Unit Area consists of a variety of fine grained and diagenetically altered Quaternary sediments overlying a sequence of mafic-intermediate volcanic rocks interbedded with altered ash tuffs, and a sequence of intermediate to silicic volcanics that have been pervasively altered to clay minerals (smectite, illite-smectite, nontronite, kaolinite). X-Ray Diffraction analysis completed by OMNI/ Weatherford Laboratories in Houston, TX corroborates core and cuttings analysis describing chlorite-smectite group (swelling clay) alteration with variable ratios of illite layering. Core analysis and X-Ray diffraction completed on Tertiary volcanic rocks as well as Cretaceous granite, granodiorite, and tonalite confirms that argillic alteration of feldspathic minerals is the dominant alteration type at depths less than 6,500 feet throughout the project area.

Cores and cuttings from drilling reveal a sequence of Tertiary volcanic rocks unconformably overlying plutonic intrusives. From top to bottom alluvial deposits ranging from a few feet to several hundred feet in thickness cap the sequence. Below the alluvial deposits, there is a group of interbedded tuffs, young Tertiary basalts, and andesitic volcanic rocks approximately 2,800 feet thick. Minor sand separates the latter from a sequence of increasingly silicic, (dacite-rhyolite) volcanic rocks that are about 1,800 feet thick. These rocks represent the base of the Tertiary volcanic section in the subsurface. Deeper in the subsurface, plutonic intrusive rocks ranging in composition from granite to granodiorite to greenstone, with rare dioritic intervals, continue for thousands of feet. One of the deeper wells (37-17ST1; 10,949 ft) drilled to date in the Patua Unit Area encountered over 6,300 feet of naturally-fractured granitic intrusive rocks. The seismic reflection data indicate fractured basement rocks to depths greater than 15,000 feet. Andesitic-basaltic dikes occur intermittently in the basement granitic sequence.

Drilling to date has revealed geothermal reservoir permeability exists at varying depths along discrete fractured pathways and stratigraphic positions. Permeable pathways are further constrained by the generation of the secondary minerals indicated above. Pressure, temperature, and pressure-temperature-spinner surveys conducted before, during, and after well testing support the concept of a structurally and stratigraphically confined geothermal system. Generally, conductive temperature gradients have been recorded in the Tertiary volcanic rocks and data showing permeable intervals with convective temperature profiles have been observed in select areas where silica rich volcanic rocks are present and throughout the granitic basement rocks.

Evidence for Stratigraphic Confinement

Pressure and temperature (PT) surveys presented in Figure 2 and Figure 3, indicate stratigraphic confinement of discrete permeable intervals within the Patua Unit Area. In Figure 2, temperature peaks shallower than 1,000 feet in this corehole are not evident in any of the other pressure-temperature surveys completed in the coreholes and deep wells within the Patua Unit

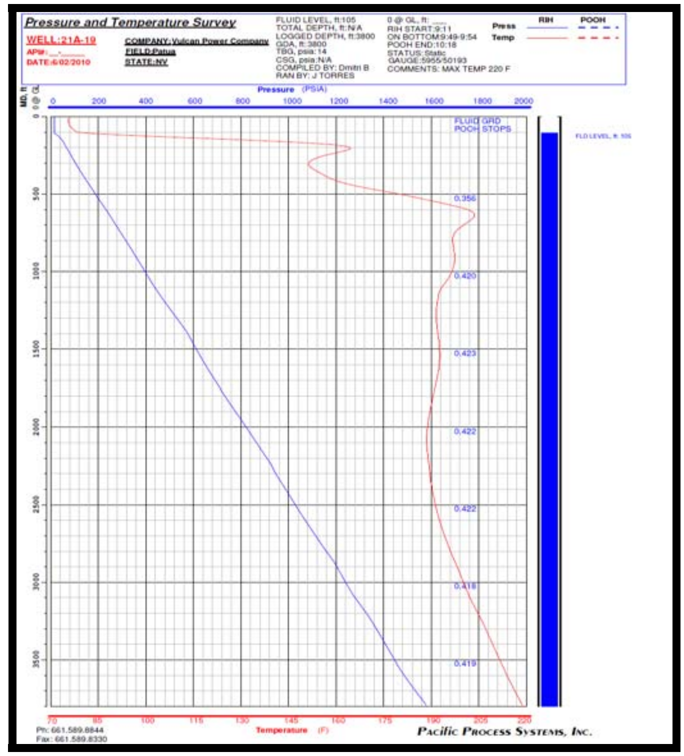

Figure 2. Static pressure and temperature survey in Patua corehole 21A-19.

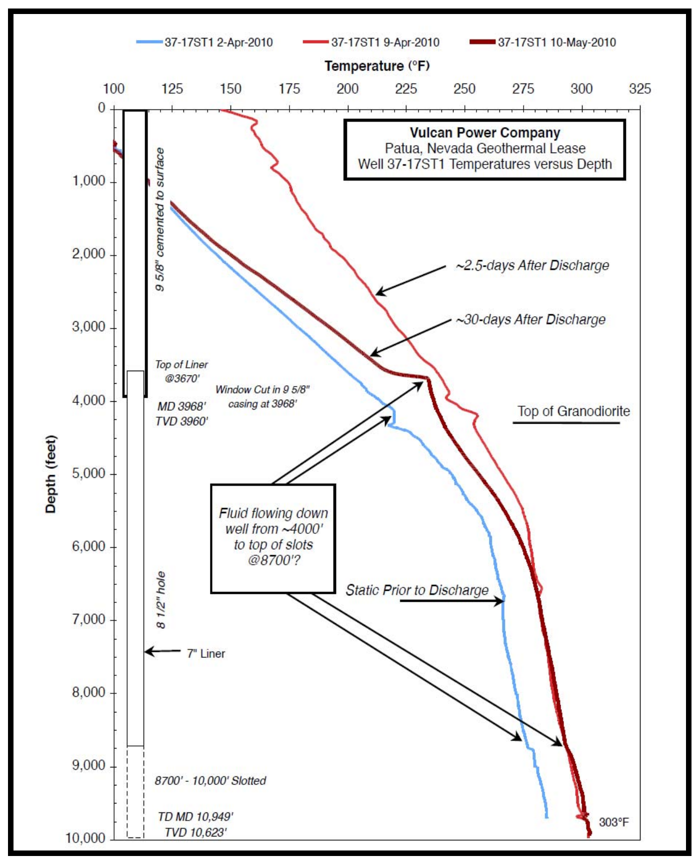

Figure 3. Comparative PT surveys as a function of time in the 37-17ST1 production well.

Area. This observation demonstrates stratigraphic confinement, in that the discharge of the deeper wells being tested does not provide any pressure or temperature increase or decrease in the shallow volcanics. Further, the lack of this shallow manifestation in other wells indicates that these shallow temperature increases are related to basin faults to the west and outside the Patua Unit Area. Lithology in this interval consists of Tertiary volcanic rocks (i.e., basalts and tuffs). In other words, the granitic basement was not penetrated by this corehole.

As noted above, the Tertiary volcanic rocks appear to have only limited permeability and the temperature-depth data indicated that the upper approximately 5,000 feet of the subsurface is characterized by conductive geothermal gradients as indicated in Figure 3. Below about 5,000 feet in the granitic basement, the naturally-fractured rocks provide enhanced permeability and the geothermal gradients are decreased indicating convective heat transfer in the reservoir. The flowing temperatures of the production wells range from 294ºF to 394ºF; the anticipated Patua power plant has an input temperature of 317ºF.

Conceptual Model of Geothermal Reservoir

A conceptual model of the Patua Geothermal Reservoir is presented in Figure 4. The subsurface can be characterized by a sequence of volcanic rocks overlying the granitic rocks of the basement. The geothermal reservoir consists of naturally-fractured granitic rocks with high-permeability stress induced fractures striking along northeastern and orthogonal northwestern trends (see Figure 1). Fractures extend Part way into the overlying volcanic rocks altering the volcanic rocks to clays through low-temperature hydrothermal alteration creating a caprock over the granitic reservoir. Subsurface flow paths are conceptually indicated in Figure 4.

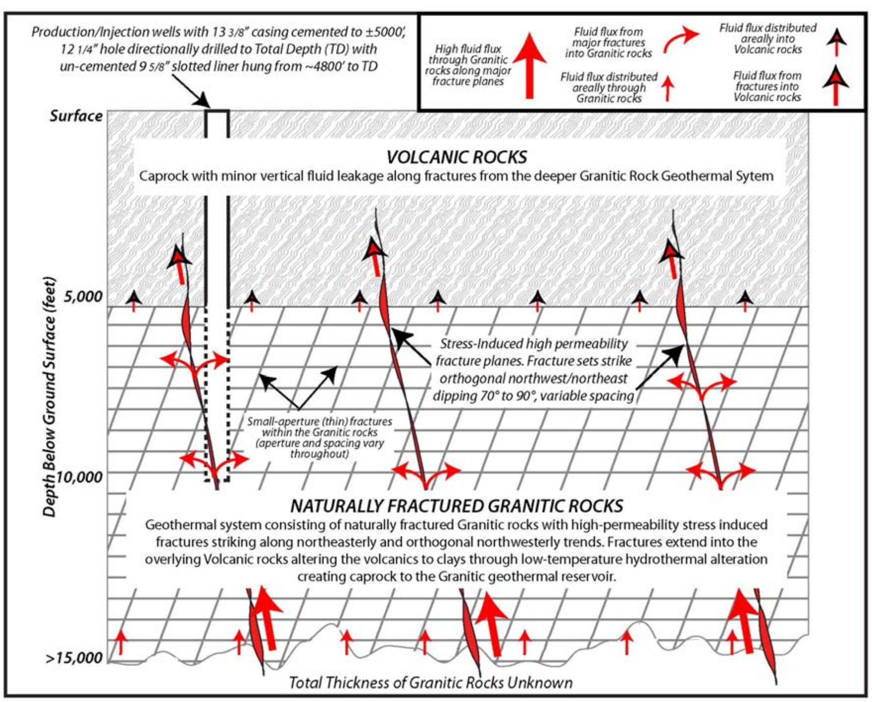

Figure 4. Conceptual model of the Patua Geothermal Reservoir.

The production and injection wells drilled into the Patua geothermal reservoir are completed with 13-3/8-inch casing cemented from surface to about 5,000 feet, which is essentially the depth to the top of the granitic basement, a 12-1/4-inch hole is directionally drilled to the total depth of the identified target zones with un-cemented blank and slotted 9-5/8-inch liner hung from approximately 4,900 to the total depth of the production or injection well.

Produced fluid samples indicate that the reservoir fluids are basically a Na-Cl type brine with low total dissolved solids (TDS) and low non-condensable gas contents. Overall the fluids are relatively benign from a scale (precipitant) formation and corrosion standpoint with TDS less than 3,000 ppm.

Separation of Volcanics and Granitic Rocks

Pressure interference data recorded in monitoring coreholes and wells during ongoing discharge testing supports the concept of discrete stratigraphic horizons within the subsurface at the Patua Unit Area. Examples of test data consisting of discharging wells along with interference observed in monitoring coreholes and wells are shown in Figures 5 through 7. The pressure interference data document the lack of interconnection between the coreholes completed in the volcanic rocks and the production wells completed in the granitic geothermal reservoir. Pressure interference between production wells indicates that the geothermal reservoir extends over at least ten (10) square miles based on the wells drilled to date.

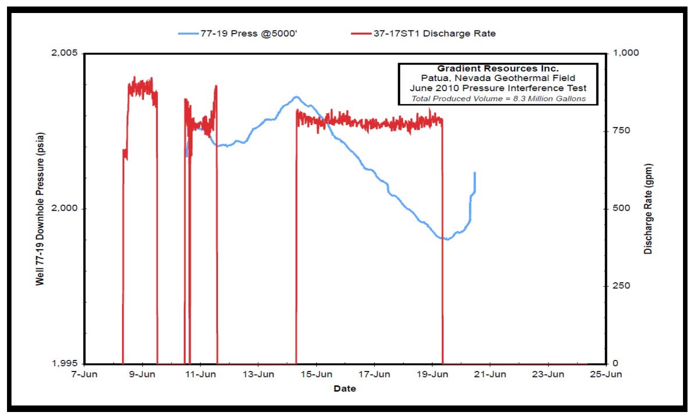

Figure 5. Discharge from 37-17ST1 well with pressure response in 77-19 well.

Figures 5, 6 and 7 (Garg and Goranson, 2011), show pressure response/ drawdown (blue lines) in 77-19, 23-17, and 23A-17 during discharge testing at 37-17ST1 with the subsequent buildup and recovery to static conditions (blue lines) after the well discharge was concluded.

In the case of testing performed at the Patua 37-17ST1 well, pressure responses in monitoring wells were observed in wells 77-19, 23-17, and

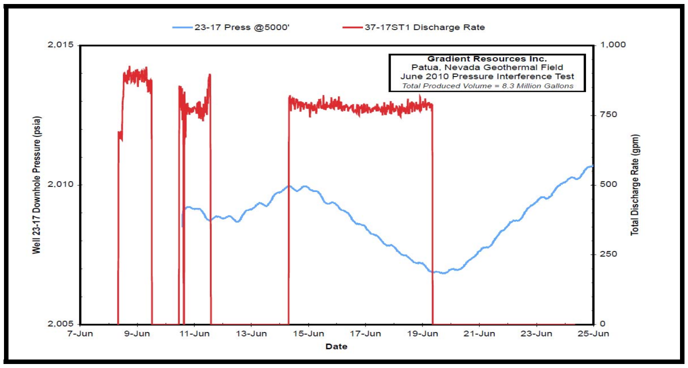

Figure 6. Discharge from 37-17ST1 well with pressure response in 23-17 well.

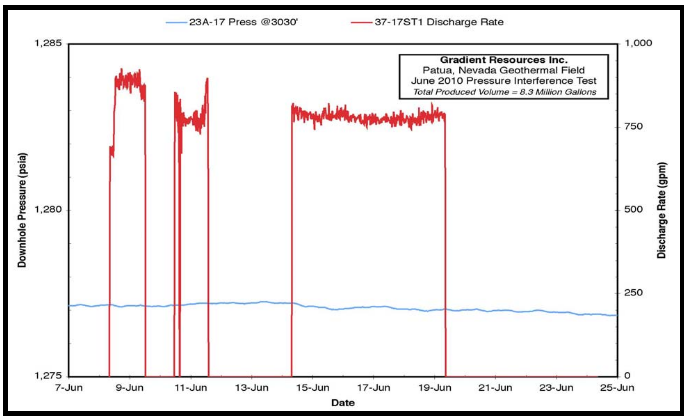

Figure 7. Discharge from 37-17ST1 well with pressure response in 23A-17 corehole.

23A-17 which were equipped with pressure monitoring equipment at the time of testing and were located in the volcanics (23A-17) and the naturally-fractured granitic rocks of the Patua geothermal reservoir (77-19 and 23-17). These two wells and a corehole are along a northeast striking fault zone that steps down to the west near the 23-17 well location.

Pressure responses resulting from discharging wells farther east within the Patua Unit Area share this type of pressure communication. This is the second major piece of the conceptual model as pertaining to structural controls along NE striking faults and the presence of separate and independent permeable pathways. The hydrologic separation of volcanic rocks (i.e., caprock) from granitic rocks (i.e., the geothermal reservoir) is clearly demonstrated in pressure monitoring of the shallow coreholes completed in the volcanics.

Interpretation of the pressure interference during discharge testing of wells completed into the deeper granitic rocks indicates a well connected reservoir with transmissivities ranging from 75 to 190 Darcy-ft.

The 30-Day Discharge and Injection Test

In order to measure the temperature and pressure response of the Patua geothermal reservoir, well 77A-19 was discharged with injection into well 44-21 for a 30-day time period. The temperature, pressure, and flow rate data from the discharge

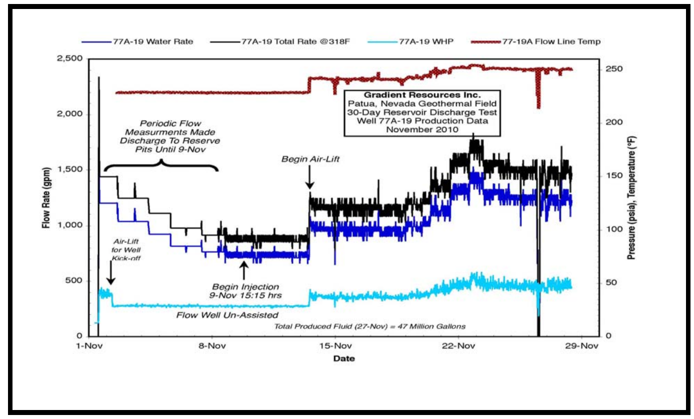

Figure 8. Time history of 30-day discharge test of the Patua 77A-19 well.

of the 77A-19 is presented in Figure 8. Discharge of the well was started on November 2, 2010; however, injection of the geothermal fluids was not initiated until November 9. The initial fluids were disposed of in sumps on several of the well pads in order to obtain additional pressure interference data before the initiation of injection into the geothermal reservoir. Two (2) air compressors injected air through tubing set at 2500 feet to allow for well discharge to be varied. Fluid discharge rate varied from 900 gallons per minute (gpm) to 1,200 gpm and finally to 1,600 gpm, which was the maximum flow rate while pumping air at 2,000 cubic feet per minute, the maximum capacity of the two air compressors.

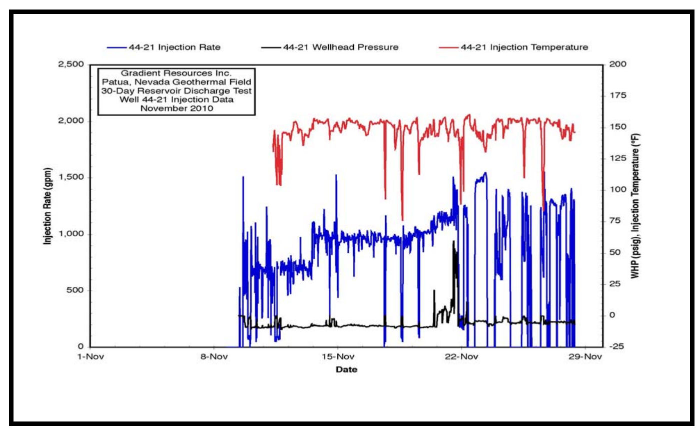

Figure 9. Time history of 30-day injection of fluids into the Patua 44-21 well.

The spent geothermal fluids were injected into the Patua 44-21 well. The injection data, including injection flow rate, wellhead pressure, and injection temperature, are presented in Figure 9. Note that the injection rate coincides with the increase in the discharge rate from 900 gpm to 1,200 gpm to the final rate of approximately 1,600 gpm. Even though the wellhead pressure at the 44-21 injection well increases slightly with a change in the discharge rate at the 77A-19 production well, the overall response of the 44-21 well during the 30-day test was to receive spent brine on a vacuum. In other words, throughout the 30-day test the spent geothermal fluids were injected into the 44-21 well under the conditions of a vacuum. Interpretation of the pressure interference data during the 30-day test indicates a highly connected reservoir with transmissivities ranging from 75 to 170 Darcy-ft.

Analysis of Production Temperature Data

While the 77A-19 well was being discharged, at weekly intervals during the 30-day test, pressure, temperature, and spinner (PTS) logs were obtained in the 77A-19 well. The resulting measurements from the temperature surveys are presented in Figure 10.

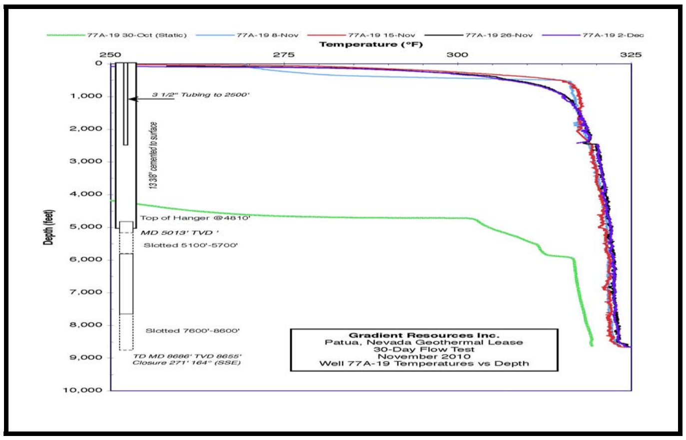

Figure 10. Temperature-depth data in 77A-19 during 30-day discharge test.

Based on the separate temperature-depth curves obtained on a weekly basis, during the 30-day discharge, the bottomhole temperature increased about 7ºF from a static temperature of 320ºF before the 30-day discharge test to a final bottomhole temperature of about 327ºF. The increase in bottomhole temperature as a function of time is caused by the production of geothermal fluids from below the bottom of the well. Based on the 2-D seismic reflection data obtained at Patua, it is evident that permeable zones extend to depths greater than 15,000 feet in the naturally-fractured granitic basement that provide the conduit for higher temperature geothermal fluids to move up from depth.

Geothermal Fluids and Geothermometers

As a standard procedure, GRI has performed complete chemical analysis on all produced geothermal fluids in the Patua Unit Area. Fluid sample analyses exhibit significant disparity, and lead us to conclude that the discrete fracture zones encountered in drilling testing to date operate separately and are subject to unique sets of inputs and hydrologic processes. Fluid sample geothermometer data indicate that the silica geothermometers range between 320ºF to 425ºF with alkali geothermometers varying from 305ºF to 490ºF. The calculated geothermometers based on the chemical data from the Patua production wells indicate that the geothermal fluids produced from the discharged production wells are derived from deeper, higher temperature, geothermal fluids. Silica contents of the produced fluid from wells at Patua are greater than silica saturation temperatures, e.g., downhole flowing temperatures in wells are less than what would be expected for the content of silica measured in the produced fluids.

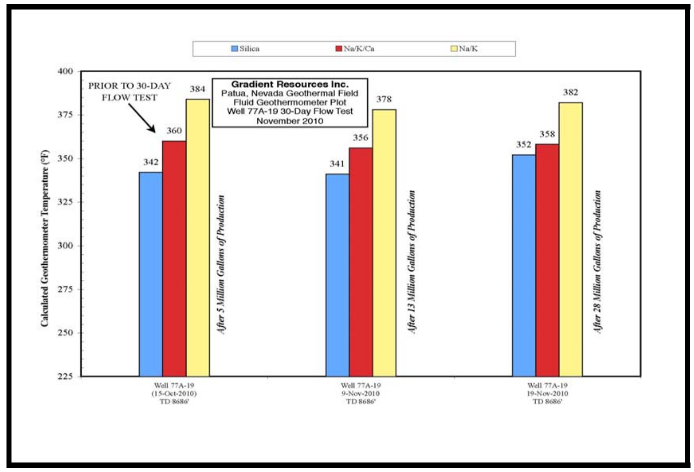

Figure 11. Geothermometers calculated from 77A-19 geothermal fluids before, during, and after the 30-day discharge test.

Silica content of the geothermal fluid samples obtained from the Patua 77A-19 well as a function of time during the 30-day discharge test indicates a temperature increase with time. The silica geothermometer temperature before the 30-day flow test was 342ºF; whereas after 28 million gallons of produced geothermal fluid, the silica geothermometer temperature was 352ºF (see Figure 11). The most reasonable explanation for the increased geothermometer temperatures and the increase in bottomhole temperatures in the 77A-19 well as a function of time is that geothermal fluids from depths greater than the total depth of the well are being drawn into the wellbore and produced at the wellhead. Based on the data from the 30-day discharge test, GRI anticipates the temperatures of the produced geothermal fluids may increase during long-term fluid production to the power plant as a function of time.

Conclusions

Based on the drilling and analysis of cores from six (6) coreholes ranging in total depths from ~5,000 to ~7,000 feet and the drilling and testing of thirteen (13) slim and large-diameter production wells ranging in total depths from ~8,400 to ~11,900 feet, a conceptual model of the Patua geothermal reservoir has been developed. The reservoir consists of a sequence of volcanics overlying a basement composed primarily of fractured granitics. There is a distinct hydrologic separation between the volcanics and the underlying granitic basement rocks based on the cores and drill cuttings, which has been confirmed by pressure interference data documenting the lack of interconnection between the coreholes in the volcanic rocks and the production wells completed in the geothermal reservoir of the granitic rocks.

The deepest well drilled to date in the Patua Unit Area encountered over 6,300 feet of naturally-fractured intrusive rocks. The seismic reflection data indicate fractured basement rocks extend to depths greater than 15,000 feet.

The flowing temperatures of the production wells range from 294ºF to 394ºF; the anticipated Patua power plant has a design input temperature of 317ºF. During the 30-day discharge, the bottomhole temperature in 77A-19 increased about 7ºF from a static temperature of 320ºF before the 30-day flow test to a final bottomhole temperature of about 327ºF. In addition, the calculated silica geothermometer temperatures based on the chemical data from the 77A-19 increased from 342ºF to 352ºF after 28 million gallons of geothermal fluids were produced. These data indicate that the geothermal fluids produced from the 77A-19 production well are partially derived from deeper, higher temperature, geothermal fluids, indicating a possible increase in temperature during the long-term fluid production to the power plant as a function of time.

References

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