Assessing the Rye Patch Geothermal Field, a Classic Basin-and-Range Resource

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Keywords

Rye Patch, Basin-and-Range, Reserve Assessment, Power Capacity

ABSTRACT

The Rye Patch geothermal field is a classic Basin-and-Range resource with a "blind" anomaly, moderate temperature and "deep circulation" as the source of heat. This paper presents a conceptual model of the field based on lithologic, geophysical and temperature logs as well as production, injection and pressure interference data from 8 deep wells drilled to date. For the hottest well in the field (405°F), we have conducted wellbore heat transfer modeling to resolve a major observed discrepancy between the flowing and static temperature profiles, the latter being shown to be affected by downflow of cooler water. The conceptual model has been developed to fit all available resource information, and had been used to estimate reserves: a minimum of 36 MW and a most-likely level of 64 MW for a 20-year project life. Based on well test data, the maximum gross power production capacity from the existing wells is estimated at 21 MW. The existing wells are capable of supplying the 12.5 MW plant installed at the site if one or two additional wells are drilled for injection.

Introduction

The Rye Patch geothermal field is located in Pershing County, Nevada. Phillips Petroleum Company discovered the Rye Patch temperature anomaly (and another one, only a couple of miles to the north at Humboldt House) in 1978, in an area where there is no surface discharge of hot water. As such Rye Patch is an example of a "blind" anomaly common in the Basin-and-Range geologic province. Like other Basin-and-Range fields it is a moderate-temperature resource with "deep circulation" as the source of heat. The project was eventually acquired by Ormat Energy Systems, who drilled a number of deep wells and installed a 12.5 MW binary-cycle power plant in 1993. However, the plant was never put on line. A succession of entities acquired rights to the project until the current owner of the project, Presco Energy, acquired it in 2001.

Figure 1 shows Rye Patch well locations combined with local geography, geology and the shallow temperature anomaly, which is described by the 10°F/100 ft contour. Within this

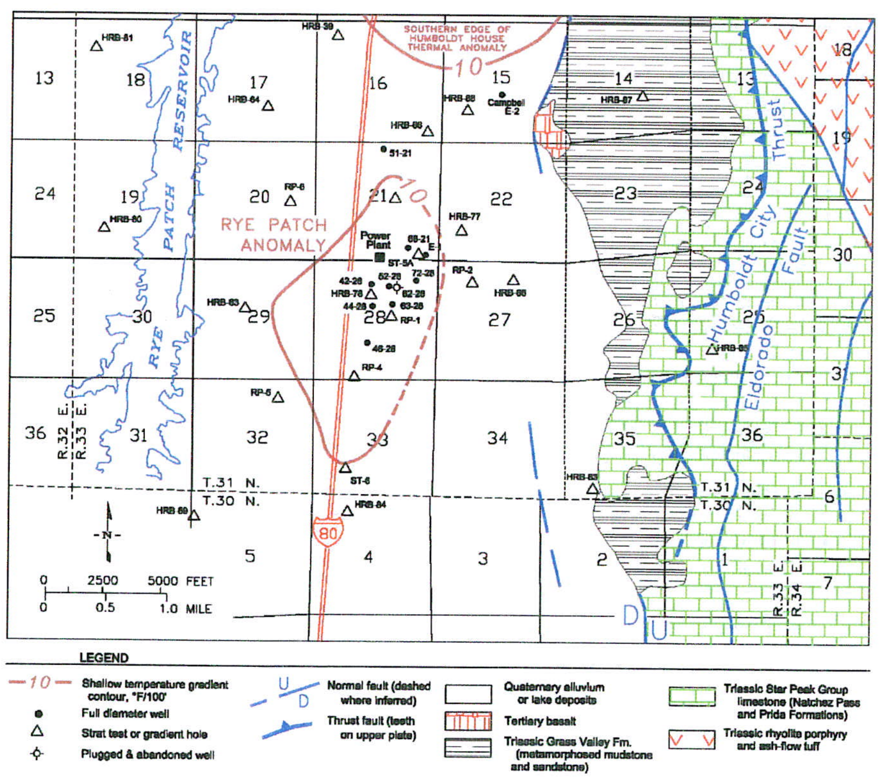

Figure 1. Well locations, geology and geography, Rye Patch, Nevada.

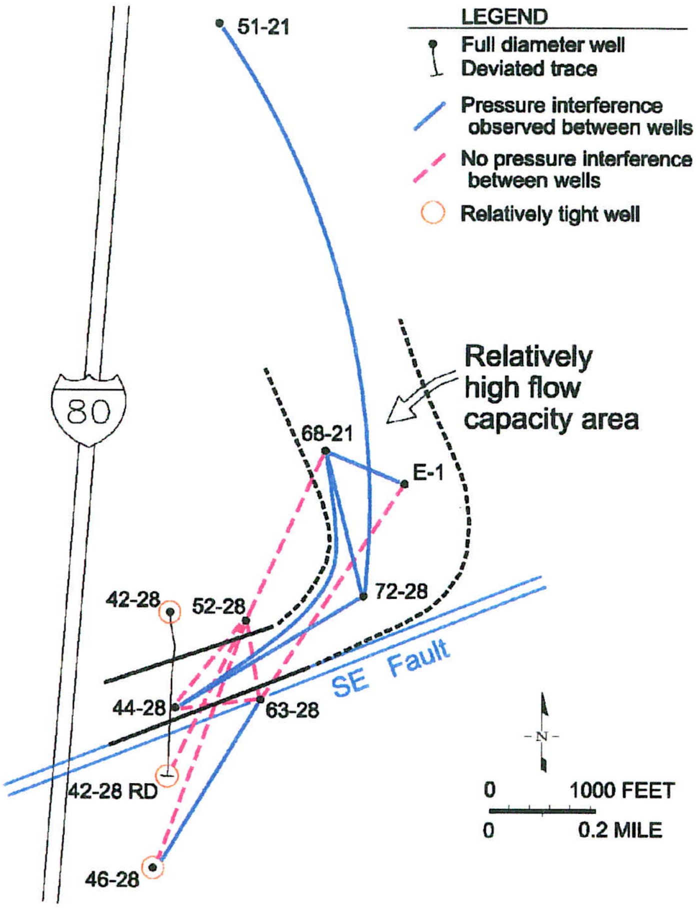

Figure 2. Definition of a relatively high flow capacity area within the Rye Patch Field.

contour, determined from shallow and deep exploration drilling, near-surface temperature (to at least several hundred feet) increases with depth at more than 10°F/100 ft. Figure 2 shows the locations of the deep and full-diameter wells drilled at Rye Patch.

Geology and Temperature Regime

The Rye Patch Field is located in the Humboldt River valley, which is a typical elongate basin of the "Basin-and-Range" structural style found throughout Nevada. Adjacent to the valley on the east is the NNE-trending Humboldt Range, a thick sequence of sedimentary and volcanic rocks of Mesozoic age, the oldest exposed in the immediate area. The sediments consist of phyllite, limestone and small amounts of siltstone and sandstone. The layers of Mesozoic rocks are tilted, so that they dip to the WNW at an angle of about 20° to 40° from horizontal.

The Rye Patch wells are well-documented by exceptionally complete lithologic and geophysical logs. These collective logs indicate that the wells penetrate younger (Tertiary) sedimentary and volcanic rocks to depths ranging from about 1,700 to 2,600 feet, before entering a part of the Mesozoic sequence of the Humboldt Range that is known as the Natchez Pass Formation. These younger rocks lie nearly horizontal, the Mesozoic rocks beneath are tilted, and the surface between the two is an unconformity that is likely to be an ancient, eroded land surface. The unconformity dips about 30° to the NW. In the wells, the Mesozoic rocks consist mainly of limestone, with lesser amounts of sandstone and siltstone. In particular, there is a sandstone and siltstone unit about 400 to 500 feet thick that separates massive limestone above and below.

Production from the field is obtained from two main zones; an upper aquifer located at the unconformity separating the Tertiary and Mesozoic rocks, or within the interval less than about 100 feet below the unconformity; and a lower aquifer located within the clastic unit separating the massive limestone units of the Natchez Pass Formation. Due to its location at and near the top of the unconformity, the permeability of the upper aquifer is probably related to karst (solution) features formed in the limestone during the development of the erosion surface. Permeability in the clastic unit is caused by fracture cleavage in the thin-bedded units formed during uplift and tilting.

Wells E-1 and 72-28 (Figure 2), because of their relatively shallow depth, encountered permeability only in the upper aquifer. Well 42-28 found permeability in the upper aquifer, which was cased off due to its relatively low temperature of 292°F, but no permeability was found in the clastic aquifer. Although well 42-28 RD-1, which was directionally drilled to the S, encountered some permeability in the clastic unit, the permeability was low. Well 68-21 also encountered permeability in the upper aquifer as well as deep in the limestone section; the clastic unit was not encountered. Due to the complexity of

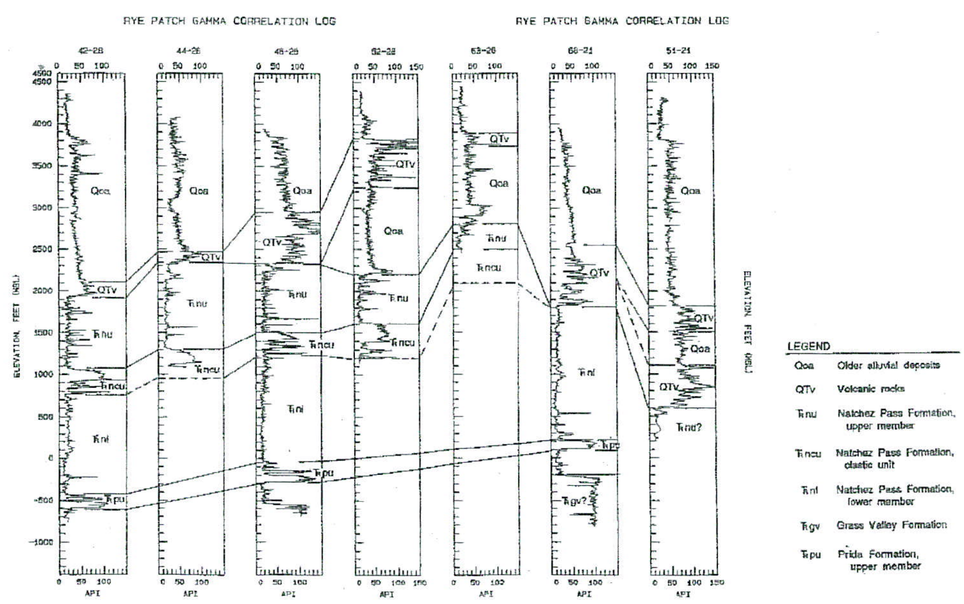

Figure 3. Stratigraphic correlation chart, Rye Patch Nevada.

the well's completion, it is difficult to determine the location of production, but the clear interference established between 68-21 and 72-28 indicates production is mainly from the upper aquifer. Well 63-28 encountered permeability 300 feet below the unconformity, which may or may not be related to solution cavities. Well 52-28 encountered permeability only in the lower aquifer. Wells 44-28 and 46-28 encountered permeability in both the upper and lower units. Although an attempt to case off the upper aquifer in 44-28 (because of its relatively low temperature) was not completely successful, the well produces mainly from the high temperature lower unit. Well 46-28 was unsuccessful due to both low temperature and permeability.

The geologic structure of the field is dominated by the presence of the unconformity and an apparent homoclinal westward dip of the underlying Mesozoic section. Based on geophysical log correlations, an example being shown as Figure 3, it is clear that bedding attitudes of the Mesozoic rocks in the subsurface are similar to those mapped to the east on outcrops of the same rocks in the Humboldt Range. In both areas, beds dip 20° to 40° to the W and WNW. A structural implication of this finding is that there is no evidence of a range-front fault separating the Humboldt Range from the Humboldt River Valley. In the Rye Patch area there is no clearly expressed fault along the western edge of the Humboldt range, and the range front could be the simple dip slope that has been created by tilting of the rocks.

Identification and mapping of faults in the subsurface have proven difficult. The only missing stratigraphic section recognized in the well logs occurs at the Tertiary/Mesozoic unconformity and, therefore, is probably due to erosion on the pre-Tertiary surface rather than faulting. The combination of well-to-well correlations and ground magnetic surveys, however, suggests the probable location of a fault that runs from WSW to ENE and appears to influence the temperature distribution and deep fluid migration in the field. The presence of this fault is supported by a distinctive distribution pattern of well flow capacities and pressure interference between wells as discussed in the next section and presented in Figure 2. The data from these tests indicate that this fault acts as a barrier to fluid flow. Wells 63-28 and 46-28 show strong pressure interference with each other but little or no interference with the other wells; the other wells, in turn, show strong mutual interference but little to no interaction with 63-28 and 46-28. Accordingly, this fault is believed to separate wells 63-28 and 46-28 from the rest of the well field.

For convenience, this fault has been named the SE (southeast) fault, because it appears to form a SE boundary to the productive area. There are two other faults, further north and running from SE to NW near wells E-1 and 68-21, which have also been identified from geophysics. These other faults, however, do not appear to have significant control on fluid migration and the deep temperature distribution.

Few of the temperature profiles from the wells show the original, undisturbed subsurface temperature distribution. Non-equilibrium transient values are due to several causes, such as, cooling caused by circulating drilling fluid; heating caused by recent production, internal well flow caused by connecting aquifers of different hydrostatic potentials (and different temperatures), and internal flow caused by convection induced in open-ended liners. In every case, therefore, determining the stabilized, pre-drilling temperatures requires some interpretation of the measured values. This need for interpretation is particularly noticeable in well 44-28, where the measured static temperature of the deep production zone is 327°F, whereas the flowing temperature of the same zone is 402°F (Figure 4). This discrepancy is interpreted to be due to downflow masking the true production zone temperature under shut-in conditions. Downflow originates from two cool zones located behind the casing or liner: a smaller inflow zone at about 300 feet behind the 13-3/8-inch casing, and a larger inflow zone at 2,100 feet at the 9 5/8-inch casing shoe. We have explained in the Appendix the basis of this interpretation using wellbore heat transfer modeling. Based on interpretation of the measured temperature profiles, temperature contour maps have been prepared at vertical intervals of 500 feet showing temperature distribution on the six elevation surfaces from +3,500 to +1,000 feet msl. These figures show temperatures increasing to the east on the upper levels and increasing to the west on the lower levels.

Figure 5, overleaf, shows the measured temperature distribution in the upper aquifer. Note that on the NW side of the fault, temperatures decrease to the SW from 354°F in well E-1 to 286°F in 44-28. In contrast, on the SE side of the fault temperatures decrease rapidly to the SSE. This pattern of temperature distri-

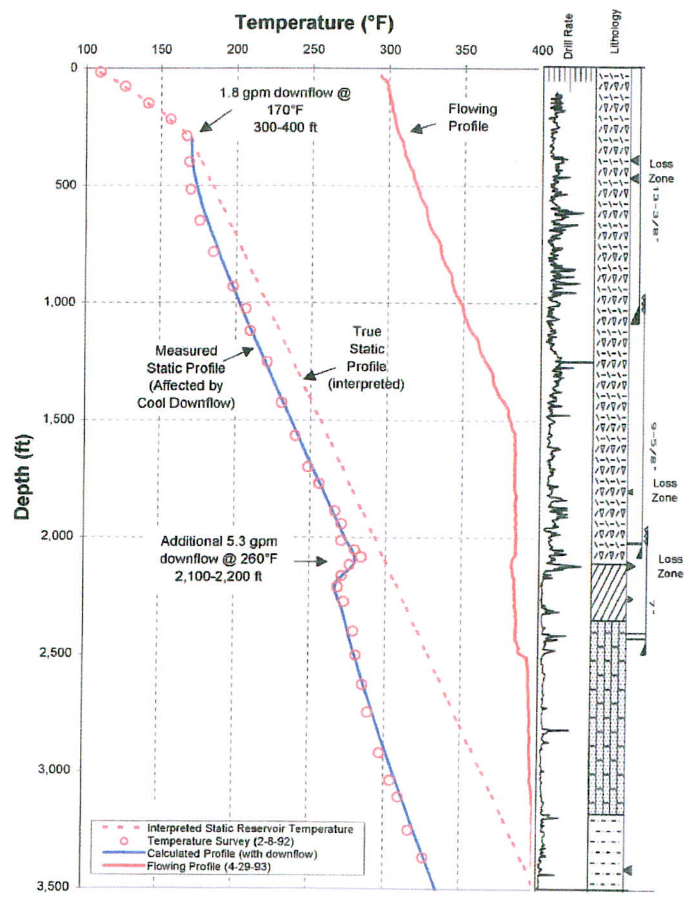

Figure 4. Static and flowing temperature profiles, Well 44-28.

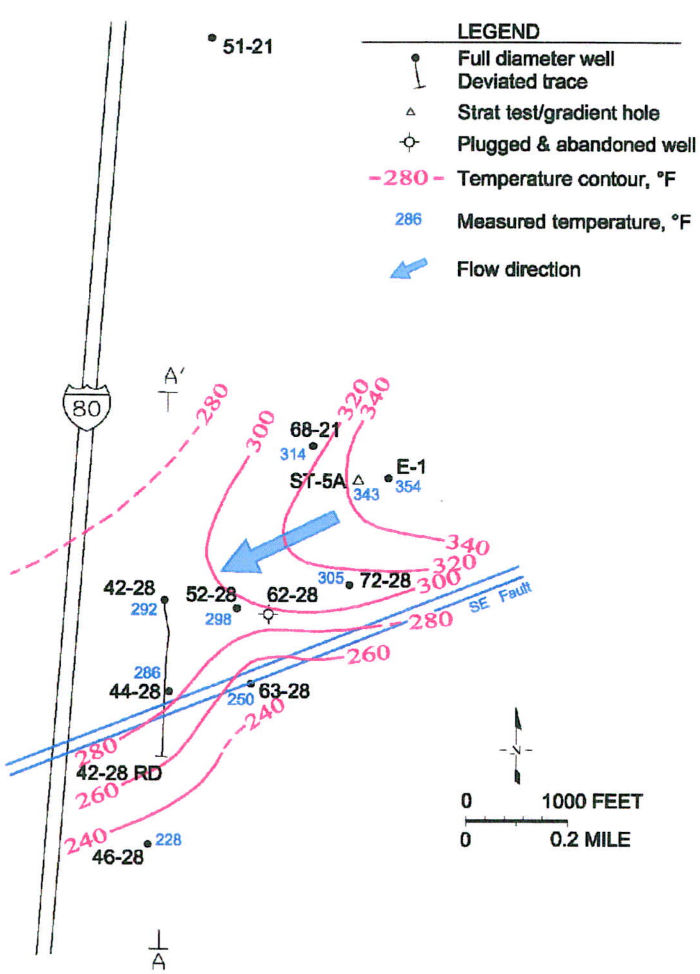

Figure 5. Temperature distribution in upper aquifer.

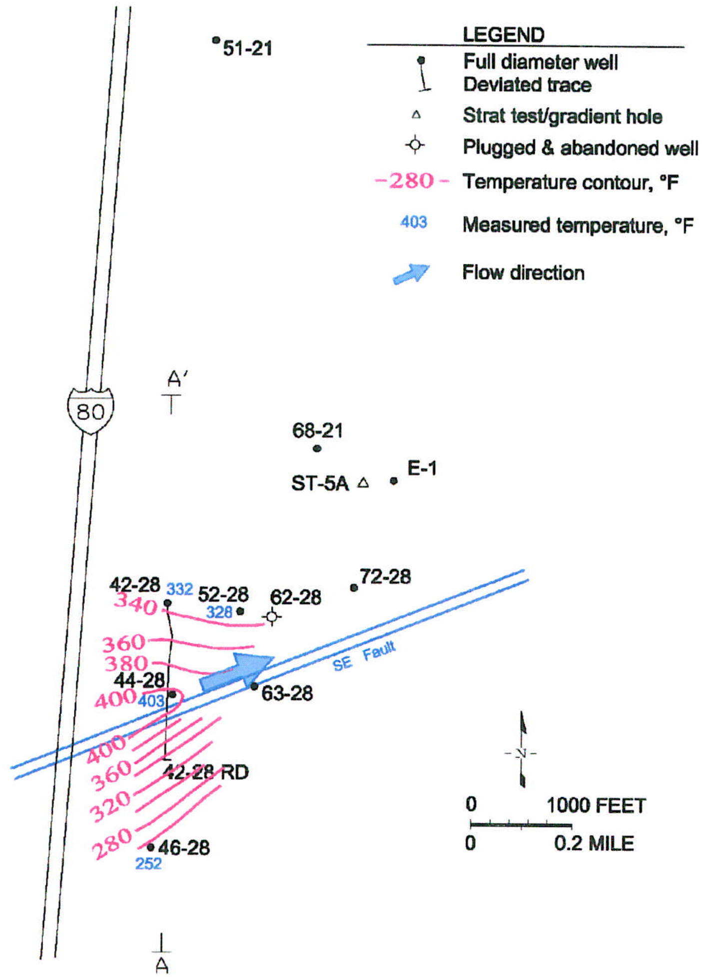

Figure 6. Temperature distribution in western part of lower aquifer.

bution implies that fluid in the upper aquifer flows down-dip to the west and is confined on the south by the SE Fault. Figure 6 shows measured temperature distribution in the western part of the lower aquifer. Temperatures in the lower aquifer are unknown in the eastern part of the field due to the lack of deep information. In spite of the scarcity of information, it appears that, unlike temperatures in the upper aquifer, temperatures in the lower aquifer are increasing toward the west, implying upflow from that direction. Chemical geothermometers (temperatures of rock-water equilibration calculated from chemical composition) were 460° to 500°F, hotter than the maximum 405°F found downhole, suggesting a hotter source at depth.

Results from Well Tests

At least 8 deep wells at Rye Patch have been tested, most of them on several occasions, for production, injection or pressure interference (in response to production or injection from neighboring wells). The following aspects of the results of analysis of well test data are particularly noteworthy:

a) Wells 72-28 and E-1, which produce from the upper aquifer, have high productivity or injectivity index values implying the presence of a high reservoir flow capacity and or high wellbore flow efficiency (otherwise represented as a high negative "skin factor").

b) This observation agrees with the postulated presence of karst features in the limestone unit forming the upper aquifer.

c) Wells 44-28 and 68-21, which appear to produce from both zones, have reasonably attractive productivity index values.

d) Wells 52-28, 63-28 and 51-21 have modest flow capacities.

e) Wells 42-28, 42-28 RD-1 and 46-28 are noncommercial, tight wells.

f) Some wells show evidence of linear flow implying the presence of a relatively narrow flow channel, as postulated below.

g) Reservoir flow capacity around the productive wells lie within a range of 20,000 to 60,000 millidarcy-feet; this range is typical for commercially developed fields in Nevada (GeothermEx, 2006).

h) Reservoir storage capacity of the reservoir lies in the range of 0.0001 to 0.0005 ft/psi, which is also typical of geothermal fields in Nevada (GeothermEx, 2006).

i) Except for well 72-28, which has an exceptionally high wellbore flow efficiency (indicated by a large negative value of skin factor), wells appear to have impaired flow efficiency (as shown by positive skin factor values).

j) Wells producing from the upper aquifer are artesian.

Figure 2 shows pairs of wells that have shown pressure interference (indicated by blue lines) and well pairs that have shown no pressure interference (indicated by dashed red lines). Tight wells are identified in Figure 2 by red circles around their bottomhole locations on the map. This figure shows the relatively high flow capacity area within the field as defined from all well available productivity, injectivity and pressure interference data.

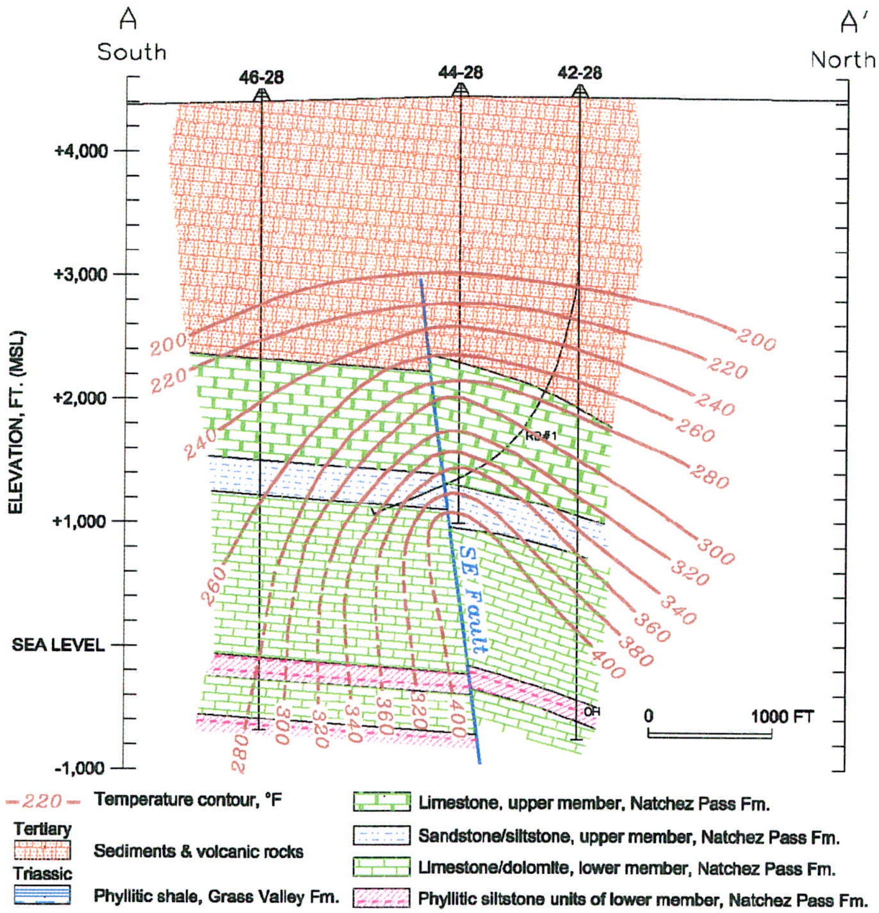

Figure 7. Schematic block diagram showing geologic control of thermal fluid up-flow, Rye Patch, Nevada.

Conceptual Model of the Reservoir

A conceptual model of the field was proposed in GeothermEx (1999) following the model presented in McNitt (1995). The model of McNitt (1995), which fits the observations in many Basin-and-Range geothermal fields, has been validated by drilling and well testing results to date at Rye Patch.

Inferred location of the SE fault and the opposed directions of fluid movement in the upper and lower aquifer, are the defining features of this reservoir model. Thermal fluid is believed to migrate, due to the buoyancy derived from its relatively low density, up-dip in the permeable clastic unit from deep in the west towards the east. However, to the SW of well 44-28, this pathway is diverted by the SE fault, which cuts through and displaces the formation. The fault acts as a barrier to fluid migration, because it juxtaposes largely impermeable limestones, and the less permeable top part of the sandstone/siltstone, against the more permeable bottom part. As a result, fluid that has been migrating upwards to the ESE is deflected and travels, still within the sandstone/siltstone, to the ENE, along a relatively narrow channel, perhaps only a few hundred feet wide, near and against the fault surface. It is possible that movement along the fault has fractured the adjacent sandstone/siltstone, enhancing its permeability. Well 44-28 succeeded in intersecting this fluid channel and was productive.

The original hole 42-28, which was noncommercial, penetrated the sandstone/siltstone unit too far from the up-flow zone. Figure 7 shows on cross-section A-A is that the re-drilled hole 42-28 RD penetrated only the top of the sandstone/siltstone before crossing the fault; section line A-A in indicated on Figures 5 and 6. Continued up-dip flow results in the fluid discharging into the upper aquifer where the clastic unit intersects the unconformity beneath the Tertiary cover. From here the fluid discharges down-dip in the upper aquifer by gravity flow.

Based on this model, Figure 8, overleaf, shows a possible temperature distribution (in dashed contours) in the lower aquifer underlying the eastern part of the field. This interpretation is supported by several observed aspects of well testing done to date at Rye Patch (see Figure 3):

- the narrowness of the WSW-ENE channel is implied by the fact that wells 42-28, 46-28 and 42-28 RD are all tight and that wells 52-28 and 63-28 have only modest permeability;
- both 44-28 and E-1 indicate more linear flow behavior than radial; and
- wells 44-28, 72-28, E-1 and 68-21 have relatively high flow capacities and communicate more readily among themselves than do the wells lying outside the channel.

The above observations agree well with the definition of the relatively high flow capacity area shown in Figure 2. This model is not a complete reservoir model, because it defines the drilled (and modeled) area as the up-flow zone of a much larger geothermal resource that lies deeper and to the west. As indicated above, chemical geothermometers suggest source temperatures as high as 460°F, and it is believed that hot-water recharge to the producing reservoir (from depth or from outside the project area) will be needed for long-term commercial exploitation. The same situation exists at other

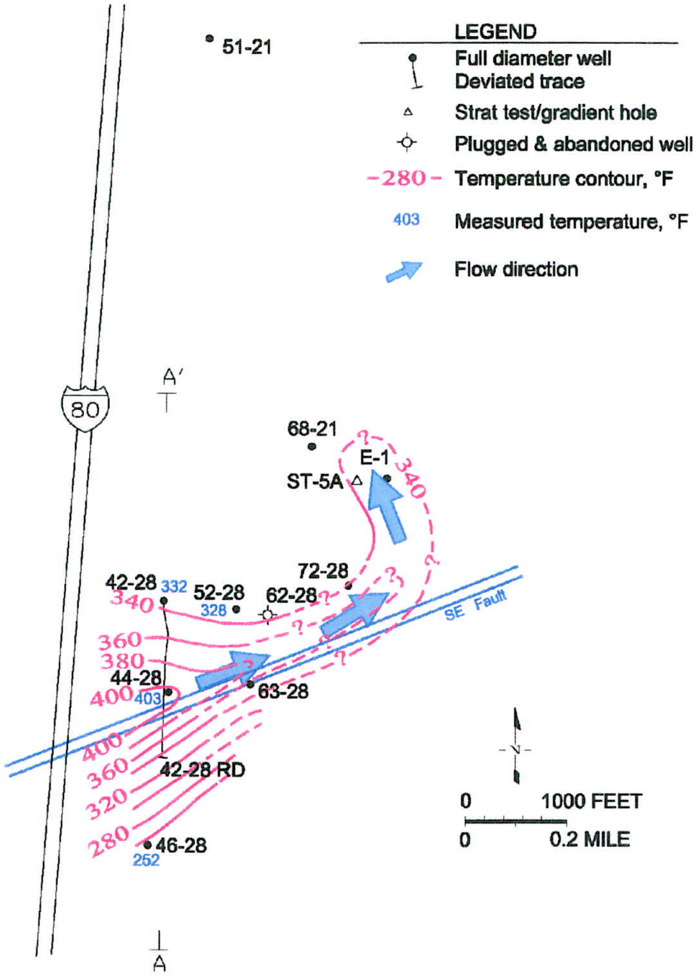

Figure 8. Possible temperature distribution in western part of lower aquifer.

commercially exploited geothermal fields in Basin-and-Range geologic province.

Available Energy Reserves

Assessment of the total energy reserves at Rye Patch is made difficult by the concentration of existing information into a relatively small area that is indicated to be the discharge zone of a larger, deeper and hotter thermal system that lies largely to the west. Since the extent of this system is unknown, we have calculated the energy in place considering mainly the area of the shallow temperature anomaly, shown in (Figure 1).

To evaluate reserves, we have employed a volumetric reserve estimation methodology introduced in 1978 by the U.S, Geological Survey; this has become the standard methodology of volumetric estimation of geothermal reserves (Muffler, 1979). We have also applied a probabilistic approach (Monte Carlo simulation) to account for uncertainties in some parameters inherent in any geothermal project.

The following parameters required for reserve estimation can be assumed for the Rye Patch geothermal field with little uncertainty:

Volumetric Specific Heat of Rock	= 39 BTU/ft$^{3}\cdot$°F (based on representative rock types)
Base Temperature	= 56°F (average ambient temperature)
Utilization Factor	= 0.45 (typical for modern geothermal plants)
Plant Capacity Factor	= 0.90 (typical for modern geothermal plants)
Plant Life	= 20 years (assumed amortization period for the project).

The following estimates of the uncertain parameters for the project were used in the Monte Carlo simulation:

Porosity:	ranges from 0.03 to 0.07 with equal probability
Recovery Factor:	ranges from 0.05 to 0.20 with equal probability
Reservoir Area (mi^2):	between 1.7 and 3.4 with equal probability
Average Temperature (°F):	between 330° and 400°F with equal probability
Reservoir thickness (feet):	between 2,700 to 5,500 feet with equal probability

The values for porosity and recovery factor are considered to be typical values for such geothermal systems. The assigned minimum value for reservoir area is the area within the 10°F/100 ft shallow gradient contour on Figure 1. Based on experience elsewhere in the Basin and Range geologic province, this is likely to be much smaller than the total area of the deep hydrothermal source reservoir; we have assumed the maximum value for reservoir area to be double the minimum. The inclusion of the area of the deeper (source) reservoir is justified by the fact that the produced reservoir will receive hot fluid recharge from the source reservoir. The minimum average resource temperature is the average of the minimum and maximum produced fluid temperatures to date. The maximum value for the average temperature has been taken to be about midway between the minimum average resource temperature (330°F) and the minimum source fluid temperature (460°F) estimated from geothermetry. The minimum value for thickness (2,700 ft) is the interval between the uppermost to lowermost zones of proven permeability plus 500 ft. The maximum value for thickness is typical for fields in the Basin-and-Range geologic settings. Monte Carlo simulation was used to estimate the cumulative probability of the existence of various levels of reserves.

Figure 9 shows the cumulative probability graph of the gross MW capacity calculated by Monte Carlo simulation for a 20-year project life. Figure 9 indicates that there is over 90% certainty that the reserves will exceed 36 MW for 20 years. The probabilistic estimation also shows a most-likely capacity of 64 MW for 20 years. These calculations describe the estimated energy in place in the geothermal system, but these levels of MW capacity can actually be sustained commercially only if wells produce at commercial rates, and the potential impact of pressure draw-down and cool water inflow from injection or surrounding cold water aquifers can be mitigated.

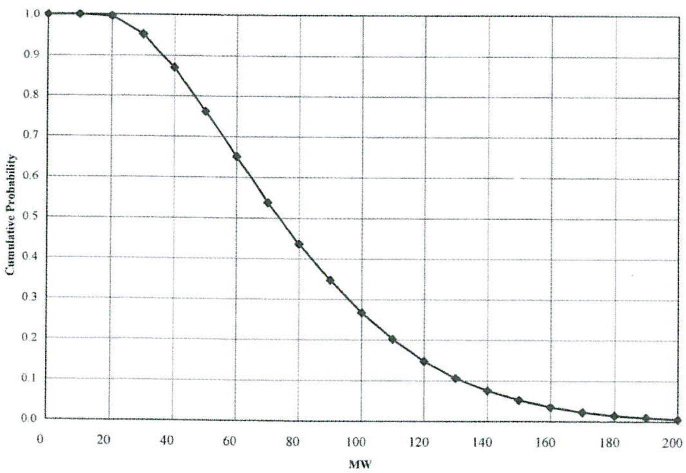

Figure 9. Cumulative probability of recoverable energy reserves, Rye Patch, Nevada.

Power Capacity Available from Existing Wells

The five available production wells at Rye Patch at this time are 44-28, 68-21, 52-28, 72-28 and E-1; in addition, wells 63-28 and 42-28 can likely be perforated, or otherwise re-completed, to produce from the upper aquifer. Well 44-28 is too hot to pump; the present pump technology allows pumping up to a fluid temperature of about 370°F. Under self-flowing condition this well has produced about 350,000 lbs/hour of 400°F water; it would be possible to rework this well to improve its productivity. The remaining wells have demonstrated production at different rates and temperatures, but all of them produce water at temperatures that should allow pumping.

The deeper the pump setting depth the higher the production rate available from a well. Given that the upper aquifer is at a depth of about 2,000 ft, this would be the maximum pump setting depth. If 13 3/8-inch casing is set to this maximum depth, a 12-inch diameter pump can be installed with a maximum pumping rate of 2,500 gpm. Wells 72-28 and E-1 have 13 3/8-inch casing at depths shallower than 2,000 ft; in these wells smaller diameter pumps, capable of producing at a maximum rate of 1,200 gpm, will have to be used. Assuming that these smaller pumps are used in all wells except 44-28, which can be self-flowed, the expected flow rates and temperatures are as shown in the table below. The gross power capacity of the wells have been estimated from First and Second Laws of Thermodynamics assuming a utilization efficiency of 45%.

Well	Maximum Production Rate (lbs/hour)	Temperature°F	Maximum Gross MW Capacity
44-28	350,000	400	3.6
68-21	510,000	310	3.1
52-28	510,000	320	3.3
72-28	510,000	305	3.0
E-1	510,000	325	3.5
42-28	510,000	292	2.7
63-28	510,000	270	2.3

The above table indicates that the maximum available production from the 7 existing potential producers is about 21 MW of gross power capacity, not counting the parasitic demand of injection and production pumps. Since the capacity of the existing power plant at Rye Patch is 12.5 MW, not all the wells listed in the table need be used as producers; some of them could be used as injectors.

Wells E-1 and 63-28 have been used as injectors in various well test programs in this field. While well E-1 has good injectivity, injection in this well introduces the risk of cooling one or more production wells in the high flow capacity area. Well 63-28 is a poor candidate for injection because of its low injectivity; in addition, being adjacent to the high flow capacity corridor, it may cause cooling in some producers. Well 51-21 is located far enough from the production area to pose any cooling problem, but it is relatively tight. Given that well 44-28 is not in mechanically sound condition and would add the complication of combining a steam-producing well with pumped wells to supply the power plant, this well could better be used, at least temporarily, as an injector. Injection in well 44-28 does carry some risk of cooling certain production wells but the risk is smaller than it would be if well E-1 were used as an injector. This scheme may be reasonable for plant start-up and operation until, and if, cooling due to injection in well 44-28 becomes a nuisance, in which case injection may be relocated to a new injector.

A possible scheme to supply the existing 12.5 MW plant would be to produce wells 68-21, 52-28, 72-28 and E-1, which have a combined gross capacity of 13.7 MW; the net capacity after deducting parasitic power should be close to 12.5 MW. It should be noted that the parasitic power required to pump the wells would be small because the wells are artesian. If these 4 wells provide a total net capacity of less than 12.5 MW, either well 42-28 or 63-28 or both can be perforated (or re-completed) in the upper aquifer and be produced to bring net generation to 12.5 MW. If the four existing producers can supply the 12.5 MW plant, either 42-28 or 63-28 or both can be perforated (and or re-completed) and kept as stand-by-wells. Well 44-28 and 51-21 can be used as injectors, but one or two additional injection wells will have to be drilled to secure the required injection capacity.

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APPENDIX: Interpretation of Temperature Profile in Well 44-28

The measured static temperature at the deep production zone in well 44-28 is 327°F, whereas the flowing temperature of the same zone is 402°F (see the solid red curve in Figure 4). This discrepancy, as we prove below , is due to downflow, essentially trickles, of cooler water in the static well masking the true formation temperature outside the well (dashed red curve in Figure 4), the result being an artificially depressed temperature profile (solid black curve in Figure 4). By calculation of heat transfer in the wellbore due to inflow of cooler water from one or more zones in the well under static condition, we have resolved the discrepancy as follows. Heat transfer in the shut-in well due to inflow of cooler water and its travel from the point of inflow downwards through the well has been estimated as follows (Horne and Shinohara, 1979). If a well segment of vertical length dz gains heat at a rate dq from the formation, then:

$$\frac{dq}{dz}=\frac{2\pi krU}{k+rUf(t)}(T_r-T), \qquad (1)$$

where T = water temperature (°F),
T_r = formation temperature (°F),
k = thermal conductivity of the formation (Btu/ft/D/°F),
r = inner radius of well casing (ft),
U = overall heat transfer coefficient between well and formation (Btu/ft^2/D/°F), and
f(t) = a dimensionless time function.

The dimensionless function f(t) is given by:

$$f(t)=\frac{-\ln r'}{2\sqrt{\alpha t}}-0.29, \qquad (2)$$

where r′ = outer diameter of well casing (ft),
α = thermal diffusivity of the formation (ft^2/day), and
t = time elapsed (day).

From an over-all heat balance on the well segment and considering the heat gained by water as it flows down the injected well, the water temperature (T) at the bottom of the segment as a function of elapsed time (t) can be derived from:

$$T(t)=T_f+az-aA+(T_i-T_f+aA)e^{-z/A(t)}, \qquad (3)$$

where T_f = formation temperature at the top of the segment (°F),
Ti = water temperature at the top of the segment (°F),
a = vertical temperature gradient in the formation within the segment (°F/ft), and
z = vertical length of the segment (ft).

In equation (3), A(t) is a "diffusion depth", defined as:

$$A(t)=\frac{Wc[k+rUf(t)]}{2\pi krU}, \qquad (4)$$

where W = injection rate (lbs/hour), and
c = specific heat of water (Btu/lb/°F).

Equation (4) can be approximated for all practical purposes as:

$$A(t)=\frac{Wcf(t)}{2\pi k}. \qquad (5)$$

By trial-and-error calculation of heat transfer in the static wellbore we have been able to match the observed temperature profile (red circles in Figure 4) and the calculated temperature profile (solid black curve) in the static well. This matching required introduction of two small inflows of cooler water into the well, either actually entering the well or trickling behind the pipe around the well:

a) 1.8 gallons per minute of 170°F water at a depth of about 300 ft, which is behind the 13 3/8-inch casing and

b) 5.3 gallons per minute of 260°F water at a depth of 2,100 ft, which is at the 9 5/8-inch casing shoe.

The physical reasons for these inflows are obvious. The upper inflow is behind the 13 3/8" casing probably due to poor cement bond at the major circulation loss zone (also marked by sudden increase in drilling rate, as shown in Figure 4). The lower inflow zone is at the major loss (and high drilling rate) zone representing the upper aquifer; the attempt to isolate the upper zone by installing the 7-inch casing was unsuccessful.