Benefit of a Typical Injection Well at The Geysers Field

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ABSTRACT

An Injection Benefit (IB) Model for a typical injection well has been developed for The Geysers Field. The IB Model is a spreadsheet based model which consists of actual and/or proposed injection rate for wells in gallons per minute (gpm) and converts the injection rate to an average megawatt (MW) increase in steam flow and is based on a rate analysis and a material balance for the entire Geysers Field and is a function of time. One aspect of the IB Model is the calculation of Injection Derived Steam (IDS) which is a tank-model and incorporates the water augmentation history of The Geysers Field and future plans for reservoir management.

The Geysers Field at the end of 2013 is made up of approximately 448 wells and electrical generation was 890 MW gross and the injection mass replacement ratio has increased to an annual rate of 78%. As the program of augmented injection has brought mass injection into near-parity with mass production, the rate of reservoir pressure decline has been significantly reduced such that steam flow decline is between 1 and 2%. An IB Model was successfully applied to California Division of Oil, Gas and Geothermal (CDOGGR) data for The Geysers Field. Historical flow data between 1987 and 2013 is included in a single model. Based on study results of a tank-model for The Geysers Field, 83% of water injection is boiling and is needed to match production. A 500 gpm injection well brings about a 4 MW benefit over ten-years. Although this paper documents the overall use of a single tank-model for the entire Geysers Field, the tank-model can be subdivided into two or more parts when a model doesn't give satisfactory results.

Introduction

The Geysers Field, located in Lake, Sonoma, and Mendocino Counties, California is the largest developed geothermal system in the world since 1973. Electric power generation started at The Geysers Field in 1960 with a 12 MW (gross) plant (PG&E's Unit 1). Injection of plant effluent, known as condensate began in April 1969, into well Sulphur Bank 1, with the startup of PG&E's Unit 3. Condensate injection alone replaces $\sim 22\%$ of mass steam withdrawal from the reservoir. This net loss of mass is due to the fact that geothermal power plants typically lose between 70 to 80% of the produced mass to evaporation in the cooling towers, depending on ambient conditions.

The total installed capacity in the field peaked in 1989 at 2,043 MW. As more and more power plants were built during the 1970s and 1980s and cumulative net mass withdrawals increased with time, reservoir pressures declined, eventually resulting in steam shortfalls and declining generation levels.

In response to this decline, field operators made modifications to augment injection and distribute water throughout the reservoir., it was determined that injection of water from outside sources was the most effective method of managing the long-term decline in the resource.

There are three significant injection augmentation programs: 1) Capture and injection of excess rain water, especially from the Big Sulphur Creek starting the early 1980s, 2) Injection of treated effluent from Lake County into the Southeast Geysers, known as the Southeast Geysers Effluent Pipeline (SEGEP), starting in late 1997, and 3) Injection of treated effluent from communities located in central Sonoma County, known as the Santa Rosa Geysers Recharge Pipeline (SRGRP), starting in 2002. (Figure 1)

Electric power generation started at The Geysers in 1960 with a 12 MW (gross) plant. The first commercial test of injection into the deep reservoir occurred when condensate from Units 1 and 2 was injected into TH-12 from April 29, 1965 through May 3, 1965. The test was stopped when water production from TH-12 broke through to well TH-8, resulting in curtailment of Unit 2. Two wells (GDC 58I-11 and GDC 38I-11) were then drilled outside of the steam reservoir for condensate disposal, but neither had sufficient injectivity. Following the startup of Unit 3, successful injection was established into SB-1 by the steam field operator Union Oil. SB-1 was chosen as an injector because it was relatively far from existing production and would not interfere with major steam producers. Tritium tracer into SB-1 later confirmed that flashed water was traveling to offset production wells. During the 1970s, injection grew but only as a result of the startup of additional power plants.

As more and more power plants were built and net mass withdrawals increased, reservoir pressures and corresponding well productivities began to decline at alarming rates. To maintain generation capacity in the face of rapid productivity decline, too many make-up wells were drilled in some parts of the field, which caused excessive interference between wells, further reducing well productivity. By 1989, drilling additional make-up wells became largely uneconomical, and the generation capacity was allowed to decline.

By 1991 the decline in generation at The Geysers had attracted the attention of the California Energy Commission (CEC), which funded an engineering study, including numerical simulation of the reservoir and a Pipeline Model to investigate options to mitigate the generation decline. Reservoir modeling showed that injection of water from outside sources was the most effective method of managing the rate decline in the geothermal resource.

The siting of injection wells becomes largely a way to aug-

ment steam benefit or alternatively, a source of IDS. Injection is considered as a pressure maintenance program. It also becomes a way to reduce non-condensable gas concentrations that results in both reduction in abatement chemicals and reduction in ejector steam.

There are three benefits due to injection at The Geysers:

Benefit 1

The calculation of the benefit of IDS production is based on the anticipated mitigation in the decline of reservoir pressure and steam flow rate. A tank-model which is a decline based model of actual reservoir performance is used to simulate the reduced decline rate based on the anticipated improvement due to augmented boiling of water. Prior to augmented injection by SEGEP and SRGRP, the decline rate of 6.5% harmonic (starting in 1987) is calculated for The Geysers. Calculated augmented injection is then incorporated to determine the new steam decline rate as compared to historical steam decline prior to the startup of augmented injection. This method is supplemented and confirmed with the tank-model.

Benefit 2

A reduction in non-condensable gas con-

centration leads to two benefits a) reduced steam for first stage injectors, and b) reduced H2S abatement costs. A cost model of these processes based on historical non-condensable gas concentrations with and without augmented injection is used to quantify the benefit. The non-condensable gas concentration reduction due to injection has been documented by Beall (2007) and incorporated into the IB Model.

Benefit 3

Condensate injectors are required to keep power plants online. The benefit of an injector is based on its anticipated share of condensate injection over the project life of the wells. If multiple injection wells are available for the plant, then the value to the plant is split between the available wells. The cost of the injection well is amortized over the expected life and required rate of return.

The IB Model is based on the three methods described above. The remainder of the paper documents the IDS recovery of an injection well with the tank-model.

Production and Injection Data Base

The Geysers database of the California Division of Oil, Gas and Geothermal Resources (CDOGGR) was the only source of production and injection information used in this study (Figure 2). CDOGGR has excellent quantity and quality information. There are over 50-years of well data on The Geysers. The GeoSteam Data Base and Well Finder is a convenient online method for retrieving CDOGGR data. There are more than 18,000 monthly records on injection alone (Austin 2014).



Figure 1. The Geysers Geothermal Field conceptual model showing the steam production wells (green dots) and the extent of the normal vapor dominated steam reservoir at a near pre-production temperature of 465F +/-. In the northern Geysers the underlying high temperature zone (in yellow) provides for higher enthalpy and longer-lived, more efficient heating and boiling of injected water. The water distribution system is shown for Calpine's wells and includes the BSC Extraction, SEGEP Pipeline and SRGRP Pipeline. Modified after Beall 2007.

Expressing water injected as an Annual Mass Replacement (%) is shown on Figure 3. Note that between 1987 and 1994, not only does the production decline smoothly, but the mass replacement is nearly a constant 28%. This forms a basis for the decline curve analysis. For the post-1994 field-wide production data, the increasing augmented injection must be included in the tank-model.





Figure 3. The Geysers Field monthly production and annual injection data. To match the 1987-2013 production data, the injection data was split into three periods: Period 1: 1987-1994, Period 2: 1995-2002, and Period 3: 2003-2013.

IDS Recovery Using Tank-Model(s)

Any reservoir study is driven by three basic criteria: 1) time and effort that can be allotted to the study, 2) quantity and quality of available data, and 3) usage of the results. The quantity and quality of information are functions of a number of variables including known reservoir boundaries, number of production and injection wells, initial thermodynamic properties of the wells, and initial fluid conditions. The results of the study depend on whether the Field is wholly owned or joint partnership, the net value of produced product, and the amount of government assistance available.

The basis for IDS recovery for this reservoir study is a tankmodel which views a reservoir as a container or tank. Graphically, the reservoir is shown as a cube. The tank is assumed to be homogeneous, or have uniform properties throughout. The tankmodel is a zero-dimensional model because reservoir properties are uniform throughout. Pressure is the same throughout the reservoir, and a change in pressure in one point of the reservoir **Figure 2.** Monthly production and injection data as reported by California Division of Oil, Gas and Geothermal Resources for The Geysers Field. Note that production peaked in 1987 at nearly 30,000 thousand-pounds per hour of steam and has been declining since. The monthly injection data is subject to much variation and the condensate is dependent on atmospheric temperature amongst other things. Modified after Enedy 2010.

is instantaneously reflected at all other points in the reservoir. Most importantly, the reservoir is considered to have sealed boundaries which do not allow fluids to naturally flow in or out of it. The cumulative effect of production can be calculated by use of the Material Balance Equation. A modeler can divide the reservoir into two or more tanks, if these assumptions place significant deficiencies in the reservoir study.

For the purpose of the tank-model, The Geysers Field can be taken as a whole or subdivided into various parts. For the purpose of this reservoir study, The Geysers Field is taken as a whole. For the purpose of valuing the benefit of an injection well, Calpine usually divides The Geysers Field into three or more sections.

The tank-model simulator is based on two sets of equations: 1) a mass balance involved in solving Arps Equations (Poston 2007) for flow rate and 2) a material balance involved in a phase change from water injected to steam produced. The equation of a line is fitted to a historical production decline curve. Future performance is calculated by manipulating the equation to solve for cumulative production. The strength of the analysis of production decline curves is that production data is available. The weakness of the analysis is that changes in operating conditions alter the shape. For The Geysers Field, the majority of production wells, injection wells, power plants, and injection augmentation projects have been completed and the reservoir acts

somewhat like a tank.

Equations Used With Tank-Model

Arps Equation is used to model production performance at The Geysers:

$$W(t) = Wi * ((1 + b*Di*t)^{(-(1/b))})$$
(1)

$$Wp = (Wi^{b}) / ((1-b)^{*}Di)^{*} (Wi^{(1-b)} - W^{(1-b)})$$
(2)

$$b = 1.0,$$

Di = 6.5%,

The Material Balance Equation:

WpIDS	= Water Injection * IDS Recovery	(3)
Water Injection	= DOGGR Geysers Field Annual Water	
	Injection: 100% water (thousands of	
	pounds)	
IDS Recovery	= fraction of water injection flashing to	
	steam that is needed to match historic	cal
	production rates (thousands of pound	s).

History Matching

Historical production and injection data as described earlier were inputs into the model, which was then allowed to run for the period from 1987 through the end of 2013. Numerous runs of the tank-model were made, adjusting the above rates on a trial-anderror basis, until a good match was obtained between observed and calculated flow rates. It was found that the best match of Monthly Production was obtained by using the *Steam Production from Injection* as shown in Figure 4. The overall average is shown for the period from 1987-1994, 1995-2002, and 2003-2013 and the average for each of the periods is 8%, 72%, 83% respectively. For each of the periods, the required *Steam Production from Injection* is increased.



Figure 4. Graph showing actual and forecast Geysers injection needed to boil and used as production support for the period 1987 to 2020. Note that the forecast starting in 2014 assumes that 104 billion pounds of water are injected and 88 billion pounds of steam boil and will be required to support the production rate (83%).



Figure 5. Tank-Model match of Monthly Geysers Field production rates with and without augmented injection programs.

The modeled decline without augmentation is best modeled with a Di = 6.5% with an 8% injection recovery factor between 1987 and 1994. This is shown on the green line (triangles) on Figure 5. The modeled decline with the SEGEP and SRGRP Pipelines are shown in red, and include the *Steam Production from Injection* which average 72% and 83% between 1995 and 2002 and 2003 to 2013.

Focusing on the post-1987 data, and including a steam usage factor, the tank-model results are shown on Figure 6 and it includes a steam conversion factor that is estimated for the Geysers Field.







Figure 7. Tank-model results showing the benefit of a 500 gpm injection well.



Figure 8. Changing flow rates to MW vs. time by using 18.5 pounds / kilowatt-hours results in 165 MW due to the increased augmented injection programs (SRGRP and SEGEP).

What benefit can we expect for a single injection well? It depends on the injection rate of that well. The injection rate is dependent amongst other things on the deep permeability available on the well and the general location of the well. Figure 7 represents the total benefit for a 500 gpm "robust" injector located in the northern Geysers Field. If an operator drills an injection well, at first there is a little response, but at the end of 10 years, it's benefit is over 4 MW.

Field-wide tank-model results, shown in Figure 8, indicate that increasing the volume of water through the SEGEP and SRGRP injected into the The Geysers Geothermal Field increased the generation rate by 165 MW at the end of 2013 or 27% (165/603 MW). These curves are shown for the period 1987 to 2013.



Figure 9. Semi-log plot of Rate vs. Cumulative Production for the period 1987 through 2070. The red squares show the benefit of augmented production and the blue diamonds are without augmented injection (SEGEP+SRGRP). The straight-line is characteristic of harmonic decline.

Another way to show the harmonic fit for The Geysers Field is Flow Rate (W) vs. Cumulative Production (Wp) in a semi-log straight-line analysis. This is the harmonic fit taken from 1987 through 2070 (Figure 9). The straight line of the data verified that this is a harmonic data trend & Di = 6.5%. The cumulative reserves are 4.6 and 7.8 trillion pounds and are the intrinsic reserves with without SEGEP and SRGRP augmented injection.

Conclusions

A tank-model was developed for The Geysers Field. Adjusted harmonic decline curves that incorporated the water injection augmentation programs fit the data. The combined IB for the two major augmentation programs at The Geysers is 165 MW as of 2013. The tank-model results of an average 500 gpm injection well at The Geysers is 4 MW after 10-years of injection. The Geysers Field continues to benefit from proper reservoir management that includes water augmentation.

Nomenclature

W	= steam production rate, pounds per hour
Wi	= initial steam production rate, pounds per hour
Wp	= cumulative steam production, pounds
WpIDS	= cumulative injection, converted to steam, pounds
D	= continuous decline rate, 1/unit of time
Di	= initial decline rate, 1/unit of time
Т	= time, usually year(s)
WDd	= dimensionless decline steamrate
WpDd	= dimensionless decline cumulative steam production
	function

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