Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Coupled Processes Analysis of Flexible Geothermal Production from a Liquid-Dominated Geothermal System: Impact on Wells

Jonny Rutqvist, Lehua Pan, Nicolas Spycher, Patrick Dobson, Quanlin Zhou and Mengsu Hu

Lawrence Berkeley National Laboratory, Berkeley, California, 94720, USA

JRutqvist@lbl.gov

Keywords: Casa Diablo, flexible generation, T2Well-FLAC3D, coupled processes, well integrity, thermal expansion, variable production, thermal pressurization, scaling

ABSTRACT

We summarize results from a study on the potential impact of flexible geothermal production on production rates, well integrity and reservoir behavior. The impact on production rates and well integrity is performed by coupled process modeling based on linking a reservoir-wellbore simulator with a geomechanical simulator, whereas potential scaling is analyzed by geochemical modeling. We consider production from a liquid-dominated system using data from the Casa Diablo geothermal field, California. The simulations related to well integrity show that production-induced temperature and pressure changes can cause non-linear mechanical responses, including frictional sliding at material interfaces and material yielding. However, if the production rates are controlled between certain limits, e.g., ramping up production slowly and not completely shutting down the production in each cycle, the impact on the well assembly can be minimized. Simulations of scaling show that the effects of scaling and corrosion can be controlled by keeping the wellhead pressure above the saturation pressure and at the same time keeping the temperature above the silica saturation temperature.

1. INTRODUCTION

The increased use of intermittent renewable energy sources (primarily wind and solar) increases demand for operational flexibility of other renewables such as geothermal energy. Negative pricing during periods of abundant, cheap power has resulted in curtailment at some geothermal power plants. Converting from (steady) base-load to (variable) flexible geothermal production may result in significant changes to the system related to corrosion and mineral deposition (scaling) in wells, mechanical damage fatigue to well components, or the reservoir. One of the main challenges related to the conversion from base-load to flexible-mode production is wellbore integrity. Flexible-mode geothermal production typically includes daily cycles in production that may result in extraordinary stress on the wellbore and reservoir system. Thus, there is a need to investigate the effects of flexible-mode production on well integrity over the operational life of a geothermal field to be able to optimize the total production and production flexibility at a reduced risk and cost of well failure.

In this study, funded by the California Energy Commission (CEC) to Lawrence Berkeley National Laboratory (LBNL), the effects of variable geothermal production on mechanical well integrity are investigated using modeling of coupled flow, heat and mechanical responses in the well assembly. The impact on production rates and well integrity is evaluated by coupled process modeling based on linking a reservoir-wellbore simulator (T2Well, Pan and Oldenburg, 2014) with a geomechanical simulator (FLAC3D, Itasca, 2012), whereas potential scaling is analyzed by geochemical modeling (CHILLER; Reed 1982, 1998). Results for a steam-dominated system were reported in Rutqvist et al. (2018). In this paper we present new results for a liquid-dominated geothermal system using published site-specific input data from the Casa Diablo geothermal field. The results are focused on the impact on well integrity and potential for scaling and corrosion within the well.

2. CASA DIABLO GEOTHERMAL FIELD

The Casa Diablo geothermal field is located in the southwestern moat of the Long Valley Caldera, east of Mammoth Lakes, California. Early exploration drilling conducted in the 1960s first identified this resource, located near the Casa Diablo hot springs and fumaroles (Suemnicht et al., 2007, Suemnicht, 2018). Power production at Casa Diablo was started in January 1985 with an initial capacity of 10 MW; two additional 15 MW plants were brought online in Dec. 1990 to increase the field capacity to 40 MW (Sorey et al., 1995). The power plants are binary due to the moderate temperature reservoir fluids. Current production comes from two locations – the original well field near Casa Diablo, where shallow (~200 m) wells produce fluids of ~170°C, and a newer production zone near Shady Rest (Basalt Canyon) that was added to the field in 2006 – this area has deeper production wells (~450 m) that have reservoir temperatures of around 185°C (Suemnicht, 2018). The current field operator, Ormat, has proposed to increase the field capacity to approximately 60 MW. In this study we use well geometry and conditions from well MBP-4, which is a relatively shallow well with a depth of 205 m at Casa Diablo.

While data from most of the existing production and injection wells of the Casa Diablo geothermal field are considered confidential, there are several wells within the California Division of Oil, Gas and Geothermal Resources (CA DOGGR) GeoSteam database that do have publically available records. The two wells that we have selected for the basis of our models are MBP-3 and MBP-4, which are located within the main portion of the Casa Diablo geothermal field. These wells, only about 60 m apart, were two of the early production wells for this field, and well and production tests reported by Miller and Vasquez (1988) provide detailed results on well flow rates, temperatures, and production during the first few years of production. The DOGGR GeoSteam database also contains additional information on the well completions, well log data, and a temperature log (for the MBP-3 well). Temperature data are also presented by Farrar et al. (2010). The stratigraphy of the MBP-4 well consists of two main units: the Casa Diablo basalt, which is present in the upper 25 m of the borehole, and the Early Rhyolite, which extends through the remainder of the borehole. It is described as varying in character from rhyolite, rhyolite glass, rhyolite breccia, and rhyolite tuff.

In this modeling study, the design of production well MBP-4 is adopted, while data from a number of adjacent wells are utilized to derive reasonable initial reservoir conditions for the modeling. The design of the MBP-4 production well is shown in Figure 1 along with geologic stratigraphy. Production occurs from an open borehole section with a slotted liner extending from 126 to 205 meters depth. As indicated in Figure 1, a downhole pump (shaft turbine pump) is installed to maintain well pressure.

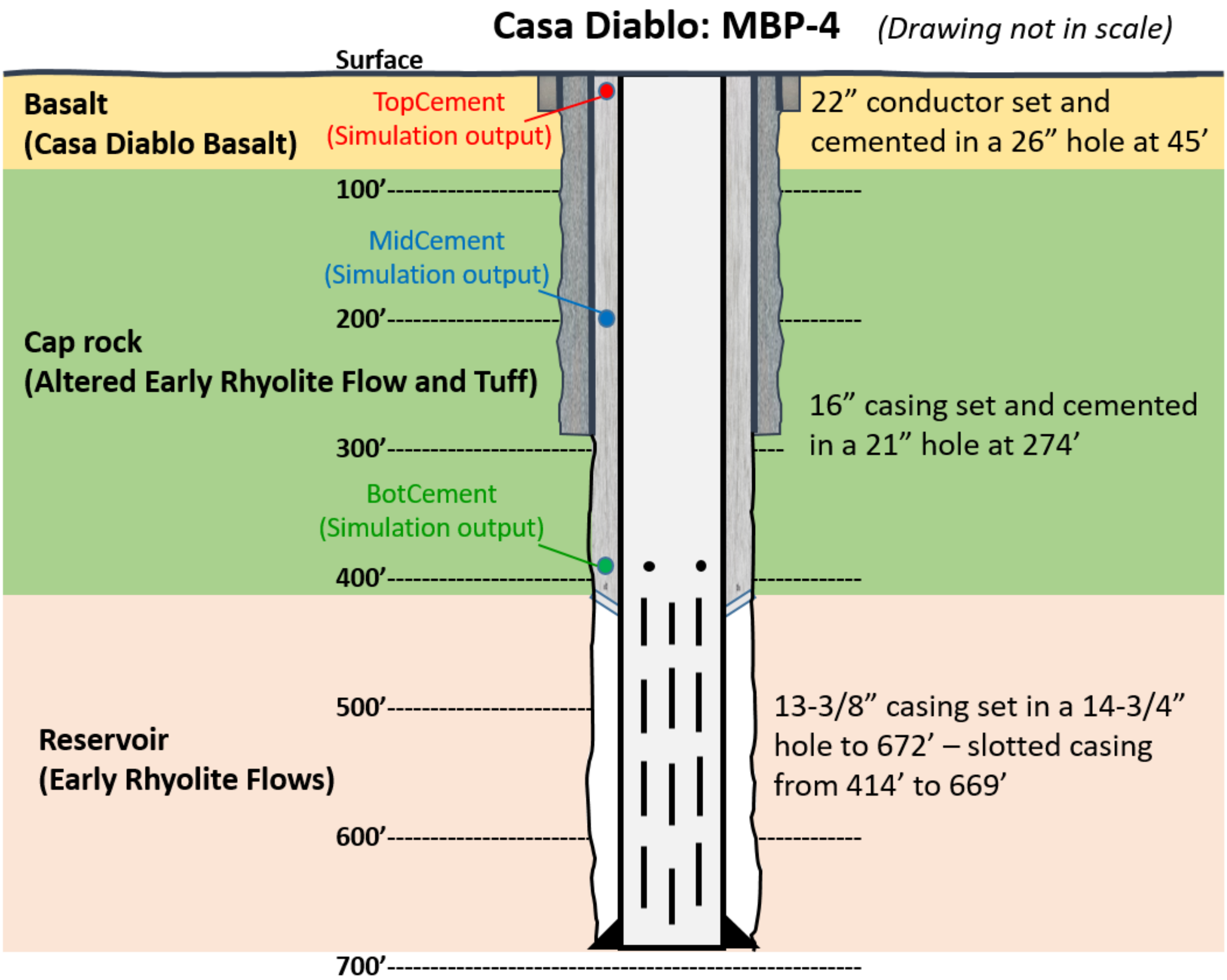


Figure 1: Casa Diablo MBP-4 production well geometry and geological units in the model (redrawn from DOGGR GeoSteam Data Base file).

3. MODEL SETUP FOR RESERVOIR-WELL INTEGRITY ANALYSIS

The well simulations of Casa Diablo (MBP-4) were conducted by an initial thermal-hydraulic analysis using T2Well, followed by a coupled T2Well-FLAC3D analysis of well integrity and a CHILLER geochemical analysis for scaling. Different but linked model domains are used in T2Well and FLAC3D (Figure 2). The thermal-hydraulic analysis with T2Well requires discretization of the entire well assembly and surrounding rock formations, while the mechanical analysis is focused on different sections of the well. For example, the mechanical analysis was in most cases focused on shallow regions of the well where the largest pressure and temperature changes could occur (Figure 2). The models include the details of the well assembly as well as the relevant geologic units, including reservoir and caprock. The models extend horizontally 1 km from the well. In the T2Well model, a constant back pressure is applied at the outlet of the wellhead with a fixed mass flow rate above the slotted zone to simulate the down-hole pump control of well pressure.

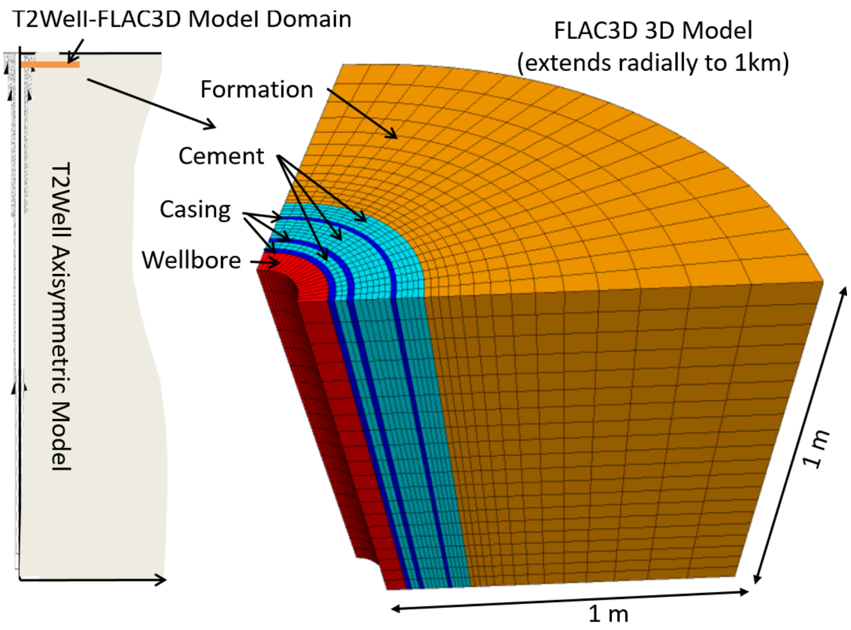


Figure 2: Coupling and interactions between T2Well for reservoir-wellbore multiphase flow and multicomponent transport modeling and FLAC3D for geomechanical modeling, with application to wellbore integrity analysis by including reservoir, wellbore and high +ΔT zone.

The initial conditions of pressure and temperature were established based on early production field data at the Casa Diablo geothermal field (Miller and Vasquez, 1988). Figure 3 shows the initial temperature used in the model and measured temperature profile in a well located about 60 m away from the MBP-4 production well (Farrar et al., 2010). Material properties are listed in Table 1. The geological unit denoted as "HotZone" is the main feed zone of the reservoir whose permeability has been adjusted manually by matching the simulated and measured flowing bottom hole pressures during a well production test (MBP-4) performed on July 6, 1984 along with the initial reservoir pressure. All other parameters are from the literature or best estimates for similar kinds of materials. Another input to the T2Well simulation is the internal wall roughness of the production well, which is assumed to be 45 microns.

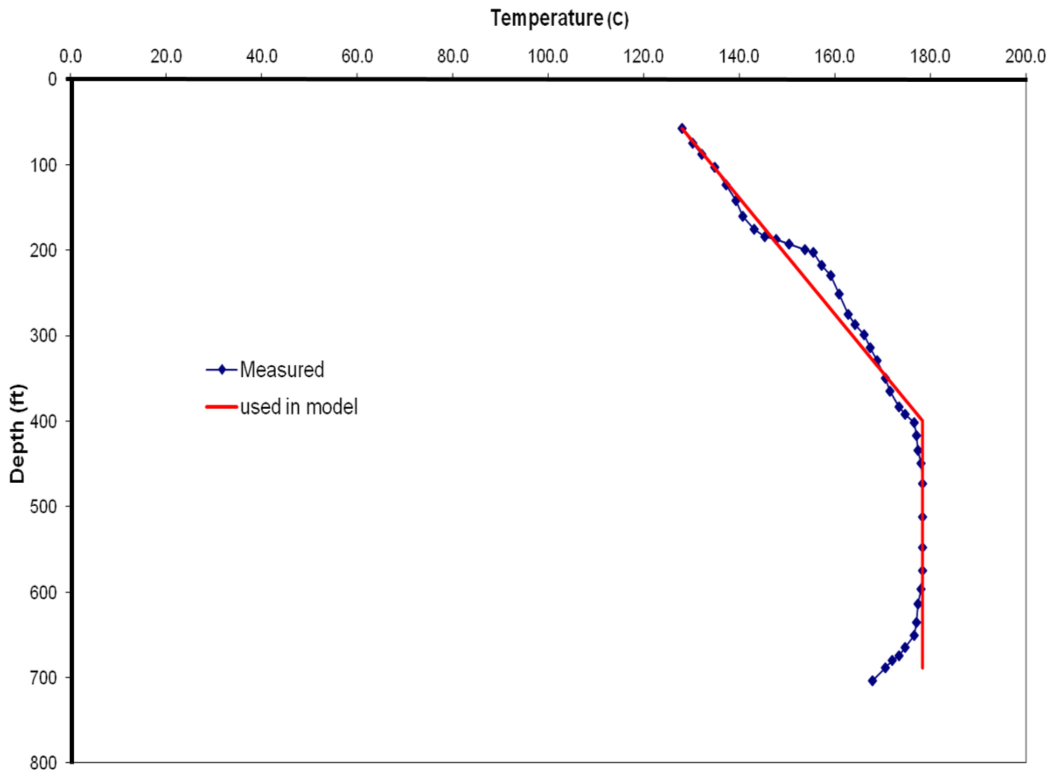


Figure 3: Profiles of measured temperature for the MBP-3 well (Farrar et al., 2010) and initial temperature used in the model

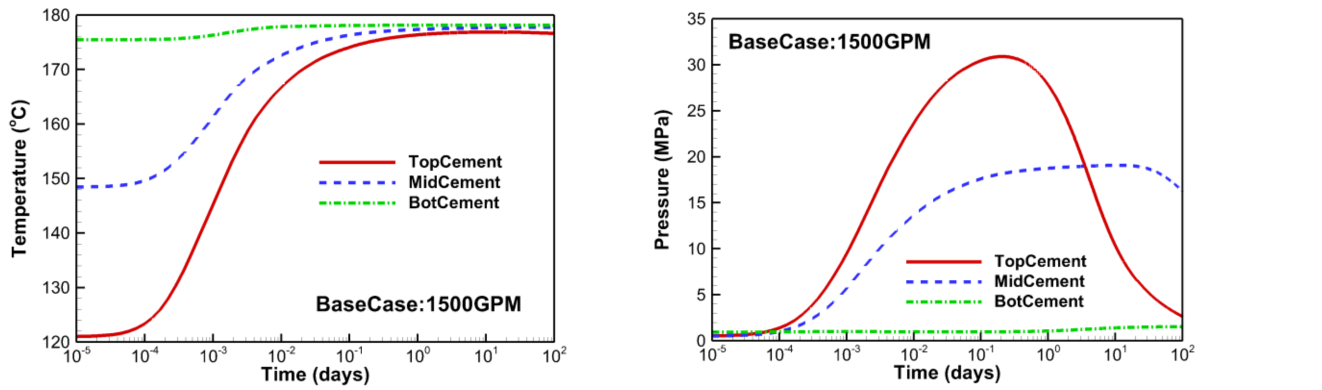
Table 1. Material properties for the T2Well thermal-hydrologic model of Casa Diablo production well.

<table>
<tr><th>Name</th><th>Depth (m)</th><th>Porosity (%)</th><th>Lateral permeability (m^2)</th><th>Vertical permeability (m^2)</th><th>Thermal conductivity (W/m°C)</th><th>Specific heat (J/kg°C)</th><th>Solid density (kg/m^3)</th><th>Maximum capillary pressure (Pa)</th></tr>
<tr><td>LowHn</td><td>203.91-204.82</td><td>10</td><td>2.0×10^{-15}</td><td>2.0×10^{-15}</td><td rowspan="6">4.5</td><td rowspan="5">1000</td><td rowspan="6">2700</td><td rowspan="2">10^5</td></tr>
<tr><td>HotZone</td><td>121.92-203.91</td><td>10</td><td>2.9×10^{-12}</td><td>2.0×10^{-12}</td></tr>
<tr><td>Caprock</td><td>83.52-121.92</td><td>14</td><td>10^{-16}</td><td>10^{-18}</td><td rowspan="2">10^7</td></tr>
<tr><td>Caprock1</td><td>24.39-83.52</td><td>34</td><td>10^{-16}</td><td>10^{-16}</td></tr>
<tr><td>Basalt</td><td>0.0-24.39</td><td>4</td><td>10^{-15}</td><td>10^{-15}</td><td>10^5</td></tr>
<tr><td>Cement</td><td>Cement outside each casing</td><td>30</td><td>2.0×10^{-18}</td><td>2.0×10^{-18}</td><td>2116.4</td><td>10^7</td></tr>
<tr><td>Slotted liner</td><td>126.19-203.91</td><td>3</td><td>10^{-12}</td><td>0</td><td>41.71</td><td>473</td><td rowspan="2">7801</td><td>10^3</td></tr>
<tr><td>Steel</td><td>Wall of casing</td><td>0</td><td>0</td><td>0</td><td>43.0</td><td>473</td><td>0</td></tr>
</table>

4. SIMULATIONS OF TEMPERATURE AND PRESSURE RESPONSES

We first conducted thermal-hydraulic analysis of well bore pressure and temperature responses as well as production, for both base-load and flexible geothermal production. That is, we first modeled steady production for 100 days, which is sufficient to achieve conditions for a steady-state production rate and steady-state temperature and pressure condition within the production well. Thereafter, a variable production rate was simulated assuming a schedule of daily production cycles. The results from these thermal-hydraulic analyses in terms of temperature, pressure and moisture content responses were also input to the subsequent well integrity analysis and chemical analysis of mineral scale and corrosion.

The base case simulation of 100 days of constant production at 1500 GPM (84.31 kg/s) shows that the pressure loss from bottom hole to wellhead is small due to down hole pumping, while temperature increases substantially in the upper part of the well. This abrupt change in well temperature causes heat loss into the well assembly and surrounding rock that is heated (Figure 4a). Pressure in the casing cement near the ground surface increases significantly as the cement is heated up by the hot water in the well and reaches its peak at about one half day, and then decreases as the pressurized water is gradually driven out (Figure 4b). At the middle depth of the casing cement, the pressure increase is lower due to lower temperature difference but the elevated pressure lasts much longer. All these changes in pressure within the well assembly are caused by thermal pressurization, which in turn depends on the temperature evolution in the system. Thermal pressurization is the process of temperature-driven changes in pore pressure that occur because the thermal expansion of the pore fluid is much larger than the thermal expansion of the porous media. This process tends to be more significant in a low permeability porous media, like cement, because it takes longer time for the pressurized fluid to diffuse away.



(a) (b)

Figure 4: Simulation results for the base case of 100 days of production at 1500 GPM (84.31 kg/s) (a) temperature and (b) pressure in casing cement at three different depths. TopCement, MidCement and BotCement output locations within the cemented portions of the well completion are shown in Figure 1.

Cyclic production was simulated for various scenarios of production cycles as the impact of cyclic production would depend on the magnitude and rate the production changes. We first conducted a simulation assuming that the production is reduced to 40% during low production cycles. However, we found that a rate of 40% would still supply hot fluid to the top of the well and therefore the well temperature does not change that much during production cycles. We therefore conducted further analyses varying the reduction in production, with the most extreme case of complete shut-down of the well during low production. Such complete shut-down of individual wells may be performed in the field, even if the total production from the field is only reduced to 40%. Thus, in this case we model the cyclic production as follows (Figure 5):

- Weekdays: 14 hours peak rate 1600 GPM (89.93 kg/s) followed by 10 hours shut-in period (0.00 kg/s)
- Weekend: 24 hours shut-in period (0.00 kg/s)
- Weekly average: 1075 GPM (60.42 kg/s)

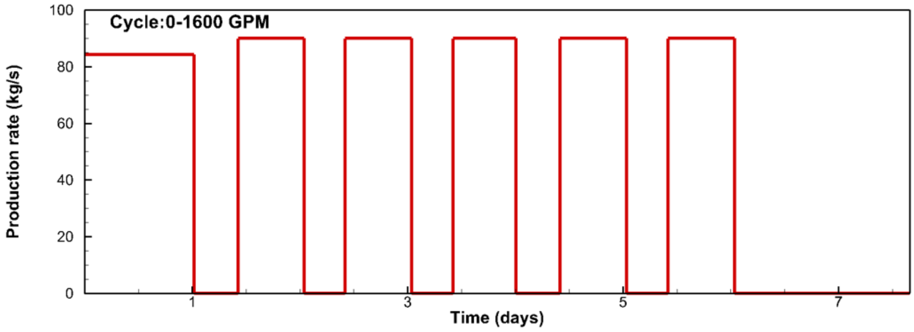
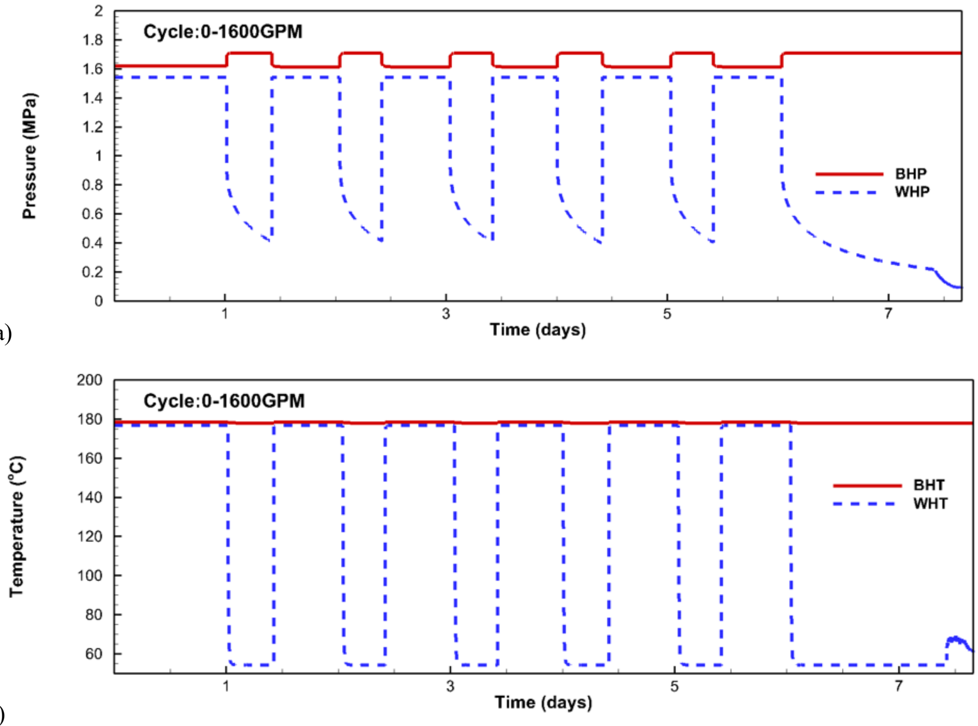


Figure 5: Simulation results for an assumed cyclic production with production rates varied between 0 and 1600 GPM.

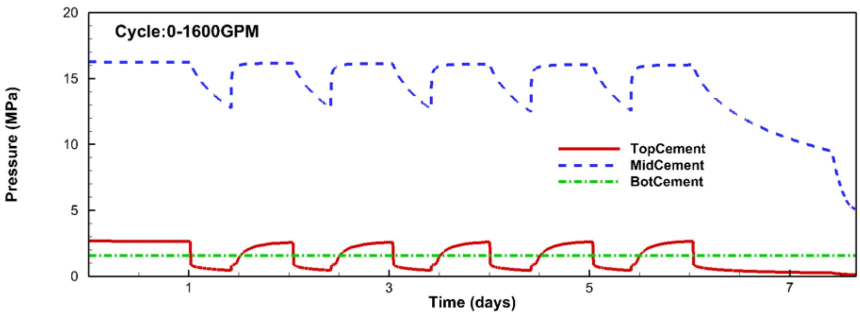
Figures 6 and 7 show the pressure and temperature responses over 1 week of cyclic production. In this case, the temperature within the well at the well head changes more than 100°C, whereas that well head pressure fluctuates about 1 MPa in each cycle. This results in significant temperature changes in the cement, with up to 30°C temperature changes at the wellhead. Pressure changes of up to 3 MPa occurs in the cement at the mid-depth of the well. These changes in pressure and temperature could induce some more significant stress changes. This shows the importance of the design of the production cycling, as keeping some hot fluid flowing can significantly reduce the potential impact of flexible production.



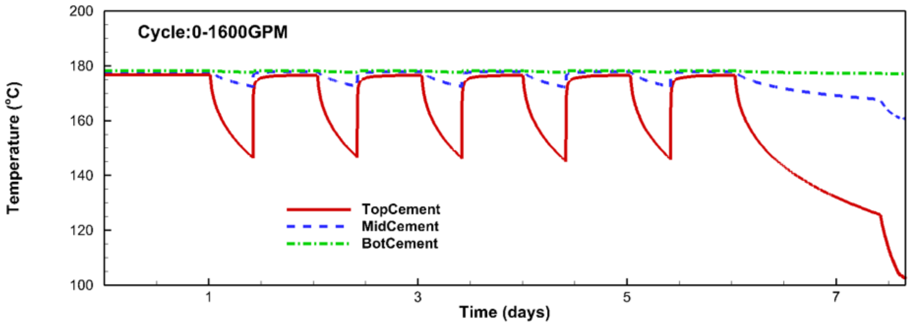
(a)

(b)

Figure 6: Simulation results for an assumed cyclic production with production rates varied between 0 and 1600 GPM. (a) Bottom hole pressure (BHP) and wellhead pressure (WHP). (b) Bottom hole temperature (BHT) and wellhead temperature (WHT).



(a)



(b)

Figure 7: Simulation results for an assumed cyclic production with production rates varied between 0 and 1600 GPM. (a) Pressure and (b) temperature in casing cement at three different depths.

In summary, the T2Well analysis of coupled reservoir-wellbore processes shows that the highest thermal perturbation, ΔT, caused by production is in the shallow formations beneath the ground surface and near the production wellbore. In this zone, the temperature increases quickly with production, and decays quickly when the production rate is changed either during the initial start-up of the production or during variable or flexible-mode operation. During this initial start-up of production, the temperature changes are the biggest as hot production fluid heats up the well from an initial ambient and relatively cool temperature near the ground surface. The ground temperature for this area appears to be elevated, as the area around the main Casa Diablo well field is often free of snow in the wintertime (G. Suemnicht, pers. comm.). In the case of a shallow geothermal system, similar to that at the Casa Diablo power plant, a temperature increase ΔT ≈ 55°C was calculated. Another important observation potentially relevant for well integrity is the sharp changes in pore-fluid pressure within the cement sheath behind the steel casing. For flexible production of daily production cycles, the largest fluctuations occurred in part of the well with temperature changes ΔT ≈ 30°C, which is also quite significant.

5. IMPACT ON WELL INTEGRITY

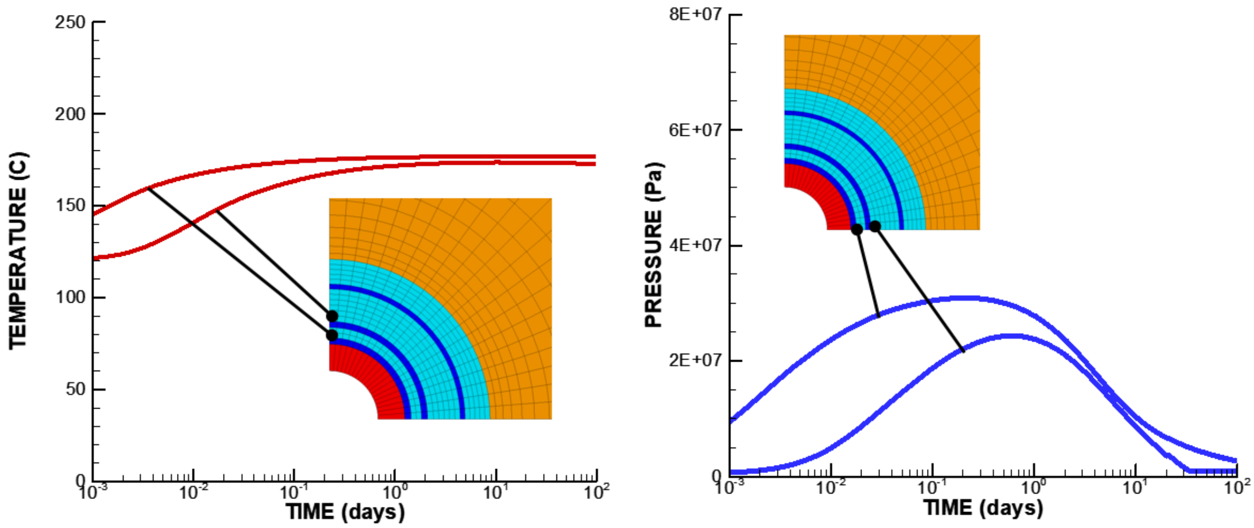
The impact on well integrity was analyzed considering coupled thermo-hydro-mechanical responses in the well bore system for both base-load and flexible production. As shown in Figure 2, the T2Well simulations were conducted using an axisymmetric model domain, but the T2Well-FLAC3D coupled THM analysis is conducted on co-located numerical grid elements. This means that the pressure and temperature evolution calculated in T2Well is imported into the mechanical analysis along the radius of the 3D model.

The mechanical properties are listed in Table 2. We simulated mechanical responses considering elasto-plastic properties of the cement, rock and frictional interfaces. We applied elasto-plastic Mohr-Coulomb properties taken from the literature regarding the cement and host rocks.

Table 2. Mechanical properties used in FLAC3D for modeling mechanical responses of the well assembly

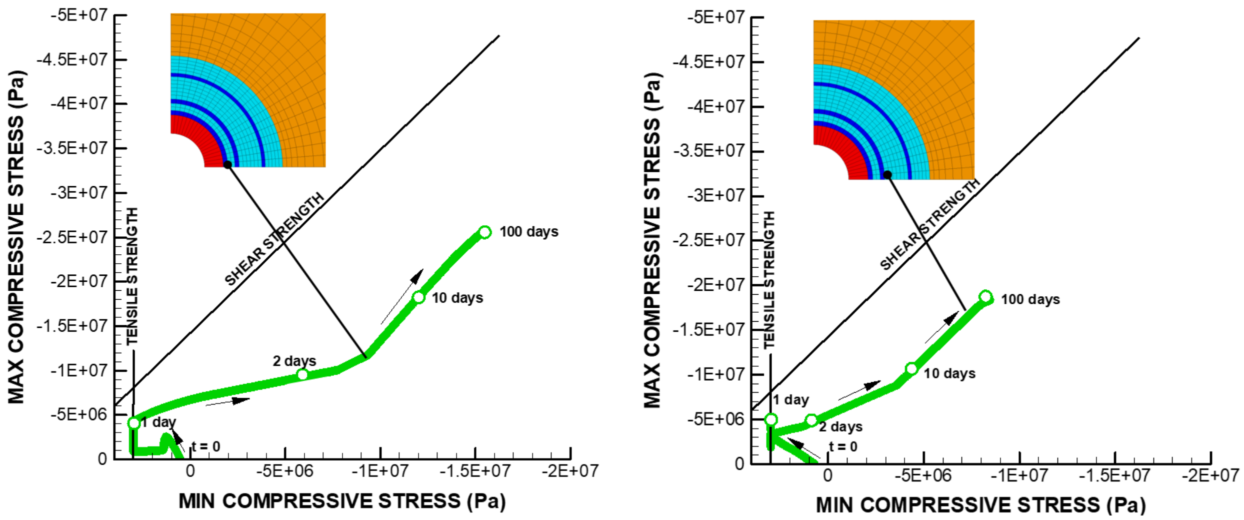
Property	Material			
	Steel Casing	Cement	Formation	Interfaces
Young's modulus, E (GPa)	200	10	5	NA
Poisson's ratio, ν (-)	0.3	0.3	0.3	NA
Thermal expansion coefficient (°C^{-1})	1.3×10^{-5}	1.0×10^{-5}	1.0×10^{-5}	NA
Friction angle, ϕ (-)	NA	20	10	20
Cohesion, C (MPa)	NA	5.0	3.0	1.0
Tensile strength (MPa)	NA	3.0	1.0	0

This initial analysis is focused on the highest impact case that is during the initial startup of the production when the greatest changes in temperature and pressure occur. As observed in Figure 8, the temperature and pressure increase very rapidly in the cement behind the innermost casing as well as between the two outermost casings. Figure 9 shows the stress path (maximum compressive versus minimum compressive stresses) at the same two locations, along with the Mohr-Coulomb failure envelope. The stress evolution is complex, with tensile failure occurring within 1 day of production. Thereafter, the principal stresses move away from the failure line as a result of increasing thermal stress that provides an increasing confining stress. High tangential stresses are also built up in the steel casing, with high compression in the innermost casing and tensile stresses in the two outermost casings (Figure 10). The high compressive stresses in the innermost steel casing is a direct effect of thermal expansion of a stiff material that when confined will lead to high thermal stress. The high tensile stress built up in the two outer casings is a result of the general thermal expansion of the cement in the inner parts of the well assembly that causes displacement and high stress on the outermost steel casings. The stress increases as high as 400 MPa, which could lead to yielding depending on the grade of the steel material. Based on the Mohr-Coulomb model, the occurrence of failure is detected, which would lead to plastic (irreversible) strain for steel material. So far, this plastic strain was not accounted for in the current analysis, but could be included if desired.



(a) (b)

Figure 8: Calculated (a) temperature and (b) pressure evolutions in two cement sections at the shallow part of the production well (production from a shallow geothermal well).



(a) (b)

Figure 9: Effective stress path for one location in (a) first cement section and (b) second cement section.

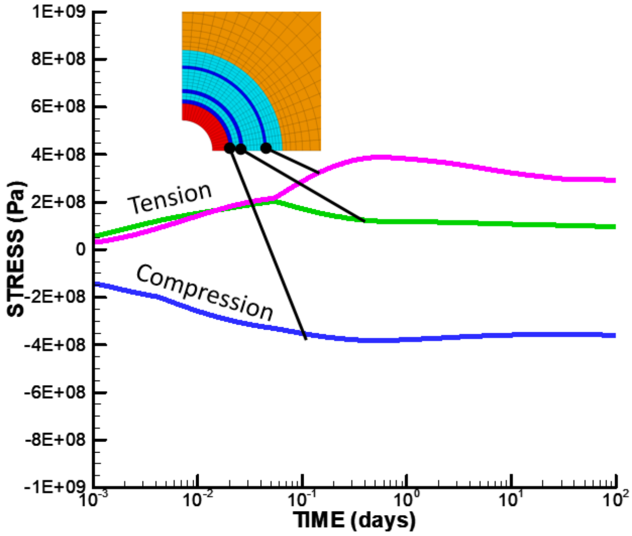


Figure 10: Calculated tangential stress evolution in all 3 casings in the shallowest part of the well.

The current model simulation indicates that the cement sheath could be weakened and damaged already during the initial start-up of production and such weakening of the cement material would remain and potentially worsen during subsequent variable production. The conditions simulated in this mechanical analysis might be extreme with rapid temperature increase and pressure buildup behind the casing. The thermal pressurization in the cement sections located between casings might have a significant effect on well integrity. Such thermal pressurization might be avoided by increasing the production in steps so that any pressure increase has time to bleed off. Nevertheless, even in the case of a slow increase in production flow rates, thermal expansion of the inner parts of the well assembly will still impact the outer parts and significant loading will occur. During variable production, the cyclic temperature and pressure changes in the cement will lead to smaller mechanical changes but could over time lead to fatigue.

6. IMPACT ON SCALING AND CORROSION

The effects for flexible production mode on scaling were evaluated using geochemical modeling with the CHILLER software (Reed, 1982, 1998), which allows computing pH at elevated temperatures and evaluating the types and amounts of solids that could form under various cooling and boiling scenarios.

Prior to running CHILLER simulations, the composition of the deep Casa Diablo geothermal fluid had to be re-constructed to account for the loss of gases prior to sampling. This was achieved with the GeoT software (Spycher et al., 2014), using water and gas analyses reported for Casa Diablo production wells by the U.S. Geological Survey (Farrar et al., 1987; 1989; Sorey and Farrar, 1998). The reconstructed (water + gas) fluid using these analyses shows near-equilibrium with several minerals reasonably expected at depth (rhyolitic formation) and temperatures (around 178°C) consistent with deep temperatures recorded in well MBP-3, thus providing confidence in the results. Simulations of cooling without and with iso-enthalpic boiling were then performed with the reconstructed fluid composition to test temperature and pressure regimes that may exacerbate mineral scaling and/or the acidity of the fluid, with the goal of constraining pressures and temperatures suitable for flexible production modes.

Results show (Figures 11 and 12) that under the current fixed production mode (with pressure maintained high enough to prevent boiling) and as long as the temperature is maintained above 70°C, limited scaling is expected to occur consisting primarily of Fe carbonates and (hydr)oxides with minor clay, carbonates, and sulfides (Figure 12b; corresponding to amounts up to ~5 kg of scale per day at 500 gpm). However, cooling the fluid below about 70°C could result in the precipitation of significant amounts of amorphous silica (Figure 12b; corresponding to amounts up to ~400 kg per day at 500 gpm), although this is would not be expected as long as temperatures at the heat exchanger were not lowered from the range currently in effect (> 85°C).

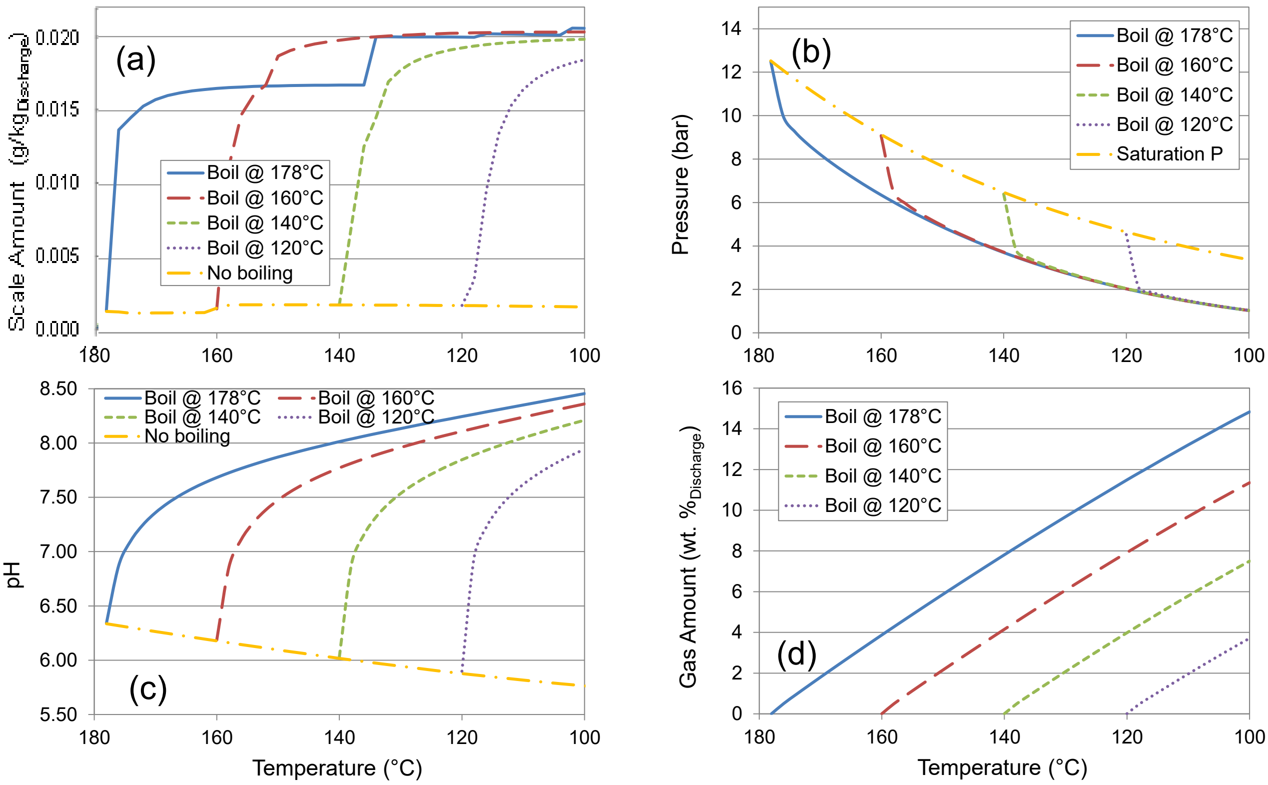


Figure 11: Simulations of cooling without boiling, and cooling with iso-enthalpic boiling initiated at different temperatures for a Casa Diablo geothermal fluid: computed total amounts of mineral precipitation (a), saturation pressure (b), pH (c) and gas amounts (d).

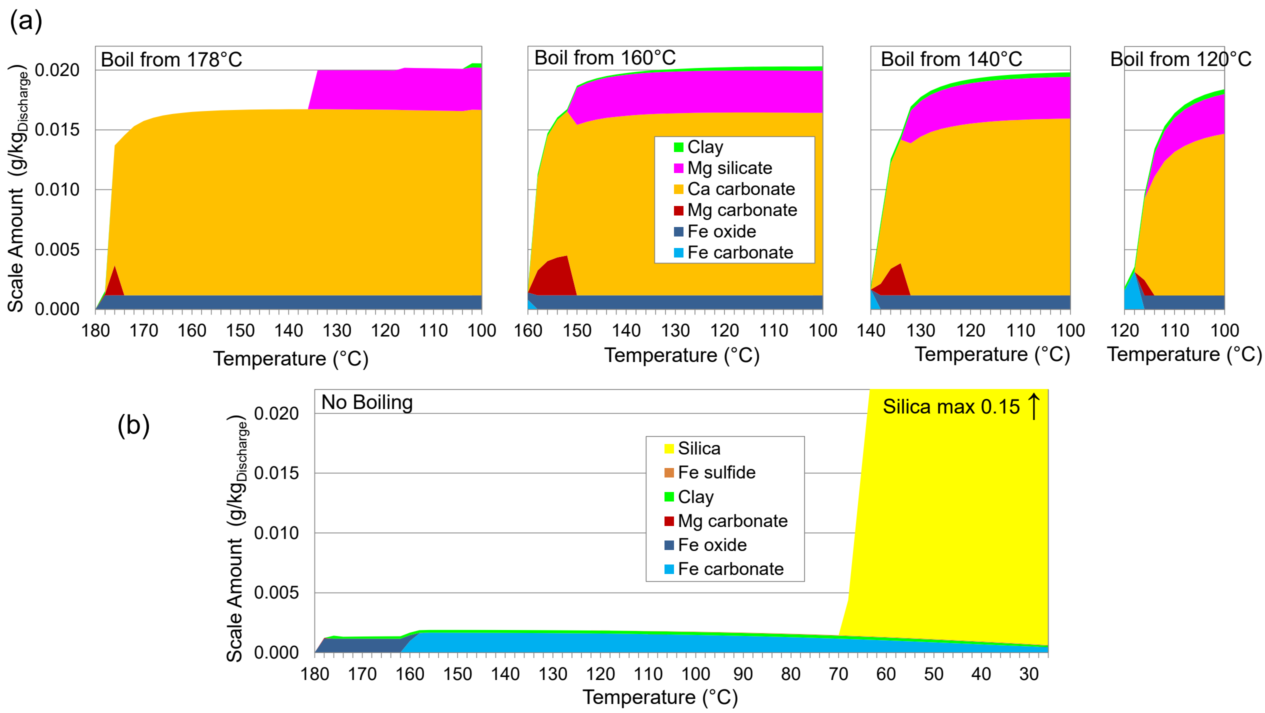


Figure 12: Simulations of cooling with iso-enthalpic boiling initiated at different temperatures (a) and of cooling without boiling (b) for a Casa Diablo geothermal fluid: computed amounts and types of deposited minerals.

In summary, for liquid-dominated systems, if boiling was allowed to occur in production wells (which is not the case at Casa Diablo), a flexible production schedule would be expected to result in smearing scale over a larger depth interval than with a fixed schedule. Boiling initiating at high temperatures would be expected to produce significantly more scaling than if pressure was controlled such that flashing was suppressed or occurred at lower temperatures, although in the case of intermediate temperature systems, the amount of scale deposited from boiling at different temperatures below about 180°C should not differ appreciably. For these systems, as long as the wellhead pressure is maintained above saturation pressure and the temperature (if possible) is kept above silica saturation temperatures (~70°C at Casa Diablo), a flexible production mode would not be expected to affect scaling or corrosion more than under a fixed schedule.

7. CONCLUDING REMARKS

We have investigated the effects of steady and variable geothermal production on mechanical well integrity issues using coupled modeling of flow, heat and mechanical responses in the well assembly.

The wellbore-reservoir modeling using T2Well-FLAC3D shows that the highest thermal perturbation, ΔT, occurred in the shallow formations beneath the ground surface near the production well. In this zone, the temperature increases quickly with production, and decays quickly when the production rate is reduced during variable or flexible-mode operation, with the highest cyclic increase and decrease of temperature. Moreover, temperature increases in the cement behind casing causes pressure increases due to thermal pressurization. These temperature and pressure changes can cause non-linear mechanical responses that are dependent on the thermal expansion of the different components of the well assembly and include effects of potential frictional sliding at interfaces and material yielding.

In the current analysis, we found that temperature changes during the initial start-up of the production could cause cement failure in the shallowest parts of the well both in tension and compression. The modeling further showed that flexible production in a liquid-dominated geothermal system may be designed to induce minor thermal perturbations by controlling the production cycles. The key would be to not shut-down the production completely, but to keep some rate of hot fluid production and thereby keeping the well assembly at approximately a constant temperature.

Related to potential impact of scaling and corrosion, geochemical modeling shows that in a liquid-dominated system, the effects of scaling and corrosion can be controlled by keeping the wellhead pressure above the saturation pressure and at the same time keeping the temperature above the silica saturation temperature.

Future work will include sensitivity studies of identified key processes and properties, such as the cycling schedule, wellbore component designs, and reservoir properties. Moreover, the impact on the fractured reservoir will be investigated using reactive transport modeling with TOUGHREACT (Xu et al., 2011) as well as new analytical simulator (SHPALib) (Zhou et al., 2019). Finally, additional site-specific data will be used, including data from pilot experiments on variable production at The Geysers geothermal field.

ACKNOWLEDGMENTS

We thank Gene Suemnicht for sharing his knowledge of the Long Valley area and the Casa Diablo geothermal field with us. Funding for this work was provided by the California Energy Commission under the EPIC grant program (GFO-16-301) under agreement EPC-16-022, as part of Work for Others funding from Berkeley Lab, provided by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

REFERENCES

DOGGR GeoSteam database (data for wells MBP-4 (API 05190036) and MBP-3 (API 05190043)) https://secure.conservation.ca.gov/GeoSteam/GeoWellSearch?district=1&county=Mono&field=CASAD&operator=Mammoth-Pacific

Farrar, C., DeAngelo, J., Clor, L., Murphy, F., Williams, C., Grubb, F., and Hurwitz, S.: Temperature data from wells in Long Valley Caldera, California. *U.S. Geological Survey Digital Data Series* **523**, Version 3.0 (Nov. 2016), https://pubs.usgs.gov/ds/523/. (2010).

Farrar, C.D., Sorey, M.L., Rojstaczer, S.A., Janik, C.J., Winnett, T.L., and Clark, M.D.: Hydrologic and Geochemical Monitoring in Long Valley Caldera, Mono County, California, 1985. *U.S. Geological Survey Water-Resources Investigations Report* **87-4090**, (1987), 71 p.

Farrar, C.E, Sorey, M.L., Rojstaczer, S.A., Steinemann, A.C., and Clark, M.D.: Hydrologic and Geochemical Monitoring in Long Valley Caldera, Mono County, California, 1986. *U.S. Geological Survey Water-Resources Investigations Report* **89-4033**, (1989), 69 p.

Itasca Consulting Group: FLAC3D, Fast Lagrangian Analysis of Continua in 3 Dimensions, Version 5.0, Minneapolis, Minnesota, Itasca Consulting Group (2012).

Miller, R.J., and Vasquez, R.: Analysis of production and reservoir performance, Casa Diablo geothermal project. SPE California Regional Meeting, Long Beach, CA, SPE 17426, (1988), 285–294.

Pan, L., and Oldenburg, C.: T2Well—An integrated wellbore–reservoir simulator, *Computers & Geosciences*, **65**, (2014), 46–55.

Reed, M.H.: Calculation of multicomponent chemical equilibria and reaction processes in systems involving minerals, gases and an aqueous phase. *Geochimica et Cosmochimica Acta*, **46**, (1982), 513–528.

Reed M.H.: Calculation of simultaneous chemical equilibria in aqueous-mineral-gas systems and its application to modeling hydrothermal processes, in Techniques in Hydrothermal Ore Deposits Geology, *Reviews in Economic Geology,* **10**, 109–124, eds Richards J. and Larson P., Society of Economic Geologists, Inc., Westminster, Colorado (1998).

Rutqvist J., Pan, L., Hu, M., Zhou, Q., and Dobson, P.: Modeling of coupled flow, heat and mechanical well integrity during variable geothermal production. *Proceedings*, 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, (2018), 13 p.

Sorey, M.L., and Farrar, C.D.: Hydrologic and chemical data from the Long Valley Hydrologic Advisory Committee monitoring program in Long Valley Caldera, Mono County, California, 1988-1997. *U.S. Geological Survey Open-File Report* **98-70**, (1998), 49 p.

Sorey, M.L., Farrar, C.D., Marshall, G.A., and Howle, J.F.: Effects of geothermal development on deformation in the Long Valley caldera, eastern California, 1985-1994. *Journal of Geophysical Research*, **100 (B7)**, (1995), 12,475–12,486.

Spycher, N., Peiffer, L., Saldi, G., Sonnenthal, E., Reed, M.H., and Kennedy, B.M.: Integrated multicomponent solute geothermometry. *Geothermics*, **51**, (2014), 113–123.

Suemnicht, G.A.: Long Valley Caldera geothermal and magmatic systems. Long Valley Caldera Field Trip Guidebook, Geothermal Resources Council field trip, Oct. 12-14, 2018. (2018), 23 p.

Suemnicht, G.A., Sorey, M.L., Moore, J.N., and Sullivan, R.: The shallow hydrothermal system of Long Valley Caldera, California. *Proceedings*, 32nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, (2007), 5 p.

Xu, T., Spycher N., Sonnenthal, E., Zhang, G., Zheng, L., and Pruess, K.: TOUGHREACT Version 2.0: A simulator for subsurface reactive transport under non isothermal multiphase flow conditions, *Computers & Geosciences*, **37**, (2011), 763–774.

Zhou, Q., Oldenburg, C.M., and Rutqvist, J.: Revisiting the analytical solutions of heat transport in fractured reservoirs using a generalized multirate memory function. *Water Resources Research*, **55**, (2019), 1405–1428.