PROCEEDINGS, 45th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2020
SGP-TR-216

Coupled Processes Analysis of Flexible Geothermal Production from Steam- and Liquid-Dominated Systems: Impact on Wells

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Keywords: Coupled process modeling, well integrity, thermal expansion, variable production, thermal pressurization

ABSTRACT

We present 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 both steam- and liquid-dominated geothermal systems using data from The Geysers and Casa Diablo geothermal fields, 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. Geochemical simulations show that the effects of flexible production on scaling and corrosion in a liquid-dominated system 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 concerns related to the conversion from base-load to flexible-mode production is wellbore integrity. Flexible-mode geothermal production may include 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 by modeling 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).

Here we summarize results obtained to date, including studies of both steam-dominated and liquid-dominated geothermal systems considering field data and conditions from The Geysers and Casa Diablo geothermal fields in California. More details on the analysis of respective systems can be found in Rutqvist et al. (2018) for the steam-dominated system and Rutqvist et al. (2020) for the liquid-dominated system, whereas this paper focuses on the comparison of the two types of systems in terms of impact of flexible geothermal production.

2. APPROACH FOR MODELING IMPACTS ON WELL INTEGRITY

The impacts on the wells are driven by multiphase fluid flow and thermal processes that could result in mechanical and chemical changes to the system. The basic approach taken here is to calculate the multiphase fluid flow and thermal processes using LBNL's T2Well reservoir-wellbore simulator and then use those as input to calculate mechanical and chemical changes to the system. LBNL's T2Well is a numerical simulator that can accurately simulate fluid and heat flow in both wellbore and reservoir (Pan and Oldenburg, 2014) including complex two-phase flow phenomena such as condensation/evaporation, counter flow, and gas lifting. In the well, the T2Well solves the two-phase momentum equation using a so-called Drift-flux model (DFM) to obtain phase velocities, whereas in the surrounding formations, the multiphase Darcy's law is used for obtaining phase velocities (Pan and Oldenburg, 2014). The TOUGH2 fluid property module EOS1 is used in these simulations (Pruess et al., 2012). The properties of pure water in its liquid, vapor, and two-phase states are calculated from steam table equations up to a temperature of 350°C, while vapor pressure lowering from capillary and adsorption effects is neglected.

For calculating mechanical changes, T2Well has been linked to the FLAC3D geomechanical simulator to investigate both wellbore mechanical integrity and geothermal reservoir behavior (Figure 1). FLAC3D is an advanced geomechanical simulator (Itasca, 2012) that has previously been linked to several of LBNL's TOUGH-family codes for modeling of coupled multiphase fluid flow and geomechanical processes (Rutqvist, 2011; 2017), including extensive applications to the high-temperature geothermal system at The Geysers geothermal field (Rutqvist et al., 2016). Linking T2Well to FLAC3D enables accurate modeling of multiphase flow processes within the wellbore and impact of wellbore pressure and temperature changes on well integrity (including casing and cement) and in the surrounding rock.

For calculating chemical changes including the effects for flexible production mode on scaling, the CHILLER software (Reed, 1982, 1998) was applied, which allows computing pH at elevated temperatures and evaluating the types and amounts of minerals that could form under various cooling and boiling scenarios. These results and the T2Well multiphase flow and temperature results are then used to evaluate the potential for scaling. In the following, the T2Well coupled thermal-hydraulic analysis is presented first (Section 3) for steam-dominated and liquid-dominated systems, followed by the mechanical integrity analysis (Section 4) and the evaluation of potential for scaling and corrosion (Section 5).

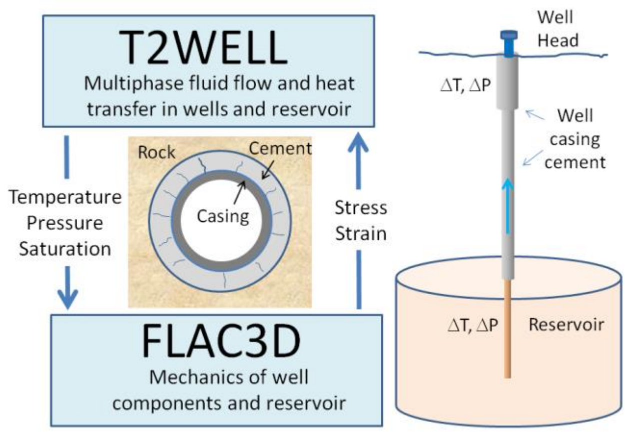


Figure 1: Coupling and interactions between T2Well for reservoir-wellbore multiphase flow and multicomponent transport modeling and FLAC3D for geomechanical modeling, with application to wellbore integrity analysis by including reservoir, wellbore and high temperature change +∆T zone.

3. THERMAL-HYDRAULIC ANALYSIS OF TEMPERATURE AND PRESSURE RESPONSES

An initial set of simulations were performed with T2Well to model the basic temperature and pressure responses associated with variable (cyclic) geothermal production. As mentioned, we considered both steam-dominated and liquid-dominated geothermal systems considering well design, field data and conditions from The Geysers and Casa Diablo geothermal fields in California. An important step for realistic modeling of pressure and temperature changes in the system is to calibrate the model against field data to set up accurate initial conditions and match the steady production data. Then the simulations are conducted by modeling steady production for 100 days to obtain pseudo steady-state conditions of temperature in the wellbore assembly and surrounding geological formations. Thereafter, variable production conditions are initiated in the model simulations and continued for 100 days. The well designs are obtained from the California Division of Oil, Gas and Geothermal Resources (CA DOGGR) GeoSteam database.

3.1 Steam-dominated System

For the steam-dominated system, well design, geology and production data from a well at The Geysers geothermal field was used to assure realistic field conditions in the model (Rutqvist et al., 2018). These data were from well Prati 25 (P25), which is one of the production wells associated with the Northwest Geysers EGS Demonstration Project (Garcia et al., 2016). The Northwest EGS Demonstration site is well characterized and extensively modeled related to reservoir pressure, temperature and properties and reservoir responses to steam production and liquid fluid injection (Garcia et al., 2016; Rutqvist et al., 2016). The main steam reservoir (so-called normal temperature reservoir at The Geysers) typically has a temperature of about 240°C and a steam pressure on the order of a few MPa. Figure 2 shows the P25 well design and geological layering that are important inputs to the modeling.

The initial thermal-hydrogeological conditions include linear gradients of pressure and temperature in the liquid-saturated overburden down to the top of the steam reservoir at about 1500 m depth (Figure 3). The pressure gradient in the overburden corresponds to hydrostatic pressure, whereas the temperature increases from 20°C at the ground surface to about 250°C at 1500 m depth. In the steam reservoir (below 1500 m), the steam pressure is as low as about 3 MPa, whereas the temperature is around 250 to 260°C down to 3500 m depth. In the modeling presented here, we assumed constant boundary conditions (1 atm and 25.46°C) at the surface except at the wellhead, whereas at the bottom of the model (3500 m depth), the pressure and temperature were held constant at 2.94 MPa and 265°C. An initial simulation was conducted using a steady production rate based on P25 well data on production rate, well head pressure and temperature to assure realistic field conditions. The key was to match the well head pressure (WHP = 78 Pa) and well head temperature (WHT = 213°C) for a given water mass production rate (16.7 kg/s) as shown in Figure 4.

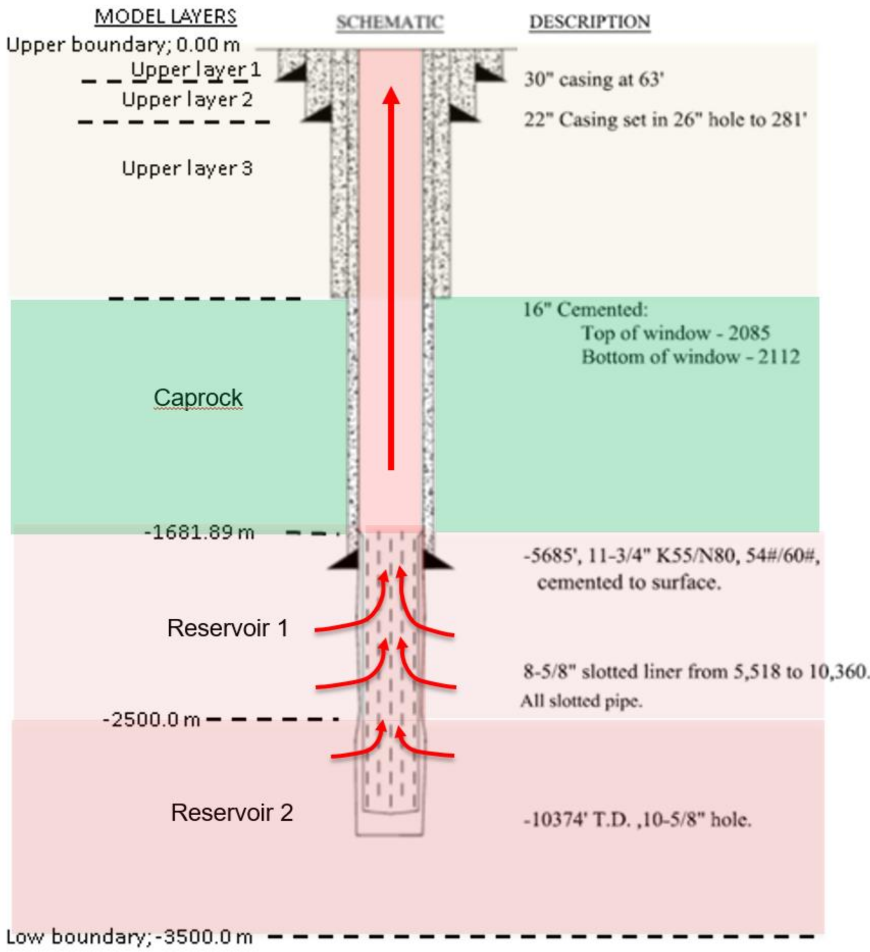
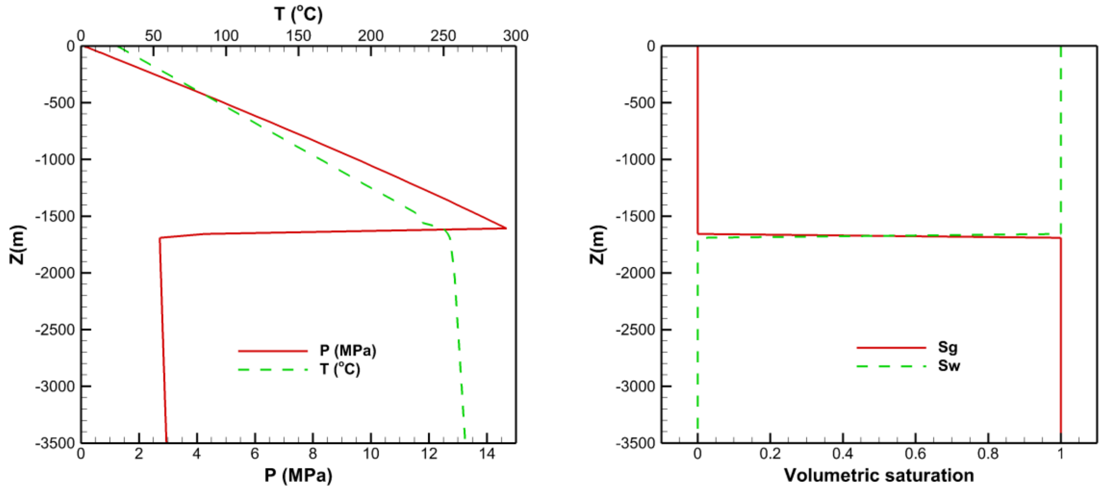
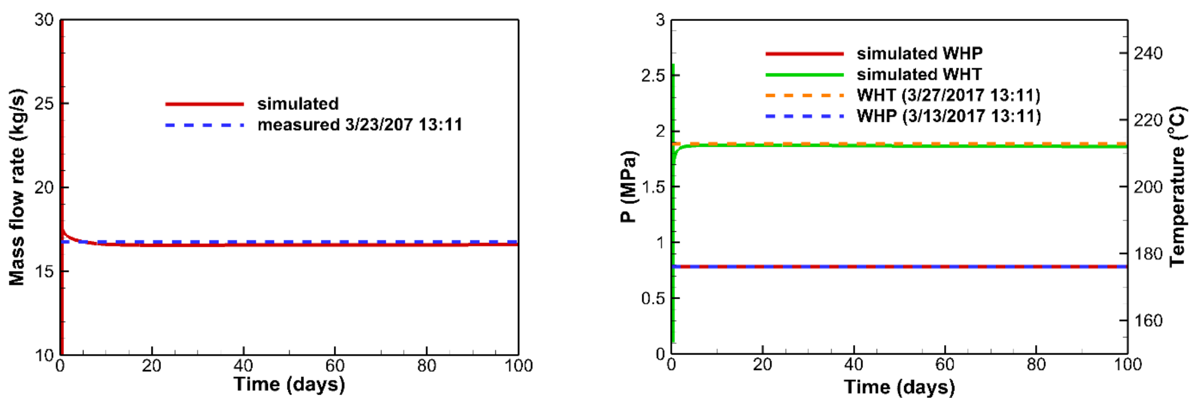


Figure 2: P25 well design at the Northwest Geysers and model layers used in T2Well for simulation of steady and variable geothermal production.



(a) (b)

Figure 3: Initial vertical profiles of (a) pressure (P) and temperature (T), and (b) gas (Sg) and liquid (Sw) saturations.



(a) (b)

Figure 4: Simulated and measured (a) mass flow rate and (b) well head pressure (WHP) and temperature (WHT) during a March 2017 production test of the P25 production well at the northwest Geysers geothermal field.

Figure 5 shows the evolution of temperature and pressure behind the casing cement for the case of a constant rate production of 8 kg/second. The temperature increases rapidly to over 200°C within a few days of production. The temperature change, ΔT, is the highest in the shallowest part of the well because of a relatively low initial temperature. At 2.4 m below ground surface, ΔT ≈ 200°C, while at 527 m depth, ΔT ≈ 130°C (Figure 5a). The rapid temperature increases can also lead to thermal pressurization due to thermal expansion of the fluid in a low permeability medium. Figure 5b shows that pressure could increase by as much as 60 MPa at 2.4 m depth with the peak pressure occurring at the 2^{nd} day of production. This appears to be a very substantial pressure increase that would be very important to consider in a well integrity analysis. The amount of pressure increase will depend on the rate of temperature increase, and the permeability of the cement. The fact that the cement in the upper part of the well is confined between two steel casings makes this high thermal pressurization possible. Thus, the well design and material properties, including permeability and pore-compressibility are important for accurately predicting these effects.

The variable production was simulated by a number of different schedules as a sensitivity analysis. Figure 6 presents an example of variable schedule of 14 hours peak rate (12.00kg/s) followed by 10 hours off-peak rate (5.14 kg/s) during weekdays, and 24 hours off-peak rate (5.14kg/s) during weekends. Using this production schedule, the average production would remain equivalent to the preceding steady production rate of 8 kg/s (Figure 6a). As a result of the variable production, the temperature fluctuates about 4 to 5°C at the well head and within the cement just behind the innermost casing (Figure 6b). These temperature fluctuations also result in pressure fluctuations of up to 2 MPa. Interestingly, the pressure oscillations in the cement behind the casing are much greater than the steam pressure oscillations within the borehole itself. We can also observe that the pressure oscillations in the cement decline with time; the magnitude of oscillations are about 2 MPa after 10 days, but as low as 1 MPa after 70 days. The T2Well simulation shows that this decline is associated with the presence of a gas bubble within the cement, indicating the importance of water being driven out from the cement (Figure 7).

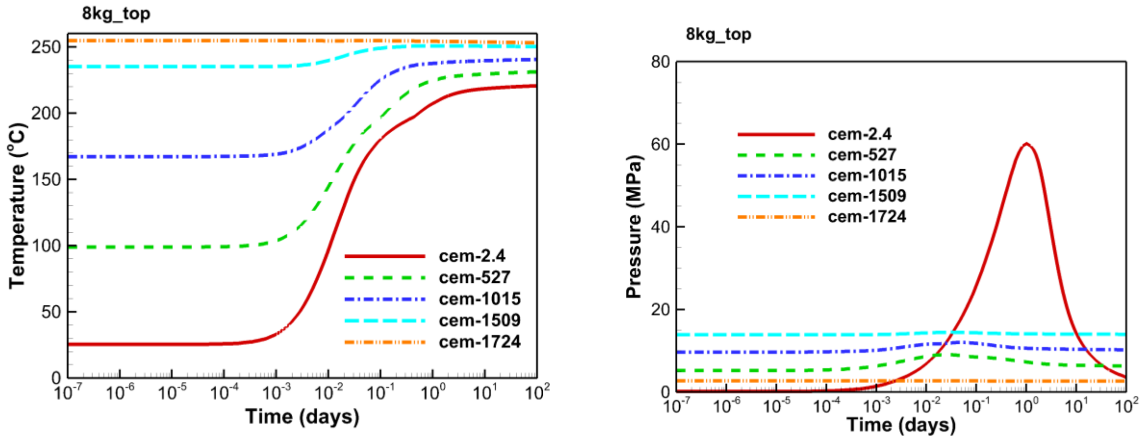


Figure 5: Simulation results for the base case of 100 days of production at a rate of 8 kg/s from a deep geothermal well in a steam-dominated field. (a) Temperature and (b) pressure evolutions within the cement behind the innermost casing at different depths (see legend, in meters). The numbers in the figure legends indicates depth in meters below ground surface.

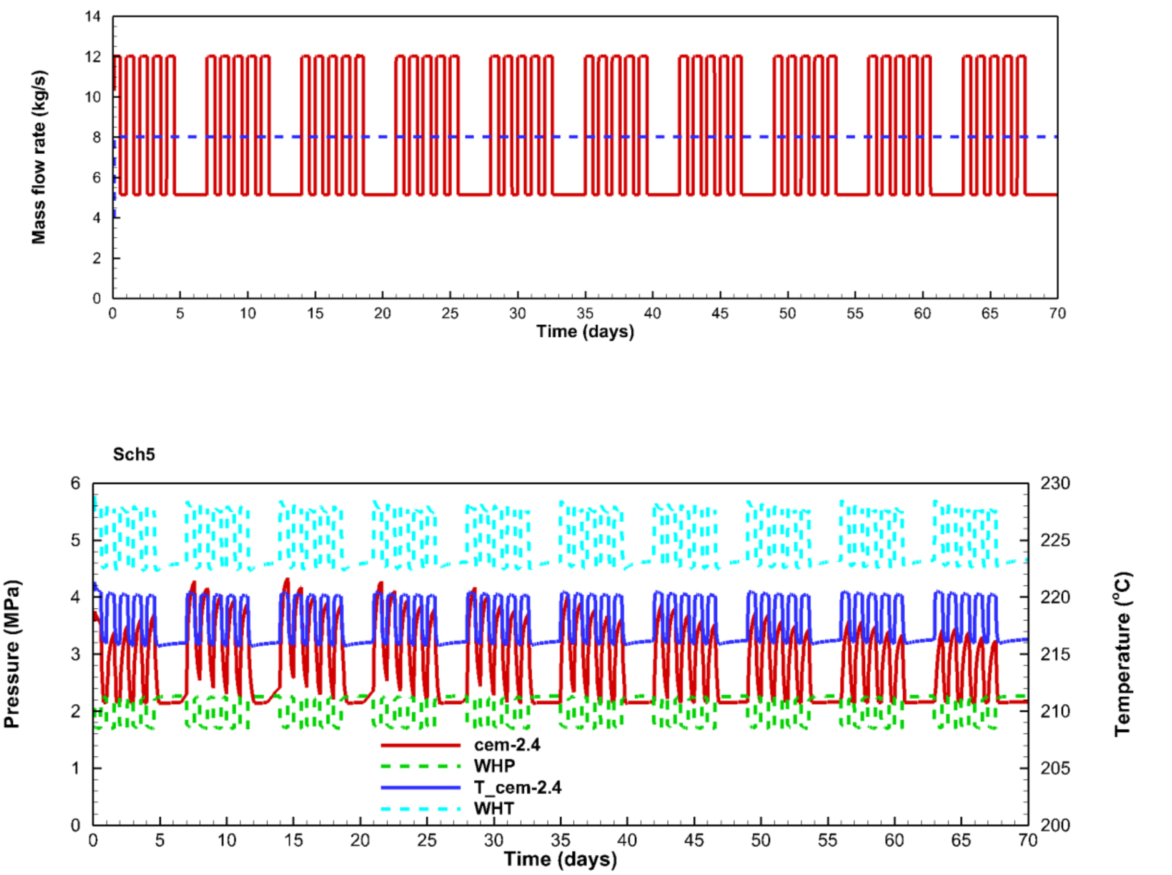


Figure 6: Evolution of (a) mass flow rate and (b) pressure (cem-2.4) and temperature (T_cem2.4) in cement behind the modeled casing at 2.4 m depth for an assumed variable production rate schedule, and well-head pressure (WHP) and temperature (WHT).

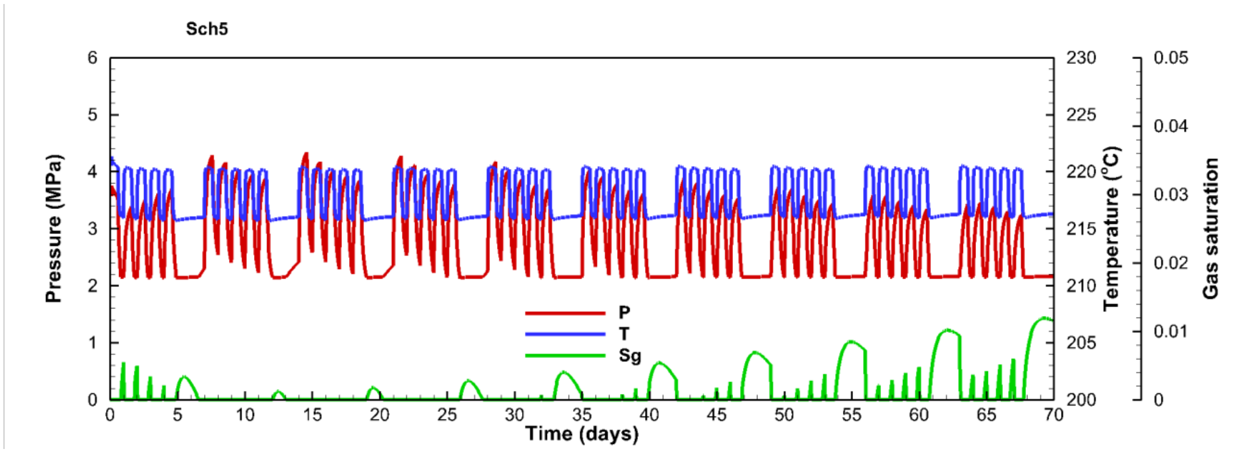


Figure 7: Evolution of pressure (P), temperature (T) and gas saturation (Sg) in cement behind the modeled well casing, showing the impact of a gas bubble and water driven out of the cement.

3.2 Liquid-dominated System

Field data from the Casa Diablo geothermal field of the Long Valley Caldera, California, was used for developing realistic conditions for the simulations of a liquid-dominated geothermal system (Rutqvist et al., 2020). The power plants at Casa Diablo are binary due to the moderate temperature reservoir fluids. 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. 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 8 along with geologic stratigraphy. Production occurs from an open borehole section with a slotted liner extending from 126 to 205 meters depth, with a downhole pump (shaft turbine pump) installed to maintain well pressure.

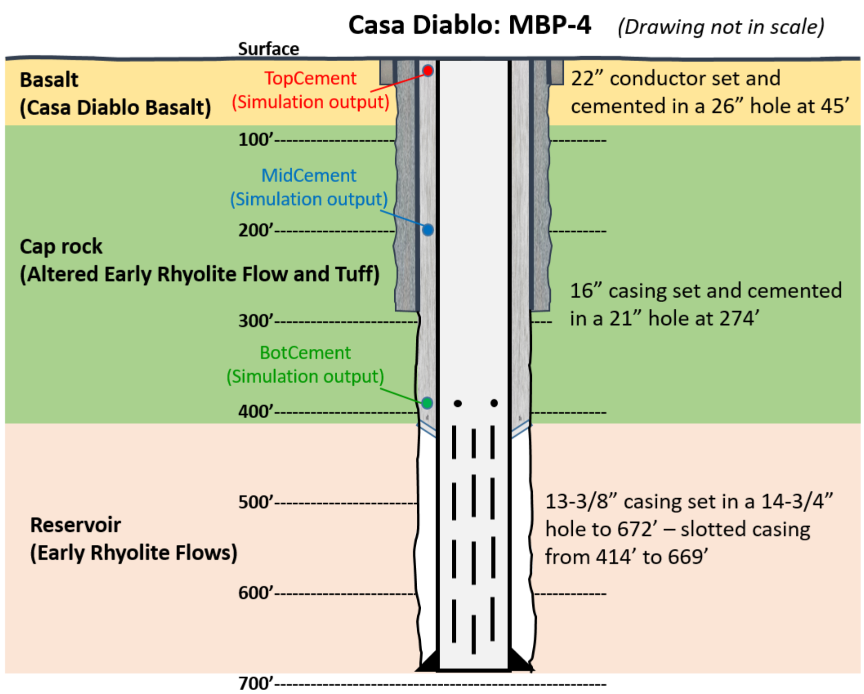


Figure 8: Casa Diablo MBP-4 production well geometry and geological units considered in the model (redrawn from DOGGR GeoSteam Data Base file).

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 9 shows the initial temperature used in the model and the measured temperature profile in a well located about 60 m away from the MBP-4 production well (Farrar et al., 2010). The geological unit denoted as "HotZone" is the main feed zone of the reservoir. The permeability of this zone has been adjusted manually by matching the simulated initial reservoir pressure and flowing bottom hole pressures to data measured during a well production test (MBP-4) performed on July 6, 1984. 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.

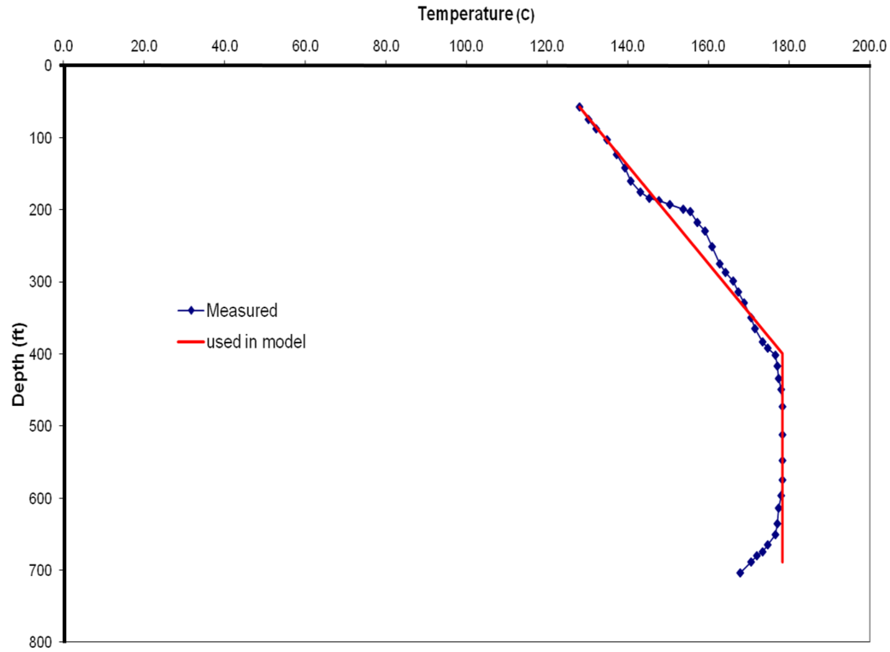
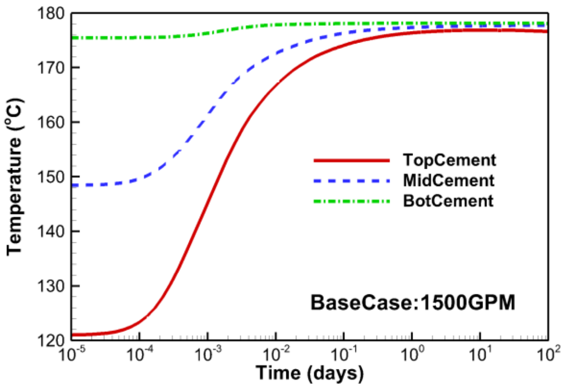


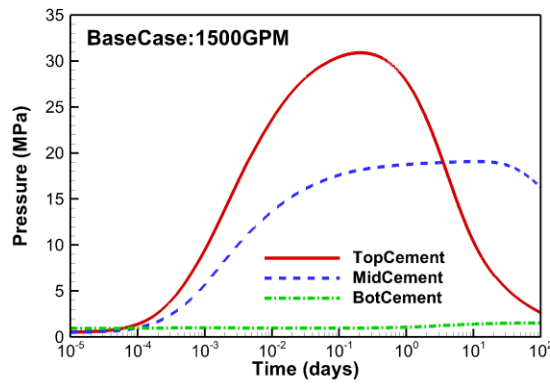
Figure 9: Profiles of measured temperature for the MBP-3 well (Farrar et al., 2010) and initial temperature used in the model

We first conducted thermal-hydraulic analysis of wellbore 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 conditions 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 considered for evaluation of the potential for mineral scaling.

The base-case simulation of constant production for 100 days at 1500 GPM (84.31 kg/s) shows that the pressure loss from the well bottom to the well head is small due to downhole pumping, while temperature increases substantially in the upper part of the well. This abrupt change in temperature causes heat loss into the well assembly and heating of the surrounding rock (Figure 10a). 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 10b). At the middle depth of the casing cement, the pressure increase is lower due to a lesser 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 solid phase. This process tends to be more significant in a low-permeability porous media, like cement, because it takes a longer time for the pressurized fluid to diffuse away.



(a)



(b)

Figure 10: Simulation results for the base case constant production at 1500 GPM (84.31 kg/s) for 100 days; (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 8.

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. Figures 11 through 13 present production rates along with temperature and pressure responses within the well assembly. Here we model cyclic production with a peak rate of 1600 GPM (89.93 kg/s) every 14 hours followed by 10 hours off-peak at a rate of 700 GPM (39.34 kg/s) during weekdays, and 24 hours off-peak a rate of 700 GPM (39.34 kg/s) during weekends. The weekly average production is 1075 GPM (60.42 kg/s).

A slight overshot in wellhead production rate occurs when high flow rate suddenly switches to low flow rate due to the induced shock wave in the well (Figure 11). This is an effect of the way with which the downhole shaft turbine pump is modeled in this simulation. That is, the wellhead back-pressure is fixed and the production rate is controlled by setting a fixed mass flow rate at down hole (e.g., top of the liner). However, in reality, the pump had only one speed and the production rate was controlled by adjusting the back pressure at the wellhead (Miller and Vasquez, 1988). Therefore, the above mentioned overshot may not occur.

The bottom-hole pressure responds to cyclic production but the magnitude is small, less than 1 bar, while the wellhead pressure changes little due to the fixed back pressure (Figure 12a). Temperature in the well show a ~1.6°C variation between peak and off-peak production while the bottom-hole temperature is almost constant (Figure 12b). Pressure and temperature conditions indicate that single-phase liquid conditions are maintained in the well during variable production in this system (downhole shaft turbine pump with back pressure at wellhead outlet).

Both temperatures and pressures in the casing cement change little in response to variable production (Figure 13). The pressure at the MidCement point is still very high although it slowly decreases with time because the very low permeability of cement (2E-18 m^2 used in this model) results in slow pressure dissipation process in the middle of the cement.

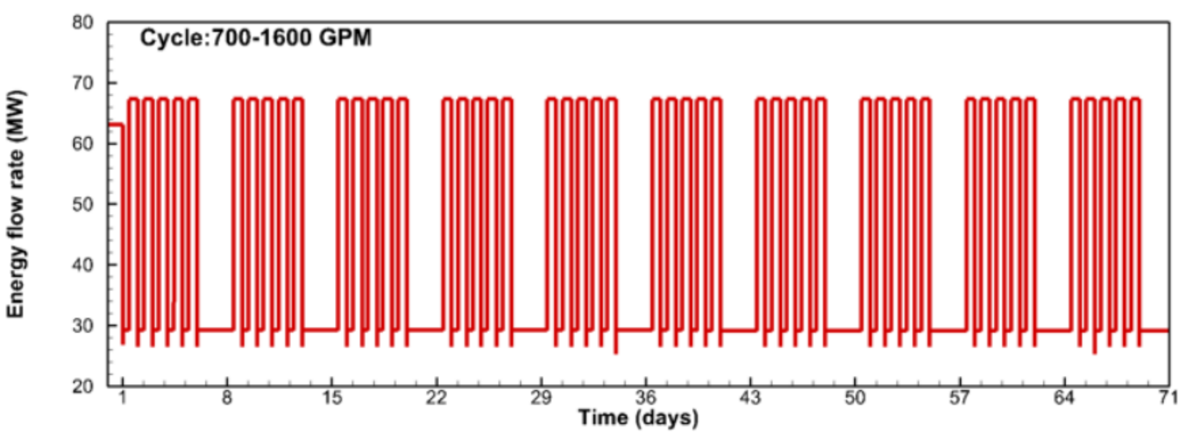
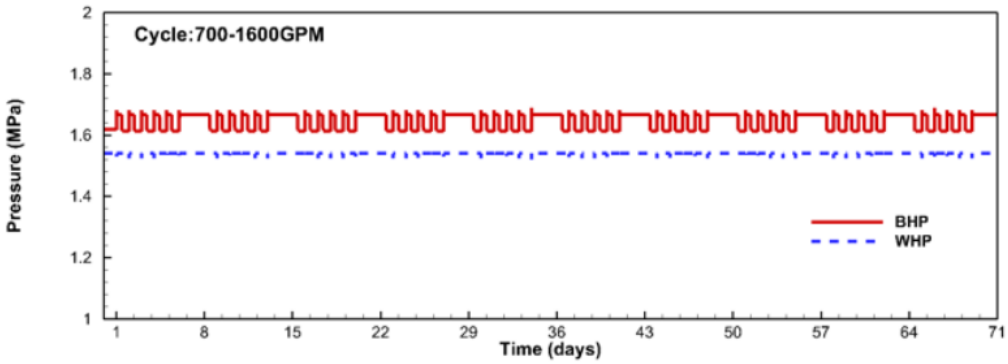
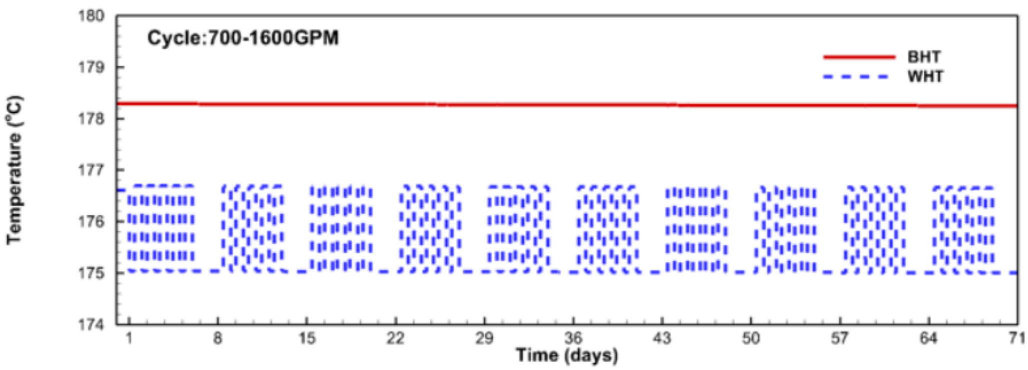


Figure 11: Calculated energy flow rate for an assumed cyclic production with production rates varied between 700 and 1600 GPM.

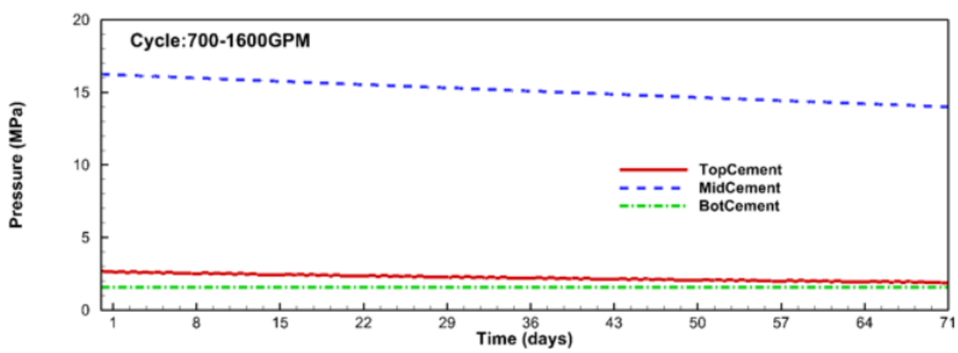


(a)

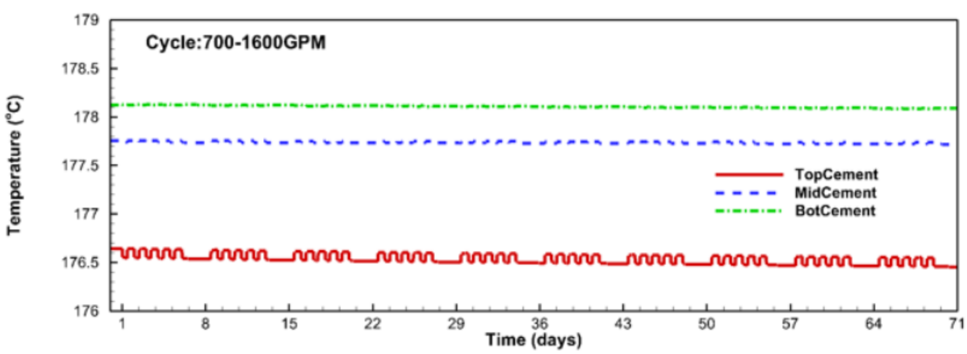


(b)

Figure 12: Simulation results for an assumed cyclic production with production rates varied between 700 and 1600 GPM; (a) Bottom-hole pressure (BHP) and wellhead pressure (WHP). (b) Bottom-hole temperature (BHT) and wellhead temperature (WHT).



(a)



(b)

Figure 13: Calculated pressure and temperature evolution in the cement for an assumed cyclic production with production rates varied between 700 and 1600 GPM; (a) pressure and (b) temperature at TopCement (2.4 m depth), MidCement (61 m depth), BotCement (120 m depth).

3.3 Summary of T2Well Analysis and Implications for Well Integrity Analysis

The T2Well analysis of coupled reservoir-well bore processes shows that the highest thermal perturbation, ΔT, caused by production occurs 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 variations are the largest as hot production fluid heats up the well from an initial ambient and relatively cool temperature near the ground surface. These temperature variations during initial start-up of the production are the highest in the case of production from a deep and hot geothermal system, such as the steam-dominated system at The Geysers, simply because the ambient ground surface temperature is lower in that case.

In the case of a shallow liquid-dominated geothermal system, similar to that at the Casa Diablo, a temperature increase $\Delta T \approx 55°C$ was calculated, whereas in the case of production from a deep geothermal well, similar to that of the P25 production well at the northwest Geysers, a temperature increase of $\Delta T \approx 195°C$ 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. These pressure changes caused by thermal-pressurization are highest for production from a deep geothermal well, though strong changes also occur for production from the shallow geothermal well.

For flexible production using daily production cycles, the largest fluctuations in shallow wellbore temperature and pressure occurred for a deep steam-dominated system, with pressure fluctuations on the order of about 1.5 MPa and temperature changes of about 5°. In fact, for a liquid-dominated system, the temperature and pressure changes are so small that they can be considered insignificant for well integrity. This is for the assumed cases of reducing the production to about 40% during low production cycles. However, in a sensitivity study, the production was not just reduced to 40%, but completely shut-down in each cycle. This case is presented in Rutqvist et al. (2020) for the same Casa Diablo system, where the temperature within the well at the wellhead changes more than 100°C resulting in significant temperature variations in the cement, with up to 30°C temperature changes at the wellhead. These temperature changes 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 (Rutqvist et al., 2020).

The implications for well integrity analysis are:

- The potential highest impact on well integrity would likely occur at the shallowest part of the well assembly, where temperature changes are the highest, for both liquid- and steam-dominated geothermal systems.
- The highest potential impact on well integrity would occur in the early start-up of production after a longer curtailment, because of rapid increase in temperature with associated thermal pressurization in the cement, behind the steel casing.
- During variable production with daily cycles, the temperature and pressure fluctuations are the highest for a steam-dominated system, while insignificant for a liquid-dominated system.
- On the basis of these results, the well integrity analysis presented in the next section focuses on the initial start-up for both shallow and deep wells, whereas cyclic changes are only investigated for a steam-dominated case.

4. MECHANICAL ANALYSIS DUE TO TEMPERATURE AND PRESSURE RESPONSES

Coupled multiphase flow, heat transport and mechanical modeling is conducted using T2Well-FLAC, with the mechanical component focused on some of the vulnerable parts of the well assembly in this context, namely its shallowest part.

4.1 Coupled Flow and Geomechanical Model Setup

Figure 14 shows a 3D mechanical model of the well assembly for the deep geothermal well in the steam-dominated reservoir (P25 at The Geysers) and how it is linked to the larger scale T2Well simulation model. As described in Section 3, 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 at a depth of 2.4 m is imported into the mechanical analysis along the radius of the 3D model. The main reason for adopting a 3D model in the mechanical analysis is that anisotropic horizontal in situ stress might be important to consider. In this particular case at 2.4 m depth, the in-situ stresses are very small and there would not be much of a mechanical force from the surrounding formations on the well assembly at this depth. The mechanical model includes components of host rock, cement and casings as well as slip interfaces between these components. These slip interfaces allow for frictional failure using Coulomb criterion as well as elastic opening of the interfaces or breaking up caused by tensile failure.

Figure 15 shows the FLAC3D model geometry for the two types of wells considered in this study considering the well design shown in Figures 2 and 8. Both types of wells have a well assembly consisting of multiple steel casings and cement sheaths, but the dimensions of the well completions are different and this will impact the coupled THM evolution. 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 (Rutqvist et al., 2018; 2020). These properties are reasonable and we are also continuously updating the properties based on site specific data.

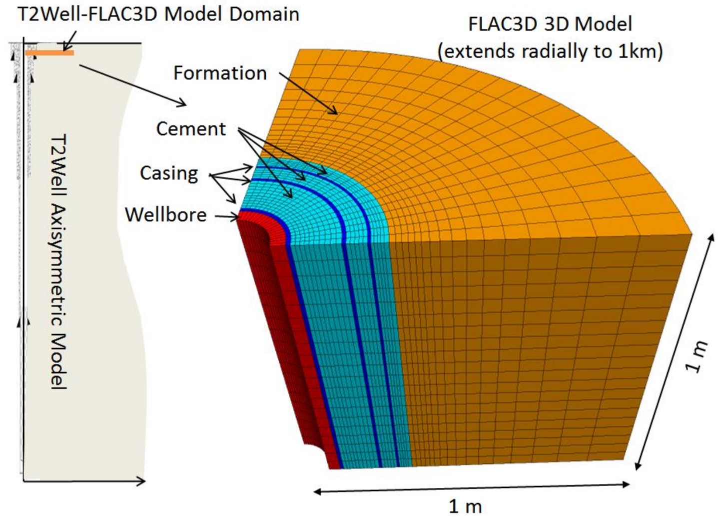


Figure 14: Coupled T2Well and FLAC3D model domains, including T2Well large scale axial symmetric model domain and FLAC3D mechanical model domain of the shallowest part of the production well.

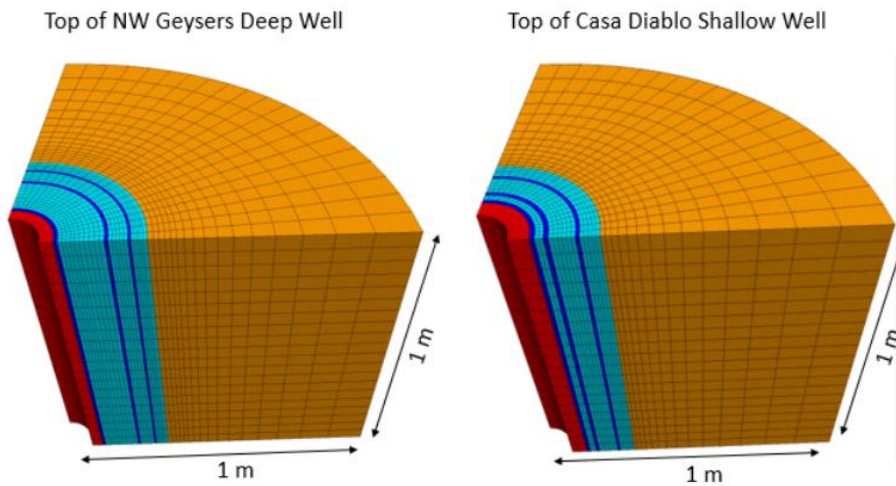


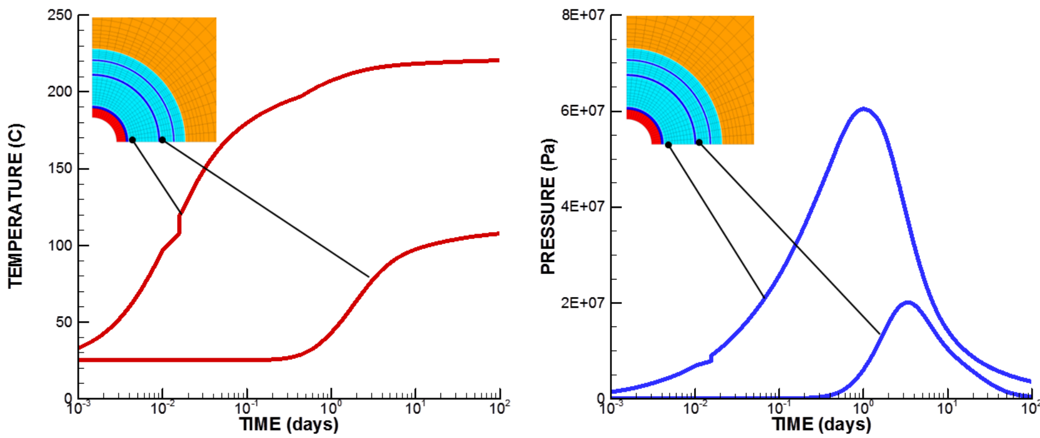
Figure 15: FLAC3D mechanical model domains of the shallowest part of the production wells at (a) NW Geysers P25 deep geothermal well and (b) Casa Diablo shallow geothermal well.

4.2 Deep Steam-dominated system

Figure 16 shows that the expansion of inner parts of the well assembly results in tensile stress and tensile failure of the outer cement sections. Here we assumed a tensile strength of the cement of 3 MPa. The surrounding sediment is very soft and has also reached its tensile strength of 1 MPa. At the same time, high compressive stresses are induced in the cement, just behind the innermost casing (Figure 4-7). These high compressive stresses are caused by thermal stress, which develops here in the tangential direction and results in a compressive shear failure that is limited in extent to the innermost cement.

Figure 17 shows the stress path (maximum compressive versus minimum compressive stresses) in the 2nd cement section, along with the Mohr-Coulomb failure envelope. The stress evolution is very complex, with both tensile and shear yielding occurring during the first few days 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. Finally, at pseudo-steady conditions at 100 days, the stresses have reached a more uniform state of 13 to 18 MPa effective stress.

High tangential stresses also build up in the steel casing, with high compression in the innermost casing and tensile stresses in the two outermost casings (Figure 18). The high compressive stresses in the innermost steel casing are 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 800 MPa, which could likely lead to yielding depending on the grade of the steel material. Yielding was not accounted for in the current analysis, but could be included in future analysis.



(a) (b)

Figure 16: Calculated (a) temperature and (b) pressure evolutions in two cement sections at the shallow part of the production well (production from a deep geothermal well).

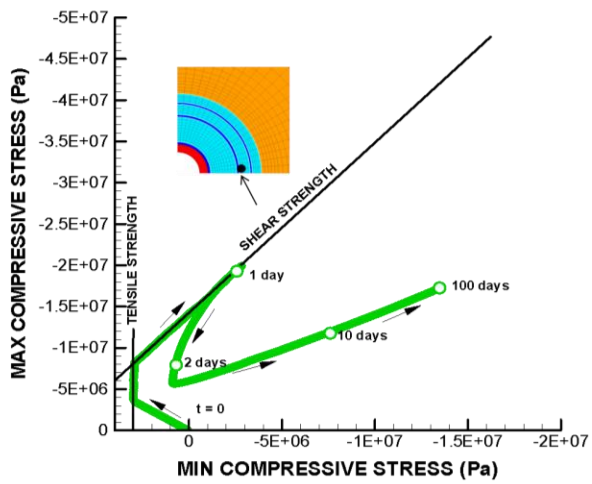


Figure 17: Effective stress path for one location in the 2nd cement section.

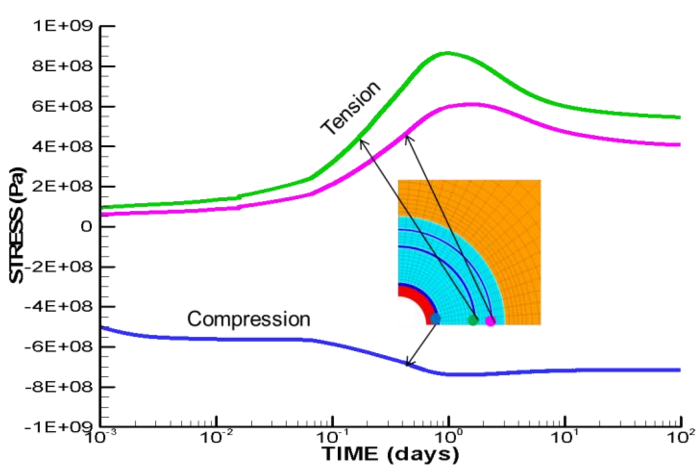


Figure 18: Calculated tangential stress evolution in all 3 casings in the shallowest part of the well.

For the simulation of variable production we concluded in Section 3 that for cyclic production with curtailment down to 40%, some pressure and temperature changes occur in the case of a steam-dominated geothermal well, while changes are negligible for a liquid-dominated geothermal system. For the steam-dominated system, the simulation of variable production resulted in both temperature and pressure variations in the cement, with the highest magnitudes in the innermost cement. With daily production variations, the temperature fluctuates with a magnitude of about 5 °C and the pressure with a magnitude of about 1.5 MPa (Figure 19). These changes in turn result in stress cycles with magnitudes of 2 MPa in the steel casing and 1 MPa in the cement (Figure 20). These changes in stress are small compared to the stress changes that occurred during the preceding start-up and 100 days of steady production. Obviously, the stress change that could occur during variable production will very much depend on the schedule and magnitudes of the production cycles.

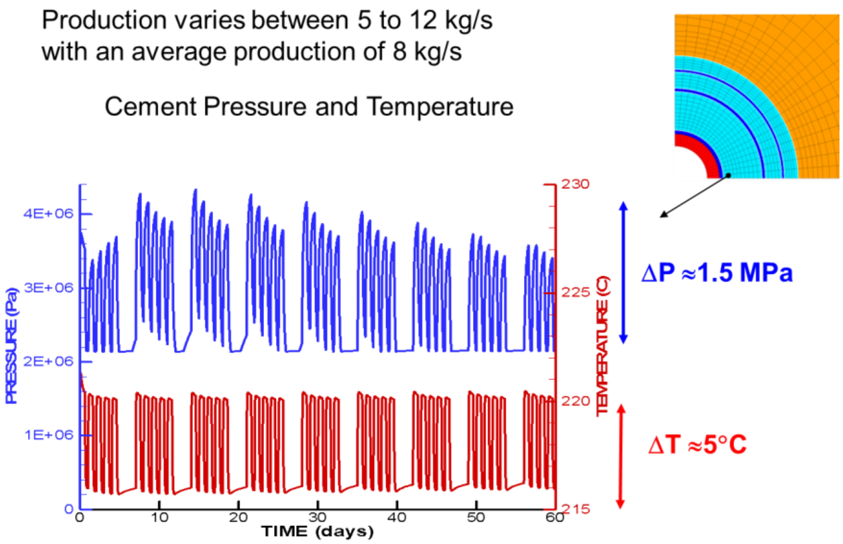


Figure 19: Calculated pressure and temperature evolution during variable production (deep steam-dominated reservoir).

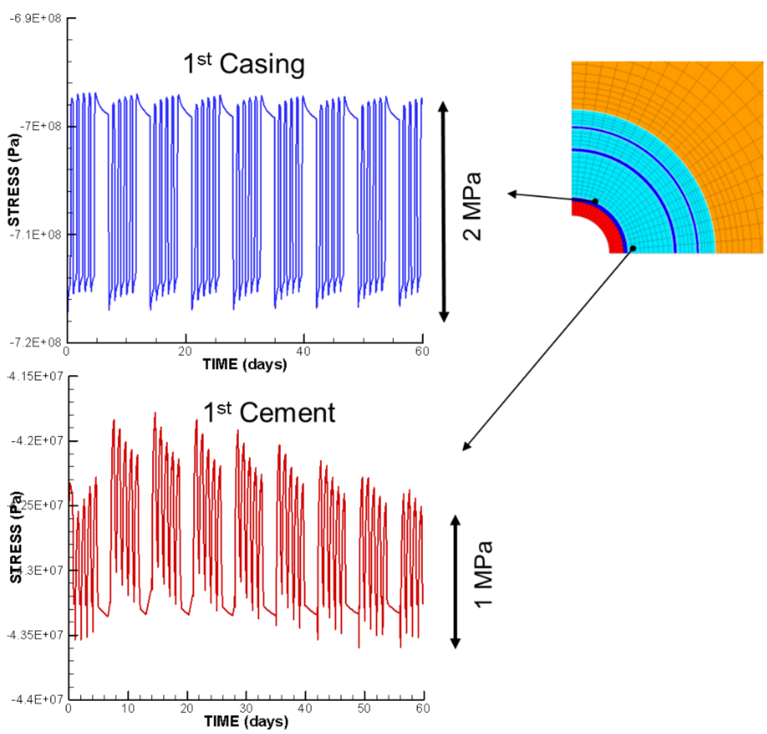
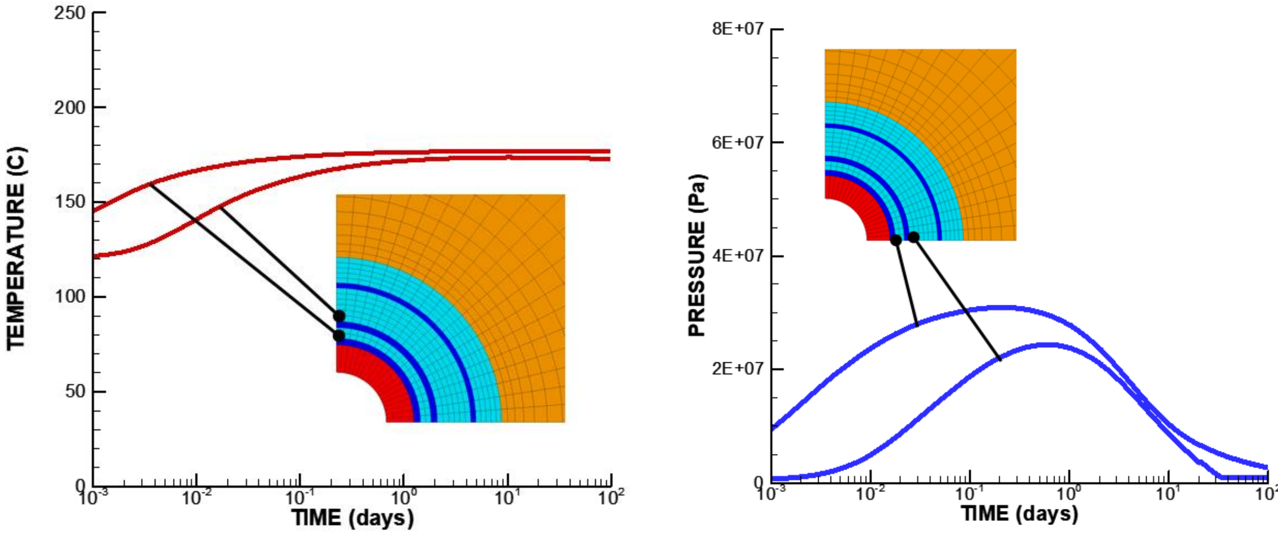


Figure 20: Calculated maximum compressive stress evolution in the inner casing and cement during variable production with daily cycles (deep steam-dominated reservoir).

4.3 Shallow liquid-dominated system

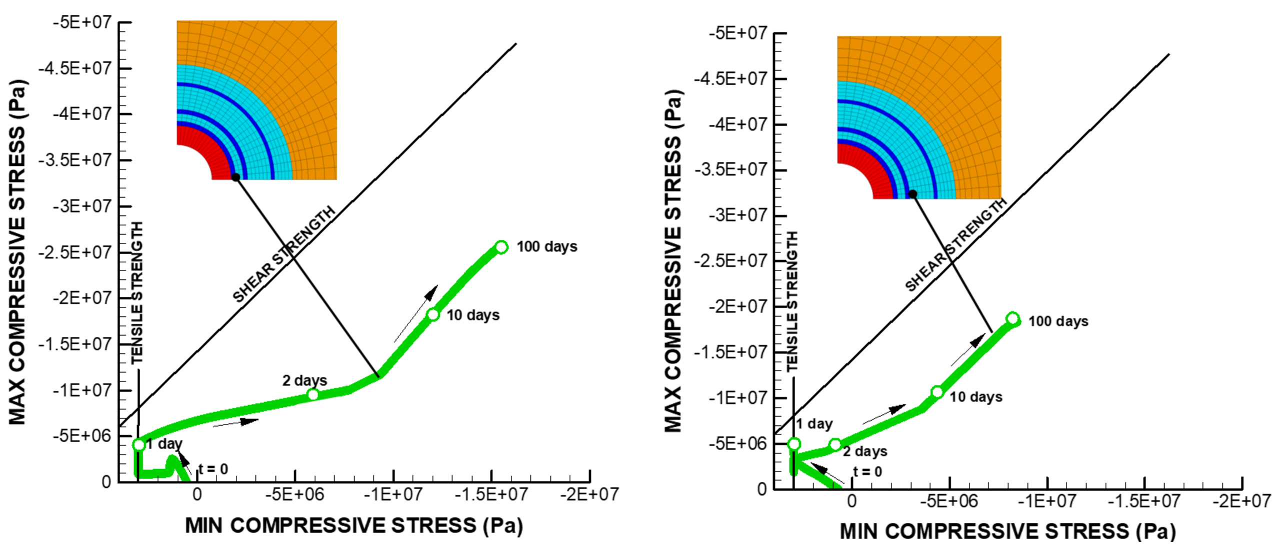
For production from the shallow geothermal well, the simulation also shows that failure in the cement behind casing could occur at an early stage during production start-up. As observed in Figure 21, the temperature and pressure increase very rapidly in the cement behind the innermost casing as well as between the two outermost casings. However, in this case the relative changes in temperature and pressure are smaller as the initial temperature is much higher. It should be said though that the initial temperature adjacent to the ground surface in this model might be overestimated. Indeed, Figure 9 shows that there is no measured data very close to the ground surface and for this depth at 2.4 m below the ground surface the initial temperature could be lower than what is indicated in Figure 21a.

Figure 22 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. The behavior is similar to that shown for the deep geothermal well in a steam-dominated geothermal field in Figure 17, but shear failure does not occur in this case.



(a) (b)

Figure 21: 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 22: Effective stress path for one location in (a) first cement section and (b) second cement section.

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 23). The peak tensile and compressive stresses are smaller than in the case of production from a deep well (compare stress evolution in Figures 23 and 18). The tangential stress changes are smaller because the temperature changes and hence thermal stresses are smaller in this case. Nevertheless, the stress increases as high as 400 MPa could still lead to yielding depending on the grade of the steel material.

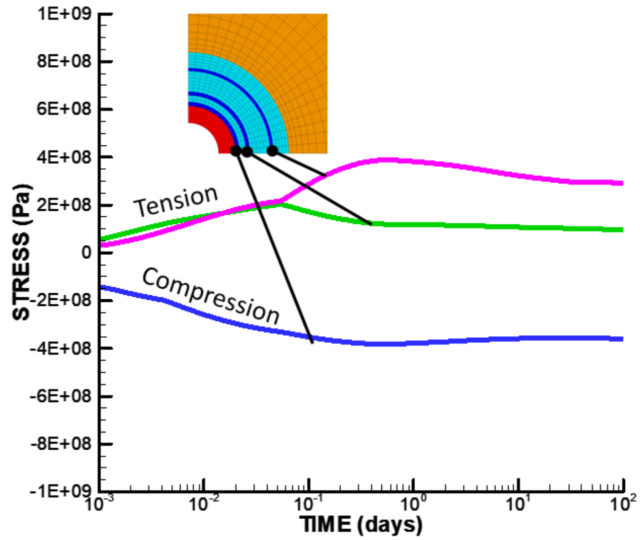


Figure 23: Calculated tangential stress evolution in all 3 casings in the shallowest part of the well.

The variable production for the Casa Diablo well considering the liquid-dominated system did not result in any significant pressure and temperature changes when production was reduced to about 40% during low production cycles (Figure 13). Thus, no significant stress changes can occur due to variable production and therefore variable production would not have an impact on mechanical well integrity for this shallow geothermal system.

5. IMPACT ON SCALING AND CORROSION

Mineral scaling is typically not an issue for a vapor dominated system such as the Geysers. However, pressure variations from a flexible production mode could affect vapor condensation and the accompanying scrubbing of acid gases such as HCl. This would possibly increase the potential for corrosion if condensation occurred in the well. Conversely, increased condensation by vapor adsorption on mineral surfaces and capillary condensation in small pores in rocks surrounding production wells could scavenge and neutralize HCl away from these wells and thus lower their corrosion potential (e.g., Pruess et al., 2007). The present study shows that under the flexible production mode considered here, increased vapor condensation within the well would not be expected, therefore cyclic production should not be detrimental in terms of corrosion. Potential variations in the amount of condensation away from the well (which would be beneficial with respect to corrosion) are currently being evaluated.

For the case of a liquid-dominated system such as Casa Diablo, .the potential for mineral scaling was evaluated using the CHILLER simulations as presented in Rutqvist et al. (2020). Fluid (water + gas) was first reconstructed and the reconstructed fluid 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.

The final results show 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 hydroxides with minor clay, carbonates, and sulfides, corresponding to amounts up to ~5 kg of scale per day at 500 gpm (Figure 24). However, cooling the fluid below about 70°C could result in the precipitation of significant amounts of amorphous silica 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).

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.

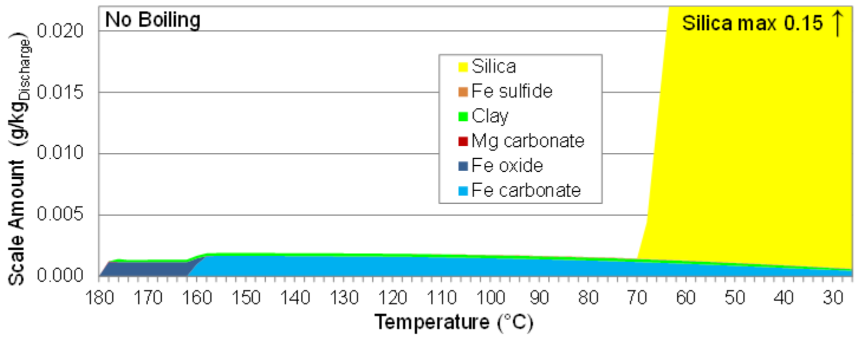


Figure 24: Simulations of cooling without boiling for a Casa Diablo geothermal fluid: computed amounts and types of deposited minerals.

6. CONCLUSIONS

The wellbore-reservoir modeling shows that the highest thermal perturbation, ΔT, occurred in the case of a steam-dominated system 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 and failure 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 production could cause cement failure in the shallowest parts of the well both in tension and compression. Such early time changes could occur for both steam-dominated and liquid-dominated systems.

The modeling further showed that flexible production results in relatively small changes in wellbore temperature and stress if the production cycles are controlled. 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, the 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. For the case a vapor-dominated system such as Geysers, as long as condensation was avoided in the well, pressure fluctuations would not be expected to affect the potential for corrosion by the scrubbing of acid gases in vapor condensate.

Future work will include sensitivity studies of identified key processes and properties, such as cycling schedule, wellbore component designs, and reservoir properties. Finally, additional site-specific data will be used, including data from pilot experiments on variable production at The Geysers geothermal field.

ACKNOWLEDGMENTS

We thank Calpine Corporation, including Julio Garcia, for generously providing well and field data for The Geysers geothermal field. 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.

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