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Thermo-Hydraulic Modeling of Long-Term Circulation Tests at the Utah FORGE Site

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ABSTRACT

The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) site recently conducted a successful 30-day commercial-scale circulation test between wells 16A(78)-32 and 16B(78)-32. Prior to the test, both wells were hydraulically stimulated using proppants creating new induced tensile fractures and opening pre-existing natural fractures. Based on the seismic data collected from the stimulation, an updated discrete fracture network (DFN) model was developed. In this study, the updated DFN served as the foundation for our thermo-hydraulic (TH) modeling of the April and August 2024 circulation tests using the FALCON (Fracturing And Liquid CONvection) code. The porosity and permeability in the hydraulic model were adjusted to incorporate the DFN. Fluid temperature, pressure, and flow rates from the circulation tests were compared to the TH simulation results. The DFN extent and zonal flow were modified to achieve a better fit between the experimental and simulation data. The refined model was then used to conduct long-term circulation simulations over a period of one year to evaluate the thermal performance of the system.

1. INTRODUCTION

The Utah FORGE site, funded by the U.S. Department of Energy (DOE), aims to advance enhanced geothermal system (EGS) research and technology development. The primary goal of the site is to create an extensive network of fluid pathways between injection and production wells to facilitate geothermal energy research. In early 2024, wells 16A and 16B underwent a comprehensive stimulation program to enhance the connectivity of the reservoir fractures which provide flow pathways between the wells.

Following the stimulation program in early 2024, several circulation tests were conducted to evaluate the effectiveness of the enhancements (EGI, 2024a). In April 2024, a 9-hour circulation test was conducted to confirm the hydraulic connection between wells 16A and 16B. This test was crucial in verifying that the stimulation had successfully created a continuous flow path between the two wells. Subsequently, in August 2024, a 30-day circulation test was performed to observe longer-term trends in pressure, temperature, and production. This extended test aimed to provide data on the sustainability of the geothermal reservoir and the efficiency of the created fluid pathways.

It is important to note that the provisional data and models for these tests were analyzed and created in a very short period of time, as they needed to be completed before the August testing. This rapid turnaround was essential to ensure that the extended 30-day circulation test could be conducted with accurate and up-to-date models.

This paper presents the results of numerical analysis of the circulation tests conducted following these stimulations, including a detailed model calibration exercise for the 9-hour test performed in April 2024. The expedited creation and analysis of these models were critical in guiding the August 2024 extended test, providing valuable insights into the effectiveness and sustainability of the geothermal reservoir enhancements.

2. NUMERICAL MODEL DEVELOPMENT

Two provisional DFN models (EGI, 2024b) were created using provisional data (prior to validation) to represent the fracture network accurately. The June 2024 DFN model included over 100 individual fractures. Stochastic fractures were added where there was high microseismic (MEQ) point cloud density but not reached by larger identifiable fractures. Hydraulic fractures were also added where perforations took fluid, even if MEQs were not clearly identifiable. Fracture sizes were scaled by flow rate to represent the varying capacities of different fractures.

However, the June DFN model had too many small, poorly connected fractures, which caused unrealistic pressure responses in the numerical model. To address these issues and improve computational efficiency, a simplified DFN model was created in July 2024. This revised model included fewer than 60 individual fractures. It used fewer stochastic fractures and added more connecting fractures to avoid dead ends and pressure buildup. The July 2024 DFN model focused on retaining larger, connected fractures to improve the accuracy of the simulation while ensuring computational efficiency. Figure 1 compares the two DFN models.

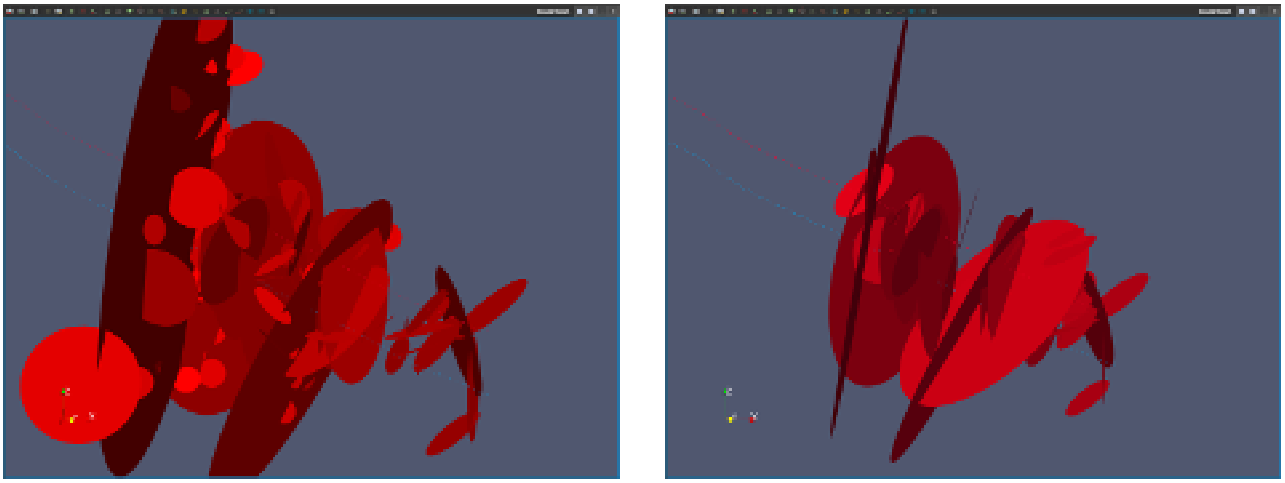

Figure 1: Comparison of June 2024 and July 2024 DFN Models

2.1 Boundary Conditions (BCs) and Initial Conditions (ICs)

The pressure and temperature conditions were extrapolated from the Native State Model (Podgorney et al., 2023) for both the initial and boundary conditions used in the current analysis. The Native State Model, which encompasses a detailed representation of the Utah FORGE site, includes dimensions of approximately 4 km by 4 km horizontally and extends vertically to a depth of about 5 km from the ground surface. This comprehensive model provided a baseline for understanding the natural state of the geothermal reservoir before any stimulations were applied.

A mixture of Neumann and Dirichlet conditions were used, as appropriate, to ensure the reservoir scale models created for this analysis remained consistent with far-field conditions predicted by the Native State Model. Neumann boundary conditions, which specify the rate of change (flux) across boundaries, were applied where it was critical to maintain the natural gradient of pressure and temperature. Dirichlet boundary conditions, which specify fixed values at the boundaries, were used to anchor the model to known far-field conditions, ensuring stability and accuracy in the simulations.

2.2 Sources and Sinks

In well 16A, sources, locations and rate were explicitly matched to stimulation cluster information. This included detailed data on pumping rates and spinner log readings, which were used to accurately simulate the locations and rates of fluid injection. By ensuring that these sources were precisely aligned with the actual stimulation data, the model could more accurately predict the behavior of the injected fluids and their impact on the fracture network.

Conversely, the sinks in well 16B were modeled based on stimulation stage and cluster information, utilizing the Peaceman formulation to simulate flow dynamics accurately. This approach allowed for the natural hydraulic flow to dictate the behavior of the sinks, providing a realistic representation of fluid extraction. The Peaceman formulation was particularly useful in capturing the complex flow patterns and pressure changes within the well.

Despite the incomplete spinner log data for well 16B, the model incorporated available information to estimate the locations and capacities of the sinks. This involved using stimulation stage data to identify potential extraction points and adjusting the model to reflect the expected flow rates. The use of the Peaceman formulation helped to ensure that the pressure and flow dynamics were realistically simulated, even with the limited data. Figure 2 provides a schematic cross-section of Wells 16A and 16B, showing the stimulation stage, perforation zones, and open-hole sections.

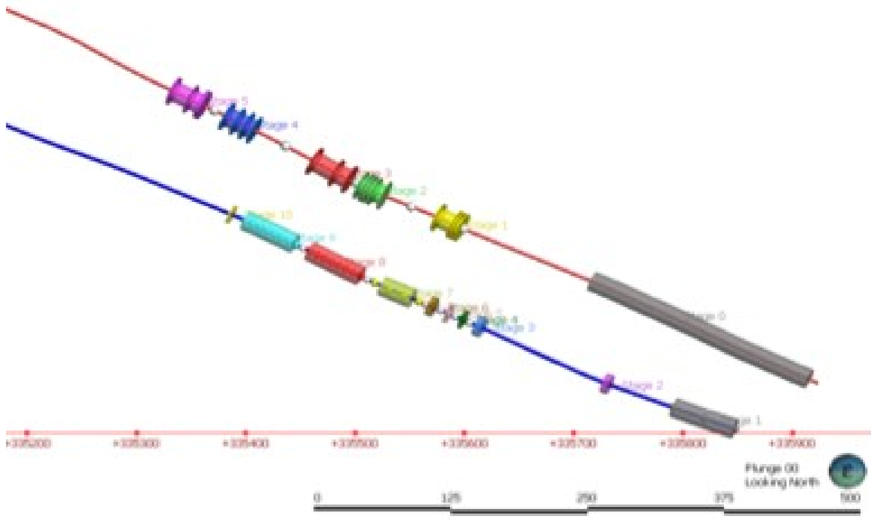

Figure 2: Schematic cross-section of Wells 16A and 16B, showing the stimulation stage, perforation zones, and open-hole sections. Each perforation zone that had measurable flow was explicitly represented in the numerical models.

CALIBRATION TO THE 9-HOUR CIRCULATION TEST

Accurate modeling and calibration are critical steps in understanding the behavior of geothermal reservoirs and predicting the outcomes of stimulation and circulation tests. This process involves adjusting various parameters to ensure that the model closely replicates observed field data. In this study, we focused on the calibration of hydraulic models to match the results of a 9-hour circulation test, which was instrumental in providing insights for a subsequent 30-day test.

At the start of the test, the injection rate was increased stepwise, from 0 to 10 barrels per minute (bpm) in 2.5 bpm increments. The pressure response exhibited a non-linear response to increased flow rate, with a more liner relationship between pressure and flow rates at lower injections rates, and increasing nonlinearity as the injection rate increased. To reproduce these general trends, experimentation with fracture and matrix permeabilities was conducted. The results showed that fracture permeability was $1x10^{-14}$ m² and matrix permeability was $1x10^{-17}$ m². It is important to note that the modeled pressure did not include the pressure drop in the well or perforations.

Due to the short time available to process provisional data, a model was created and calibrated to the 9-hour test to provide insights for the planned 30-day test. This process involved adjusting the porosity and permeability in the hydraulic model to accurately incorporate the discrete fracture network (DFN). Figure 3 shows the pressure calibration results for the 9-hour circulation test.

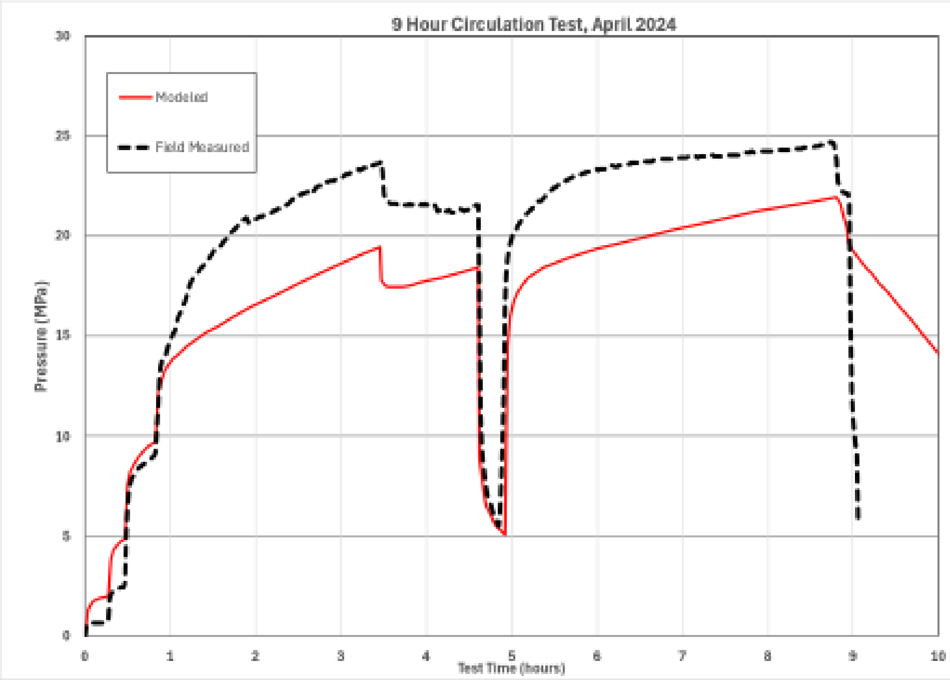

Figure 3: Pressure Calibration Results for the 9-hour circulation test.

The model captured the field-measured outflow well. In some cases, erratic field measurement data were suspected to be due to equipment issues. Approximately 500 psi of extra pressure was added to account for flow exit from well 16B, considering wellhead pressure during production and pre-test static water level. Without this correction, flow rates were too high, implying the need for submersible pumps for extraction. Figure 4 shows the outflow calibration results for the 9-hour circulation test.

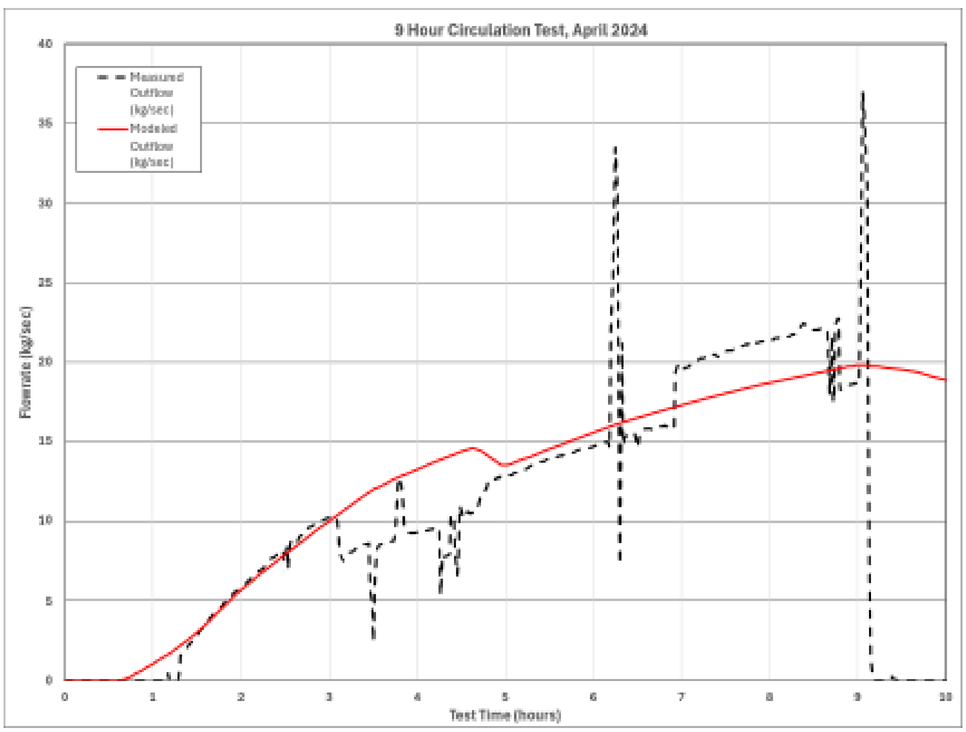

Figure 4: Outflow calibration results for the 9-hour circulation test.

Six feed zones were modeled in well 16B, corresponding to open hole and perforated zones in the well. All but one zone delivered fluid to the well. The simulated temperature of the produced fluids were enthalpy and rate averaged, which were used as input for a wellbore thermal hydraulics analysis that included heat transfer through the casing as the produced fluid traveled up the well.

The wellbore thermal analysis simulation estimated flowing wellhead temperatures. The temperature boundary condition (BC) at the top of the model, based on the Native State reservoir model, seemed too high. Changes in the outflow rate were evident in the temperature but subdued. Figure 5 shows the produced temperature calibration results.

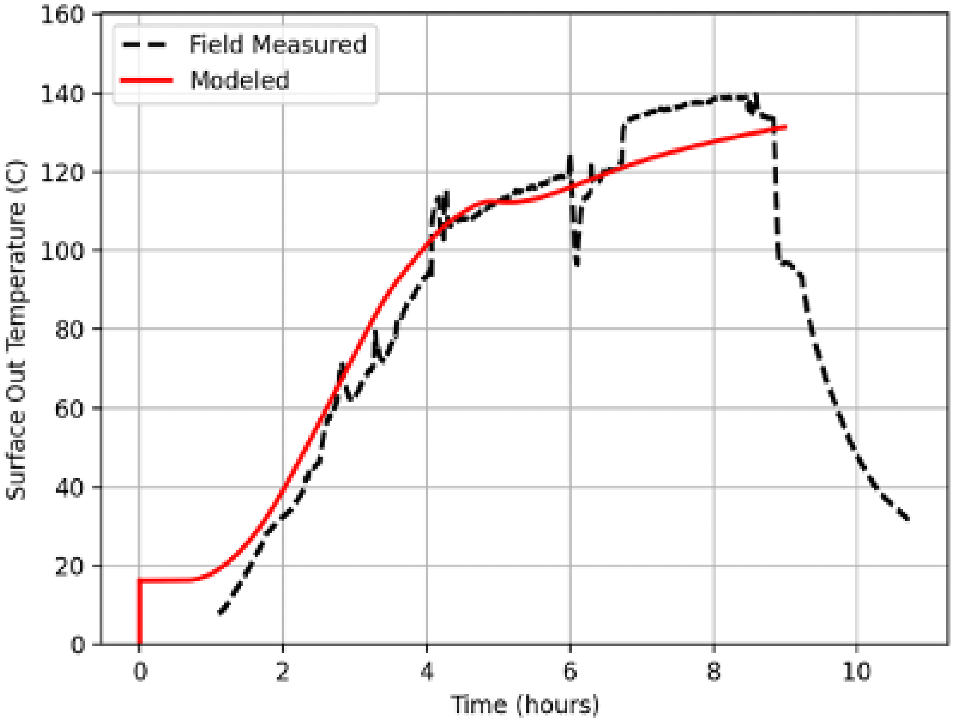

Figure 5: Produced Temperature Calibration Results

LONG-TERM CIRCULATION TEST SIMULATION

Using the model developed for the 9-hour circulation test, a long-term simulation was conducted with the July 2024 DFN representation. These simulations, performed prior to the 30-day test, were conducted to help inform the planning process. The simulation did not include several cycles of injection and shut-in at the start that were added to the field test plan after the modeling was completed. The models ran for a 1-year simulation time, and no significant thermal breakthrough was estimated after 30 days. A calibration/history matching exercise is now beginning for this 30-day circulation test, as all collected data have been fully analyzed and verified.

Figure 6 compares the long-term feed zone temperature results. During the long-term circulation test simulation, 10 bpm injection was maintained over the majority of the test. Feed zone temperatures are shown, not wellhead temperatures. The temperature climbed until about 55-60 days, then began to decline. Feed zones 3 and 4, mostly consisting of Stage 8 and 9 hydraulic fractures, cooled the most. The "Temp_out" is the temperature of fluid after it travels past the uppermost perforations, calculated using lumped fluid enthalpy.

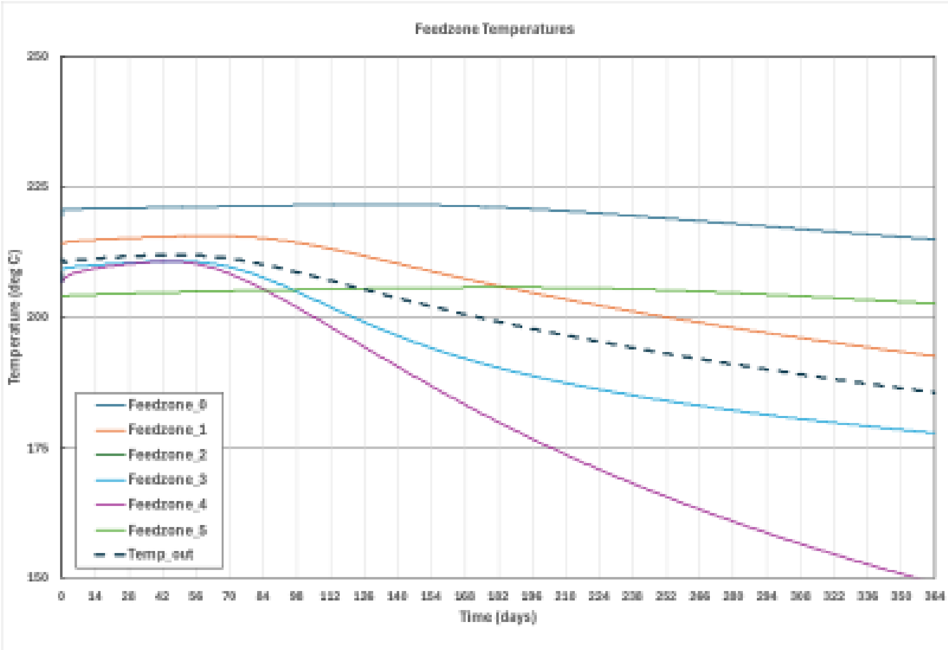

Figure 6: Long-Term Feed Zone Temperature Results.

As shown of Figure 7, the wellbore thermal analysis simulation was used to estimate flowing wellhead temperatures, in the same manner as was done for the 9-hour test. The blind, preliminary simulation matched the test observations quite well, considering the difference between the test procedures and the numerical model.

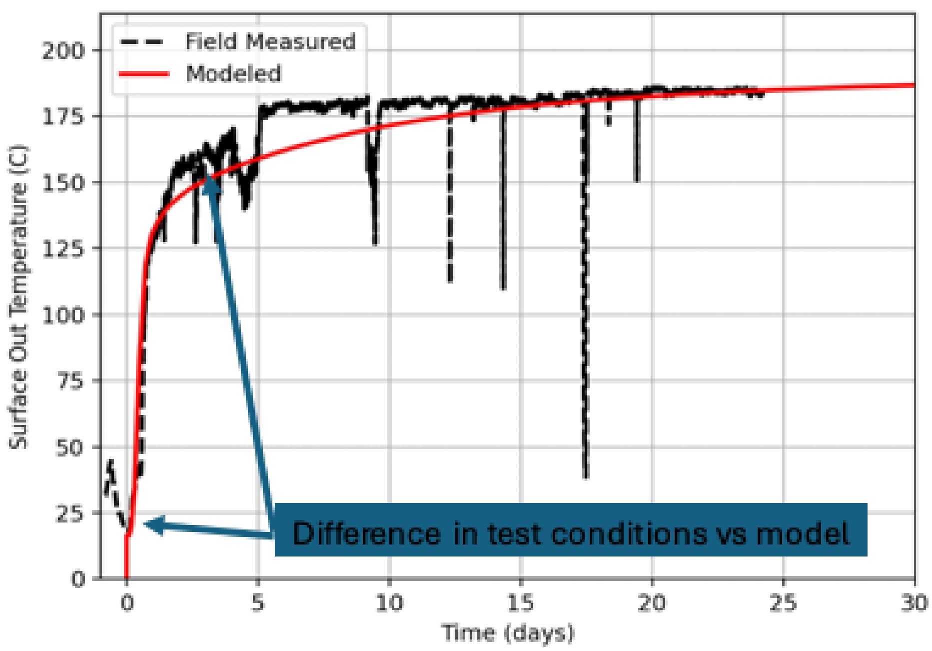

Figure 7: Long-Term Fracture Temperature

At the conclusion of the 30-day field test, the recovery efficiency was approximately 90%. Simulated recovery efficiency after the 30-day simulation time was approximately 95%. The simulated outflow rate took approximately 90 days to equal inflow rates. Long-term pressure decline data from wells 16A, 16B, and 58-32 will help calibrate far-field conditions.

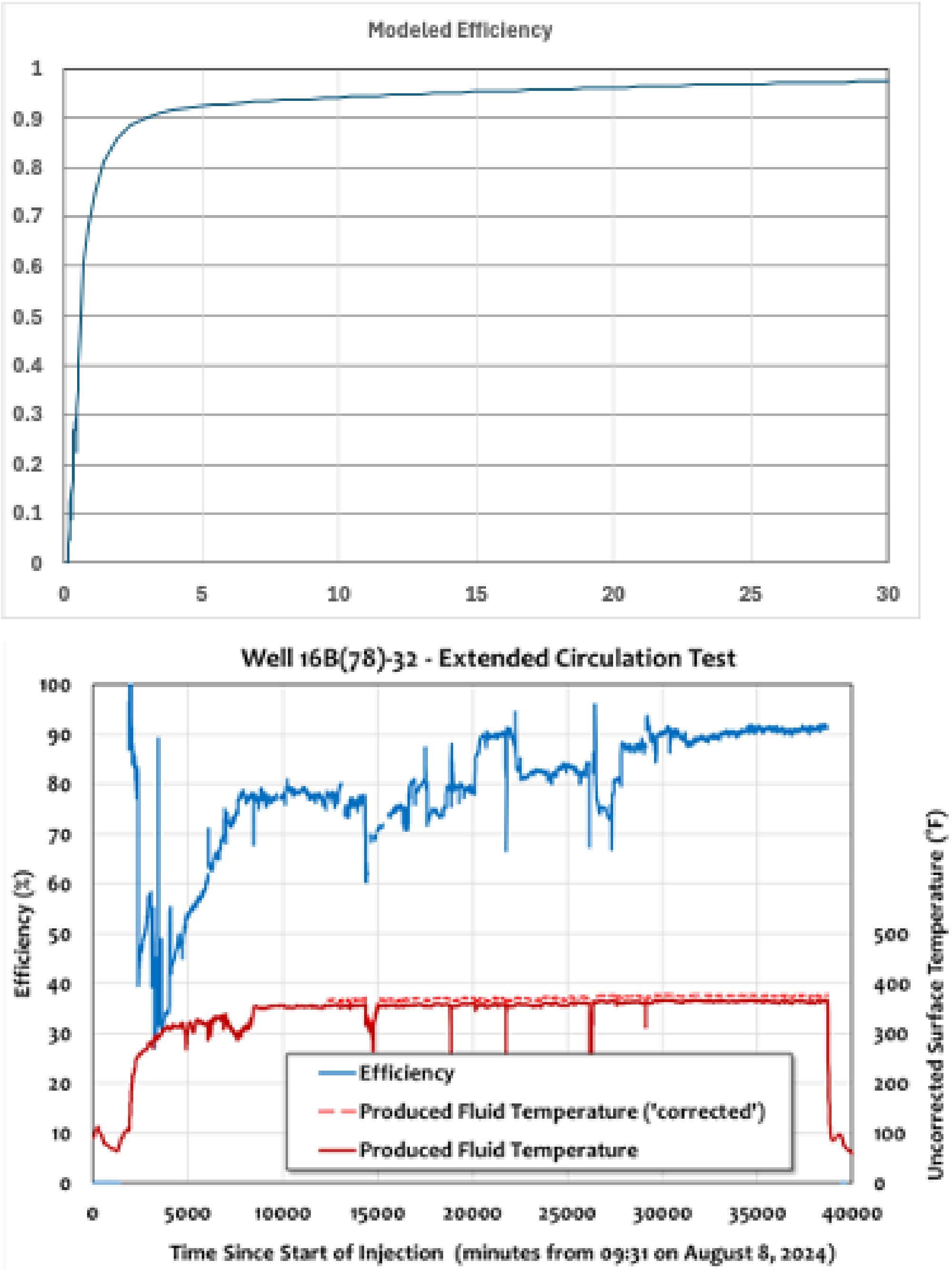

Figure 8. Modeled (top) and field measured (bottom) production efficiency

SUMMARY, CONCLUSIONS, AND FUTURE WORK

Multiple circulation tests were conducted between wells 16A and 16B in 2024. The FORGE modeling team developed and calibrated a numerical model using provisional data from a short-term test. The simulation matched both the short-term and extended circulation tests well. Significant near-wellbore pressure drop in well 16A is likely due to perforations or tortuosity.

The FORGE doublet exhibited high efficiency, approximately 90% at the end of the test, but the reservoir experienced large pressure perturbation. A submersible production pump may be needed for higher efficiencies and pressure management.

A model calibration exercise for the 30-day test is about to begin, using all available data, including frack hits, MEQ, flow and pressure, temperature, geochemistry, tracer, etc. These efforts will inform future circulation tests, new well locations, and operational scenarios.

REFERENCES

Energy and Geoscience Institute at the University of Utah. Utah FORGE: Wells 16A(78)-32 and 16B(78)-32 Extended Circulation Test Data - August and September 2024 [data set]. Retrieved from https://dx.doi.org/10.15121/2475065. (2024a)

Energy and Geoscience Institute at the University of Utah. (2024b). Utah FORGE: 2024 Discrete Fracture Network Model Data [data set]. Retrieved from https://dx.doi.org/10.15121/2440870. (2024b)

Podgorney, R., Munday, L., Liu, J., Finnila, A., Damjanac, B., Xing, P., and Radakovic-Guzina, Z: Thermal-Hydraulic-Mechanical (THM) Modeling of Fluid Flow and Heat/Tracer Transport Between Injection and Production Wells at the Utah FORGE Site, Proceedings, 48th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California. (2023)