Date: 22-September-2020 (final)

From: Richard Holt

Subject: LDG numerical model update and forecasts

Summary

This memo outlines the results of the 2020 update of the Lightning Dock Geothermal (LDG) numerical model. The model needed significant adjustment to match the rapid cooling that began in late-2019. Model experiments concluded that a cold water downflow was the most plausible cause of the abrupt cooling. As of late-2020, the cooling has slowed, but is not consistent with long-term sustainability of the resource. The revised numerical model matches both the rapid cooling, followed by the recent leveling off. Two model forecasts were run. The first continues as-is and the second considers that half of the cold downflow could be stopped (well 55-7 has a cold downflow in its idle state). The forecast (with half of the cold downflow ceased) shows a significant reduction in the cooling. While it is not known if the downflow in 55-7 represents half of the cooling downflow, plugging it off is a plausible way to reduce the downflow and it associated cooling.

Background

The original LDG numerical model was developed by Geothermal Science, Inc. (GSI), in late-2017. The LDG numerical model was based on a geological conceptual model provided to GSI in 2017 (Innovate Geothermal Ltd., "3D Geoscience Data Compilation, Visualization, and Interpretation: Lightning Dock Geothermal, New Mexico", July 2017). The model grid is shown in Figures 1 and 2.

In 2018, the numerical model was used to quantify resource supply, feasibility, and design parameters for the expansion of production from a planned new well LDG 45A-7, which was planned as a "twin well" to production well LDG 45-7. The model was calibrated against all available data, and a forecast was made for the production behavior of the wells when operated together as planned. Well LDG 45A-7 was drilled and then put on production in late-2018. The original model provided a good match to the performance of the wells for one year. In late-2019, however, both wells began to cool abruptly, at a rate much higher than the expected range seen in geothermal. The cooling rate was faster than thermal breakthrough indicated by the tracer tests. Therefore, is was postulated that the cooling was from a source in addition to the elements in the model. For example, possibilities considered were dilation of fractures between injectors and producers, an induced fracture (due to pressure drawdown) connecting the production zone to shallow cold water, or a cold downflow in an idle well which is known to be in strong connection with the 45-pad wells. Added motivation for the experiments was gained when, in process with the modeling update, idle well 55-7 was found to have a cold downflow and is also known from tracer tests to be very well connected to the 45-pad wells.

Model Experiments and Update

To determine which set of physics was the most likely, or even plausible, a series of “numerical experiments was conducted with the numerical model. The goal was to implement each possibility in the model and the run the model to check for plausibility. This would be shown by a model version which provided better matches to data. As for matching, emphasis has been on recent accelerated cooling followed by apparent stabilization. The following table outlines the tasks.

1. Updated with data through August 23, 2020
2. Completed runs I57, I58, I59 aimed at modeling variations on sudden new flowpaths developing in 12/2019. These runs investigated changes in fracture spacing, a change in the flowpath from shallow aquifers to the reservoir, and an increase in perm in the flowpath from injection well 53-7 to the 45-pad.
3. Results showed that a sudden increase in a downflow was providing promising results and was investigate further with serious of new runs.
4. New runs were created, run, and processed, Runs: I61, I70, I71, I72, I73. These runs were variations of properties and geometry of the modeled downflow.
5. Findings were that one variation of the model provided an improved match on 45-7 and different variation provided an improved match on 45A-7
6. The permeabilities and geometries of the above runs was combined into one version (model I75) which provided a reasonable match to the rapid cooling which started in late-2019 and more recently has reduced.

Results and Forecast

The overall conclusion from the numerical experiments, was that the inclusion of a cold downflow (which was activated in 12/2019) is a plausible explanation for the cooling in 45-7 and 45A-7. While this finding does not rule out the possibility of another causes, it does provide the best matches to data as compared to the theories tested with the model.

Figure 3 shows permeability on a representative N-S cross-section through the model showing the original model permeability (no high perm connection from the 45-pad well feedzone to shallower cold water). Figure 4 shows permeability on a representative N-S cross-section through the model showing the model permeability after the introduction of the cold downflow. As shown in the figure, the cold downflow as achieved in the model with a high permeability streak from the feedzones of the 45-pad wells to the shallow cooler waters.

Figure 5 shows the updated model match with the inclusion of the cold downflow in place. A reasonably good match was obtained to the temperature behavior. Therefore, the concept of a cold downflow developing in the reservoir is deemed to be plausible, in fact, the most plausible of the mechanisms tested.

The forecast portion is being done as below (on all runs). Note that 53-7 is shut-in and the combined flow of 45-7 and 45A-7 is reduced. See table 1. Figure 6 shows a 10-year temperature forecast with run I75B, which supposes the cold downflow continues as-is into the future. While the initial rate of cooling is reduced, the simulation predicts continued cooling with the plant inlet reaching 255 ^{o}F by year 2031.

Additional forecast was run (I75G) which hypothetically supposes that half of the cold downflow ceases in early 2021. The result is a much-improved forecast. In this scenario, the plant inlet temperature first recovers significantly, gradually increasing to reach 298 ^{o}F in early-2022. This is followed by a gradual decline of 1 ^{o}F/year over the next eight years reaching 290 ^{o}F by year 2031. While the run is hypothetical, the purpose is to show the potential for stopping the downflow in idle well 55-7 by plugging back with sand. It is known that a downflow exists, however, it is not known what percentage of the cooling is coming from that downflow. There could be more than one source of cold downflow. If the downflow in well 55-7 represents half of the cold downflow affect the 45-pad wells, a favorable result is predicted if that downflow is halted by plugging it back.

	tph (injection)	tph (production)
'P45-7'	0	-325
'I63-7'	6.8	0
'I53-7'	0	0
'I13-7'	98.9	0
'I75-7'	305.5	0
'I76-7'	46.6	0
'I66A-7'	294	0
'P45A-7'	0	-506
'I47-7'	15.5	0
'I17A-7'	22.9	0
'I17-7'	20.1	0

Table 1: Flow rates used in the 10-year forecasts

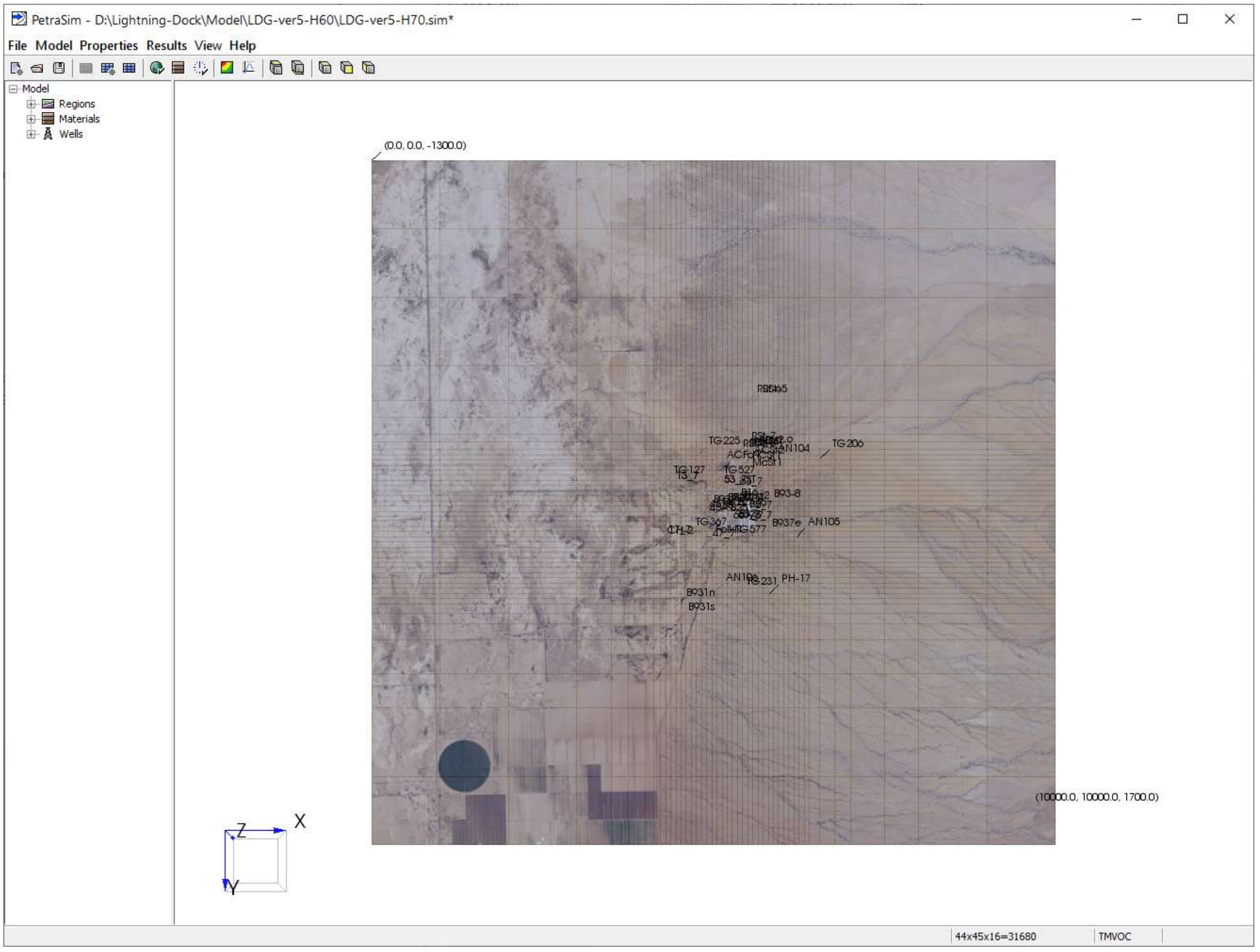

Figure 1: LDG numerical model grid viewed from above

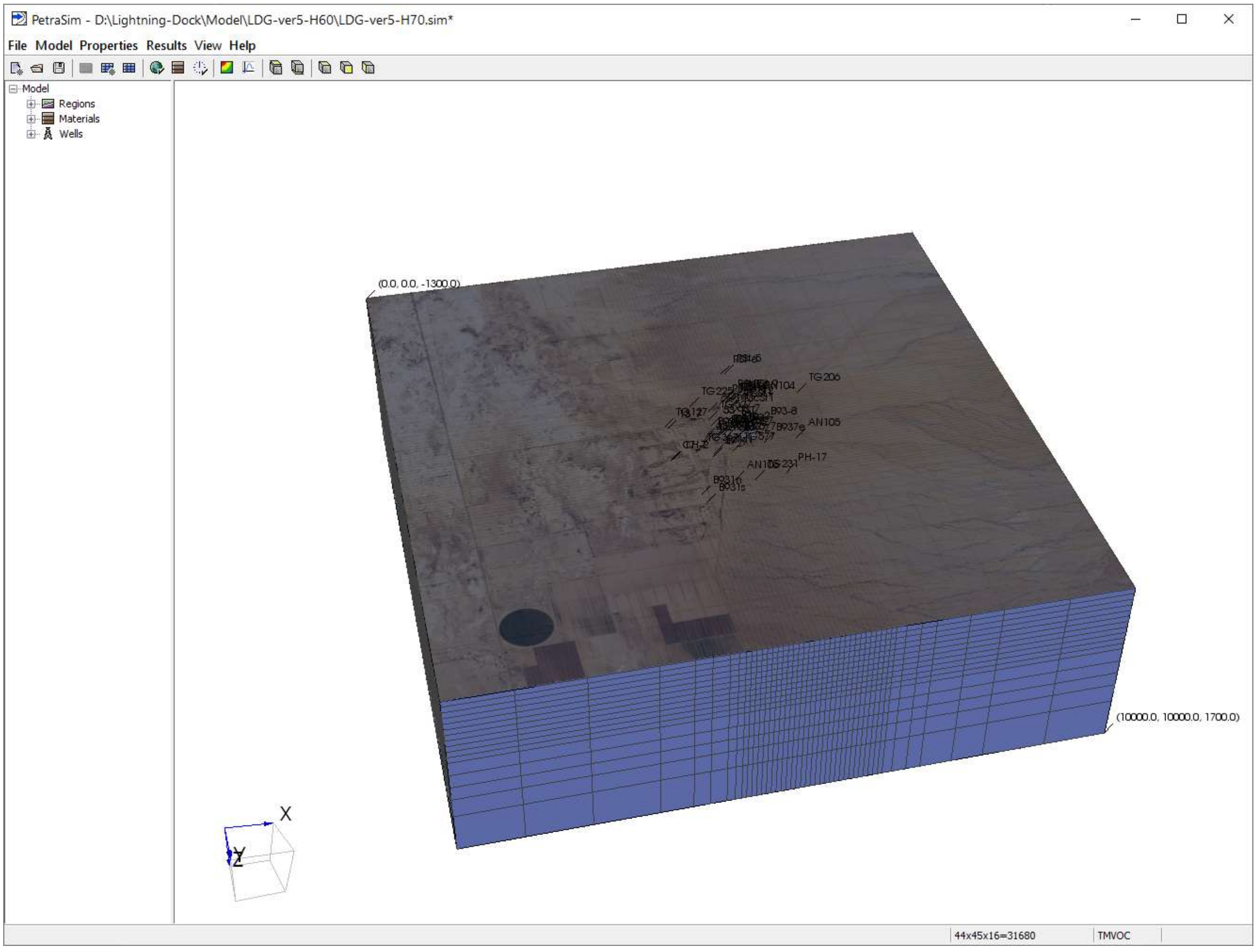

Figure 2: Three-dimensional view of LDG numerical model grid

Perm Before 12/2020:

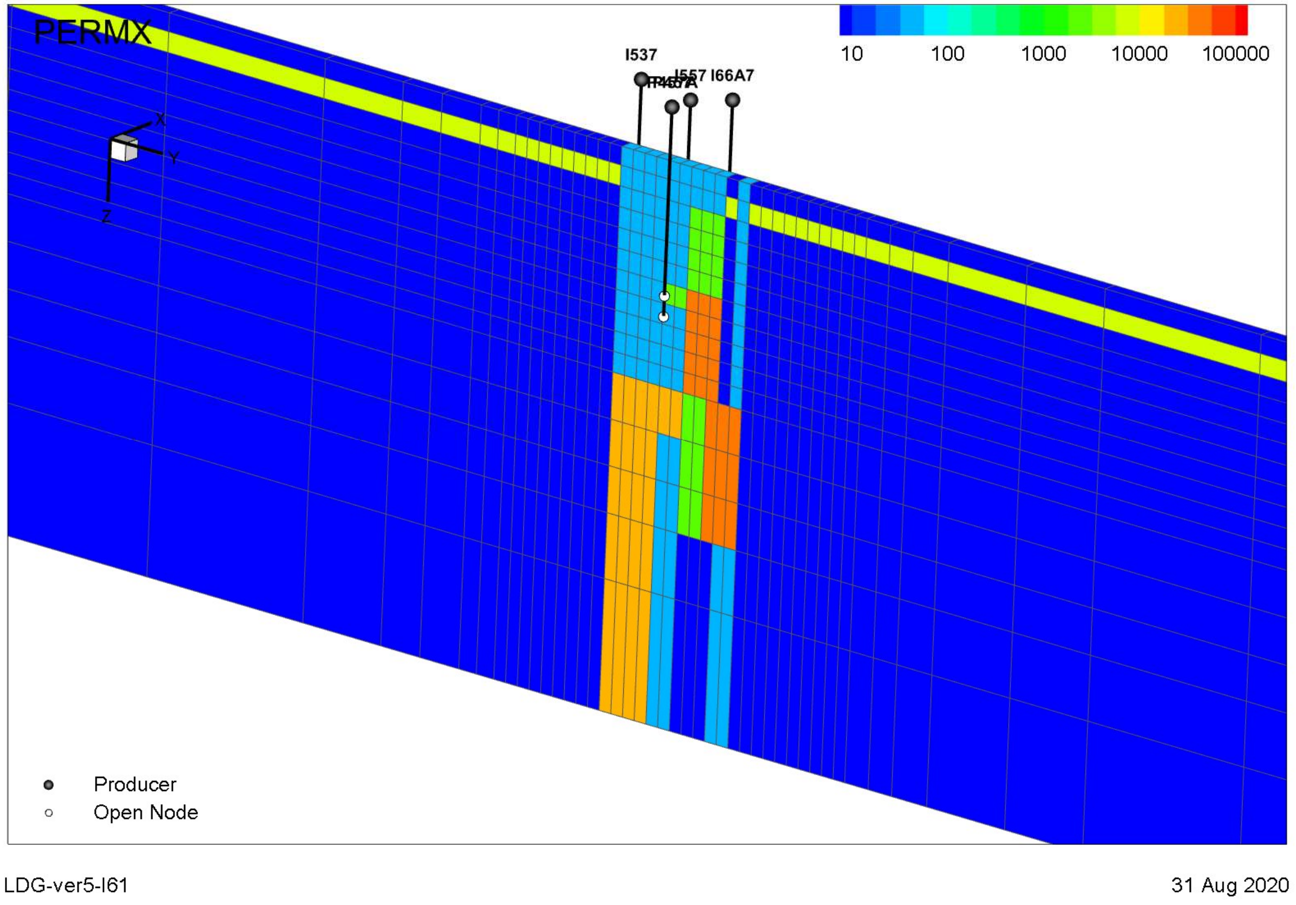

Figure 3: Fracture domain permeability on a N-S vertical slice directly east of the 45-pad, the shallower white sphere is the completion of 45A-7, the deeper one is 45-7. No high permeability conduit extending to surface.

Perm After 12/2020:

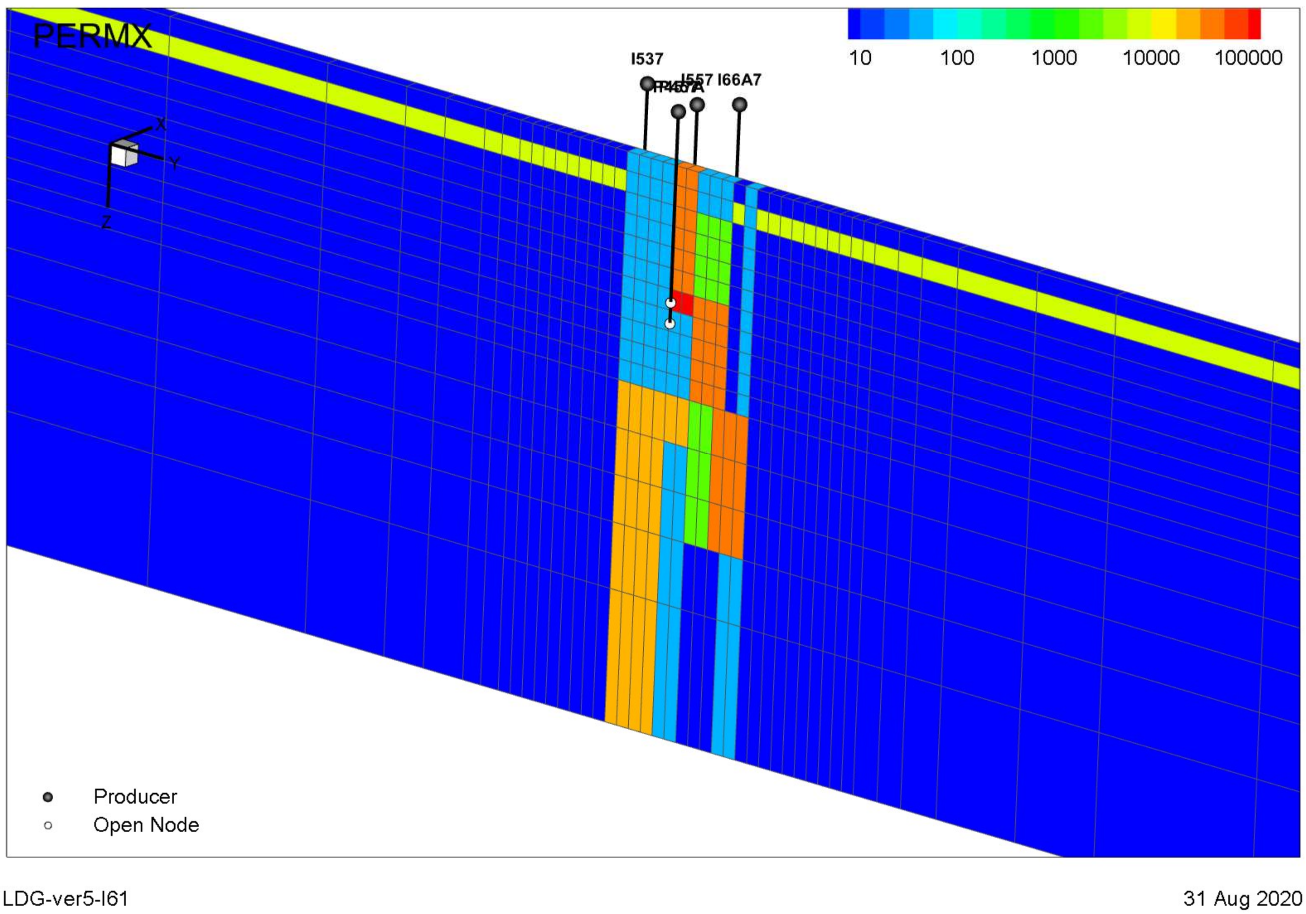

Figure 4: Fracture domain permeability on a N-S vertical slice directly east of the 45-pad, the shallower white sphere is the completion of 45A-7, the deeper one is 45-7. The high permeability fracture (orange) is the conduit for cold downflow.

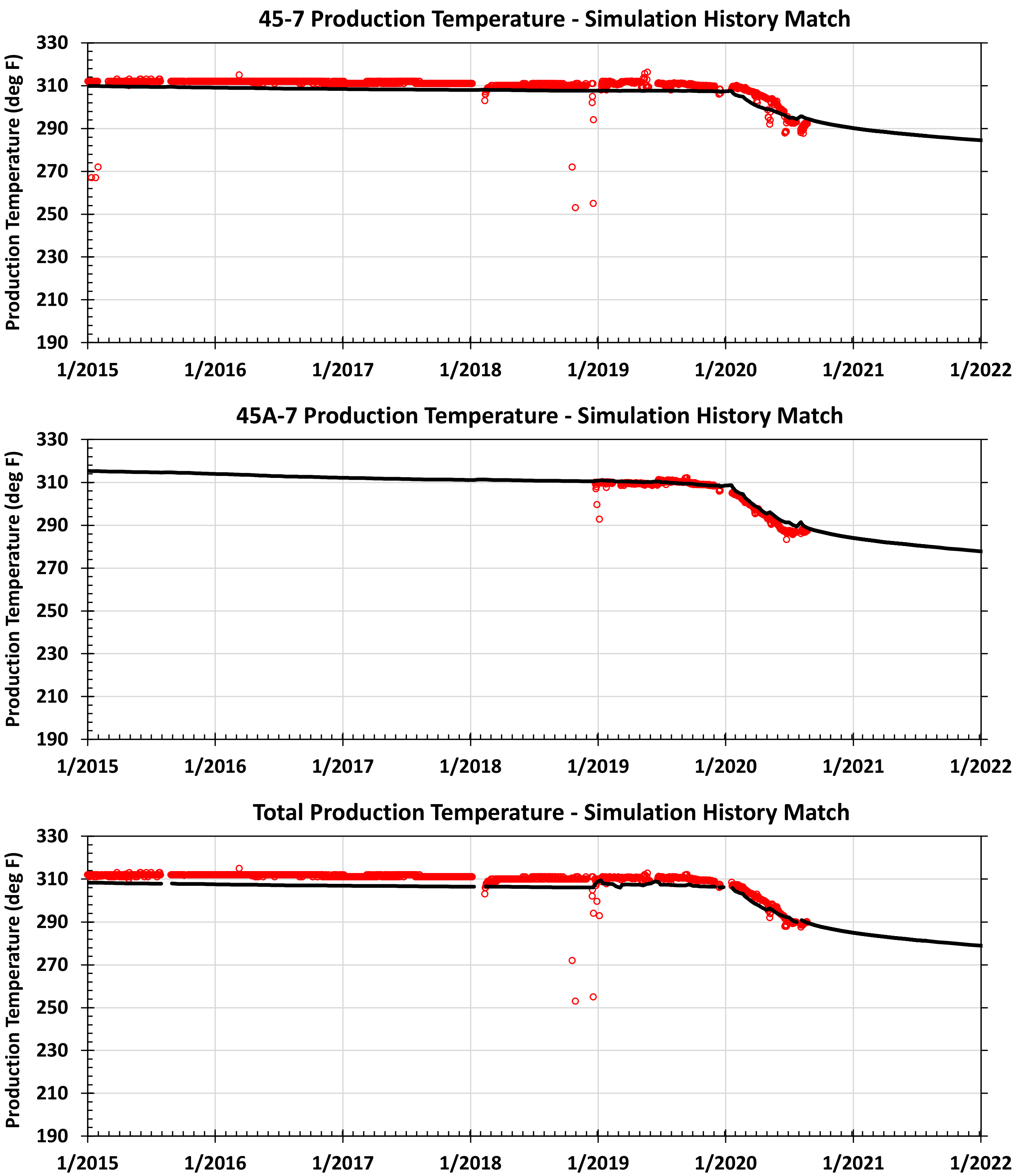

Figure 5: Run I75 history match with cold downflow developing in 12/2019

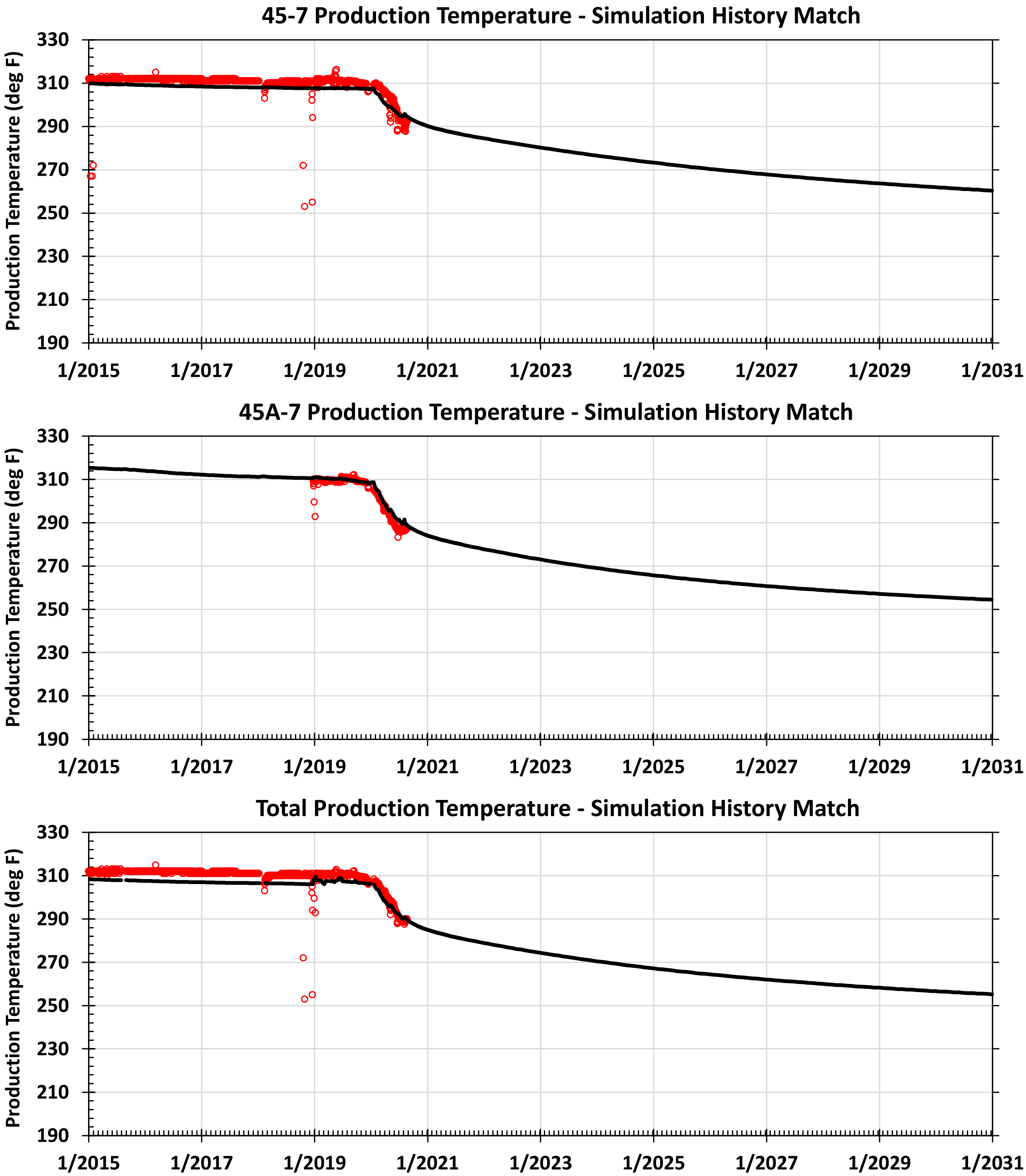

Figure 6: Run I75B showing ten-year forecast continuing as-is with fully active cold downflow.

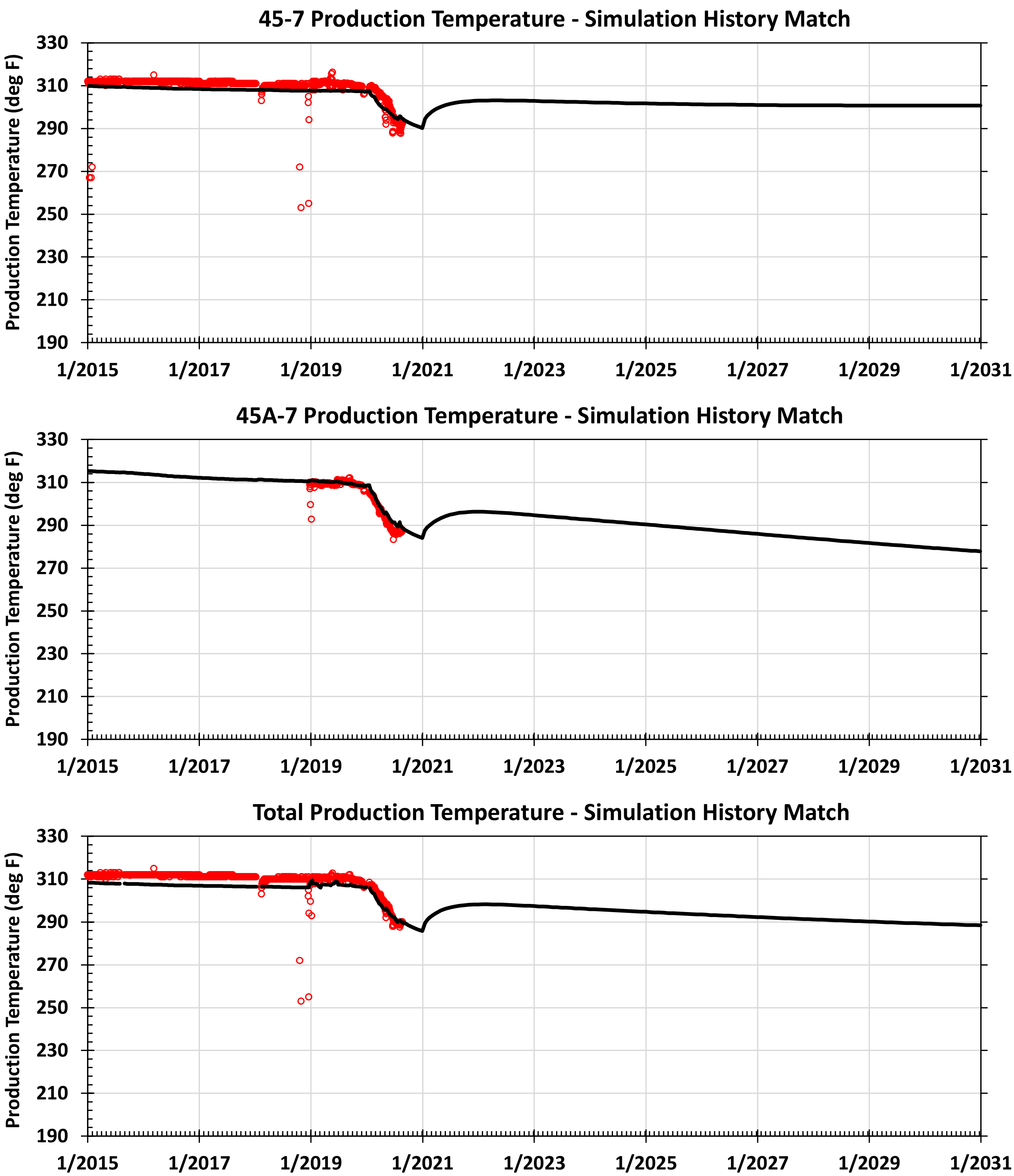

Figure 7: Run I75G, ten-year forecast if half the cold downflow is shut-off in early 2021