Thermal Contouring Methods for In Situ Thermal Remediation Projects

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ABSTRACT: The purpose of this study is to develop and compare thermal contouring methods to better assess heating and treatment progress during in situ thermal remediation. History matching numerical simulation is performed within a pseudo symmetry element, using field data extracted from the ET-DSP™ in situ thermal remediation implementation at the AMCO Chemical Superfund Site. Simulated temperatures are compared to gridding with kriging and minimum curvature methods, using virtual nodes to increase resolution. Relationships are also generated between the temperature measured at the centroid of an electrode triangle and the percentage of the simulated treatment volume that has achieved target temperature. Results indicate that the simulated temperature distributions can be better approximated by incorporating virtual nodes into the kriging and minimum curvature approaches. However, terms in the energy balance not directly measured in the field, such as local rates of steam generation and heat loss, are difficult to estimate without numerical simulation.

INTRODUCTION

Subsurface temperature monitoring during in situ thermal remediation is a fundamental part of the overall data acquisition strategy to assess treatment progress, and is often used as a contractual performance standard. Typically, discrete temperature data is collected at the locations that are anticipated to heat the slowest (i.e., closer to the centroids of the electrode or heater triangles) to provide a degree of conservatism when assessing the achievement of temperature targets. Selected monitoring points may also be installed closer to the electrodes or heaters to better estimate the range of temperatures achieved over time. However, because of installation costs, this discrete temperature data is often much more sparse than the density of the subsurface components that control the heat transfer processes (e.g., electrodes, heaters, multiphase extraction wells). The operation of these components can vary substantially at a local scale. Furthermore, considering temperatures at only the coldest locations introduces considerable bias when assessing temperature-dependent mechanisms, such as vapor migration behavior and mass recovery rates. As a result, it is important to be able to generate more continuous temperature distributions, using robust thermal contouring methods, to better assess treatment progress and optimize performance.

METHOD

Field data are extracted from within a pseudo symmetry element of the ET-DSP™ in situ thermal remediation application at the AMCO Chemical Superfund Site (McMillan-McGee Corp., in preparation), and used as input values for a three dimensional finite difference numerical simulation (McGee and Vermeulen, 2007) to generate a dense temperature distribution for thermal contouring. Horizontal discretization of the pseudo symmetry element and the depths of the vertical nodes below ground surface (BGS) are presented in Figure 1. Electrode and extraction well construction details within the pseudo symmetry element are presented in Figure 2.

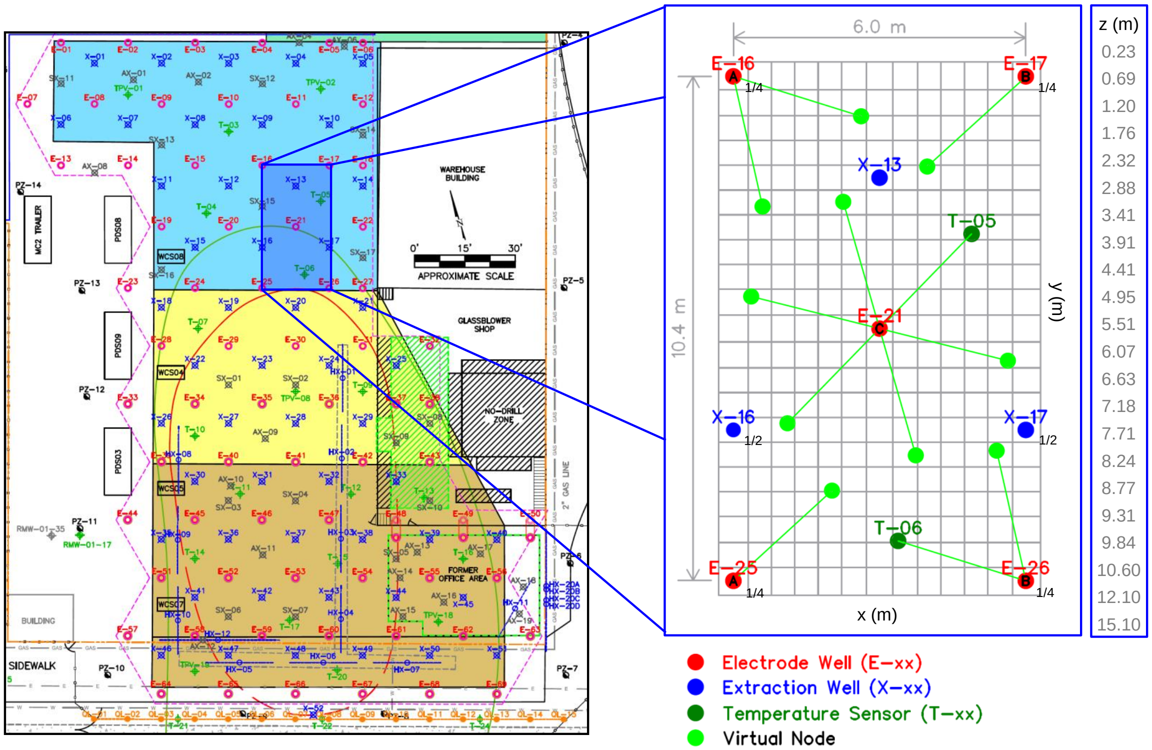

FIGURE 1. Pseudo symmetry element of the AMCO Chemical Superfund Site.

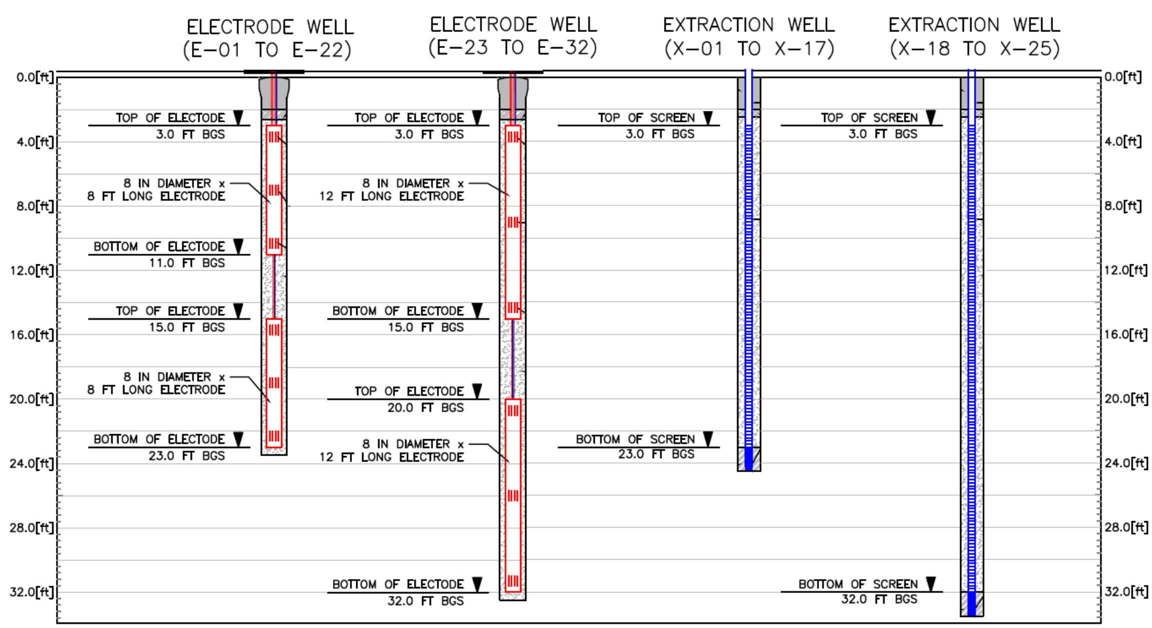

FIGURE 2. Electrode and extraction well construction details within the pseudo symmetry element.

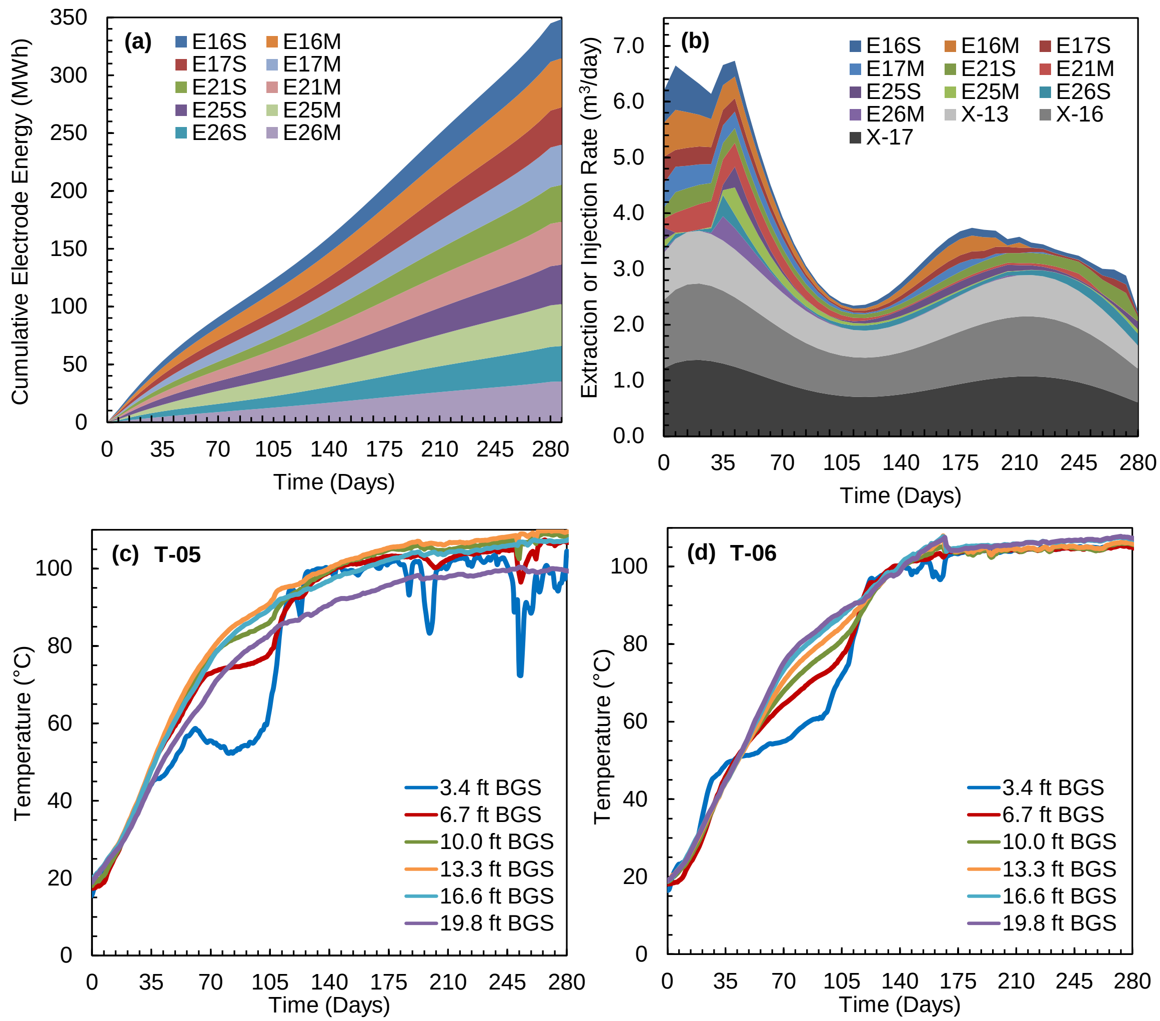

FIGURE 3. Field measurements of (a) cumulative electrode energy, (b) water extraction or injection rate, (c) temperature at T-05, and (d) temperature at T-06.

Field measurements of cumulative electrode energy, water extraction or injection rates, and temperature are presented in Figure 3. Other input parameters are derived from McMillan-McGee Corp. (2016), including an average bulk soil resistivity of 38.1 Ω·m and dynamic resistivity ratio of 3.25 from ambient to near-boiling temperatures. History matching of the numerical simulations to the field data is performed by iterating thermal conductivity and soil density parameters, until good agreement is found between the simulated and measured responses at temperature monitoring points T-05 and T-06.

After history matching is performed, two dimensional horizontal slices through the simulated domain are compared to temperature distributions created by gridding the field data at T-05 and T-06 using Kriging and Minimum Curvature methods. Virtual sensor nodes of equal temperature are added by (i) rotating around the nearest electrode, or (ii) translating to another electrode location, keeping the virtual sensor the same distance away from the nearest electrode. Virtual nodes within the pseudo symmetry element are shown in Figure 1. Gridding methods are described further in Krige (1951) and Smith and Wessel (1990). Note that the target treatment volume within the pseudo symmetry element at the AMCO Chemical Superfund Site was from 10 to 20 ft BGS.

Virtual nodes are also estimated at the electrodes using a simple linear relationship between the cumulative electrode energy (E_e) and the estimated energy needed to achieve steam temperatures near the electrode (E_{steam}):

$$T_e = \frac{E_e}{E_{steam}}(T_{sat} - T_i) + T_i \text{ if } E < E_{steam}\text{ , else } T_e = T_{sat}$$

where T_e is the virtual electrode temperature, T_{sat} is the saturation temperature, and T_i is the initial temperature. In this study, E_{steam} is estimated to be 3,200 kWh, based on the simulated temperature response observed at the electrode locations. It is noted that this approximation does not consider differences in simulated temperature distribution with depth (e.g., electric field intensities are greater near the ends of finite length electrodes, heat losses are greater near the top and bottom boundaries, etc.), and does not consider the slowing rate of temperature increase as the electrodes approach the saturation temperature.

Other methods to estimate temperatures near the electrodes were also tested, but discarded due to poor agreement with the simulated temperature distributions. For instance, the one dimensional unsteady radial case with negligible heat conduction (e.g., the analytical model of Killough and Gonzalez, 1986, and similar numerical approximations) over-predicted temperatures near the electrodes. This was likely because vaporization of the connate water was neglected in the energy balance. A better approach might incorporate a moving vaporization front into the boundary value problem (e.g., Soliman, 1997).

RESULTS AND DISCUSSION

Numerical Simulations. A comparison of the simulated and measured responses at temperature monitoring points T-05 and T-06 is presented in Figure 4. Good agreement is found, with most of the simulated temperatures within 5 to 10°C of the field data.

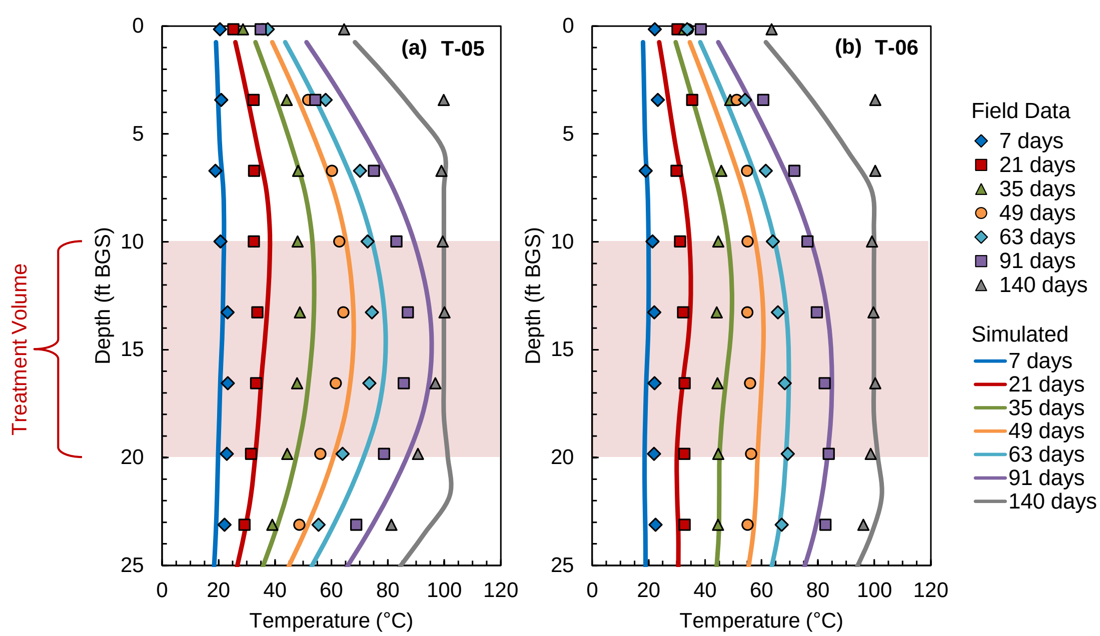

FIGURE 4. Comparison of the simulated and measured responses at temperature monitoring points (a) T-05 and (b) T-06.

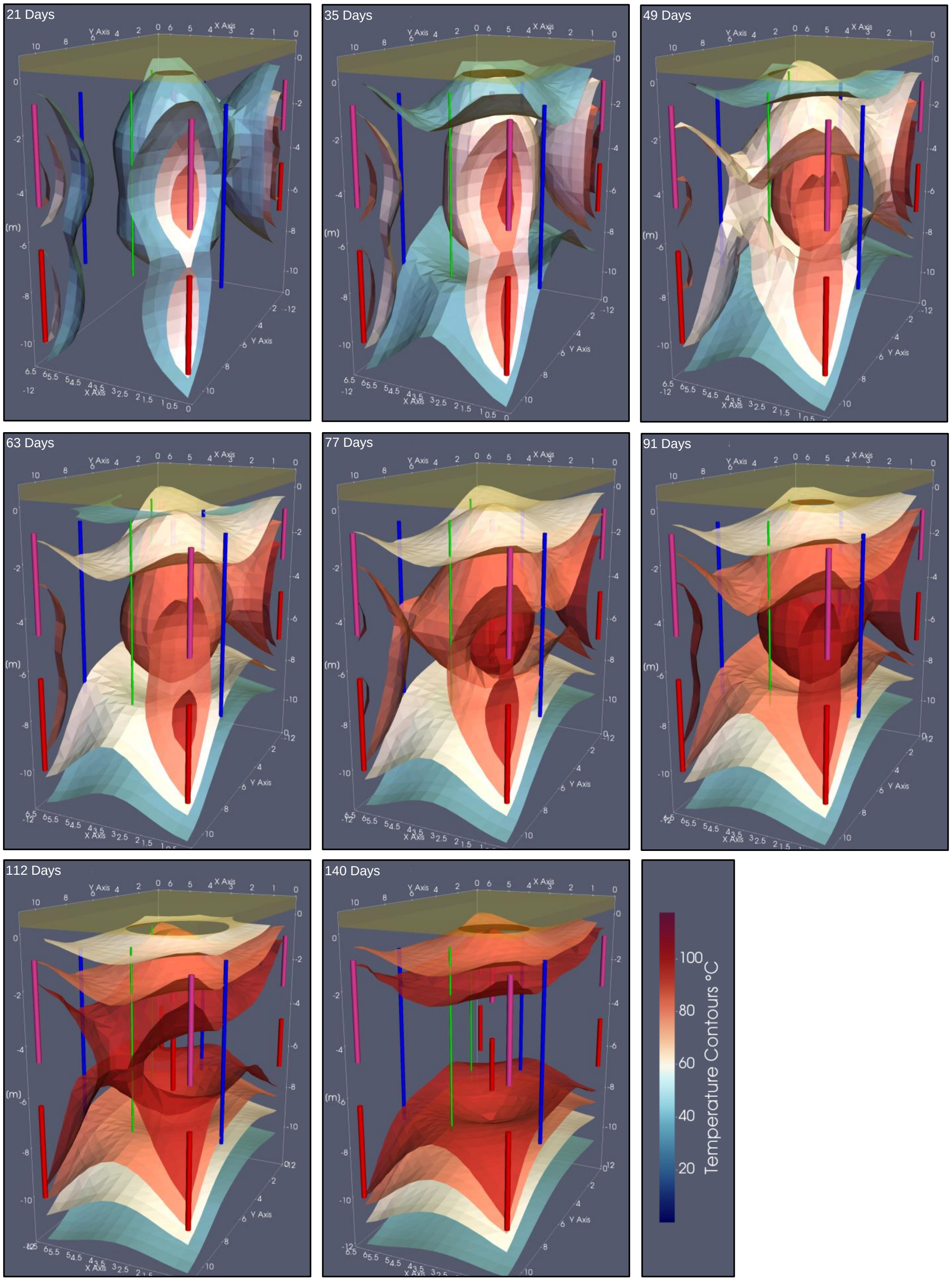

FIGURE 5. Simulated three dimensional temperature distributions for the pseudo symmetry element with 40, 60, 80, and 100°C isotherms contoured.

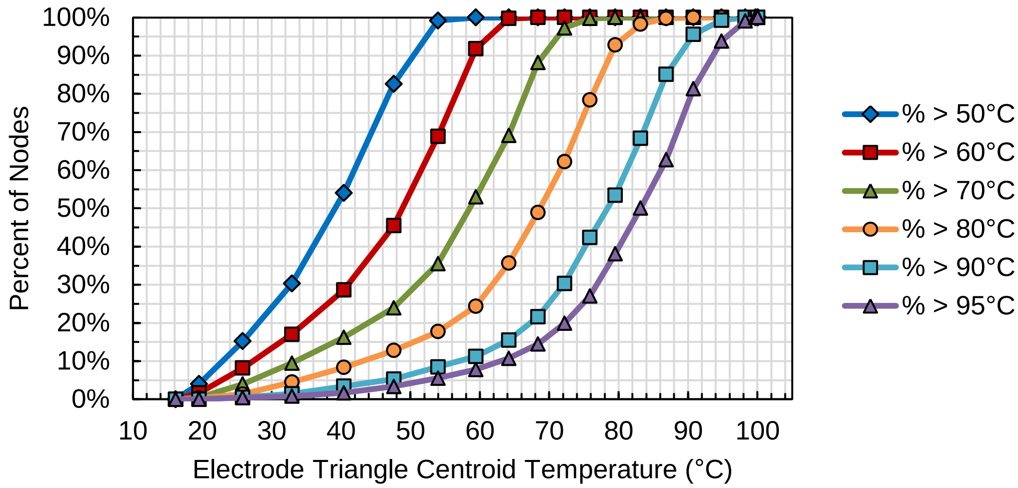

FIGURE 6. Percent of simulated treatment volume that has achieved a temperature target, given the average temperature at the centroid of the triangle formed by electrodes E-21, E-25, and E-26.

Simulated three-dimensional thermal contours are presented in Figure 5, depicting higher temperatures near the electrodes bodies at earlier time, but becoming more uniform as heat transfer propagates throughout the domain (e.g., Hegele and McGee, 2017). Figure 6 presents the relationship between the temperature measured at the centroid of an triangle formed by electrodes E-21, E-25, and E-26, and the percentage of the simulated treatment volume (10 to 20 ft BGS) that has achieved target temperature. For this particular simulation, a 90°C target is achieved at over 50%, 70%, and 90% of the nodes in the treatment interval at average temperatures of approximately 78°C, 83°C, and 88°C at the centroid of triangle formed by the electrodes, respectively.

Gridding with Virtual Nodes. Figure 7 presents comparisons of thermal contours generated using kriging and minimum curvature methods to the numerical simulations for the 10 ft BGS slice at 14, 35, and 91 days of heating. Horizontal slices from the numerical simulation are Kriged to assist with the comparison. Results indicate that introducing virtual nodes at a similar density as the subsurface components that control the heat transfer processes (i.e., the electrodes) can more accurately represents the simulated temperature distribution, so long as thermal convection associated with groundwater flow is negligible (e.g., Hegele and McGee, 2017). The incorporation of virtual nodes is expected to reduce bias when assessing temperature performance within the domain. Although kriging and minimum curvature methods yield similar temperature distributions, some minor variation is noted along the boundaries.

Average temperatures measured in the field and calculated using the various contouring methods in the 10 ft BGS slice are compared in Figure 8. This demonstrates the lag between temperatures measured at more conservative locations (T-05, T-06) and the overall temperature of the domain. Despite the good agreement in the overall shape of the temperature distributions, the gridding approaches tend to underestimate temperatures in the vicinity of the electrodes. This might be because saturation temperatures are assumed only at the virtual electrode nodes. Incorporating a moving vaporization front into the gridding routine in the vicinity of each electrode might improve on this result.

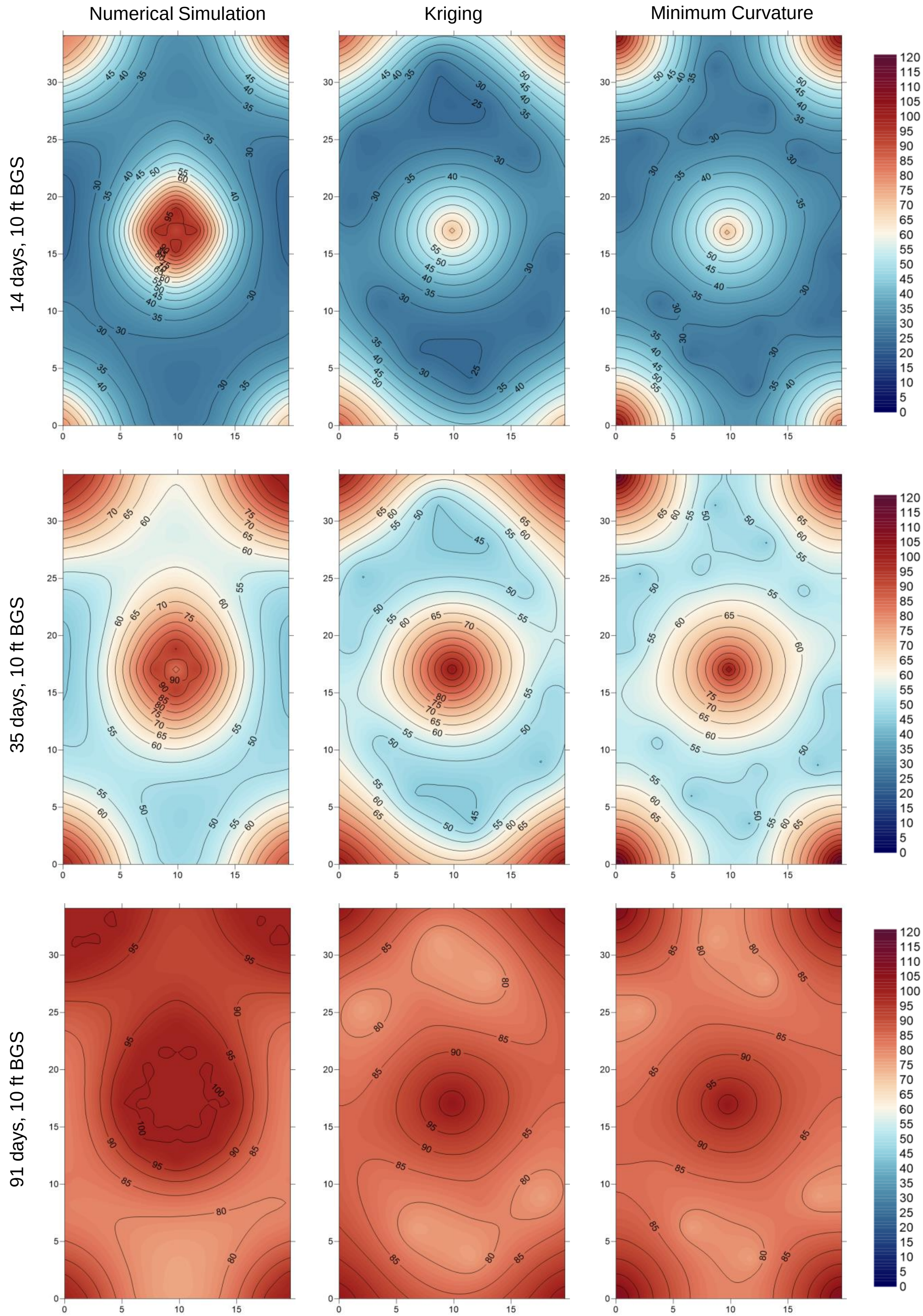

FIGURE 7. Comparison of history matched numerical simulations to thermal contours generated by contouring with Kriging and Minimum Curvature.

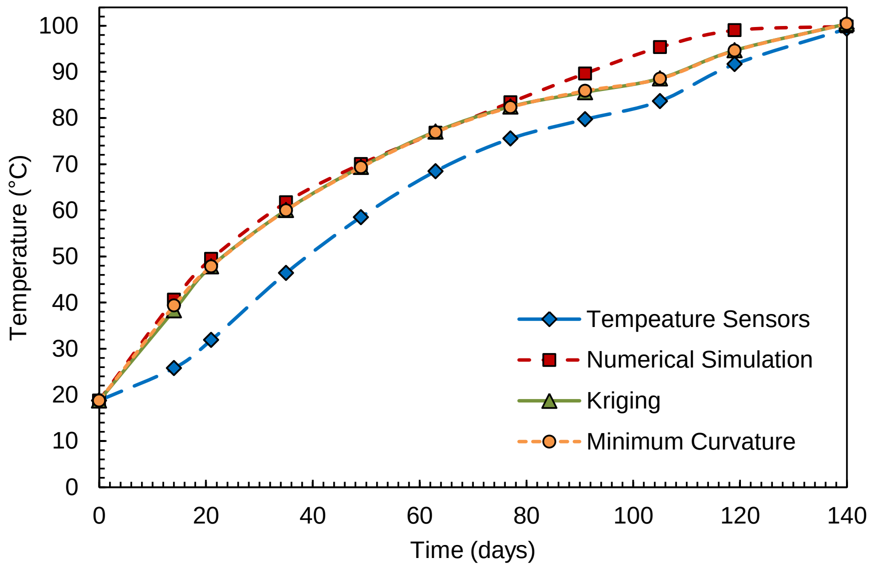

FIGURE 8. Average temperatures (i) measured in the field at sensors T-05 and T-06 and (ii) calculated in the 10 ft BGS slice using the various contouring methods.

SUMMARY AND CONCLUSIONS

The results of this study suggest that thermodynamic principles and additional local-scale field data can be incorporated into the contouring approach to more accurately represent the overall distribution of subsurface temperatures. Virtual nodes can improve contouring resolution and reduce the bias associated with conservative temperature monitoring point geometries. However, terms in the energy balance that are not directly measured in the field, such as local rates of steam generation and heat loss, can be difficult to estimate without numerical simulation. It is also noted that groundwater flow can smear the temperatures through the heated volume, and may be difficult to incorporate into a gridding approach. As a result, it is suggested that future work extend the numerical simulations to the field scale.

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