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Simulation Model for Ground Freezing Process: Application to Shell's Freeze Wall Containment System

Sepehr Arbabi, Wolfgang Deeg, and Ming Lin
Shell Exploration and Production Company
Houston TX

Abstract

Shell's Freeze Wall Test (FWT) has resulted in construction of an effective containment system in a Colorado oil shale formation to control ground-water flow for Shell's In-situ Conversion Process (ICP). The circulation of coolant through subsurface pipes causes the formation water to freeze and plug off permeable water-filled channels, resulting in an impermeable flow barrier. This paper describes the development of a reservoir simulation model for the ground freezing process with specific application to FWT. Key numerical modeling challenges will be briefly discussed. The developed model has been successfully calibrated with various types of field data and has been used for forecasting and making operational decisions. Modeling results of thermal simulations will be presented along with a FWT status update. Geomechanics monitoring and modeling activities to enhance our understanding of the mechanical integrity of freeze wall containment system will also be briefly introduced.

Introduction

Shell's ICP uses tightly spaced electric heaters to slowly and uniformly heat the oil shale to reach pyrolysis conditions at which long chain kerogen molecules within the oil shale are thermally cracked to smaller oil, gas, and water molecules. The Green River Formation in the Piceance Basin contains multiple water-bearing or permeable zones in the target resources and needs to be properly managed for the success of ICP and the protection of ground water. Confining conversion products to the process area requires a robust containment system. One of the groundwater control technologies that Shell has pursued is the ground freezing process (Fowler and Vinegar, 2009). The circulation of coolant through tightly spaced subsurface pipes causes the formation water to freeze and plug off permeable channels (Khakimov, 1966). This results in an impermeable flow barrier, or a freeze wall to isolate the developed area from the undeveloped area for ground water protection, to provide product containment, and to enable post-heating remediation to remove residual products in the developed area.

We start with a brief status update for FWT. Key simulation challenges of modeling ground freezing process in a reservoir simulator are noted next. Development of the thermal simulation model for FWT is the main focus of this paper and is discussed in some detail. Model calibration and sample simulation results are presented next. We conclude this paper with a brief discussion on geomechanical monitoring and modeling.

Status Update

Shell's Freeze Wall Test (FWT) is being conducted to demonstrate the viability of a freeze wall as a subsurface lateral containment system for Shell's ICP. Work has been continuing to successfully establish the freeze wall across the entire commercial oil shale interval in Colorado's Piceance Basin. Freezing commenced in early 2007 and in late 2009 the freeze wall closed across the entire commercial interval effectively isolating the interior from the exterior. Isolation was demonstrated by various means including:

- Observing a continuous increase in pressure in the zones surrounded by the freeze wall relative to the constant pressure observed in these zones outside the freeze wall.

- Producing individual water bearing strata outside (or inside) the freeze wall while monitoring pressure inside (or outside). During these production tests no pressure communication was observed across the freeze wall in the zone or zones being produced confirming isolation across the wall.
- Lack of pressure response across the freeze wall to pressure transients occurring either inside or outside the freeze wall.

Upon freeze wall closure an extensive test program to evaluate the freeze wall as a viable containment system was started. To date, tests have been conducted to identify various vertical sealing strata within the freeze wall and to demonstrate that the freeze wall will withstand the inside to outside pressure differential expected during a commercial process.

To test the ability of the freeze wall to remain intact while fluids and gas are produced from the volume enclosed by the freeze wall, pressure was lowered in critical water bearing zones to represent the expected commercial operating back-pressure with a full hydrostatic head remaining outside the wall. In each zone tested, no communication was noted across the freeze wall at pressure differentials as high as 430 psi (2965 kPa) across the wall. Work is continuing to evaluate the reparability of the freeze wall. After intentionally breaching the wall, various repair techniques will be attempted.

Thermal Simulation Model for Ground Freezing

Thermal simulation of the ground freezing process was conducted with commercial simulator STARS because of its modeling capability of water freezing and/or ice thawing processes (CMG, 2008). A general discussion on simulation models for ground freezing along with key modeling challenges has recently been provided in an SPE paper, (Shen, Mckinzie and Arbabi, 2010). Key modeling challenges are identified as

(1) Diminishing Porosity – As liquid water converts to solid ice, fluid porosity diminishes and numerical solutions to flow equations become more difficult and much slower. This situation was circumvented by a "rubbery fluid model" where a small amount of rock volume was repartitioned as a pseudo oleic component which does not change under freezing. The rubbery fluid component was assigned the same mass and thermal properties as that of the rock and a sufficiently high viscosity to minimize its mobility. To compensate for the effects of repartition, the initial void and fluid porosities, fluid saturation, and the end points of relative permeability curves were adjusted accordingly. This approach significantly improved simulation run performance.

(2) Freezing Point Depression (FPD) – The current Ice model in STARS is based on pure water chemistry. FPD was effectively modeled by shifting the initial temperature of bulk volume upwards by the amount of freezing point depression at the water salinity in a prevailing water zone.

(3) Variation of Inter-hole Distance – Conduction heat transfer is the dominant transport mechanism for formation of a freeze wall and as such, representation of freeze hole trajectories and thus honoring spacing between adjacent holes is crucial. This issue is discussed in some detail below when we describe the simulation model for the FWT.

Description of FWT Simulation Model

A typical freeze-hole is completed with circulation tubing inside a larger liner pipe. A refrigerant is pumped through the inner tubing down to bottom hole and returns to surface via the tubing/liner annulus. Every freeze hole in the FWT model has been realistically represented as a circulation Discretized Wellbore (DW). As such, heat transfer during refrigerant entry to the wellbore, circulation and return are included in the simulations. The DW model allows us to specify detailed pipe dimensions and thermal properties for circulation modeling.

Because the freeze wall closure time depends strongly on inter-hole distance (or spacing), it is critical to honor the hole trajectories, and the variation of spacing between adjacent boreholes. STARS requires that the borehole blocks have the same vertical index address for a borehole, and therefore makes it difficult to honor the variation of inter-hole distance (on the order of 3.0 ft (0.91 m)) in a regularly generated fine-grid model (with typical block size of 1 to 3 ft (0.3048 to 0.91 m)). In addition, manual representation of trajectories for 100+ holes is tedious and prone to mistakes. Therefore, an automated approach was developed to build the FWT simulation grid.

An in-house grid generation tool called “WellTraGrid” was developed which generates corner point grids with specific feature of an automatic grid deformation algorithm and advanced 2D and 3D editing capabilities. It generates all necessary grid files which can be imported to CMG simulators. It keeps wells at well block centers thus avoiding ambiguous recalculation of the well index for each well. It deforms the underlying corner grids in the near wellbore region to ensure that the centers of a column of grid blocks align with a freeze-hole trajectory, as shown in Figure 1. STARS, however, does not allow a radial hybrid refinement in a corner-point grid with DW wells. Alternatively, upscaled thermal conductivities are computed and assigned to well blocks, which produce near wellbore temperature variations as if obtained on finer spatial scales.

Variation of spacing along depth impacts the timing of freeze wall formation or closure time. An example is shown in Figure 2, where progression of freeze wall formation is compared at the same time with trajectories of holes either ignored or accounted for. Larger inter-hole distances for deep zones when properly included in the model result in a longer closure time as observed in the right temperature plot, Figure (2b).

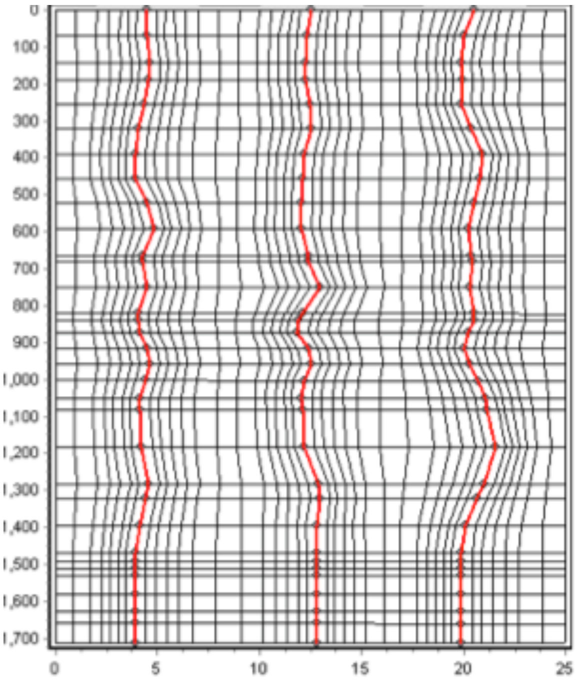
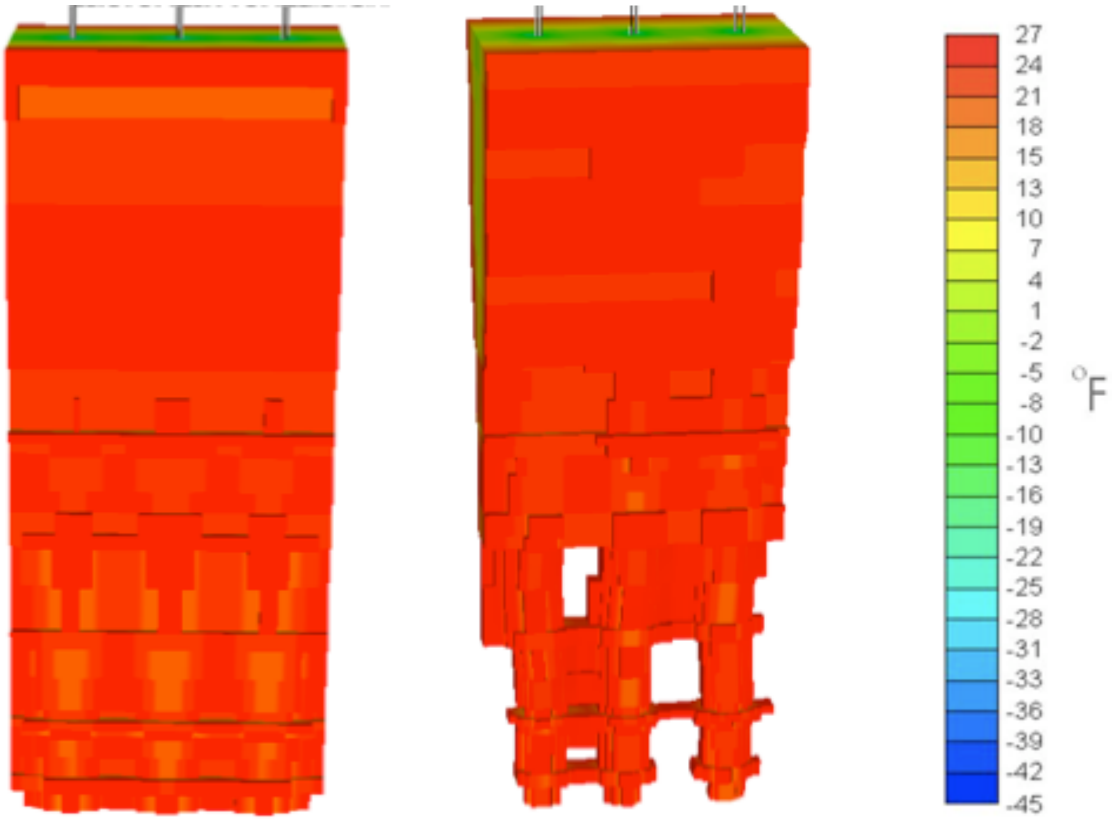


Figure 1: An example of 3 freeze-hole trajectories (in red) and the corresponding deformed grid from in-house tool WellTraGrid. Dimensions in feet.

Figure (3a) displays the surface layout for the FWT with 136 freeze holes with nominal grid size of 2.75 ft (0.8382 m). There are 97 other holes (not shown) used for monitoring, surveillance and operational purposes at various depths. A map of hole trajectories for all freeze holes from “WellTraGrid” as implemented in the full-field thermal simulation model is depicted in Figure (3b).

Static input properties and their variations with depth, based on core data from nearby holes, were utilized in building the model for various lean and rich zones. Initial background temperatures have been measured and are directly used in the model. Results of pumping tests were used to extract estimates of permeability



a) **b)**

Figure 2: Temperature plot for 3 freeze holes modeled as (a) vertical holes (b) holes with their trajectories

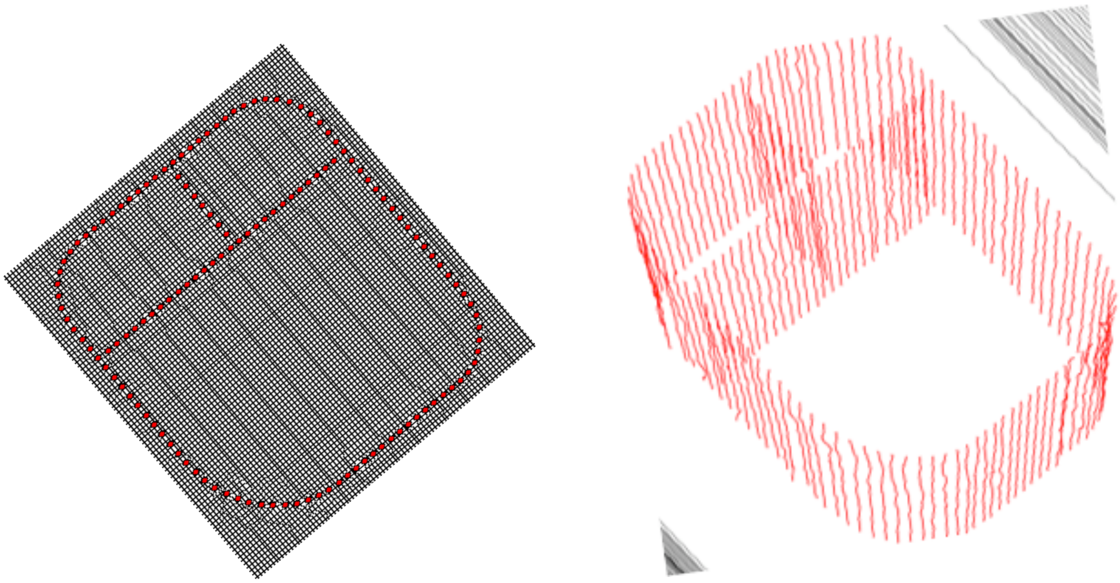


Figure 3: Layout of FWT with 136 freeze holes (a) and hole trajectories from WellTraGrid (b)

used to extract estimates of permeability thickness, which are honored in the model. Hydrology tests and modeling provided estimates of hydraulic gradients for ground water flow in water bearing zones and estimates of permeability anisotropy, which are also accounted for in the model. The model follows operational history of the pilot with one-day resolution. Refrigerant circulation rate and injection temperature are periodically updated in the simulation model to reflect monitored field data.

Model Calibration and Sample Results

Various field data have been used to calibrate the FWT thermal simulation model. These include fiber-optic temperature data along freeze holes at various locations and depths, temperature data at various depths from twelve monitoring holes located 4 (1.22) to 8 feet (2.44 m) from the freeze wall centerline, and short and extended shut-in temperature data. The main calibration parameter is the effective thermal resistance at various subsurface depths. It is noted that thermal conductivity of oil shale at temperatures below water freezing temperature is not well known. Extrapolation of available thermal conductivity data at higher temperatures to water subfreezing temperatures suggests an increasing trend in thermal conductivity of oil shale (Somerton, 1957 and 1959).

Starting from mid 2007, temperature data from freeze and monitoring holes have been used in calibration of the model. The calibration procedure has been carried out consistently at various depths both manually and through the optimization tool MEPO (SPT Group, 2007). Key operational history of the pilot is included in the simulation model and is being updated regularly. An example of model prediction from 2007 is presented in Figure 4 where temperature variation with depth is shown at early stages of freezing (10-40 days after start of freeze) in an inactive freeze hole with its neighbors on each side actively freezing.

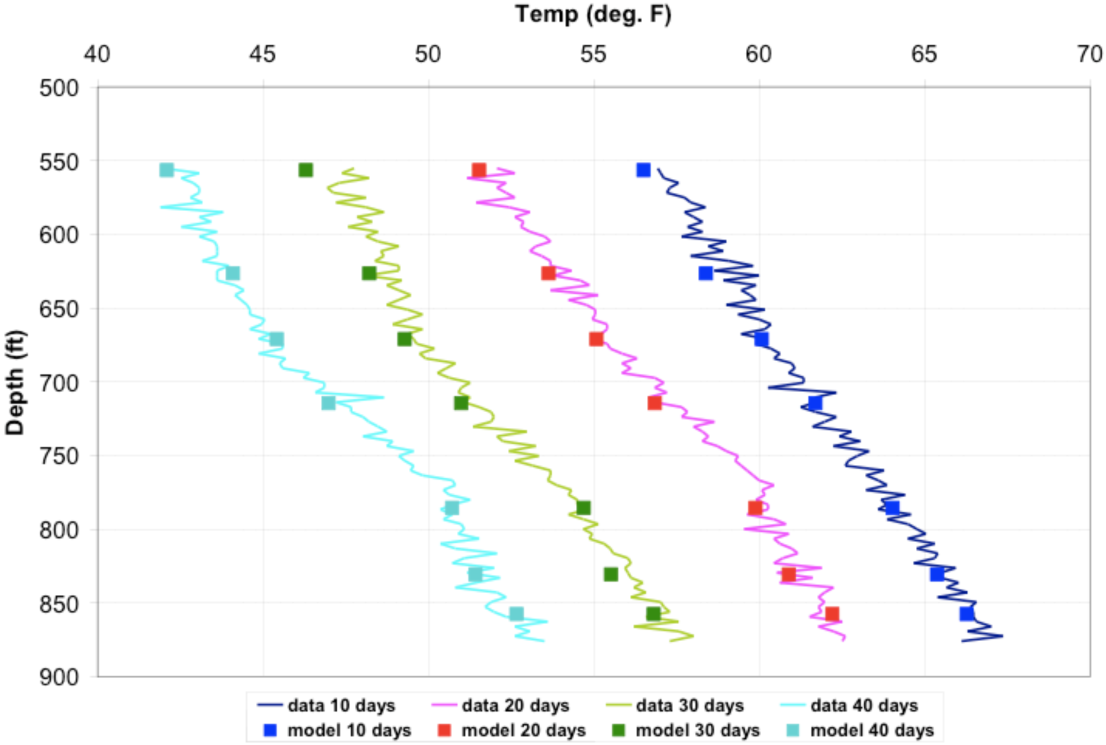


Figure 4: Comparison of model prediction and temperature data vs. depth for an inactive freeze hole surrounded by active holes

Shut-in temperature data from freeze holes are another valuable source for calibration purposes. Figure 5 depicts an example of a 3-day temperature build up in a freeze hole at various depths after temporarily stopping refrigerant circulation. It can be observed that various zones have different initial states and respond differently during build up. The model result shown at one depth is in close agreement with temperature build up data. In fact both short-term and extended shut-in temperature data have been used to extract estimates of effective thermal conductivities of the subsurface. This procedure serves as a verification of calibration values obtained by manual or optimization procedures described above, with results in general good agreement between the two procedures.

In addition to all freeze holes being equipped with fiber-optic temperature sensors, twelve temperature monitoring holes distributed at various locations around the FWT site also have this capability. Periodic review of data from these monitoring holes against model results provides confidence on how closely the simulation model is predicting propagation of freeze wall formation. Figure 6 displays a comparison of model results with temperature data on one of the temperature monitoring observation holes at two depths from the start of the freeze for more than 1000 days. Figure 7 shows an example of typical agreement observed between model prediction and data from all 12 temperature monitoring holes at a given depth and time.

Applications of Simulation Model

The FWT calibrated thermal simulation model has been employed to aid in design of operational events, sizing of equipment, scheduling of chiller operation, testing program, and future plug and abandonment operations. An example of chiller operation is provided below. After full-

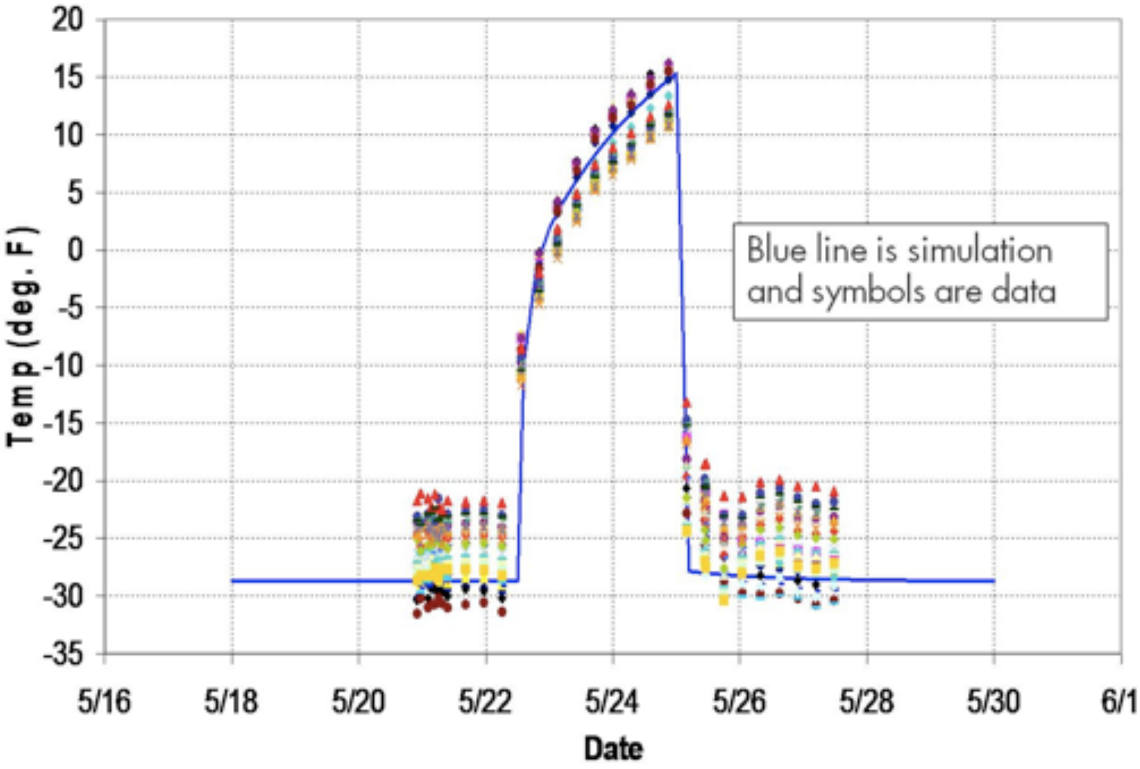


Figure 5: Example of temperature build up data in a freeze hole at various depths vs. model result at one depth

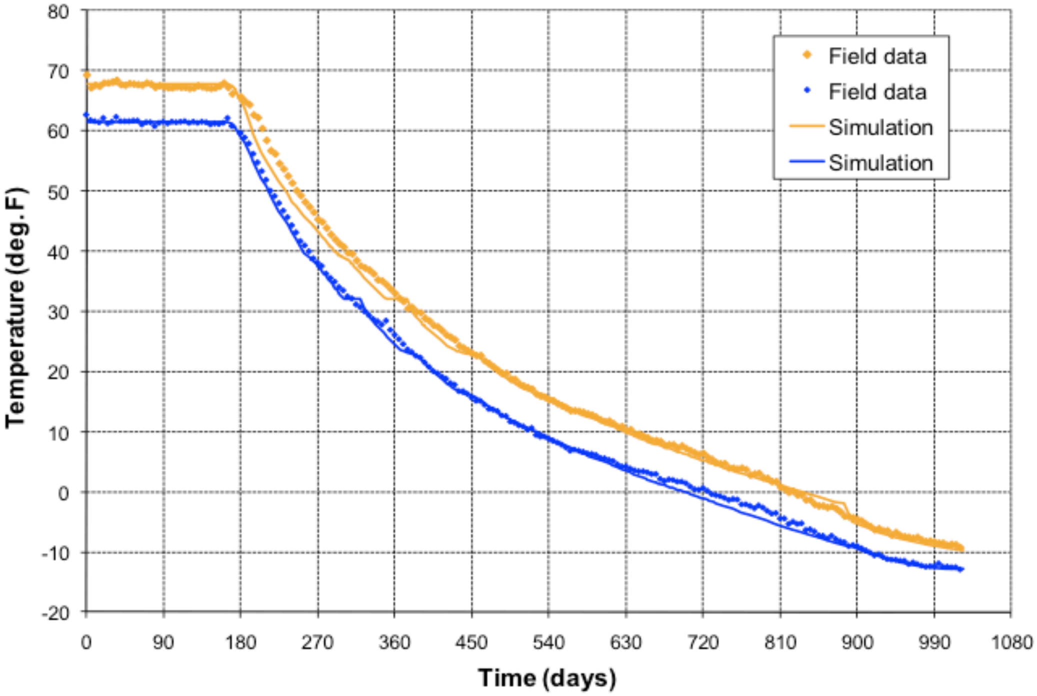


Figure 6: Comparison of simulation and temperature data for a monitoring hole at two different depths at FWT

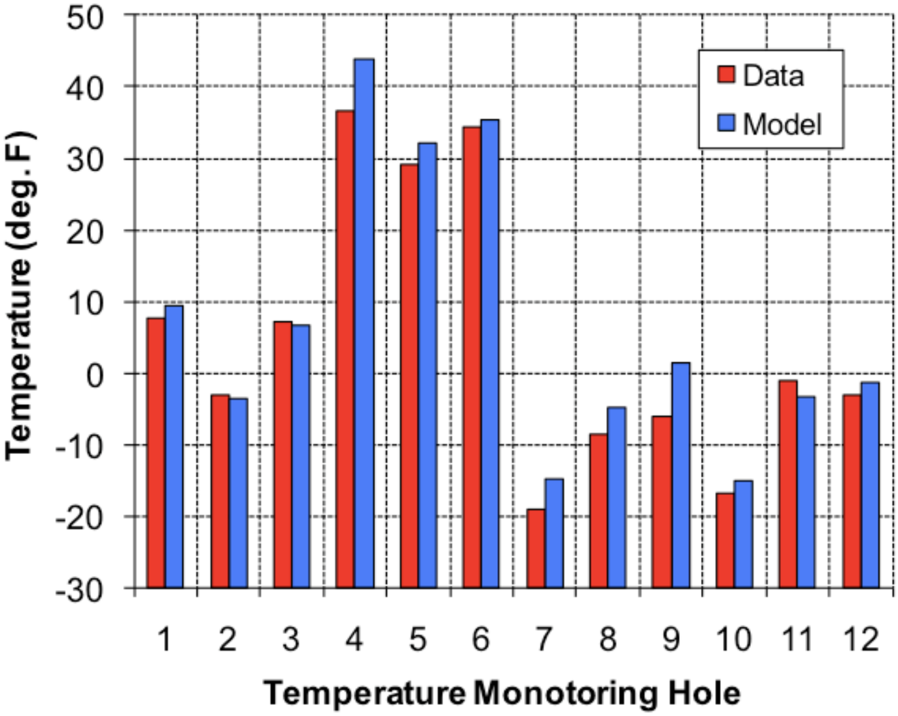


Figure 7: Comparison of model results with data for all 12 temperature monitoring holes at a given depth and time.

interval formation of the freeze wall, and once the freeze wall has become thick enough, continuous chiller operation can be modified where chillers are operated intermittently to save on power cost without any adverse effect on the freeze wall. The frequency and duration of the chiller "off" cycles have been determined through thermal simulation runs. Figure 8 shows the temperature inside two freeze holes at the same depth through off/on/off cycle of chillers. Corresponding model results agree reasonably well with fiber optic data.

Geomechanics monitoring and modeling for FWT

Geomechanics monitoring at the FWT site consists of (1) surface deformation measurements from 33 surface monuments and (2) subsurface deformation logs from three geomechanical wells with radioactive markers embedded in the casing. Figure 9 shows the locations of the surface monuments and geomechanical wells. The vertical component of surface deformation was measured using Trimble DiNi Digital Precision Level with achievable accuracy of 0.3 mm/1 km (0.001 ft/3280 ft) and the horizontal component of the surface deformation using Trimble 5700 GPS Survey System with achievable accuracy of 5 mm. The subsurface deformation logging was conducted using Halliburton's Formation Compaction Monitoring Tool (FCMT) with accuracy better than 2.5 mm (0.008 ft).

A geomechanical model was constructed consisting of a three-dimensional finite-element grid including layered media with consideration of thermomechanical behavior of rock under freezing. The temperature histories calculated in the thermal simulations were read into the mechanical model with interpolation to the nodal points of the finite-element mesh. The model was calibrated against both the

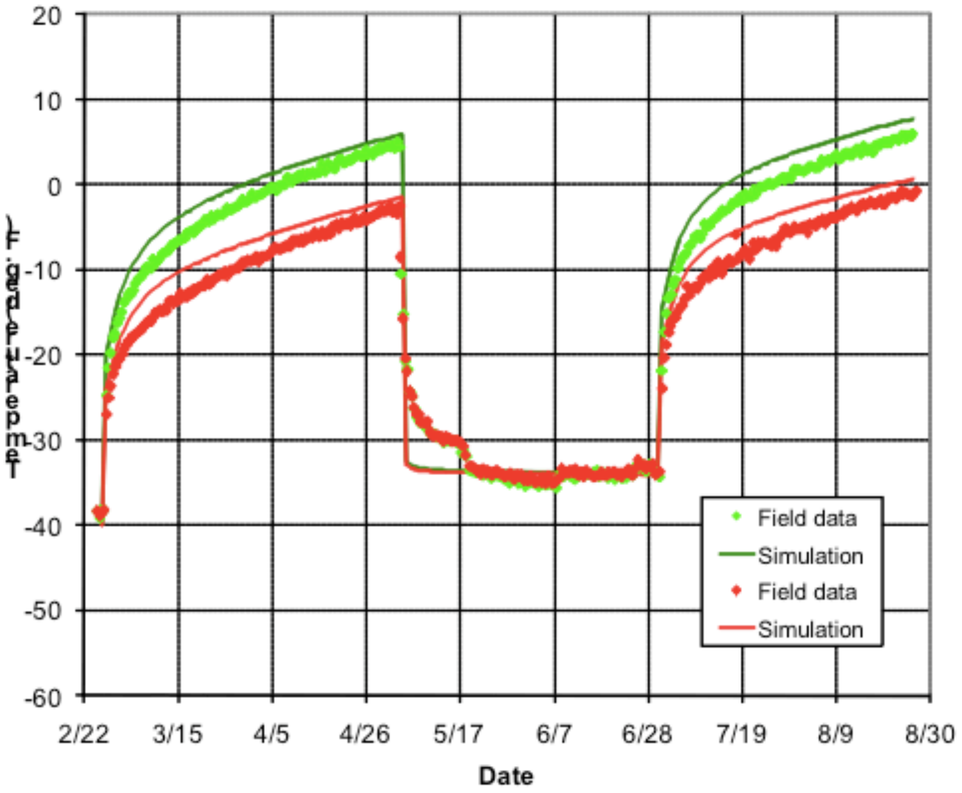


Figure 8: Temperature inside two freeze holes through intermittent operation of chillers at the same depth

Figure 9: FWT Surface Monuments (M30 – M33 primary control points not shown) and Geomechanical Well Locations

surface and subsurface deformation data. The estimated stress field within the freeze wall and surrounding rock provides valuable information on the containment integrity of the freeze wall system in ICP process.

Acknowledgement

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