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

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Outline

- FWT Status Update
- Ground Freezing Process
  - Modeling and Challenges
- FWT Thermal Simulation Model
  - Development and Calibration
- Example Results
- Geomechanics Monitoring and Modeling
- Summary
**FWT Status Update**

- Freezing commenced March 2007
- Freeze Wall (FW) closed in late 2009 across entire commercial interval (500 through 1700 feet)

**Isolation demonstrated by:**

- Observing a continuous increase in pressure in zones surrounded by FW relative to constant pressure outside
- During production tests, no pressure communication have been observed across FW in test zones
- Lack of pressure response across FW to pressure transients either inside or outside of FW

**Tests conducted to identify vertical seals**

**Breach and repair testing in progress**
STARS Ice Model

- To simulate water freezing (pore filling) and ice thawing processes
- Based on pure water
- Water freeze reduces fluid porosity
  - Desired, but numerically troublesome
  - Numerical singularity with vanishing fluid porosity
- Permeability decreases with fluid porosity

Void vs. Fluid Porosity

- **V** (fixed)
- **V_f**
- **V_v**
**Simulation Challenges – Diminishing Porosity**

- **Approaching Numerical Singularity**
  - A “rubbery” fluid approach to circumvent near-zero porosity and to improve run performance

- **Improved simulation performance with the "rubbery" fluid model.**
  - Runs at least one order of magnitude faster

- **Introduce a “solid” like pseudo fluid (oleic) component**

- **Repartition some of the “rock” volume to the pseudo oleic component**
  - Same property values as rock
  - High enough viscosity to minimize movement

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*Graph from SPE 132418, 2010*
Simulation Challenges – Representation of Hole Trajectories

- **Variation of inter-hole distance**
  - FW closure time strongly depends on hole spacing
  - Important to capture hole deviation
  - Grid restrictions with STARS hybrid refinement

- **Example of hole trajectories and a deformed grid**

- An in-house developed grid generation tool for CMG
- Auto deform grids to follow hole trajectories
Impact of Deviated Wells on FW Closure
(Hybrid-Vertical and Corner Point-Deviated)

Center Point Grid
(Vertical Wells)

Corner Point Grid
(Deviated Wells)

Time = 160 days

°F
Example of Freeze Wall Formation

$t = 90$ days

$t = 150$ days

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Grid Dimension
NX = 112
NY = 112
NZ = 31
Nominal DX, DY = 2.75 ft

Well Data
136 freeze holes
each hole is modeled as a discretized circulation well
Initial and Input Properties

- Static input properties based on measurements on cores
- Data on initial background temperatures and geothermal gradient are directly used in the model
- Estimates of permeability thickness based on pumping tests
- Hydraulic gradients and permeability anisotropy based on hydrology tests and modeling
- Refrigerant circulation rate and injection temperatures based on data are periodically updated in the simulation model
- Simulation model honors operational history (i.e., start of freeze for each freeze hole, chiller operation, etc.)
Procedure and Data used in Calibration

- Calibration main parameter is effective thermal resistance at various subsurface depths
- Manual and optimization (through software MEPO) have been employed starting in 2007
- Fiber-optic DTS data in freeze holes and 12 monitoring holes
- Short-term (3-day) and extended (up to 3 months) temperature shut-in data
- Estimates of thermal conductivities have been extracted from temperature buildup data
- Generally good agreement is observed among calibration procedures used
Example of Simulation Results – Temperature Buildup

Blue line is simulation and symbols are data

Date

Temp (deg. F)


5/30

5/28

5/26

5/24

5/22

5/20

5/18

5/16

5/30

5/28

5/26

5/24

5/22

5/20

5/18

5/16

-35 -30 -25 -20 -15 -10 -5 0 5 10 15 20

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Example of Simulation Results – One Monitoring Hole

![Graph showing temperature over time for field data and simulation results.](image-url)
Example of Simulation Results – Comparison with All Monitoring Holes

![Simulated Temperature Monitoring Data](chart.png)

- **Temperature (deg. F)**
- **Temperature Monitoring Hole (1-12)**
- **Data**
- **Model**
Example of Simulation Results – Intermittent Chiller Operation
Geomechanics Monitoring and Modeling

- **Monitoring**
  - Surface deformation measurements from 33 surface monuments
  - Deformation logging at 3 well locations with embedded radioactive markers

- **Modeling**
  - 3D finite element model with thermomechanical rock behavior under freezing
  - Input of temperature histories from thermal simulations
  - Calibration to surface and subsurface data
Summary

- Freeze wall closure has been achieved in late 2009 across entire commercial oil shale zone in Colorado’s Piceance Basin.
- Tests have been conducted to identify sealing strata.
- Tests have been started to demonstrate wall robustness including breach and repair tests.
- A reservoir simulation model for ground freezing process has been developed with modeling and numerical challenges identified and rectified.
- An in-house grid generation tool has been developed and used to build the FWT full-field thermal simulation model, which honors hole trajectories, heat transfer during circulation, and operational history.
- FWT simulation model has been successfully calibrated using measured DTS data from monitoring and freeze holes along with short and extended temperature build-up data.
- FWT geomechanics monitoring includes surface deformation measurements and subsurface deformation logging.
- A 3D finite element model has been constructed and calibrated to the data.
Acknowledgements and Main References

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Main References: