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# THERMAL PERFORMANCE OF DIRECTIONAL WELLS FOR EGS HEAT EXTRACTION

*Elena Kalinina, Teklu Hadgu, Katherine Klise, and Thomas Lowry*

Sandia National Laboratories, Albuquerque, New Mexico

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# INTRODUCTION

According to the U.S. Energy Information Administration (EIA) exploration and production risk is one of the factors responsible for slow development of EGS resources (*http://(www.eia.gov*):

- Even in well-characterized resource areas, there is significant exploration and production risk, which can result in high development costs.

This analysis investigates the ability of the horizontal and directional wells to reduce the exploration and production risk and to improve heat extraction. The risk can be reduced if the heat extraction is to a lesser degree affected by the following factors and related uncertainties:

- Injection interval length
- Fracture properties
- Well separation distance
- Stimulation conditions

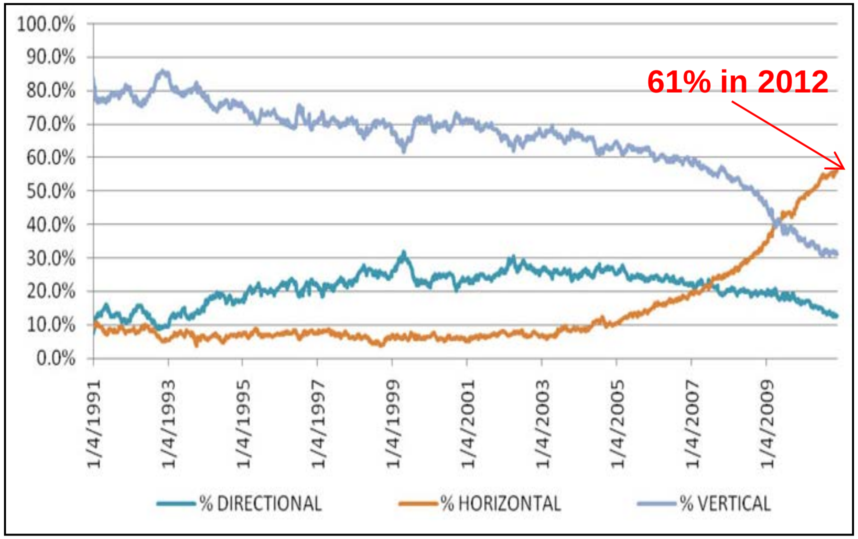
The economic benefits of an improved heat extraction have to be evaluated in conjunction with a higher costs of the horizontal and directional wells. This is a topic of the next presentation: "Economic Valuation of Directional Wells for EGS Heat Extraction".

# Horizontal Wells: Why Now

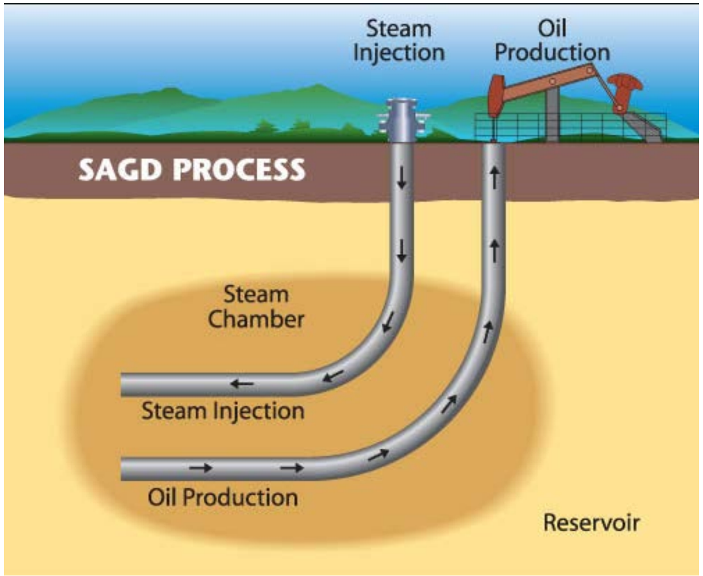
Horizontal and directional well drilling technology has significantly advanced due to oil and gas exploration:

- ➢ Larger horizontal displacements
- ➢ Shorter distances to bend
- ➢ Lower costs

US Rig Count Percentage by Type




Data from Baker and Hughes (2012)




*Source: Canadian Centre for Energy Information*

The horizontal and directional well technology can be adopted for EGS conditions.

# Design Specification Assumptions

Design specifications and cost estimation were developed for SNL by Baker Hughes for the conditions typical for EGS.

*The design specifications and cost estimates rely upon oil and gas industry best practices and are **preliminary**.*

Well Profiles:

i. Vertical well

ii. "J" type well with tangent inclination of 45° (inclined well)

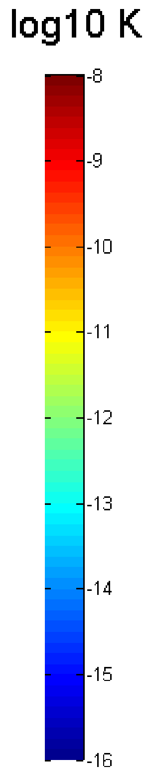
iii. Horizontal well with sail angle of 90°

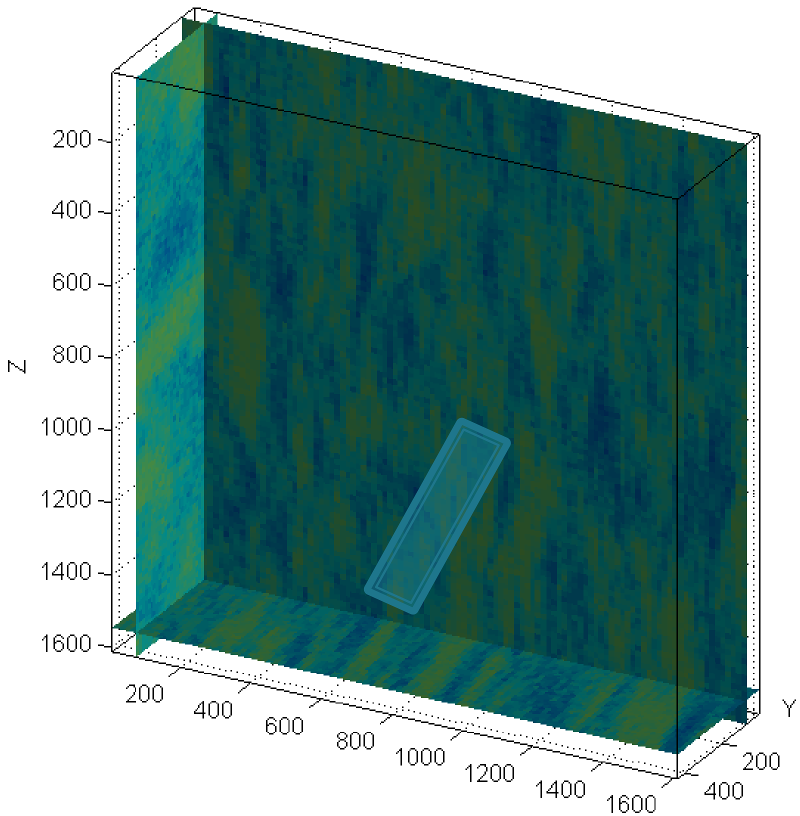
Assumptions:

- Depth interval: 1,600 m to 3,200 m.
- Reservoir rock: granite, granodiorite, or basalt (rock density 2,850 $kg/m^3$).
- Overlying formation: claystone, siltstone, or sandstone (rock density 2,650 $kg/m^3$).
- Reservoir temperature: $200^0C$.
- Pair of two wells: vertical; horizontal; inclined.
- Production liner: up to 1,400 m long.

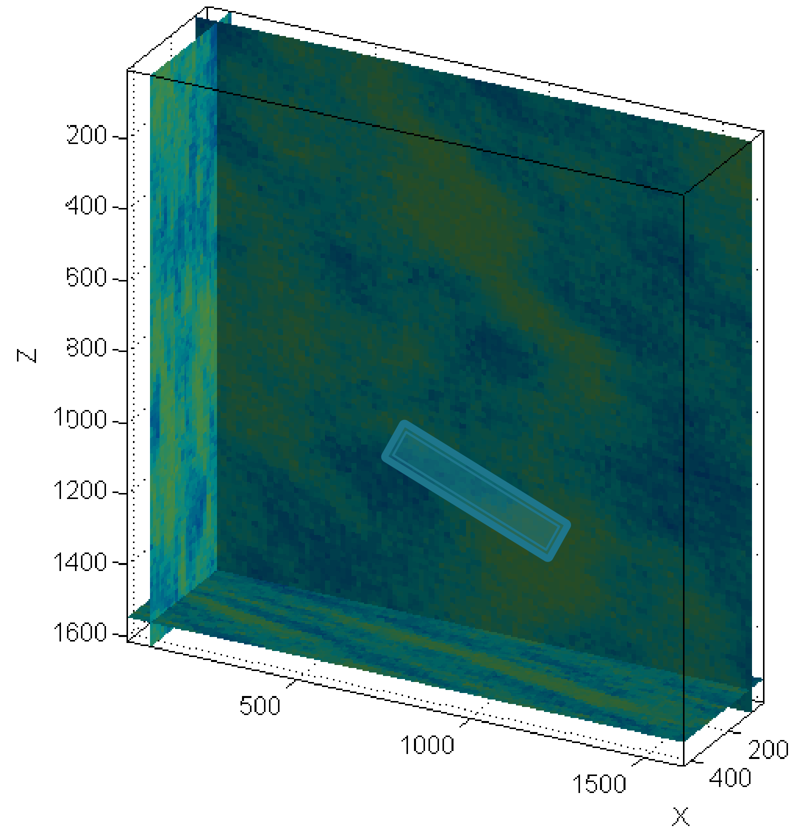
# Reservoir Representations

The fracture continuum model (FCM) approach was used to generate different EGS reservoir representations.



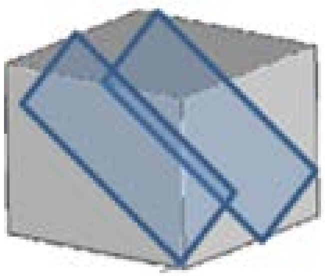

Permeability Field for One Fracture Set with Strike 10$^0$ and Dip 18$^0$.




Permeability Field for One Fracture Set with Strike 80$^0$ and Dip 18$^0$.

Fracture Plane

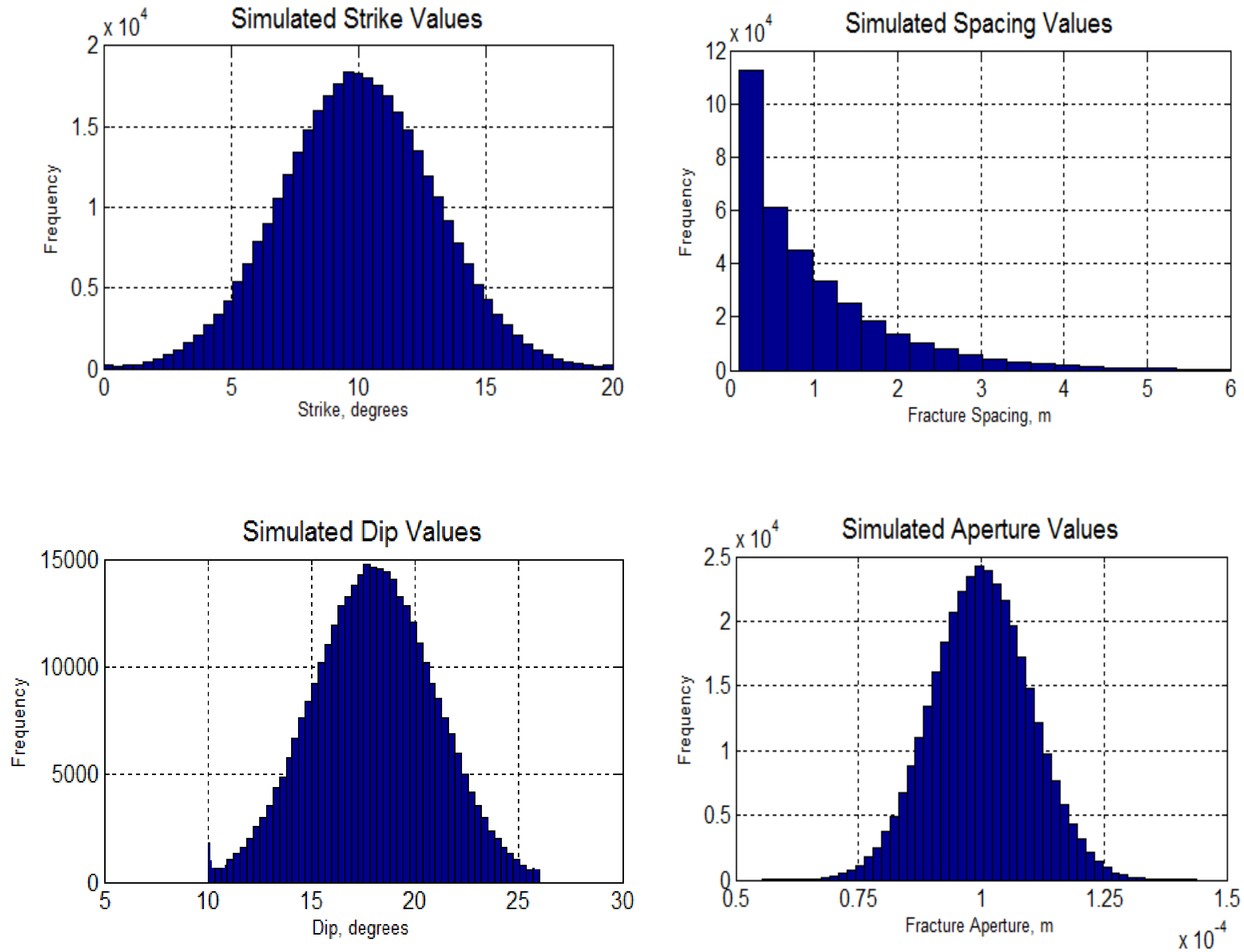
# Example of Fracture Property Probability Distributions Used to Generate Permeability Fields



- Fracture strike
- Fracture dip
- Fracture spacing
- Fracture aperture

*Kxx, Kyy, Kzz*

(338,256 grid blocks )




Fracture Property Probability Distributions for Natural Fracture Network with Strike $10^0$ and Dip $18^0$.

# Summary of Fracture Property Assumptions

## Pre-Stimulation Conditions (Natural Fracture Network)

- One fracture set
- Mean strike values: $80^0$ and $10^0$
- Mean dip values: $75^0$, $18^0$, and $5^0$
- Mean fracture spacing: 1.0 m
- Mean fracture aperture: 100 μm
- Average reservoir permeabilities: $2x10^{-13}$ (in two directions) and $2x10^{-14}$ (in one direction)
- Strike and dip: normal probability distributions with standard deviation $3^0$
- Fracture spacing: exponential probability distribution with min=0.1 m and max=15 m
- Fracture aperture: normal probability distributions with standard deviation 10 μm

## Stimulated Conditions

- Stimulation will enlarge the existing fractures
- Fracture spacing will be the same as in pre-stimulation condition
- Mean fracture aperture under stimulation: 220 μm (moderate) and 470 μm (significant)
- Average reservoir permeabilities: 10 times unstimulated (moderate) and 100 times unstimulated (significant)

Different combinations of fracture strike, dip, spacing, and aperture values result in different permeability fields (reservoir representations).

# Injection Interval Length

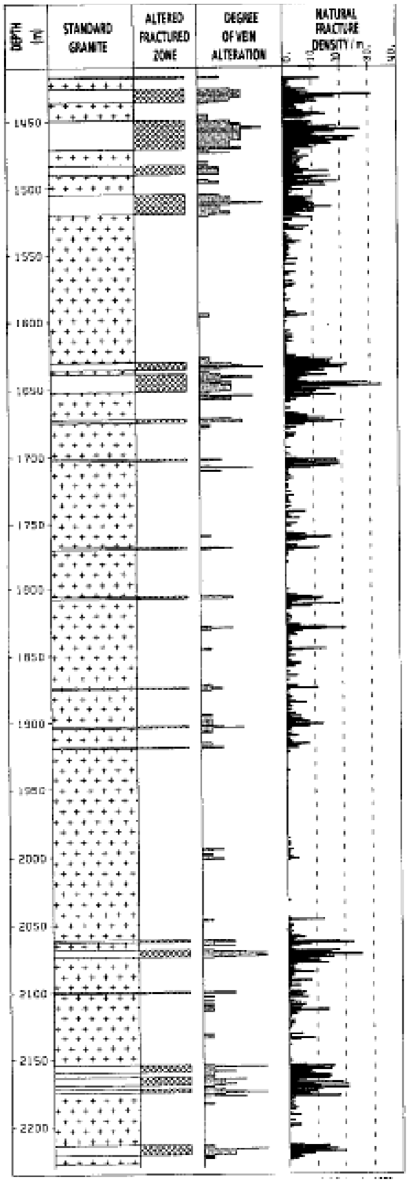
One of the common features of granite rocks is significant fracture density variation with depth.

- The intervals with high fracture density suitable for injection may have limited vertical extent.

In our simulations the injection interval length ranges from 250 m to 1,400 m.

The representative injection interval length is probably significantly smaller than 1,400 m.

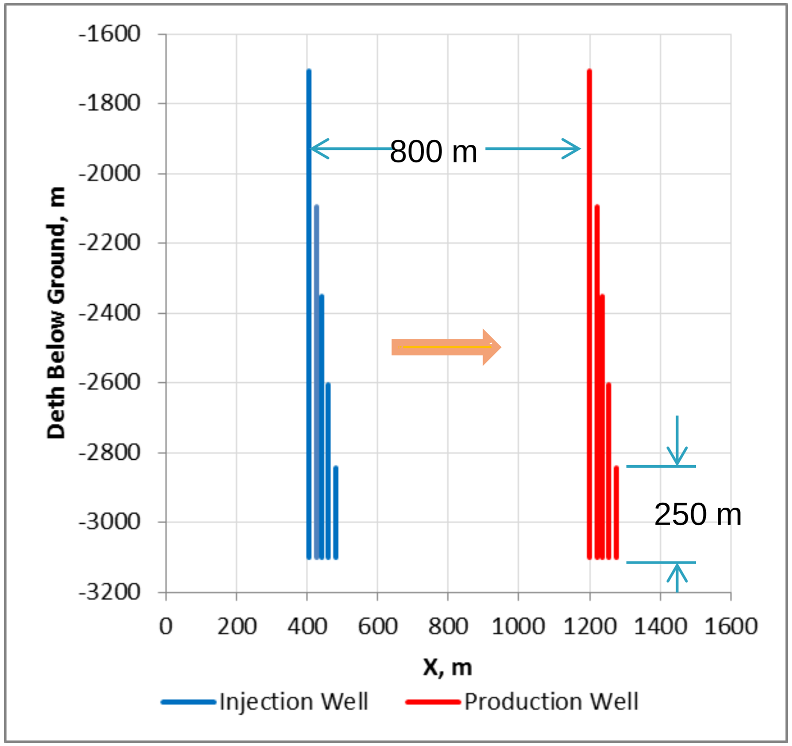
Soultz, Borehole EPS-1



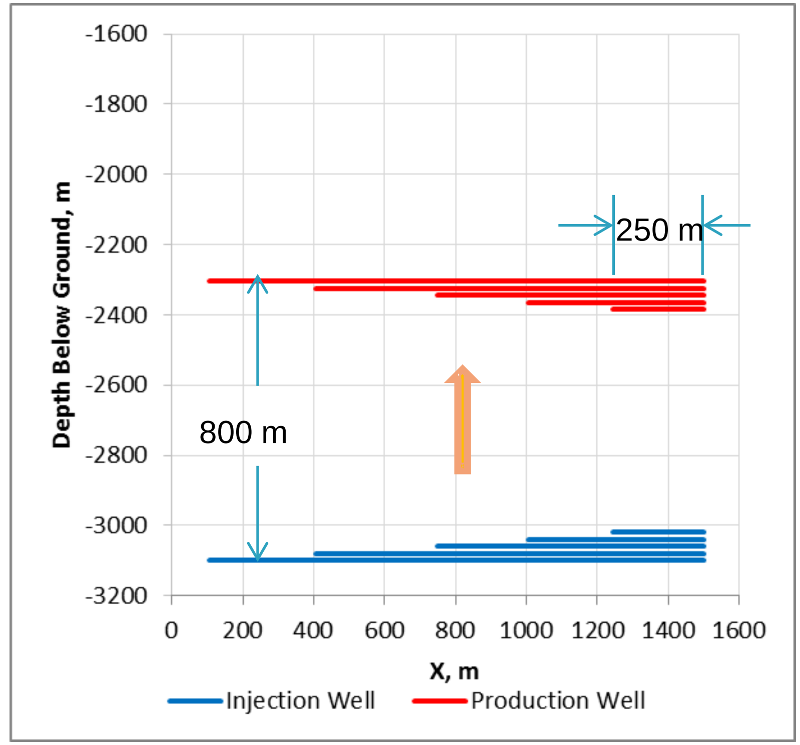

*A. Genter and H. Traineau (1992)*

# Vertical and Horizontal Well Setups

Vertical Wells




Horizontal Wells



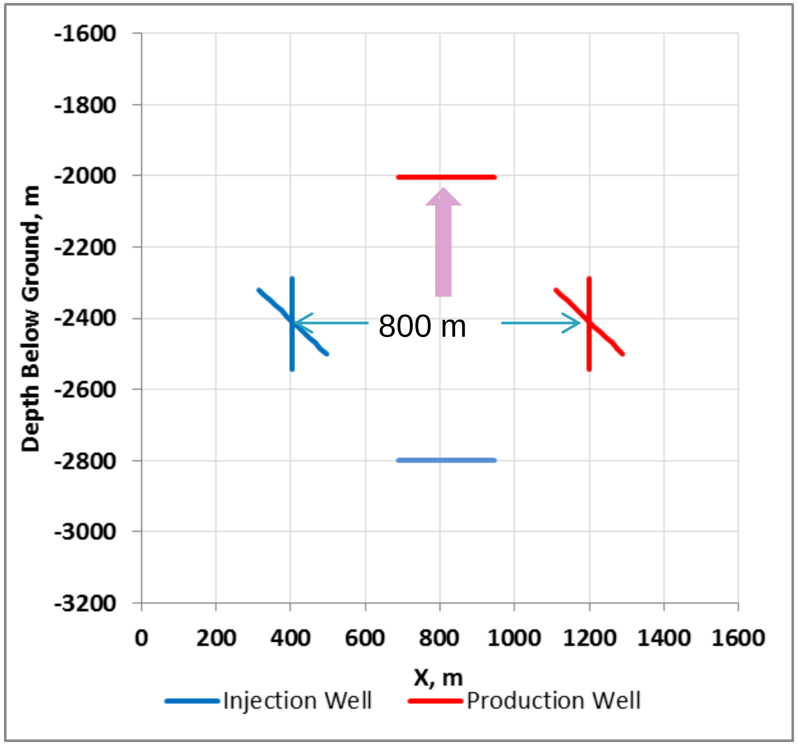

Injection Well
Production Well
Direction of Injection

<u>Injection Interval Length:</u>

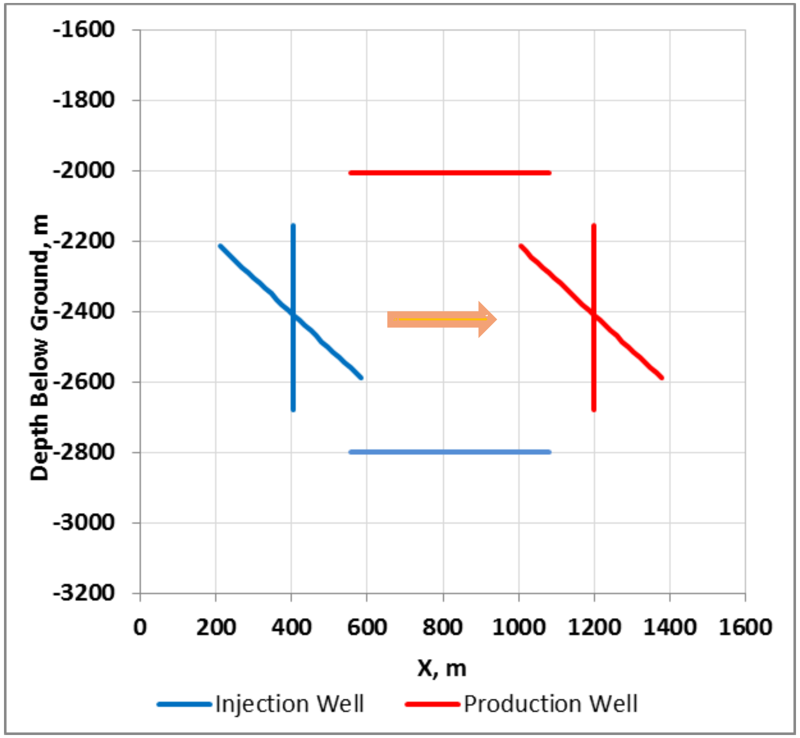
- 1,400 m
- 1,000 m
- 750 m
- 500 m
- 250 m

# Inclined Well Setups

250 m Injection Interval




525 m Injection Interval




Injection Well

Production Well

Direction of Injection (Horizontal Wells)

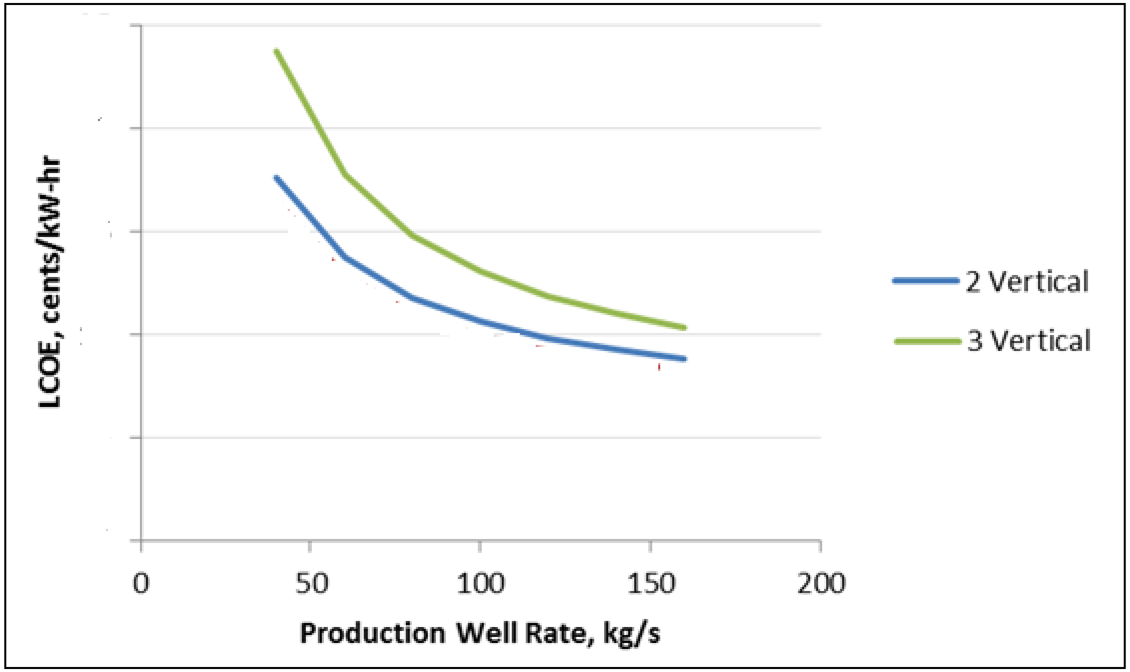
Direction of Injection (Vertical and Inclined Wells)

<u>Injection Interval Length:</u>

- 525 m
- 250 m

# Selection of the Injection Rate

LCOE as a Function of the Injection Rate for a 2-Point and 3-Point Injection Schemes (Vertical Wells)




NOTE: the LCOE scale is not shown intentionally.

The selected value (120 kg/s) is within the flat part of the LCOE curve.

# Summary of Heat Transport Problem Formulation

<u>Constant Parameters:</u>

- Initial reservoir temperature: 200$^0$C
- Injection temperature: 80$^0$C
- Injection rate: 120 kg/s
- Injection Duration: 30 years
- Depth to reservoir top: 1,600 m
- Rock density: 2,850 kg/m$^3$
- Porosity: 0.01

<u>Variable Parameters:</u>

- Permeability field: based on variable fracture properties
- Injection interval length: from 250 m to 1,400 m
- Well separation distance: from 390 m to 800 m
- Stimulation conditions: pre-stimulation, moderately stimulated, significantly stimulated

**Well Setup**

- Two Vertical Wells
- Two Horizontal Wells
- Two Inclined Wells

**Over 100 Runs**

**Calculation of Average Temperature ($T_{ave}$) in the Production Well**

$$T_{ave} = f(h_{ave}) \qquad h_{ave} = \frac{\sum_1^n h_i q_i}{\sum_1^n q_i}$$

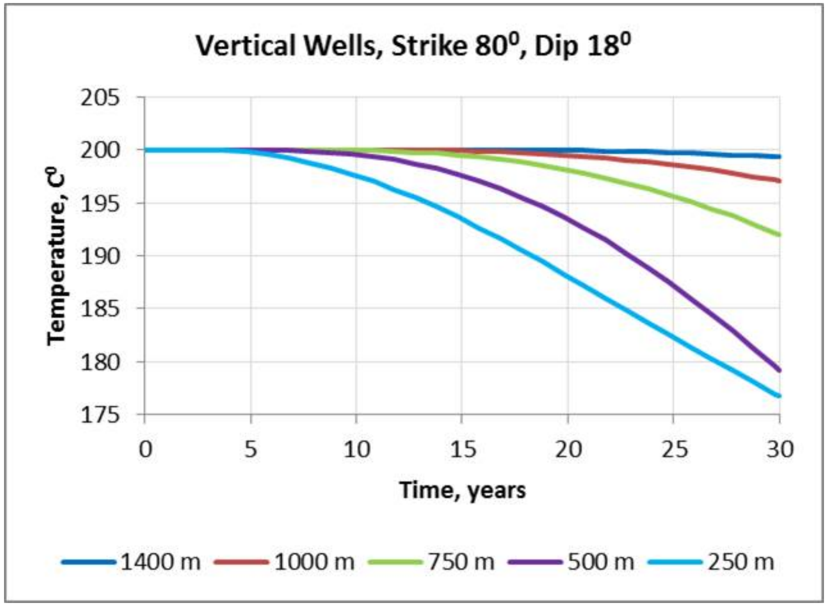
*n* - number of nodes representing the production well

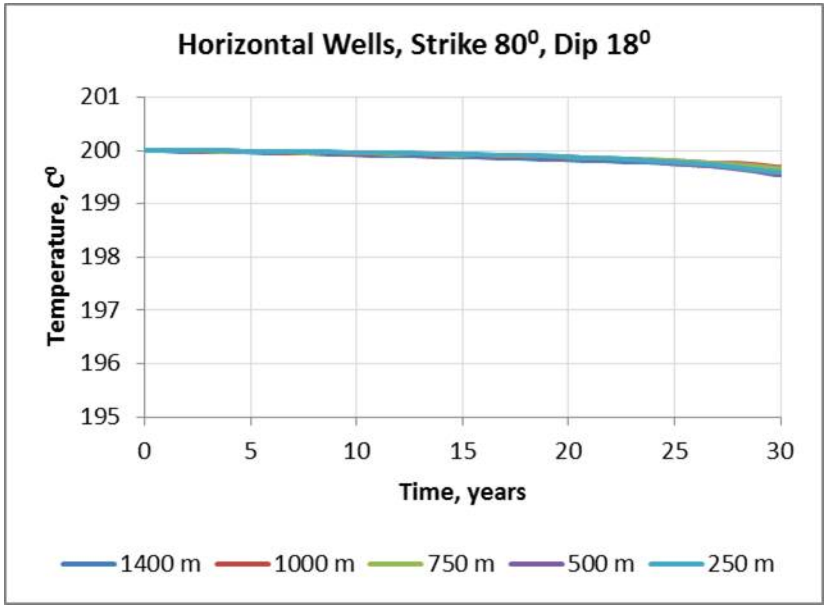
$h_i$ - node enthalpy

$q_i$ - mass flow exiting the node

$f(h_{ave})$ –steam table relationship

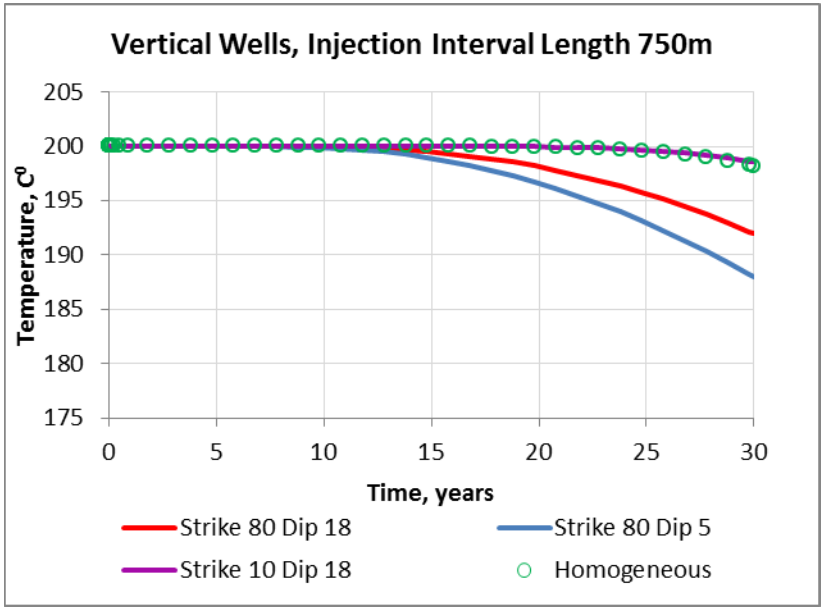
# Simulation Results: Injection Interval Length

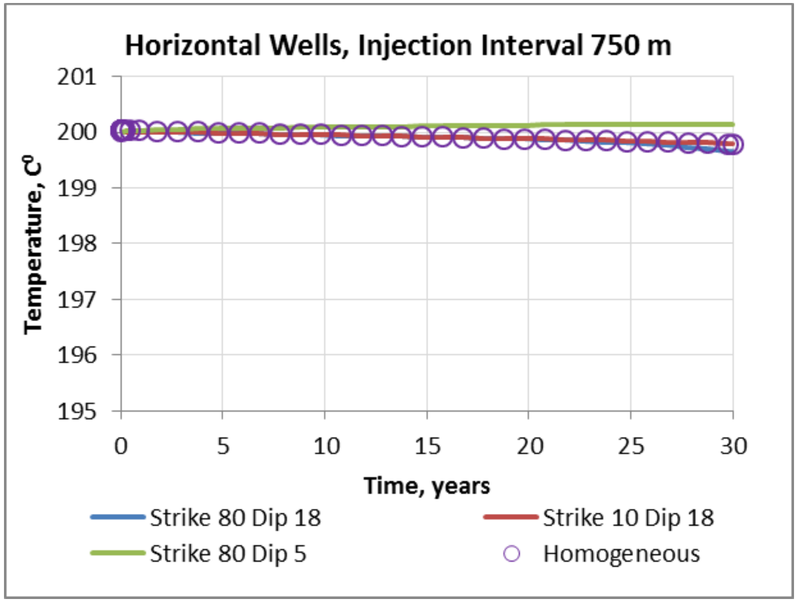


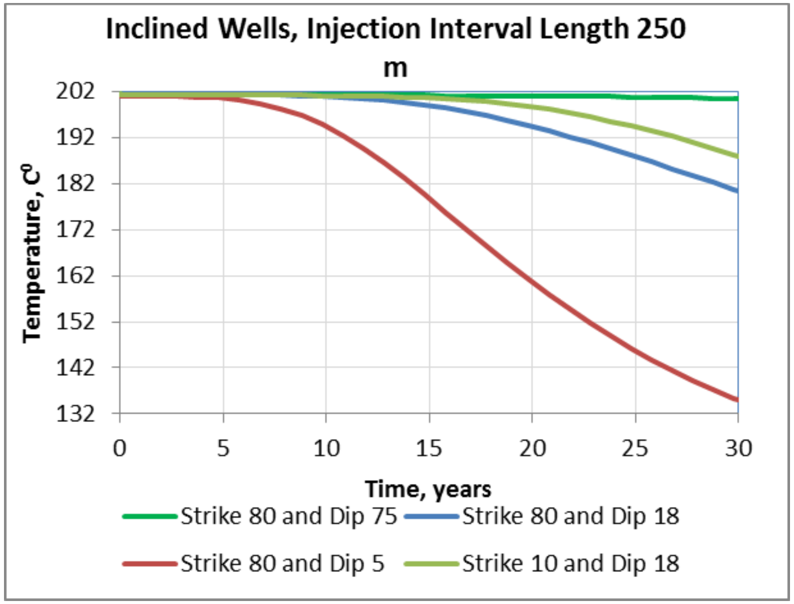

- ❑ The production temperature in the vertical well setup is strongly affected by the injection interval length.
- ❑ The injection interval length in the horizontal well setup has very small effects on the production temperature.

# Simulation Results: Fracture Orientation

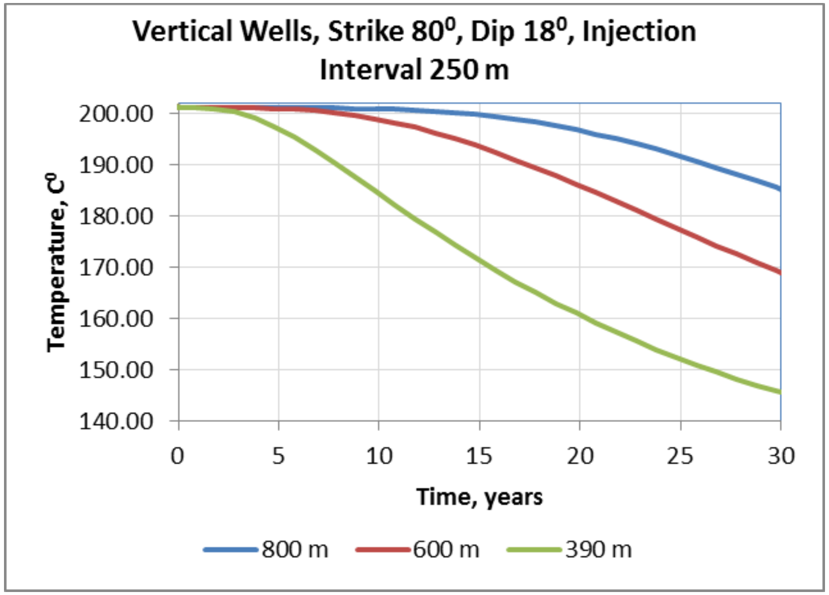


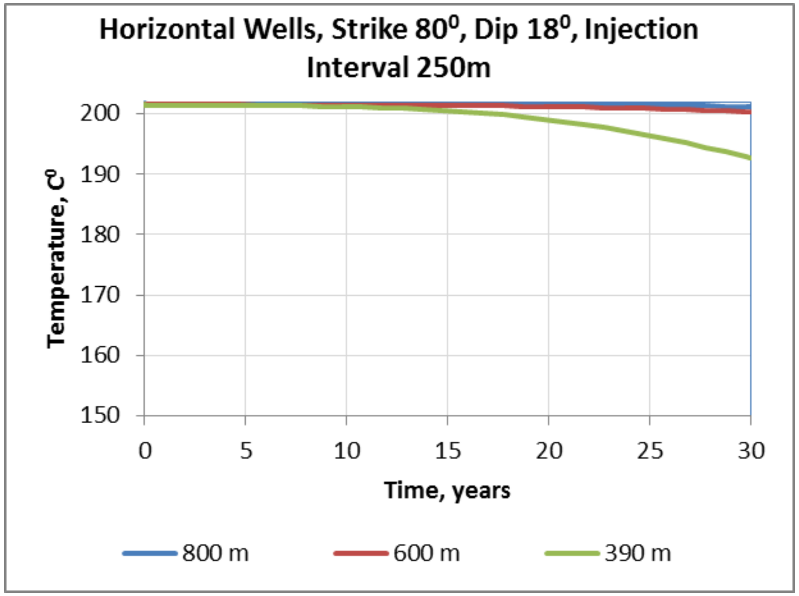




- The production temperature in the vertical and directional well setups is strongly affected by the properties of the fracture network.
- The properties of the fracture network have very small effects on the production temperature in the horizontal well setup.



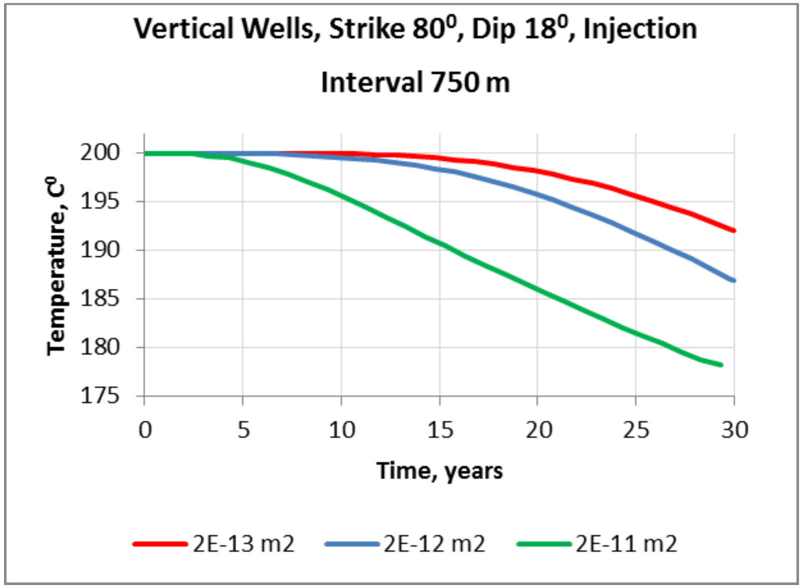
# Simulation Results: Well Separation Distance

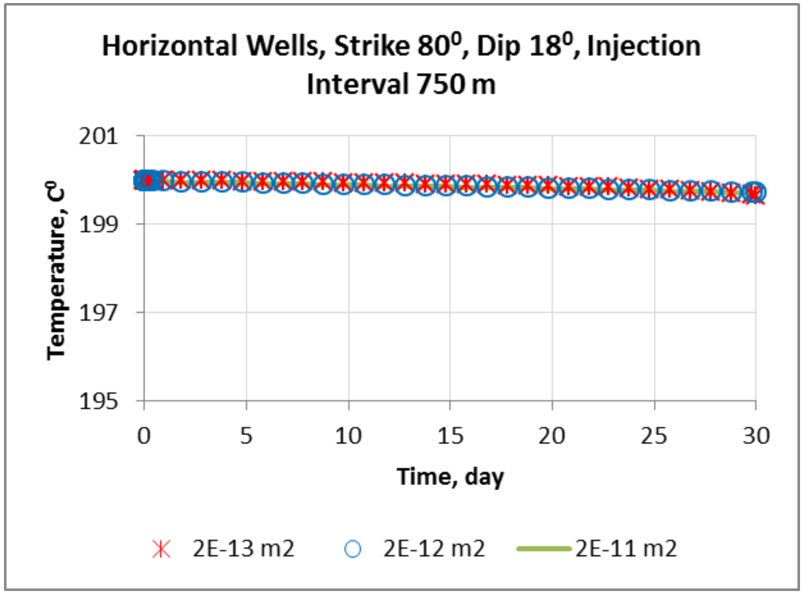



- ❑ The production temperature in the vertical well setup is strongly affected by the well separation distance.
- ❑ The separation distance smaller than 400 m has some effect on the production temperature in the horizontal well setup

# Simulation Results: Permeability

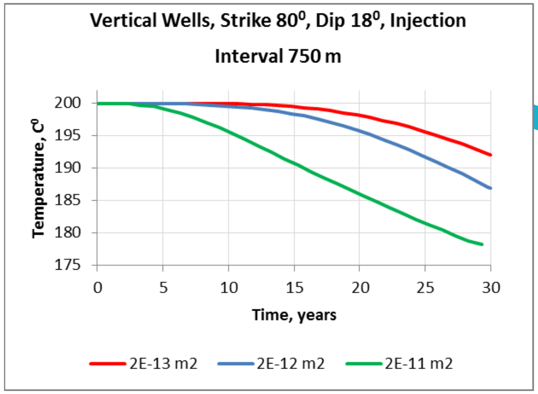


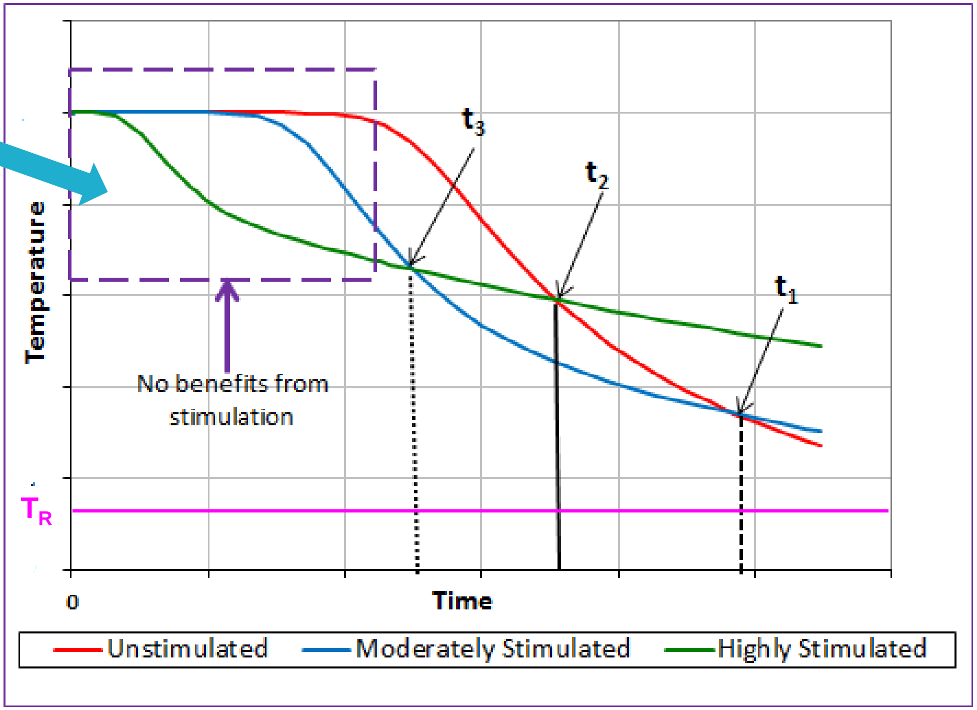




- ❑ The reservoir stimulation does not result in a better heat extraction in the vertical well setup.
- ❑ The reservoir stimulation has little impact on the heat extraction in the horizontal well setup.

2E-13 $m^2$ – pre-stimulation average permeability
2E-12 $m^2$ – moderate stimulation average permeability
2E-11 $m^2$ – significant stimulation average permeability

# Successful Reservoir Stimulation Conditions (Vertical Wells Example)




$T_R$ is Rejection Temperature

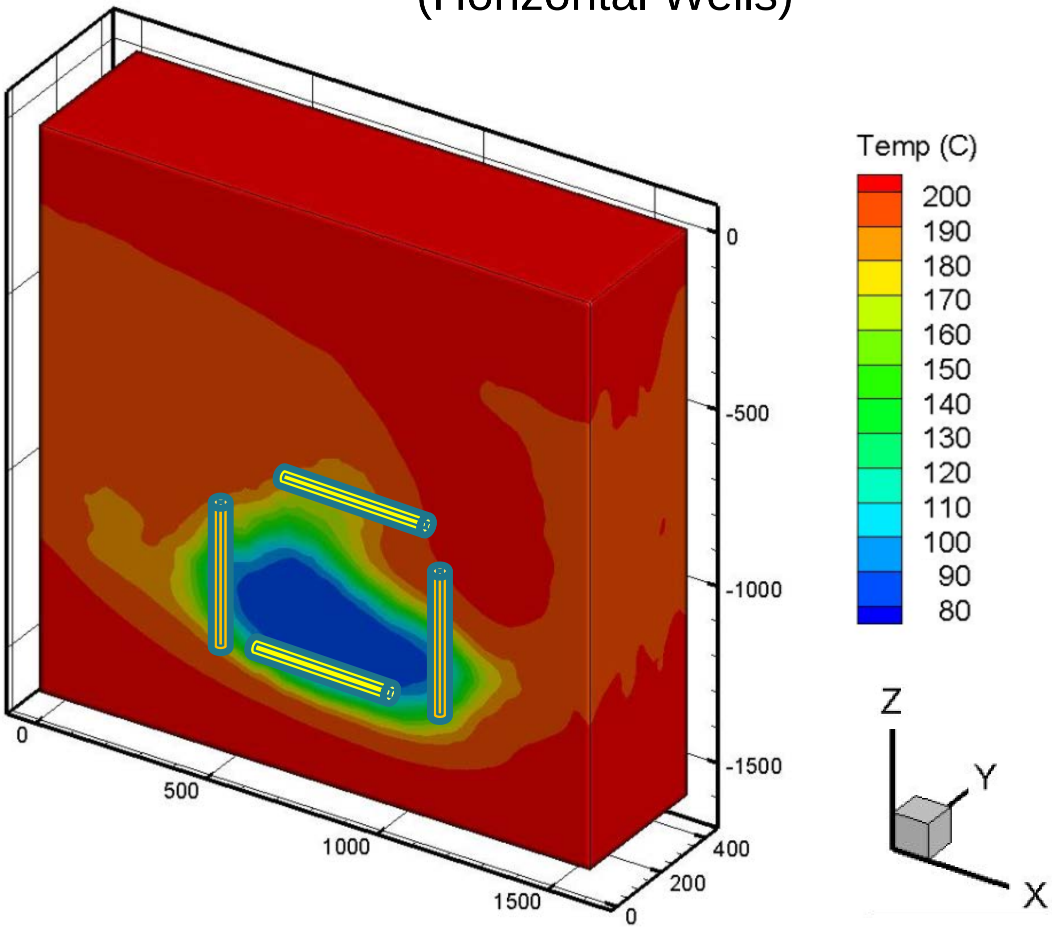
*$t_1$*, *$t_2$*, and *$t_3$* are affected by the injection rate, separation distance, injection interval length, and fracture properties.

- A moderate stimulation is successful after time *$t_1$* compared to no stimulation.
- Significant stimulation is successful after time *$t_2$* compared to no stimulation.
- Significant stimulation is successful after time *$t_3$* compared to moderate stimulation.

Condition of success: *$t_1$*, *$t_2$*, and *$t_3$* << 30 years

# Vertical versus Horizontal Well Setup

Temperature Field at the End of Injection
(Horizontal Wells)




- The cold water front extent in the horizontal directions is greater than in vertical direction.
- This impacts the production well temperature in the vertical well setup.
- The horizontal wells are not impacted as long as the separation distance is greater than the vertical spread.

# CONCLUSIONS

PURPOSE: Investigate the ability of the directional wells to reduce exploration and production risk and improve heat extraction.

The horizontal wells allow for reducing risks associated with:

- The uncertainty in fracture parameters and their spatial distribution.
- The unsuccessful stimulation.
- The insufficient length of the injection interval.

## Summary of Findings

- The performance of the horizontal wells is minimally affected by the length of the injection interval and fracture properties.
- Horizontal wells may require stimulation in the case of low vertical permeability.
- The performance of the horizontal wells is only to some extent affected by the well separation distance when it is 400 m or less.
- The performance of the vertical wells is significantly affected by the length of the injection interval, well separation distance, and fracture properties. The probability of the successful reservoir stimulation is hard to predict.
- The performance of the inclined wells is affected by the same factors as the performance of the vertical wells.