PROCESS MODELING OF A CLOSED-LOOP SCO_2 GEOTHERMAL POWER CYCLE

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Introduction

- Geothermal provides renewable baseload power that compliments wind and solar
- There are many hydrothermal installations, but the full value of geothermal is constrained by
  - Water usage
  - Exploration risks (i.e., dry holes)
  - Thermal depletion

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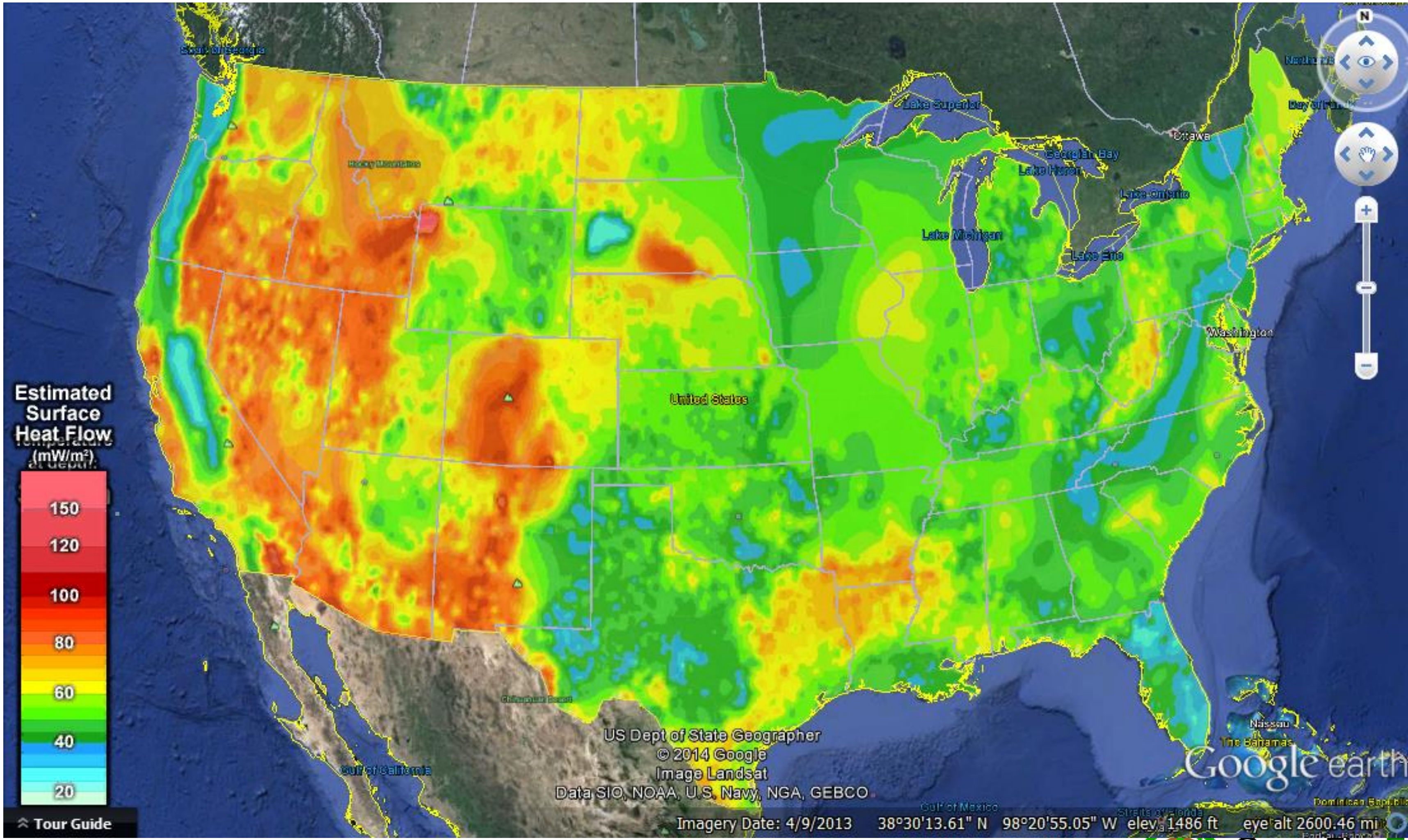
US Geothermal Resources



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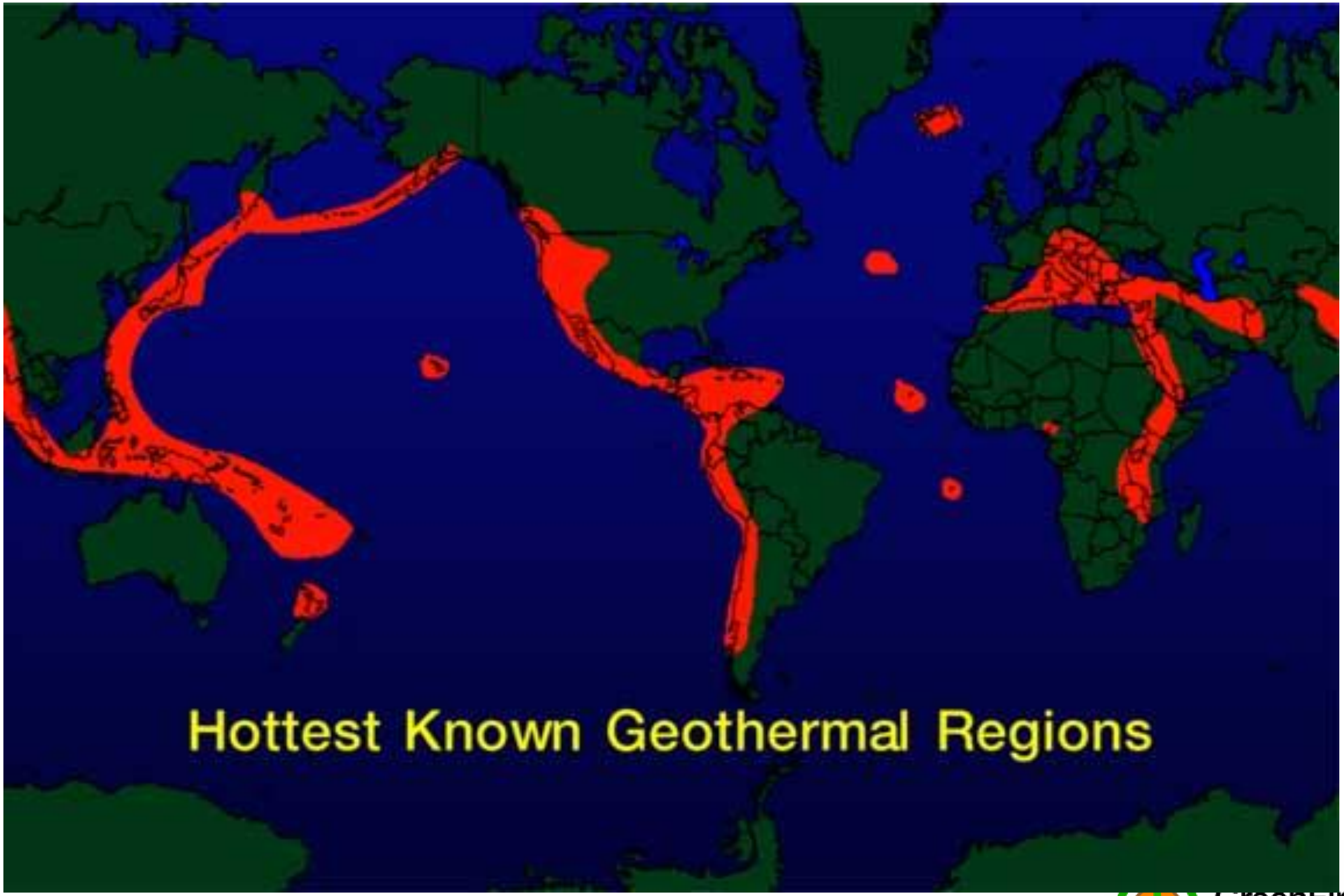
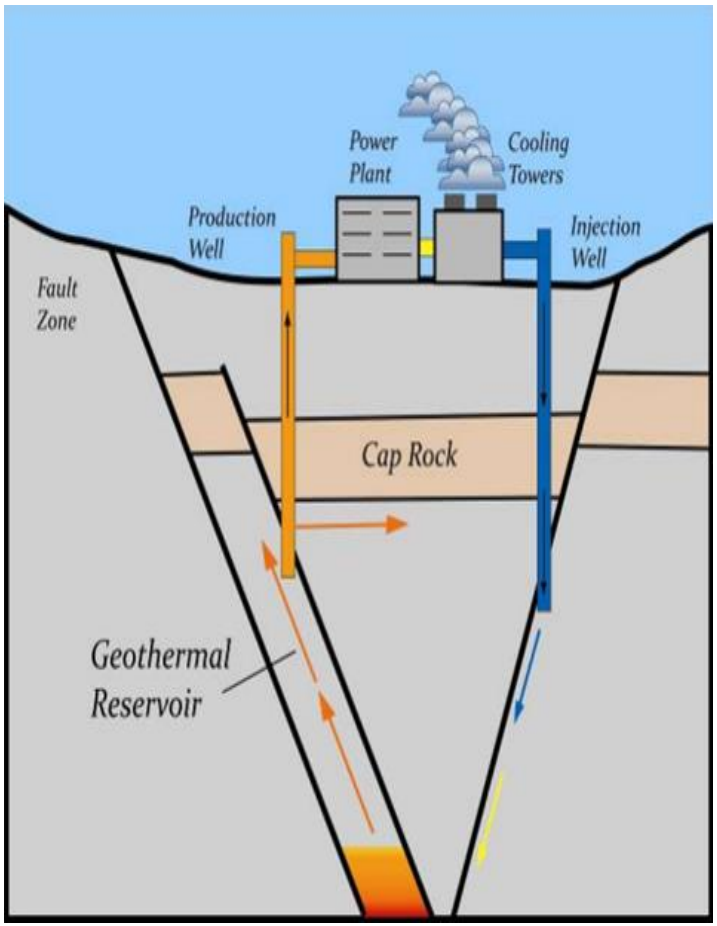
Global Geothermal Resources

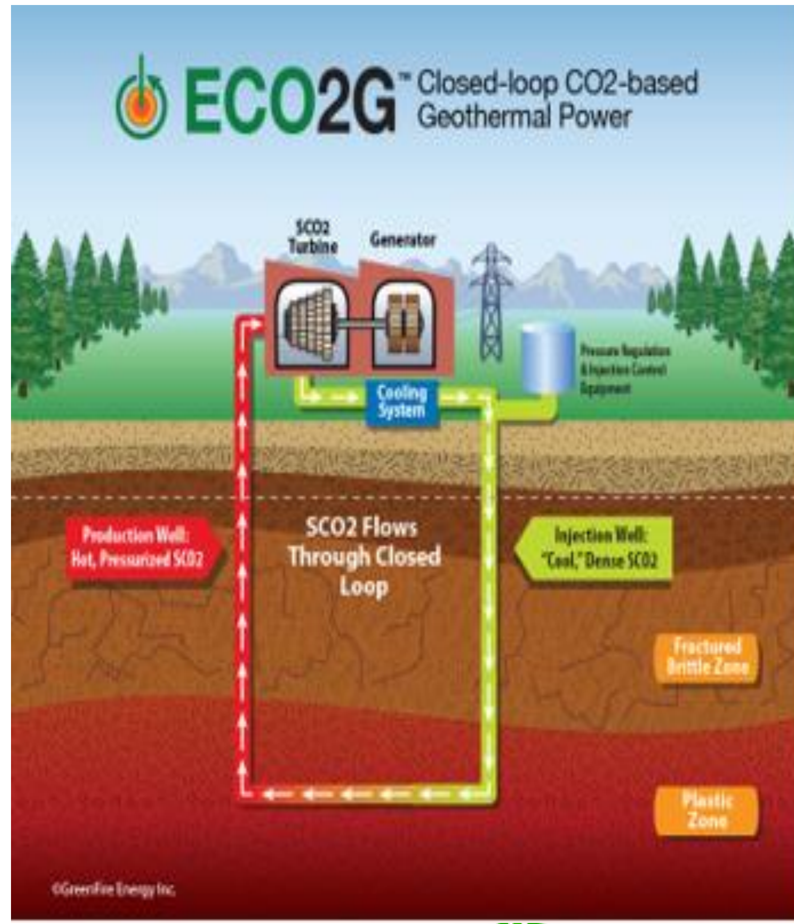


ECO2G

Conventional Hydrothermal



Closed-Loop Supercritical CO_2



Environmentally Friendly

- No Process Water Required
  - Heat rejection can be air only or hybrid with water
- No Emissions
  - No smog, no waste stream, no contribution to global warming, zero liquid discharge
- No subsidence
- Small Footprint
- Wildlife Preservation
  - Not a hazard to birds, land animals, or fish

Performance Modeling

- 1-D Process Modeling
  - Conservation of mass, momentum, and energy
- 3-D Resource Depletion Modeling
  - CFD modeling of full resource
  - Includes convection within the resource
- Surface Equipment Model
  - Isentropic turbine with specified efficiency
  - Heat rejection as a function of ambient conditions

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Governing Physics for 1-D Model

- Isentropic Compression and Expansion
  - As the gas goes down and up
- Friction
  - Darcy friction factor (Haaland Eq.)
- Heat Transfer
  - Time dependent conduction through rock (Ramey, 1962)
    - Convection through permeable rock is not considered
  - Conduction through cement and pipe walls (Fourier's law)
  - Convection into working fluid (Dittus-Boelter Eq.)
- ΔK.E. and ΔP.E.
  - Should be included, as they are not negligible

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Supercritical CO_2

- Highly Compressible
  - Produces a strong thermosiphon
- Inexpensive
- Relatively Inert
- High-Efficiency, Small Turbines
- No Process Water
- Outperforms Hydrothermal
  - Steam (flash tank) and binary (ORC) cycles

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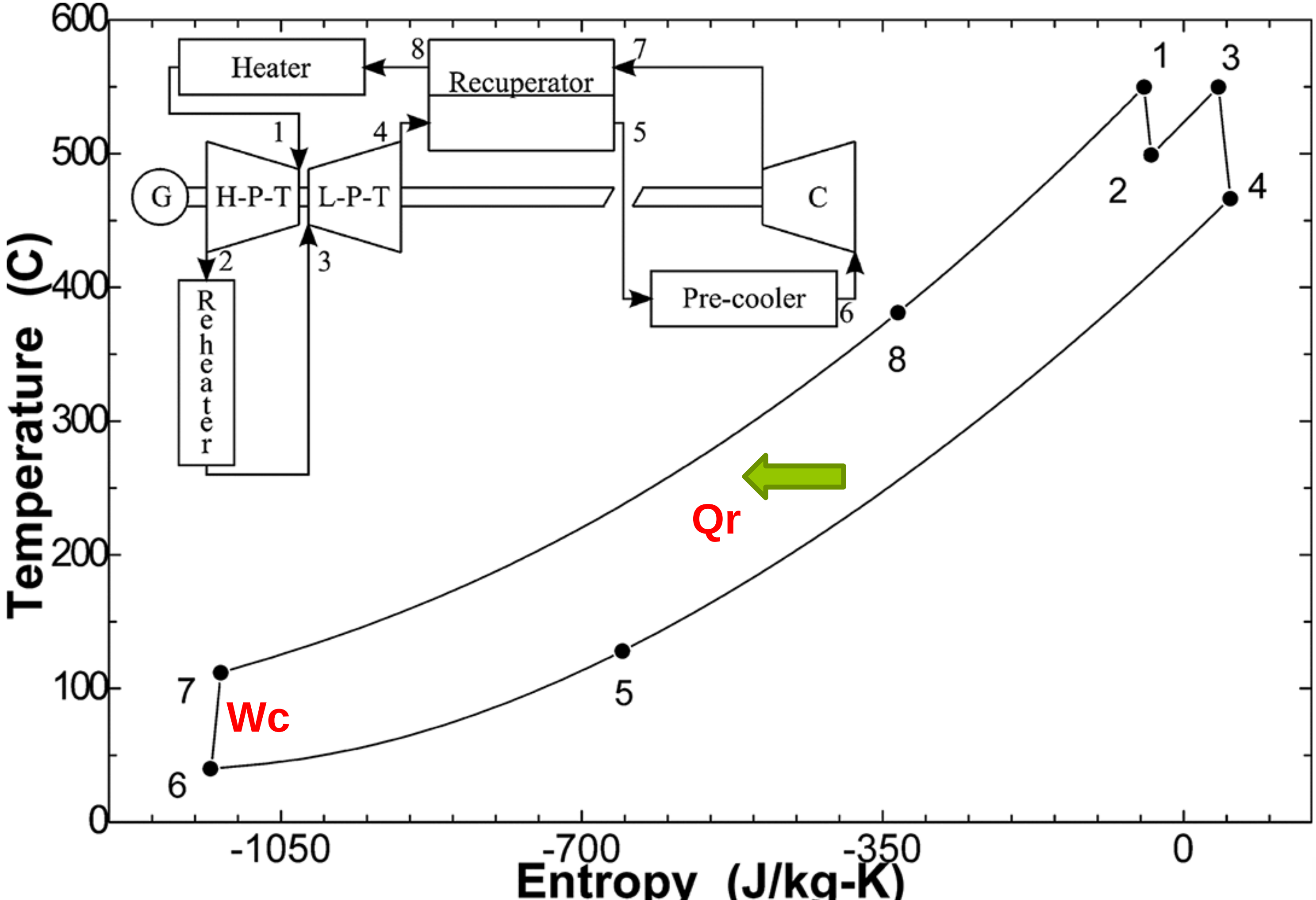
Normal Brayton Cycle
(with compression and recuperation)



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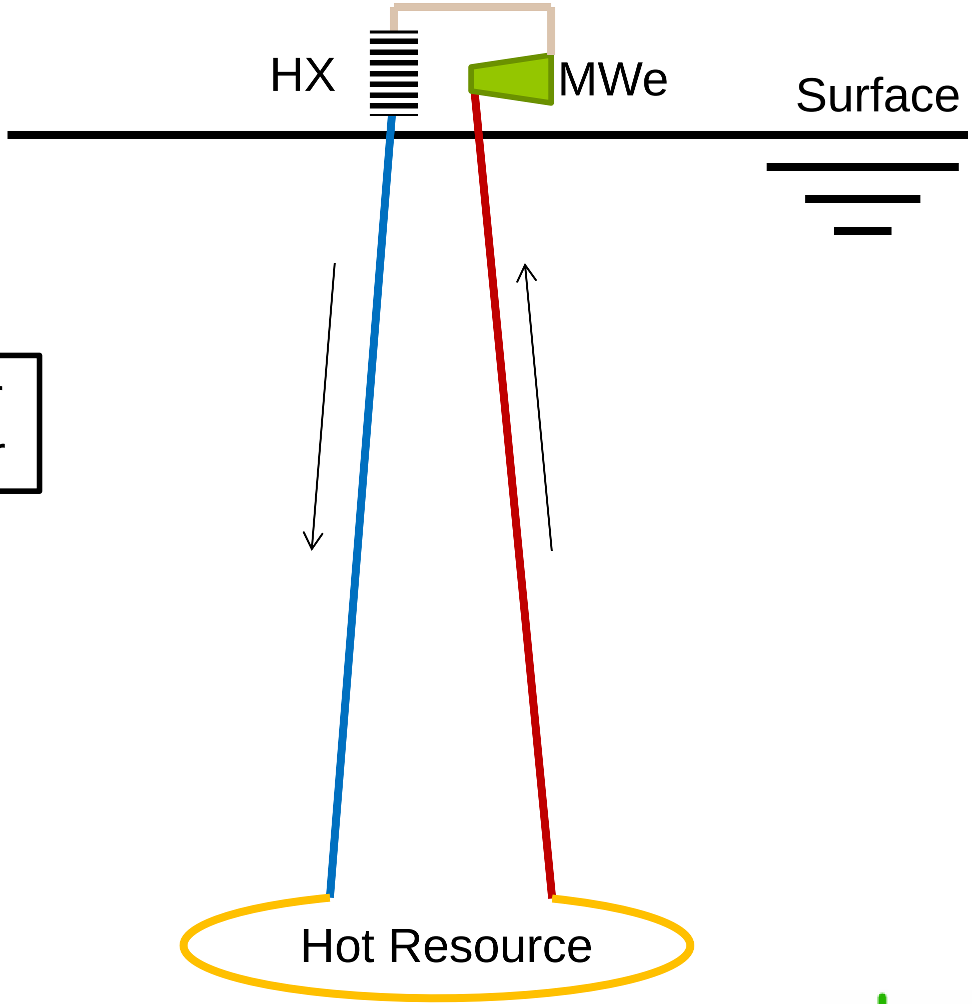
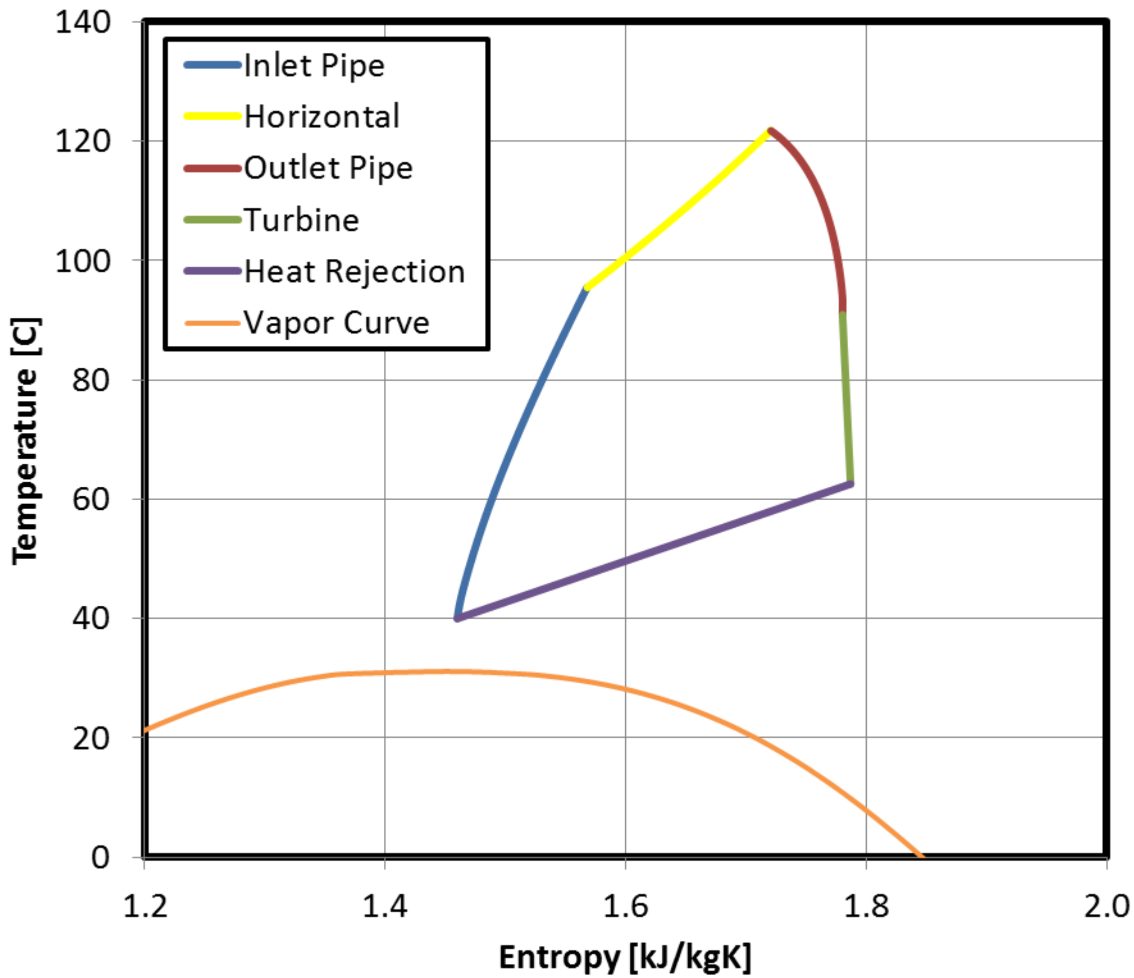
Closed-Loop

No Compressor
No Recuperator



T-s Diagram



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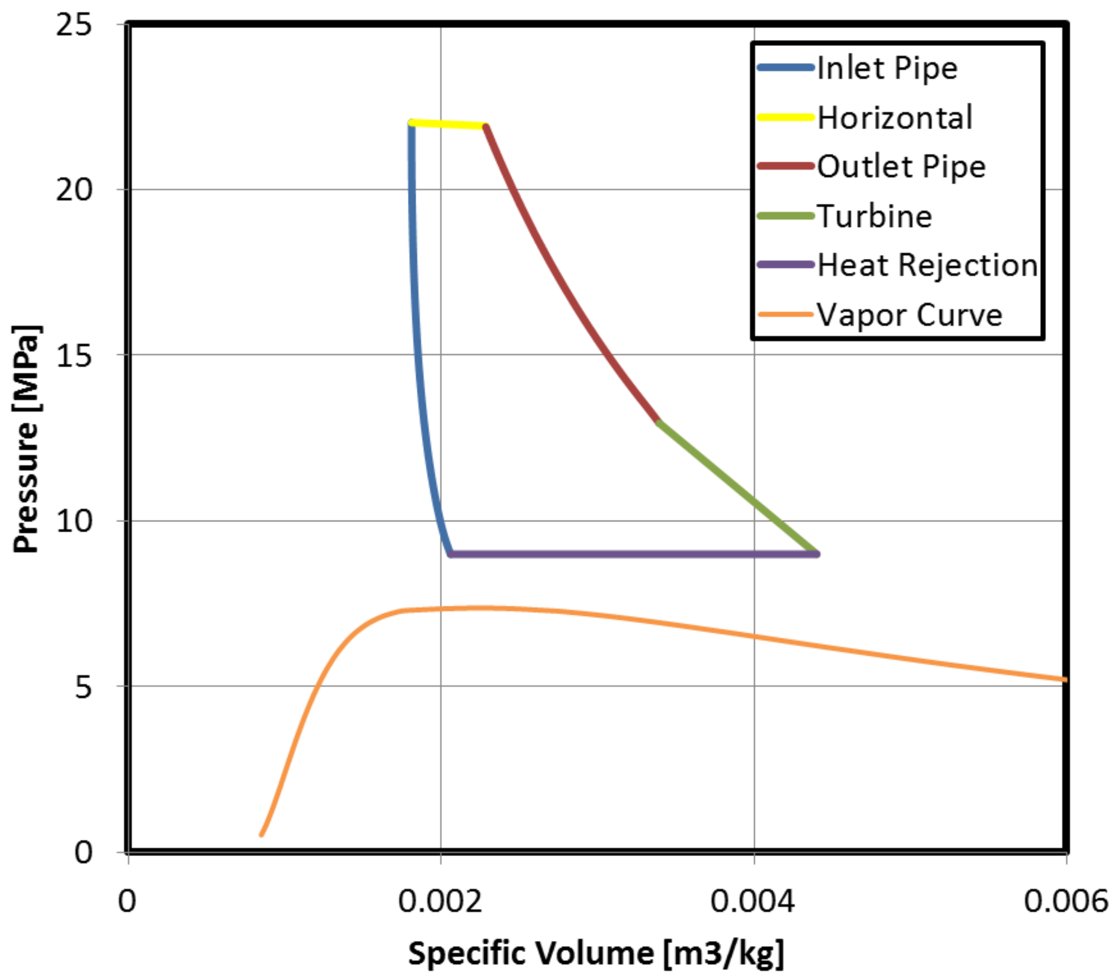
P-v Diagram



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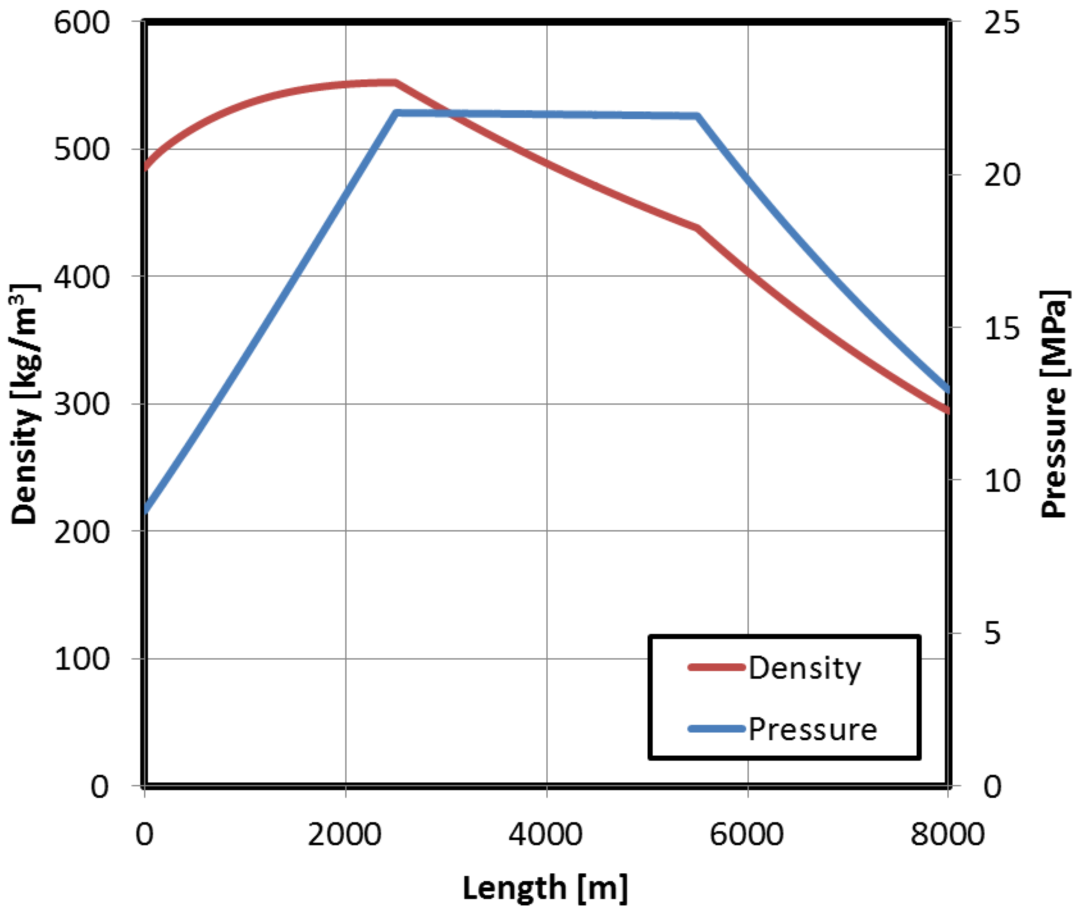
Thermosiphon
P & ρ *versus* Distance



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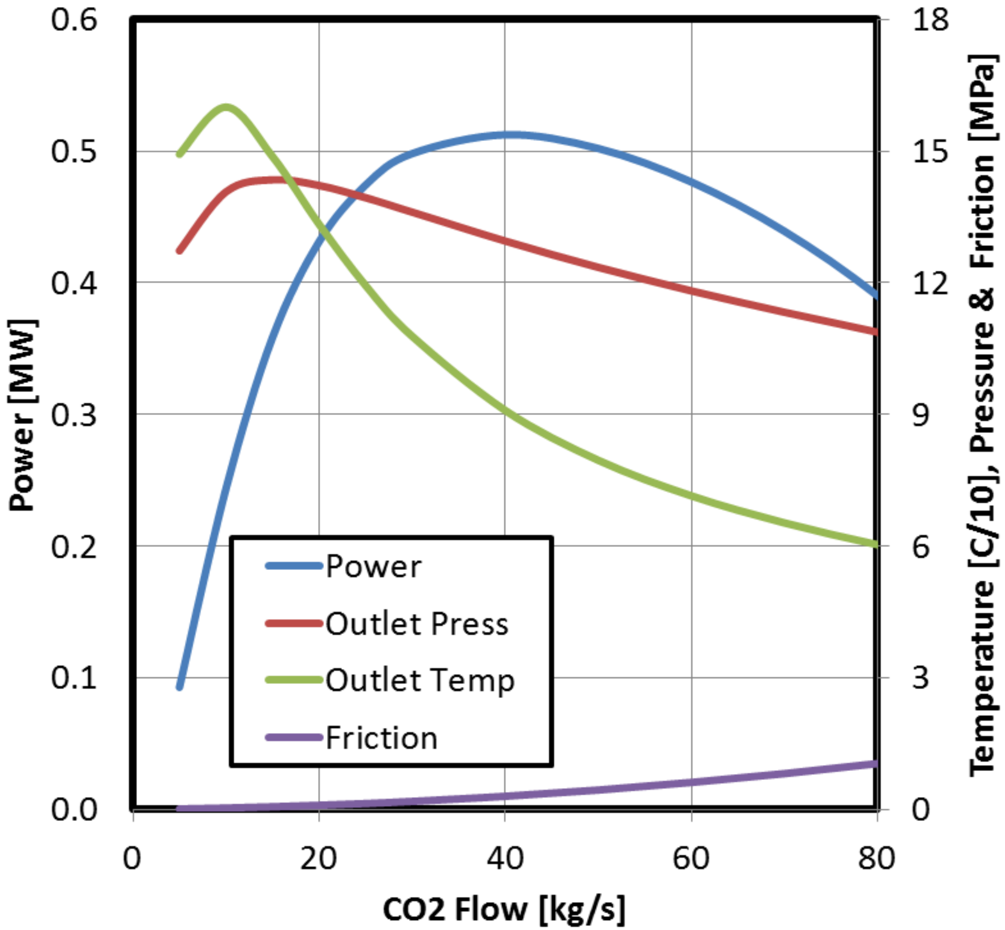
Process Design

- Optimization parameters

- Inlet thermodynamic conditions
  - Near the critical point produces good results
    - 31°C and 7.4 MPa
  - But heat rejection is a big factor

- Increasing the flow of CO_2 leads to an optimized design
  - Low flow → good temperature and pressure, but low mass flow
  - High flow → drop in temperature and pressure, but lots of enthalpy
  - Graph on next slide

Changes in CO_2 flow rate



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Multiplexed Wells

- Power production is very resource dependent
  - Temperature, thermal conductivity, depth, …
- Turbines are expected to be size specific
  - 1 MWe, 8 MWe, 15 MWe, …
- Therefore, we envision multiplexed wells on a common pad at the surface with several shared turbines
  - 10 MWe to 20 MWe
- Hot geothermal fields would hold 10 to 100 such multiplexed pads
  - 100 MWe to 1 GWe
- Many turbines…
  - Standard sizes
  - Moved to adjust to resource

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3D Modeling to Investigate Depletion

- Worked with LBNL to perform 3D modeling
  - 2016 *Stanford Geothermal Workshop* paper with more details

- Specifically looked at resource depletion issues
  - With and without local “stimulation”
  - Modest resource depletion

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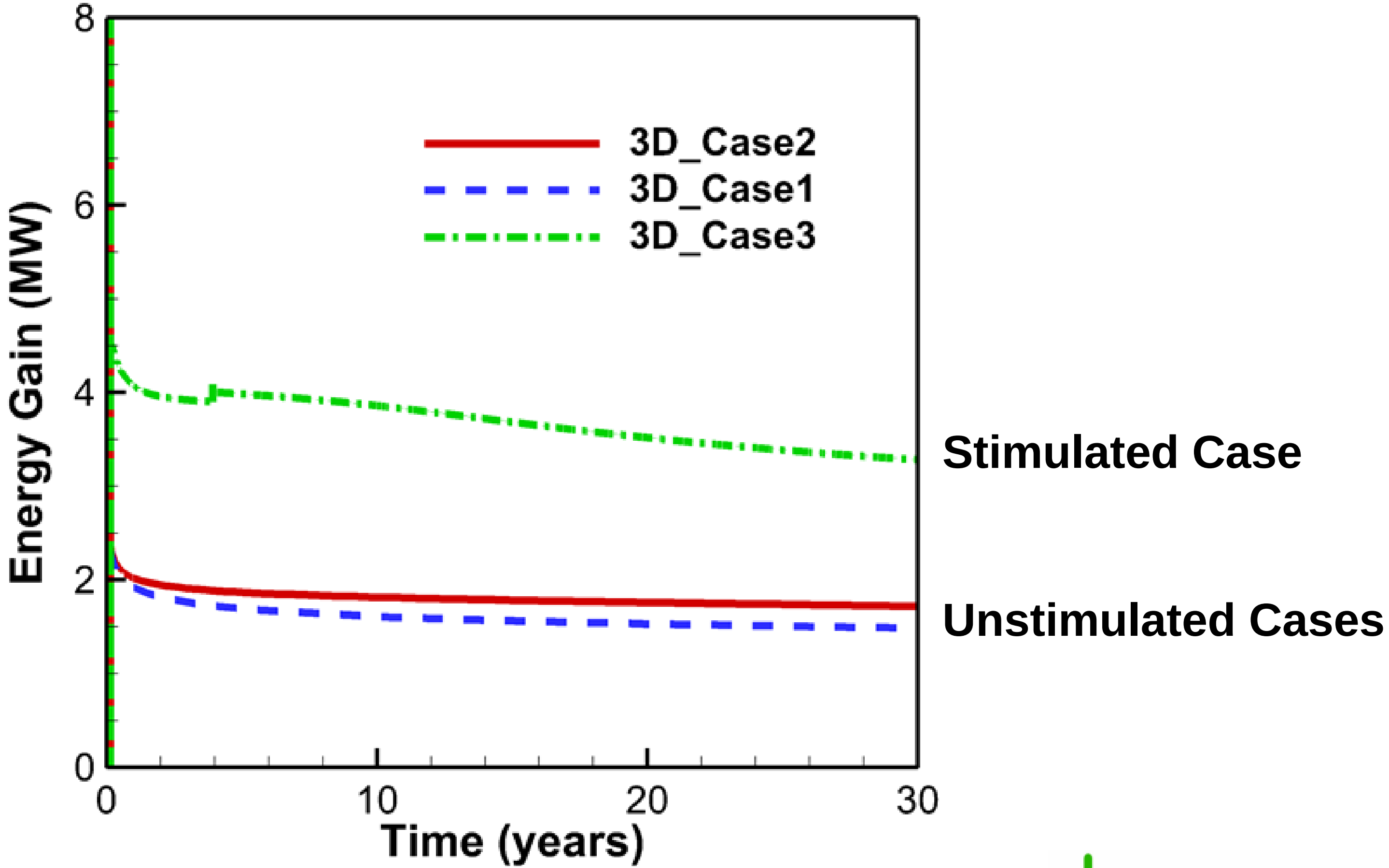
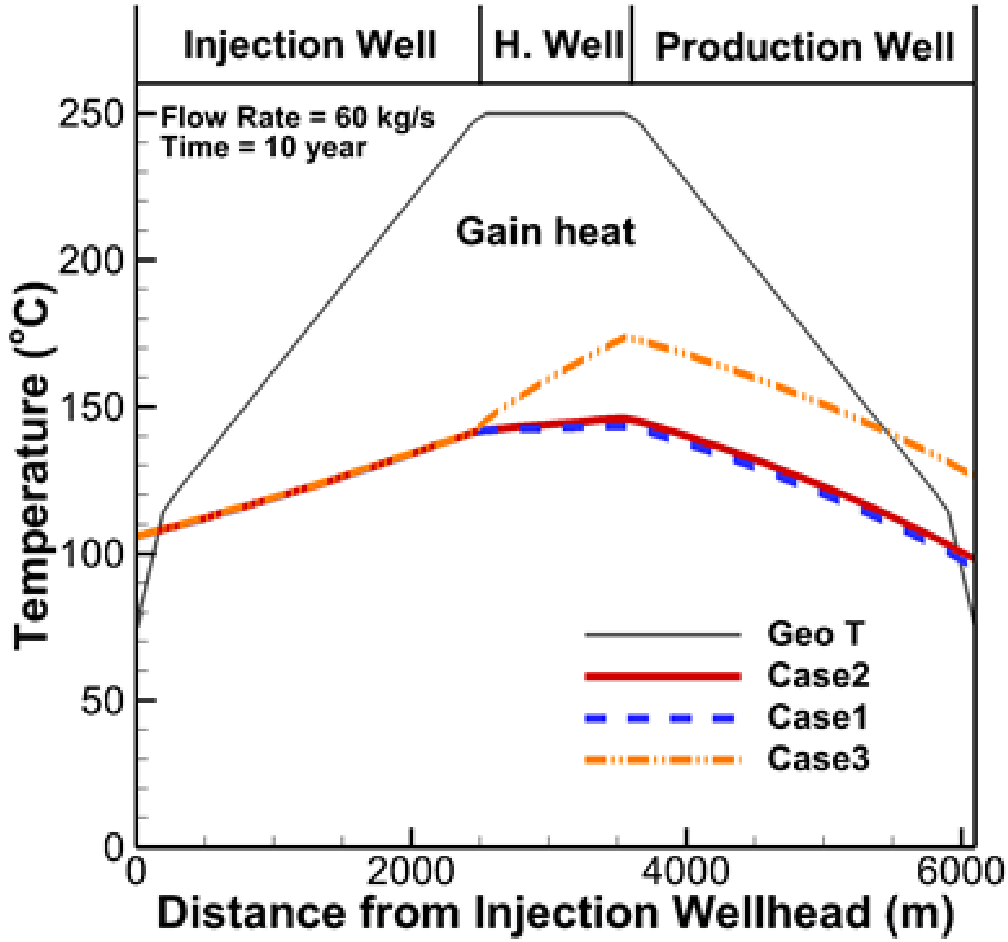
Resource Depletion over 30 years



Heat Gain w/ & w/o Stimulation



Stimulated Case

Unstimulated Cases

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Performance

- Piecewise approach to financial projections
  - Process design analysis (model optimization)
  - Drilling plan
  - Surface equipment design

  - Financial model (LCOE)

- Encouraging Results

- Power Production
  - Electrical power is typically 1 to 2 MWe per well
  - Electrical power can exceed 5 MWe for some cases

- Financial Projections
  - 25 Year LCOE ranges from $0.05 - $0.10/kWh

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Challenges

- Drilling
  - Directional drilling (“meeting in the middle”)
  - Completion (“connecting the two wells”)
  - High costs of drilling are all upfront

- sCO_2 Turbines
  - Commercial availability
  - Design schedule and costs

Next Steps

- Proof of Concept
  - Finished
- Fundraising
  - Series A – Summer 2016
- 12 Month Goal
  - Demonstration well
  - Multiple potential test sites identified
- 18-36 Month Goal
  - Commercial Scale Installation

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THANK YOU!

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