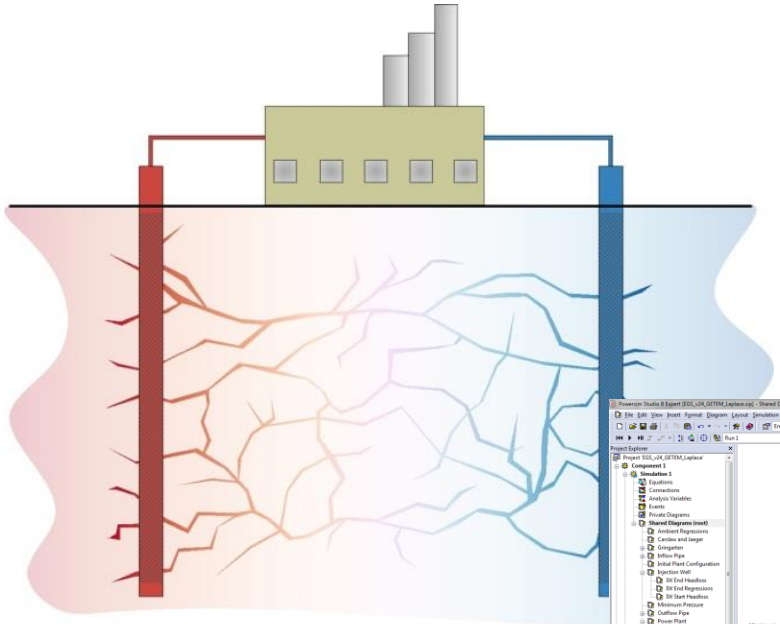
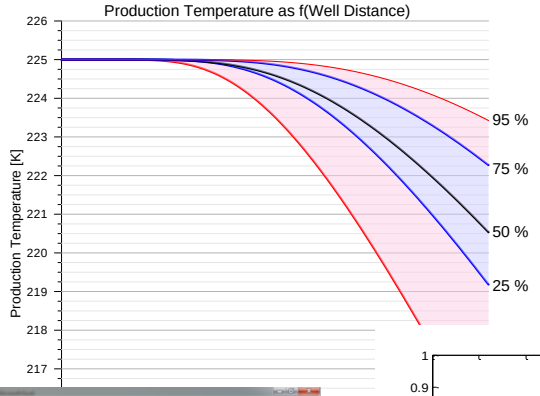
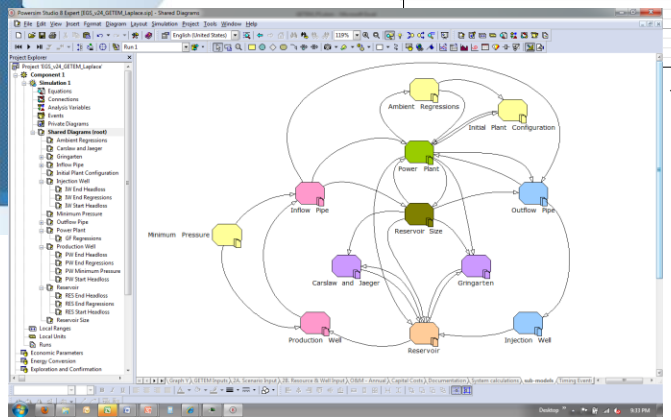
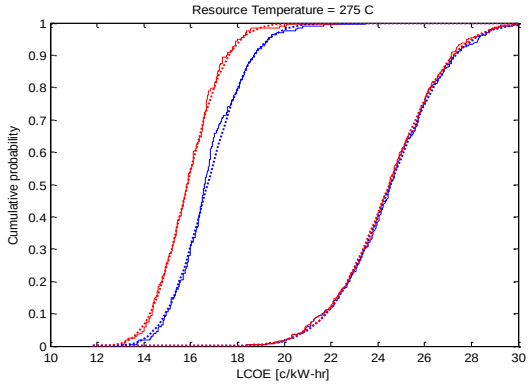








Geothermal Systems Engineering

GT-Mod

Project Officer: Timothy Reinhardt

Total Project Funding: $250k

May 11, 2015

Thomas Lowry

Sandia National Laboratories

Systems Analysis

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Relevance/Impact of Research

GT-Mod is a systems-based model of geothermal energy production that simulates system and sub-system interdependencies and feedbacks to capture non-linear coupled responses to uncertainties in one or more input values. This approach allows users to:

- Produce probabilistic output of economic and physical performance as a function of uncertainty and various system configurations
- Conduct probabilistic risk assessment to identify and prioritize technology development strategies
- Optimize system design and operation
- Answer 'what if' questions with regards to technology advancement, system design, and thermal performance

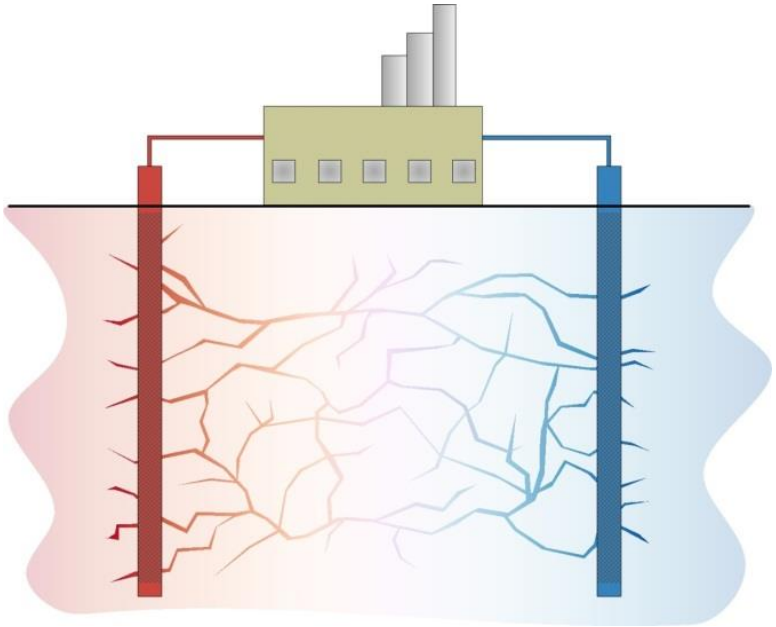
Relevance/Impact of Research

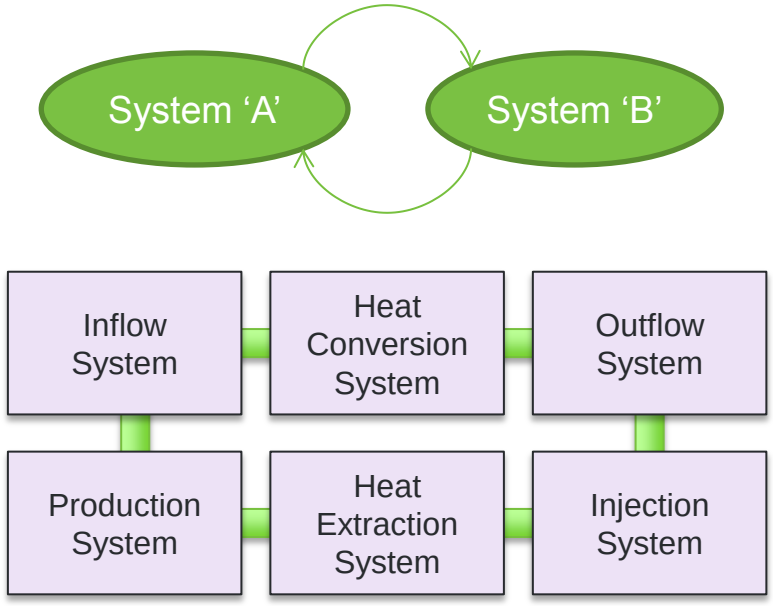
- Impacts
  - Allows us to gain insight in an environment of uncertainty
  - Lowers risks and costs of development
  - Identifies and prioritizes areas where improvements and/or better understanding will impact the bottom line the most
- Innovation
  - System dynamics: combines realistic, physics based simulations at the component level to simulate total system performance
  - Risk assessment addresses the always-constant uncertainties to produce probabilistic output of total system performance
  - Modular architecture can be easily extended and adapted to other problems or other analyses: 2015 work is being extended to direct use applications
- Challenges
  - How to include ‘realistic’, physics based simulations in a system dynamics model?
  - Connect physical performance with economic performance
  - How do we define uncertainty?

Scientific/Technical Approach

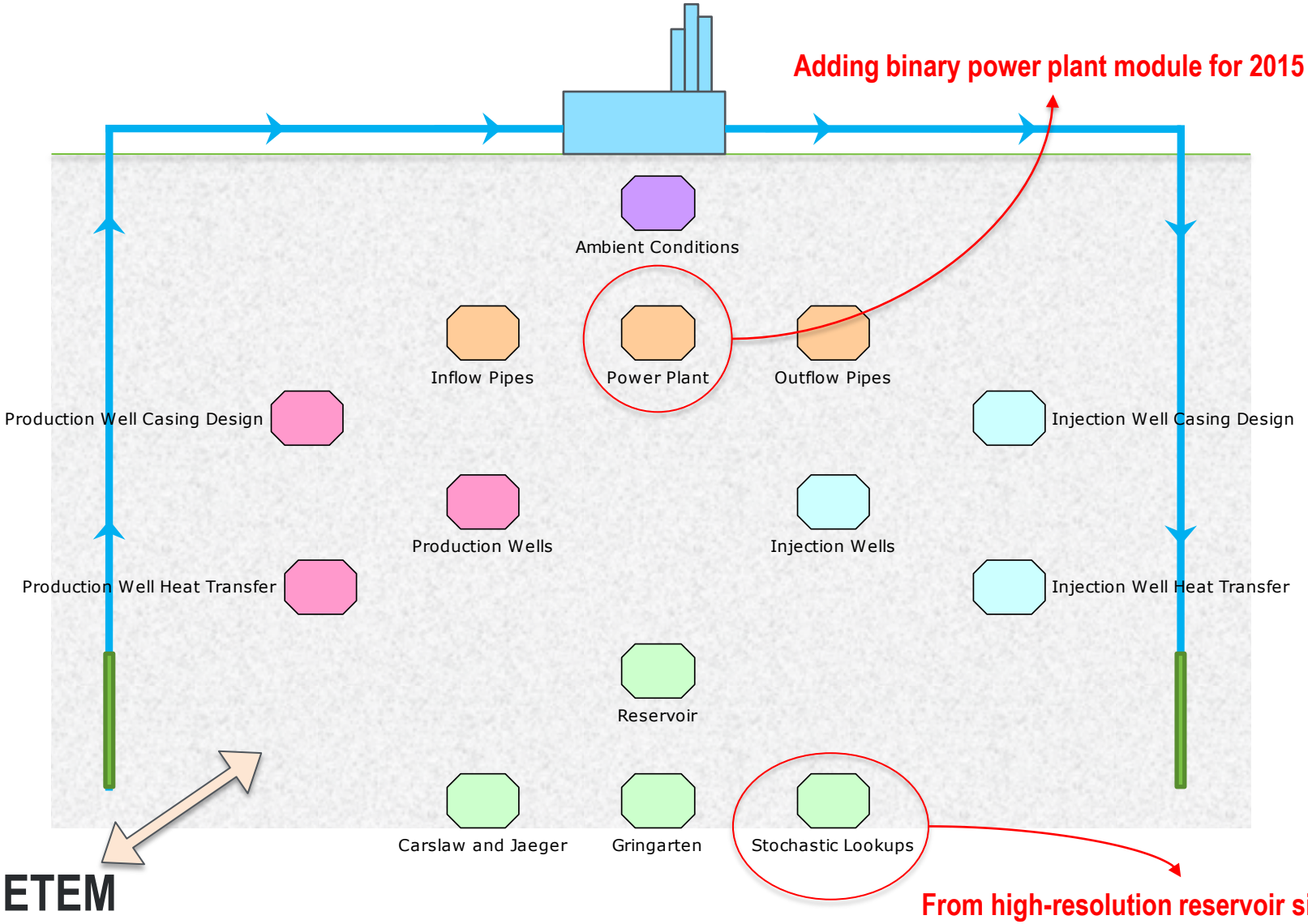
Geothermal Energy as a Complex System of Systems

- Systems are interdependent
- Each are linked and considered simultaneously
- Focus is on dynamic complexity





Scientific/Technical Approach

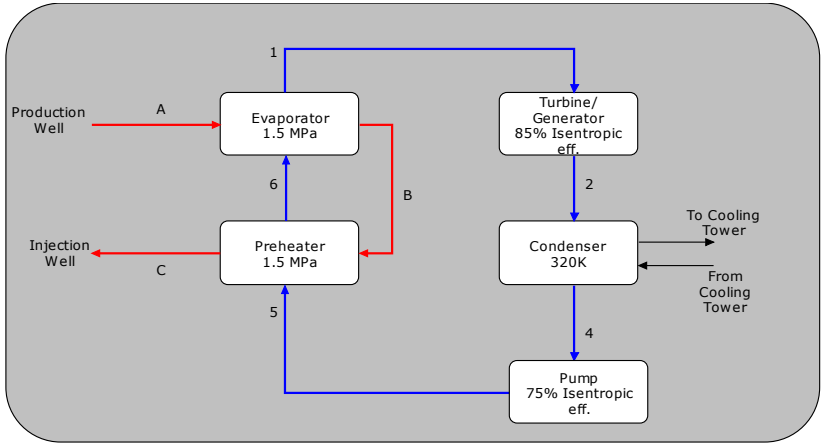


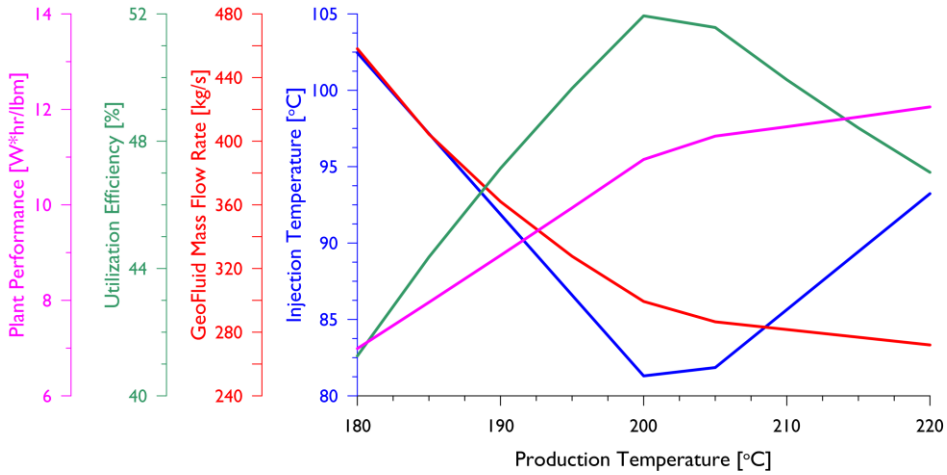
Scientific/Technical Approach

Use of SYSTEM DYNAMICS (SD)

- SD is a formal modeling discipline that captures the dynamic complexity between connected systems and sub-systems
- Dynamic complexity is a function of direct influences, feedback, and delays
- SD is scalable to the spatial or temporal scale of interest

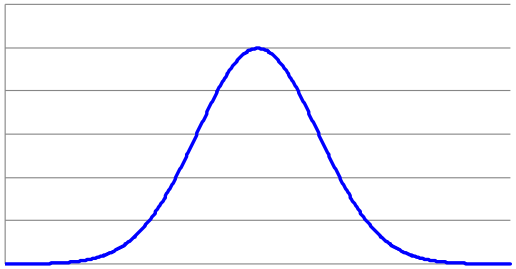
Dynamic complexity example from new binary power plant module



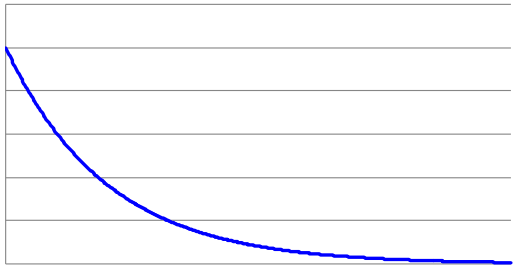


Uncertainty and Risk

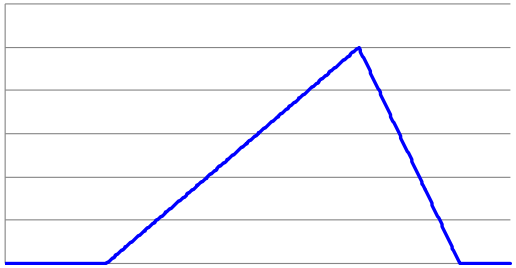
- Mathematically, uncertainties are expressed as PDF's (probability distribution functions)
- They are a reflection of what we don't know
- Uncertainty is not necessarily a 1:1 transfer between independent and dependent variables
- Uncertainty = Risk



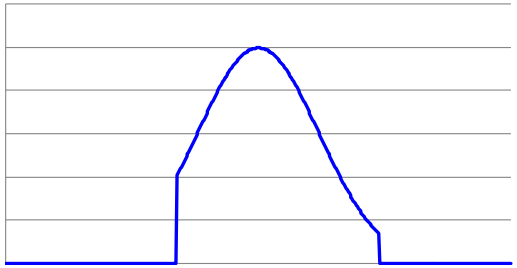
Normal



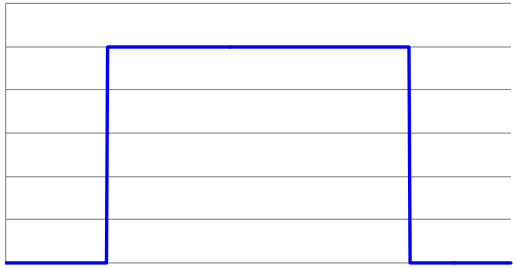
Exponential



Triangular



Truncated Normal



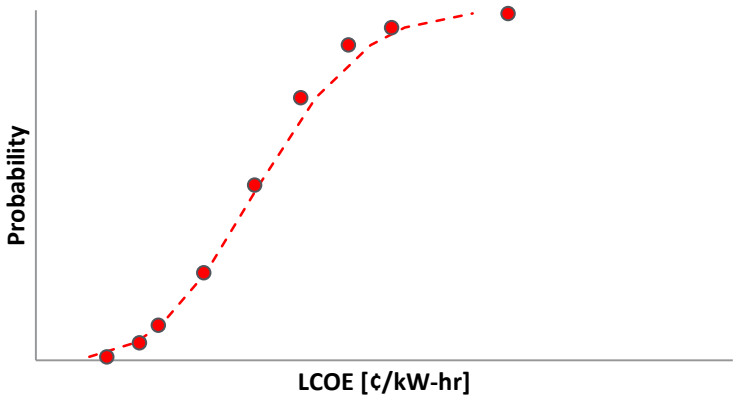
Uniform

Risk Assessment

- Risk is the consequence times the probability:

$$R = \sum_{t} \sum_{n} C(n,t) \Delta P(n)$$

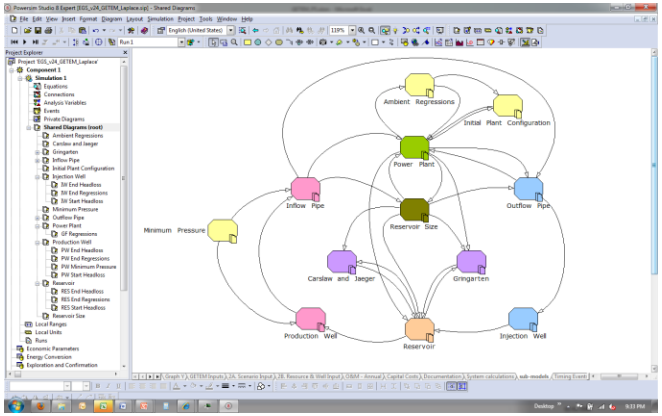
R = risk, C = consequence, P = probability, n = # of probability intervals, t = time



- Consequences can be defined in many different ways
- User defines PDF's and consequence
- Output is probabilistic
- Allows for answering 'inverse questions':
  - Given a set of uncertainties, what is the probability that you will hit your target?
  - What do we need to know better to have a XX% chance of reaching our target?

AOP Objectives

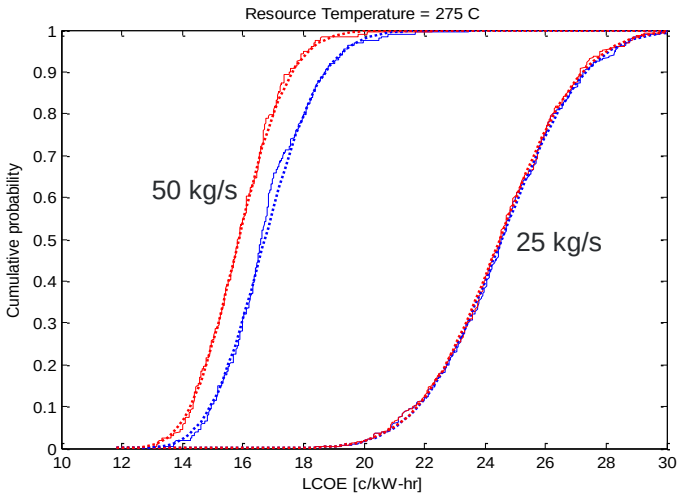
- The objective for FY15 is to continue the advancement and maturing of GT-Mod to support the DOE GTO in its work with regards to the Quadrennial Technology Review, the Geothermal Vision Study, and other needed analyses as directed. Development work will focus on additional functionality as needed to complete the various analyses as well as increasing the general usability and usefulness of GT-Mod to allow for broader adoption and application of the tool in out years.
- Complete validation analysis for ad hoc “what-if” analysis as defined by the program
- Complete analyses for the DOE GTO’s vision study as defined by the office



Screen shot of GT-Mod modeling platform.

Accomplishments, Results and Progress

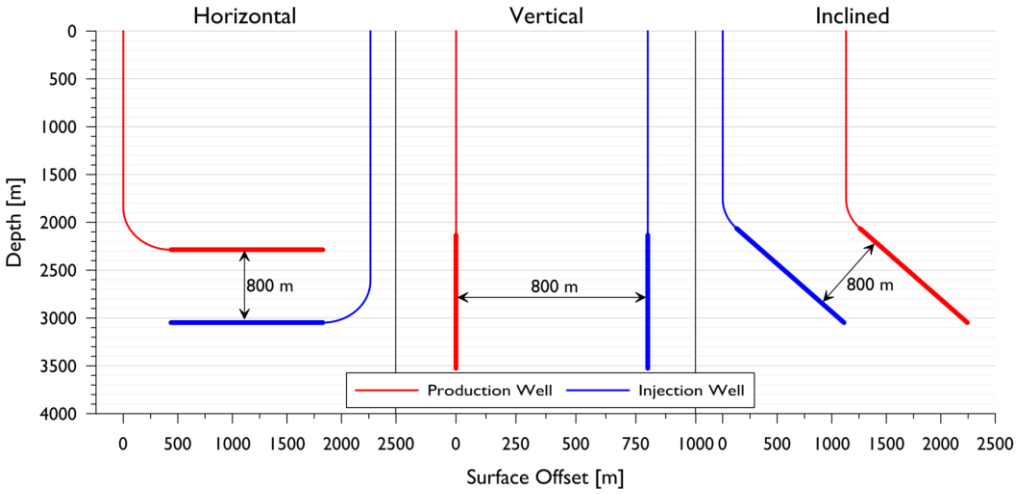
- Project has transitioned from development phase to analysis phase
- Developed and presented dimensionless parameter approach for reservoir performance simulation
- Developed Laplace Transform inversion for use in SD models
- Created lookup table interface that allows the model to use high resolution reservoir simulations
- Created stand-alone power plant model to be integrated later this year
- 10 conference presentations/proceedings, 1 journal article, 1 in review

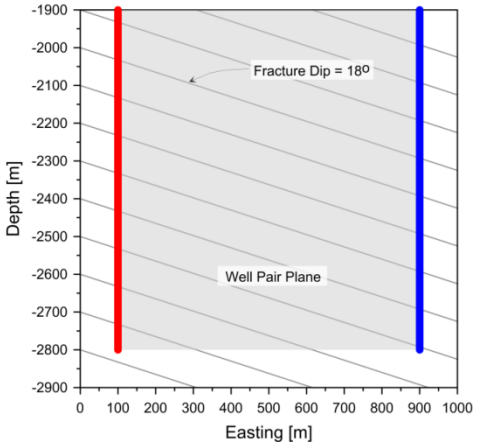


Influence of thermal drawdown solution method on uncertainty and risk for 50 and 25 kg/s flow rates at 275 °C. The red line is the Gringarten analytical solution and the blue line is the annual drawdown rate method.

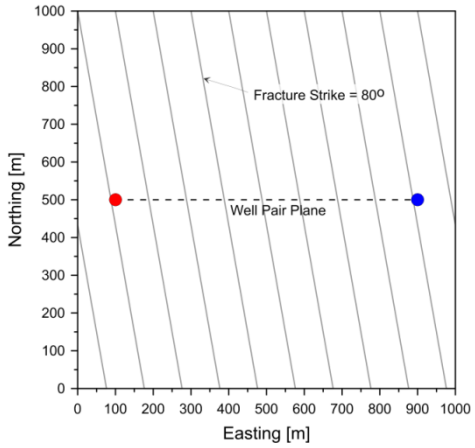
Comparing horizontal, inclined, and vertical well orientations

- Reservoir modeling with FEHM
- Fracture properties
  - Dip (5^o, 18^o, & 80^o)
  - Strike (80^o, 10^o)
- Pumping Rates (60, 90, 120, 150, 200 kg/s)
- Well Separation Distance (390, 600, 800 m)





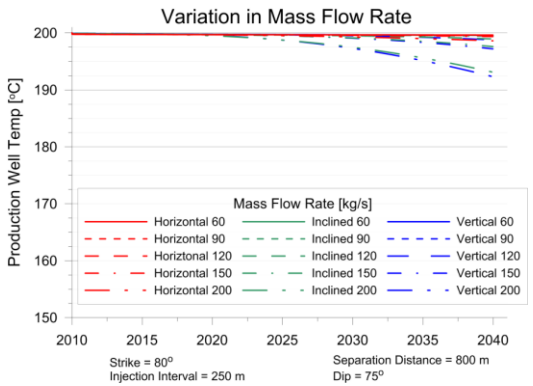
Dip Relative to Well-Pair Plane

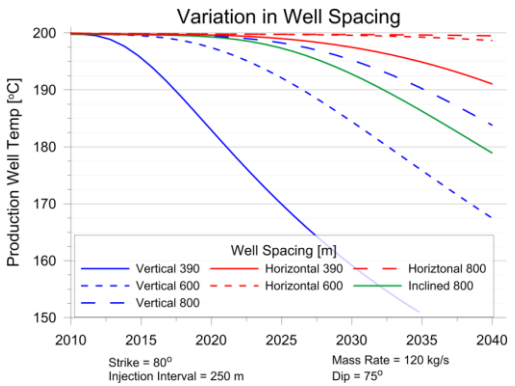


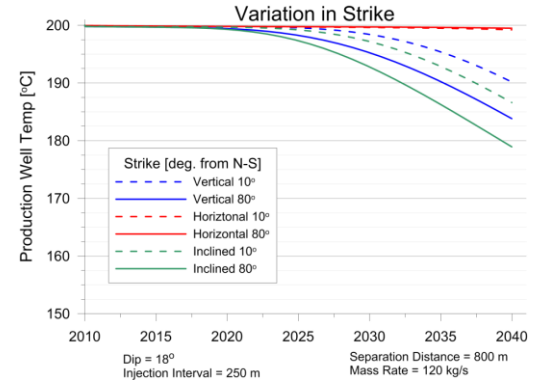
Strike Relative to Well-Pair Plane

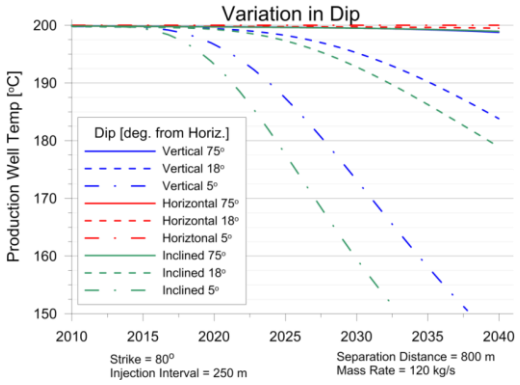
Accomplishments, Results and Progress

- Horizontal wells are economically equivalent to the other configurations (for scenarios tested)
- Because the thermal performance of horizontal wells is more consistent across the different scenario's, the economic risk is reduced
- Pumping requirements for horizontal wells may be higher in low, fracture-dip formations
- Results indicate that there may be an optimal relationship between fracture strike and dip and well orientation
- Stimulating the reservoir will help reduce pumping costs but not improve thermal performance









Future Directions

- Extend the focus of GT-Mod beyond EGS to examine deep direct use applications
  - Power plant module
  - Add economic calculations for LCOH
  - Add other comparison metrics (e.g. equivalent power, CO2 offset, etc.)
- For power plant module
  - Add ability to use different working fluids (currently isopentane only)
  - Add ability to optimize plant design
  - Expand to more complex systems (out years)
- Analysis
  - Revisit reservoir simulations for horizontal well analysis
  - Examine combined EGS and direct use systems
  - Support GTO in vision study analyses as needed

Mandatory Summary Slide

GT-Mod allows users to:

- Produce probabilistic output as a function of uncertainty
- Conduct probabilistic risk assessment to identify and prioritize technology development strategies
- Optimize system design and operation
- Answer ‘what if’ and inverse questions

Extending functionality to look at direct use in both standalone and co-generation systems

Main role is in support of the GTO for analyses as needed