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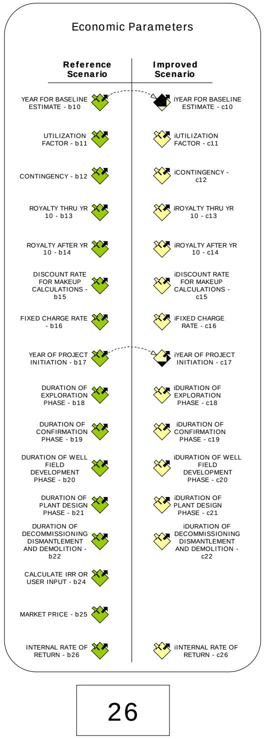

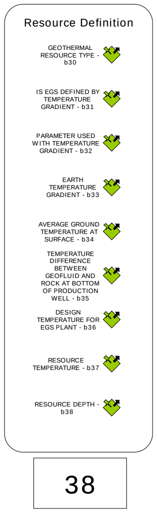

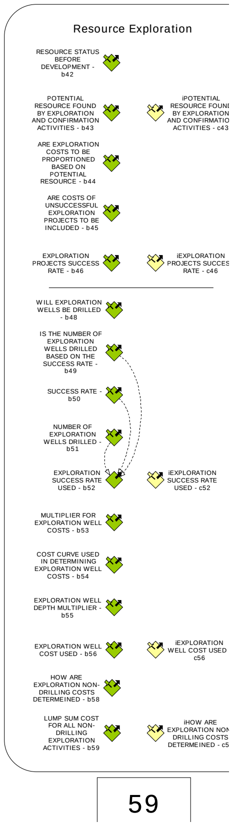

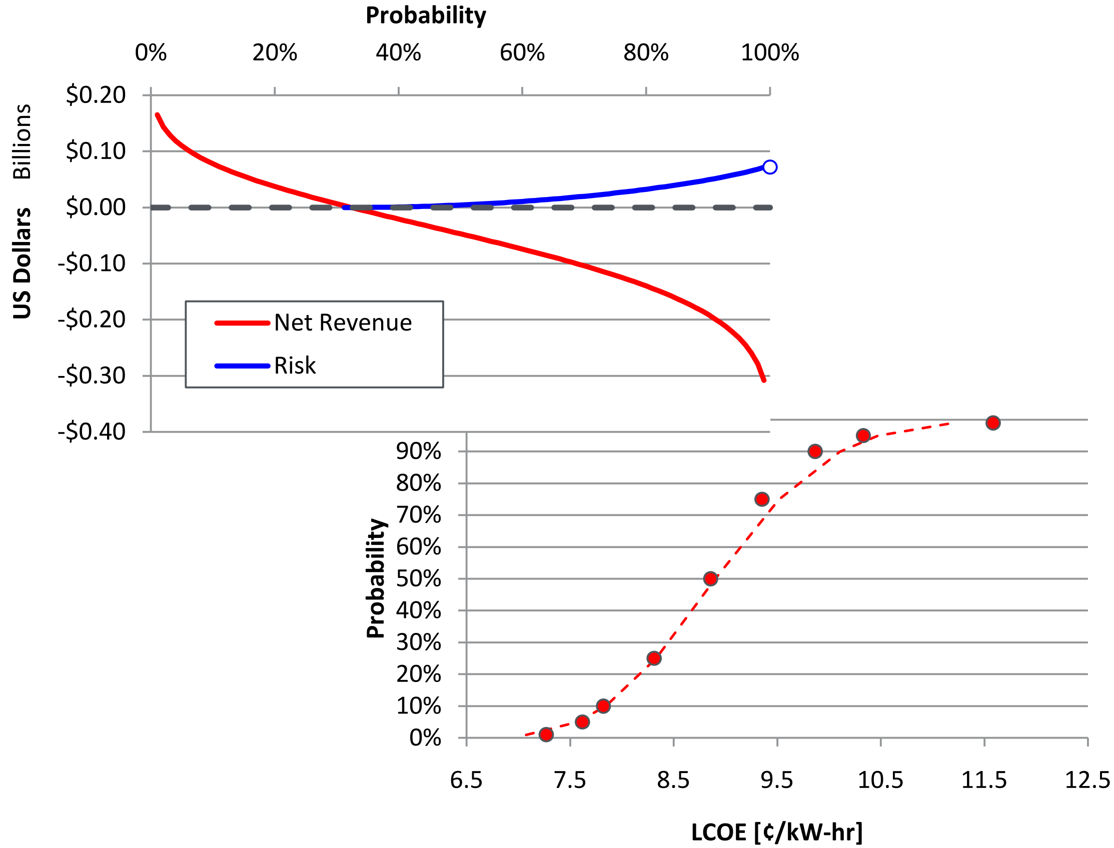

Systems Engineering Analysis

June 06, 2011

Thomas S Lowry

Sandia National Laboratories

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.

Overview

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- GT-Mod - a simulation and analysis tool for geothermal physical and economic performance assessment
  - Two Tasks:
    - Systems modeling
    - Stochastic reservoir simulations
  - Seamlessly connects physical performance and economic estimates
  - Quantitative Risk Assessment
    - Accounts for full range of uncertainties across any combination of inputs
  - Leverages ongoing work in reservoir modeling and economic analysis
- Support decision makers and analysts from DOE, Industry, other National Labs
  - Risk-based decision making
  - Identify key uncertainties to reduce risk

Overview

- Timeline
  - FY09 (July – Sept.): Demonstration Study
  - FY10: Year 1: Implementation
  - FY11: Year 2: Beta version (fully capable)
- Budget
  - FY09: $125,000, AOP
  - FY10: $500,000, AOP, $115k spent
  - FY11: $385k carryover / $350k spent, $400k due in May

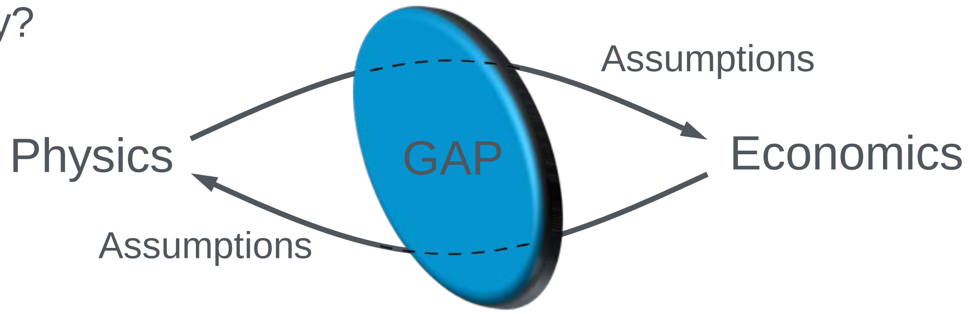
	Start	Finish	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Systems Model													
Alpha Version	2010	Feb-11											
Beta-1	Jan-11	May-11											
Beta-2	May-11	Dec-11											
Stochastic Simulations													
Homogeneous	2010	May-11											
Heterogeneous	May-11	Dec-11											

Carryover

FY11 Funding

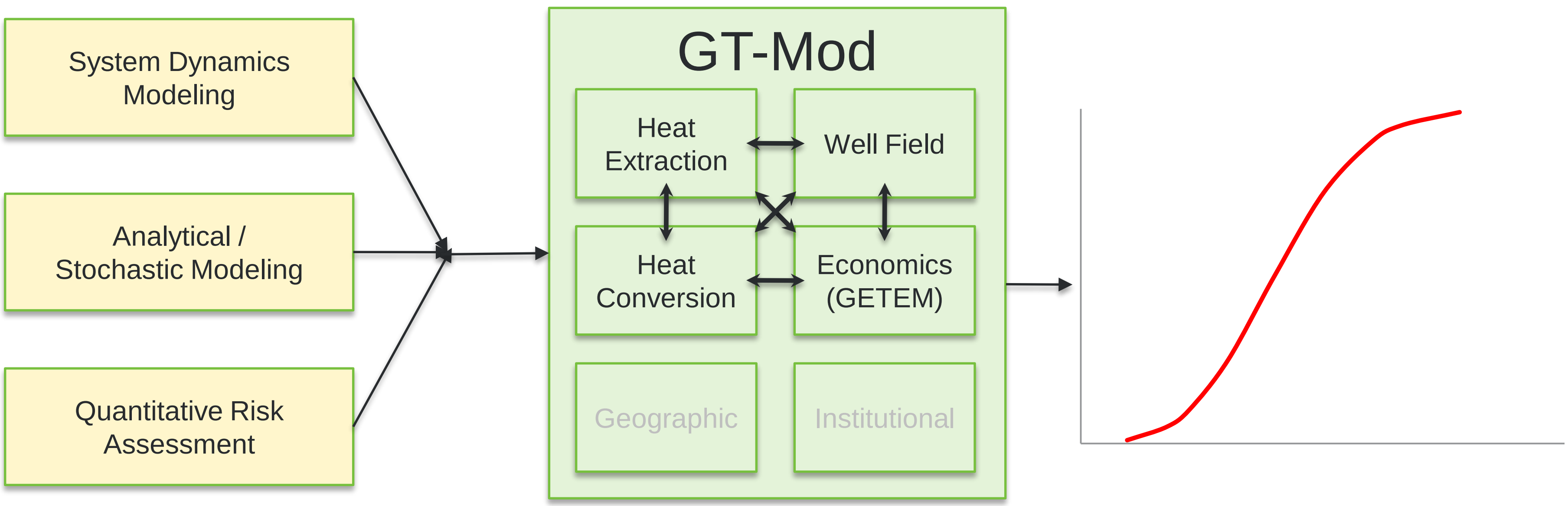
Relevance/Impact of Research

- Challenges
  - How to include 'realistic', physics based simulations in a system dynamics model
  - Connect physical performance with economic performance
  - How do we deal with uncertainty?
- Impacts
  - Increases decision certainty
  - Defines the 'solution space'
  - Turns information into insight
  - 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 for any metric of interest
  - Modular architecture can be easily extended and adapted to other problems or other analyses

Scientific/Technical Approach



Combine:

- System Dynamics Modeling
- Analytical and Stochastic Modeling
- Quantitative Risk Assessment

Scientific/Technical Approach

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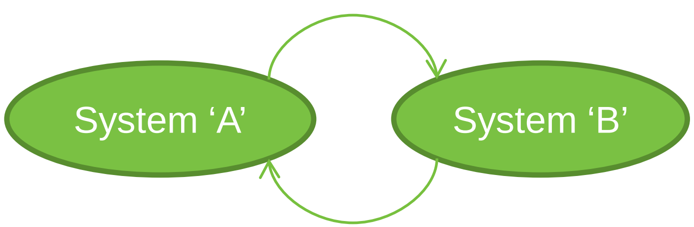
SYSTEM DYNAMICS

- SD captures the temporal dynamics between connected systems and sub-systems
- Temporal dynamics capture direct influences, as well as feedbacks and delays and are defined by 'causal loops' (pde's)
- SD is easily scalable to the spatial or temporal scale of interest
- Deployable to multiple users
- GT energy production is comprised of many, integrated causal loops, across a wide range of temporal and spatial scales

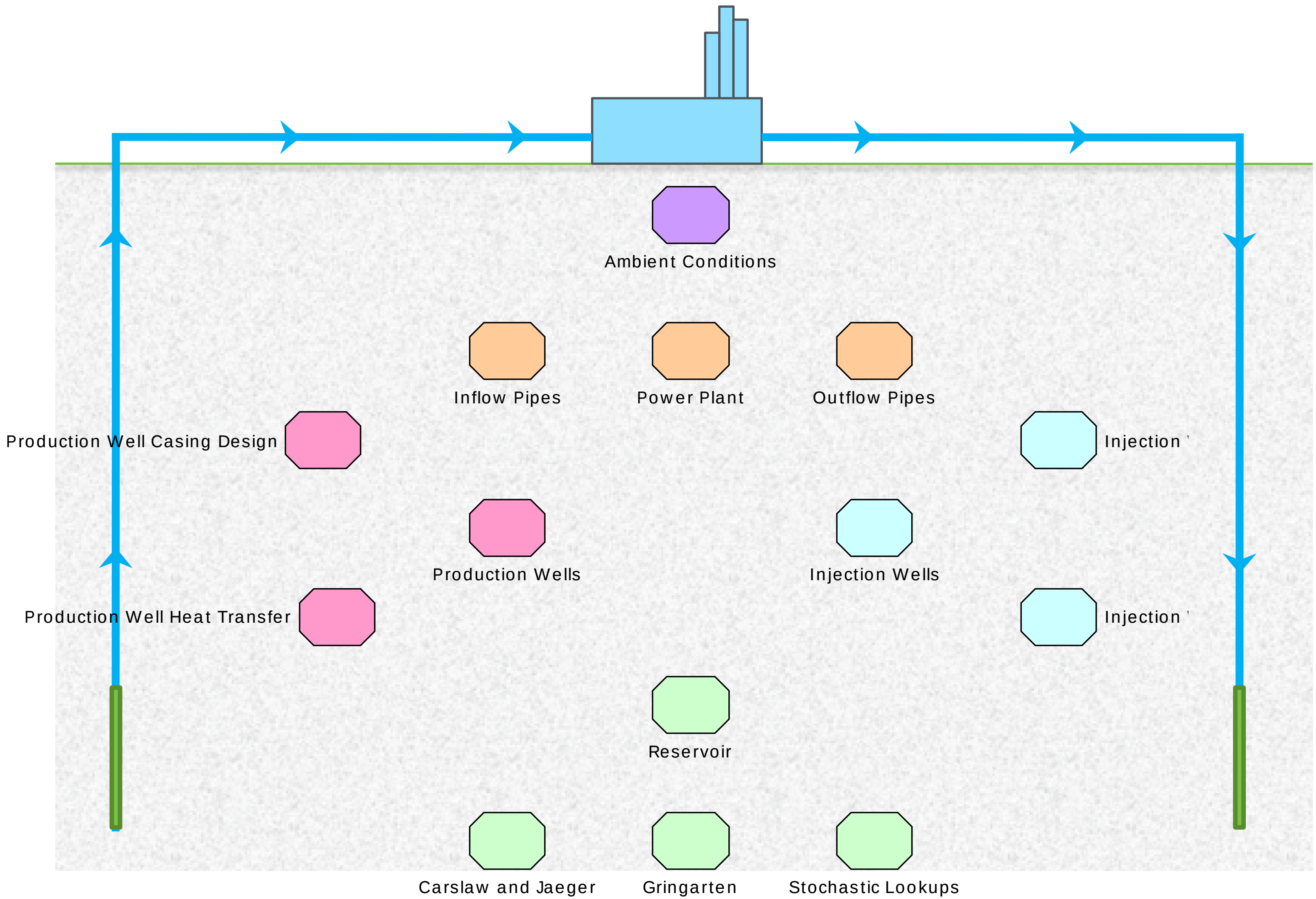


Schematic of a causal loop where the state of system 'A' is dependent on the state of system 'B', which in turn is dependent on the state of system 'A'

$$\frac{\partial A}{\partial t} = mB + n \qquad \frac{\partial B}{\partial t} = pA + q$$

Mathematically, a causal loop can be represented as a system of partial differential equations.

Scientific/Technical Approach



Scientific/Technical Approach

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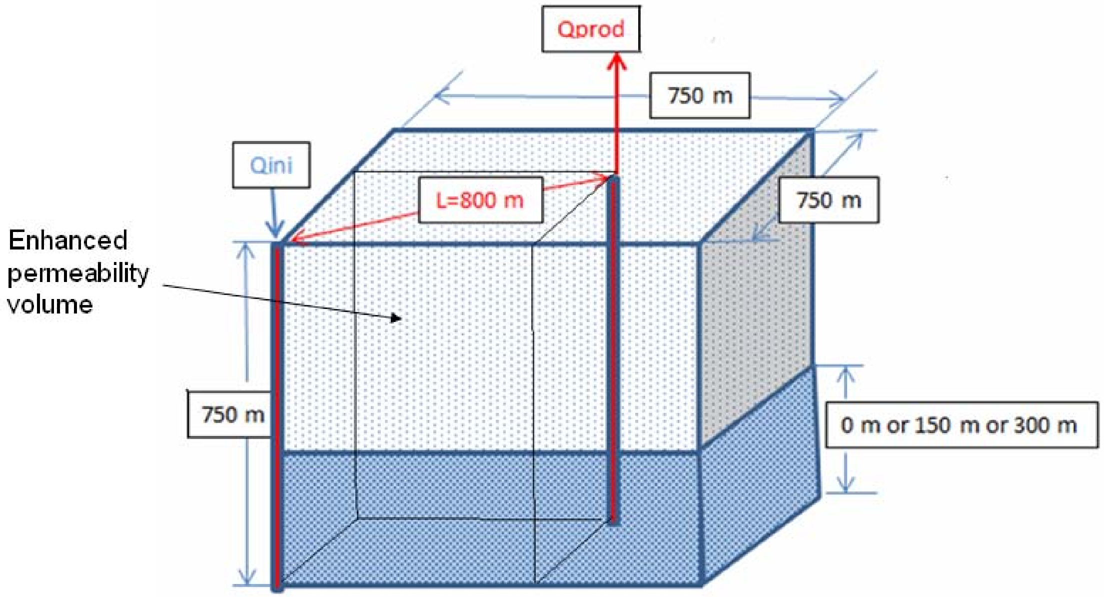
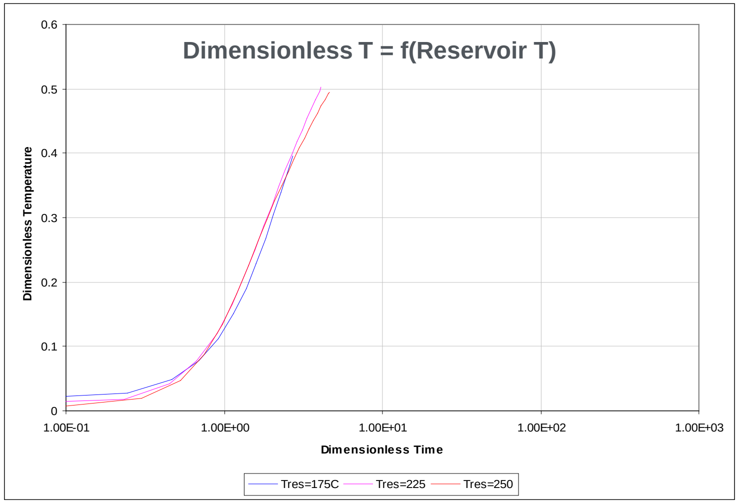


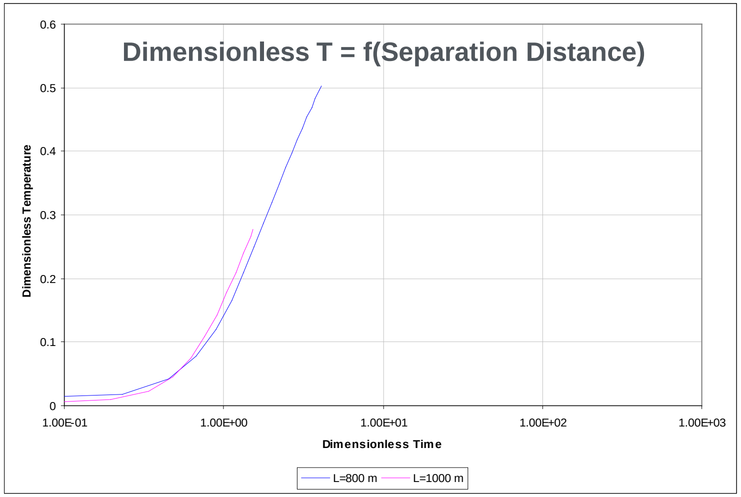


Dimensionless Temp

$$T_d = \frac{T_{res} - T}{T_{res} - T_{inj}}$$

Dimensionless Time

$$t_d = \frac{(\rho_w c_w)^2}{\rho_r c_r K_r} \left[\frac{Q}{LBN_{fr}}\right]^2 (t - t_{lag})$$



Stochastic Simulations

- Homogeneous and Heterogeneous
- Dimensionless Parameter Approach ala Gringarten
- Develop lookup tables for systems model

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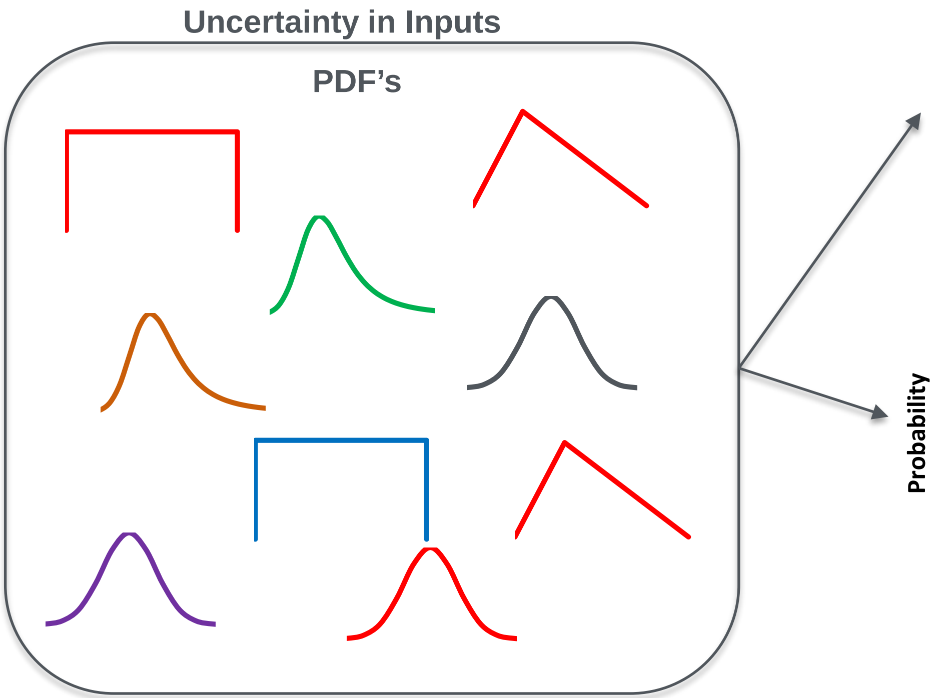
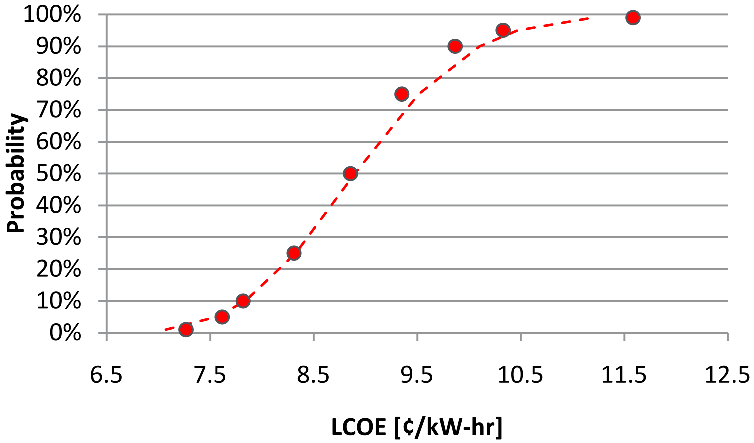
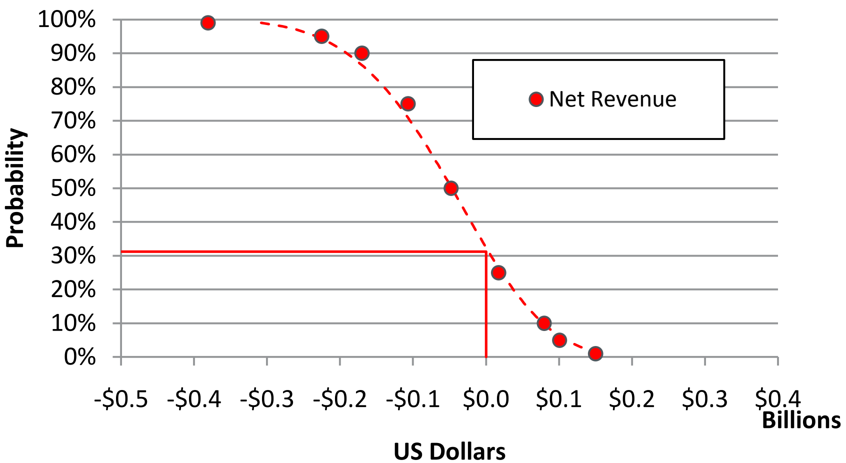
- Quantitative Risk Assessment
  - Risk = sum(consequence x probability)
  - Increases 'decision certainty'
  - Uncertainty = Risk







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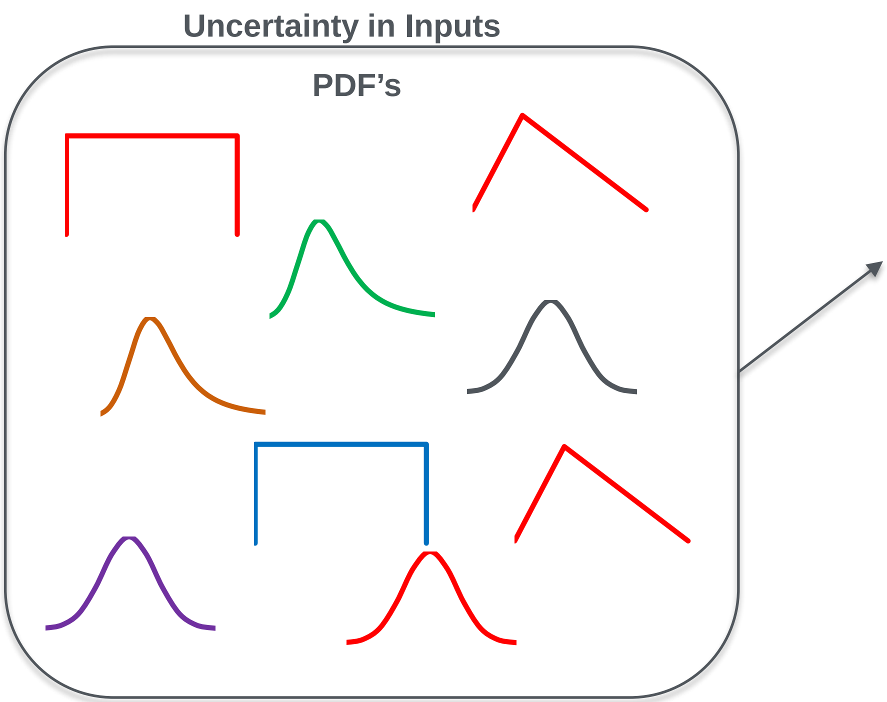

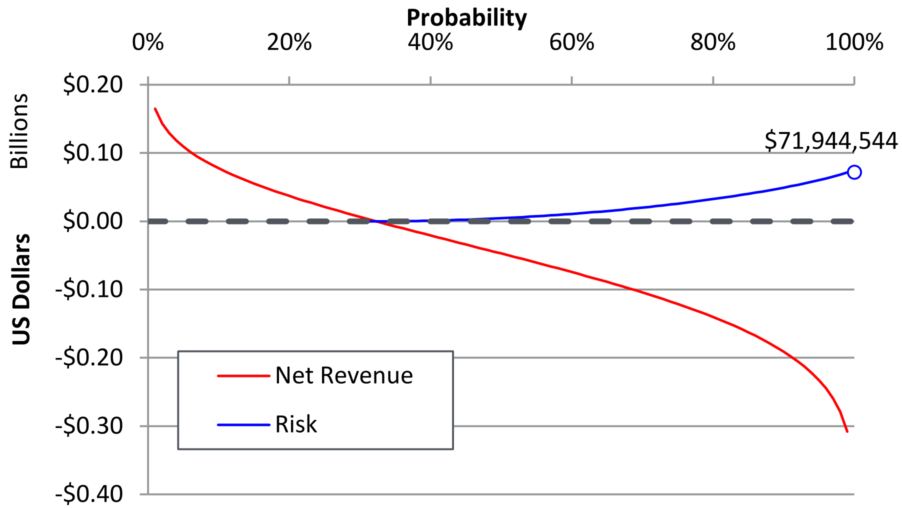

Scientific/Technical Approach

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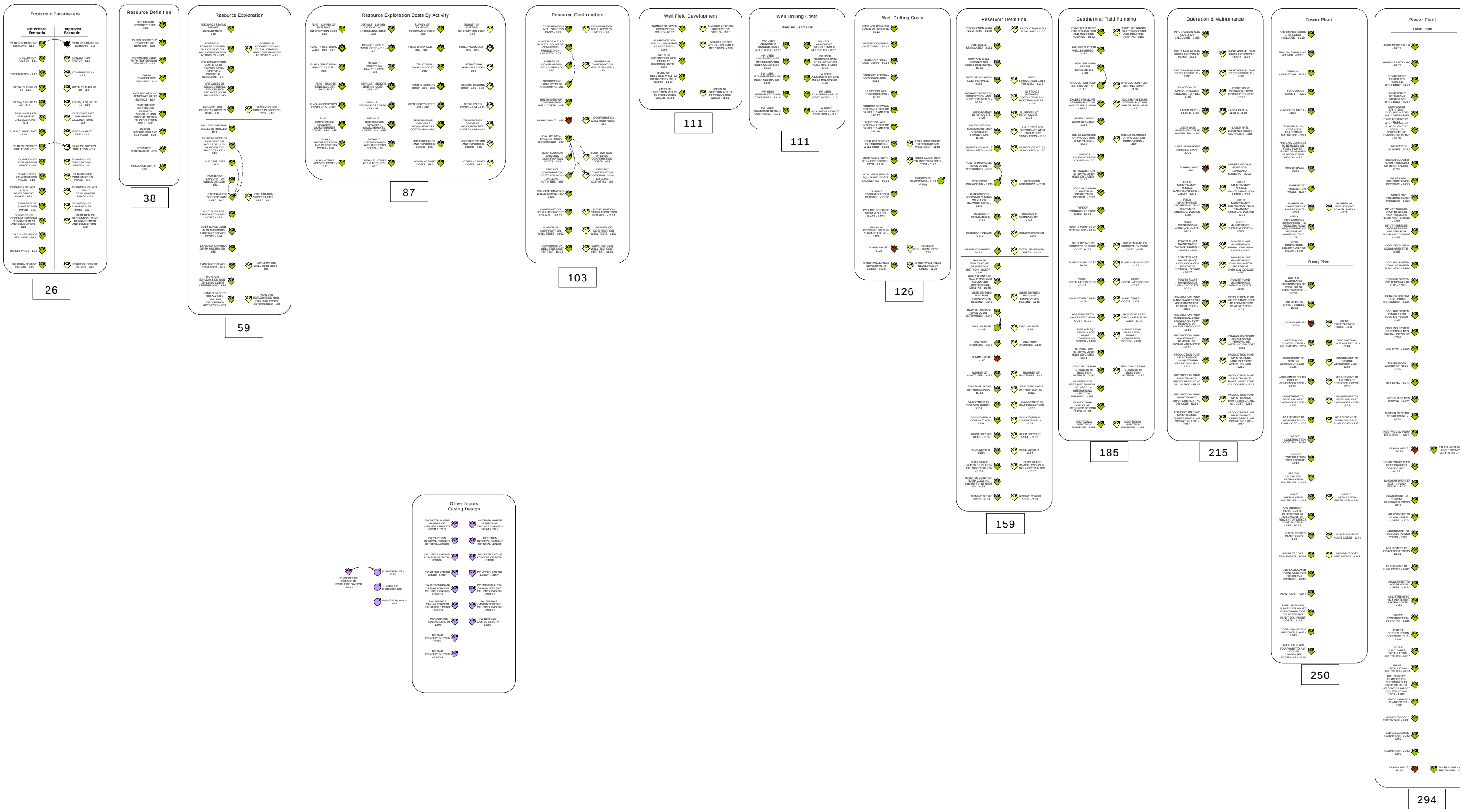
- Two-way Dynamic Connection with GETEM
  - Can use PDF input for any of the 300+ inputs to GETEM



Scientific/Technical Approach

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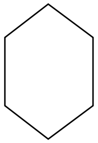
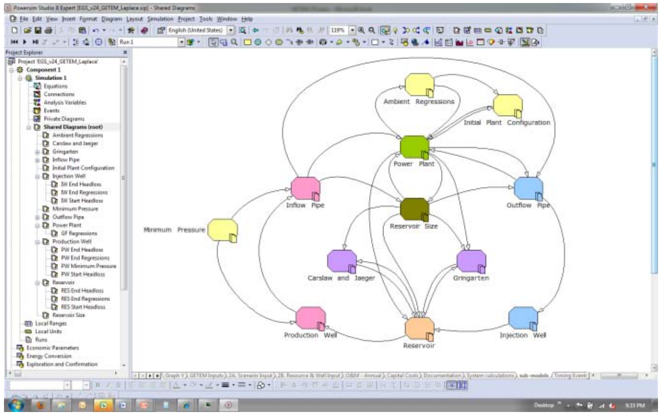
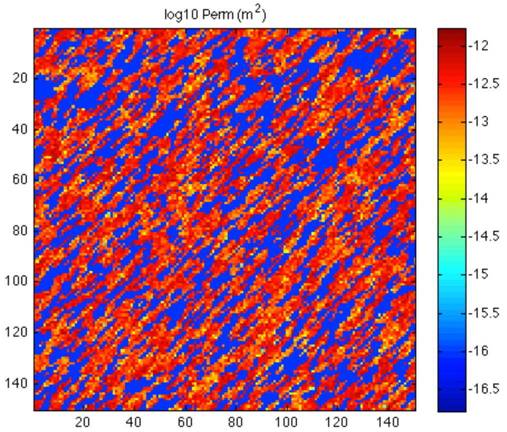


Accomplishments, Results and Progress





	Alpha	Beta-1	Beta-2
Completion Date	Jan. 31, 2011	Mar. 31, 2011	Sep. 30, 2011
Thermal Performance	1. Carslaw & Jaeger 2. Gringarten 3. Constant Drawdown	1. Carslaw & Jaeger 2. Gringarten 3. Constant Drawdown 4. Task 2 - Homogeneous	1. Carslaw & Jaeger 2. Gringarten 3. Constant Drawdown 4. Task 2 - Homogeneous 5. Task 2 - Heterogeneous
Well Dynamics	1. Single Diameter 2. Constant heat loss/gain	1. Multiple Casings 2. Constant heat loss/gain	1. Multiple Casings 2. Variable heat loss/gain 3. Pump Placement
Power Generation	1. 2nd Law Theory	1. 2nd law theory 2. Binary plant model	1. 2nd law theory 2. Binary plant model 3. Flash plant model
Economics	1-way static to GETEM	1-way dynamic to GETEM	2-way dynamic with GETEM
Interface	1. Physical Inputs 2. GETEM Inputs 3. Basic Outputs	1. Physical Inputs 2. GETEM Inputs 3. Basic Outputs 4. Basic GETEM Outputs	1. Physical Inputs 2. GETEM Inputs 3. Full Outputs 4. Full GETEM Outputs 5. Risk Analysis Outputs
Risk Analysis	None	Physical parameters	Physical and economic parameters

Presentations: Stanford 2010, GRC 2010, GRC 2011 (accepted)

Project Management/Coordination

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- Moving target
  - Project has been re-scoped several times to try and fit specific needs
  - Current scope (systems modeling for quantitative risk assessment) set's the project apart and fill's an important gap in the geothermal analysis toolset
- Delays in receiving funding created a man-power issue early in the project – FY10 carryover

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Carryover

FY11 Funding

Data Sharing

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- As a pure analysis tool, no physical data are being created
- It is anticipated that analysis results for specific problems will be published through internal reports, conference proceedings, and peer-reviewed journals

Collaborations

- Partners
  - No official co-funded partners
  - Integrating closely with INEL (GETEM) and NREL (economic analyses)
  - Will leverage 3-D simulation efforts at Sandia and INEL

Future Directions

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- Modeling:
  - Thermal performance: complete and add results from stochastic simulations
  - Well dynamics: add well pump dynamics
  - Power generation: add binary and flash power plant models at the component level (heat exchanger, turbine/generator, cooling, etc.)
  - Economics: quality check linkages with GETEM
  - Risk Assessment: add user interface for defining PDF’s and setting output
  - Interface: Design and complete GUI’s for ‘Basic’, ‘RA’, and GETEM
- <u>Using GT-Mod for analysis of specific problems</u>

Future Directions

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- Deployment
  - Beta-2 version deployed to DOE and others via a player license for Powersim
    - May prove problematic due to licensing change from Powersim
- Beyond FY11
  - Refinements to different components, esp. thermal performance & power generation
    - Geostatistical approaches
    - Finite analytic approaches
  - Maturing the interface and simulation capabilities
  - Inclusion of 3-D model results from other Labs
  - Adding additional functionality incl. geographic, institutional, power grid, etc.

Mandatory Summary Slide

- GT-Mod: A simulation and analysis tool for geothermal physical and economic performance assessment
- Combines:
  - System Dynamics Modeling
  - Analytical and Stochastic Modeling
  - Quantitative Risk Assessment to support decision making

Task	Item / Component	Model Progress*
1. System Dynamics Modeling	Reservoir model	90%
	Well dynamics	80%
	Power plant	50%
	Economics	90%
	Risk Assessment	75%
	Interface	40%
2. Stochastic Modeling	Homogeneous	90%
	Heterogeneous	40%

*Model progress does not necessarily reflect the relative time for completing a task