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Sandia National Laboratories

ENG 505 - ENERGY SURETY AND SYSTEMS

Geothermal Energy

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SANDIA REVIEW & APPROVAL NUMBER

Outline of Presentation

- Introductory comments
- Overview of geothermal energy, today and tomorrow
- Sandia activities
- Analyses to illustrate and understand complexity
- Summary

Douglas Blankenship

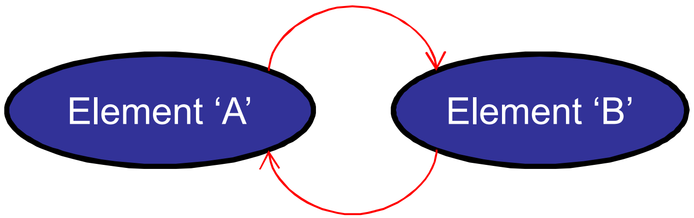
- MS Geological Engineering
- 30+ years making, monitoring, and analyzing underground excavations – 12 years at Sandia
- Dry and solution mined storage and drilling for mineral / O&G / geothermal energy
- Manager of the Geothermal Research Department – responsible for numerous projects focused on development of engineering of geothermal systems with a general focus on the the drilling and monitoring in harsh environments

Thomas Lowry

- Ph.D. Environmental/Civil Engineering - Modeling of natural flow and transport systems
- PMTS – Earth Systems Analysis Department (6926)
- Integrated modeling of water-energy-climate systems
  - Geothermal systems modeling for uncertainty analysis and risk assessment (DOE)
  - Hydro-Power Optimization (DOE)
  - Water resource infrastructure model (NZ)
  - Hydrogeologic water resource assessment for SE New Mexico

Recall: What is a Complex System?

- A **complex system** is a system composed of interacting elements that as a whole exhibit one or more properties (behavior among the possible properties) not obvious from the properties of the individual parts
- Common Attributes
  - Multiple interacting phenomena
  - Heterogeneous element
  - Non-linear dynamics and effects
  - Adaptive behavior
  - Elements with memory
  - Large network of elements or nested complexity



Schematic of interacting elements where the state of element ‘A’ is dependent on the state of element ‘B’, which in turn is dependent on the state of element ‘A’

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

Mathematically, a complex system can be represented as a set of partial differential equations. The difficulty lies in defining the nature of the differential relationships.

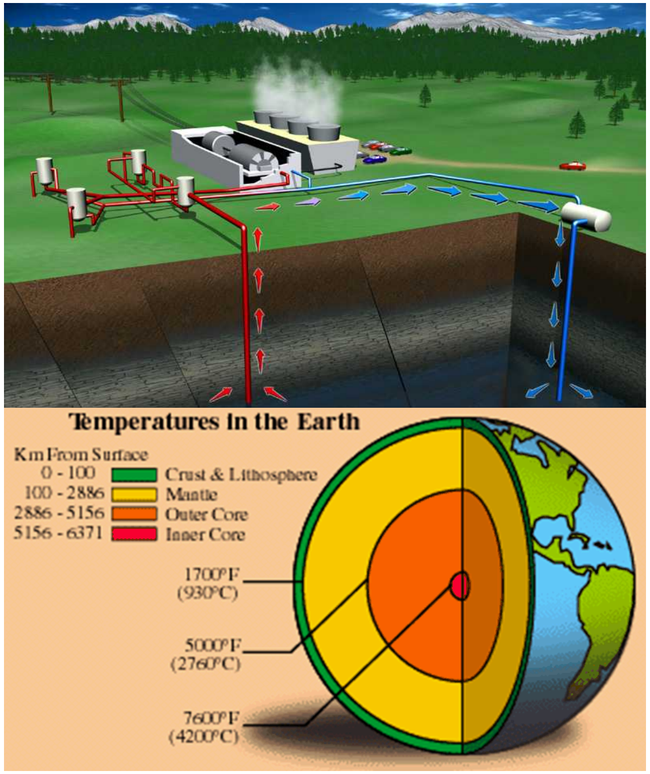
Slide 4

TSL1 Are these your words or boiler plate for the class?

If we can change it, we could add the graphics to illustrate this.
Thomas Lowry, 3/20/2012

Exploiting geothermal energy is simple in principle, but the reality is different

- The heat resource is ubiquitous but the exploitable reserves depend on many interrelated and complex factors
  - Depth, temperature, geology, stress, mechanical properties, local structure, chemistry, fluids, permeability, ….
- Resource is largely hidden
  - Resource definition and viability depend on factors that are not easily measured and not completely understood
- Boundary conditions are not well constrained and evolve over time
  - For example, as the resource is exploited stress states evolve which can effect fluid flow, which can affect geochemical interactions
- Understanding interdependencies of critical parameters is vital to moving geothermal out of its niche status
  - Discussion of such efforts later in the presentation



Courtesy: Geothermal Education Office

Using the Earth's heat for electricity production, direct use applications, and as a heat exchange medium for geothermal heat pumps

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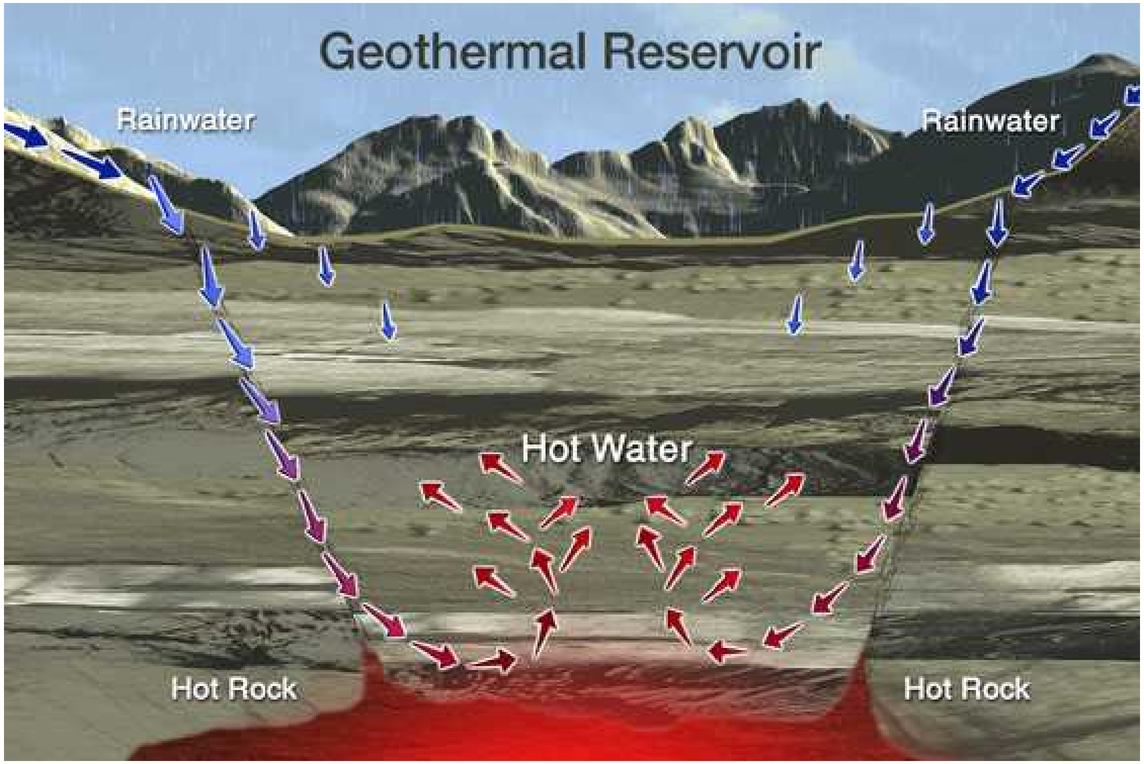
Geothermal Reservoir Requirements

- Temperatures
  - Greater than 350 C to "warm"
    - Temperatures largely dictate use
      - Power generation to direct use
- Permeability
  - Measure of fluid transmission ability of the rock
    - Orders of magnitude variability
      - Tight to open
- Fluid Availability

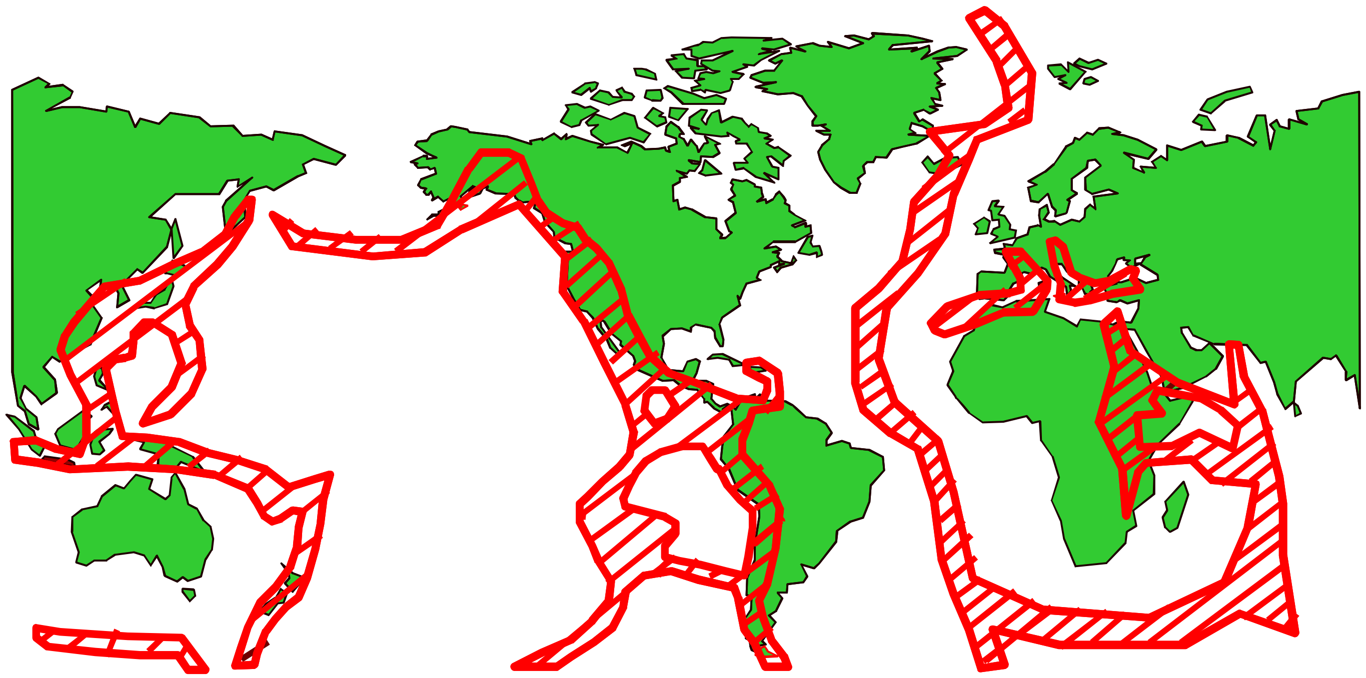
Hydrothermal (current) → Enhanced Geothermal Systems (future)

Hydrothermal Geothermal Systems

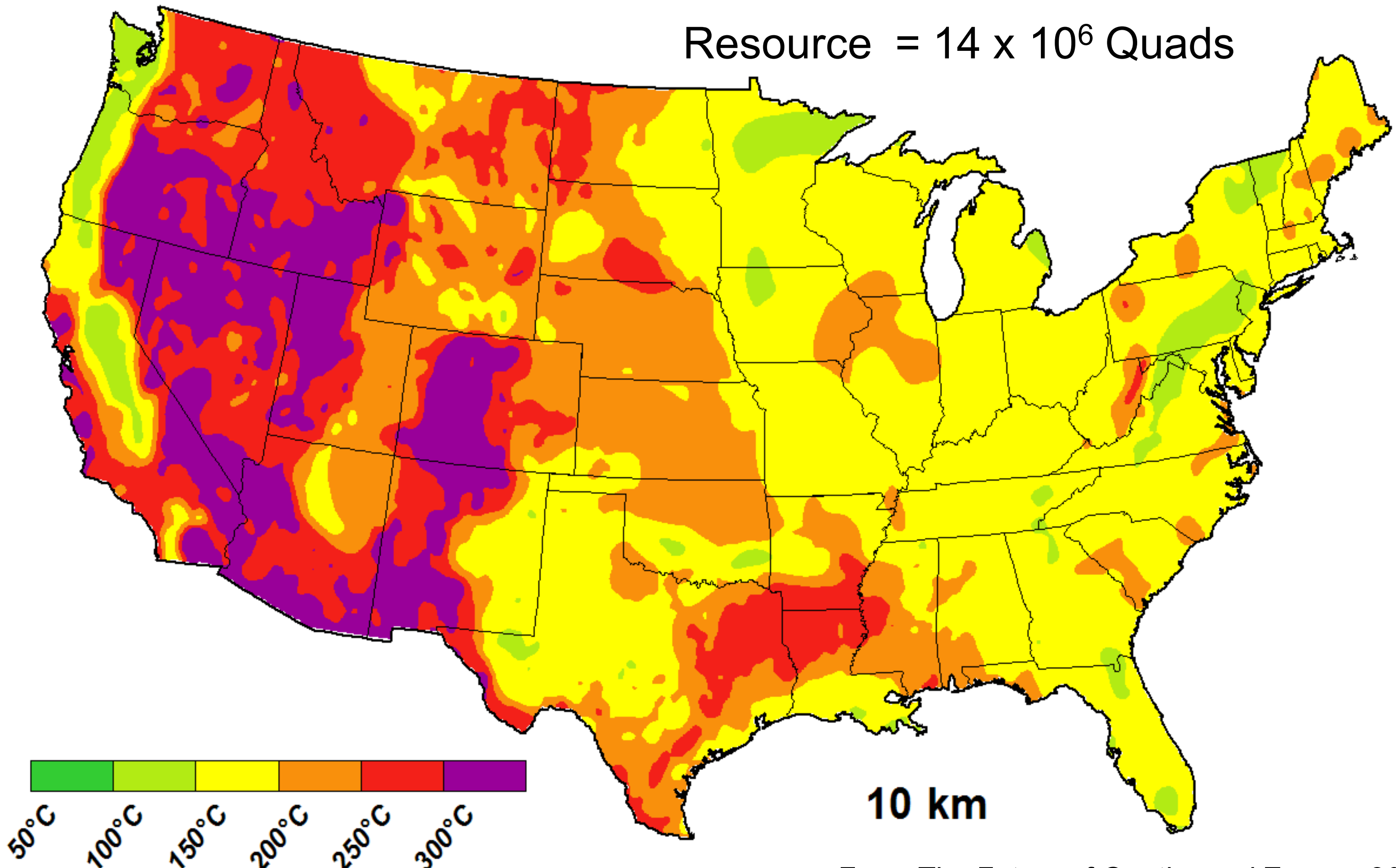


Hydrothermal Geothermal resources are found where geological activity has brought hot rock near the surface. When hot water and steam is trapped under a layer of low permeability rock, it forms a geothermal reservoir.

Worldwide Hydrothermal Electric Potential



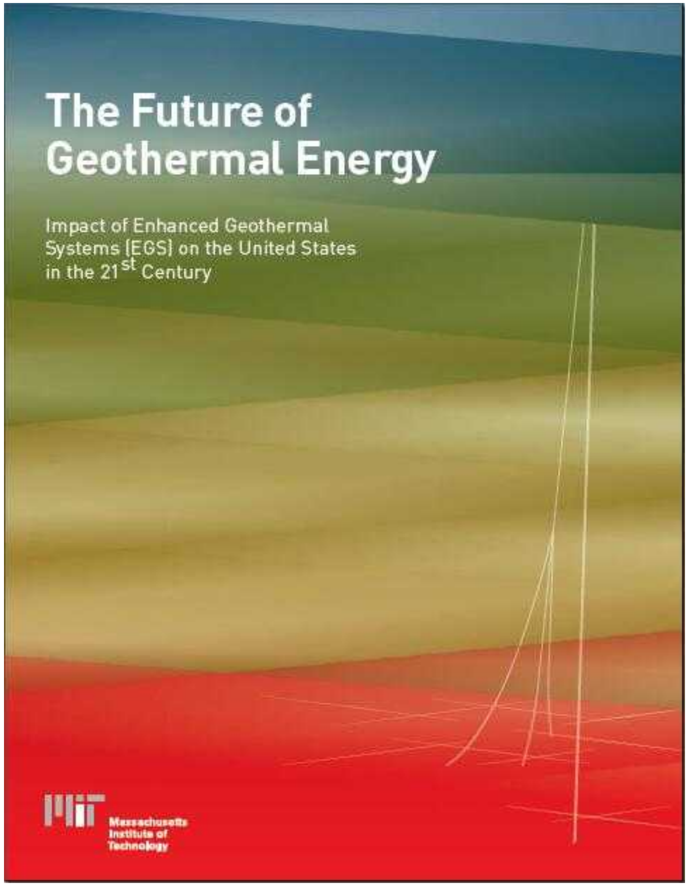
Geothermal Heat Resource in the United States



From *The Future of Geothermal Energy, 2006*

Current Focus on EGS

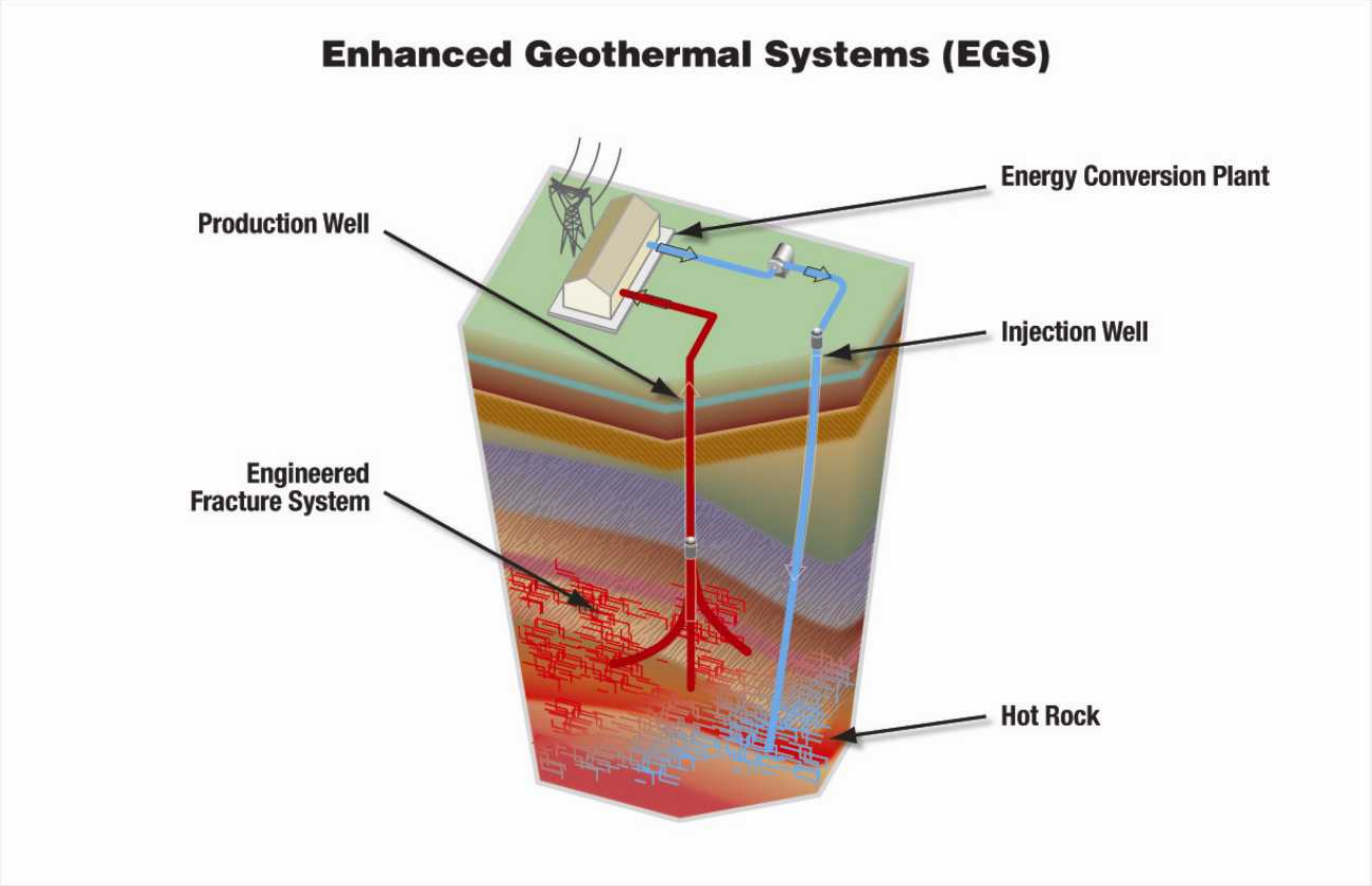
Study of Enhanced Geothermal Systems (EGS) by MIT-Led Panel of Experts



Key Findings/Recommendations

- Extractable geothermal resource exceeds 2000 times the annual energy consumption of the United States
- EGS are versatile, modular, and scalable from 1 to 50 MWe unit sizes
- Technical issues are surmountable – no showstoppers
- Cumulative EGS capacity of 100,000 MWe can be achieved in the United States within 50 years

EGS System Components

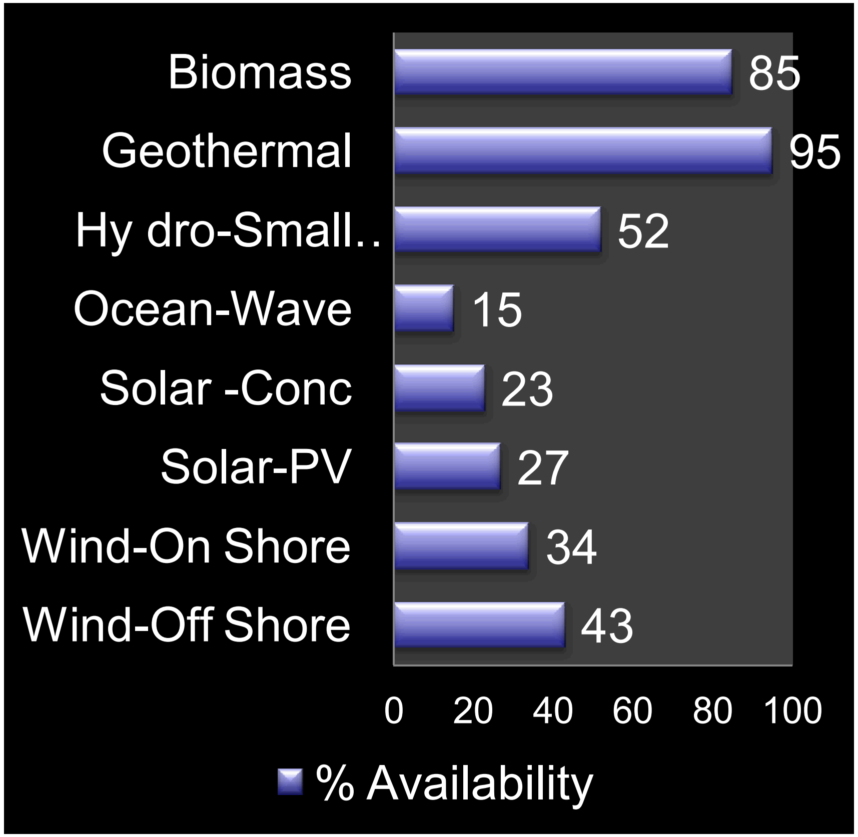


Geothermal Resources(USGS Fact Sheet 2008-3062)

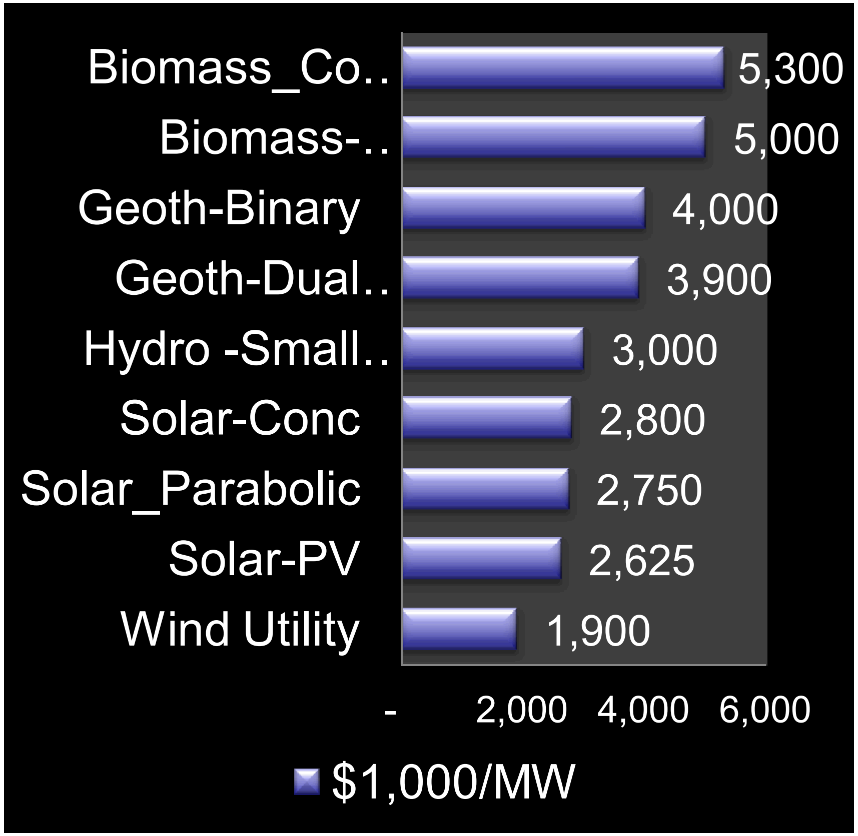
State	Systems	Identified Mean (MWe)	Undiscovered Mean (MWe)	EGS Mean(MWe)
Alaska	53	677	1,788	NA
Arizona	2	26	1,043	54,700
California	45	5,404	11,340	48,100
Colorado	4	30	1,105	52,600
Hawaii	1	181	2,435	NA
Idaho	36	333	1,872	67,900
Montana	7	59	771	16,900
Nevada	56	1,391	4,364	102,800
New Mexico	7	170	1,498	55,700
Oregon	29	540	1,893	62,400
Utah	6	184	1,464	47,200
Washington	1	23	300	6,500
Wyoming	1	39	174	3,000
Total	248	9,057	30,033	517,800

Selected Renewable Energy Technologies

Capacity Factors

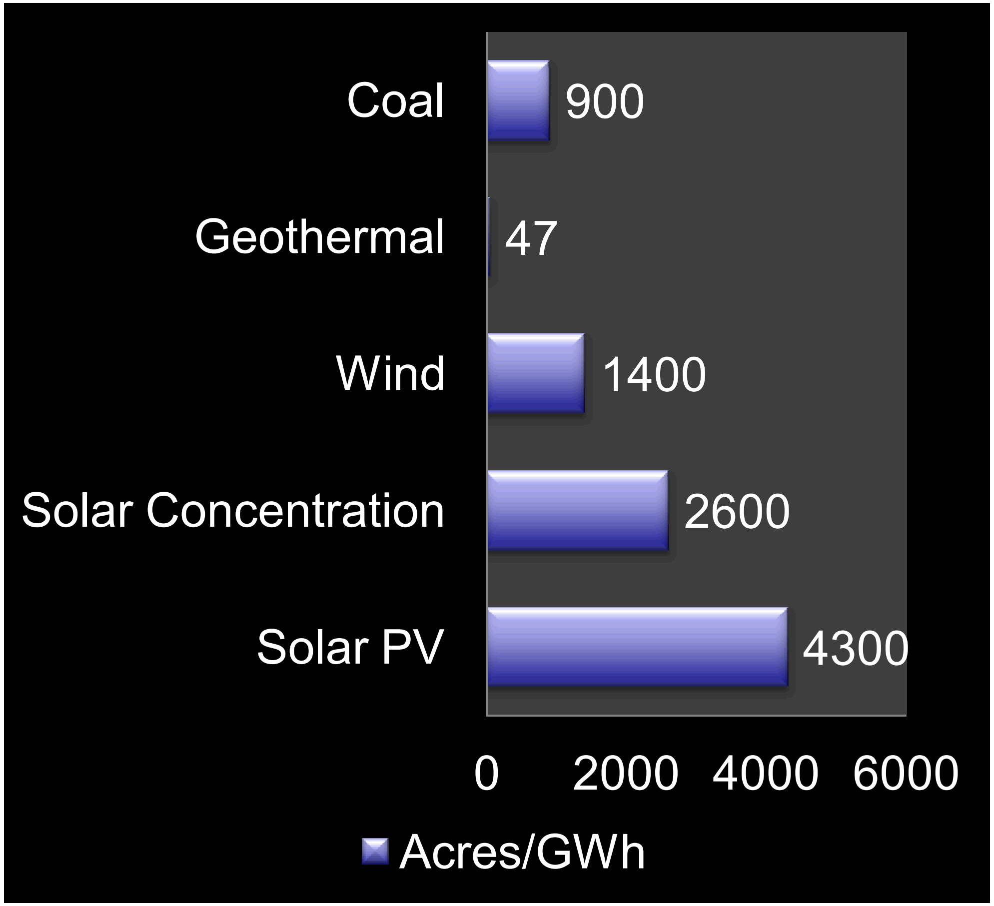


Investment Cost



Courtesy of Kermit Witherbee, NREL

Land Use by Energy Technology



Courtesy of Kermit Witherbee, NREL

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Sandia Activities

- Geothermal well construction
  - Historical Roots
  - Broad technology areas
    - High-temperature electronics
    - Rock reduction technologies
    - Diagnostics
    - Wellbore integrity and lost circulation
    - Drilling dynamics mod/sim
    - Vibration mitigation
    - Downhole telemetry
- Energetics for reservoir stimulation
- Reservoir Analyses
- Systems Engineering

Apply capability and technology to other industries and agencies

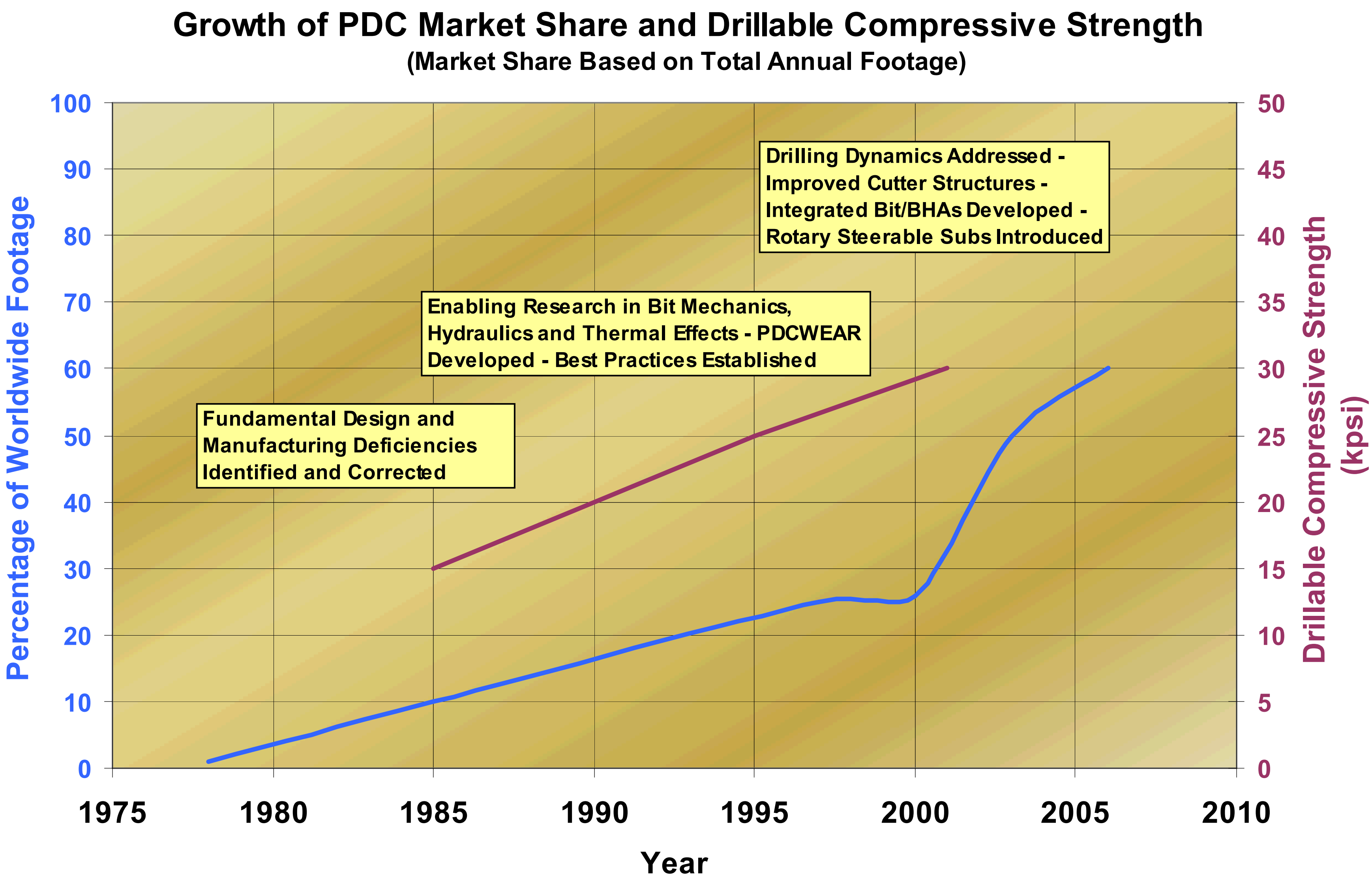
Significant Sandia Geothermal Accomplishments – Technology and Products to Industry

- Polycrystalline diamond compact (PDC) bits
- High-temperature electronics
- Diagnostics-while-drilling
- LEAMS
- Active vibration control
- Slimhole drilling
- Acoustic telemetry
- Rolling float meters
- Insulated drill pipe
- Cavitating mud jets
- Drilling dynamics simulator
- Well cost models
- …

Polycrystalline Diamond Compact (PDC) Bits

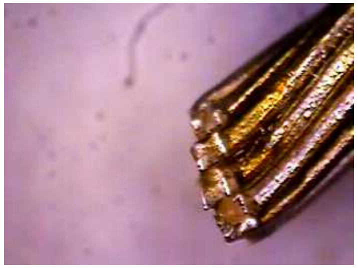
- Fundamental work
  - FEM analyses
  - Bonding
  - Cutter tests
  - Bit design / analysis
  - Lab / field testing
  - CRADAs
- Catalyzed a major industry
- PDC bits now a ~ $1.5 billion industry
- PDC bits save industry $ billions annually
- Over 60% of world footage today

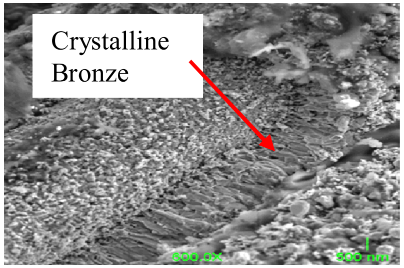
DOE Energy 100 Award for *Synthetic Diamond Drill Bits*



Growth of PDC Market Share and Drillable Compressive Strength
(Market Share Based on Total Annual Footage)
Percentage of Worldwide Footage
Drillable Compressive Strength (kpsi)
Year
100
90
80
70
60
50
40
30
20
10
0
50
45
40
35
30
25
20
15
10
5
0
1975
1980
1985
1990
1995
2000
2005
2010
Drilling Dynamics Addressed - Improved Cutter Structures - Integrated Bit/BHAs Developed - Rotary Steerable Subs Introduced
Enabling Research in Bit Mechanics, Hydraulics and Thermal Effects - PDCWEAR Developed - Best Practices Established
Fundamental Design and Manufacturing Deficiencies Identified and Corrected

High-Temperature Electronics





- Includes components, tools, seals, batteries, fiber, …
- The enabling technology
  - High Temperature = High Reliability
- De facto "UL Labs" for high-temperature components
  - Work with almost all manufacturers
- Analyze failure and provide solutions
  - Exploit capabilities from weapons programs
- Develop tools and fabrication methods
  - Prototypes supplied to industry
- Broad application
  - Geothermal, aerospace, auto, O&G, PV, …
- Long-term testing
- Extensive interactions w/ industry motivate work activities

Current Sandia Geothermal Program Areas

- Downhole seismic monitoring
- Fluid sampler (> 350 °C)
- High temperature component research (solders, ceramic boards, MCMs, optical fiber)
- Flow though fractured media
- Advanced bit demonstrations
- Downhole motor development
- Controlled propellant stimulation methods
- Emerging technologies
- Best practice sharing
- Rotational seismometer
- Expandable casing
- High temperature hammers
- Televiewer operations
- Self consuming downhole tools
- New tool sealing methods
- MWD support
- Systems engineering and analysis (systems dynamics approach)
- Field demonstration support
- Technical monitoring for DOE HQ
- International program support

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Uncertainty on Top of Uncertainty

"*To summarize, the economics of climate change* ***consists of a very long chain of tenuous inferences fraught with big uncertainties in every link****:* ***beginning with*** *unknown base-case GHG emissions; then* ***compounded by*** *big uncertainties about how available policies and policy levers will transfer into actual GHG emissions;* ***compounded by*** *big uncertainties about how GHG flow emissions accumulate via the carbon cycle into GHG stock concentrations;* ***compounded by*** *big uncertainties about how and when GHG stock concentrations translate into global average temperature changes;* ***compounded by*** *big uncertainties about how global average temperature changes decompose into specific changes in regional weather patterns;* ***compounded by*** *big uncertainties about how adaptations to, and mitigations of, climate-change damages at a regional level are translated into regional utility changes via an appropriate damages function;* ***compounded by*** *big uncertainties about how future regional utility changes are aggregated into a worldwide utility function and what should be its overall degree of risk aversion;* ***compounded by*** *big uncertainties about what discount rate should be used to convert everything into expected-present-discounted values. The result of this lengthy cascading of big uncertainties is a reduced form of* ***truly extraordinary uncertainty*** *about the aggregate welfare impacts of catastrophic climate change, which mathematically is represented by a PDF* [probability density function] *that is spread out and heavy with probability in the tails*."

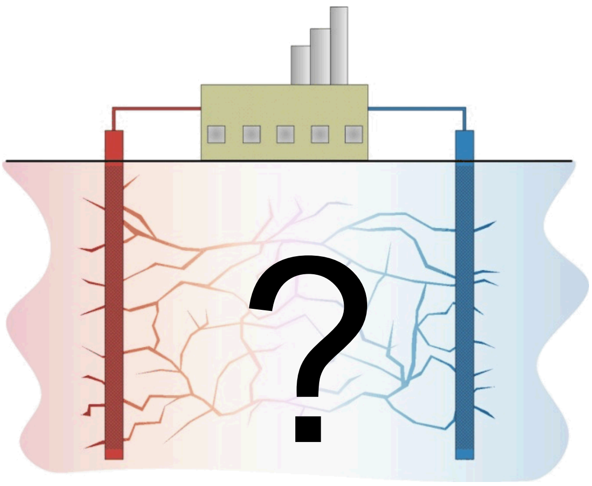
Weitzman, M.L. (2011), "Fat-Tailed Uncertainty in the Economics of Catastrophic Climate Change", Review of Environmental Economics and Policy, **5**(2), 275-292pp

Overview

- A new tactic for geothermal evaluation and analysis
  - We must think probabilistically: a single answer is meaningless
    - "The LCOE is 15 ¢/kW-hr" vs.
    - "There is a 40% probability that the LCOE is 15 ¢/kW-hr or less"
  - We must be able to put into context the true risk as a function of uncertainty
    - What does it mean when we say there is a 40% probability?
- GT-Mod: A full geothermal energy simulation tool, *because how you get there matters*
- Example analysis focused on a specific area of uncertainty

Sources of Uncertainty

- Physical Setting
  - Temperature at depth, rock type and characteristics, etc.
  - Can be reduced through field site exploration (and $$)
- Geologic Performance
  - Effectiveness of stimulation, thermal performance, water losses, etc.
  - Can be 'somewhat' reduced through field site exploration (and $$)
- Plant Performance
  - Conversion of heat to electricity
  - Most certain for a given set of inputs
- Economic Future
  - Material & labor costs, electricity sales price, discount rate, etc.
  - Cannot be reduced
- Regulatory Future
  - Tax and market incentives, environmental controls, etc.
  - Cannot be reduced

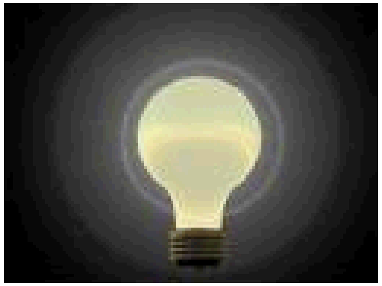


Balancing Tradeoffs

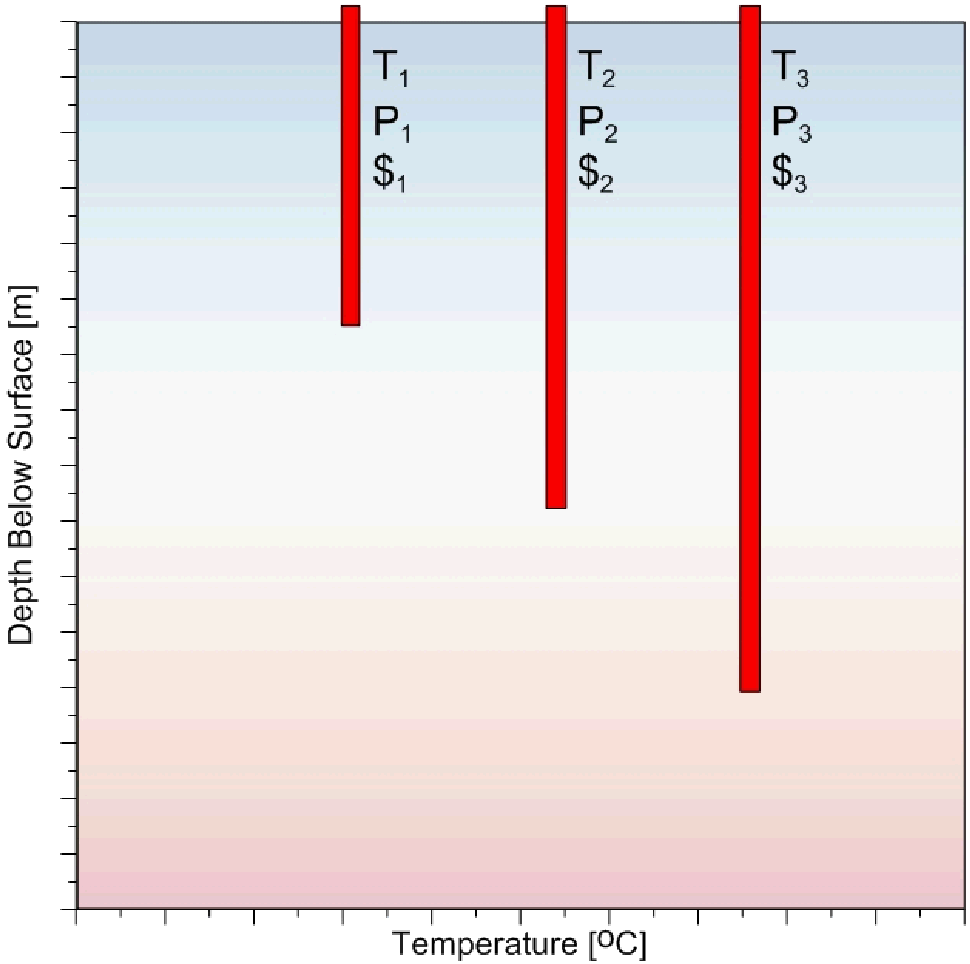
To Turn Information into Insight

- Goal is informed decision-making
- Ground decision process in best available science
- Create a common basis for decision-making

2002								
JAN	34880	---	7.1	35170	0	1630	0	
FEB	30580	---	6.5	29140	0	224	0	
MAR	43210	---	318	35340	3100	478	0	
APR	59010	6720	0.9	46680	4010	121	0	
MAY	75750	7000	284	62450	4260	424	0	
JUN	74340	6680	71	59130	4160	248	12	
JUL	58800	5150	16	45970	3510	90	0	
AUG	56160	4690	2	45960	3370	437	0	
SEP	35910	4120	2.8	29680	2350	2610	69	
OCT	23180	3370	4.2	18540	1300	619	6.7	
NOV	21880	---	2.8	20510	106	1170	0	
DEC	26180	---	1.4	25740	0	1900	0	
total	539880	37730	716.7	454310	26166	9951	87.7	
2003								
JAN	29080	---	2.2	26550	0	1830	0	
FEB	27660	---	2.5	24660	789	1380	0	
MAR	37510	4960	5.3	28940	2610	3590	0	
APR	55730	4900	6.8	42770	3830	9400	0	
MAY	69270	4550	142	57920	3380	5300	24	
JUN	61830	4840	508	47000	3920	560	130	
JUL	61710	4670	434	46360	3650	19	34	
AUG	48220	4040	665	38230	2340	898	103	
SEP	29500	4130	262	21510	2500	1750	44	
OCT	23840	2980	261	17720	1540	9210	0	
NOV	26950	223	42	24810	136	377	0	
DEC	36450	0	3.7	33370	0	800	0	
total	507750	35293	2334.5	409840	24695	35114	335	
2004								
JAN	30800	0	3.9	30200	0	802	0	
FEB	30300	0	2.9	27640	0	783	0	
MAR	71970	3800	5	59250	3540	6170	0	
APR	85870	4290	143	78130	3020	17470	388	
MAY	144000	5880	902	144200	4160	4720	0	
JUN	65560	5510	496	54170	3510	1080	2.8	
JUL	51080	4840	412	40820	3520	1950	69	
AUG	43010	4870	396	32150	3090	825	546	
SEP	38080	3890	358	29550	2730	784	43	
OCT	25410	---	344	20530	---	---	---	--
NOV	42500	---	158	39630	845	437	0	--
DEC	50500	---	111	---	---	1170	0	--
total	679080	33080	3331.8	556270	24415	36191	1048.8	



GT-Mod: Geothermal Systems Analysis EGS as a Complex System of Systems



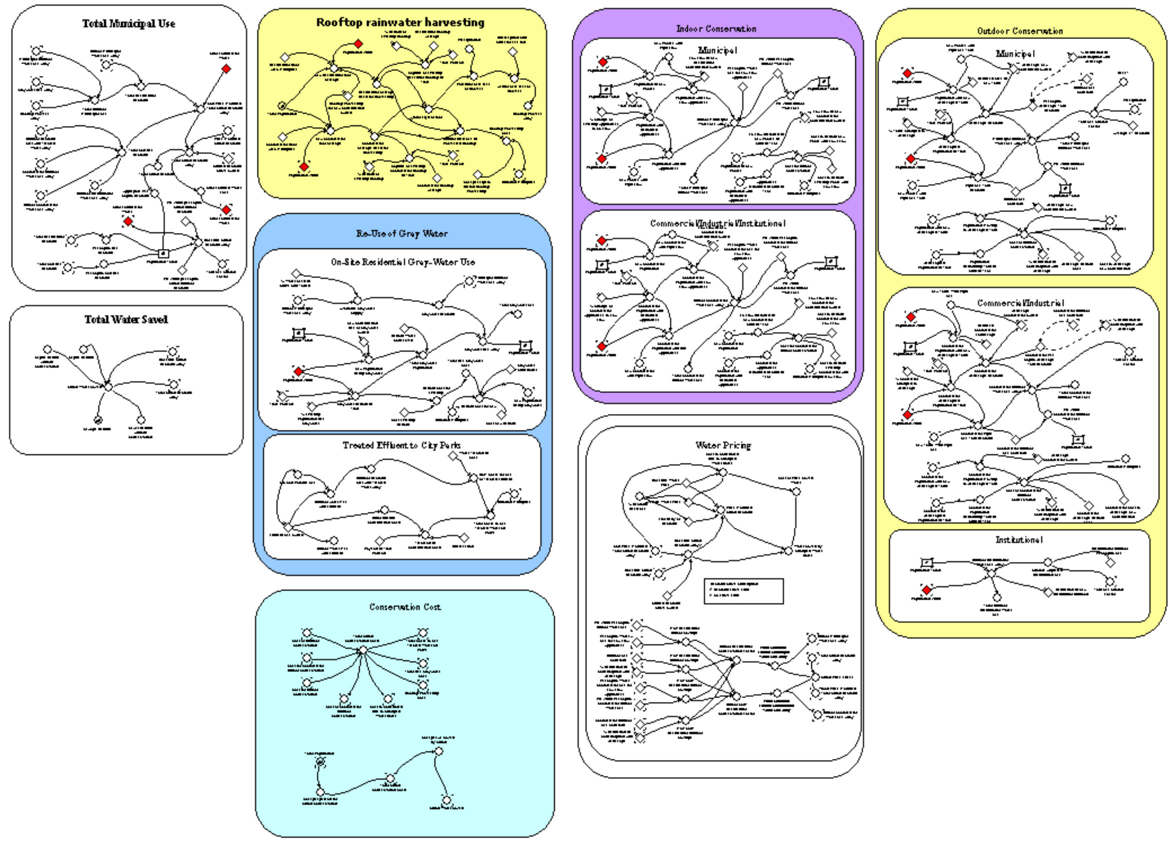
Questions

- Given T, P, and $, which well is most profitable?
- Which well presents the most risk?
- What uncertainties matter the most?
- What technological improvements would have the greatest impact?

System Dynamics

Sandia National Laboratories

- We employ *System Dynamics*, which provides a formal framework for managing multiple interacting subsystems, each of which vary in time
- With system dynamics we are able to quantify feed-back, time delays, and coupling between subsystem components



Focus is on ***Dynamic Complexity*** rather than ***Detail Complexity!***

GT-Mod: Conceptual Model

Inflow Feeder Pipe

Key Inputs	Calculates	Model
Diameter Length Elevation Change Pipe Material	Pressure loss	Darcy-Weisbach

Outflow Feeder Pipe

Key Inputs	Calculates	Model
Diameter Length Elevation Change Pipe Material	Pressure loss	Darcy-Weisbach

Power Plant

Key Inputs	Calculates	Model
Size Type Efficiency	Energy Production Outlet Temperature	2nd Law Estimation

Production Well

Key Inputs
Diameter
Type (open, cased, etc.)
Depth
Screened interval
Separation Distance
Number

Calculates
Temperature change
Pressure change
Pump depth & size
Casing design

Model
Temperature
Pressure
1. Darcy-Weisbach

Reservoir

User Input	Calculates	Model
Size Depth/Gradient Temperature Fracture aperture Fracture frequency	Temperature change Pressure change	Temperature: 1. Carslaw and Jaeger 2. Gringarten 3. Average annual drawdown 4. (Homogeneous equivalent) 5. (Fractured network approximation) Pressure 1. Snow et al. (cubic law) 2. High resolution transfer function

Injection Well

Key Inputs
Diameter
Type (open, cased, etc.)
Depth
Screened interval
Separation Distance
Number

Calculates
Temperature change
Pressure change
Pump depth & size
Casing design

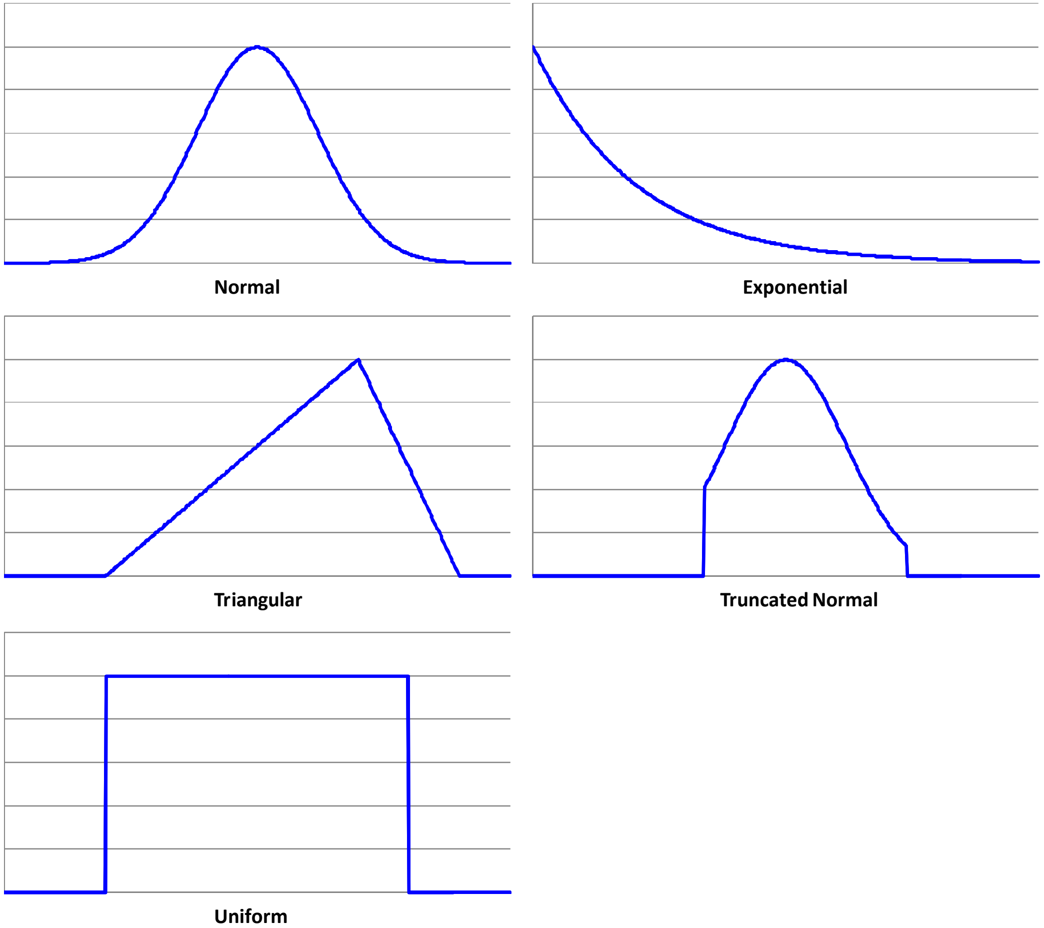
Model
Temperature:
Pressure
1. Darcy-Weisbach

GT-Mod Outputs

Thermal drawdown over time
Reservoir lifespan
Pressure distribution
Energy production

Uncertainties 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 (i.e., small uncertainties in the inputs can lead to large uncertainties in the output)

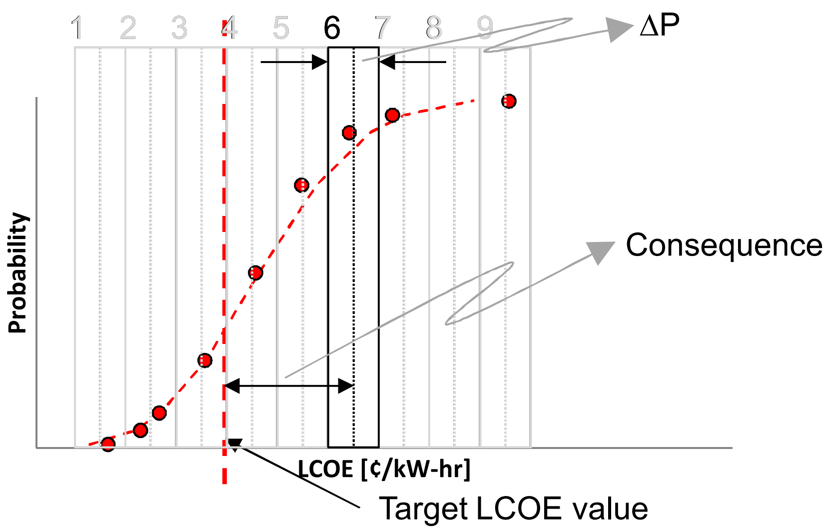


Integrated Risk Assessment

- 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



- Risk tolerance is dependent on the consequence

  e.g. - 50% chance of getting rained on during a picnic vs. a 50% chance of dying during surgery

- Consequences can be defined in many different ways
  - Deviation from target
  - Projected revenue
  - Thermal drawdown
  - Costs to mitigate
  - CO_2 emissions
  - Etc.

GT-Mod: Geothermal Systems Analysis

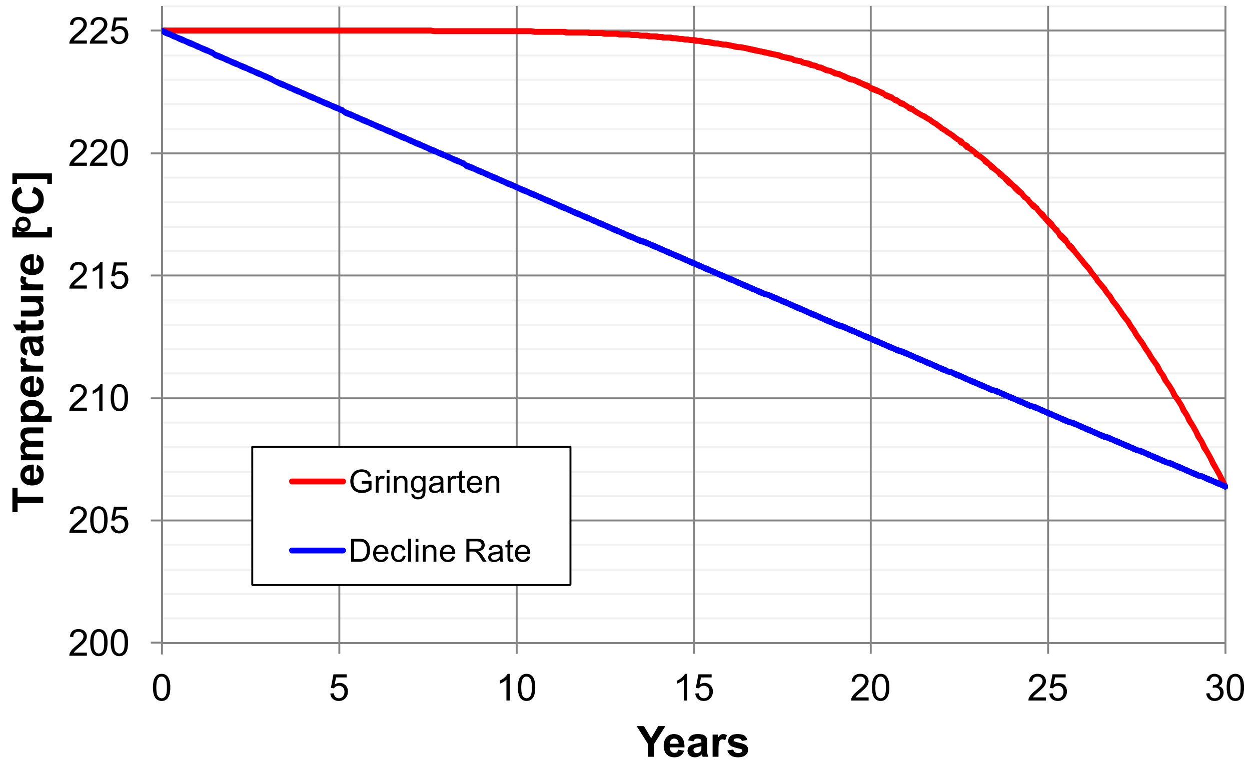
Example – Importance of Solution Method

Compare integrated risk of two solution methods
Gringarten vs Annual decline rate

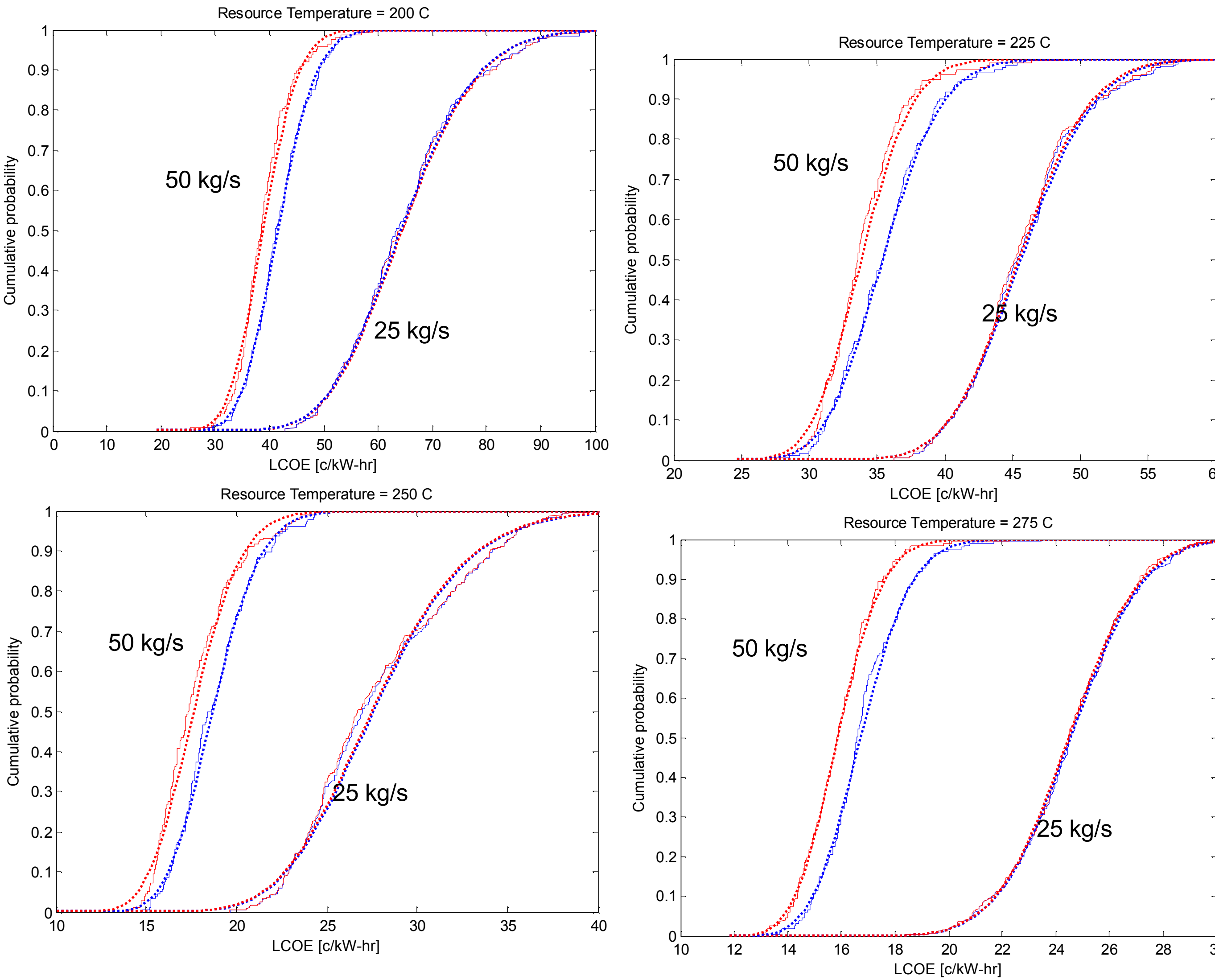
Name	Influence	Distribution Type	Distribution Parameters
Depth	Drilling time, pressure at depth	Normal	Mean: 5000 m Std Dev: 400 m
Reservoir Width	Thermal performance, well separation distance	Uniform	Min: 400 m Max: 800 m
Reservoir Height	Thermal performance, well separation distance	Uniform	Min: 100 m Max: 150 m
# of Fractures	Thermal performance, pressure loss thru reservoir	Uniform	Min: 2 Max: 10
Fracture Aperture	Thermal performance, pressure loss thru reservoir	Truncated Log-Normal	Mean: 0.2 mm Std Dev: 0.6 ln(mm) Min: 0.02 mm Max: 1.0 mm
Rock Thermal Conductivity	Thermal performance	Normal	Mean: 2.85 W/m°C Std Dev: .3833 W/m°C
Rock Specific Heat	Thermal performance	Normal	Mean: 0.95 kJ/kg°C Std Dev: .05 kJ/kg°C
Rock Density	Thermal performance	Normal	Mean: 2700 kg/m^3 Std Dev: 18 kg/m^3
Mass Flow Rate per Production Well	# of wells, pressure distribution, thermal performance, plant performance	Defined Values	25, 50, 75 kg/s/pw
Resource temperature	Thermal performance, # of wells, plant performance	Defined Values	200, 225, 250, 275 °C

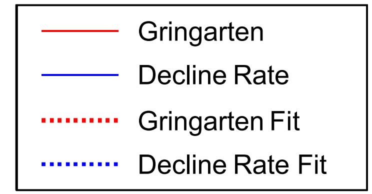
- Uncertain variables defined using a PDF
- Stimulated volume = 0.9 km^3 (distance b/t wells = f(W,H))
- 20 MW binary plant
- 350 simulations using the Gringarten solution for each combination of mass flow rate and temperature (4200 total)
- Results were filtered for $T_{end} < T_{min}$ (2095 remained)
- Filtered runs were run again using equivalent annual decline rate for T_{end}

Example – Importance of Solution Method



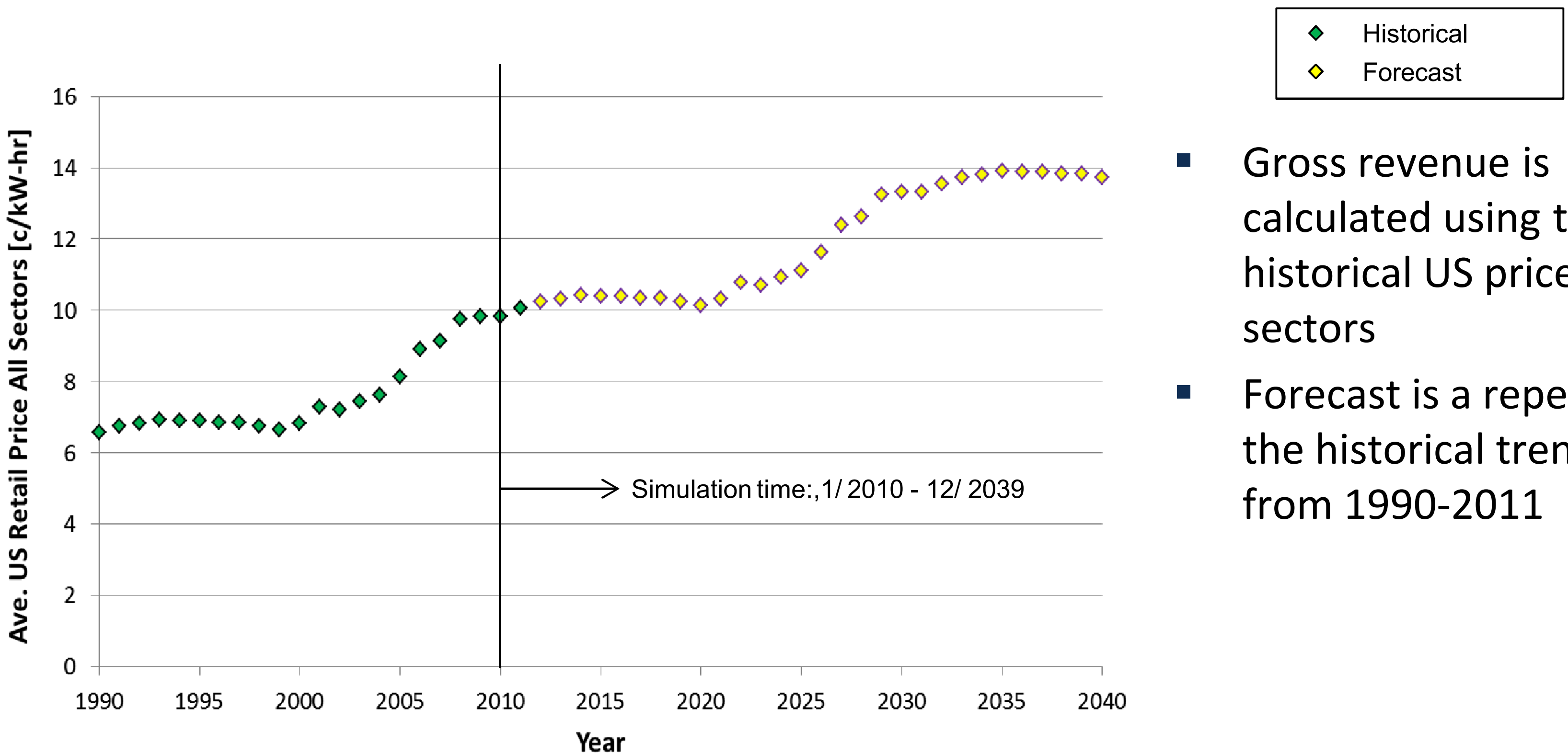
Probability - LCOE





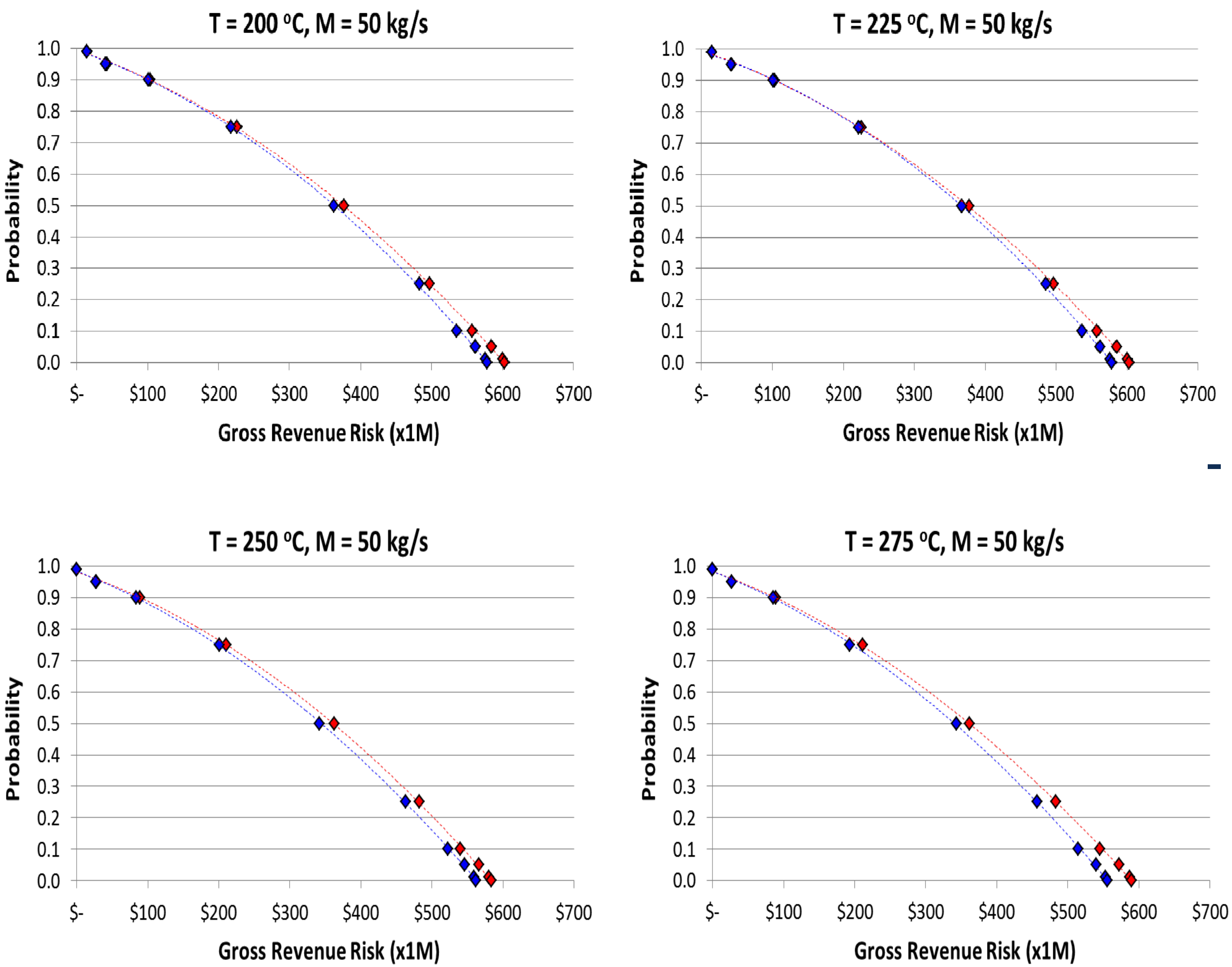
- 75 kg/s filtered out
- No difference in 25 kg/s runs
- Smaller deviation with increasing flow and temperature

Gross Revenue



- Gross revenue is calculated using the historical US price for all sectors
- Forecast is a repeat of the historical trend from 1990-2011

Gross Revenue Risk

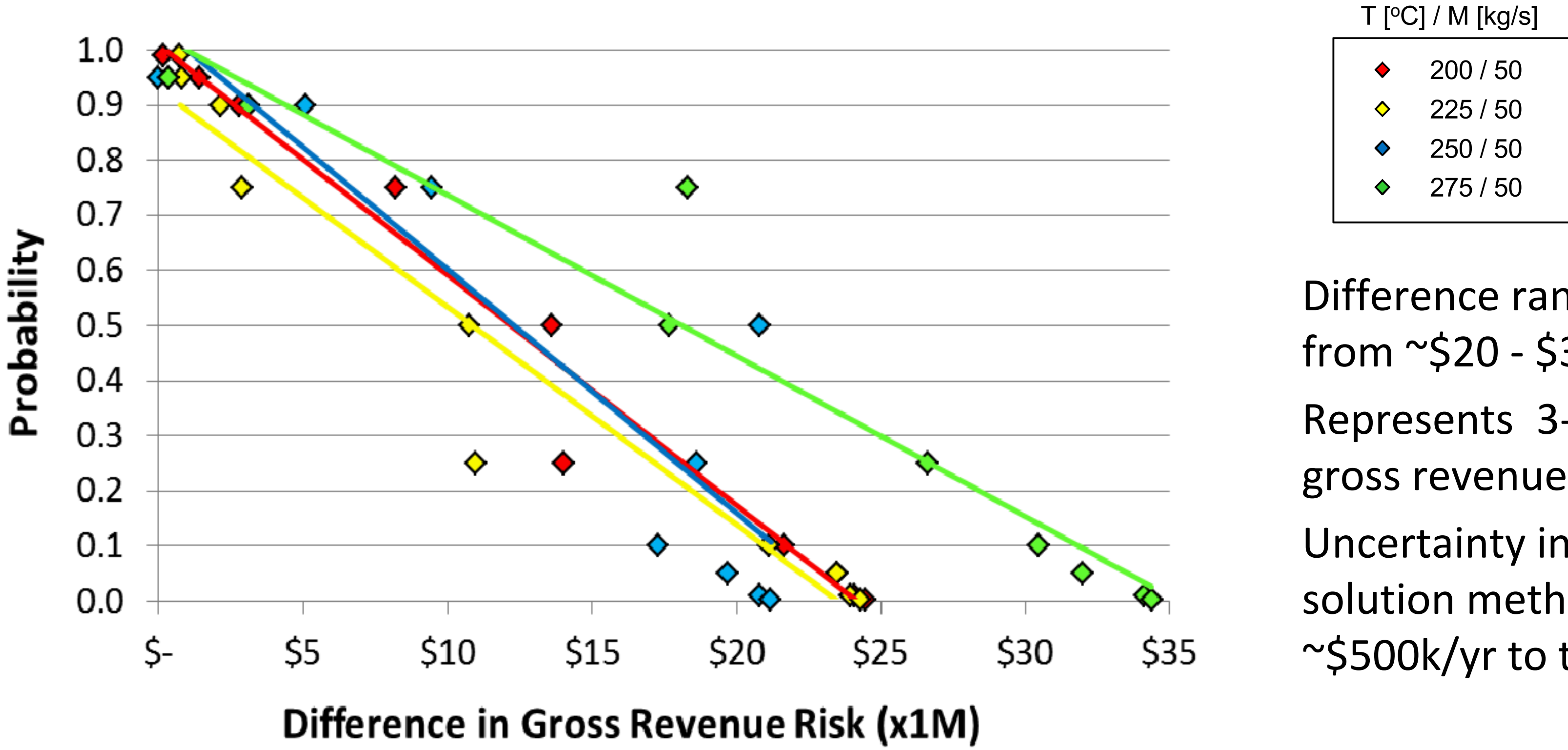


‘Consequence’ is defined as gross revenue over 30 year lifetime

- Risk in this case is the probability weighted value

25 kg/s case is similar

Difference in Gross Revenue Risk



Difference ranges from ~$20 - $35M

Represents 3-6% of gross revenue

Uncertainty in solution method adds ~$500k/yr to the Risk

Summary

- While currently a niche industry, geothermal energy (EGS in particular) has significant potential to be a substantive contributor to the Nation's energy supply
- As baseload power it is complementary to intermittent renewables
- Geothermal systems by their nature are complex natural systems where in situ conditions are often poorly understood
- GT-Mod and similar systems analyses tools are important to understanding the risks associated with geothermal exploration and production

THANK YOU!

QUESTION & ANSWER SESSION

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