SPEE Denver Chapter April Luncheon Meeting

Wednesday, April 10, 2024

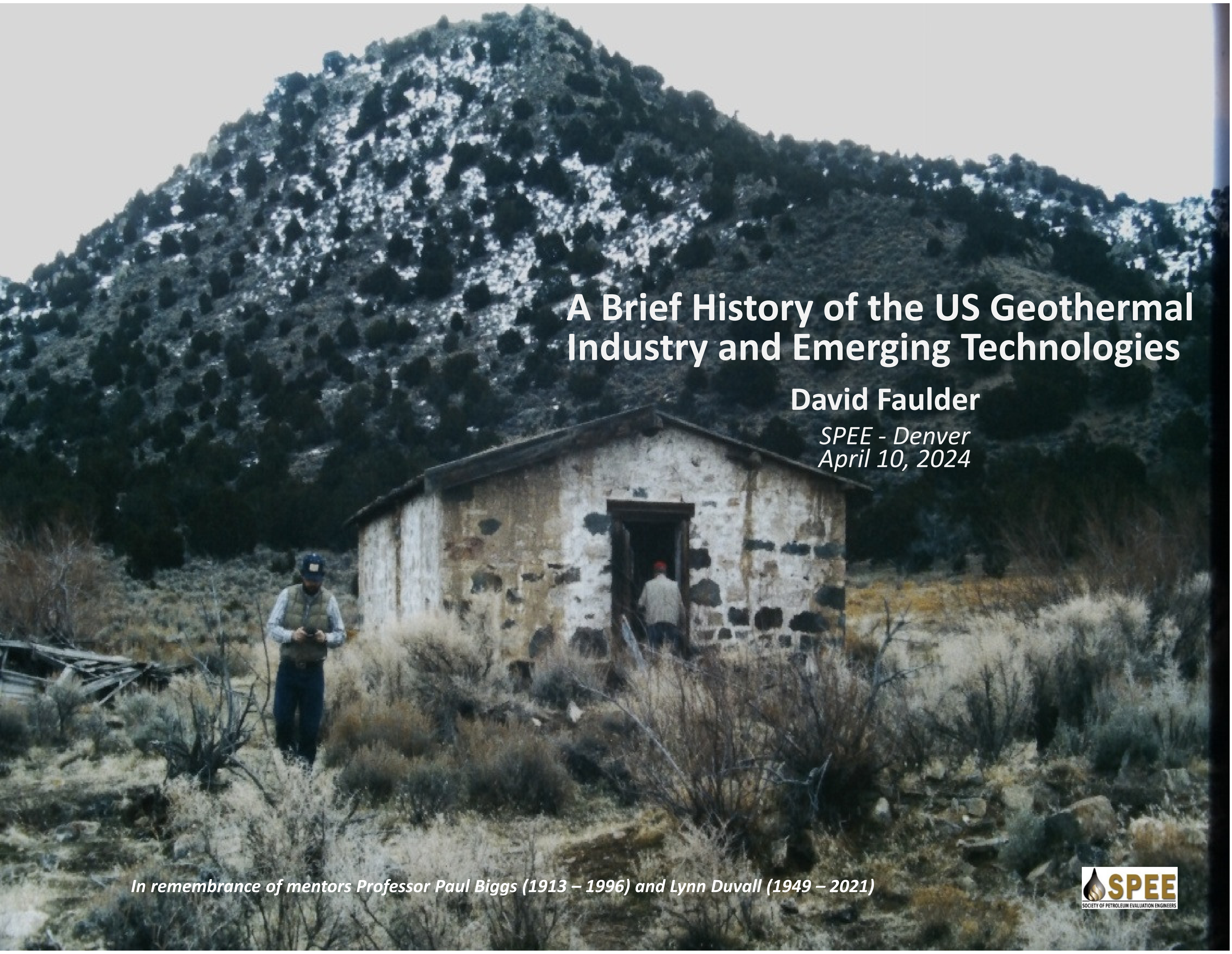
SPEE Members: Fred LeGrand (left) **and David Faulder** (right)

A Brief History of the US Geothermal Industry and Emerging Technologies

Speaker Bio.: **Dr. David Faulder** is a registered Petroleum Engineer in California and Colorado with three degrees in Petroleum Engineering (Univ. of Wyoming and Colorado School of Mines) and a member of SPEE, SPE, and GRC. He has over 43 years of experience as a petroleum and geothermal reservoir engineer in a wide variety of geologic and reservoir settings. Specialized reservoir engineering skills include well testing, pressure transient analysis, reservoir characterization, reservoir modeling, horizontal well design and modeling, wellbore modeling, project economics, and reserves estimation. His research interests include sustainable agriculture, electrolytic methods, and unconventional resources. He lives on a family farm in south-east Nebraska with his son Brandon and Pocket.

Speaker Bio.: **Fred LeGrand** is a retired Petroleum Engineer with 41 years of experience in various basins ranging from the Americas to Europe. Fred earned a BS in Chemistry from GVSU and an MS in Chemical Engineering from Michigan State University. Fred has served the SPEE as a Denver Chapter officer, SPEE Board member and served as the SPEE International Membership Chair through 2023. Fred has recently reawakened an interest in heat transfer (MS Thesis topic), specifically as it relates to closed loop geothermal modeling and software development.

Abstract.: The domestic geothermal industry has grown by the development of conventional hydrothermal resources. A brief review of the historical growth, the types of geothermal resources developed and emerging technologies such as enhanced geothermal systems and closed loop geothermal systems currently being considered for Oil-Gas well repurposing.



A Brief History of the US Geothermal Industry and Emerging Technologies

David Faulder

SPEE - Denver
April 10, 2024

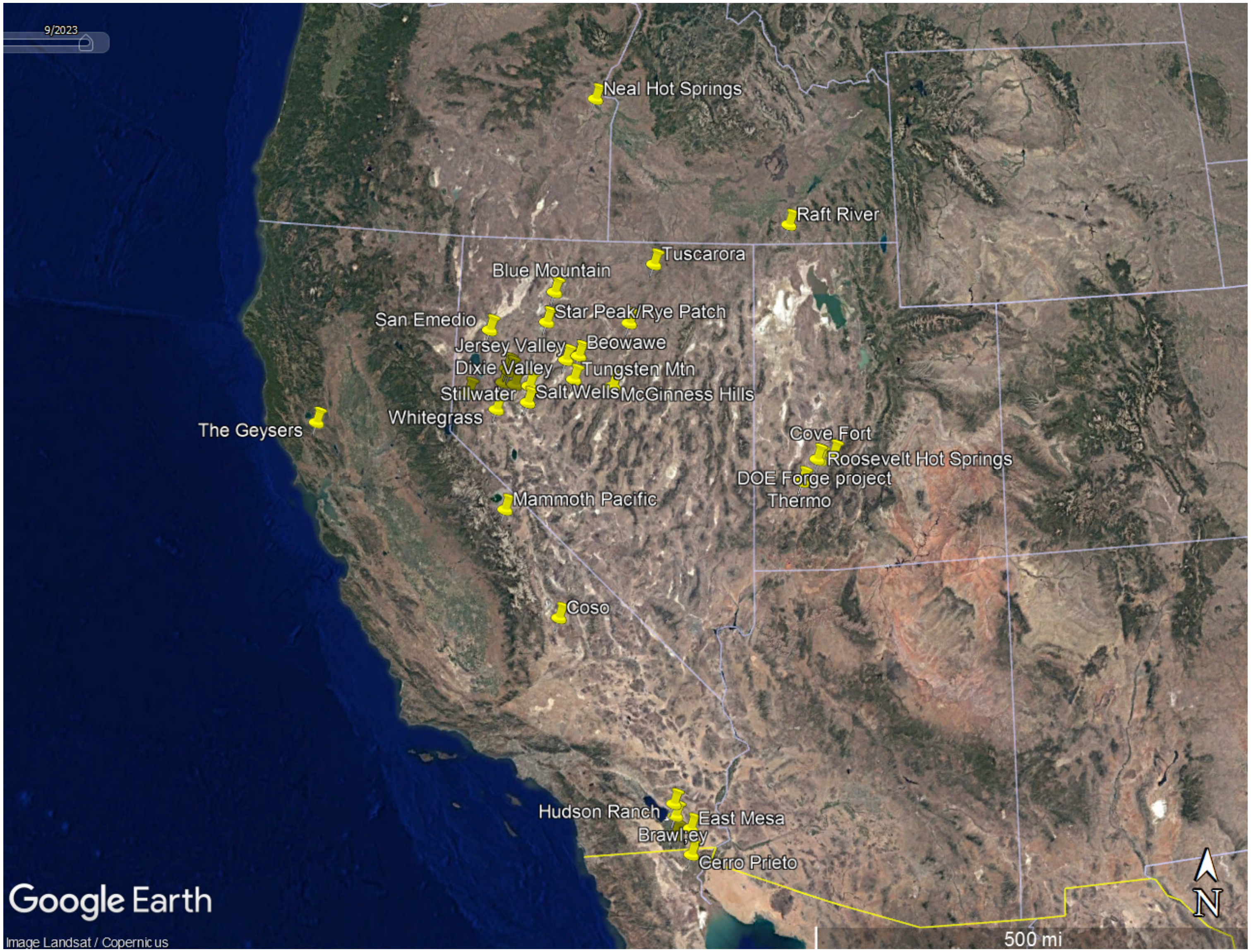
In remembrance of mentors Professor Paul Biggs (1913 – 1996) and Lynn Duvall (1949 – 2021)

Outline

- Introduction
- Where geothermal is located
- Nature of geothermal reservoir systems
- Overview of the US geothermal industry by decade
  - Select fields for details
- Continuing role of technology

Western US physiographic regions

- **Basin & Range extension**
  - Thinner crust, high crustal heat flow
  - High angle faulting
- **Cascades volcanoes**
  - Back-arc volcanism
- **Colorado plateau**
  - Stable craton
- **Yellowstone hot spot track**
  - Across southern Idaho
- **San Andreas fault rifting**
  - California Imperial Valley
  - Salton Sea
  - The Geysers
  - Coso Hot Springs



Geothermal reservoirs

- Unlike petroleum reservoirs, geothermal are dynamic flow systems
  - The deep hydrothermal fluids are brought to the shallow crust by dominantly vertical structural features and regions of high heat flow
    - **Liquid dominated** systems typically interact with the shallow hydrology
    - **Vapor-dominated** systems are hydrologically isolated to great depth
  - Can be found in metamorphic or granitic rocks
    - In close association with magmatic features
    - Or deep-seated structural features
      - Fractured dominated reservoir behavior
  - Can encompass a range of temperatures up to the critical point of water and above
    - Supercritical water has great interest
- Reservoir engineering is similar to petroleum with the addition of non-isothermal conditions
- Pure water is a well-defined substance
  - Difficulties start with dissolved solids and gases
    - Salton Sea brines are ~600°F and +25% dissolved solids
- Geothermal reservoir engineering requires a more holistic view of the flow system using a conceptual hydrothermal model
  - The conceptual model is used to organize and test geoscience data
    - Geoscience data sets are not as rich as petroleum
  - Uses typical reservoir engineering tools
    - Well testing, reservoir modeling, geostatistics, tracer testing, well bore modeling, reservoir characterization

Elements of a conceptual hydrothermal model

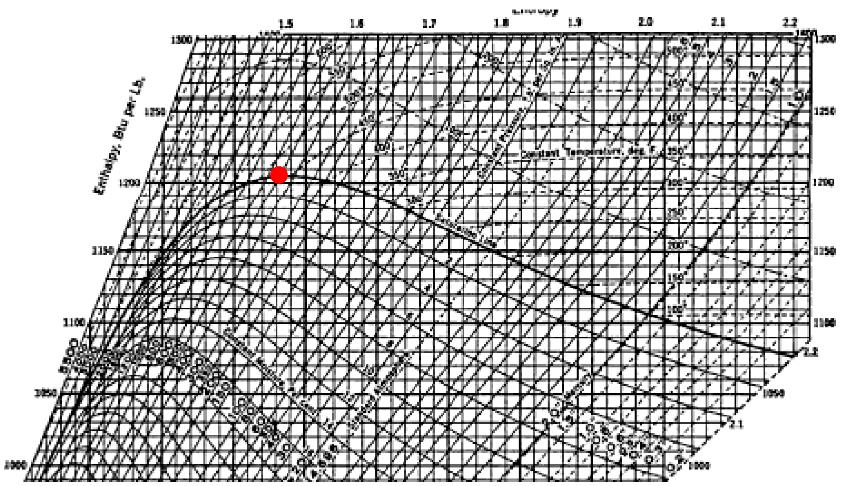
- **Heat source**
  - Where does the heat come from?
    - High regional heat flow in an extensional setting, association with magmatic features, deep circulation of meteoric water, other
- **Permeable pathways**
  - Define the likely pathways for mass and heat transport
    - Geologic setting – crustal extension, rifting, magmatic
    - The deep-seated structural features intersect permeable stratigraphic units and flow laterally
- **Recharge**
  - How is the heat moved in the subsurface?
    - Series of deep seated, intersecting, high-angle structure features transporting hot geofluids to shallower depths
- **Commercial reservoir**
  - A characterized reservoir with productive wells
    - The develop field is associated with a deep-seated structural features and permeable features providing lateral flow into the developed reservoir
- **Outflow**
  - Discharge of the geothermal fluids into the shallow hydrology
    - Basin and Range type hydrology
      - Some association with surface hot spring deposits with Pleistocene lakes, Bonneville and Lahaton

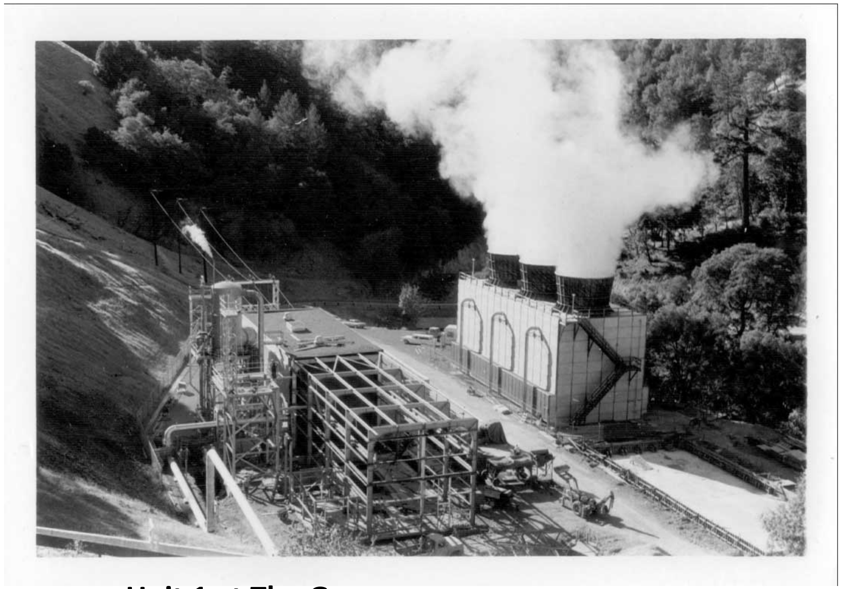
1960’s

The Geysers, California

- North of Santa Rosa
- Unique dry-steam, fractured reservoir
  - About 472°F and 515 psia at discovery
    - Point of maximum enthalpy for pure steam on Mollier entropy-enthalpy chart
- Initial development in the early 1960’s by Magma power, first 11 MW power plant in 1960 selling steam to PG&E
  - First geothermal power plant in the western hemisphere
  - By 1968 82 MW installed capacity

- The Geysers is an analogous dry steam to **Larderello, Italy**
  - Which started power generation 1904





Unit 1 at The Geysers

1970's The Geysers, California

Name	Unit	Type	Status	Capacity (MW$_{el}$)	Commissioned	Decommissioned
PG&E 1 & 2	PG&E 1	Dry steam	Decommissioned	12	September 1960	1993 (Dismantled)
PG&E 1 & 2	PG&E 2	Dry steam	Decommissioned	14	September 1960	1993 (Dismantled)
PG&E 3 & 4	PG&E 3	Dry steam	Decommissioned	28	March 1963	1995 (Dismantled)
PG&E 3 & 4	PG&E 4	Dry steam	Decommissioned	28	March 1963	1995 (Dismantled)
McCabe	Calpine 5	Dry steam	Operational	55	April 1971	
McCabe	Calpine 6	Dry steam	Operational	55	April 1971	
Ridge Line	Calpine 7	Dry steam	Operational	55	July 1972	
Ridge Line	Calpine 8	Dry steam	Operational	55	July 1972	
Fumarole	Calpine 9	Dry steam	Offline since 2001	55	November 1973	
Fumarole	Calpine 10	Dry steam	Offline since 2000	55	November 1973	
Eagle Rock	Calpine 11	Dry steam	Operational	110	December 1975	
PG&E 15 [note 2]	Calpine 15	Dry steam	Decommissioned	62	June 1979	1997 (Dismantled)
Cobb Creek	Calpine 12	Dry steam	Operational	110	August 1979	
Sulfur Springs	Calpine 14	Dry steam	Operational	114	February 1980	
Big Geysers	Calpine 13	Dry steam	Operational	60	April 1980	
Lake View	Calpine 17	Dry steam	Operational	119	November 1982	
NCPA 1 & 2	NCPA 1	Dry steam	Operational	55	February 1983	
NCPA 1 & 2	NCPA 2	Dry steam	Operational	55	February 1983	
Socrates	Calpine 18	Dry steam	Operational	119	November 1983	
Sonoma	Calpine 3	Dry steam	Operational	78	December 1983	
Calistoga	Calpine 19	Dry steam	Operational	80	March 1984	
Bottle Rock	BRP	Dry steam	Operational	55	March 1985 [note 1] October 2007	
Grant	Calpine 20	Dry steam	Operational	119	October 1985	
Quicksilver	Calpine 16	Dry steam	Operational	119	October 1985	
NCPA 3 & 4	NCPA 3	Dry steam	Operational	55	November 1985	
NCPA 3 & 4	NCPA 4	Dry steam	Operational	55	November 1985	
Coldwater Creek	CCPA 1	Dry steam	Decommissioned	65	May 1988	2000 (Dismantled)
Bear Canyon	Calpine 2	Dry steam	Operational	20	September 1988	
Coldwater Creek	CCPA 2	Dry steam	Decommissioned	65	October 1988	2000 (Dismantled)
West Ford Flat	Calpine 4	Dry steam	Operational	27	December 1988	
Aidlin	Calpine 1	Dry steam	Operational	20	May 1989	
Buckeye	Calpine	Dry steam	Planned	?	TBD	
TBD	Ormat	Dry steam	Planned	30	TBD	
Wild Horse	Calpine	Dry steam	Planned	?	TBD	

1. ^ Bottle Rock was re-commissioned in October 2007 after being brought offline in 1991 by its former owner DWR.
2. ^ Calpine never renamed PG&E 15 due to its decommissioning two years before being acquired from PG&E and Unocal Geothermal.

- Continued development at The Geysers attracts more companies
- 1970 Geothermal Steam Act allowed leasing of Federal land for geothermal exploration and development
  - Established Known Geothermal Resource Areas (KGRA)
  - 'Type' lease and unitization documents
- Major oil companies start geothermal exploration
  - Focus on Basin and Range
    - Roosevelt Hot Springs, Desert Peak – Phillips
    - Beowawe, Heber - Chevron

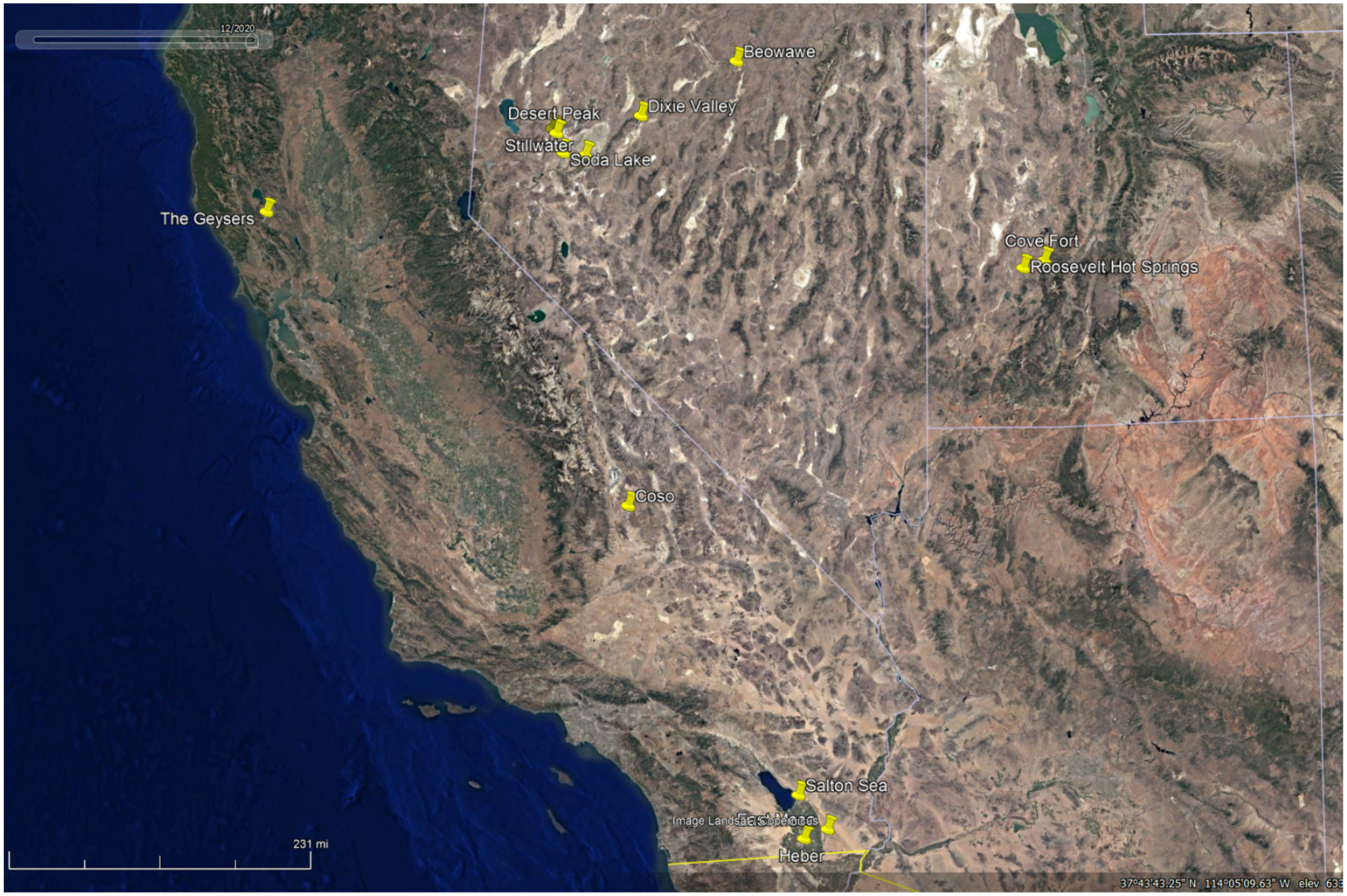
1980’s

Major oil company exploration and divestitures

Series of new projects with *Standard Offer 4* pricing

The Geysers reaches maximum development in 1987 at 2043 MW

- **Basin and Range development starts**
  - *Roosevelt Hot Springs -1984*
  - Beowawe -1985
  - Cove Fort - 1987
  - Desert Peak - 1985
  - Dixie Valley - 1987
  - Soda Lake - 1987
  - Stillwater - 1987
  - Brady Hot Springs - 1989
- **New development in California**
  - *Salton Sea - 1982*
    - DOE test well State 2-14 in 1986
  - Mammoth - 1984
  - Heber - 1986
  - East Mesa - 1989
  - *Coso Hot Springs - 1989*



Roosevelt Hot Springs Unit, Beaver Co. Utah

- Developed by Phillip, sold steam to Utah Power Light, started 22 MW 1984
  - Phillips had an underground blowout of RHSU 27-3 that reached the surface
    - Consequence of using 15% HCl acid to clean out wellbore scale, instead cleaned out the cement around casing shoe
- Chevron purchased in 1986
  - One of my early fields, lots of pressure transient tests
    - Fractured tombstone granite – Bailey ridge lava flow
    - Recent volcanism ~240 kya, inferred magma chamber at about 20,000 ft depth

RHSU pressure transient testing

Phillips had conducted three long-term flow tests (up 180 days) prior to project development to confirm deliverability, with observation wells

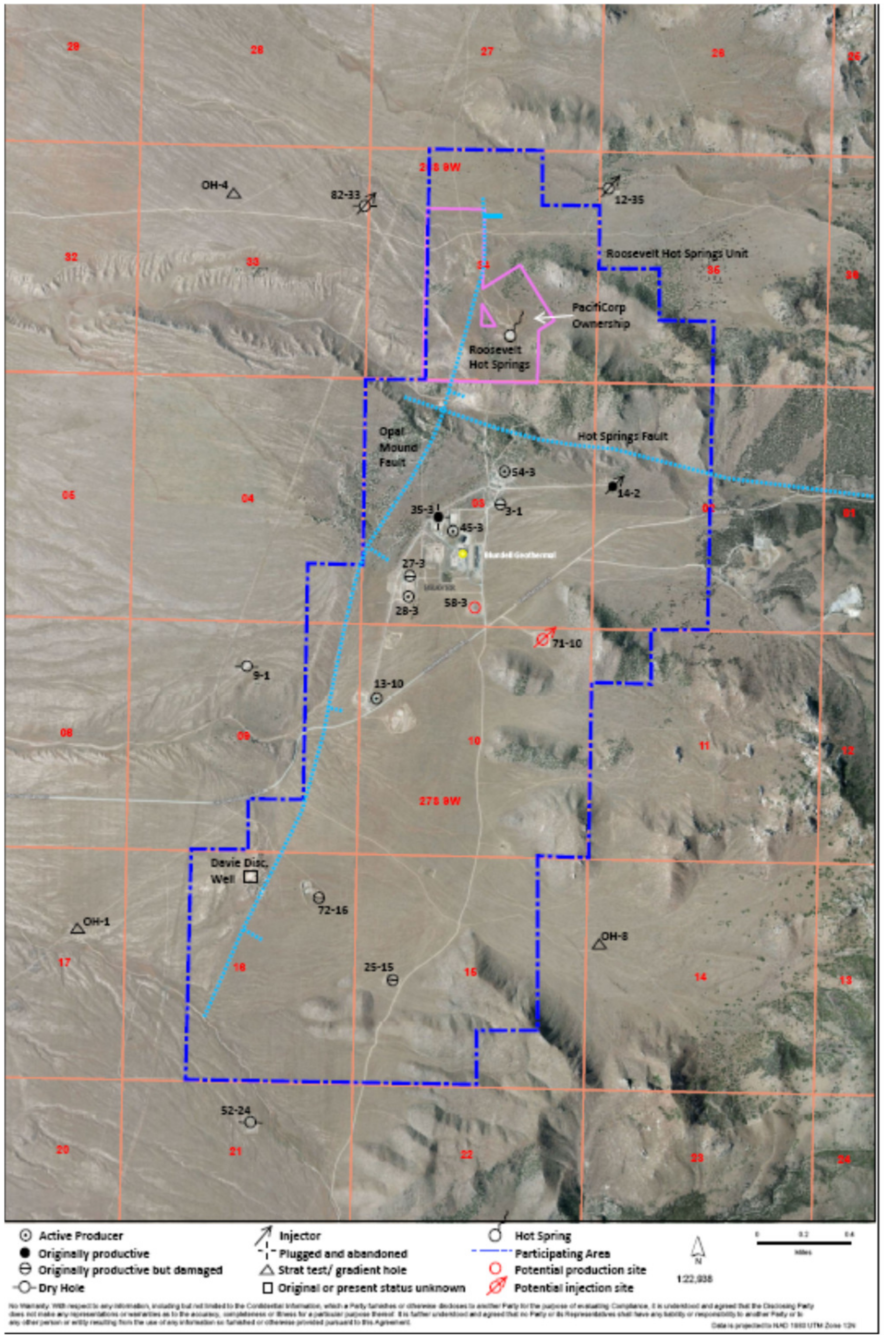
- Located this data on 132 column computer printout paper and technician key punched into a spread sheet
- The long-term flow test data allowed an estimate of the native state recharge of ~400 Klbm/hr of +500°F geofluid

First learned pressure transient analysis at RHSU *(CAWTAP)*

- Flow test design, execution, and analysis
- Pressure buildup tests
  - *kh* from 500,000 to 1,000,000 mD-ft
- Injection fall-off tests
- Interference tests
  - Tested many well doublets
    - Very high permeability, low storage system
- The pressure derivative method was new and was applied to PTA

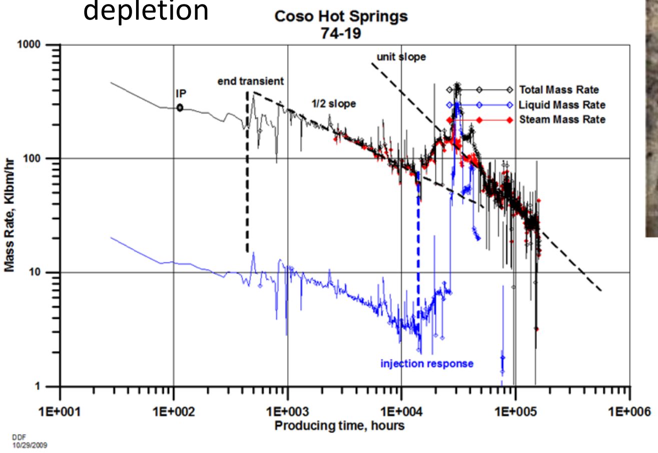
Importance of understanding the geologic setting in interpreting pressure transient data

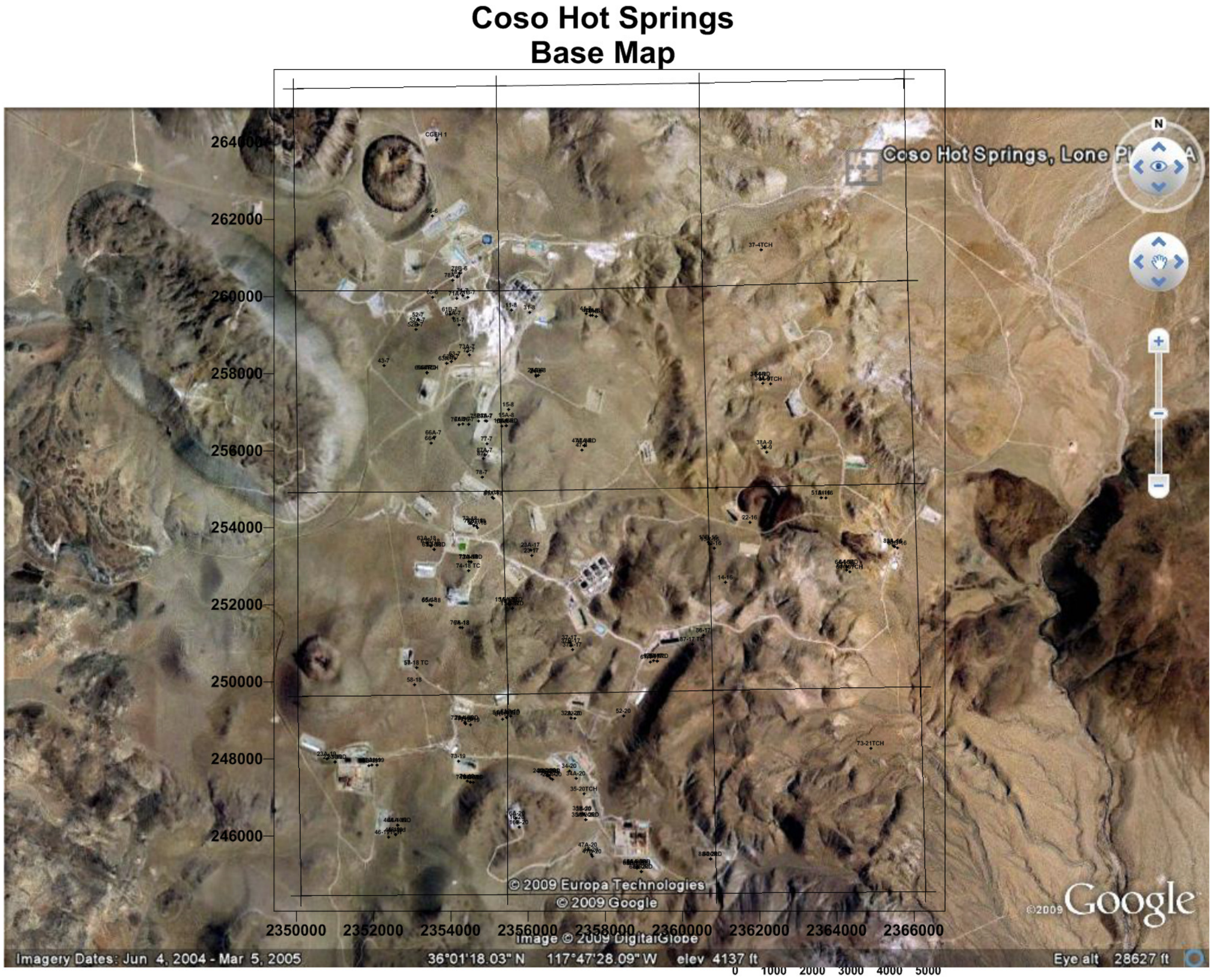
- ***Beowawe example***



Coso Hot Springs, California

- **Developed by California Energy Co in 1989**
  - Nine power plants for a total of 240 MW nameplate capacity, currently ~140 MW
  - Over 200 wells drilled
    - Abundant production data
  - Water augmentation project started 2010 – terminated ~2020
- In close association with recent magmatism ±20kya
  - Very hot, some regions approaching 680°F
  - Magma chamber at about 20,000 ft
  - Liquid-dominated reservoir
    - Individual well responses vary from radial, to linear, to bi-linear flow regimes
    - Now large steam reservoir due to mass depletion





1990's

- The Geysers decline
- ☐ Salton Sea development continues
- ☐ Puna, Hawaii 1992
- ☐ Brady Hot Springs, Nevada 1992
- Further industry consolidation as major oil companies leave Chevron, Phillips, Unocal
  - New domestic entrants – Ormat, Calpine and a number of smaller, under-capitalized companies

2000's

Adjusting to full market pricing as 10-year SO4 contract expire and power price falls off the cliff

- Continued development at the Salton Sea, California
- Chena Hot Springs, Alaska 2006
- Blue Mountain, Nevada 2009
- Thermo, Utah 2009

2010's

- Hudson Ranch, Salton Sea 2012
- Neal Hot Springs, Oregon 2012
- McGinness Hills, Nevada 2012
- Tungsten Mountain , Nevada 2017

Salton Sea field

- Long history of development starting in 1982 by Magma/Unocal
- Large resource base
- Technically very challenging
  - Very hot
  - Extremely saline brine – corrosive
    - Wellbore and process scaling
    - Fluid thermodynamics are much different than pure water

Plant	Year start up	Number of units	Capacity, MW	Cum capacity
Salton Sea Unit 1	1982	1	10.3	10.3
Vulcan	1985	2	39.7	50.0
Salton Seat 3	1989	1	54	104.0
Del Ranch	1989	1	35.8	139.8
Elmore	1989	1	35.8	175.6
Salton Sea 4	1996	1	47.5	223.1
Salton Sea 2	1999	3	19.7	242.8
Leathers	1999	1	35.8	278.6
Salton Sea 5	2000	1	58.3	336.9
CE Turbo	2000	1	11.5	348.4
Hudson Ranch 1	2012	1	55	**403.4**

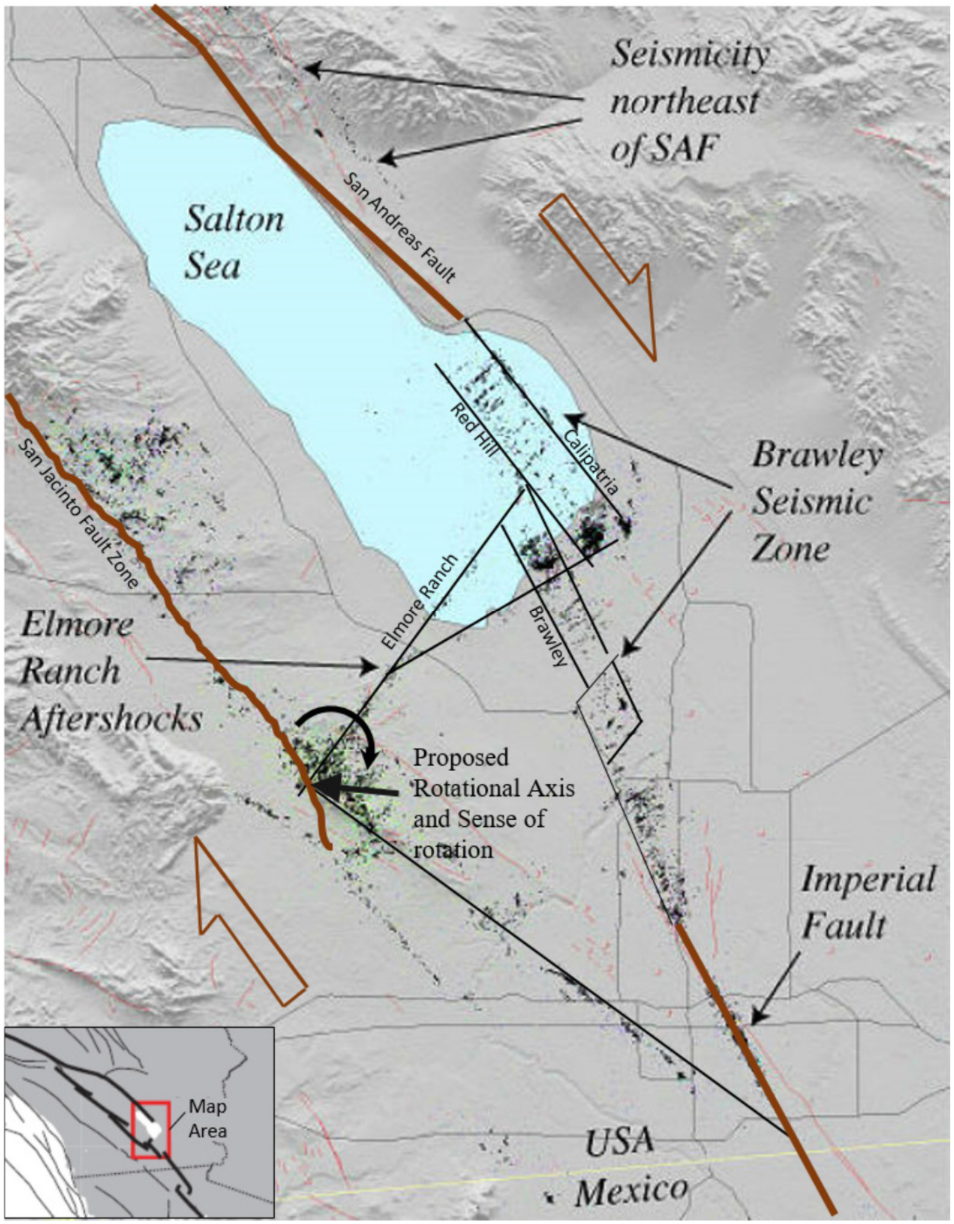


Fig. 4, Kaspereit et al., 2016.

Salton Sea field, California

- Large areal extent ~22 square miles
- Initially developed by Magma/Unocal in the 1980-90s, later acquired by CalEnergy owned by Berkshire Hathaway Energy
  - 12 operating power plants with a nameplate generation capacity of 400 MW electrical
- Resource is very hot
  - ~600°F hypersaline geofluid
    - 25-30% dissolved solids
  - Wells can be very productive
    - Require special metallurgy for casing
      - Titanium, Inconel 625, other exotics
- Additional development potential
  - 400 MW - **installed**
  - 990 - **proven**
  - 2950 MW – ***potential***
  - Receding Salton Sea has exposed 545 MW of potential

*There are **NO** SEC requirements or standards for reporting geothermal reserves*

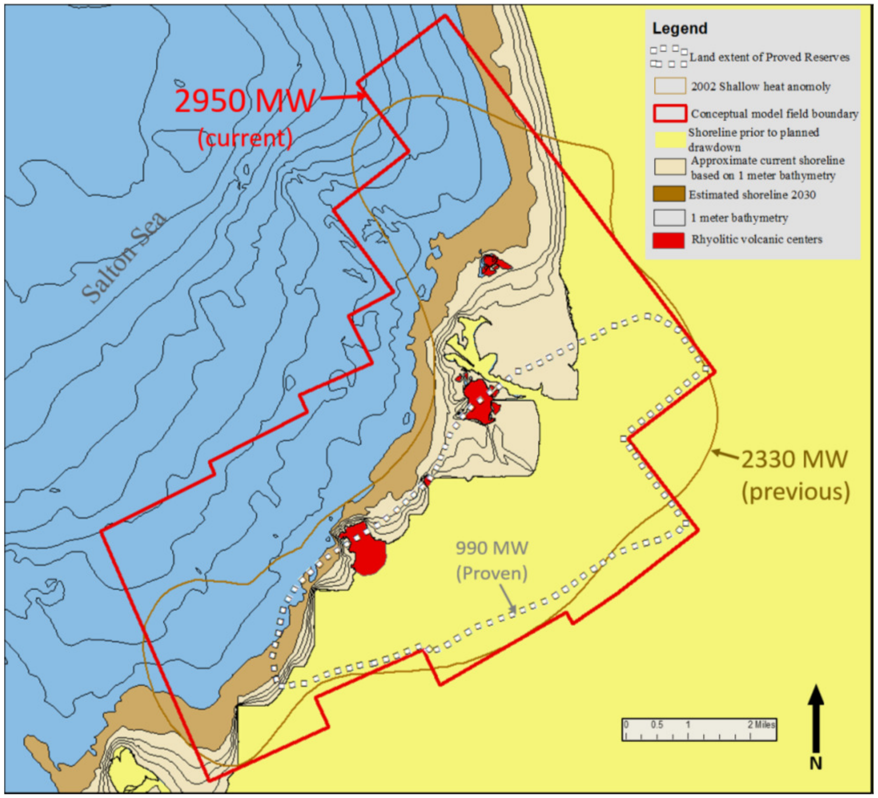


Fig. 14 Kaspereit et al., 2019.

Hydroblast head - 8 inch diameter – note extreme corrosion of carbon steel after 160 days in a well

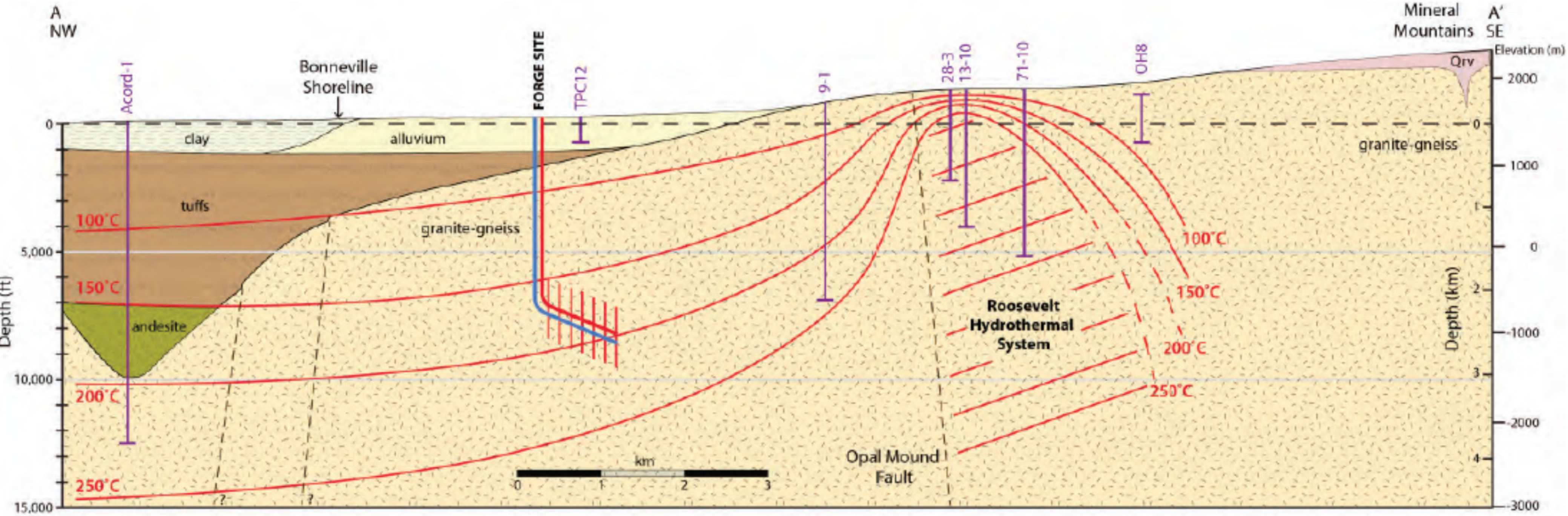
Kaspereit, D., Mann, M., Sanyal, S., Rickard, B, Osborn, W., and Hulen, J., 2019. *Updated Conceptual Model and Reserve Estimate for the Salton Sea Geothermal Field, Imperial Valley, California*, GRC Trans, vol. 40, p. 57-66

2020's

- The Geysers at 725 MW
- Salton Sea at 400
- Coso at 140 MW
- Major operators
  - Atlanticia
  - Calpine – The Geysers
  - BHE – Salton Sea
  - Ormat – Western US and international
  - Cyrq – Western US
- Application of emerging technologies
  - AltaRock at Newberry Crater, Oregon – supercritical water
  - DOE FORGE EGS project in Utah
  - Fervo in Utah
  - Other

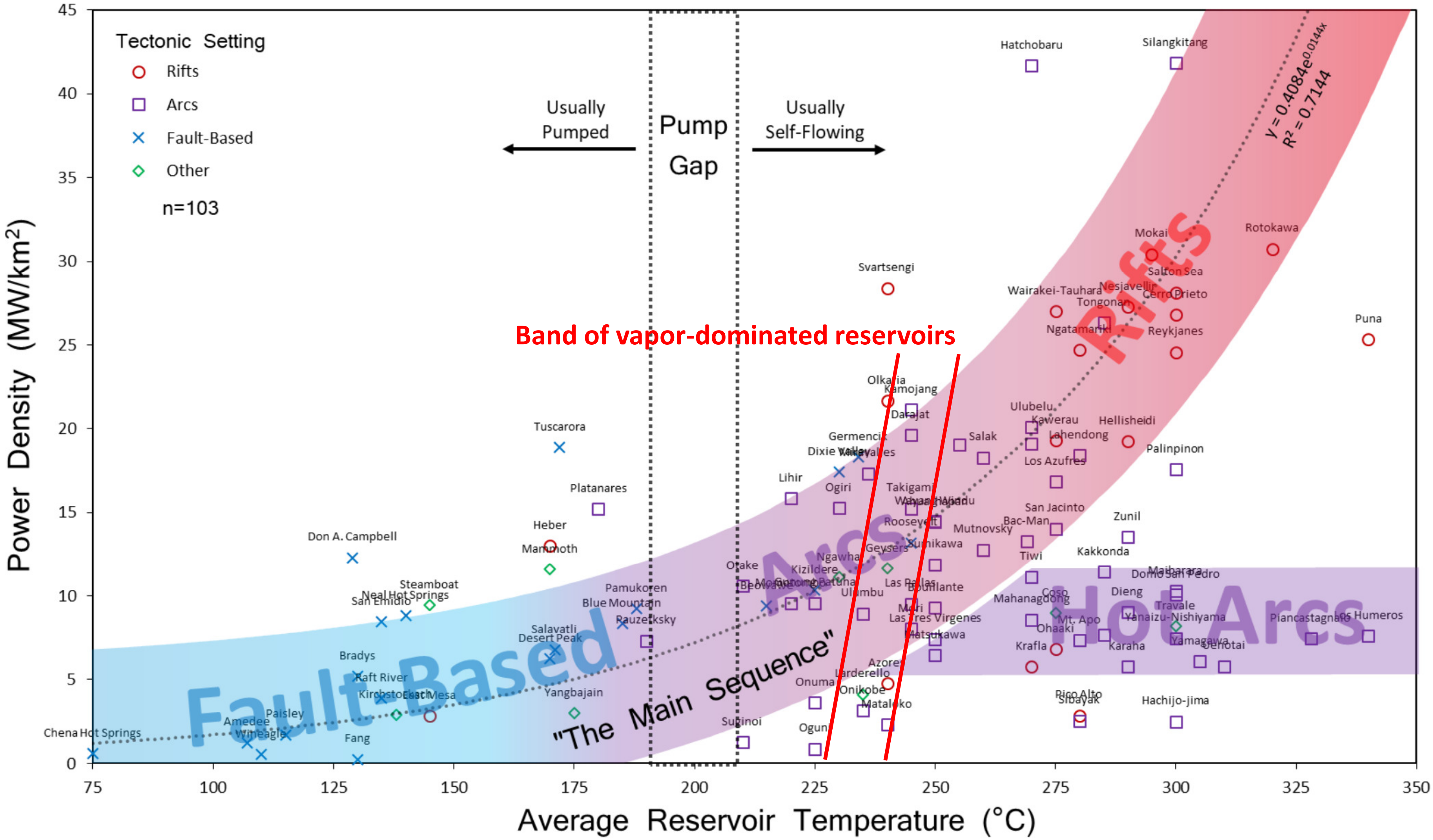
EGS FORGE - Southern Utah

- Forge Project applying advanced drilling and completion technologies to develop Engineered Geothermal Systems (EGS)
  - Project is west of Roosevelt Hot Springs
  - 1987 Bechtel made a study of the technical and economic feasibility of ‘hot dry rock’, the predecessor term for EGS
    - Concluded that all the technical pieces were available, have not put them all together in a project



A cross section of the geology around the FORGE Utah site in southern Utah. COURTESY UTAH FORGE

Power density – updated



Wilmarth, M., Stimac, J., and Ganefianto, G., 2021. *Power Density in Geothermal Fields, 2020 Update*, Proc. World Geothermal Congress, Reykjavik, 2021, 8p.

The Future

- The long-term path is de-carbonization of the economy
  - This will require non-carbon-based sources of base-load electrical power
  - Academic institutions are examining EGS for a portion of the base-load thermal requirements (heating/cooling)
    - Decarbonization trumps present value economics
- Lower temperature resources
- Advanced well technology
  - Horizontal
  - Re-purpose old hydrocarbon fields
  - Closed loop
- Continued need for technology transfer from the O&G to geothermal

SPEE bylaws

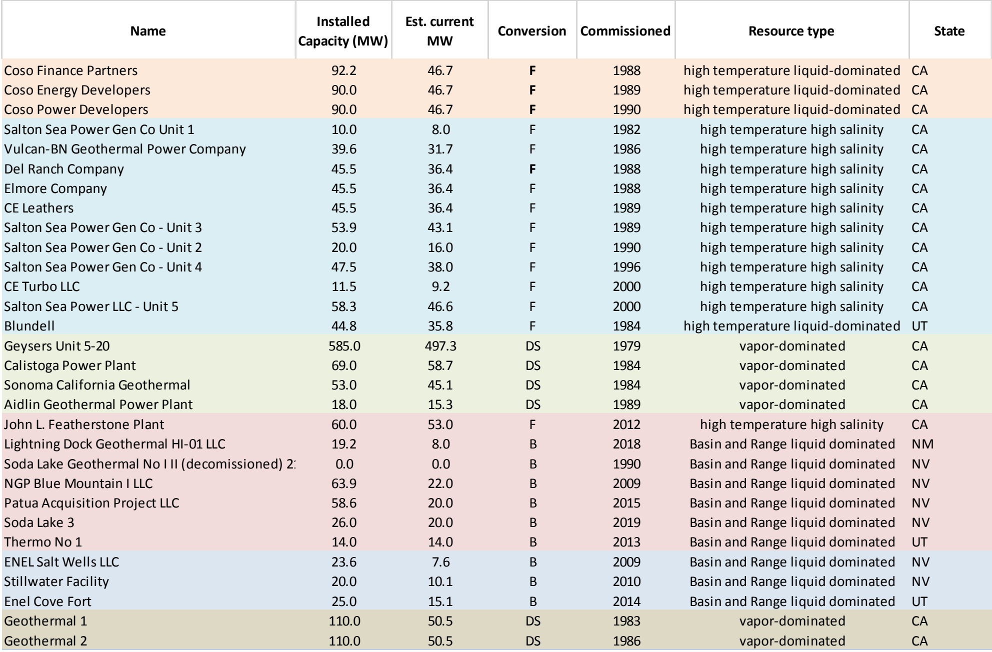
ARTICLE II. OBJECTIVES

The objectives of this Society are to promote the profession of *petroleum* evaluation engineering, to foster the spirit of scientific research among its Members, and to disseminate facts pertaining to *petroleum* evaluation engineering among its Members and the public.

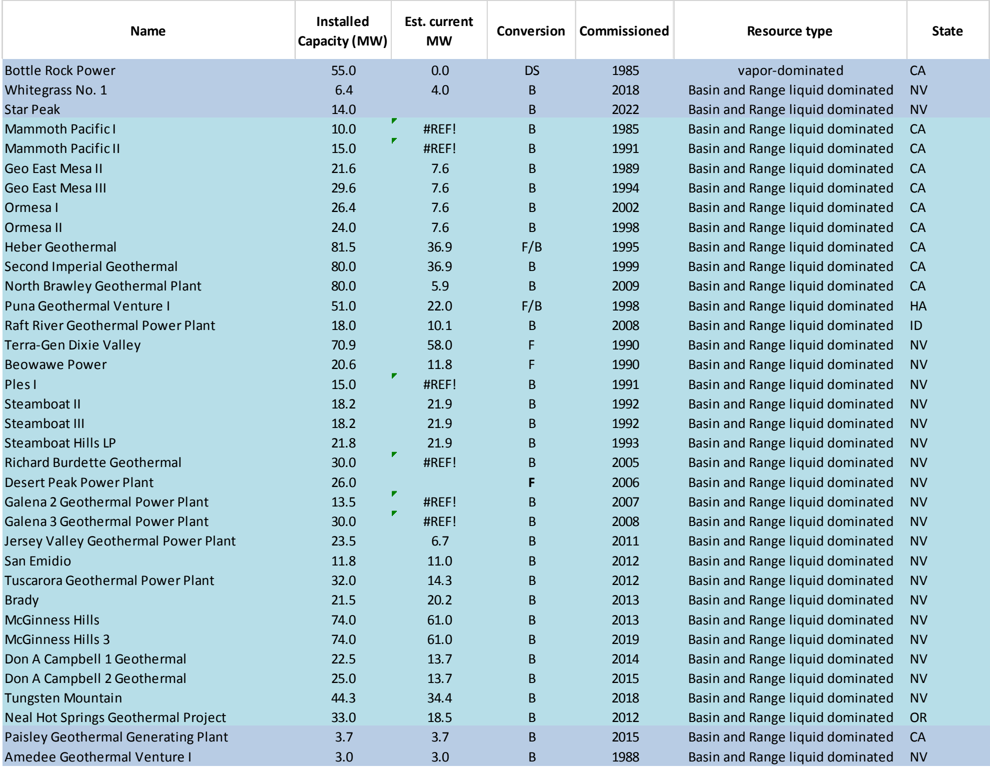
(italics added)

Back pocket slides

US geothermal projects



Name	Installed Capacity (MW)	Est. current MW	Conversion	Commissioned	Resource type	State
Coso Finance Partners	92.2	46.7	**F**	1988	high temperature liquid-dominated	CA
Coso Energy Developers	90.0	46.7	**F**	1989	high temperature liquid-dominated	CA
Coso Power Developers	90.0	46.7	**F**	1990	high temperature liquid-dominated	CA
Salton Sea Power Gen Co Unit 1	10.0	8.0	F	1982	high temperature high salinity	CA
Vulcan-BN Geothermal Power Company	39.6	31.7	F	1986	high temperature high salinity	CA
Del Ranch Company	45.5	36.4	**F**	1988	high temperature high salinity	CA
Elmore Company	45.5	36.4	F	1988	high temperature high salinity	CA
CE Leathers	45.5	36.4	F	1989	high temperature high salinity	CA
Salton Sea Power Gen Co - Unit 3	53.9	43.1	F	1989	high temperature high salinity	CA
Salton Sea Power Gen Co - Unit 2	20.0	16.0	F	1990	high temperature high salinity	CA
Salton Sea Power Gen Co - Unit 4	47.5	38.0	F	1996	high temperature high salinity	CA
CE Turbo LLC	11.5	9.2	F	2000	high temperature high salinity	CA
Salton Sea Power LLC - Unit 5	58.3	46.6	F	2000	high temperature high salinity	CA
Blundell	44.8	35.8	F	1984	high temperature liquid-dominated	UT
Geysers Unit 5-20	585.0	497.3	DS	1979	vapor-dominated	CA
Calistoga Power Plant	69.0	58.7	DS	1984	vapor-dominated	CA
Sonoma California Geothermal	53.0	45.1	DS	1984	vapor-dominated	CA
Aidlin Geothermal Power Plant	18.0	15.3	DS	1989	vapor-dominated	CA
John L. Featherstone Plant	60.0	53.0	F	2012	high temperature high salinity	CA
Lightning Dock Geothermal HI-01 LLC	19.2	8.0	B	2018	Basin and Range liquid dominated	NM
Soda Lake Geothermal No I II (decomissioned) 2	0.0	0.0	B	1990	Basin and Range liquid dominated	NV
NGP Blue Mountain I LLC	63.9	22.0	B	2009	Basin and Range liquid dominated	NV
Patua Acquisition Project LLC	58.6	20.0	B	2015	Basin and Range liquid dominated	NV
Soda Lake 3	26.0	20.0	B	2019	Basin and Range liquid dominated	NV
Thermo No 1	14.0	14.0	B	2013	Basin and Range liquid dominated	UT
ENEL Salt Wells LLC	23.6	7.6	B	2009	Basin and Range liquid dominated	NV
Stillwater Facility	20.0	10.1	B	2010	Basin and Range liquid dominated	NV
Enel Cove Fort	25.0	15.1	B	2014	Basin and Range liquid dominated	UT
Geothermal 1	110.0	50.5	DS	1983	vapor-dominated	CA
Geothermal 2	110.0	50.5	DS	1986	vapor-dominated	CA



Name	Installed Capacity (MW)	Est. current MW	Conversion	Commissioned	Resource type	State
Bottle Rock Power	55.0	0.0	DS	1985	vapor-dominated	CA
Whitegrass No. 1	6.4	4.0	B	2018	Basin and Range liquid dominated	NV
Star Peak	14.0		B	2022	Basin and Range liquid dominated	NV
Mammoth Pacific I	10.0	#REF!	B	1985	Basin and Range liquid dominated	CA
Mammoth Pacific II	15.0	#REF!	B	1991	Basin and Range liquid dominated	CA
Geo East Mesa II	21.6	7.6	B	1989	Basin and Range liquid dominated	CA
Geo East Mesa III	29.6	7.6	B	1994	Basin and Range liquid dominated	CA
Ormesa I	26.4	7.6	B	2002	Basin and Range liquid dominated	CA
Ormesa II	24.0	7.6	B	1998	Basin and Range liquid dominated	CA
Heber Geothermal	81.5	36.9	F/B	1995	Basin and Range liquid dominated	CA
Second Imperial Geothermal	80.0	36.9	B	1999	Basin and Range liquid dominated	CA
North Brawley Geothermal Plant	80.0	5.9	B	2009	Basin and Range liquid dominated	CA
Puna Geothermal Venture I	51.0	22.0	F/B	1998	Basin and Range liquid dominated	HA
Raft River Geothermal Power Plant	18.0	10.1	B	2008	Basin and Range liquid dominated	ID
Terra-Gen Dixie Valley	70.9	58.0	F	1990	Basin and Range liquid dominated	NV
Beowawe Power	20.6	11.8	F	1990	Basin and Range liquid dominated	NV
Ples I	15.0	#REF!	B	1991	Basin and Range liquid dominated	NV
Steamboat II	18.2	21.9	B	1992	Basin and Range liquid dominated	NV
Steamboat III	18.2	21.9	B	1992	Basin and Range liquid dominated	NV
Steamboat Hills LP	21.8	21.9	B	1993	Basin and Range liquid dominated	NV
Richard Burdette Geothermal	30.0	#REF!	B	2005	Basin and Range liquid dominated	NV
Desert Peak Power Plant	26.0		**F**	2006	Basin and Range liquid dominated	NV
Galena 2 Geothermal Power Plant	13.5	#REF!	B	2007	Basin and Range liquid dominated	NV
Galena 3 Geothermal Power Plant	30.0	#REF!	B	2008	Basin and Range liquid dominated	NV
Jersey Valley Geothermal Power Plant	23.5	6.7	B	2011	Basin and Range liquid dominated	NV
San Emidio	11.8	11.0	B	2012	Basin and Range liquid dominated	NV
Tuscarora Geothermal Power Plant	32.0	14.3	B	2012	Basin and Range liquid dominated	NV
Brady	21.5	20.2	B	2013	Basin and Range liquid dominated	NV
McGinness Hills	74.0	61.0	B	2013	Basin and Range liquid dominated	NV
McGinness Hills 3	74.0	61.0	B	2019	Basin and Range liquid dominated	NV
Don A Campbell 1 Geothermal	22.5	13.7	B	2014	Basin and Range liquid dominated	NV
Don A Campbell 2 Geothermal	25.0	13.7	B	2015	Basin and Range liquid dominated	NV
Tungsten Mountain	44.3	34.4	B	2018	Basin and Range liquid dominated	NV
Neal Hot Springs Geothermal Project	33.0	18.5	B	2012	Basin and Range liquid dominated	OR
Paisley Geothermal Generating Plant	3.7	3.7	B	2015	Basin and Range liquid dominated	CA
Amedee Geothermal Venture I	3.0	3.0	B	1988	Basin and Range liquid dominated	NV

RHSU March 1981

Dr. Faulder

- Have been associated with geothermal development since 1985, Chevron Geothermal Co. of California
- Nine years at INEL for Geothermal Reservoir Technology Program
- Oil and gas with Chevron, Bill Barrett and Nighthawk
- Reservoir engineering consultant since 1991
- Geothermal projects worked
  - Different geologic settings
    - Wide range of reservoir settings
      - 168°F to +680°F temperature
      - Fresh to 30% dissolved solids
      - Sedimentary – metamorphic – granitic rocks
      - Porous – dual porosity – fractured dominated
      - Dry steam to flowing to pumped
  - Worked primarily as a geothermal reservoir engineer
    - Well testing
    - Wellbore modeling
    - Reservoir simulation
    - Well operations
- Oil & gas since 1981
  - Drilling in the Wyoming Overthrust
  - Reservoir engineer for Rangely, Colorado
  - Rocky Mtns and DJ basin – conventional and unconventional oil reservoirs
  - Colorado Oil & Gas Commission testimony

- Chena Hot Springs, Alaska
- Coso Hot Springs, California
- Heber, California
- Salton Sea, California
- The Geysers, California
- Raft River, Idaho
- Beowawe, Nevada
- Blue Mountain, Nevada
- Desert Peak, Nevada
- Dixie Valley, Nevada
- Hot Sulphur Springs, Nevada
- Patua, Nevada
- Rye Patch, Nevada
- Soda Lake, Nevada
- Steamboat Springs, Nevada
- Lightning Dock, New Mexico
- Roosevelt Hot Springs, Utah
- Thermo, Utah
- Harrat Khaybar, Saudi Arabia

RYDER SCOTT

SPEE
SOCIETY OF PETROLEUM EVALUATION ENGINEERS

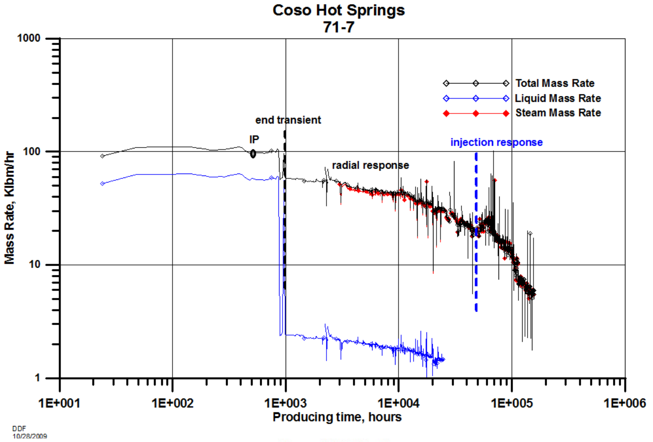
Advanced production decline curve analysis

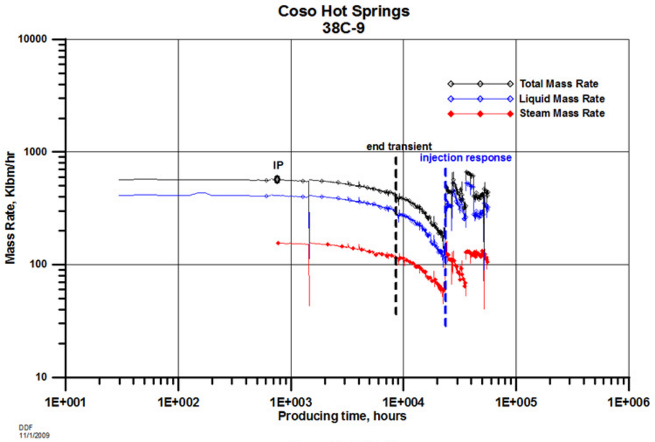
Used to identify flow regimes

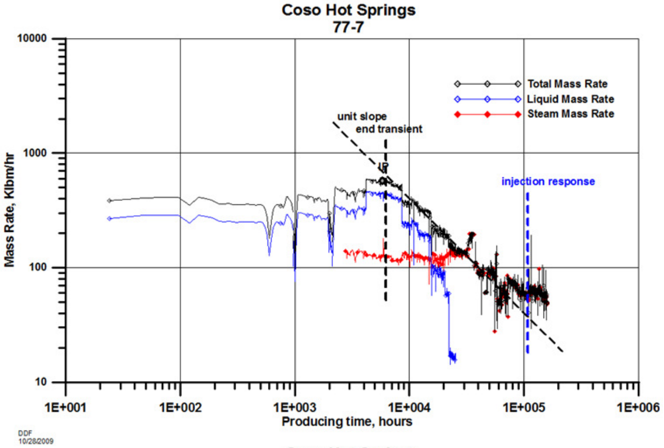
- Radial
- Fractured, ½ slope
- Bi-linear, ¼ slope
- Injection response

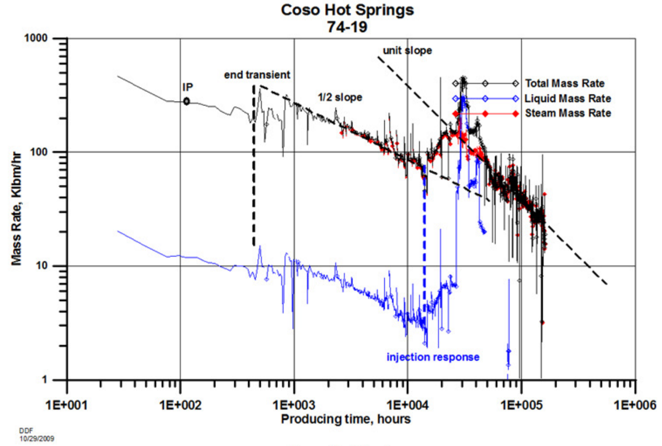
A simple numerical model was used to develop type decline response for a two-phase reservoir. The data was reduced to type curves and used to estimate the *kh* for each well

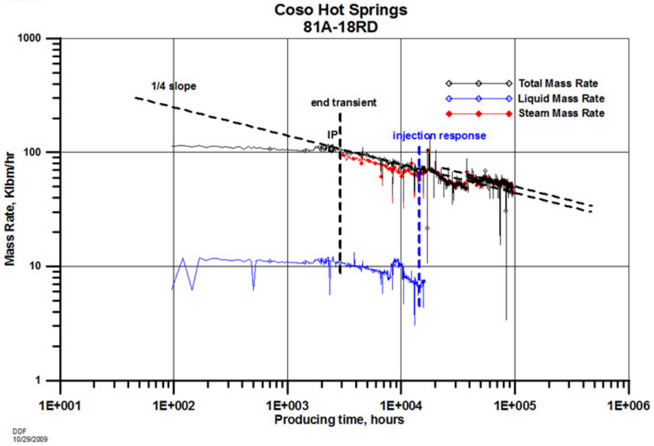
- Used to construct a kh model by depth
- Pre-processing production data analytically greatly assists the reservoir model calibration

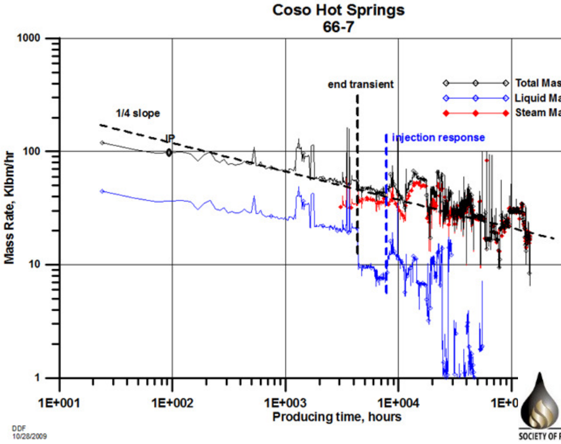












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Closed Loop Geothermal

A Brief Overview

by Fred LeGrand, LGAN Earth LLC

Objectives of this Talk

- ☐ Define Closed Loop Geothermal (CLGT)
- ☐ Introduce you to CLGT well types, components and EGS
- ☐ Discuss Pro’s and Con’s of Well Types
- ☐ Talk a little about Rt …. Thermal Resistance
- ☐ What’s Important and also… What’s NOT
- ☐ Do a little ENGINEERING
- ☐ Put some <u>rough</u> Size-Scale on this problem

What does "Closed Loop Geothermal Well" Mean?

(Fred's Working Definition)

Geothermal heat transfer primarily via <u>Conduction</u> mechanism

- ☐ A wellbore designed to capture the Earth's inherent heat energy (Enthalpy)
- ☐ Typically accomplished via circulating a working fluid within the wellbore
- ☐ No introduction/exchange of hydrothermal fluids occurs outside the wellbore
  - (…….. or almost none …. I'll explain later)
- ☐ So …. No <u>Mass Transfer</u> occurs between working fluid and subsurface hydrothermal formations
- ☐ Simply stated … Earth's Heat-Enthalpy → Casing → Working fluid
- ☐ All Enthalpy gains within the Working fluid are via Conduction from the Earth

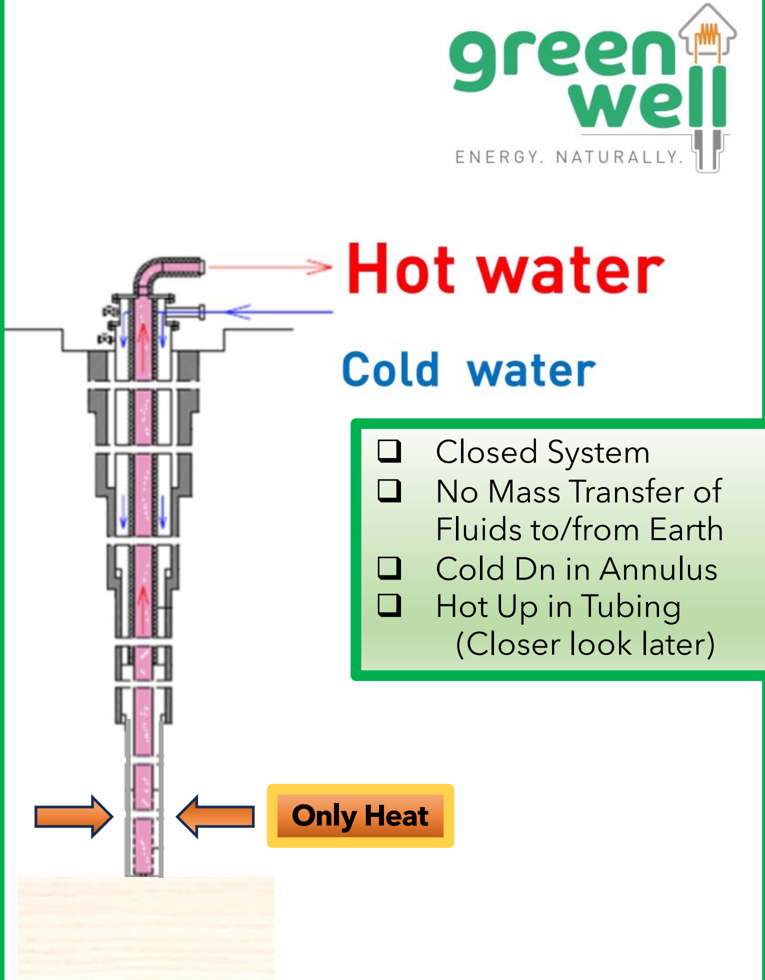
What are some Closed Loop Geothermal Designs?

Several Closed or "Nearly Closed" Loop designs are being tested :

- ☐ Single well Concentric flow (typical re-purposed O-G well-GreenWell)
- ☐ Vertical existing GT well (Closed loop liner – GreenFire)
- ☐ Single well Concentric flow HZ well (or high angle - Eden)
- ☐ Single well Repurposed w/Frac (GeoThermal Huff n' Puff "Battery" – Sage)
- ☐ U-tube design Casing flow (2 BHoles w/HZ section -- Eavor Lite design)
- ☐ "Doublet" well Casing flow (2 Multi-lateral wells -- Eavor Loop 1.0 & 2.0 design)
- ☐ "Enhanced Doublet" well Casing flow (2 HZ wells with Frac -- Fervo design)

Closed Loop Designs

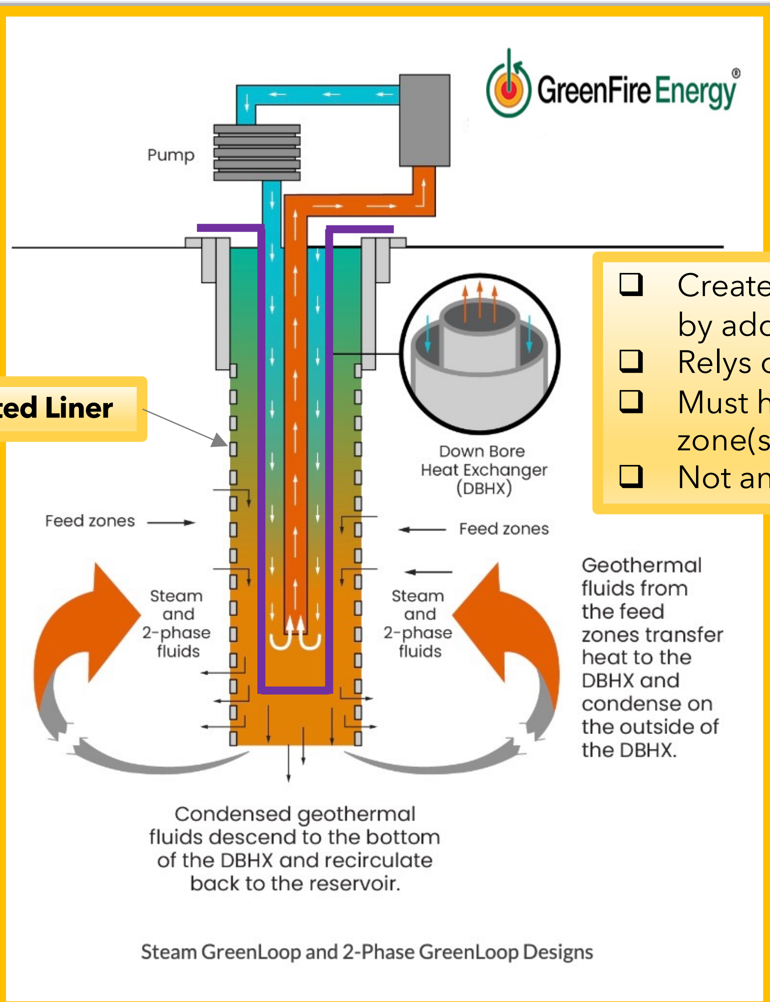
Single well Concentric
Typical Repurposed O-G Vertical or
HZ or Pad well



- ☐ Closed System
- ☐ No Mass Transfer of Fluids to/from Earth
- ☐ Cold Dn in Annulus
- ☐ Hot Up in Tubing (Closer look later)

Only Heat

Retrofitted GeoThermal well or
New Fit-for-Purpose (SAGD?)



Slotted Liner

Geothermal fluids from the feed zones transfer heat to the DBHX and condense on the outside of the DBHX.

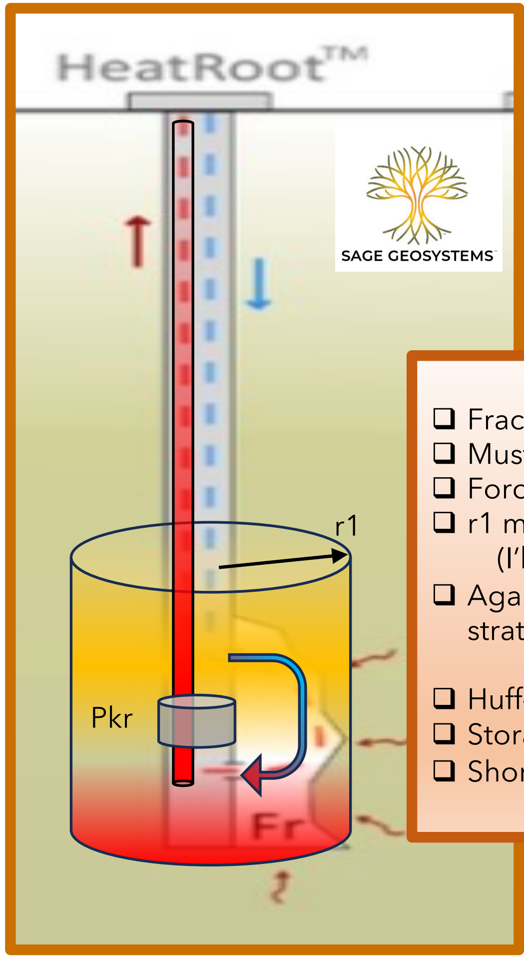
Condensed geothermal fluids descend to the bottom of the DBHX and recirculate back to the reservoir.

Steam GreenLoop and 2-Phase GreenLoop Designs

- ☐ Create Closed Loop conditions by adding a Casing String
- ☐ Relys on Natural Convection
- ☐ Must have Hydrothermal zone(s) to be effective
- ☐ Not an "EveryWhere Solution"

EGS Closed Loop Geothermal Designs

Sage Geosystems

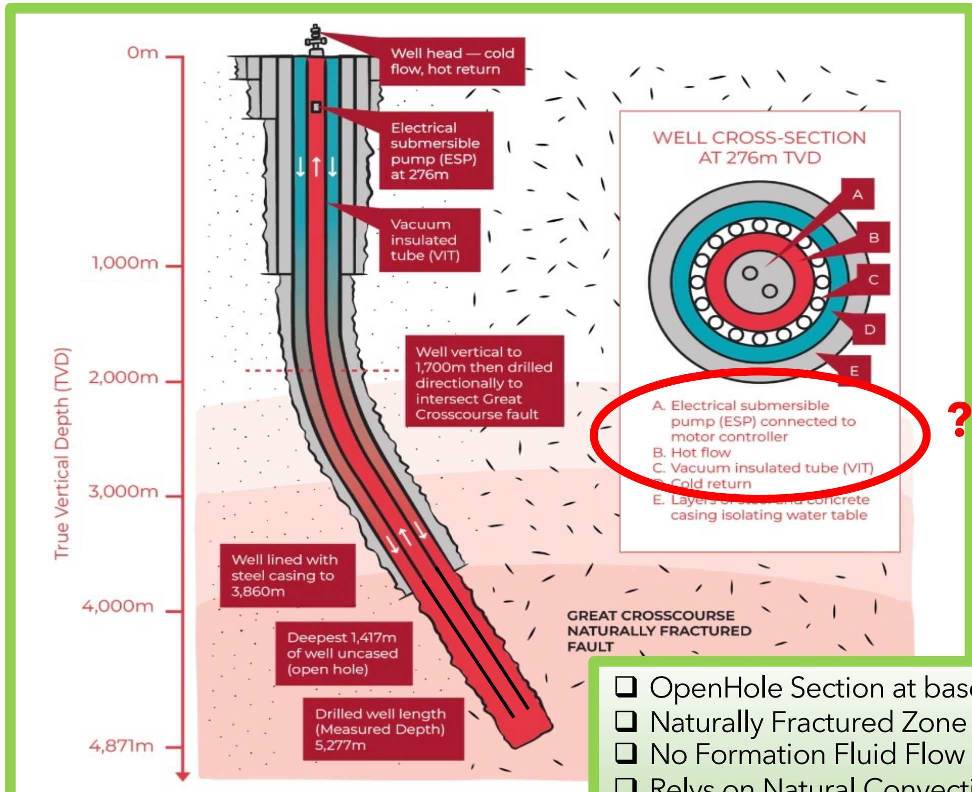


Interesting ideas…..

- ☐ Fracture Flow (HeatRoot tm)
- ☐ Must have Hydrothermal Zone(s)
- ☐ Forced Convection
- ☐ r1 maybe small (Rwe)?
  (I'll explain later)
- ☐ Again, Limited utilization areal and stratigraphic

- ☐ Huff-N-Puff (HeatCycle tm)
- ☐ Storage Battery idea
- ☐ Short Cycle (4-18 Hrs)

eden geothermal

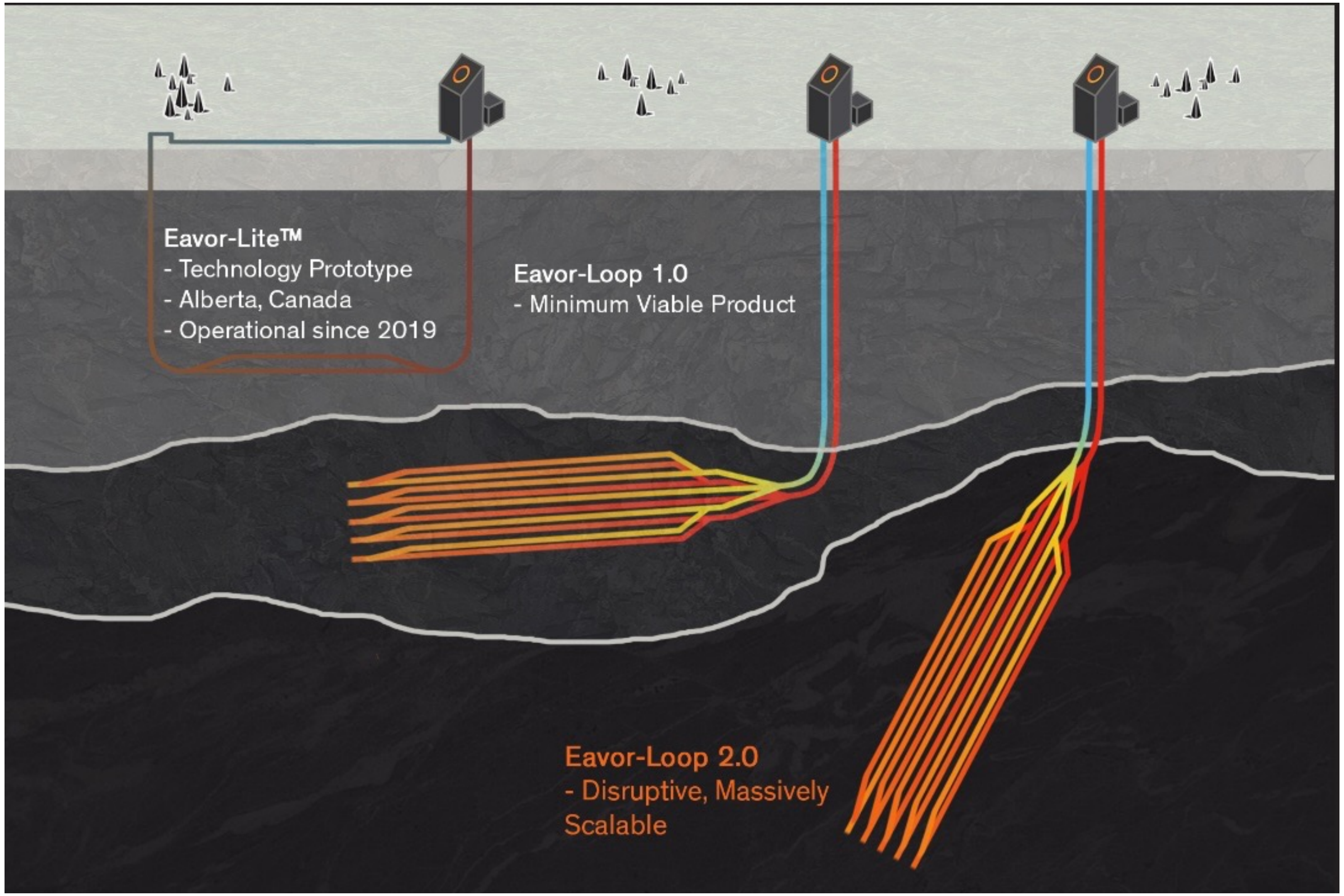


The plate heat exchanger at the surface of the well site transfer
transports it to the heat loads on the Eden Project site: the Eden
other buildings) and Growing Point – Eden's newly-constructed
associated buildings.

- ☐ OpenHole Section at base
- ☐ Naturally Fractured Zone Reqd
- ☐ No Formation Fluid Flow In??
- ☐ Relys on Natural Convection
- ☐ Must have Hydrothermal Zone
- ☐ ESP ? … Why not surface pump
- ☐ VIT may be over-kill & $$$

EGS Closed Loop Geothermal Designs

Eavor™



<u>3 Designs… E-Lite, E-Loop 1.0 & 2.0</u>

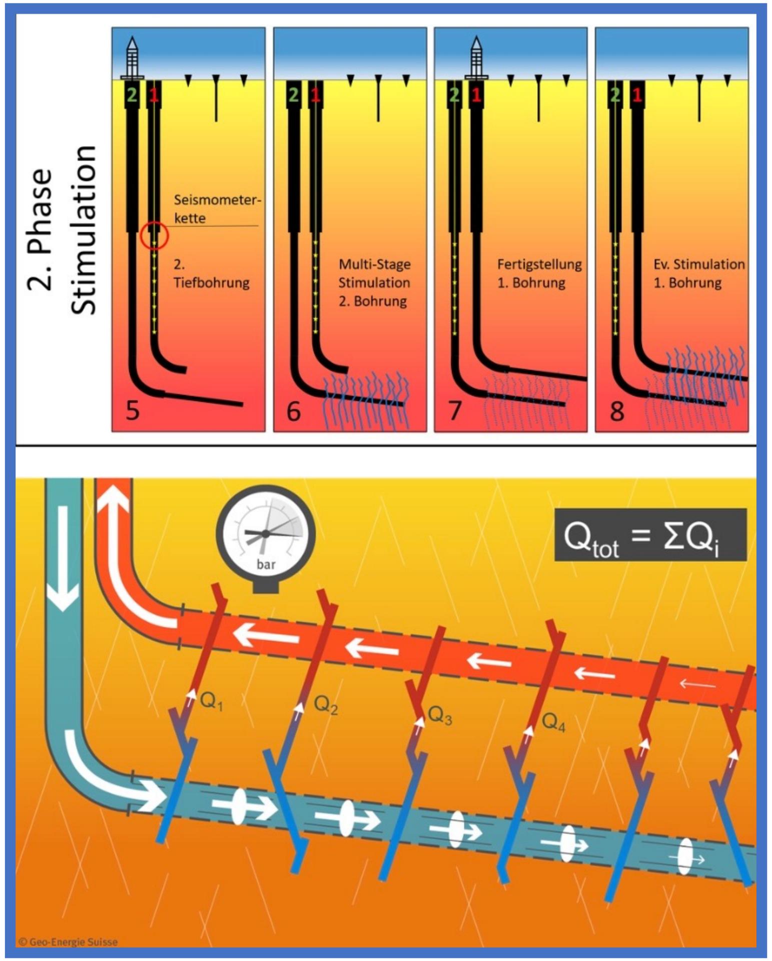
❑ E-Lite… Two HZ wells connected as U-Tube
❑ Dr Ramey modelled this in the 1980's
❑ On Prod since 2019 (Commercial??)

❑ E Loop(s) …. Cased to KOP
❑ Multi Lateral OH connected at "Toe"
❑ OH Treated with Silicate solution to "seal it up" … no Casing in "radiator"
❑ Avoids Fracture Stimulation …. Social Fear?
❑ Downhole "Radiator" per se
❑ Need to consider Rinv for multi-lateral spacing
❑ Trying this in Europe now

EGS Geothermal Designs with Frac Stimulation

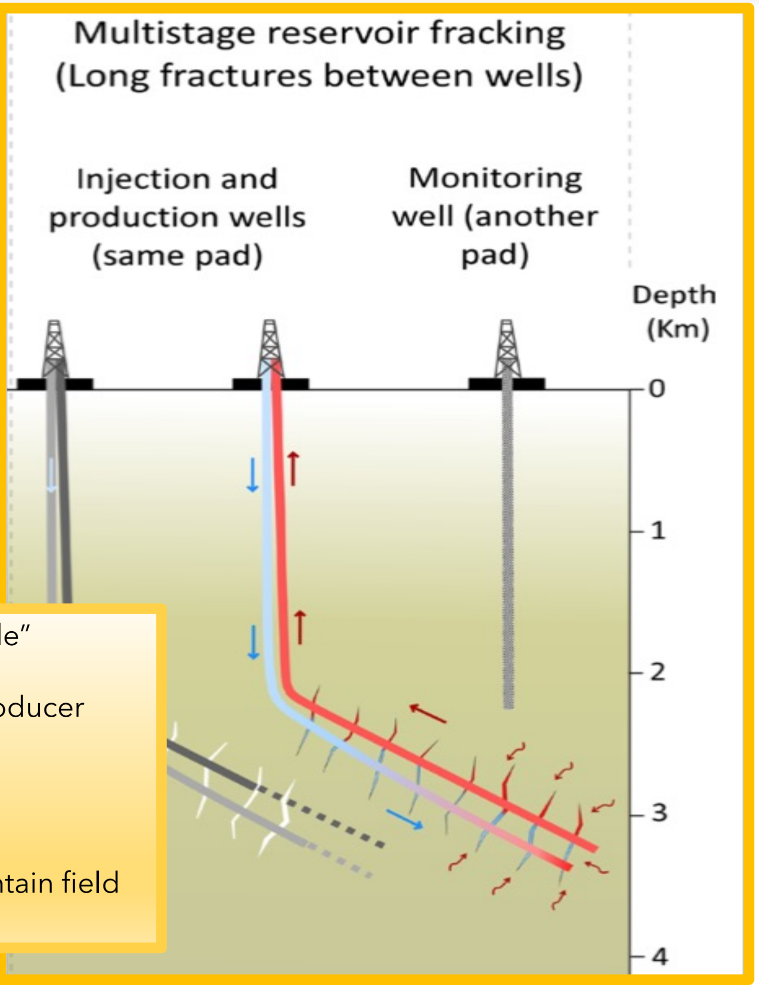
GEO ENERGIE SUISSE

FERVO ENERGY



- ☐ Prefer Natural Fractures
- ☐ EU is Sensitive to induced seismicity
- ☐ Multi-Stage "Stimulation" not FRAC
- ☐ EU is sensitive to FRAC idea
- ☐ No WFluid flow Outside SRV?

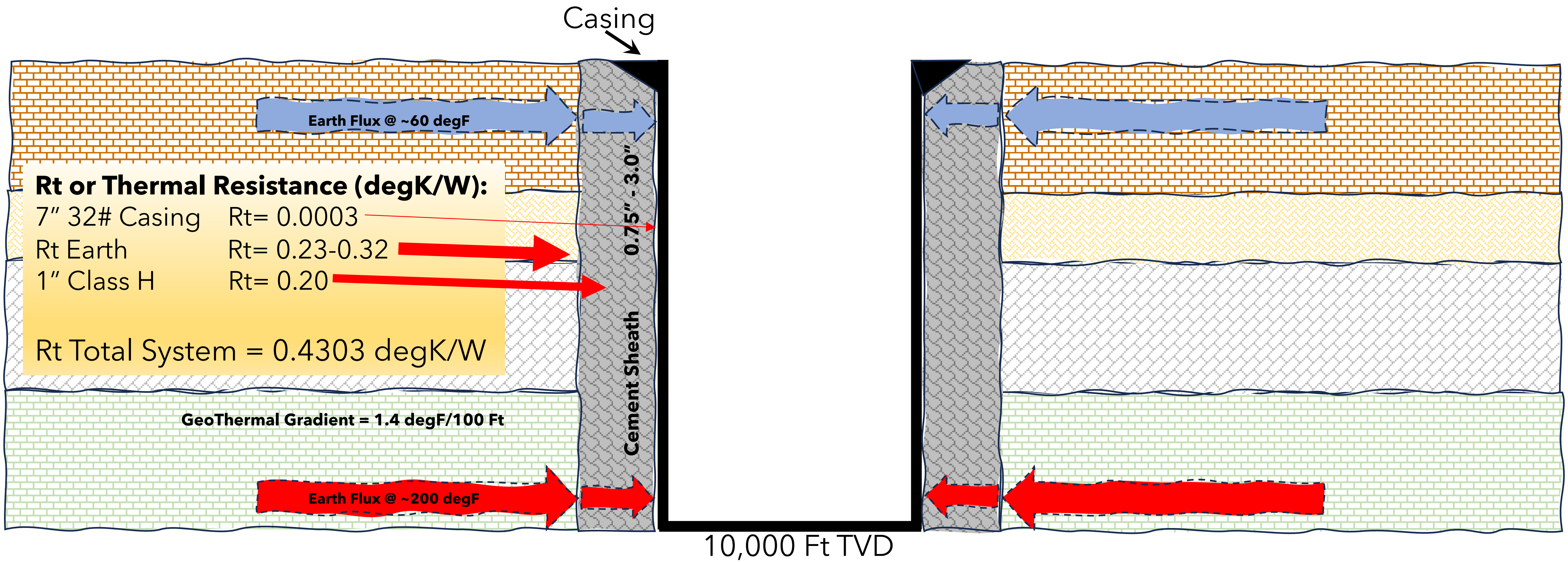
Essentially Fervo Design



- ☐ Target is HOT "Impermeable" Granite-Diorite
- ☐ High Angle Injector and Producer
- ☐ Both Cased to TD
- ☐ Both Multi-Stage Frac'd
- ☐ Plug and Perf … SOFP
- ☐ Closed Loop? …. Maybe?
- ☐ Design tested in Blue Mountain field

Closed Loop Geothermal Well Engineering

Simple Concentric from Earth Side



Rt or Thermal Resistance (degK/W):

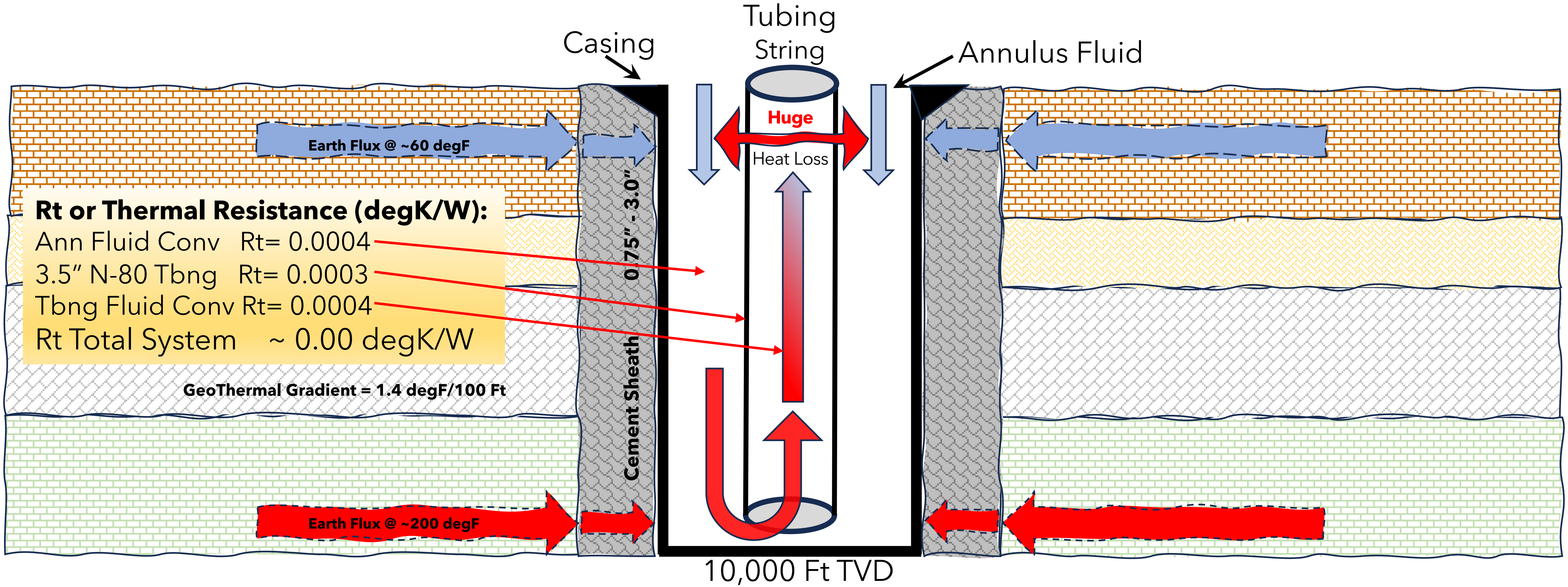
7" 32# Casing	Rt= 0.0003
Rt Earth	Rt= 0.23-0.32
1" Class H	Rt= 0.20

Rt Total System = 0.4303 degK/W

Closed Loop Geothermal Well Engineering

Without Tubing Insulation the System Goes to ~Equilibrium

"IT BECOMES A WASHING MACHINE not a Heat Exchanger"



Rt or Thermal Resistance (degK/W):

Ann Fluid Conv	Rt= 0.0004
3.5" N-80 Tbng	Rt= 0.0003
Tbng Fluid Conv	Rt= 0.0004
Rt Total System	~ 0.00 degK/W

Lesson is - Model First ...... then Demo/Test

Hrušky Z40

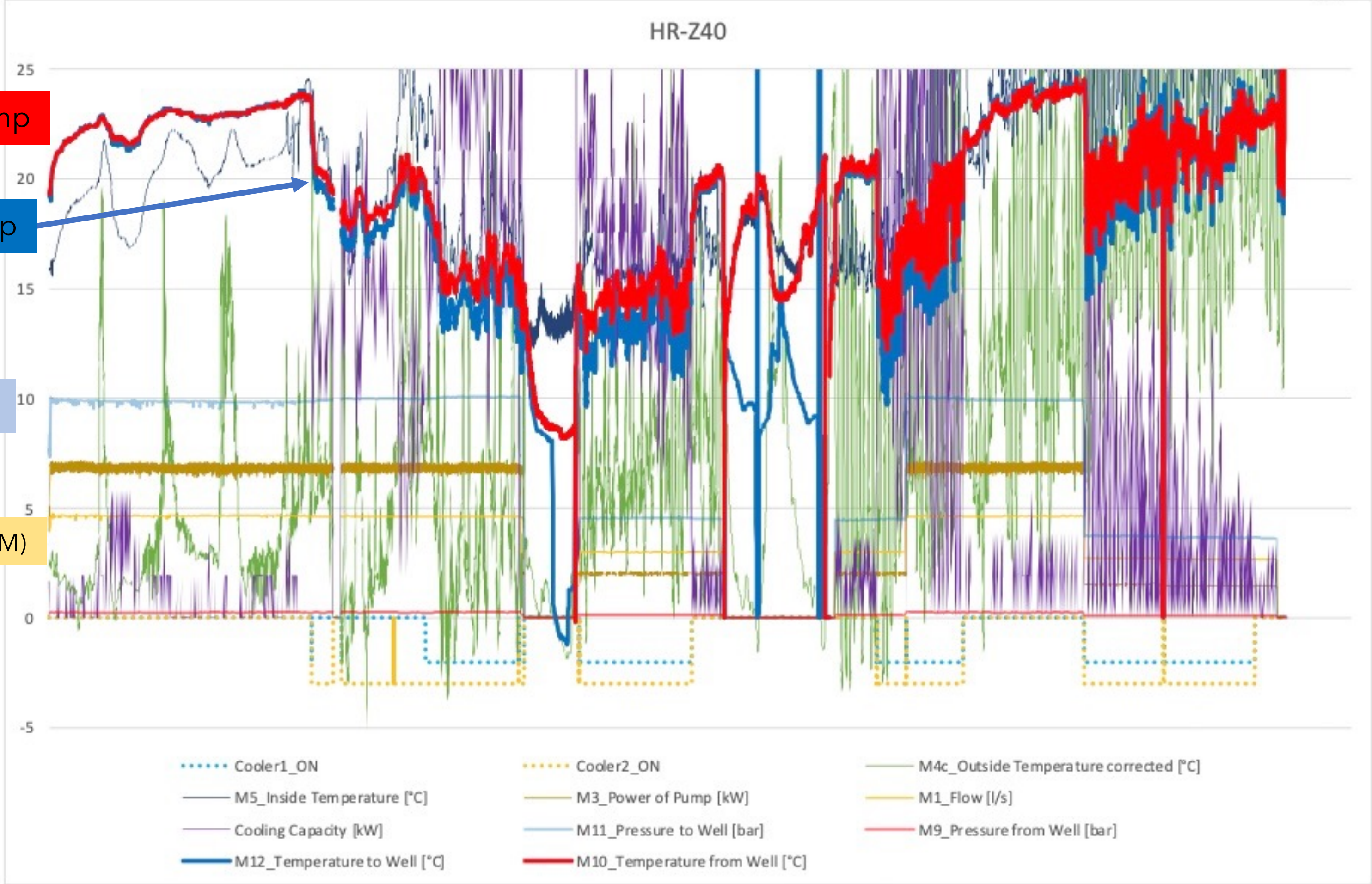
green well
ENERGY. NATURALLY.

Centralizers →
Not Needed!

Outlet Temp
||
Inlet Temp

145 psi Inlet

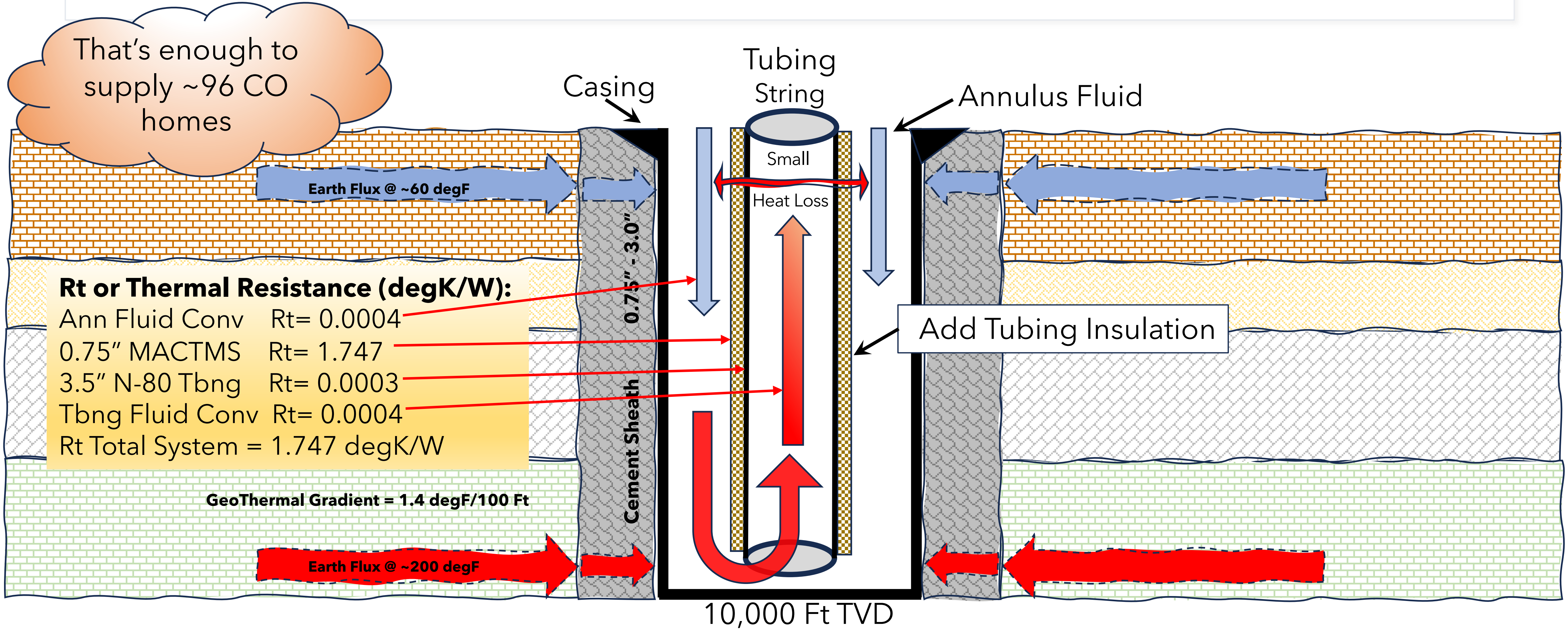
4.8 LPS (1.8 BPM)



Typical Closed Loop Geothermal Well Designs

Tubing Insulation provides a large Thermal Barrier

But ….. Moderate heat loss exists → Iterative Calculation



That’s enough to supply ~96 CO homes

Rt or Thermal Resistance (degK/W):

Ann Fluid Conv Rt= 0.0004

0.75” MACTMS Rt= 1.747

3.5” N-80 Tbng Rt= 0.0003

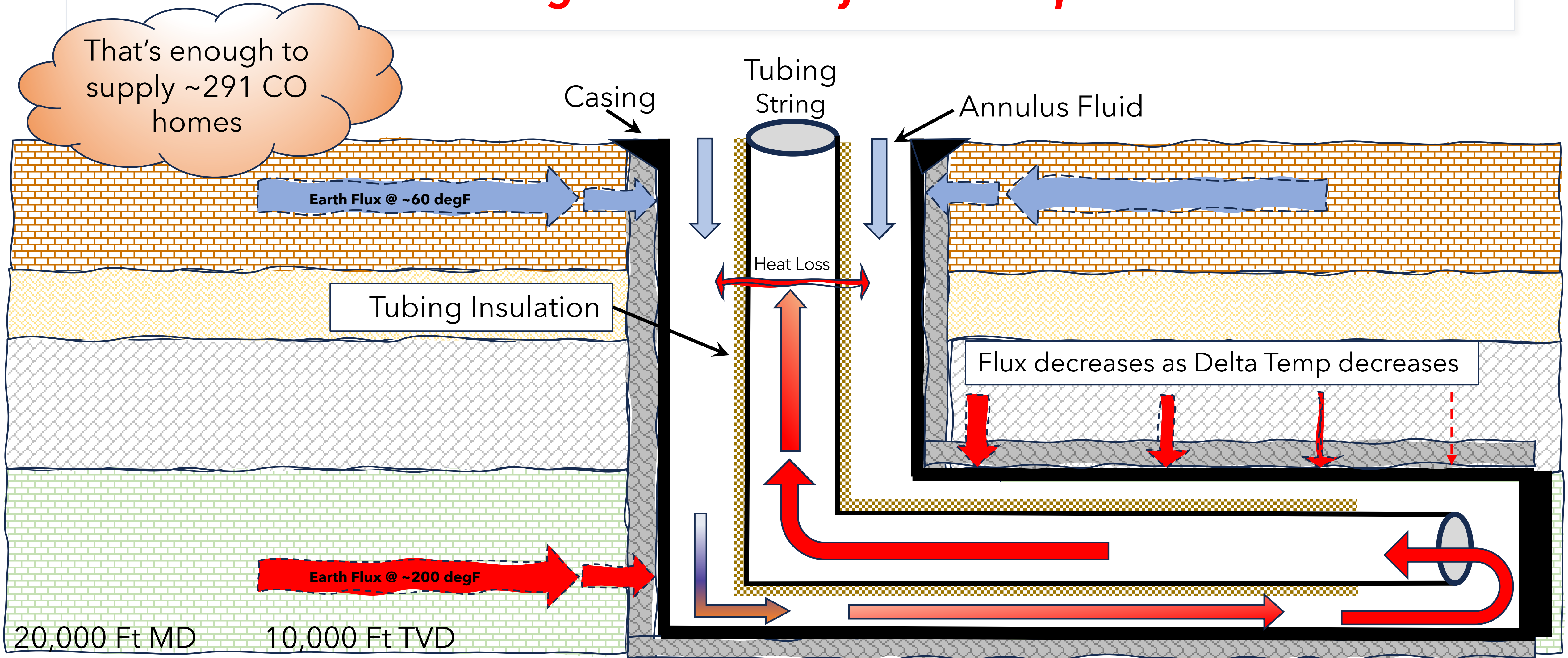
Tbng Fluid Conv Rt= 0.0004

Rt Total System = 1.747 degK/W

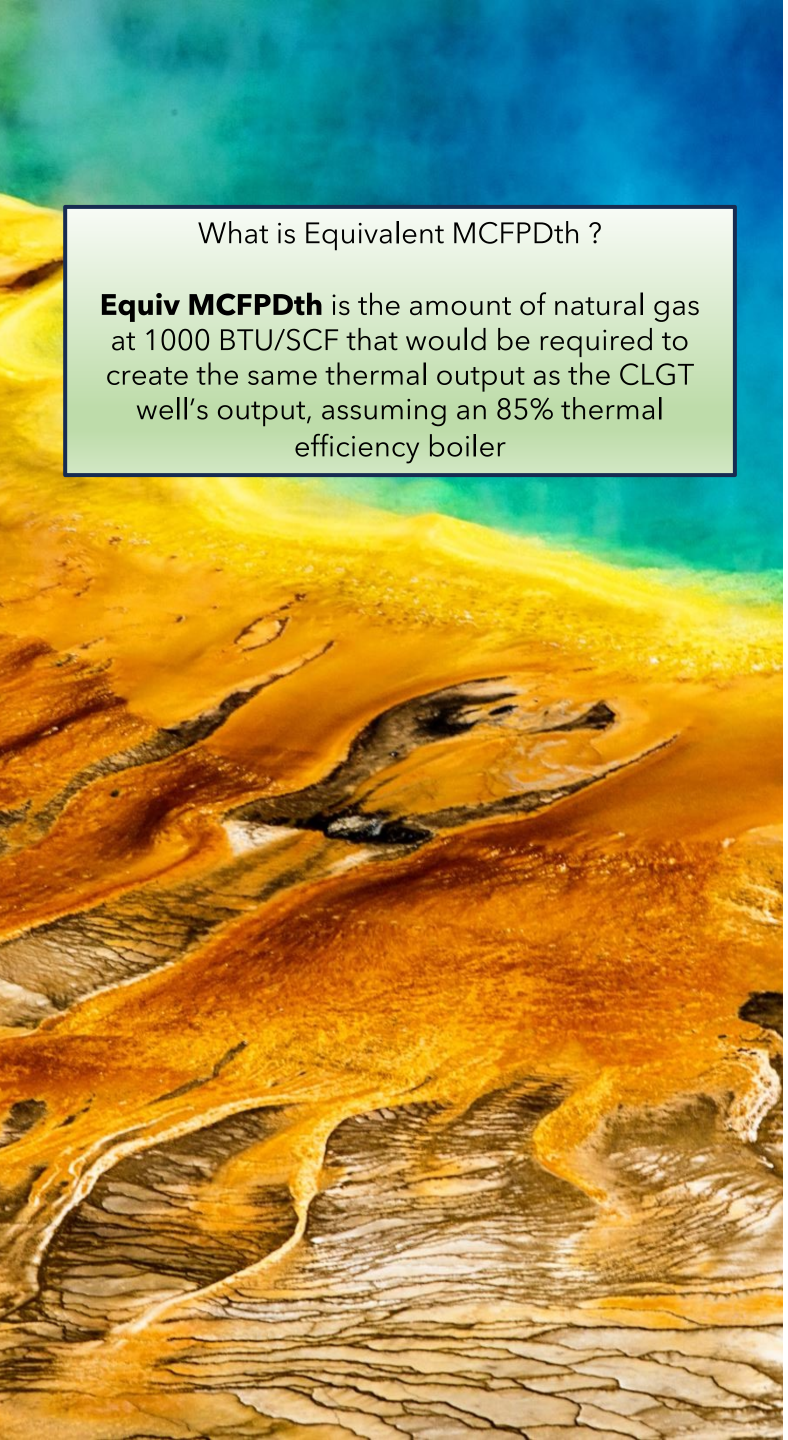
Typical Closed Loop Geothermal Well Designs

ALL Closed Loop wells should be modelled First!

Modelling allows for Projection & Optimization



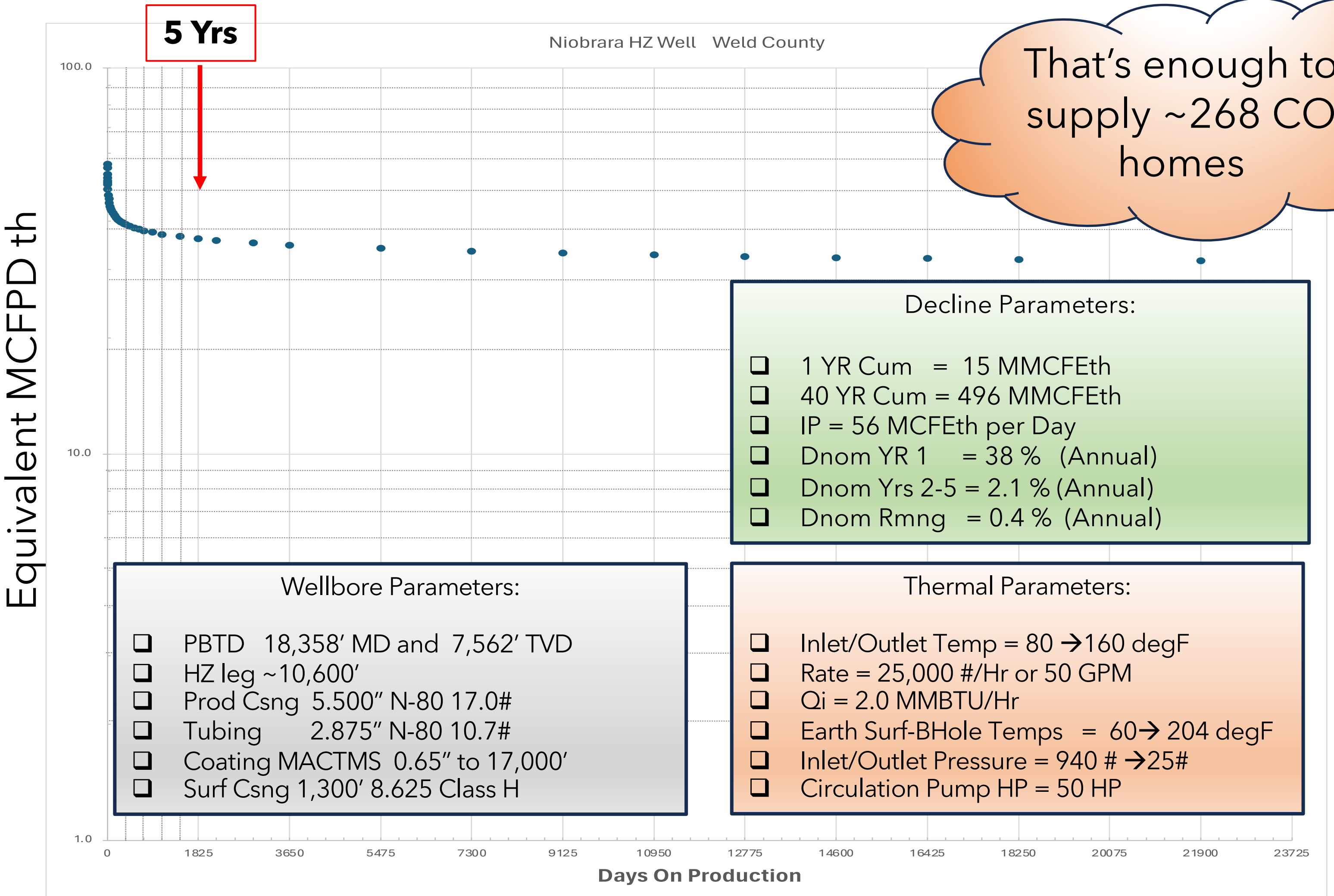
That's enough to supply ~291 CO homes



What is Equivalent MCFPDth ?

Equiv MCFPDth is the amount of natural gas at 1000 BTU/SCF that would be required to create the same thermal output as the CLGT well's output, assuming an 85% thermal efficiency boiler

Weld County Niobrara HZ Re-Purpose Existing Well



That's enough to supply ~268 CO homes

Decline Parameters:

- ☐ 1 YR Cum = 15 MMCFEth
- ☐ 40 YR Cum = 496 MMCFEth
- ☐ IP = 56 MCFEth per Day
- ☐ Dnom YR 1 = 38 % (Annual)
- ☐ Dnom Yrs 2-5 = 2.1 % (Annual)
- ☐ Dnom Rmng = 0.4 % (Annual)

Wellbore Parameters:

- ☐ PBTD 18,358' MD and 7,562' TVD
- ☐ HZ leg ~10,600'
- ☐ Prod Csng 5.500" N-80 17.0#
- ☐ Tubing 2.875" N-80 10.7#
- ☐ Coating MACTMS 0.65" to 17,000'
- ☐ Surf Csng 1,300' 8.625 Class H

Thermal Parameters:

- ☐ Inlet/Outlet Temp = 80 →160 degF
- ☐ Rate = 25,000 #/Hr or 50 GPM
- ☐ Qi = 2.0 MMBTU/Hr
- ☐ Earth Surf-BHole Temps = 60→ 204 degF
- ☐ Inlet/Outlet Pressure = 940 # →25#
- ☐ Circulation Pump HP = 50 HP

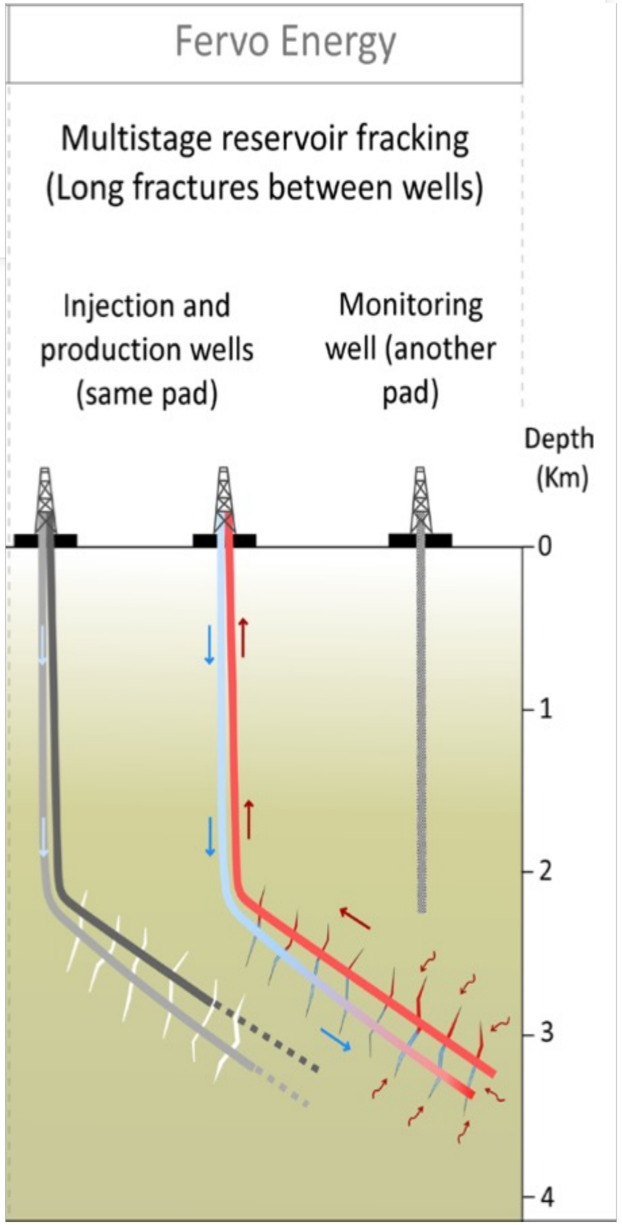
Fervo Conceptual EGS "Closed Loop" Geothermal Design

Fervo design

- ☐ A Pair of High Angle HZ Wells drilled into hot impermeable formation
- ☐ Drilled with laterals ~3250 feet long and ~365 feet apart
- ☐ Injector drilled slightly deeper than Producer to induce natural convection
- ☐ Multi-Stage Hydraulic Frac stimulation (both wells plug and perf)
- ☐ RESULT : High volume working fluid flow between the two laterals

Why this design?

- ☐ High Volume Flow : Takes advantage of full casing flow versus concentric
- ☐ Huge Increase in Earth Flux : Increases Rweff from 1 foot to ~ 400 feet



Fervo #34A-22 Actual SRV Results from MicroSeismic

Fervo #34A-22 Doublet Pair Design

❑ A Pair of HZ Wells drilled into hot impermeable Diorite-GranoDiorite

❑ Blue Mountain Field in N Central Nevada

❑ Blue dots are Injector Micro-Seismic events

❑ Red dots are Producer Micro Seismic events

❑ SRV dimensions are:

    ❑ Up to 3,250 ft in Lateral length
    ❑ 1,600-2,300 ft perpendicular to wells
    ❑ 800-2,500 ft high

❑ This may have been too aggressive??

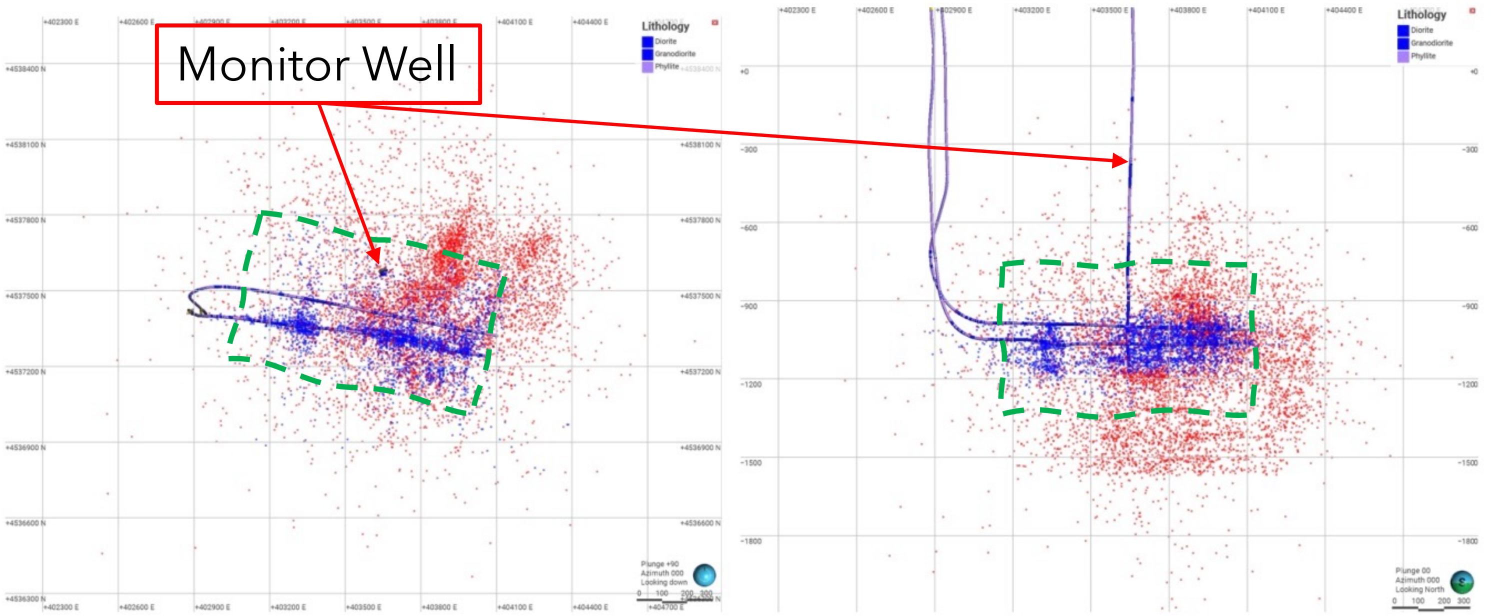


Fig. 13 Plan view (left) and cross-section view (right) of the distribution of microseismic events recorded during the stimulation treatments of Injection Well 34A-22 (blue dots) and Production Well 34-22 (red dots). These events represent the locations of the highest quality events detected on the multiwell DAS fiber optic sensing array.

Fervo EGS Results

That's enough to supply 8,500 CO homes But…..
It's a **really** long pipeline from Nevada

Fervo Results

- ❑ Tested Doublet pair for 43 Days
- ❑ Injection rates 650-900 GPM and pressures of 1600 to 2200 psi
- ❑ Inlet fluid temperature of 80 to 125 degF
- ❑ Outlet temperature of 280 to 330 degF fluid!
- ❑ Generating up to 3.5 MW of electricity
- ❑ Using about 0.8 MW for circulating pump
- ❑ Had leakoff issue during test but apparently resolved it?

- ❑ Most current rate to Blue Mountain Thermal Plant:
  - ❑ **750 GPM (~18 BPM) of 355 degF water**
  - ❑ **Inlet temperature of 150 degF**
  - ❑ **Looks like it's getting hotter post test**
- ❑ That's thermal energy of **1,700 MCFEth per day**

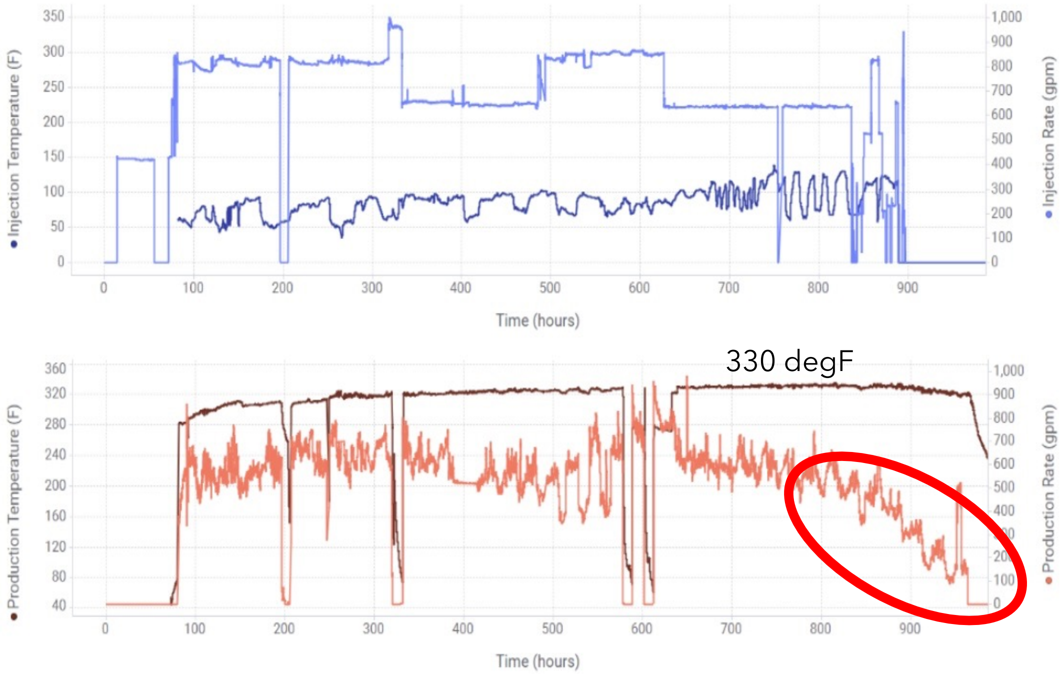


Fig. 4 Flow rate and flowing wellhead temperature recordings during the 37-day circulation test for Injection Well 34A-22 (top) and Production Well 34-22 (bottom).

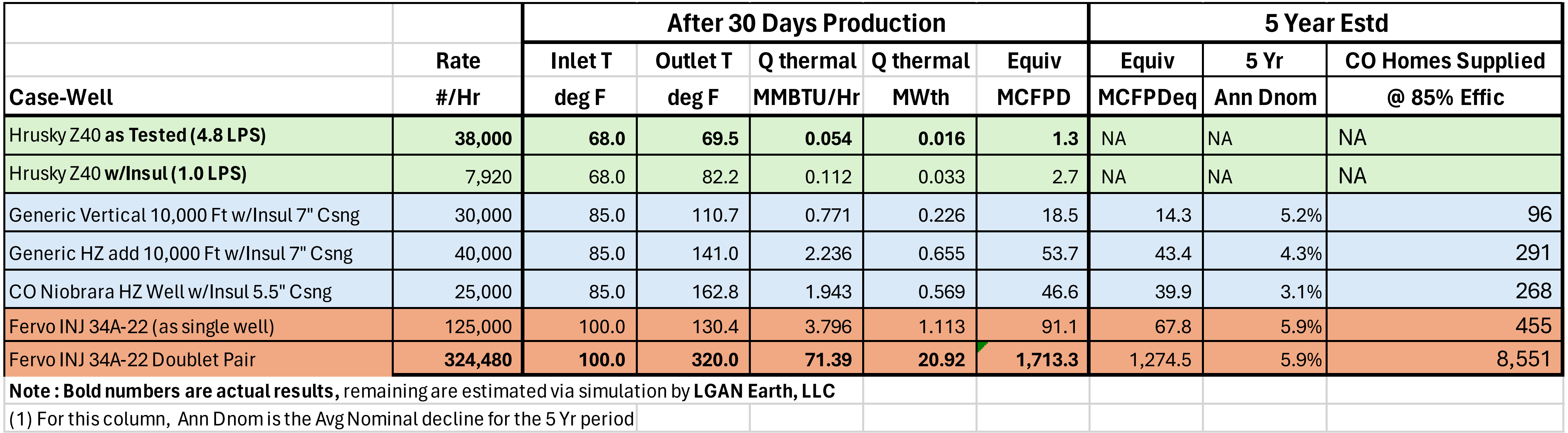
Why is this important?

- ❑ This is their **first attempt** and a huge technological success

Remember when George Mitchell fracked the first Barnett Shale well 25 plus years ago

Closed Loop GeoThermal Output Comparison

Let's examine/compare some Thermal Output values:



		After 30 Days Production					**5 Year Estd**		
Case-Well	**Rate #/Hr**	**Inlet T deg F**	**Outlet T deg F**	**Q thermal MMBTU/Hr**	**Q thermal MWth**	**Equiv MCFPD**	**Equiv MCFPDeq**	**5 Yr Ann Dnom**	**CO Homes Supplied @ 85% Effic**
Hrusky Z40 **as Tested (4.8 LPS)**	**38,000**	**68.0**	**69.5**	**0.054**	**0.016**	**1.3**	NA	NA	NA
Hrusky Z40 **w/Insul (1.0 LPS)**	7,920	68.0	82.2	0.112	0.033	2.7	NA	NA	NA
Generic Vertical 10,000 Ft w/Insul 7" Csng	30,000	85.0	110.7	0.771	0.226	18.5	14.3	5.2%	96
Generic HZ add 10,000 Ft w/Insul 7" Csng	40,000	85.0	141.0	2.236	0.655	53.7	43.4	4.3%	291
CO Niobrara HZ Well w/Insul 5.5" Csng	25,000	85.0	162.8	1.943	0.569	46.6	39.9	3.1%	268
Fervo INJ 34A-22 (as single well)	125,000	100.0	130.4	3.796	1.113	91.1	67.8	5.9%	455
Fervo INJ 34A-22 Doublet Pair	**324,480**	**100.0**	**320.0**	**71.39**	**20.92**	**1,713.3**	1,274.5	5.9%	8,551

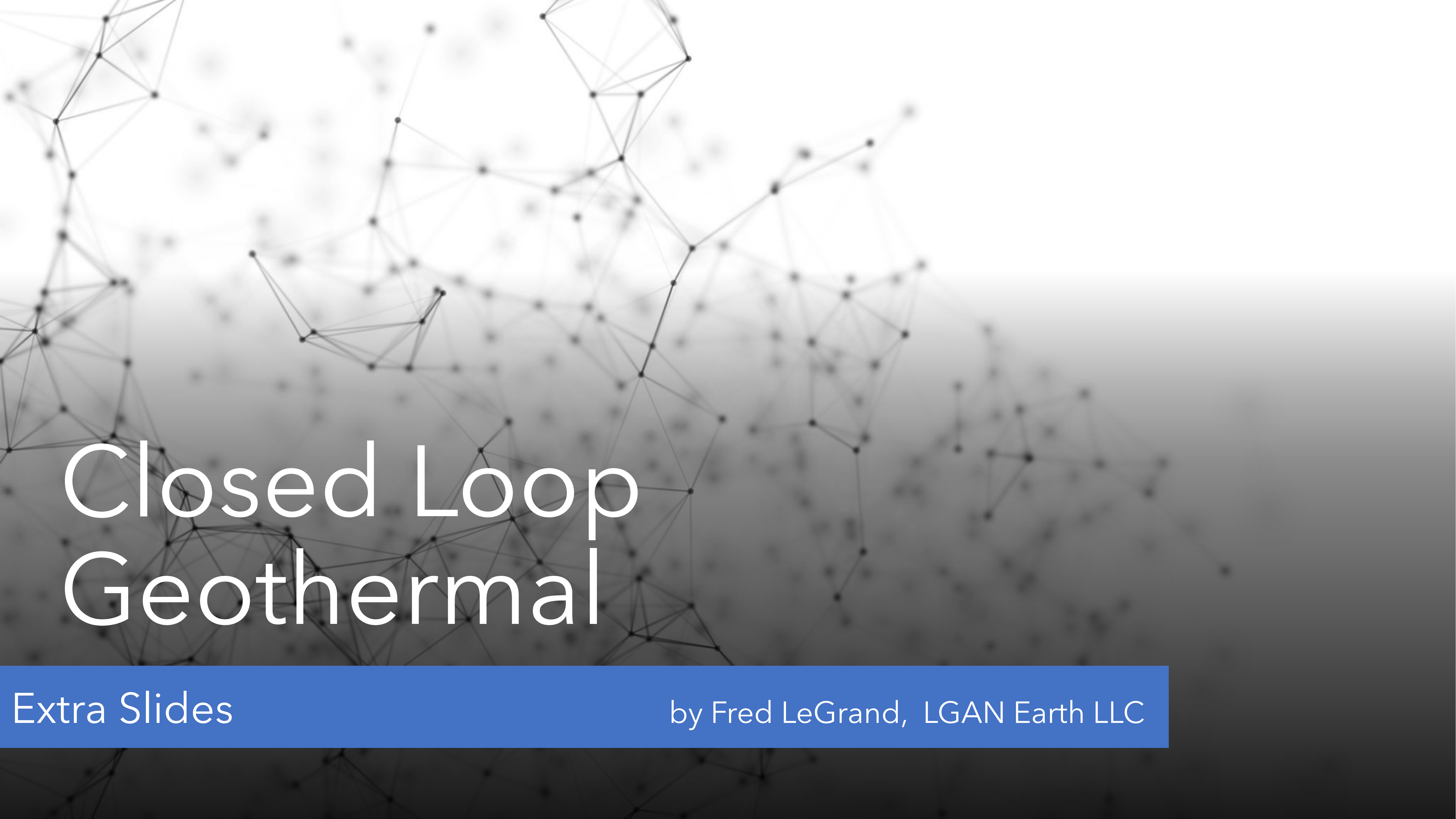
Note : Bold numbers are actual results, remaining are estimated via simulation by **LGAN Earth, LLC**

(1) For this column, Ann Dnom is the Avg Nominal decline for the 5 Yr period

Closed Loop Geothermal

Thank You !!

by Fred LeGrand, LGAN Earth LLC



Closed Loop Geothermal

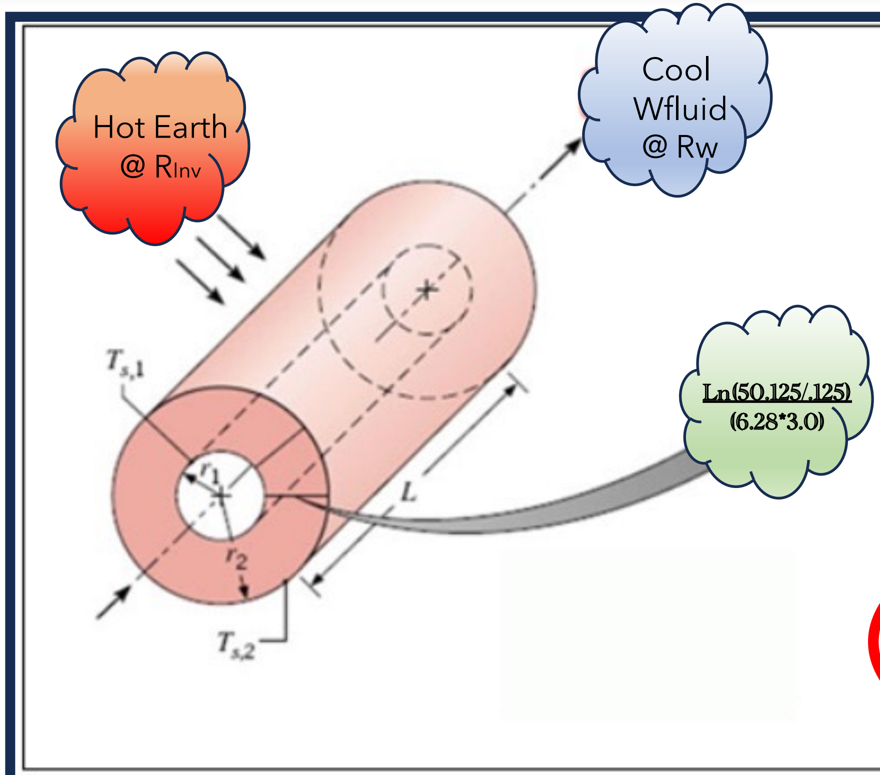
Extra Slides

by Fred LeGrand, LGAN Earth LLC

The Thermodynamics of EGS Design
Radial Conduction and Rt Computation

How do we compute Rt for the Earth?
(in cylindrical slabs or layers)

- ☐ **It changes with the drainage boundary … Rinv**
- ☐ **But … We can calculate Rinv as a function of time !**
- ☐ **Let's compute at time slice 25 Yrs elapsed time**
- ☐ **r1 is our wellbore plus cement radius or about 0.125 meters**
- ☐ **r2 is the drainage boundary of our "reservoir" or ~50 meters (in 25 years constant flow)**
- ☐ **L =1m & k = 3.0 W/m-K**
- ☐ **So …. Rt Earth = 0.32 degK/W (BTW it's ~ 0.23 at 1 yr)**



$$\dot{Q}_{cond} = \frac{2\pi Lk\left(T_{s,1} - T_{s,2}\right)}{\ln\left(r_2 / r_1\right)}$$

PE's out there …Does this equation look familiar?

$$R_{cond} = \frac{\ln\left(r_2 / r_1\right)}{2\pi Lk}$$

$$R_{tot} = \cancel{\frac{1}{h_1 A_1}} + \frac{\ln\left(r_2 / r_1\right)}{2\pi Lk}$$

(~ 0.0001) (~ 0.32 at 25 Yrs)

The Thermodynamics of EGS Design
Can we Reduce the Rt of the Earth?

That's enough to Heat ~8,500 CO homes!!

- ☐ **How do we Reduce Rt ....**

  Simply Thermo Dynamics !

  (Remember the Single well Rt = 0.32 $\text{degK}_{\text{diffl}}$/W)

  - **NOW ... For the "Boiler"**

    r1 = 125 m (not 0.125 m)

    r2 = 125+50 = 175 m

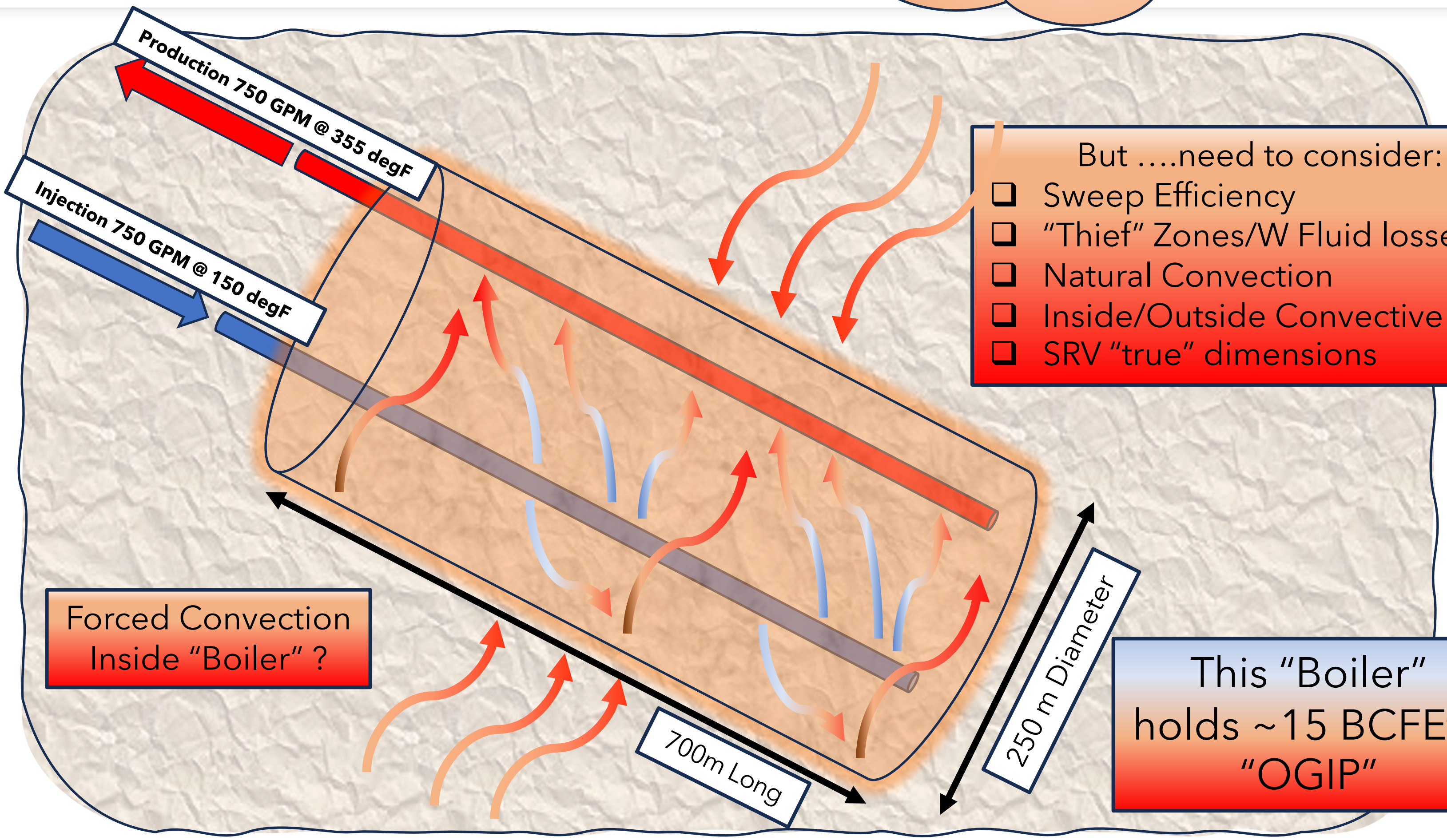
Now Rt =
$$\frac{\text{Ln}(175 / 125)}{(6.28*3.0)}$$

- **Rt = 0.018 $\text{degK}_{\text{diffl}}$/W**

  or a Reduction in R of >94%

<u>Adding 1 wellbore plus a frac achieves 19x " Ideal Earth Output"</u>

(56x at 1 Yr time slice)



Forced Convection Inside "Boiler" ?

But ....need to consider:
- ☐ Sweep Efficiency
- ☐ "Thief" Zones/W Fluid losses
- ☐ Natural Convection
- ☐ Inside/Outside Convective HTC
- ☐ SRV "true" dimensions

This "Boiler" holds ~15 BCFEth "OGIP"