Glenn Research Center

Sept 8, 2008

Perma Works

An energy company reaching new deep resources in geothermal power production

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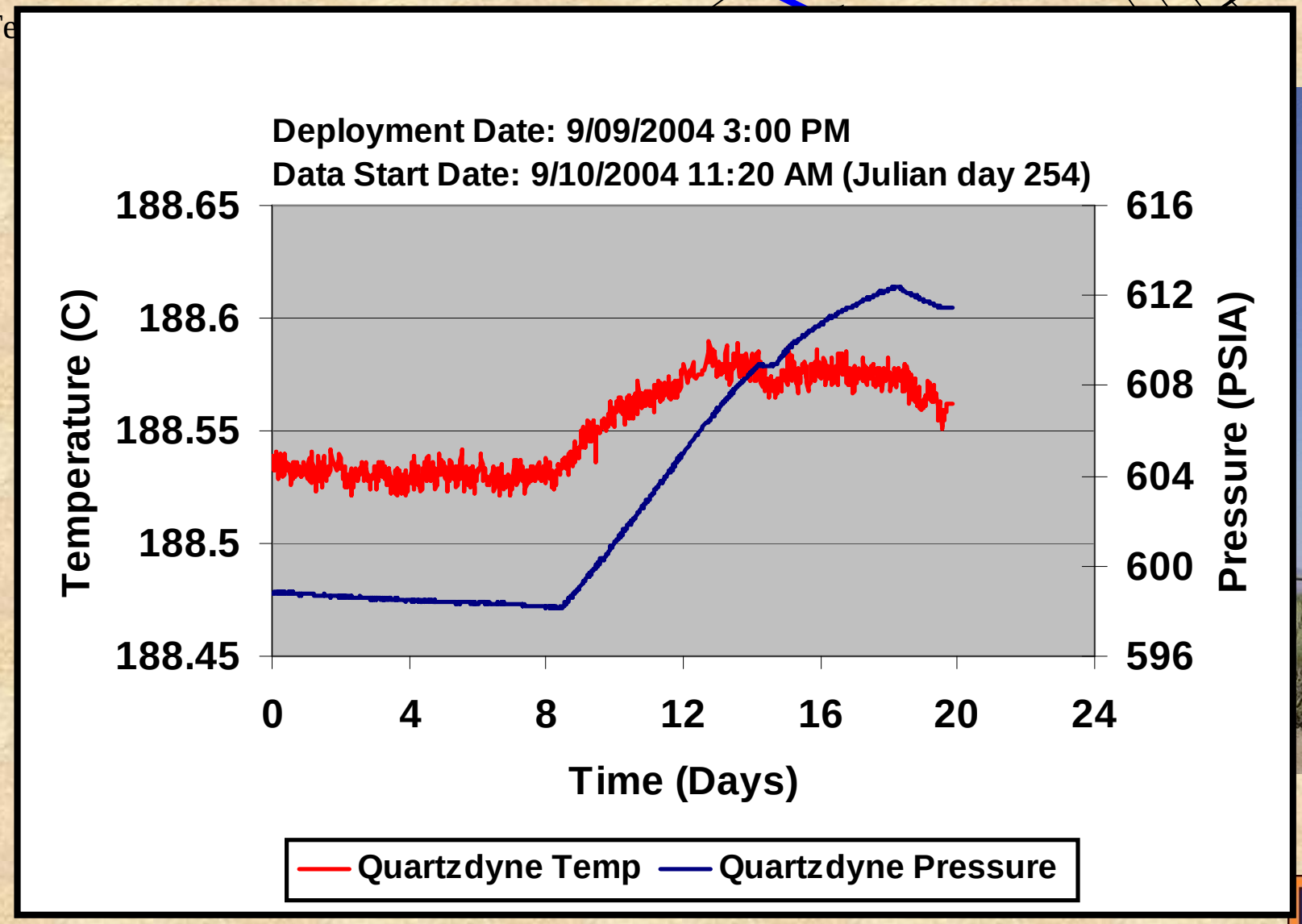
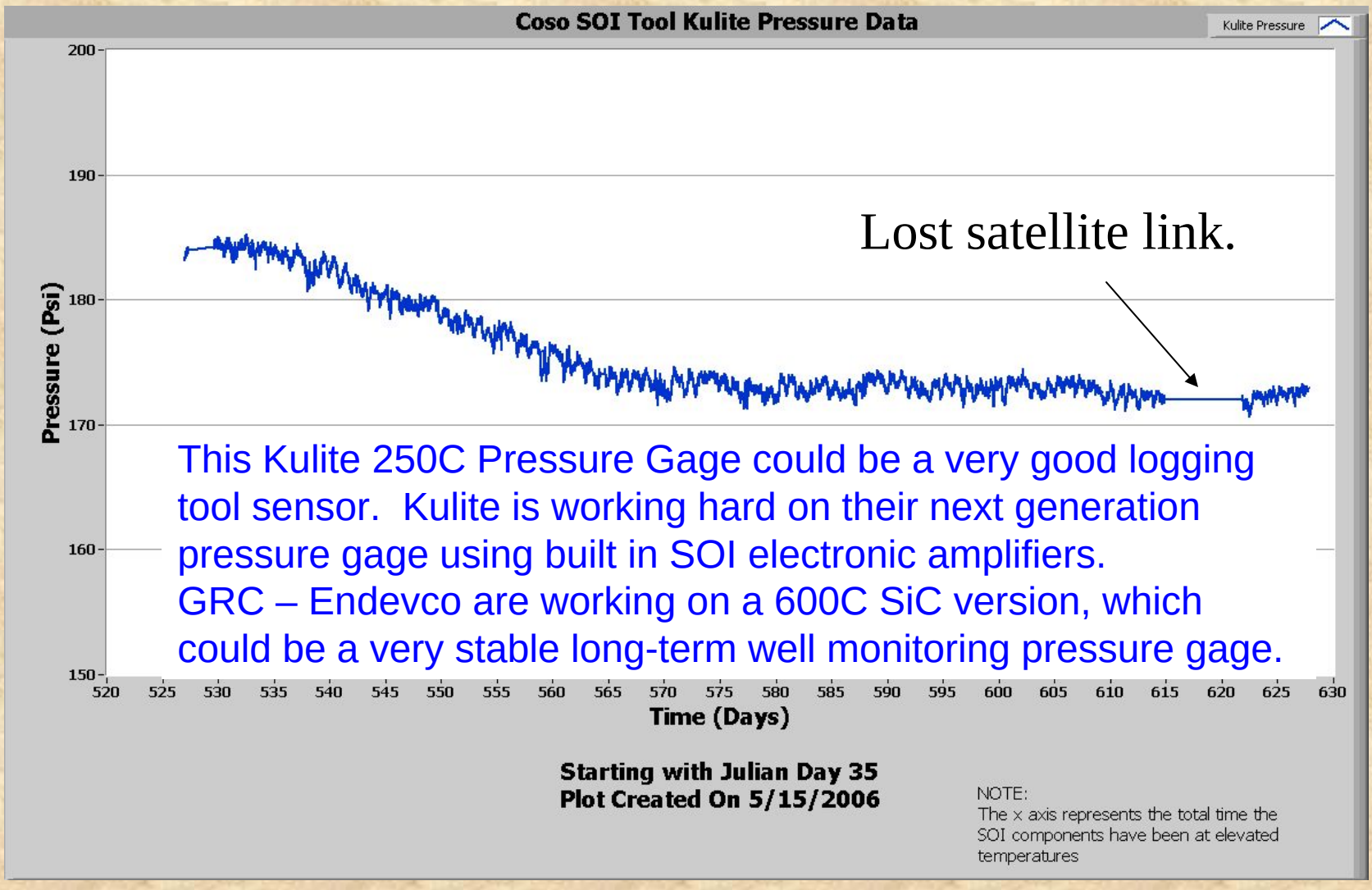
First Time Ever; Reservoir Recovery



Why Geothermal Monitoring Systems Fail or Areas of Potential Improvements

- Need WBG sensors and precision electronics to reduce drift at temperature
- Organic materials break down
  - Eliminates most seals
- Hydrogen changes resistor values
- Most metals are chemically attacked
- Large valued capacitors (>10uF) don’t exist
- HT Solders are difficult to work with
  - Manual fabrication

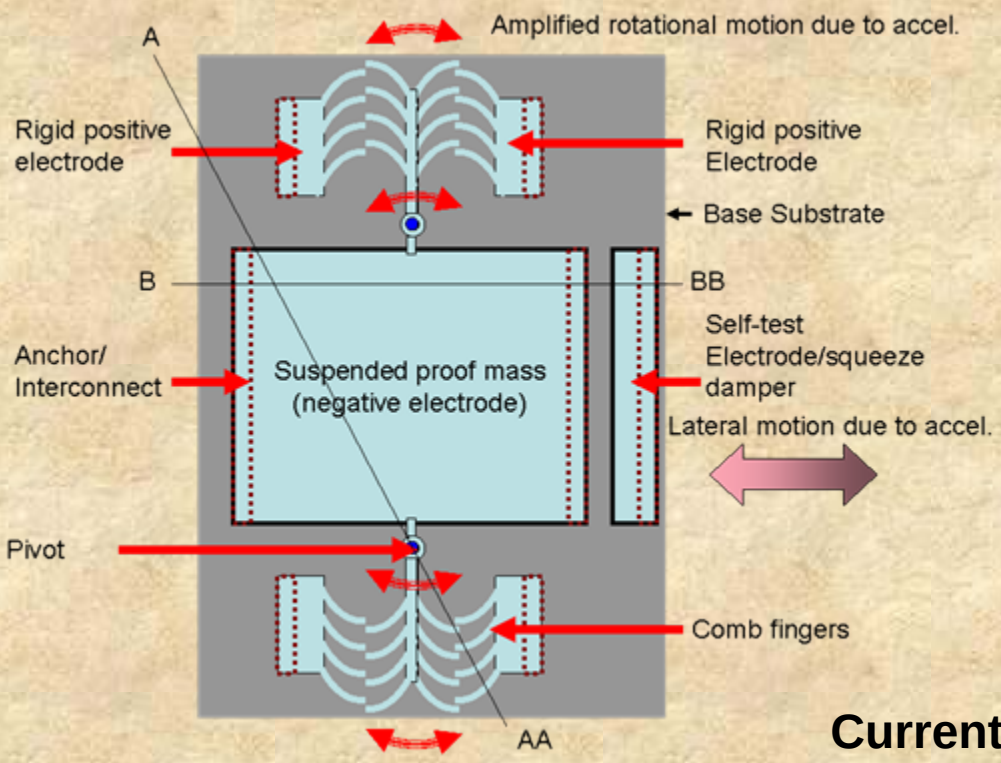
Silicon Pressure Gauge



350C HT Inclination/Seismic Sensors

Applications

- **Inclination for Measurement-While-Drilling;**
- **In well seismic measurement during hydraulic fracturing operations**

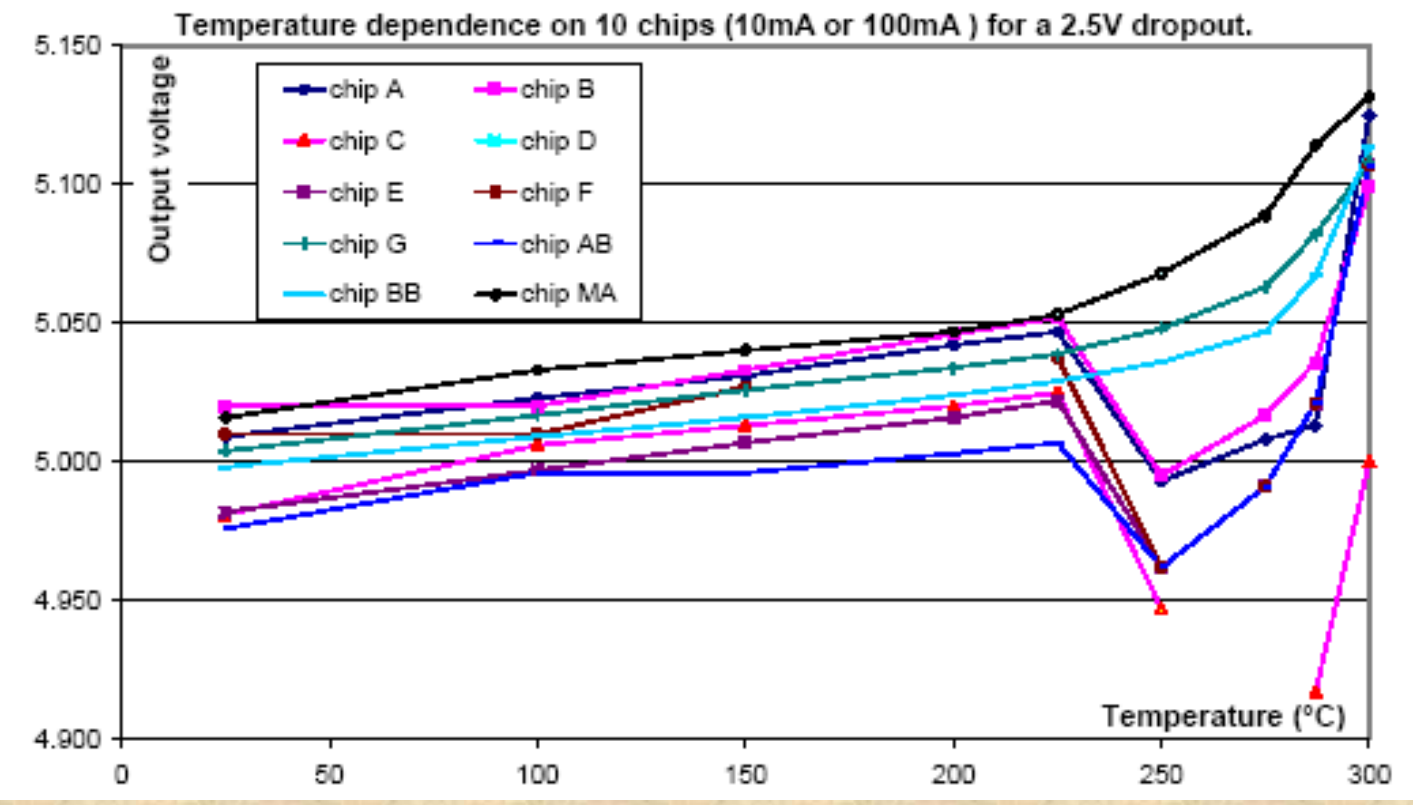


Performance Parameters	Estimates
Dynamic Range	135 dB
Temp. Range	-40 °C to 350 °C
Shock Resistance	>5,000 g
Seismic Sensor Sensitivity	~ 50 pF/g
Inclination Dynamic Range	60°
Inclination Sensitivity	20 μm/°

Currently, this program is unfunded

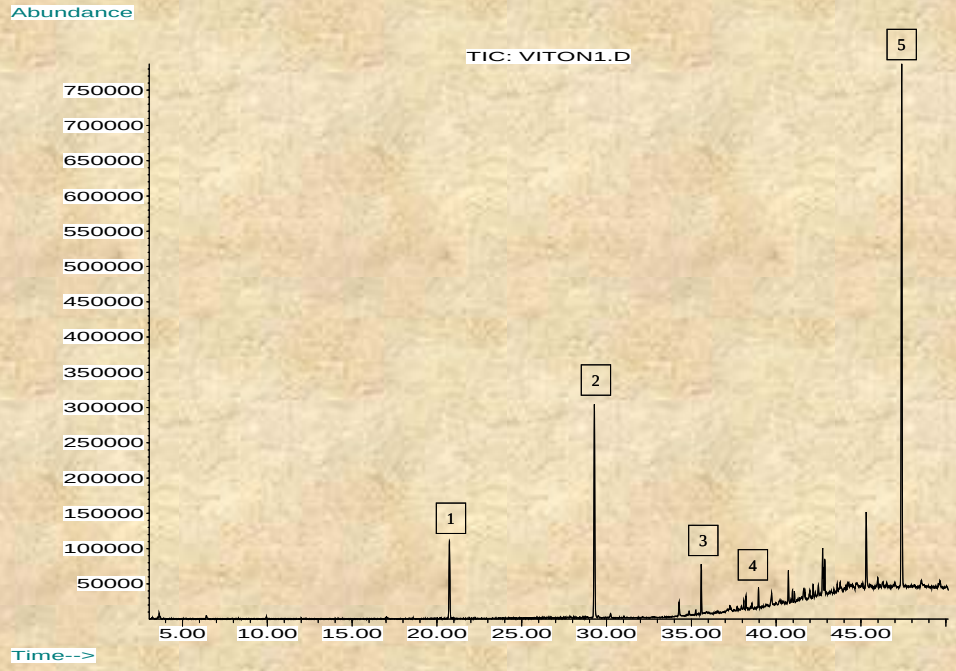
Improved Voltage Reference

- Cissoid: a commercial 300°C voltage reference
- WBG voltage reference and regulators should provide better results up to a needed 350°C



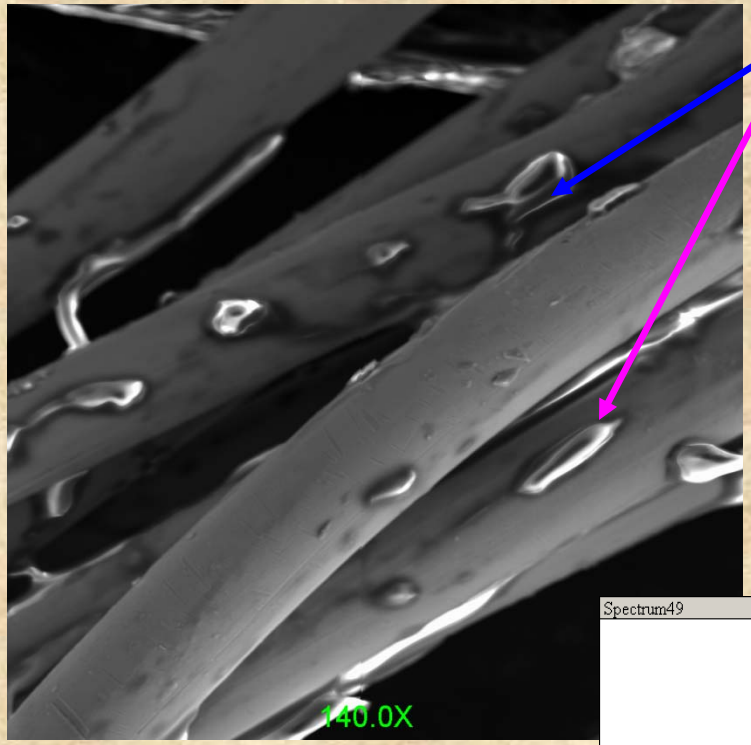
Classic O-Ring Seals Off-Gassing

- A number of tool lubricants and materials are undergoing off-gassing testing.

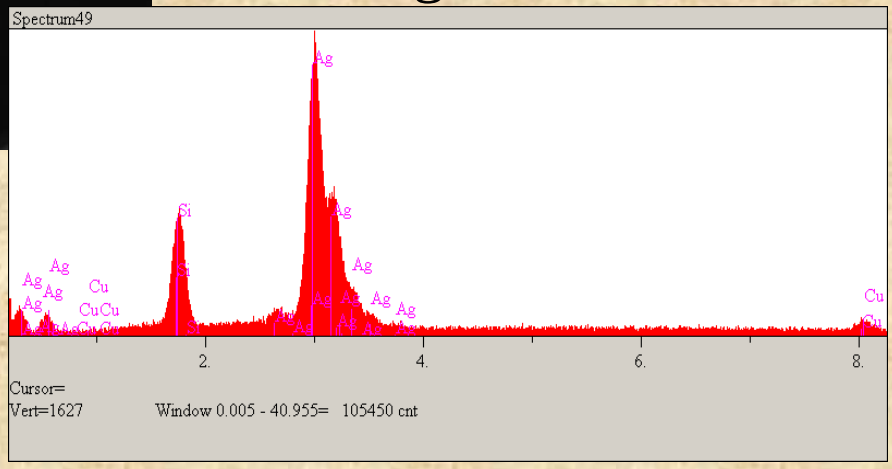


These are results of a Viton O-ring offgas test at 200 C showing cyclic silicones being released. We also have 250 C results.

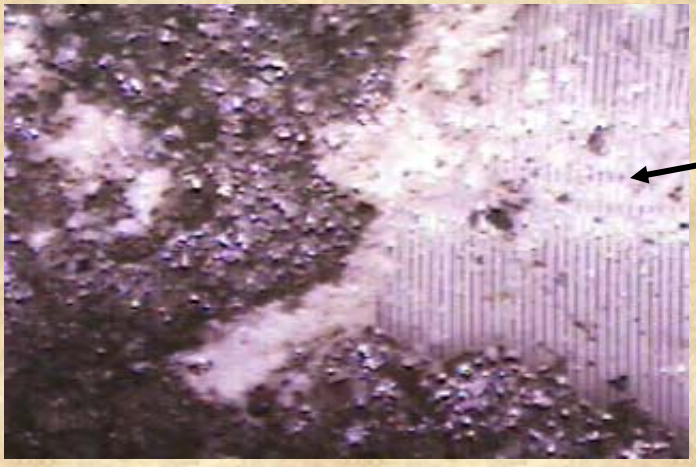
HT Silicon Materials Transformed



SEM image of blobs of silicone "grease or oil?" found under the insulation of all wires internal to the tool. Sandia's team determined this to be the missing silicon. Extremely small amounts of well brine was entering the tool over time.



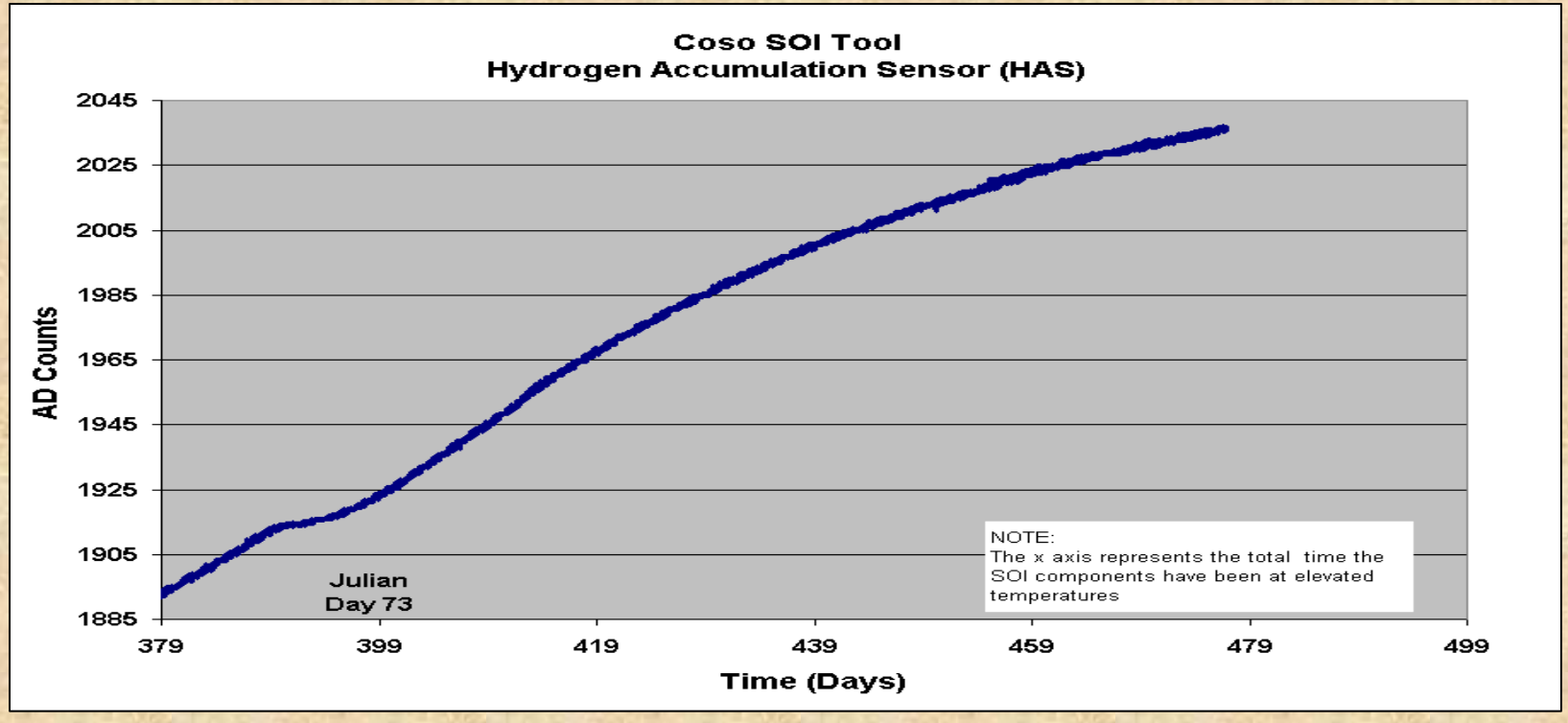
Dale HT 250C Resistors



The wound wire is exposed and can be seen in this photo.

- Dale 1W, 250C, wire wound resistor (RS-1A)
- The *silicone based insulation* became ash
- The resistor did not change value or fail to work within the circuit. This problem needs to be addressed for tools seeing vibration

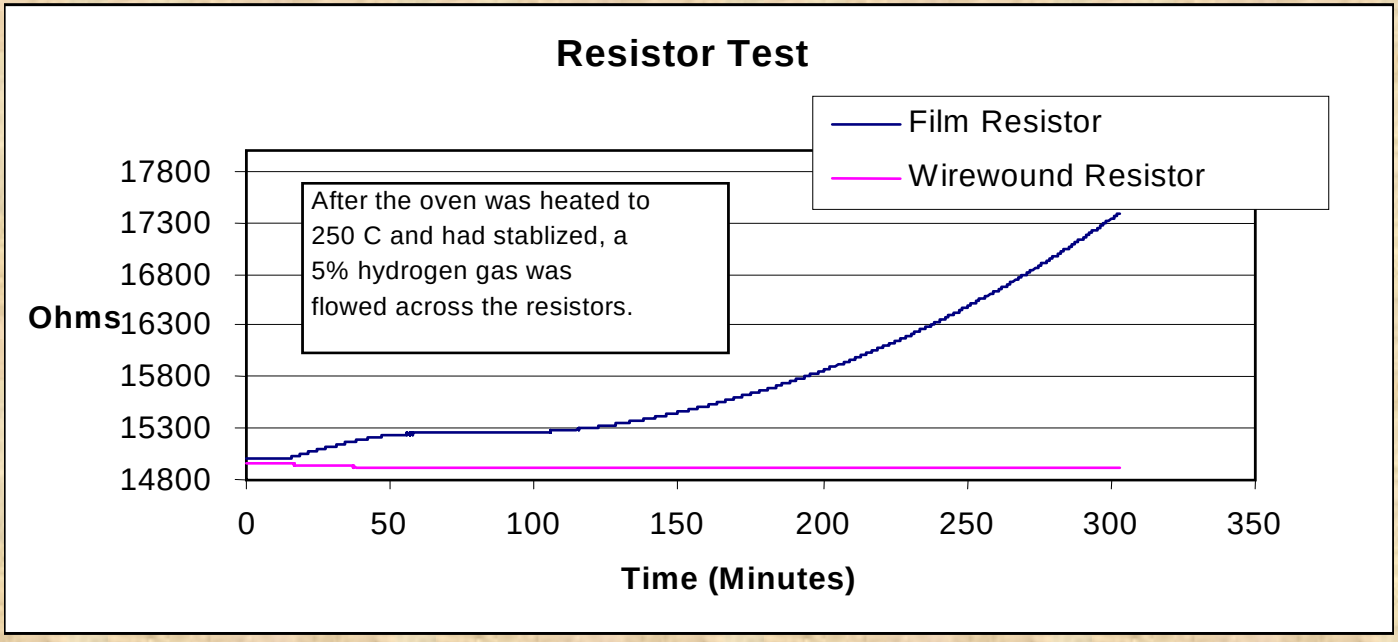
No Seal Can Stop Hydrogen from Entering



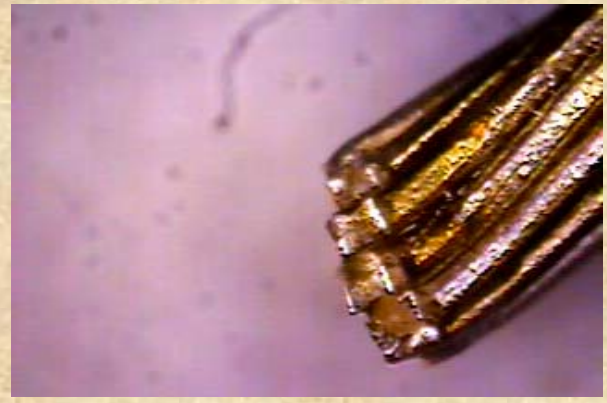
An hydrogen sensor was installed in a tool. The sensor saturated within 100 days. Hydrogen is a product of all wells, both geothermal and fossil. Fortunately, hydrogen seams to have no impact on the HT SOI or SiC devices.

Some Resistors are Sensitive to Hydrogen

- Demonstration testing discovered hydrogen effects on some electronic resistors (& fiber optic cables)
  - Some commercially rated 250°C resistors are hydrogen sensitive

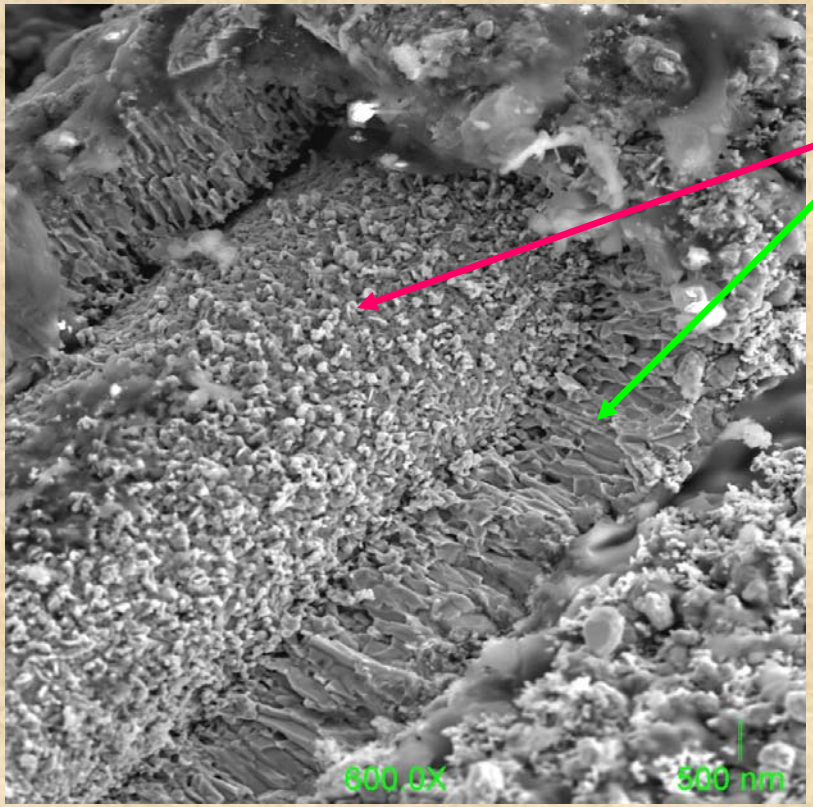


250C Silver-Plated Copper - Fails



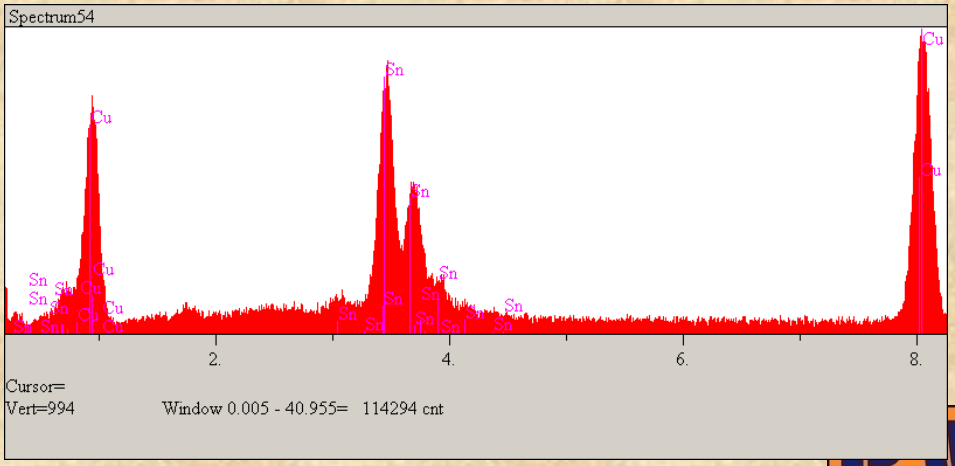
- Top image shows a clean ‘cut’ silver-plated copper wire from the Coso tool.
- However, silver-plating copper wire is no protection from inter-metallic growth.
- The copper migrates through the silver to react with the tin (found in the solder) to form bronze crystals.
- This is a solid-phase interaction which leaves the wire joint fragile as can be seen in the lower photo.

Silver Doesn't Protect the Copper

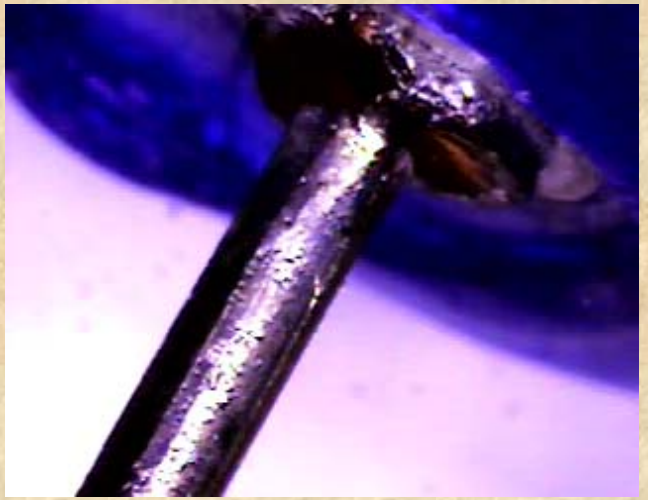


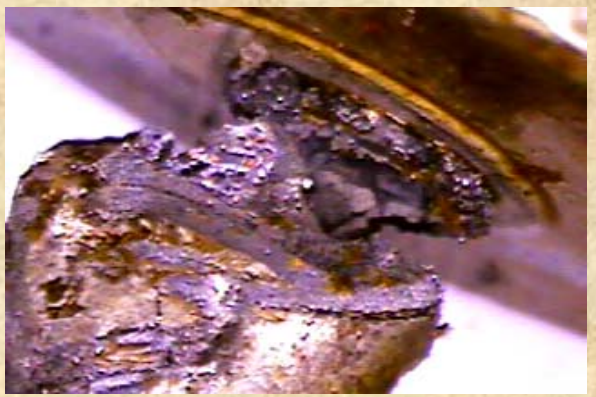
SEM (scanning electron microscope) photo came from the wire end shown in the last view graph.

A reaction occurred on the surface of the wire transforming it into a Cu-Sn alloy in a crystal form.



Conventional Tinned Copper Lead

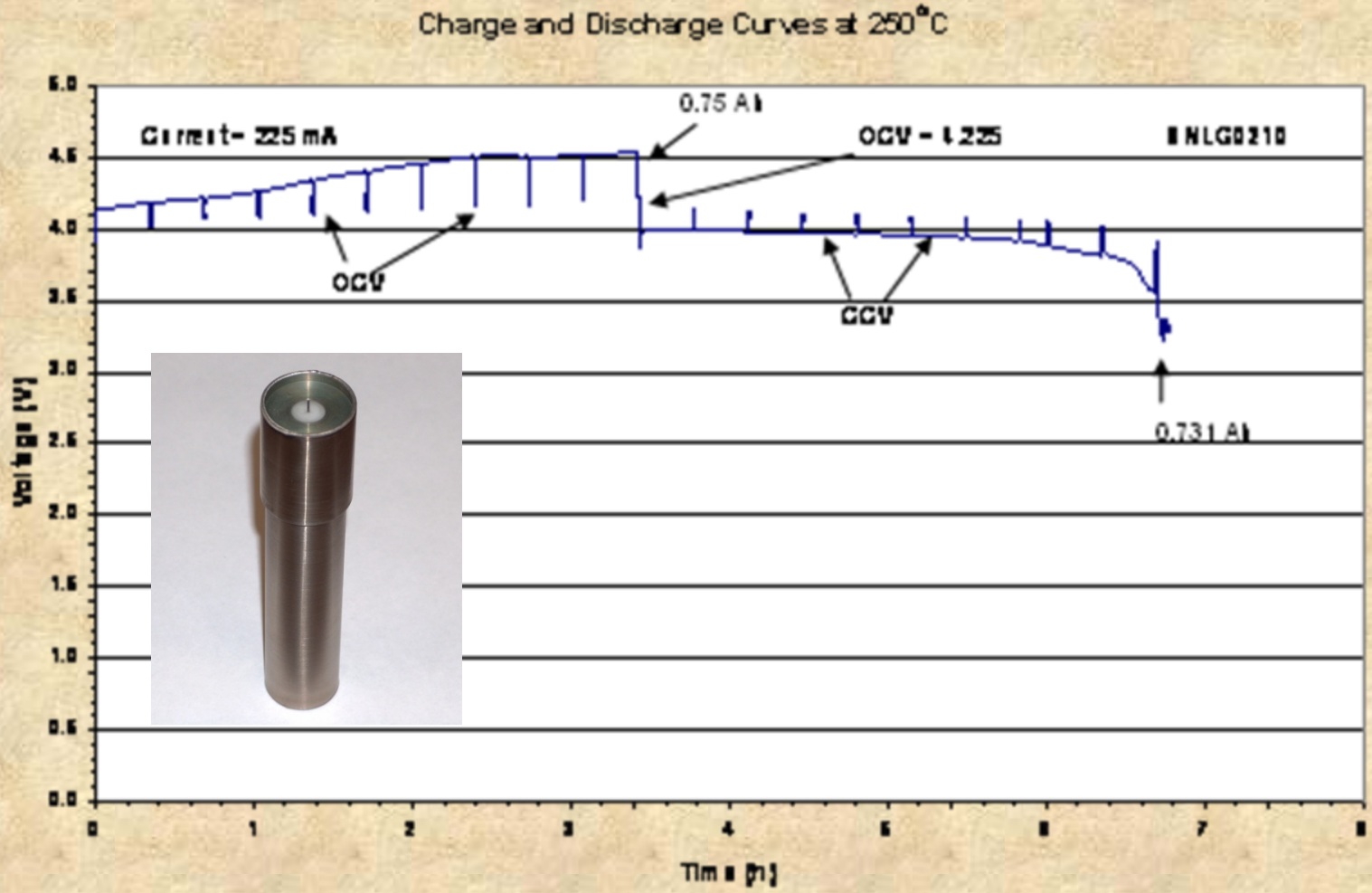




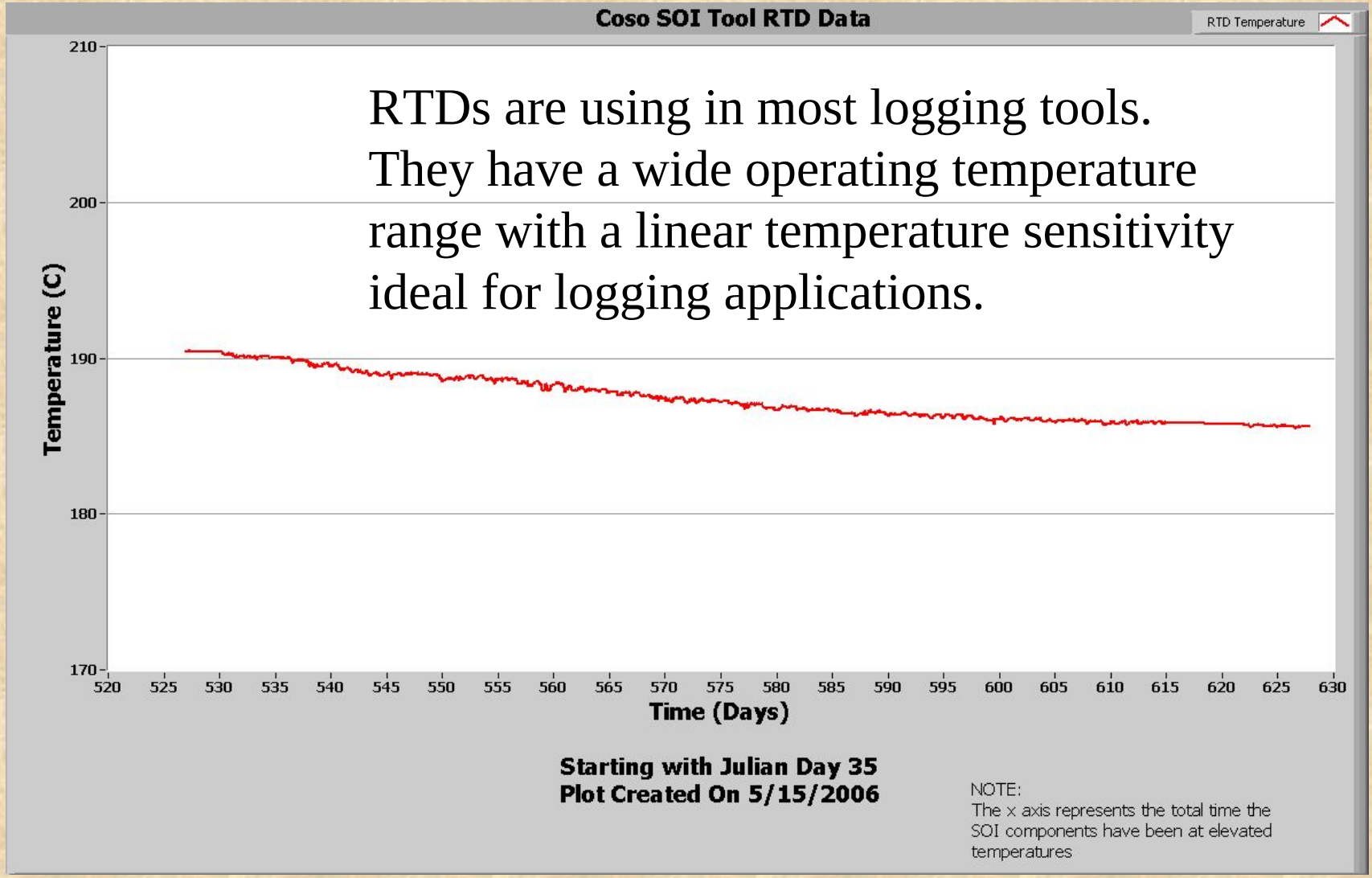
- The top photo is of an untested “new” capacitor lead designed for automotive use, 125C continuous with 200C extrusions.
- The photo below is of a capacitor lead coming out of the Coso tool.
- The automotive industry can sneak by with conventional solder tinned copper leads the drilling industry cannot.

250C Batteries

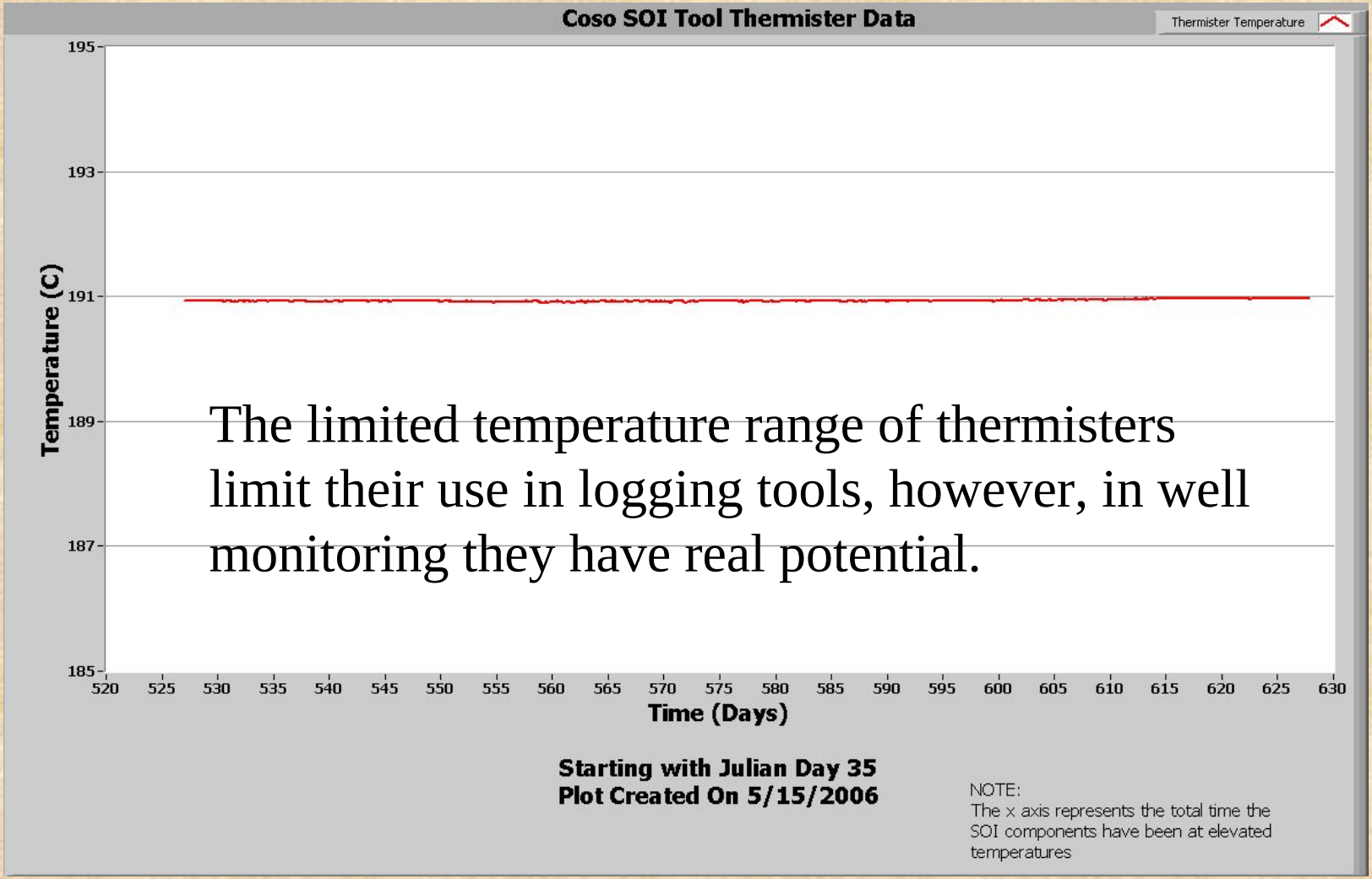
Needed for Memory Logging Tool and MWD Tools



Replaced the RTD in 2006



First Time to Use a Thermister



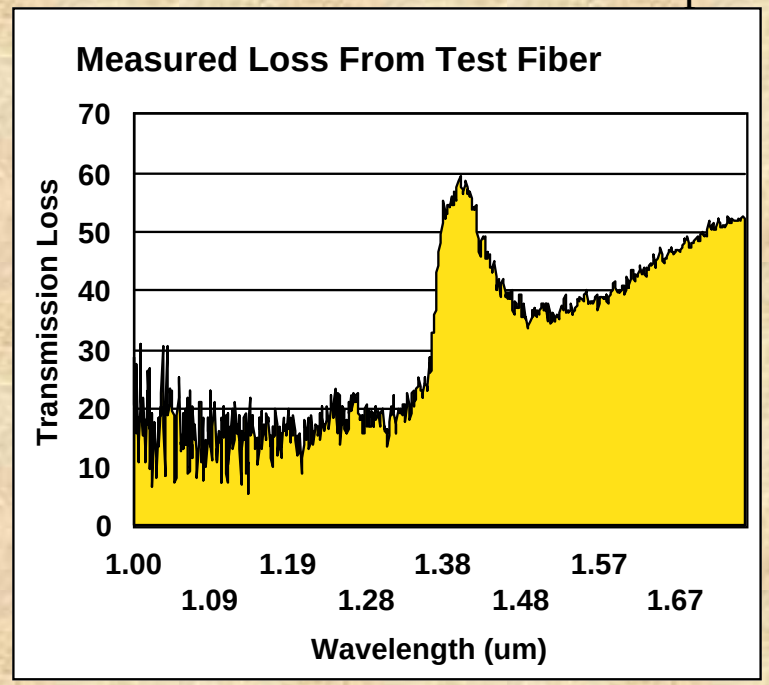
The limited temperature range of thermisters limit their use in logging tools, however, in well monitoring they have real potential.

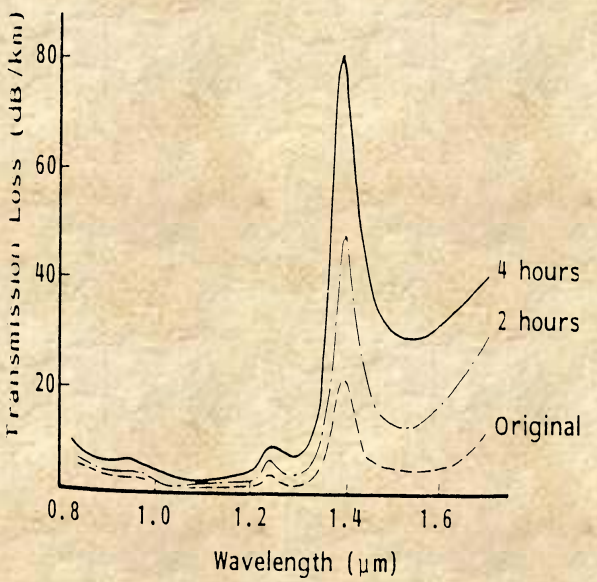
Fiber Optics in Geothermal Wells

- Fiber Optic Temperature Logs
  - Optic fibers for permanent placement in geothermal production wells
    - Instantaneously measures T as a function of depth
    - Eliminates mobile logging system
    - Passive, simple

The Measured Effects of Hydrogen

Taken from an actual fiber exposed to the geothermal environment



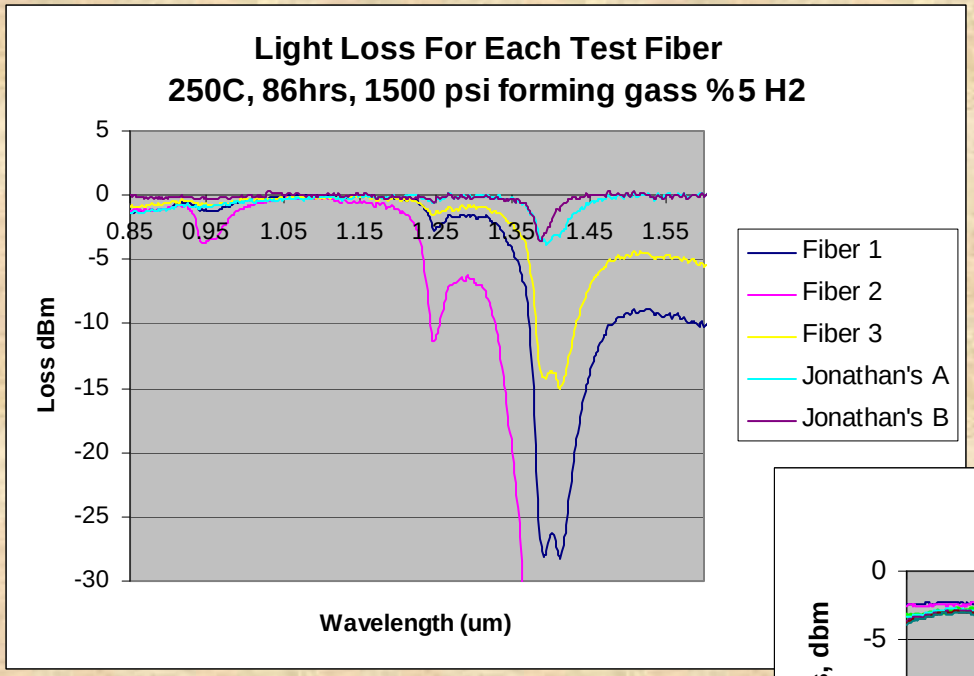


igure 2.39 Transmission loss of germanium-doped silica fiber after ating in hydrogen atmosphere (1 atm) at 200°C. (From Ref. 48.)

Especially important losses at: 0.94, 1.24, 1.38, 1.90, 2.20 and 2.72 um

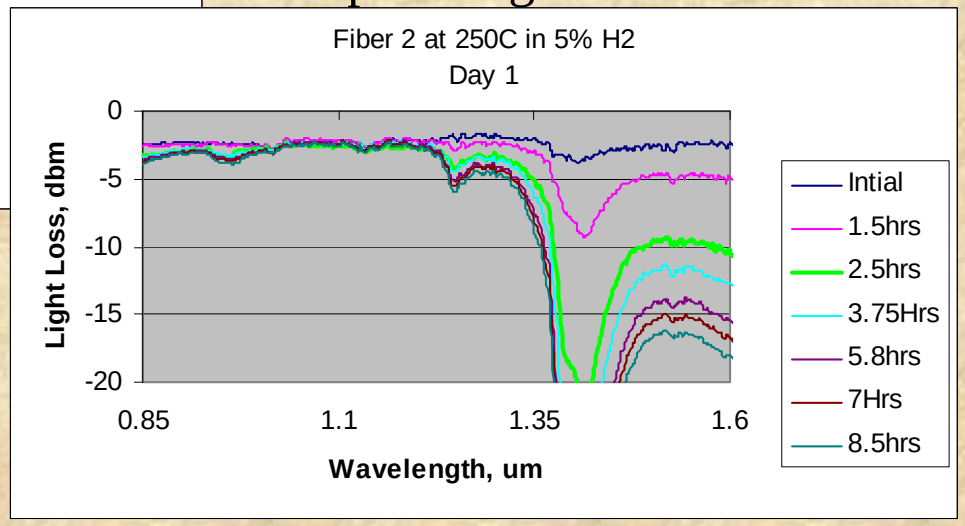
Figure 2.39 taken from “Handbook of Optical Fibers and Cables” by Hiroshi Murata

Fiber Testing 250C, 5% H2

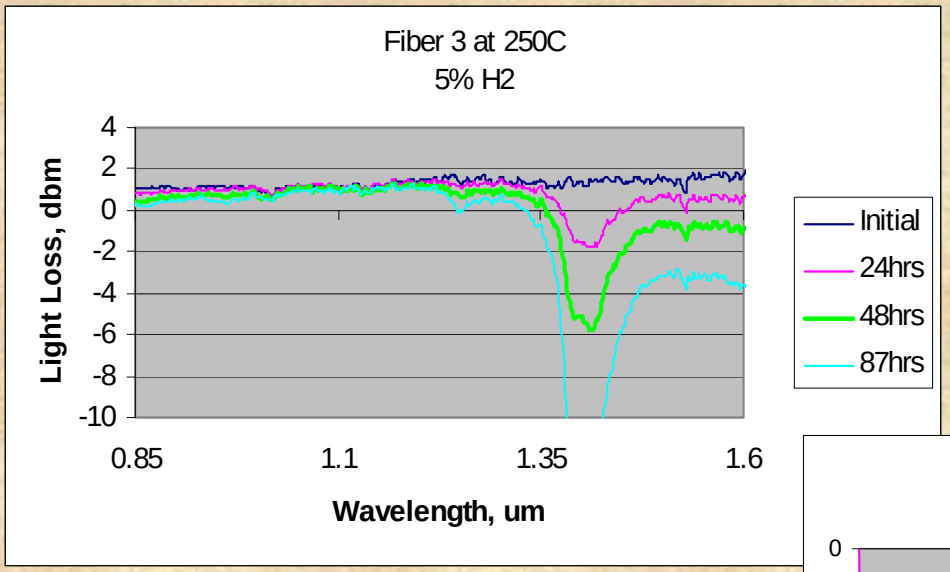


Fiber 1 is carbon coated fiber used in most wellbore applications. Fiber 2 is the same fiber without the carbon coat. Fiber 3 is an improved carbon coating. Fibers A & B NOT have any carbon coating but have an improved glass core.

You can see how quickly these processes occur buy watching Fiber 2.

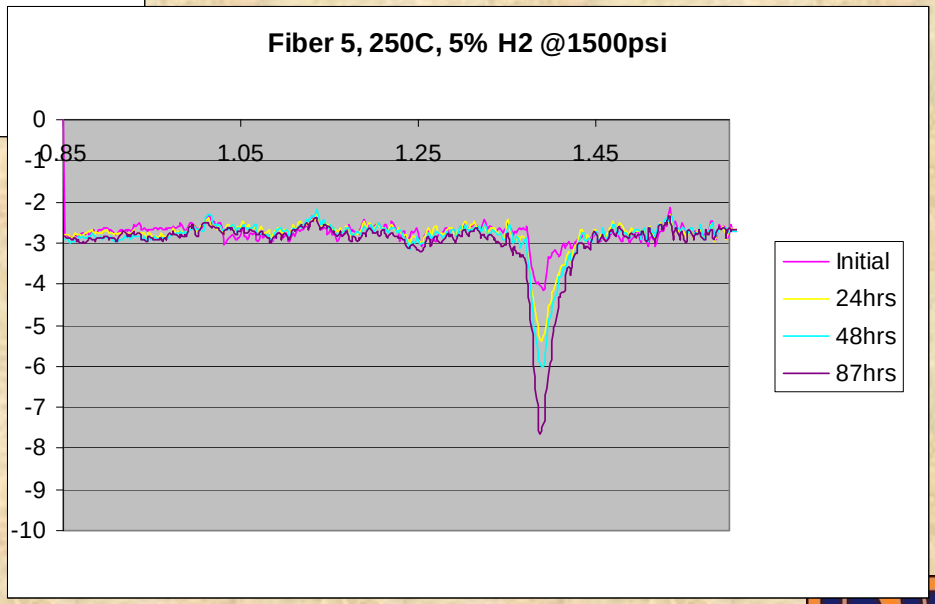


Best Carbon Coating to the Improved Glass Core



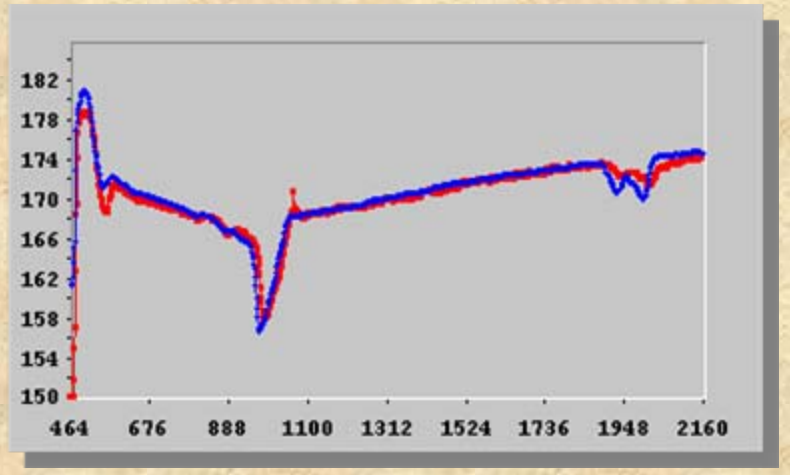
Fiber 3 is lagging Fiber 2 in time. This improvement will more than double time in the wellbore.

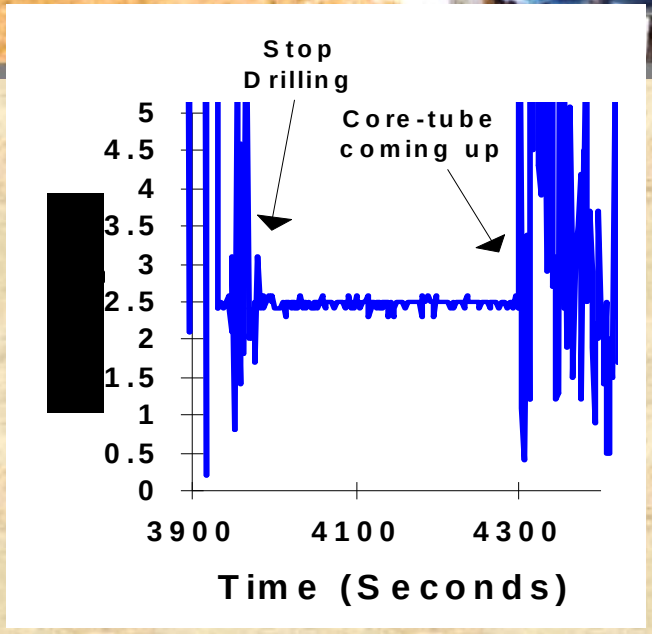
Fiber 5 is not only doing better at the OH wavelength but there is no measurable change at 1.064um where the DTS measurement is made!



Iceland Core Tube Data Logger

- Core-Tube-Data-Logger
  Attaches to the coretube latchhead assembly, providing free log with core retrieval
  - Core orientation?
  - New HT sensors are needed for pressure, inclination and acoustic





Joint Iceland-Australia Project

Core-Barrel Electronics

- Measure Pres, Temp, Inclination and Core vs Time
- Target temperature 300C, 20Kpsi
- GRC developments
  - SiC pressure sensor
  - SiC inclination/seismic sensor with electronics
  - SiC or GaN voltage ref and regulator
  - 600C Dewar pressure housing
- Perma Works
  - 300C Digital clock (funded under a DOE grant)
  - Printed circuit boards (funded under a DOE grant)
  - Acoustic sensor
- Sandia
  - Solders/wire interconnection (funded jointly with Perma Works)

Team at Perma Works

Conclusion

- Geothermal power plants built in the 80s are still in operation today
  - Online power production greater than coal plants and better than solar and wind combined
- EGS can expand the availability of geothermal power production to more areas of the country
- Research is needed on engineering the geothermal reservoir to make EGS a reality
- High-temperature electronics are needed to control and manage future man made geothermal reservoirs

Geothermal Provides Secondary Benefits

Drilling challenges SC fluids

- Drilling into extremely high tempeatures.
- Control of wells during drilling.
- Cementing of long casing strings in HT.
- Coring at HT.
- Acid fluids.
- Corrosion resistance.

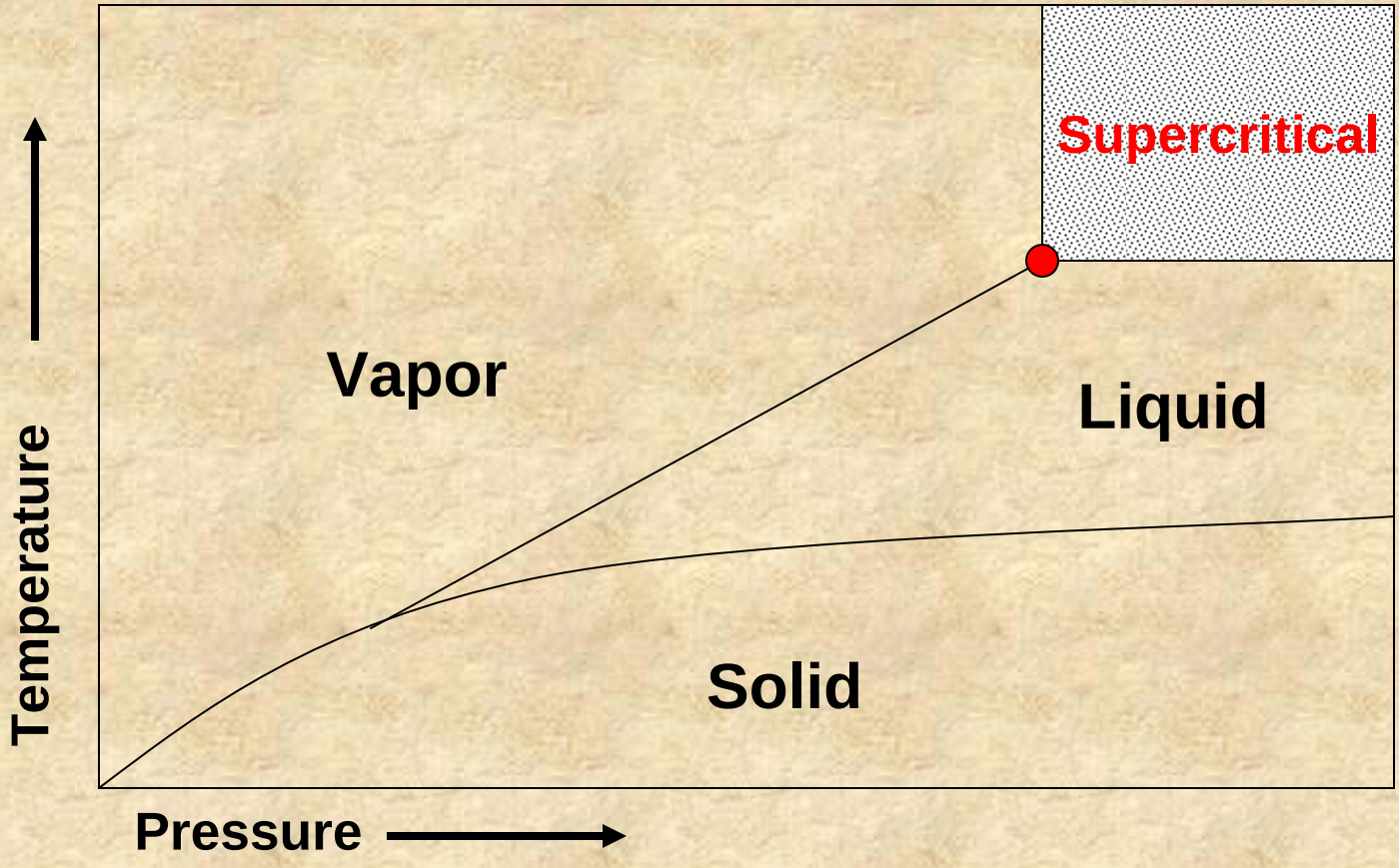
Supercritical Geothermal

Supercritical fluids hold 3-4 times the energy of superheated fluids.

Supercritical geothermal power production can increase energy from a geothermal well by a factor of 10X!!

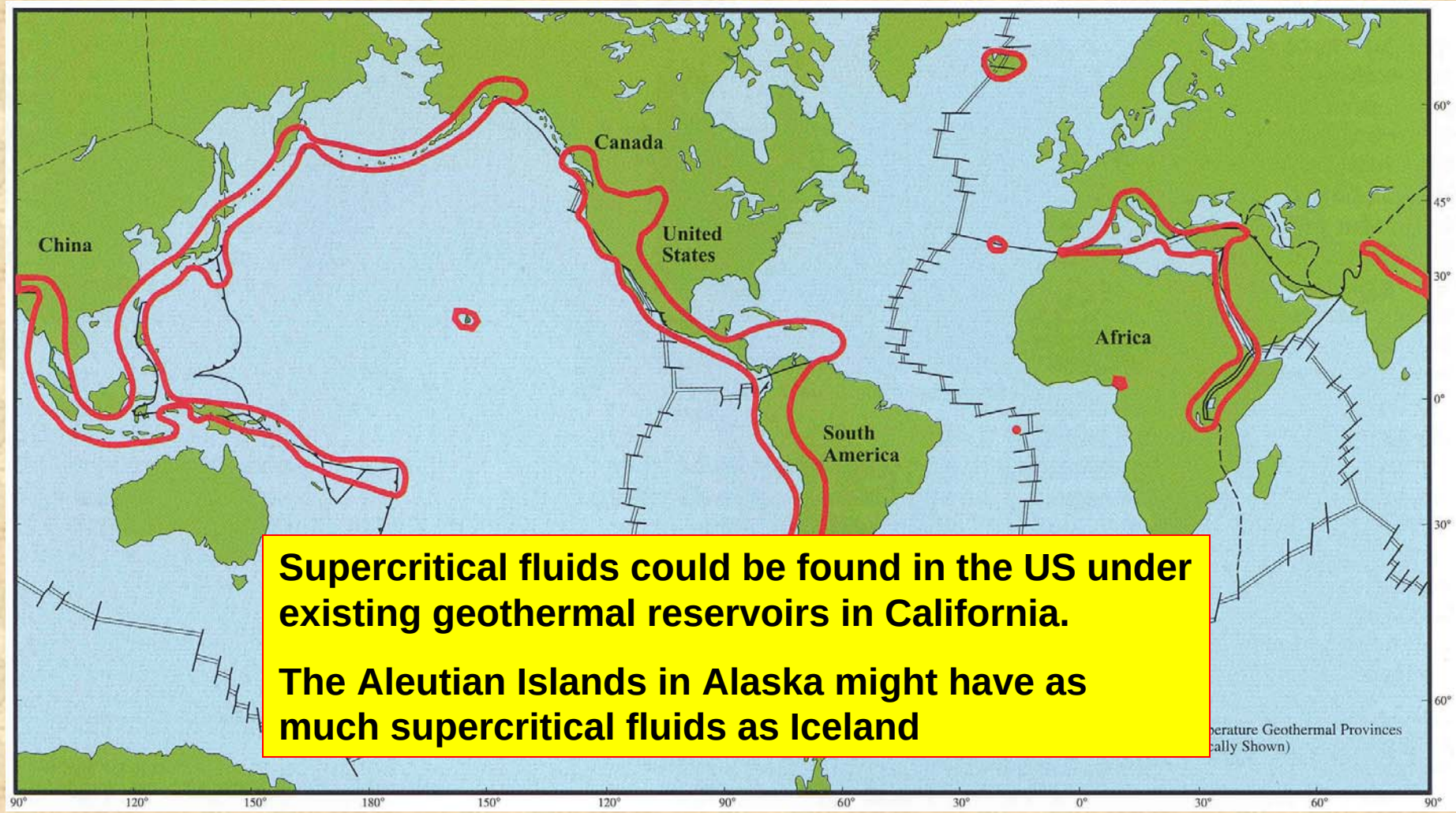
What is Supercritical H2O

(374°C, 22 MPa, or 705°F, 3208 psia)



The three, natural states of water - solid, liquid and vapor - don't apply for supercritical

High Temperature Geothermal Provinces at Plate Boundaries

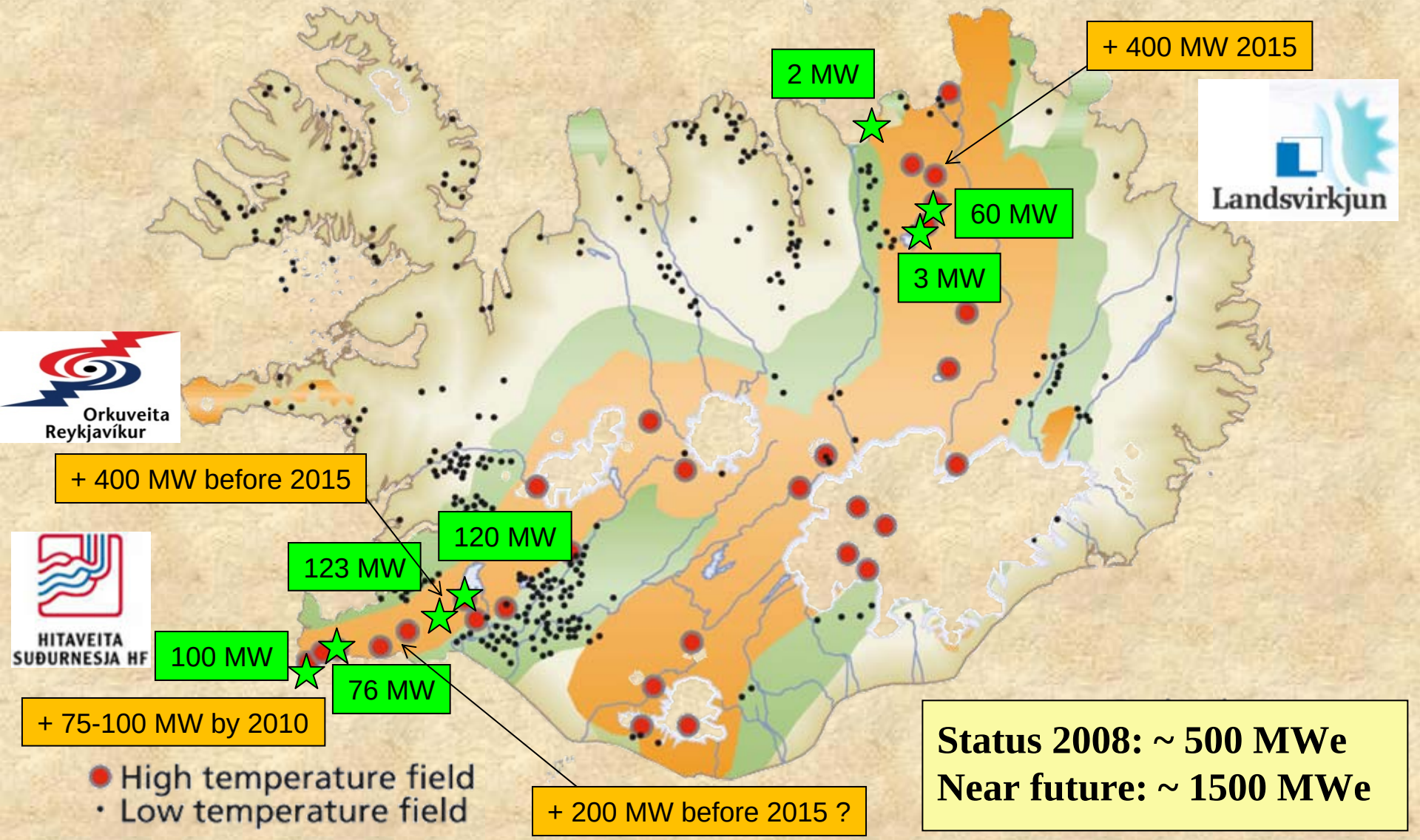


Supercritical fluids could be found in the US under existing geothermal reservoirs in California.

The Aleutian Islands in Alaska might have as much supercritical fluids as Iceland

Courtesy Dr. Wilfred Elders, HITI 2008

Geothermal Installed Power in Iceland



Status 2008: ~ 500 MWe
Near future: ~ 1500 MWe

Courtesy ICELAND GEOSURVEY

The IDDP Consortium

HITAVEITA SUÐURNESJA HF.

Landsvirkjun

Orkuveita Reykjavíkur

ORKUSTOFNUN

(Iceland National Energy Authority)

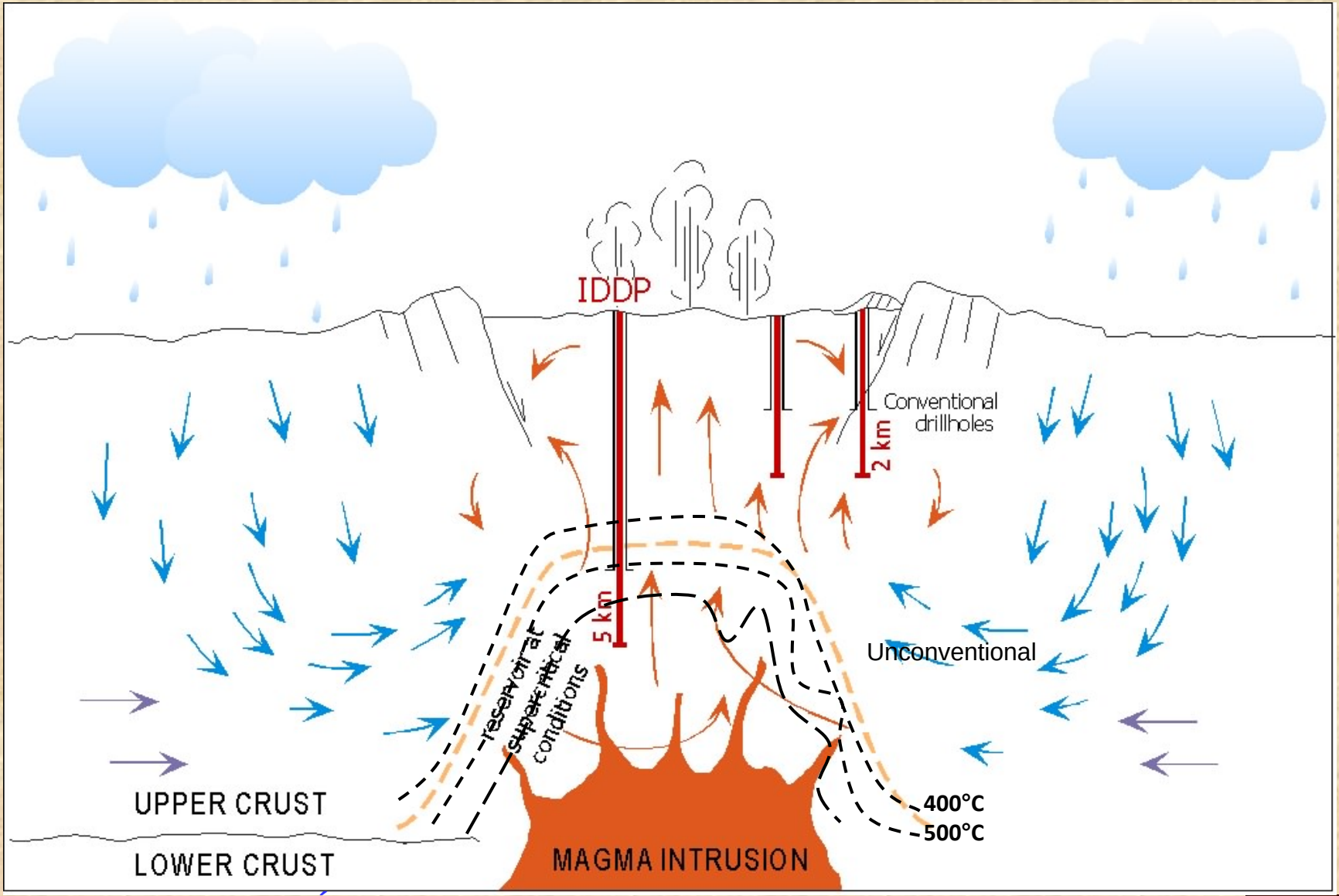
ALCOA

StatoilHydro

IDDP Principal Investigators and a team of international scientists

www.icdp-online.org

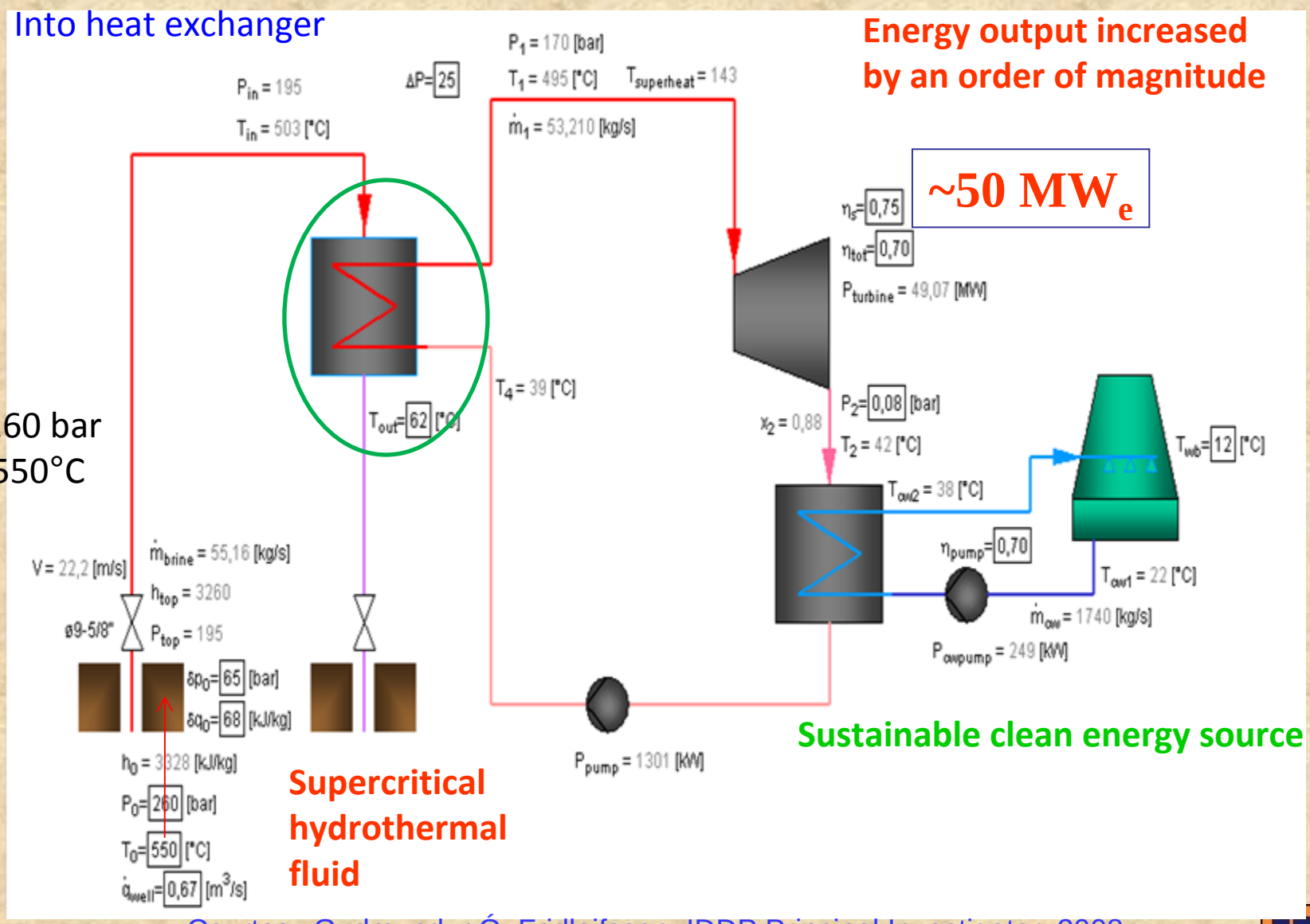
Simplified Model Geothermal System



Courtesy Gudmundur Ó. Fridleifsson, IDDP Principal Investigator, 2008

Clean water circuit

Into heat exchanger



Energy output increased by an order of magnitude

~50 MW_e

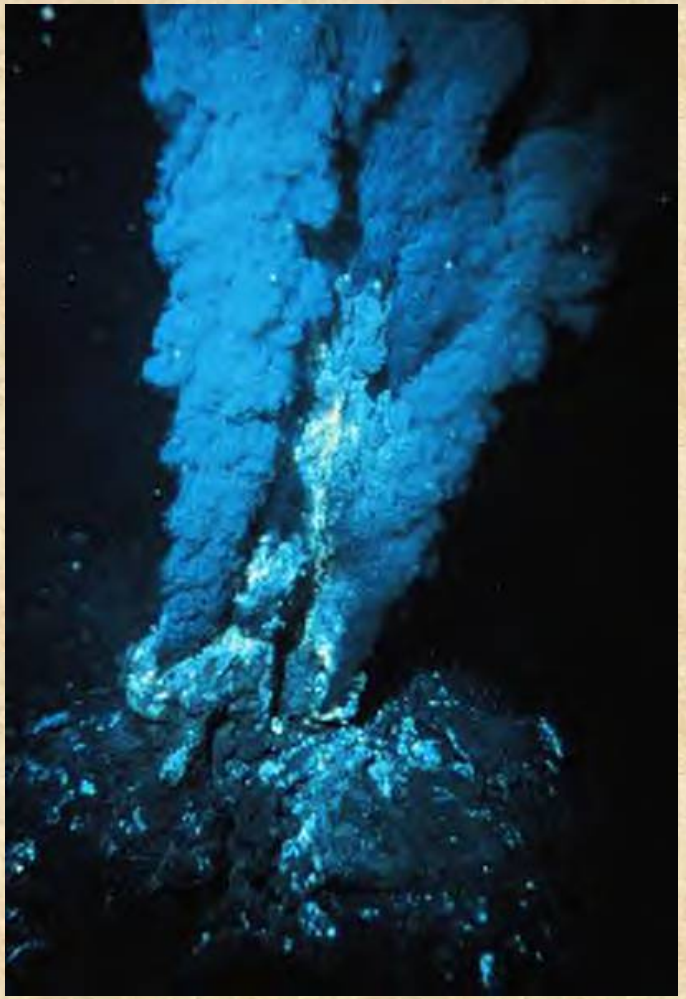
P: 260 bar
T: 550°C

Supercritical hydrothermal fluid

Sustainable clean energy source

Courtesy Gudmundur Ó. Fridleifsson, IDDP Principal Investigator, 2008

Supercritical Measurements



- Supercritical water stable during drilling?
  - Need to monitor pressure & temp. while drilling
- Will the production well seal it's self off?
  - The heat exchanger?
- In general, electronics need 500-600C Dewar-flasks
  - 600C Fluid Sampler
  - PT drilling tool
  - PT & flow logging tool

The steam plume from the K-36 well was black for ~30 min. at the beginning of the flow test.
Photo: 12.12.2007-time:11:36 – photo Ásgrímur Guðmundsson

Curtisy Gudmundur Ó. Fridleifsson, IDDP Principal Investigator

After ½ an hour or so the steam plume turned to normal color. The flow yield was estimated 20-30 MWe, but a 2nd improved flow testing will take place late January 2008. Well K-36 yields valuable information to IDDP.

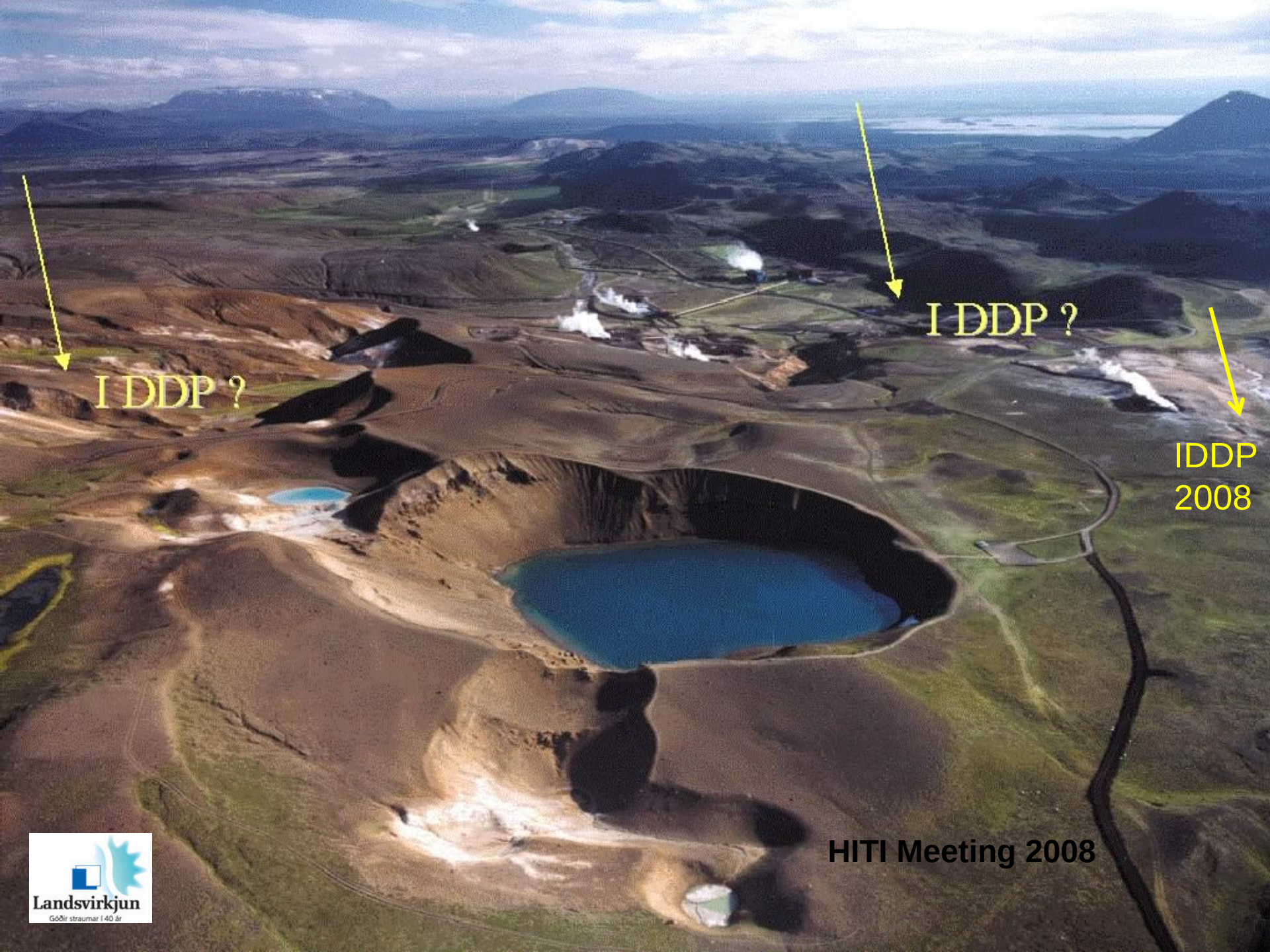
Photo: 12.12.2007-time:13:02 – photo Ásgrímur Guðmundsson


Krafla 60 MW
Geothermal Power Station
HITI Meeting 2008

The IDDP schedule for drilling and flow testing:

- Landsvirkjun drills the 1. well to the CP - (estimated 3.5 km) **2008 and 2009**
-
- IDDP drills the well to total depth – (estimated 4.5 km) **2009**
- Spot Cores will be collected from 2.4 km to total depth – funded by ICDP and NSF
- Flow testing and pilot study for power production during **2009-2015**
- Extensive scientific research and engineering studies will be undertaken during and after drilling
- Total estimated operational Cost for well 1 with testing 20-25 M €
- OR and HS Ltd. will drill IDDP wells 2 and 3 to CP depth in **2010-2012**

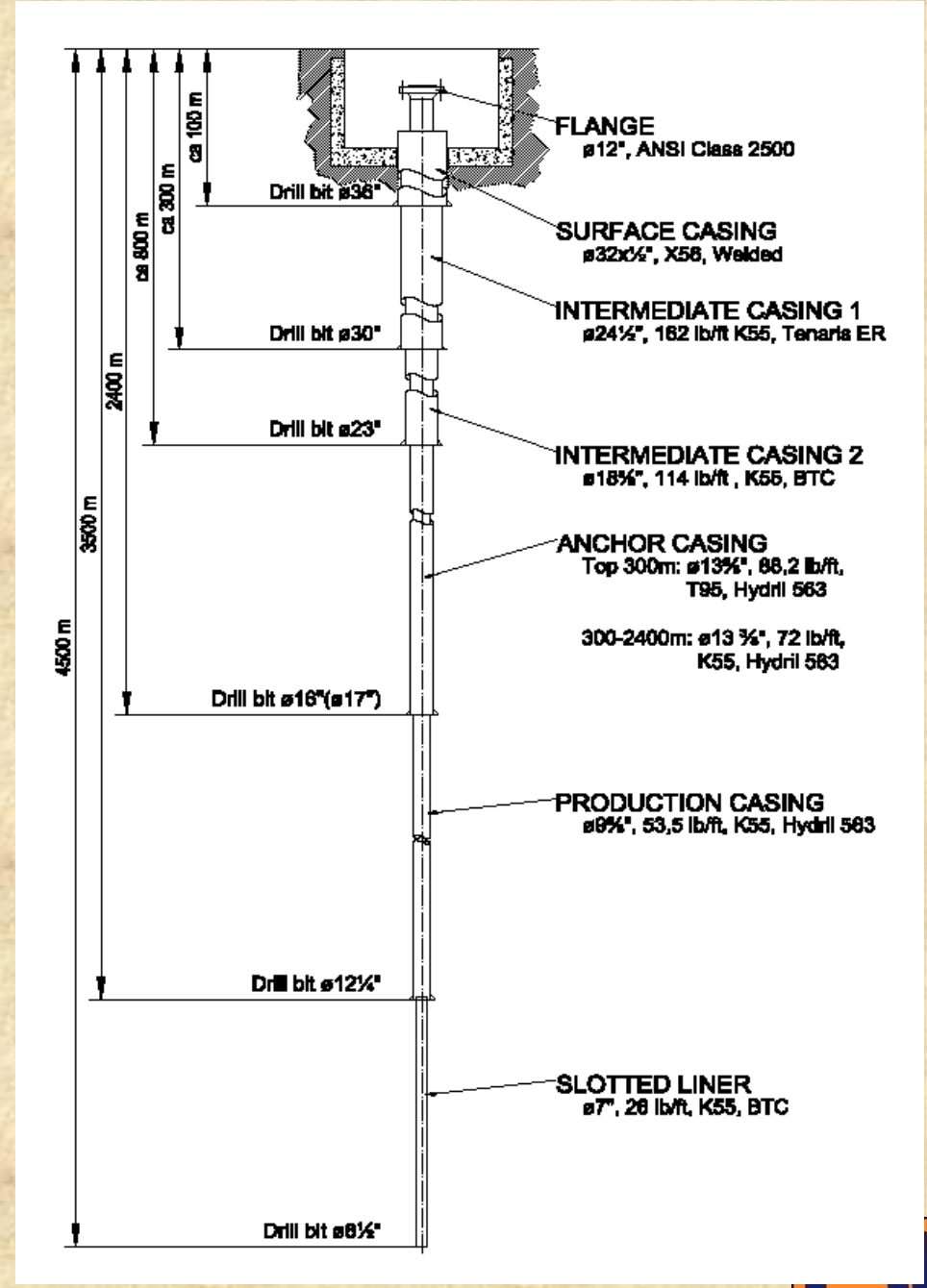
Curtisy Gudmundur Ó. Fridleifsson, IDDP Principal Investigator


I DDP ?
I DDP ?
IDDP
2008
HITI Meeting 2008
Landsvirkjun
Góðir straumar í 40 ár

IDDP Casing Design

Features:

- Five cemented casing strings.
- Steel grade K-55 except for top of Anchor casing T-95.
- Premium connections Hydril 563.
- Tie-back for the Anchor and Production casing strings.
- Wellhead ANSI class 2500.
- Stainless cladding of expansion spool and master
- No valve below the master valve.

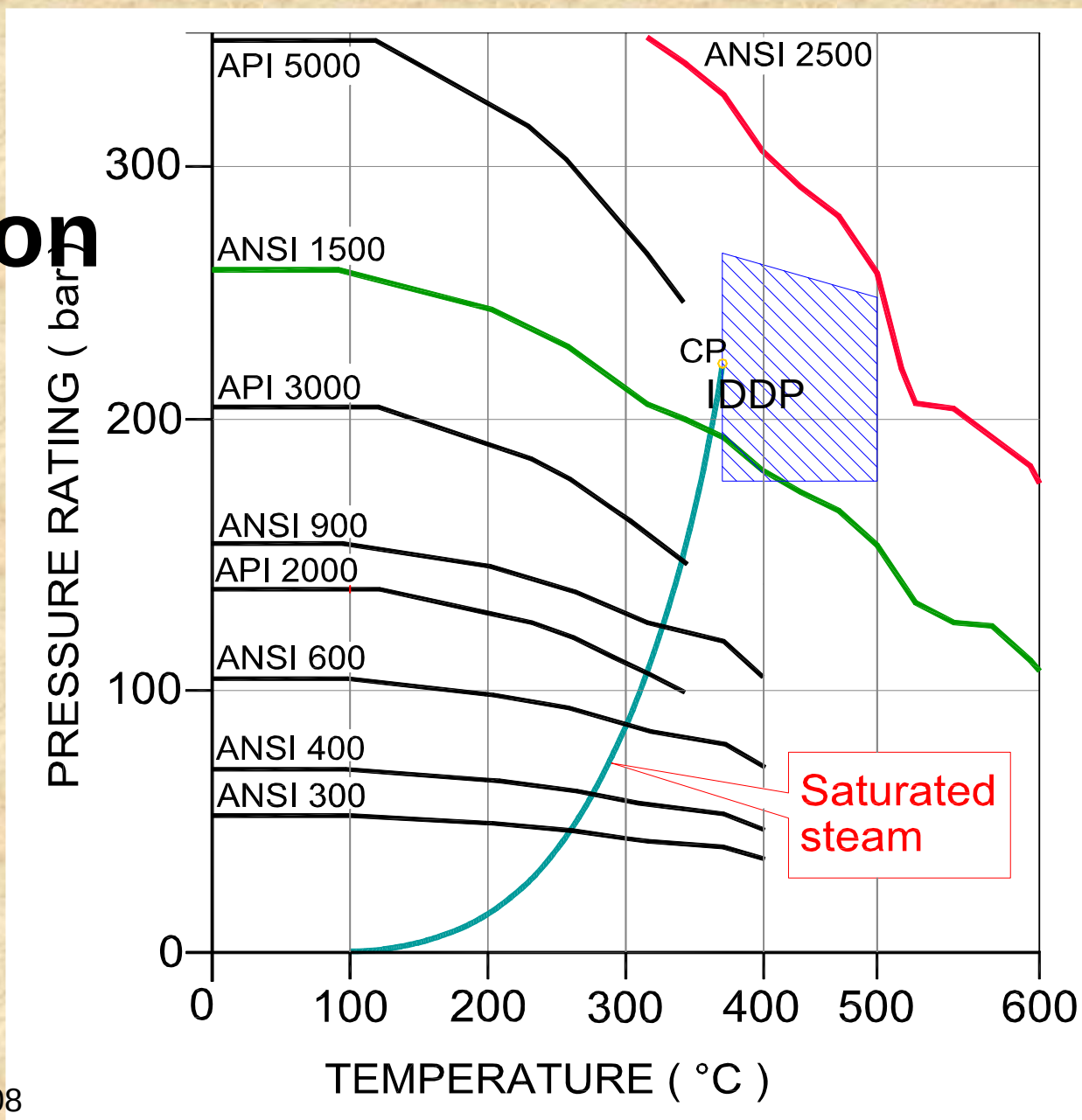


Courtesy Sverrir Thorhallson, HITI 2008

Effect of tempeature on pressure rating

For IDDP:

- BOP´s are API 5000
- Wellhead is ANSI 2500



Courtesy Sverrir Thorhallson, HITI 2008

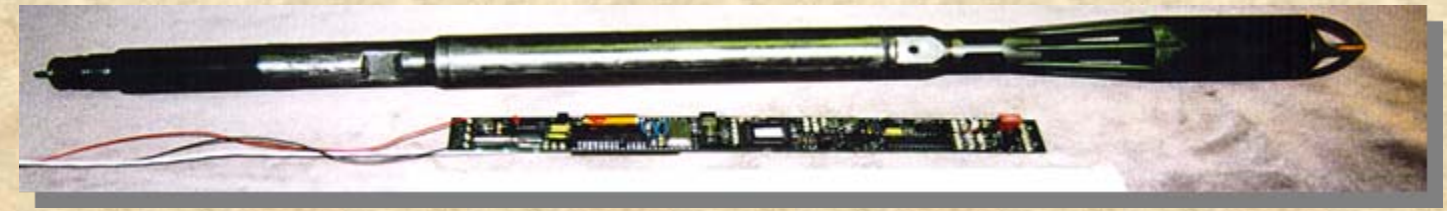
Supercritical Statistics

- Temp: 450 to 600C
- Press: > 3500 psi
- No wells today, experimental
- Ten times the potential energy of hydrothermal wells

•Supercritical temperatures could be found anywhere at 8-12 Km depths!!

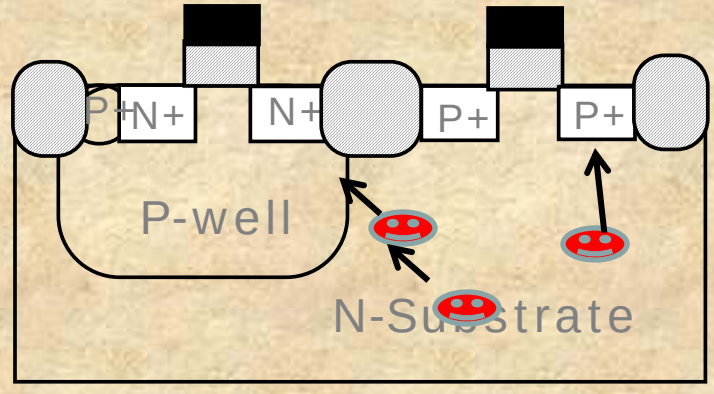
•There are considerations for supercritical EGS power plants!!

HT Electronics

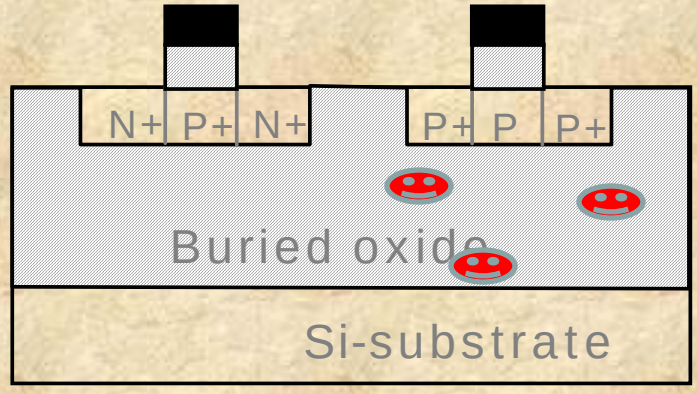


What is HT SOI?

- Increasing temperature increases the random release of thermally generated electrons!
- Silicon-On-Insulator (SOI) isolates transistors on an insulating material providing:
  - Reduced leakage currents by almost 100 times!
  - 25% Faster switching
  - Better isolation for analog and digital on the same die
  - SOI is simply a better way to design integrated circuits: your PC uses SOI



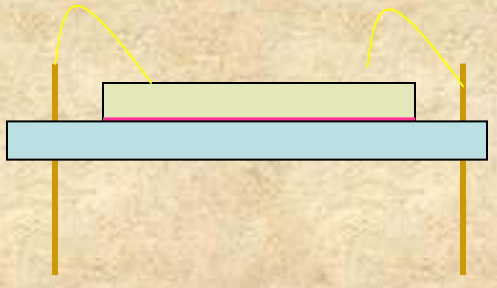
A: Cross-section of bulk CMOS inverter



B: Cross-section of a SOI CMOS inverter

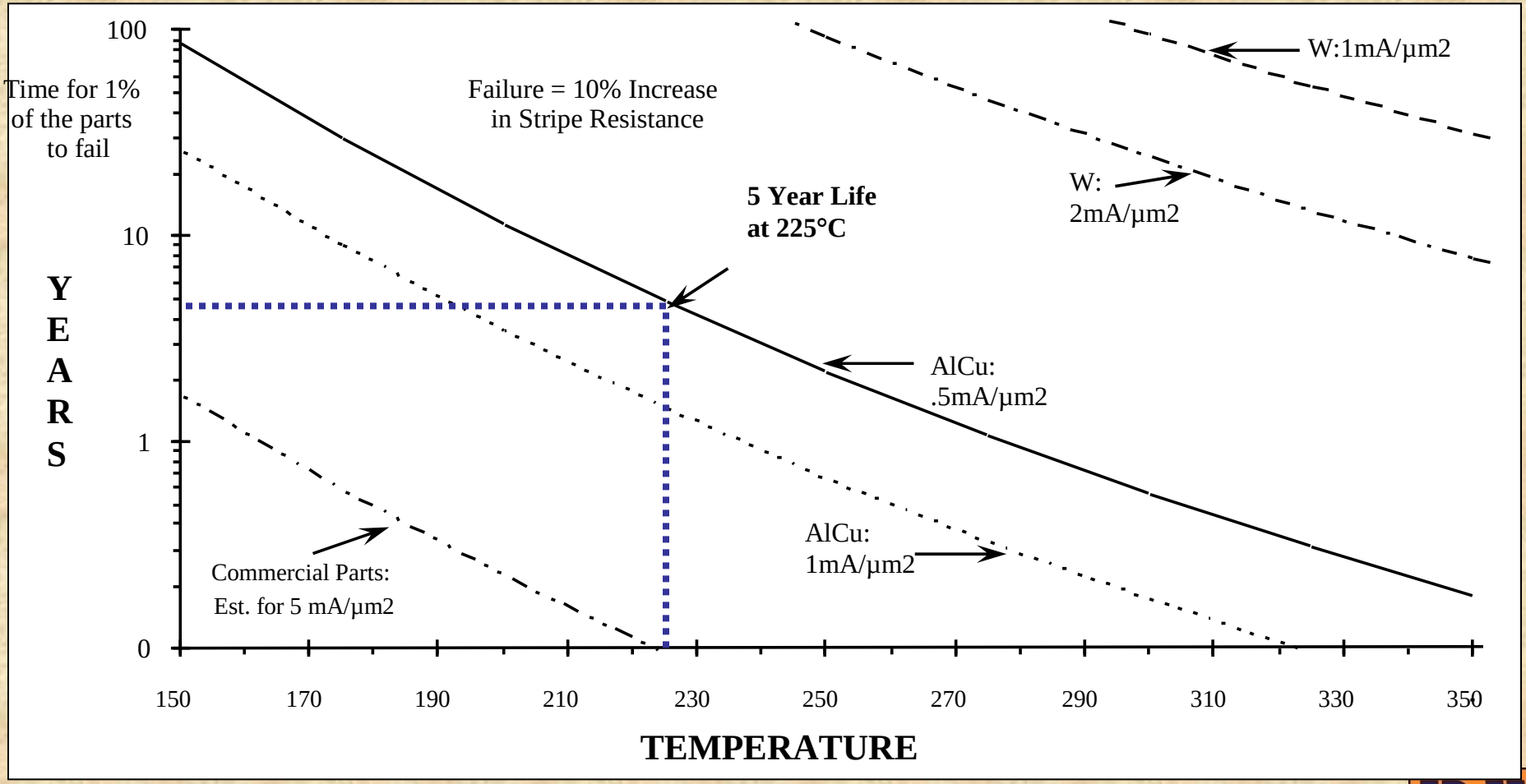
High Temperature = Long Life

- Temperature accelerates the aging process
- In HT we doing everything to stop aging
  - No right angle metallization paths
  - No on chip metal bridges
  - No voids in the die attach
  - Keep TCEs matched
  - Eliminate inter-metallic growth
  - Design for metal migration



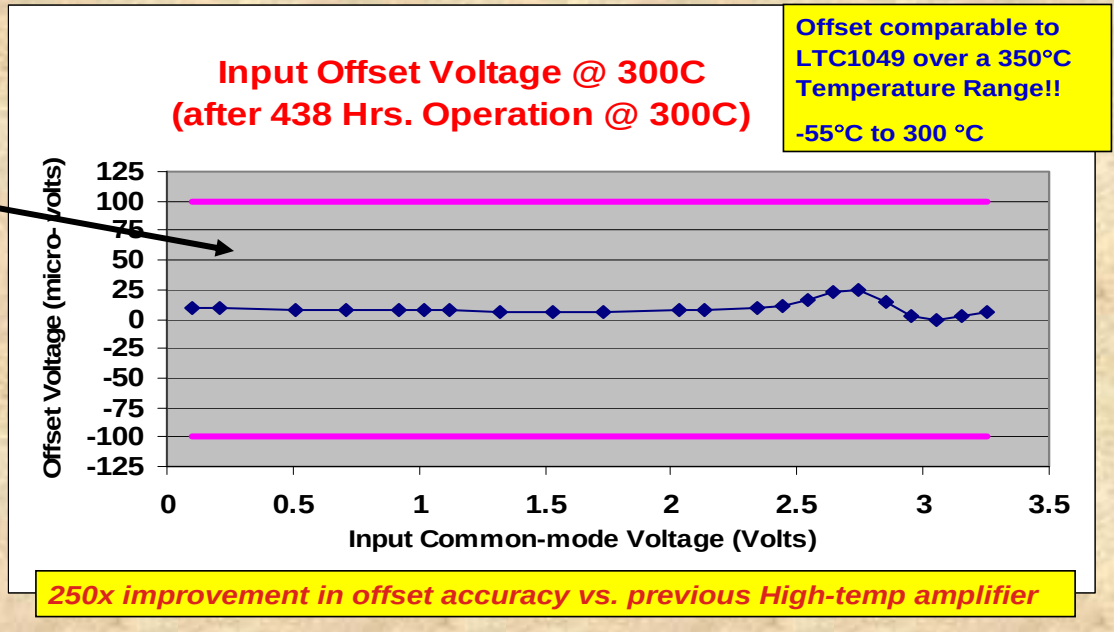
Designing Long Life Electronics

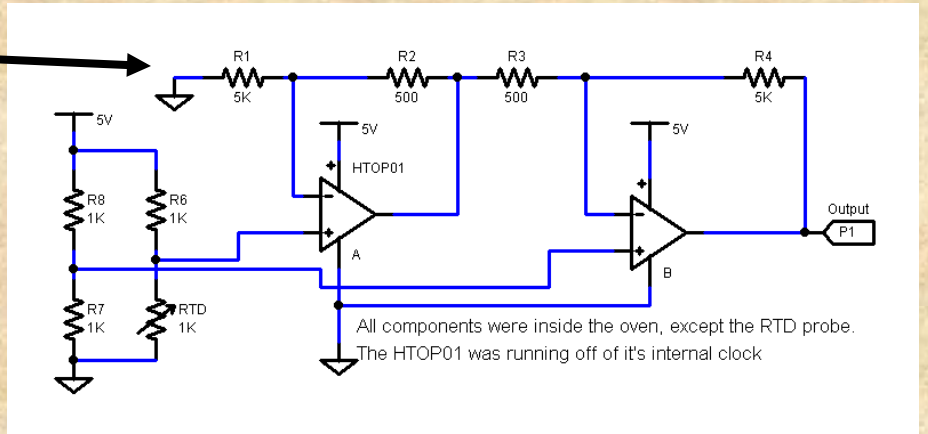
Metal Migrated Curves



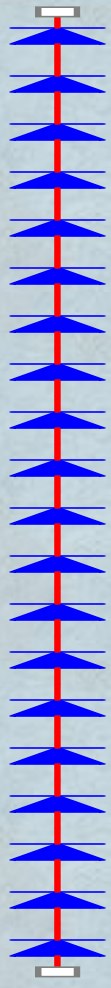
An Example: Precision Amplifier

- Achieved 18-bit dynamic range
- Achieved high input impedance:
  - < 1nA input offset current at 225°C
- Demonstrated operation:
  - -55°C to 375°C



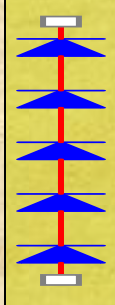


Utility Industry 100KV Si vs SiC



Silicon 5 kV GTO

20 Devices



SiC 20 kV GTO

5 Devices

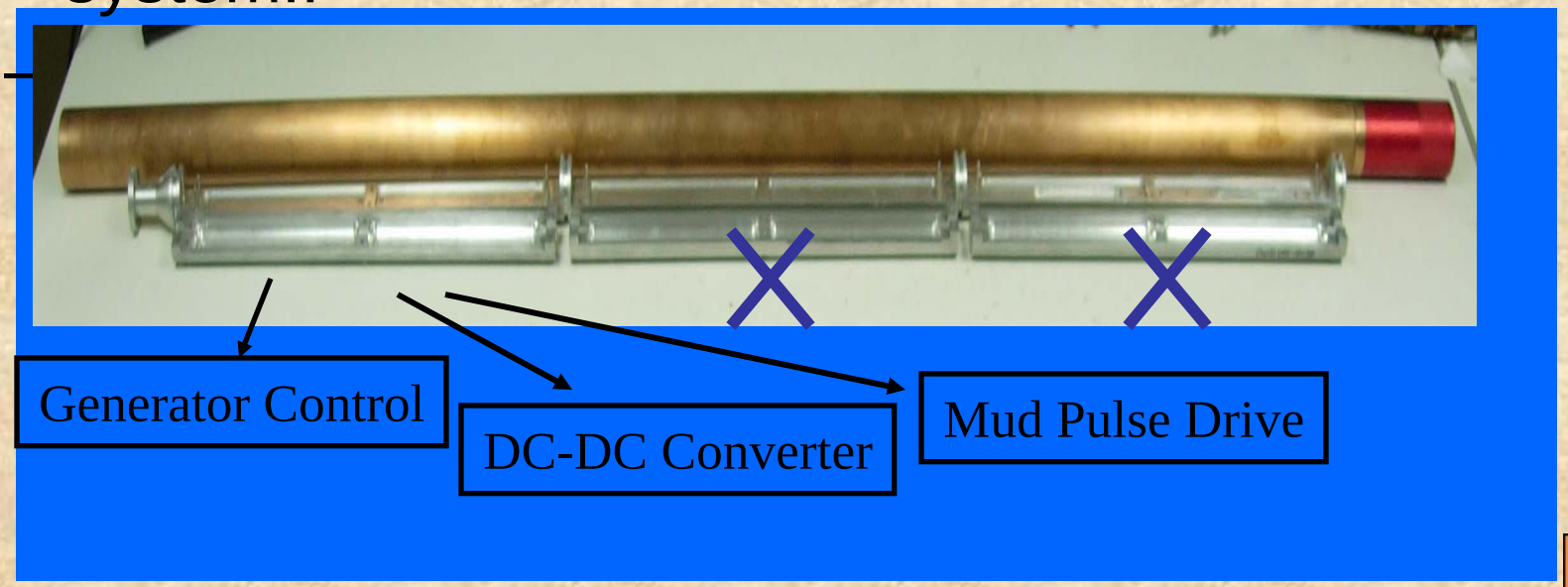
- Lower Part Count
- Reduced Cooling

→ Lower Cost

Courtesy Anant Agarwal, Cree HiTEC 2006

Using HT SOI and SiC Together

- Sandia's HT Turbine Regulator/Power Supply/Mud Pulse Drive using HT SOI and SiC electronics
  - ~1/3 the size of the old commercial 200°C Si system!!



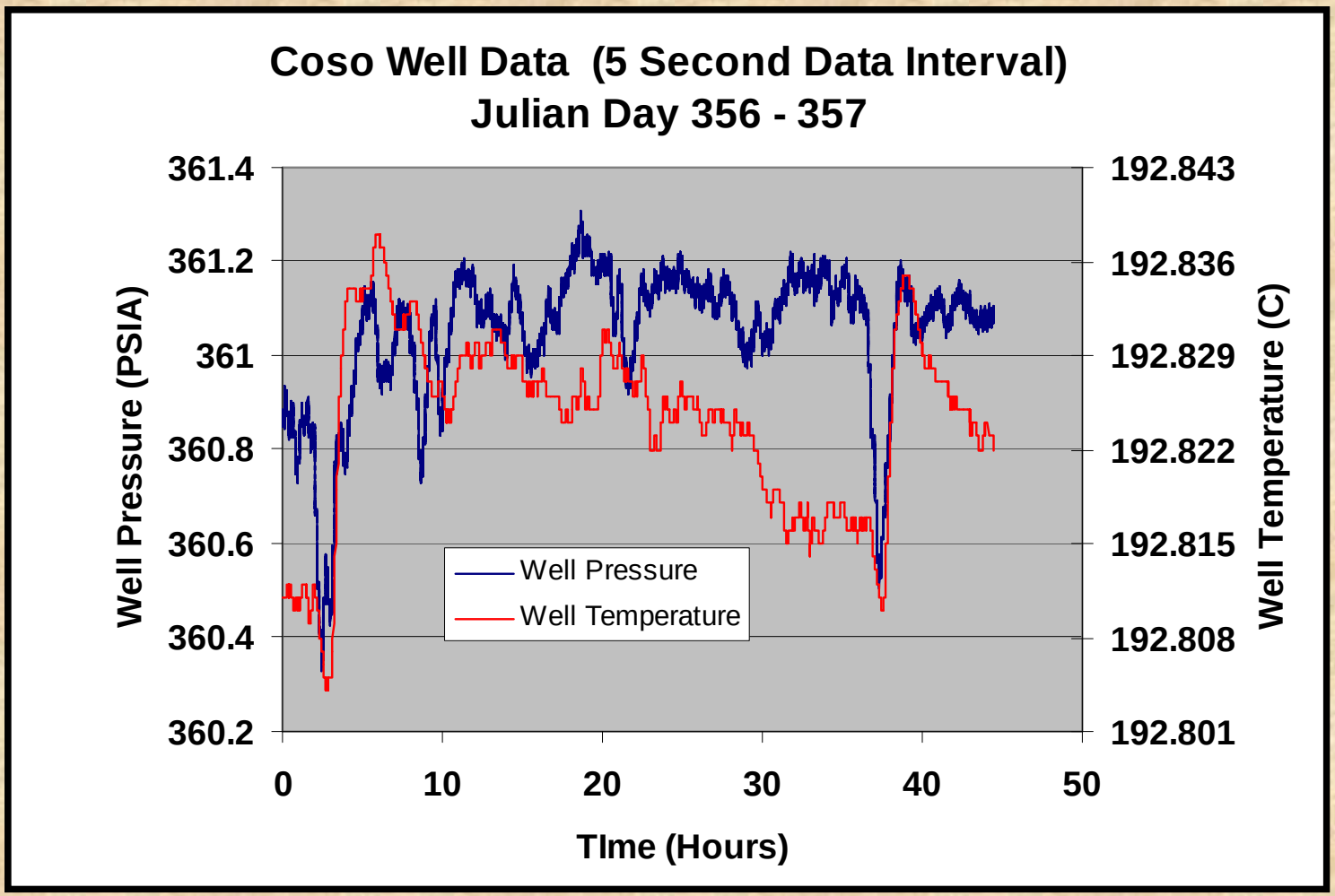
Sandia's Long-Term HT SOI Tool Demonstration

Objective: Demonstrate a HT SOI uP controlled, multi-channel data collection system for well monitoring.

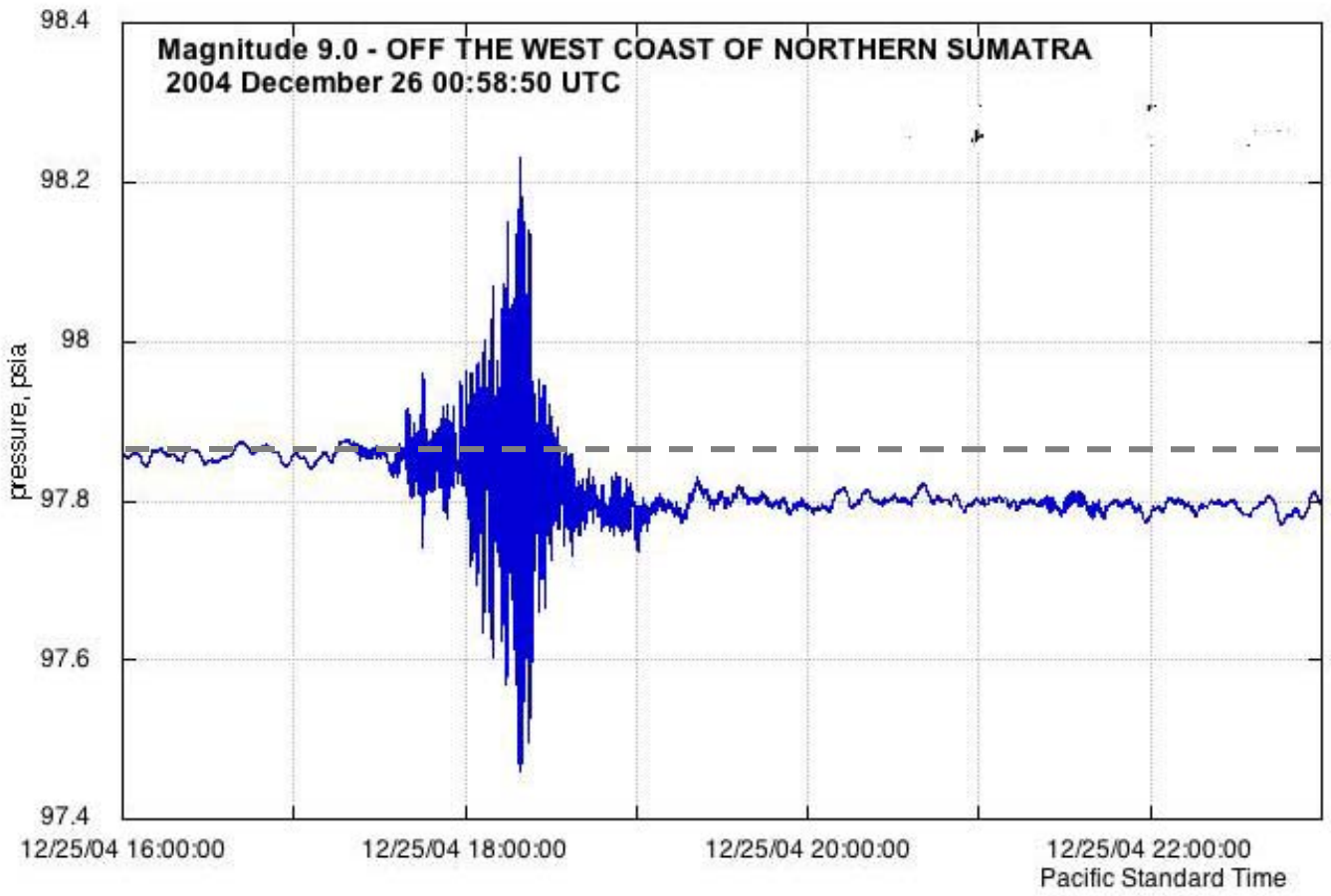
The Coso Navy well was chosen at 193C. The tool operated for 800 day in the well, along with an additional 31 days for burn-in at 200C inside a test oven.

A major service company rates their tools for only 17 days at 175C.

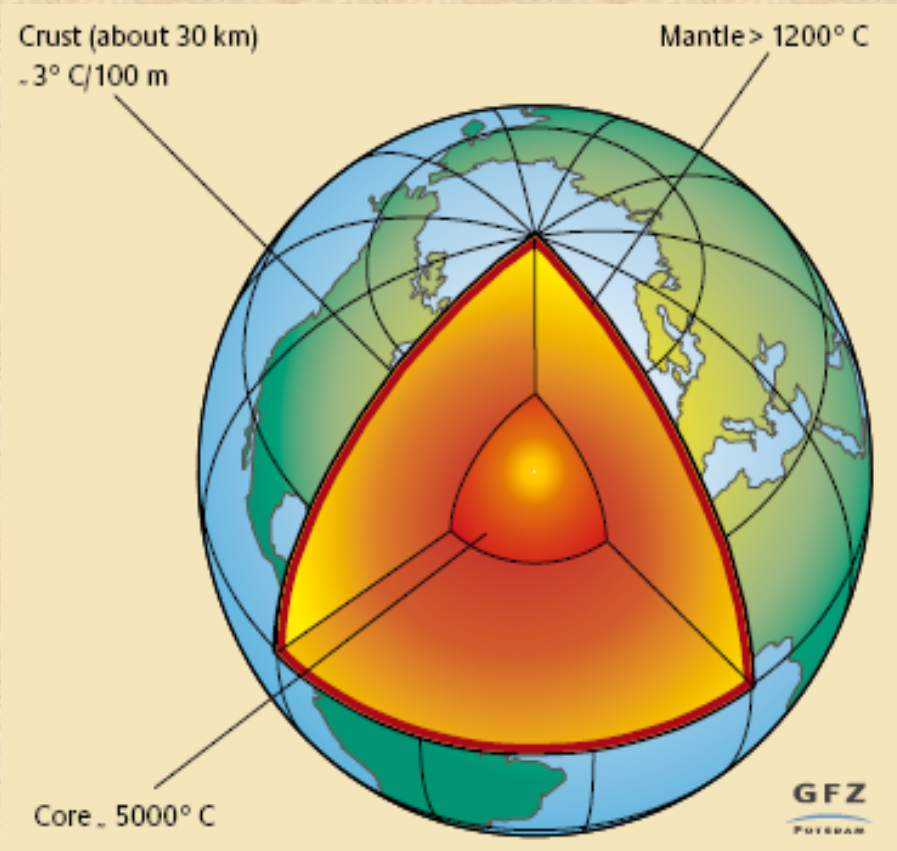
Well Monitoring Brings Results



Hydraulic-Seismology

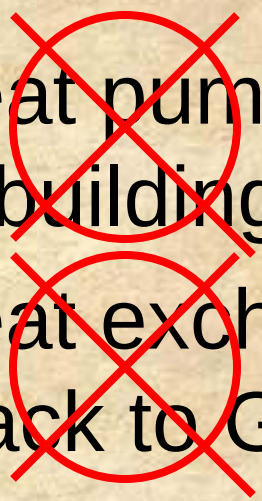


Heat Of The Earth



- Approximately 99% of the earth is >1000C (1800F)
- Approximately 99.9% of the earth is > 100C
  - Information from the German Energy Agency
- The molten earth is the highest energy density humanity has to work with.

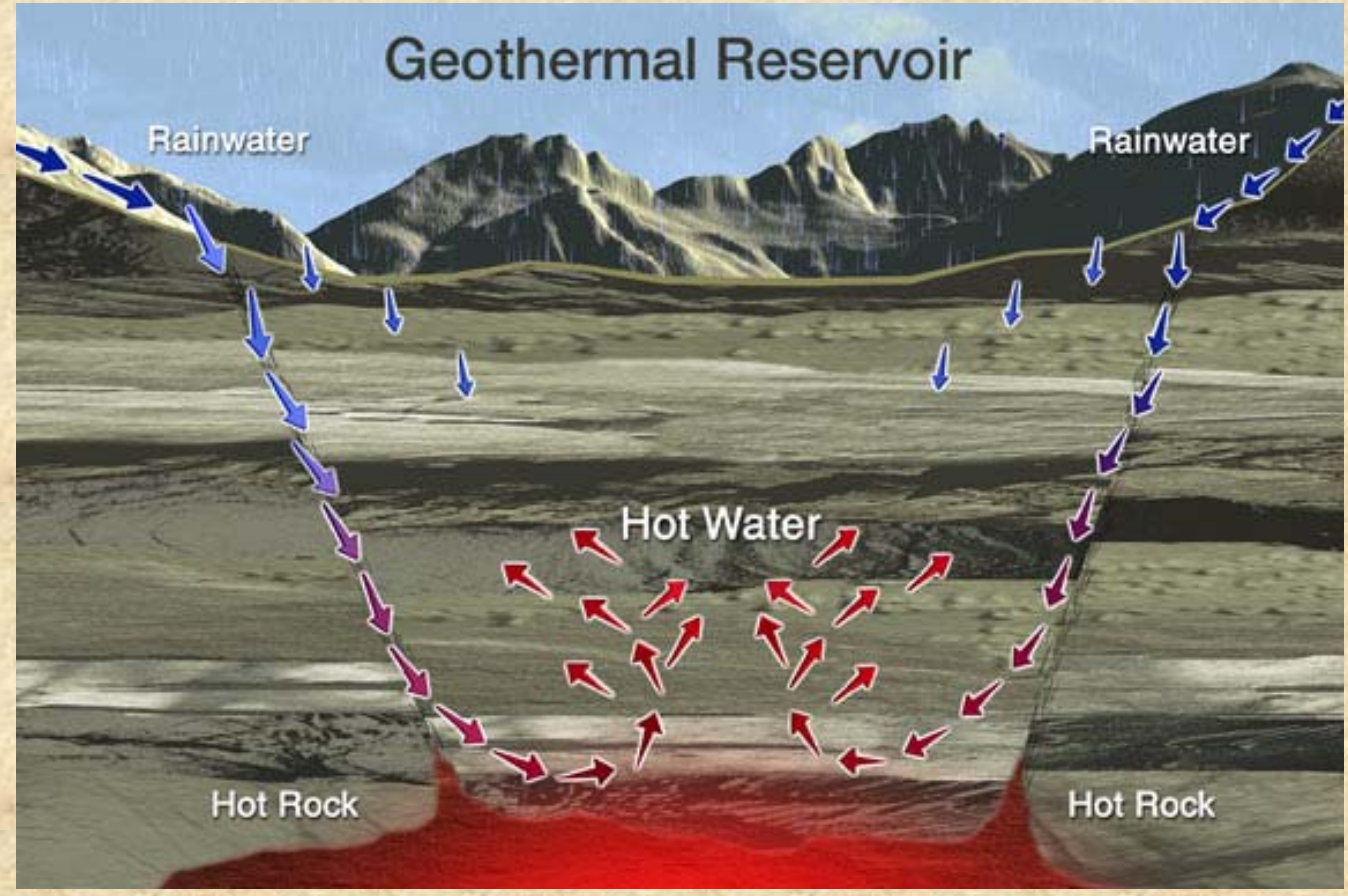
How to Harvest Earths Energy?



- Heat pumps for local heating and cooling of buildings
- Heat exchangers for converting wells from Black to Green
- Hydrothermal power plants
- Enhanced Geothermal Systems (Hot Dry Rock)
- Super-critical geothermal power plants

Conventional Geothermal (Hydrothermal)

- Here geothermal energy is produced from naturally occurring geothermal reservoirs

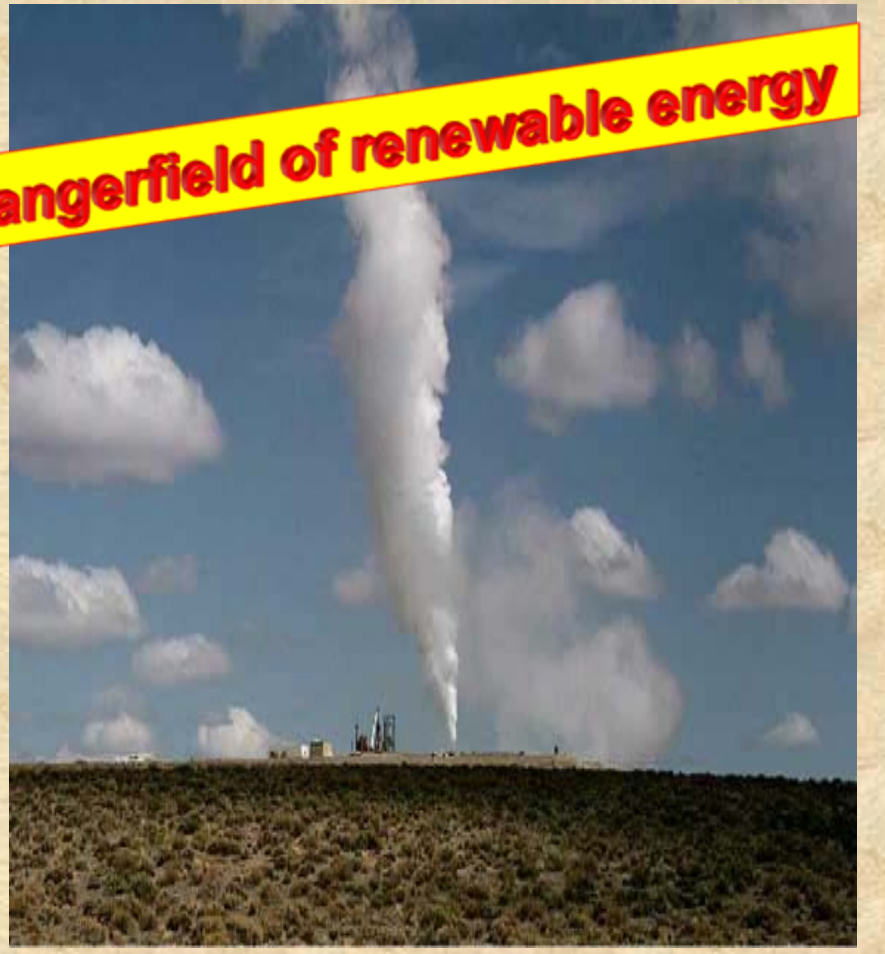


Top Hydrothermal Electric Power Countries (WGC, 05)

Country	MWe
U.S.A.	2,600
Philippines	2,000
Indonesia	1,000
Mexico	950
Italy	810

Hydrothermal Statistics

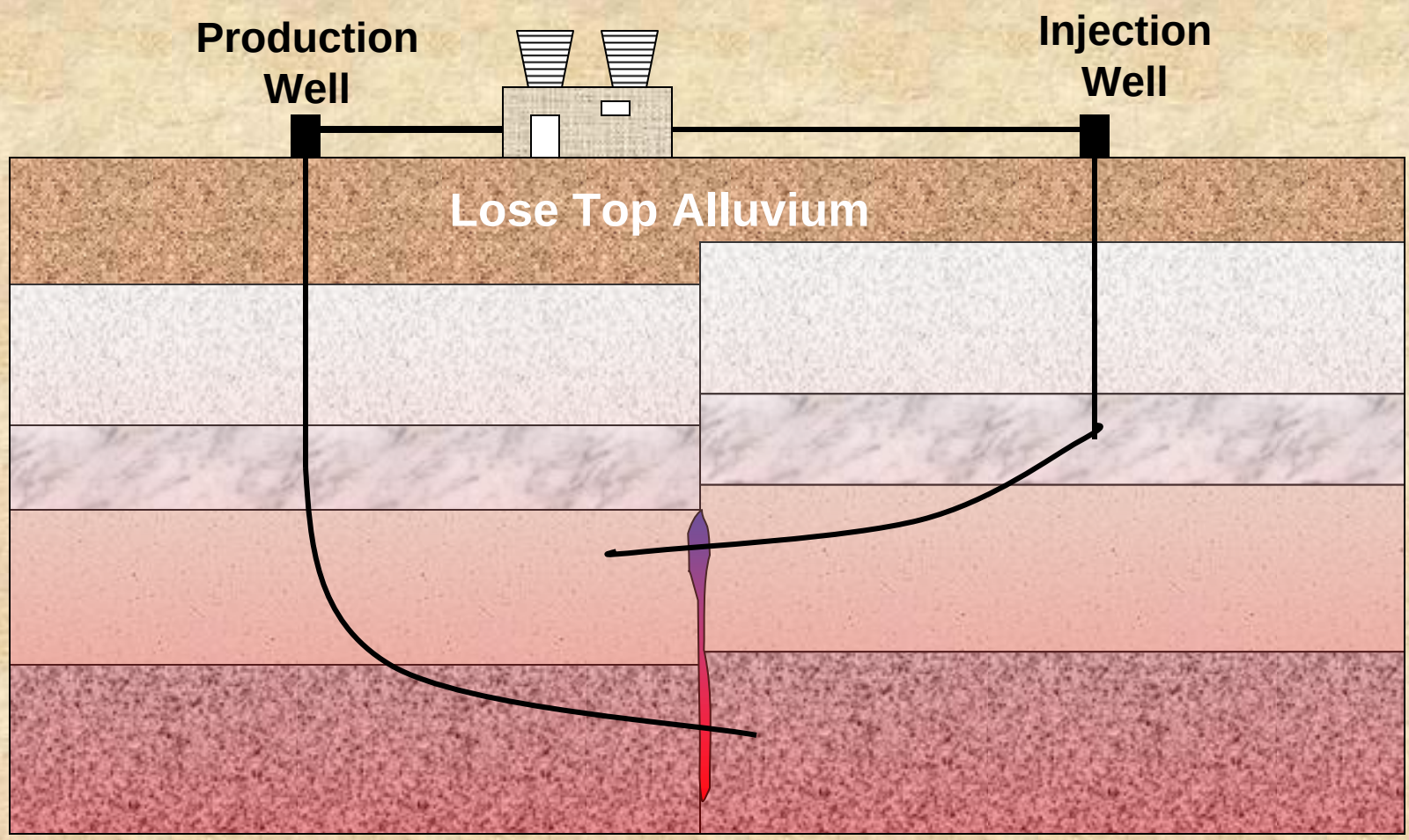
- Temp: 180 to 320C
- Pressure <10 Kpsi, 690Bar
- [illegible]housand wells
- Hydrothermal plant have >90% online power production
  - Equal to Coal plants!
  - Better than the combined wind and solar energy!!



Conventional Geothermal (Hydrothermal)

- Conventional hydrothermal is primarily found in the westerner United States
- Active faults create fractures in the earth which trap water
  - If the water could flow through the formation, it would cool
  - Some of the hottest formations in the US contain no water
- Active fault mean things can change
  - Earthquakes can damage or crush a geothermal well
  - Cold water from high level reservoirs can break through
  - Even so, every geothermal power plant built in the 1980s is still running today.

Hydrothermal Power Production



Hydrothermal Technology Needs

- Most wells are directionally drilled
  - Increases probability of hitting the facture
  - Measurement-While-Drilling improvements
    - HT azimuth and inclination to track direction
    - HT rotating face seals
    - Must survive 40-400 hrs @ 250C and
      - 30G vibration
      - 200G shock
- Well construction costs are ~50% of the plant cost.

From Conventional Hydrothermal to EGS

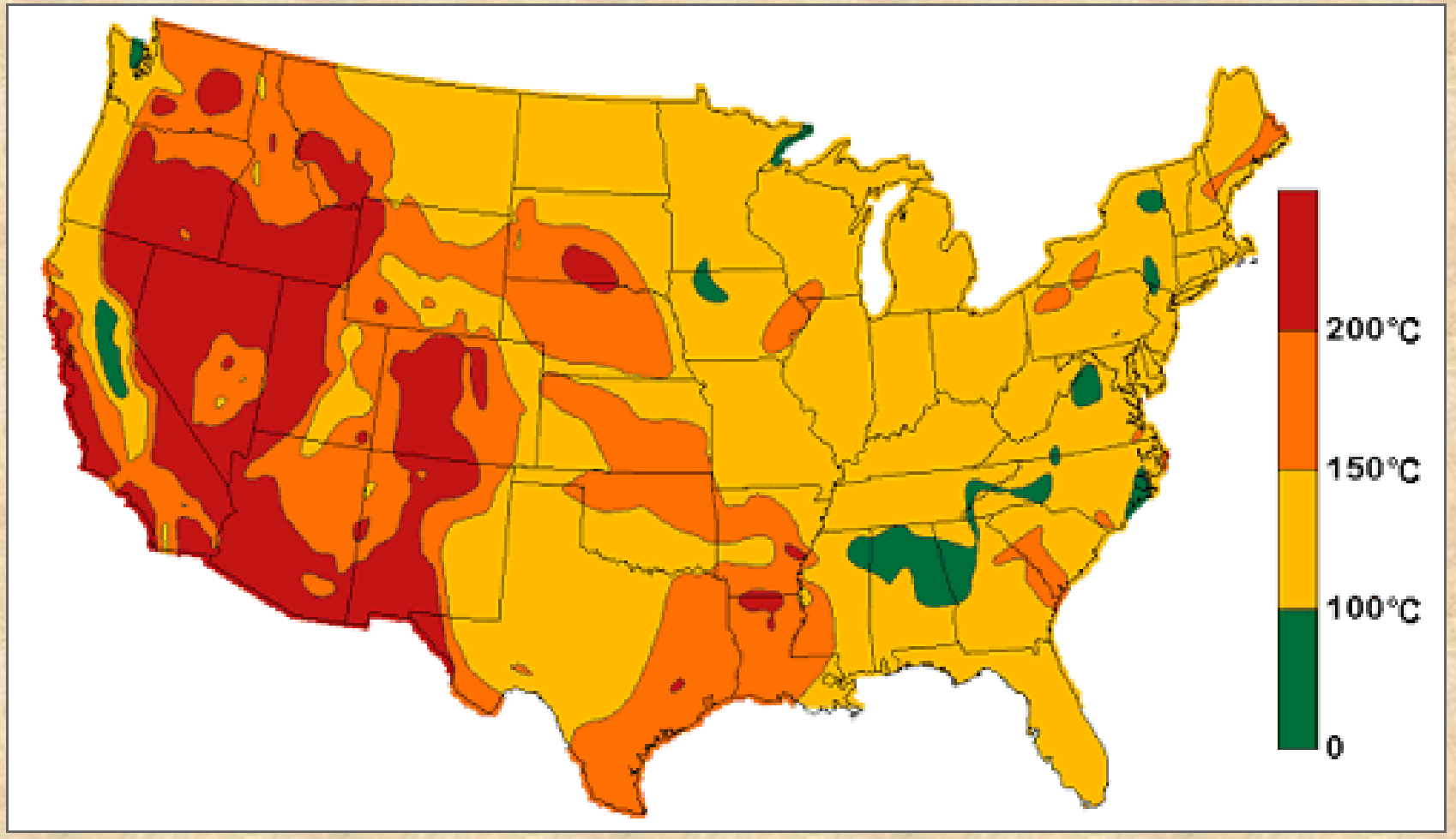
Research is now directed at making geothermal available everywhere

- EGS: Enhance Geothermal System
  - Man made reservoirs
  - H_2O or CO_2 could be used as the heat conductor
- EGS is also called Hot Dry Rock

- Geodynamics (Australia) is nearing the completion of a major EGS power plant

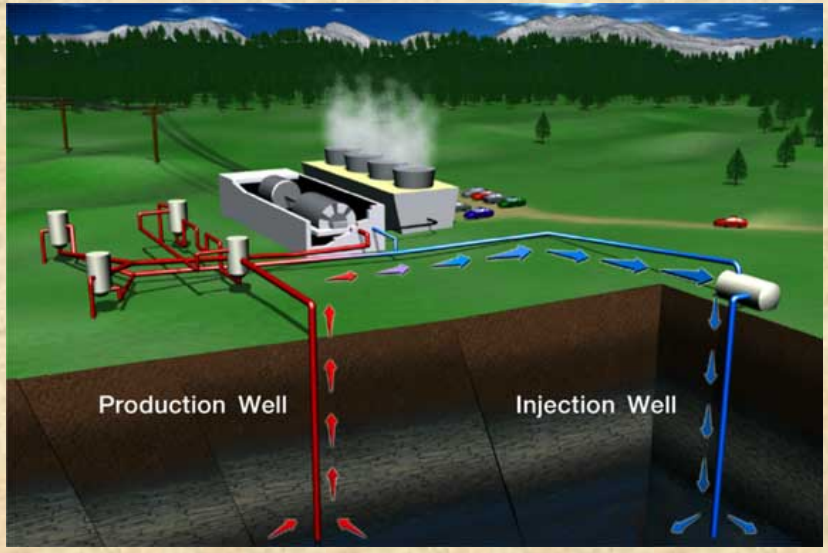
Expected US Temperatures at 6km

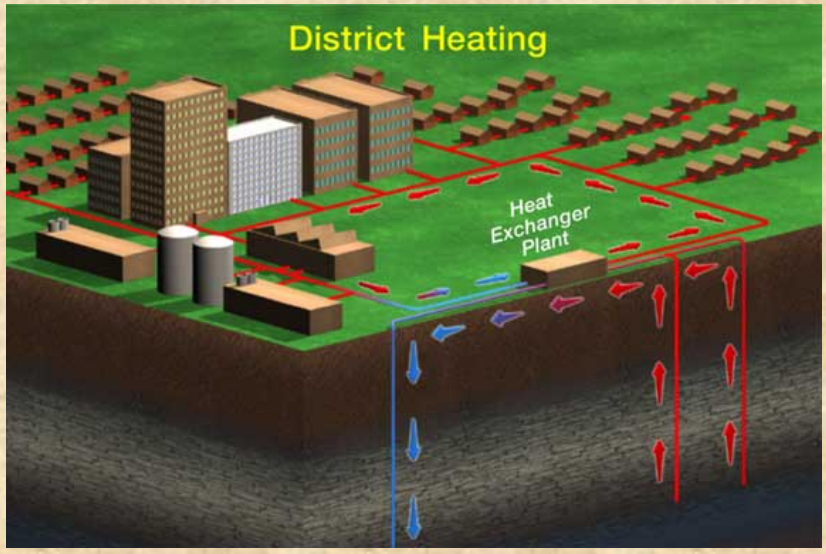
DOE & Dr. Dave Blackwell, SMU



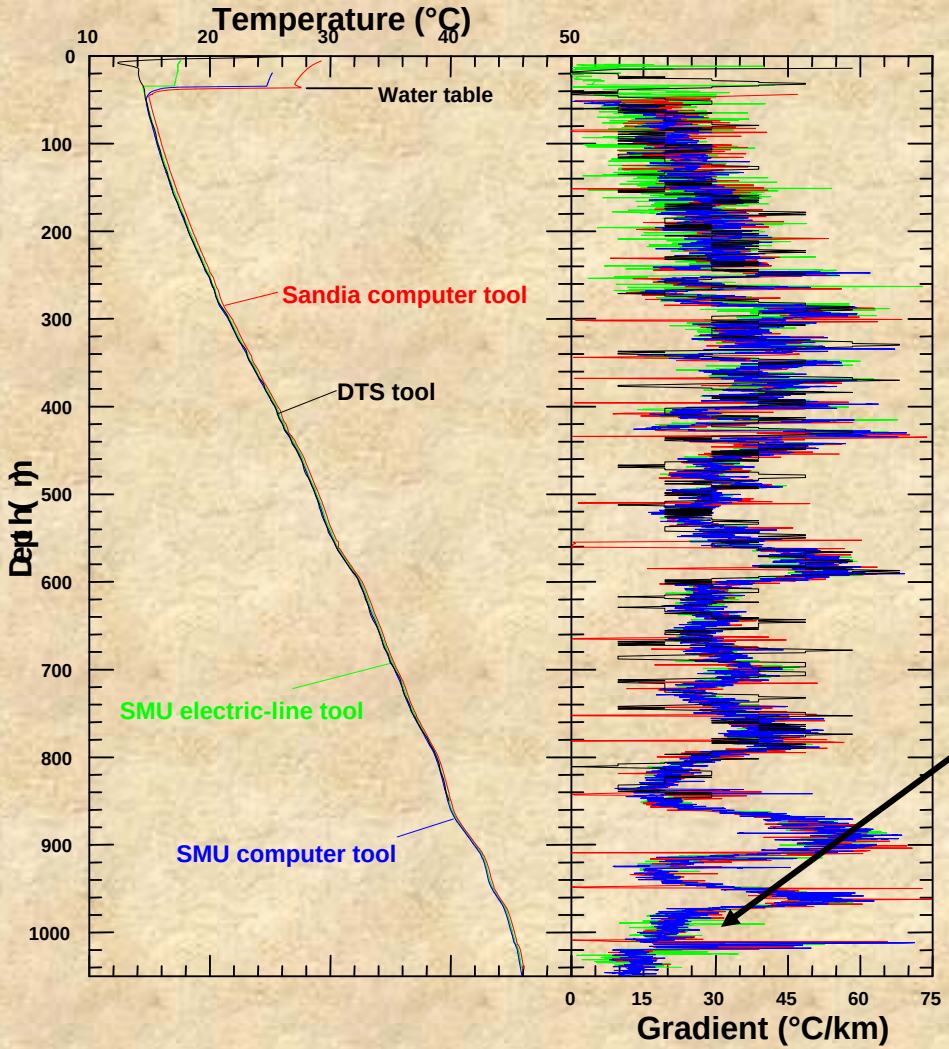
In general, geothermal temperatures are reached everywhere at 10km

"The potential of EGS energy worldwide is estimated at 50,000 times the world's oil and natural gas reserves", Department of Energy funded MIT Report, 2007





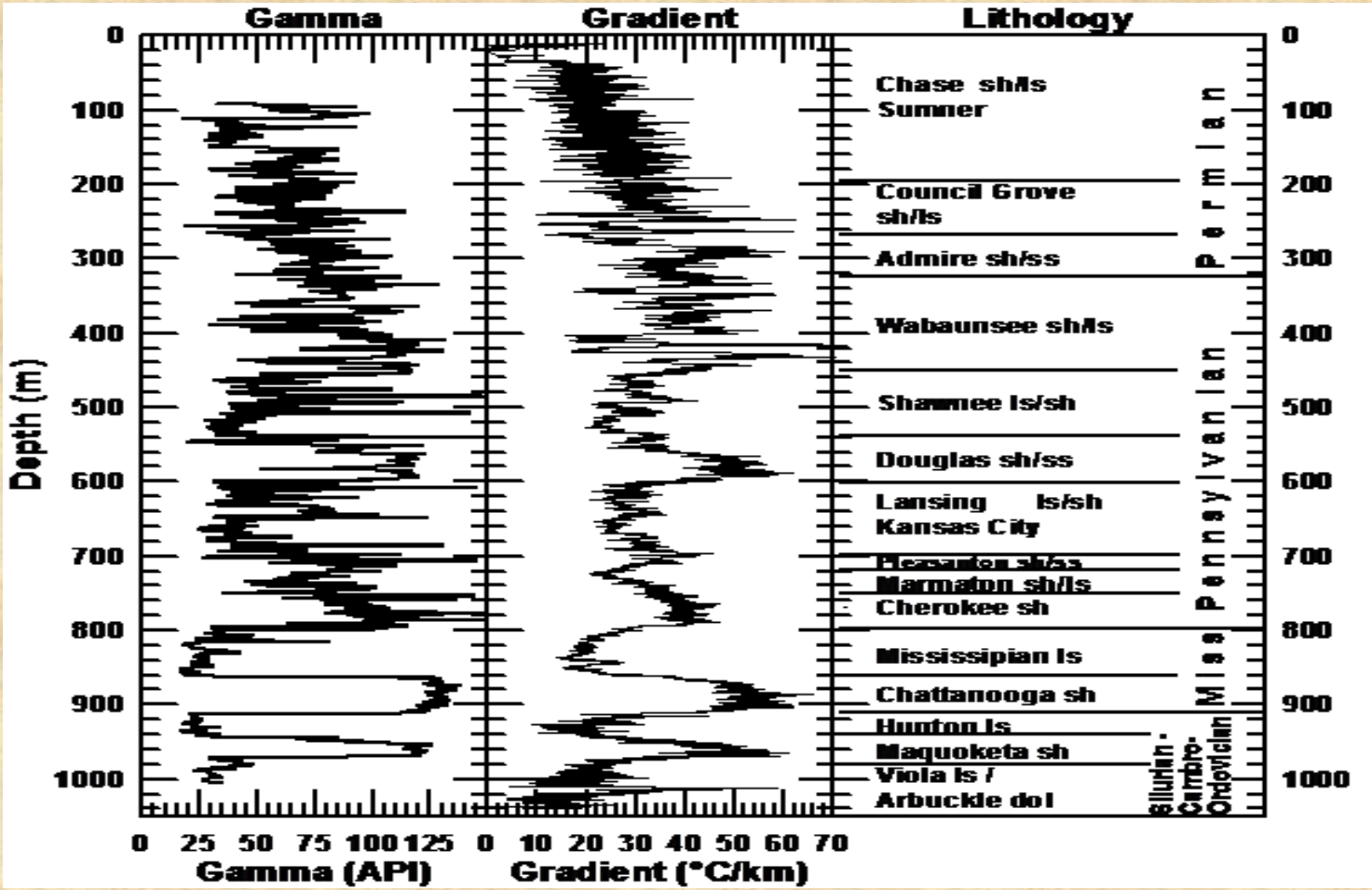
Increasing Temperatures as a Function of Depth



- The Earth temperature gradient is between 17-30C/Km
- Even this Kansas well temperature profile to the left is increasing as a function of depth
- This formation has better thermal conductivity than the formation above it. So, lets place our reservoir here.

From: “how Hot Is It” , Ken W. Wisian et al, GRC trans. V20,September/Oct 1996

The Earth is Renewable Energy

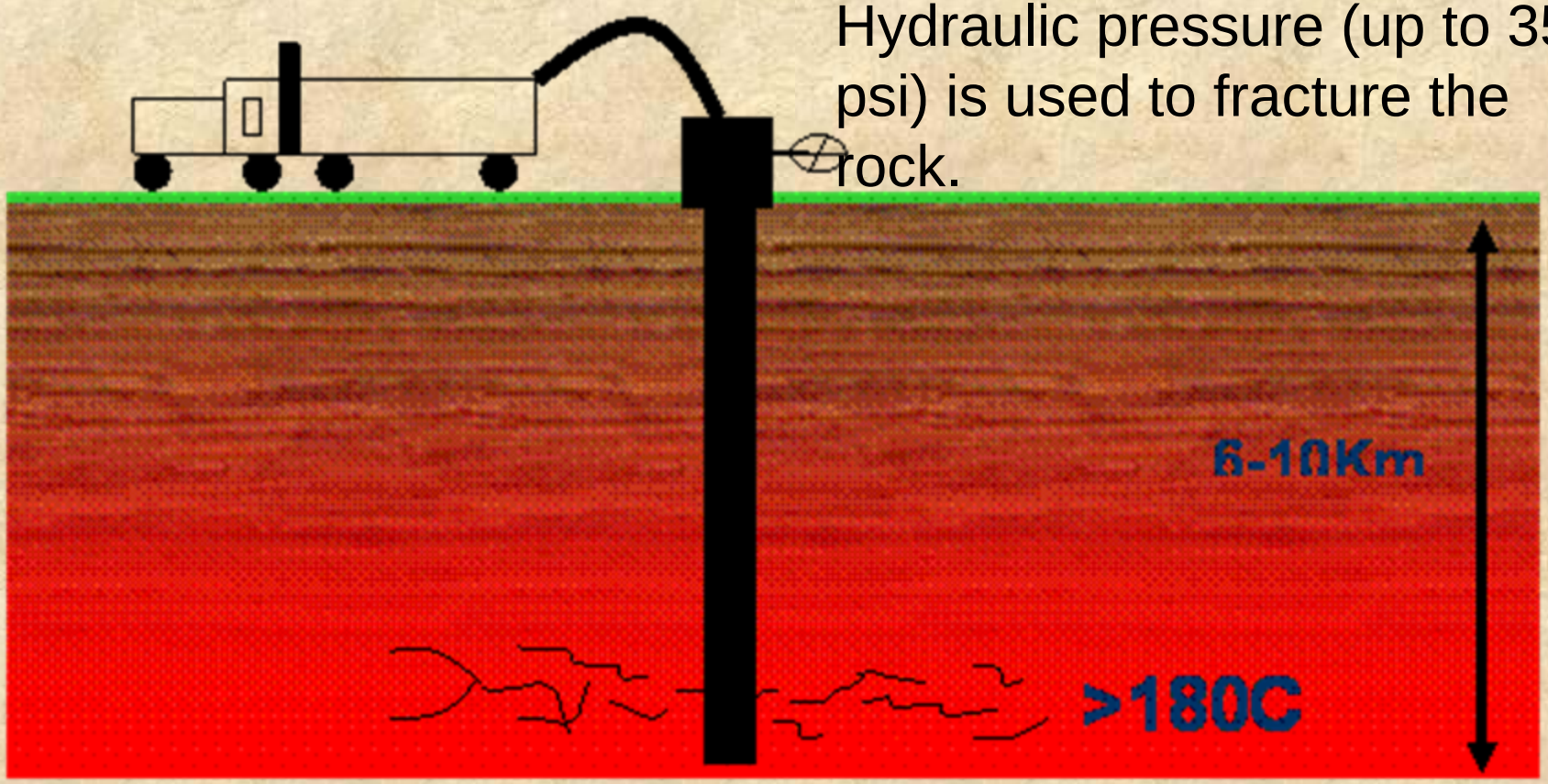


The Earth has had a molten center for more than 4 Billion Years!

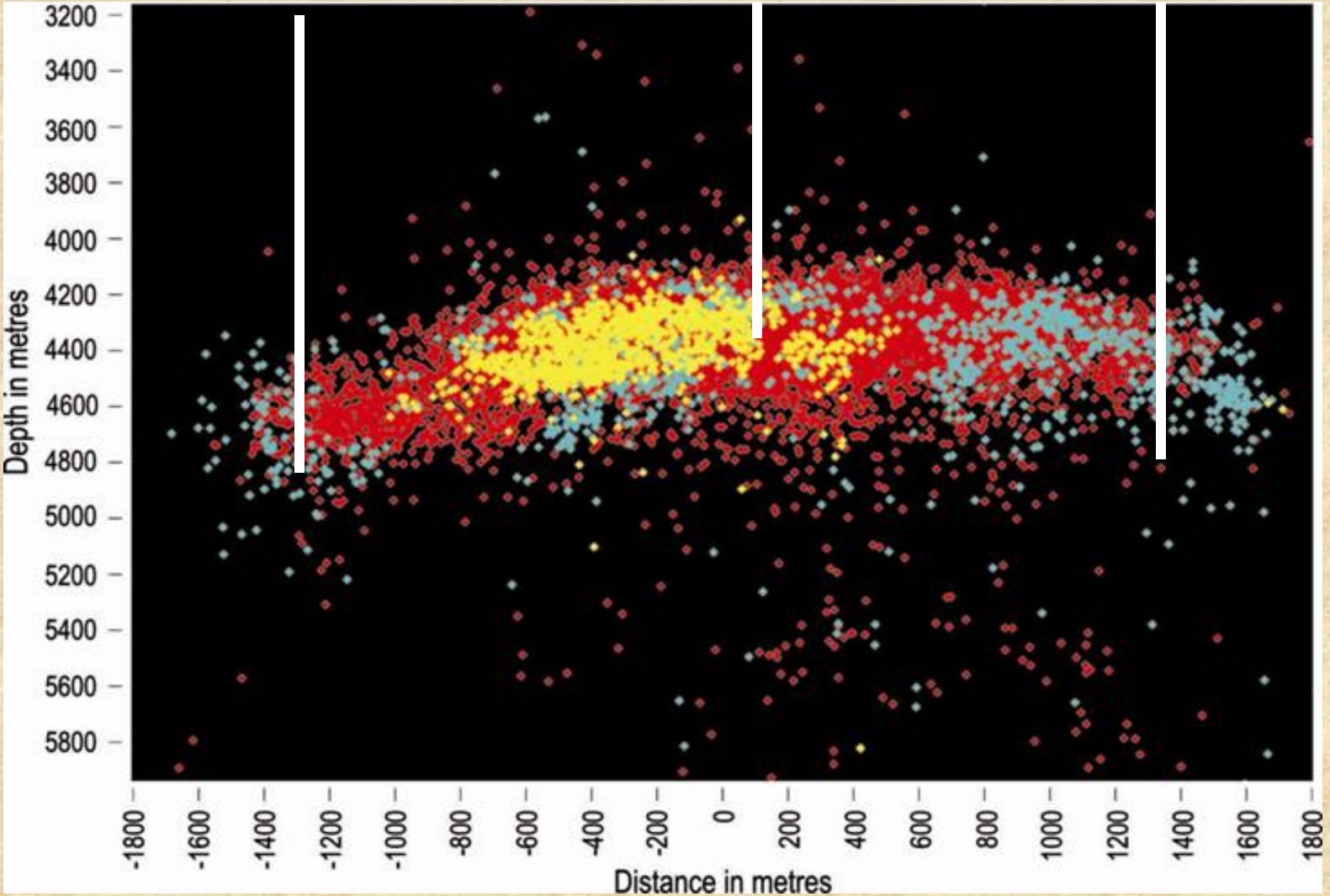
From: “how Hot Is It” , Ken W. Wisian et al, GRC trans. V20,September/Oct 1996

EGR: Engineered Geothermal Reservoir

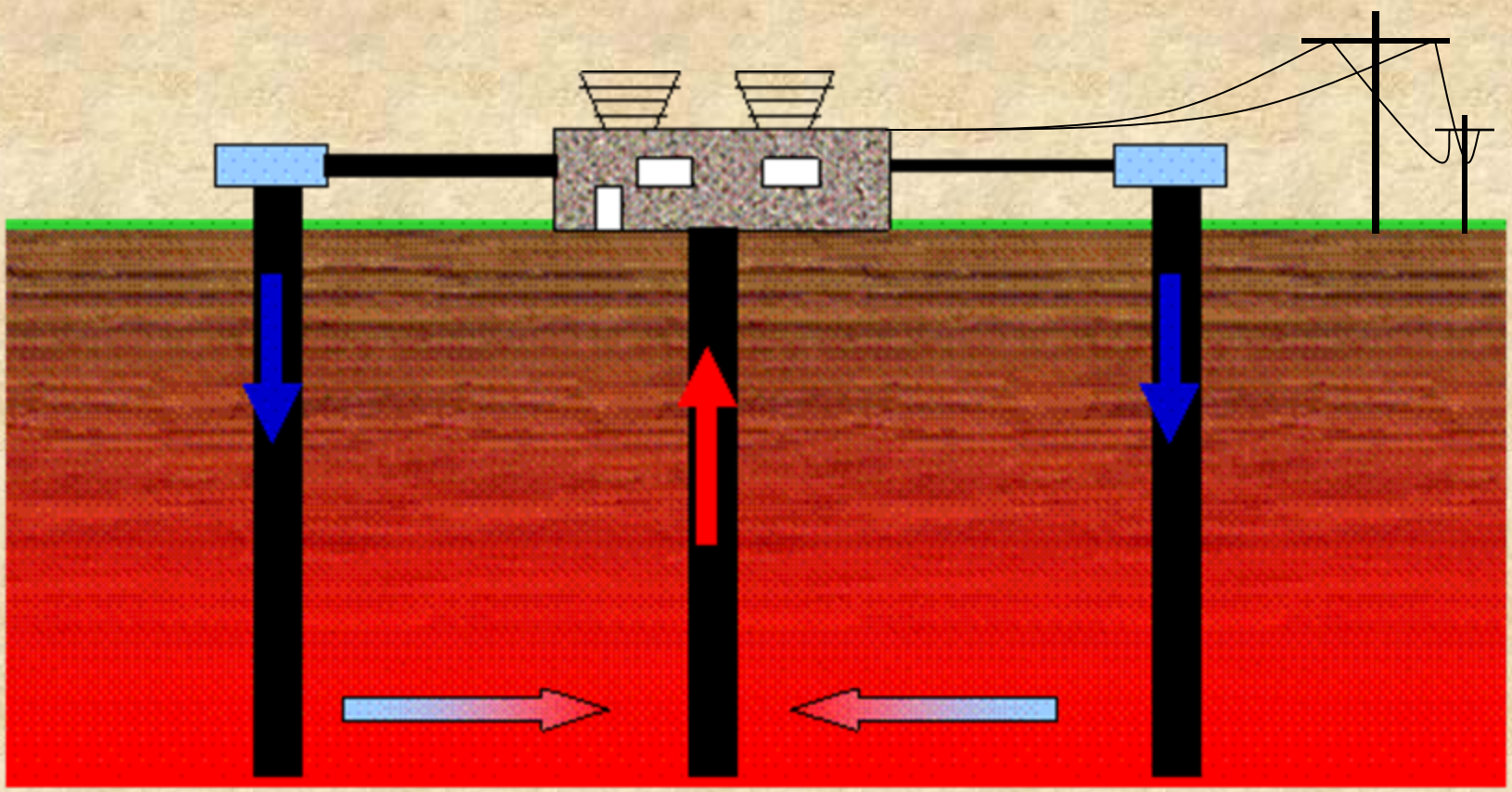
Well is drilled to desired temperature and rock type. Hydraulic pressure (up to 35K psi) is used to fracture the rock.



Fractures Can Reach 1000s of Feet Away From the Well

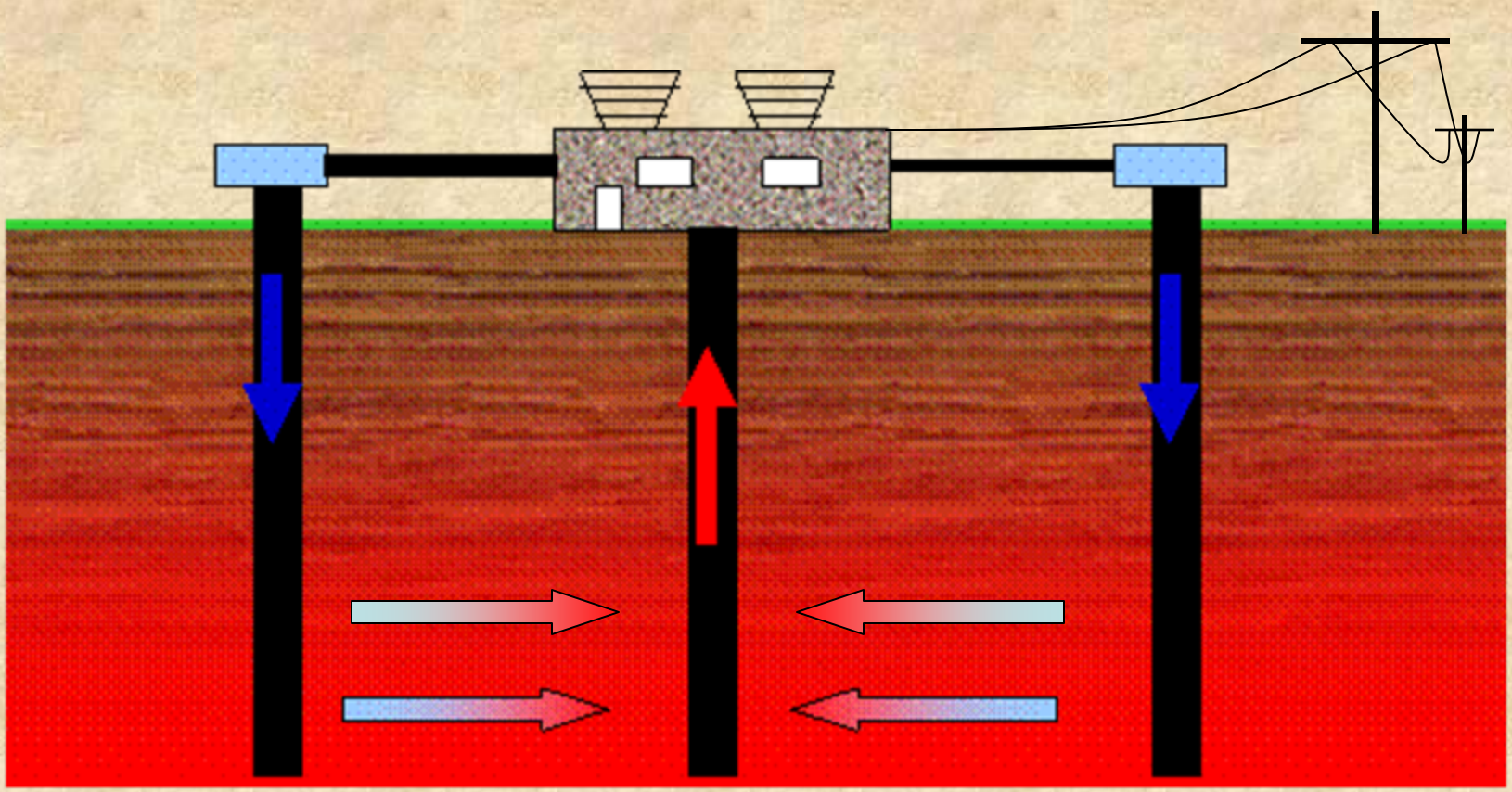


Enclosed Geothermal System



The fractured rock is used as an heat exchanger. This is the standard concept shown in most EGS presentations.

Enclosed Geothermal System



Wells are expensive. Most people realize that we need to produce multiple heat exchangers for every set of wells.

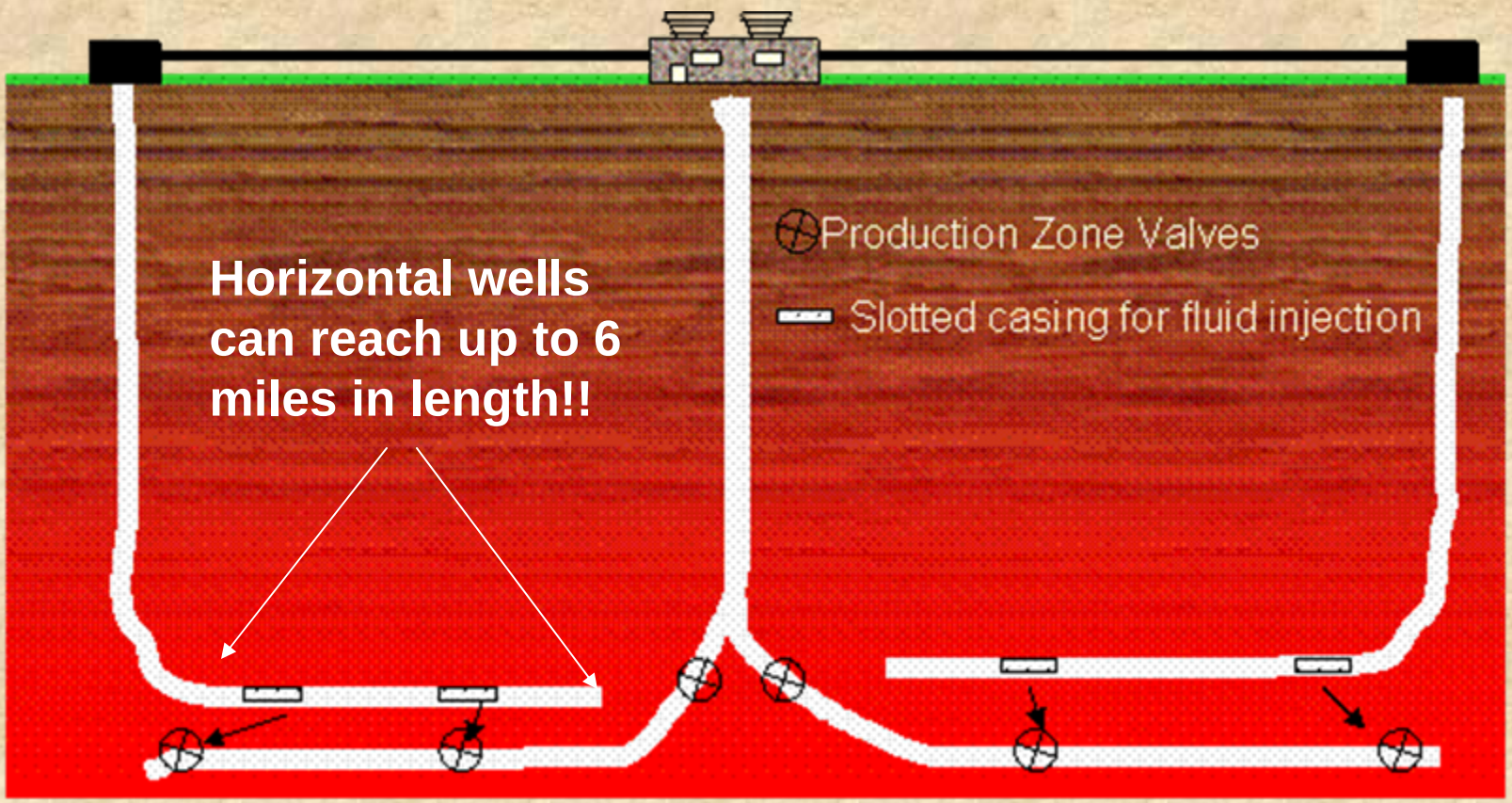
Reservoir Design Example

Fluid low out at higher depth, 180C

Fluid flow in at a lower depth, 150C

Problems of short circuiting or poor connectivity can be reduced

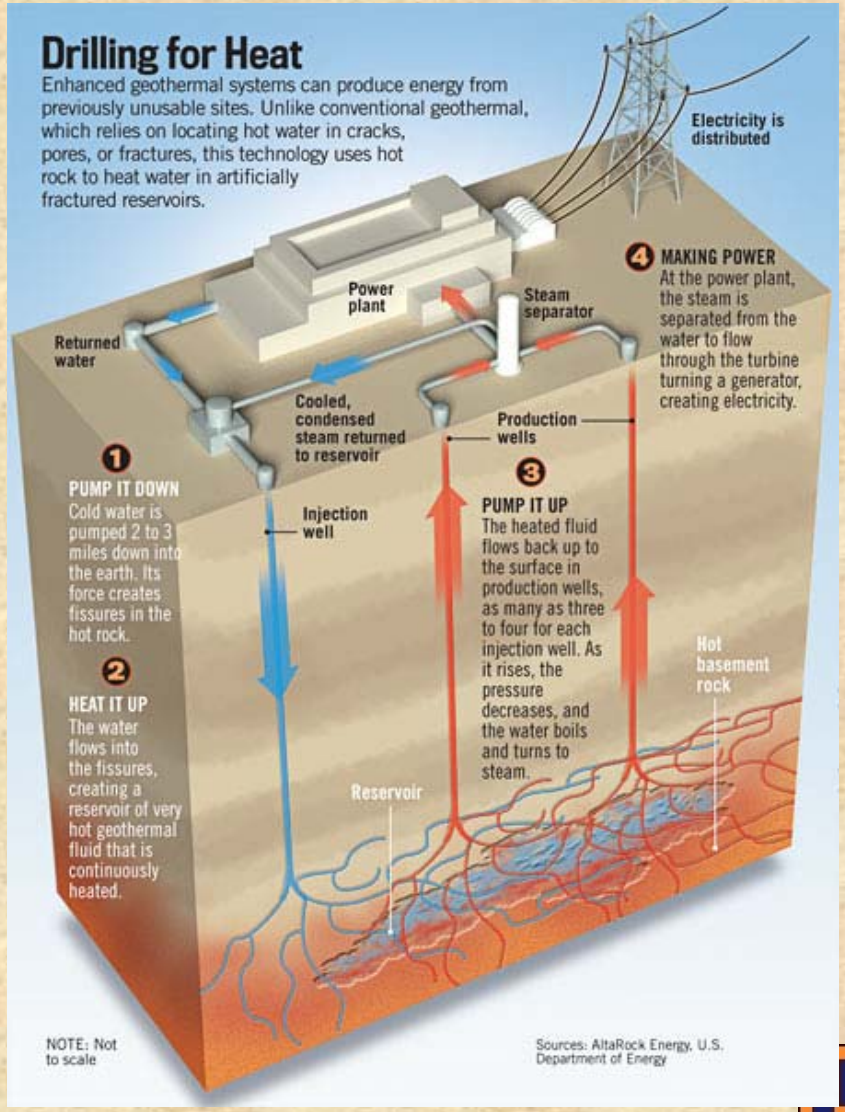
A More Realistic View



Horizontal wells in the hot formations can greatly increase the size of the reservoir. Oil industry record for horizontal drilling is 6.5 miles.

EGS Requirements

- Temp: 150 to 250C
- Pressure <15 Kpsi, 1000Bar
- Permanent installations of electronics for controlling reservoir power production



EGS Technology Needs

- Same directional drilling requirements as hydrothermal
- Permanent well monitoring systems
  - Pressure, temperature, flow
- Production control valves with a 20 yr life
  - Motor drives
  - Valve materials must be resistant to:
    - Abrasive sands
    - Chemical resistant (H2, HCl, H2S)
- Well construction costs >200% of the plant cost