Universal Heat Mining
Geothermal Energy for Everyone

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Overview

- ☐ Global sustainability issues that influence the energy landscape
- ☐ Some examples of more sustainable approaches that require improved characterization and prediction of subsurface behavior
- ☐ Characteristics and role of geothermal energy
- ☐ Potential of heat mining from Hot Dry Rock
- ☐ Current Status of the technology
- ☐ Economic projections and requirements for commercial feasibility
- ☐ A proposed US program

The Big Energy Questions

- Can we satisfactorily reduce emissions and remediate wastes residing in our water and air basins?
- Can we offset changes being introduced by our consumption of fossil fuels?
- Can we significantly reduce our dependence on imported oil?
- Can nuclear, renewable, and other non-fossil energy resources be deployed quickly enough to make a difference?

Even in an asymptotic world the challenge is great!!

- ☐ Population - 6+ billion growing to 10 to15+ billion
- ☐ Total primary energy –
  - 400 quads growing to 2000+ quads annually
  - 73 billion growing to 365+ billion bbl of oil/yr
- ☐ Per capita energy per year –
  - 10 BOE/yr-person growing to 25 BOE/yr-person
- ☐ Number of cars and trucks -
  - 750 million now growing to 5 + billion
- ☐ MW electric generating capacity -
  - 3.5 million MWe now growing to 15+ million MWe

Transitioning to new supply system on a global scale will need robust technologies, favorable economics and proactive policies

Desirable Characteristics of a Sustainable Energy Supply System

- **Renewable** – non-depletable on a short time scale
- **Accessible and well distributed** – available close to demand
- **Emissions free** – no NO_x, SO_x, CO_2, particulates, etc.
- **Scalable** – from < 1 MW to 1000 MW (t or e)
- **Dispatchable** - for base load, peaking, and distributed needs
- **Robust** - simple, reliable, and safe to operate
- **Flexible** - applications for electricity, heat, and cogen
- **Competitive** with fossil fuels when externalities are included in the price

More sustainable approaches

☐ **Require increased use of indigenous, renewable energy resources**

☐ **There are two fundamental sources of renewable energy –**

1. **The sun -- "*looking outward*"**
2. **The earth – " *looking inward*"**

☐ **Currently we are focused on *looking outward* for a solution – e.g. PV, CSP, bioenergy, wind, etc**

☐ ***Looking inward for geothermal energy* requires improved technology and understanding of subsurface environments**

Multiple Opportunities

- ☐ Universal geothermal heat mining
- ☐ Carbon dioxide sequestration in geologic formations
- ☐ Advanced infrastructures using smart tunneling methods
  - ▪ intra and inter city transportation
  - ▪ water supply and redistribution
  - ▪ sewage and MSW transport and treatment
  - ▪ communication and electric power distribution
- ☐ Natural hazard mitigation – earthquakes and tidal waves
- ☐ Exploration of the earth to depths of 20+ km

Looking inward for Geothermal Energy

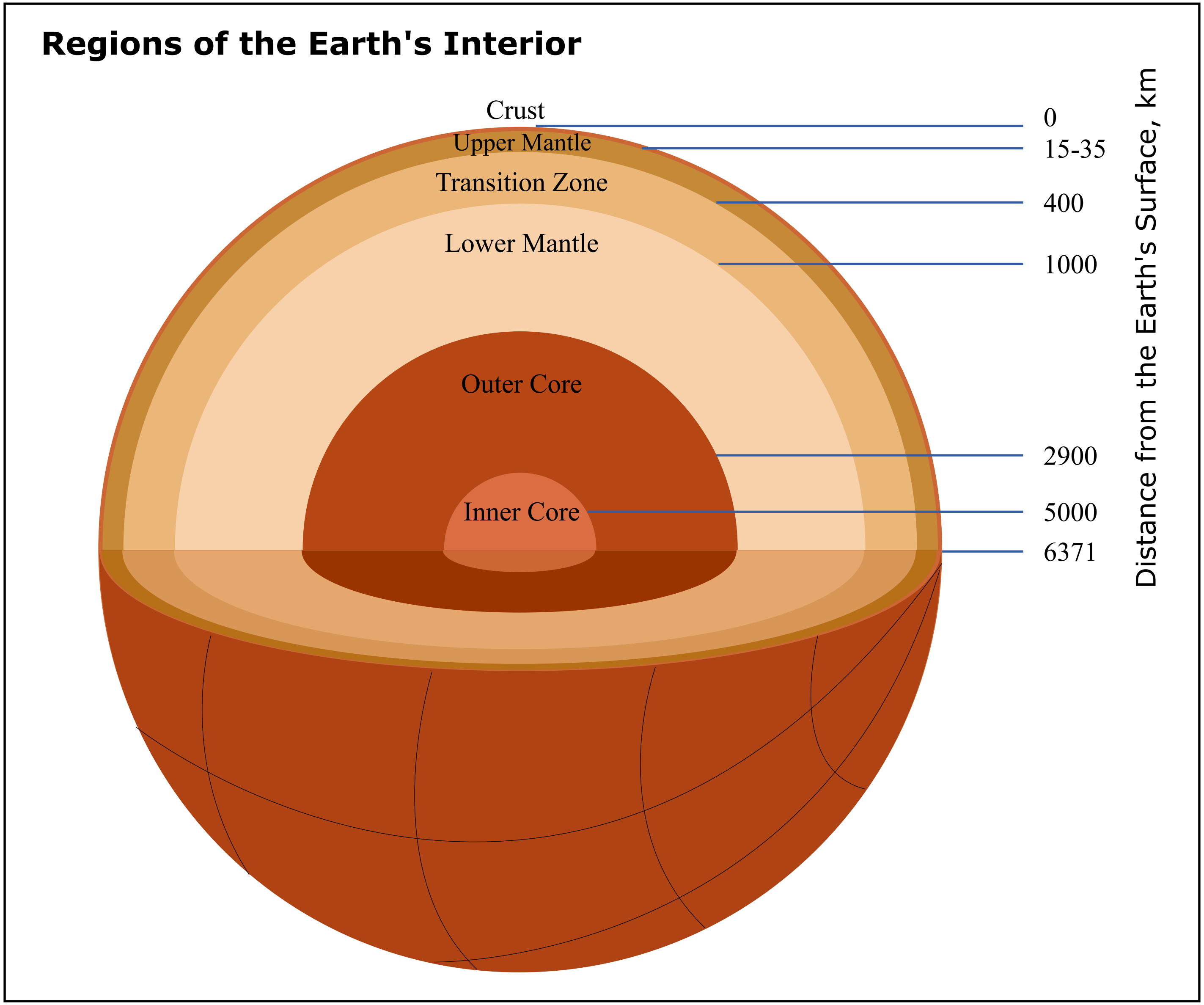
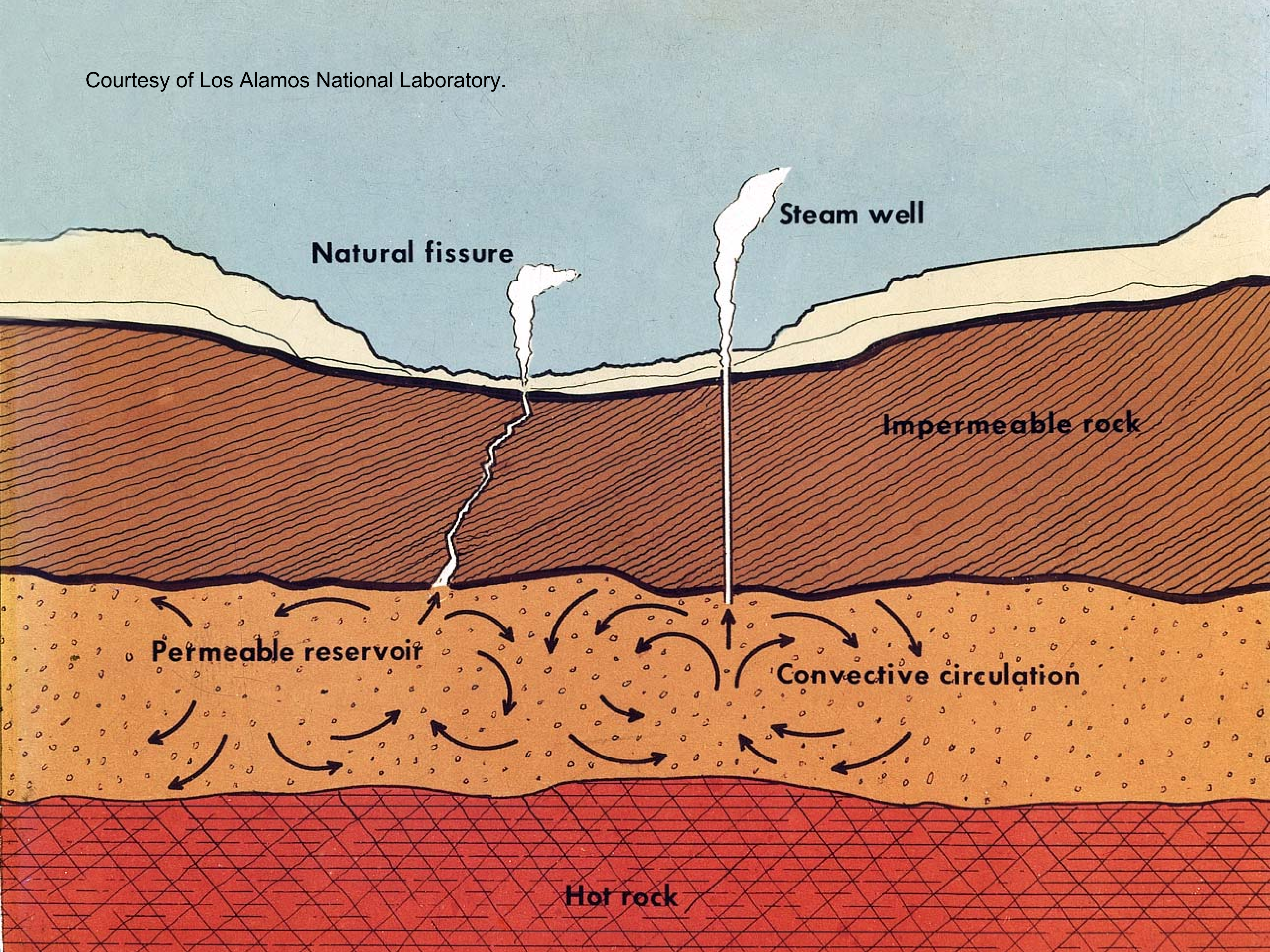


Figure by MIT OCW.

Universal Heat Mining

A few simple questions?

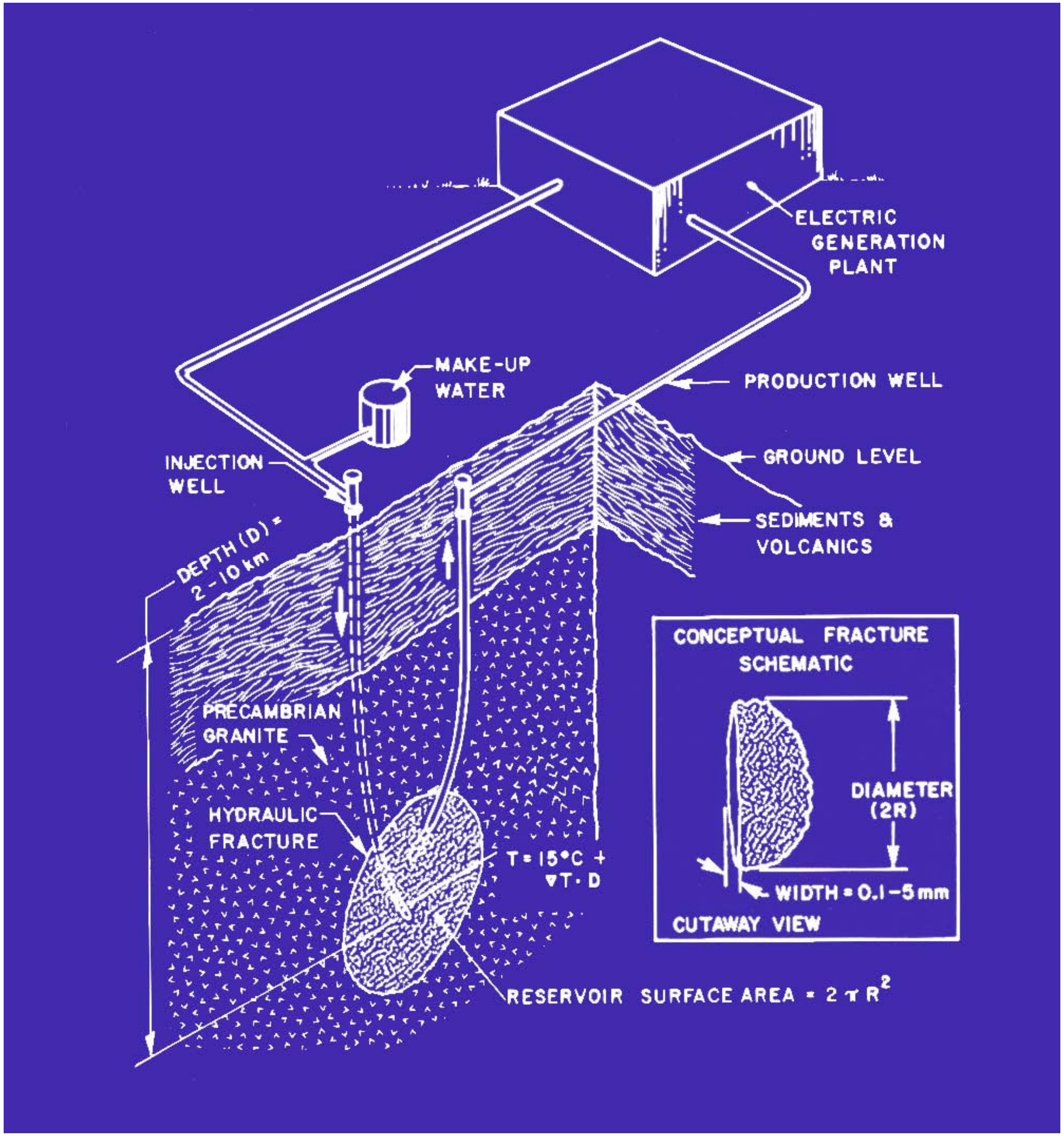
1. What is it?
2. How big is it?
3. How is it distributed?
4. How will energy be recovered?
5. How is the technology progressing?
6. Is there a path to economic viability?

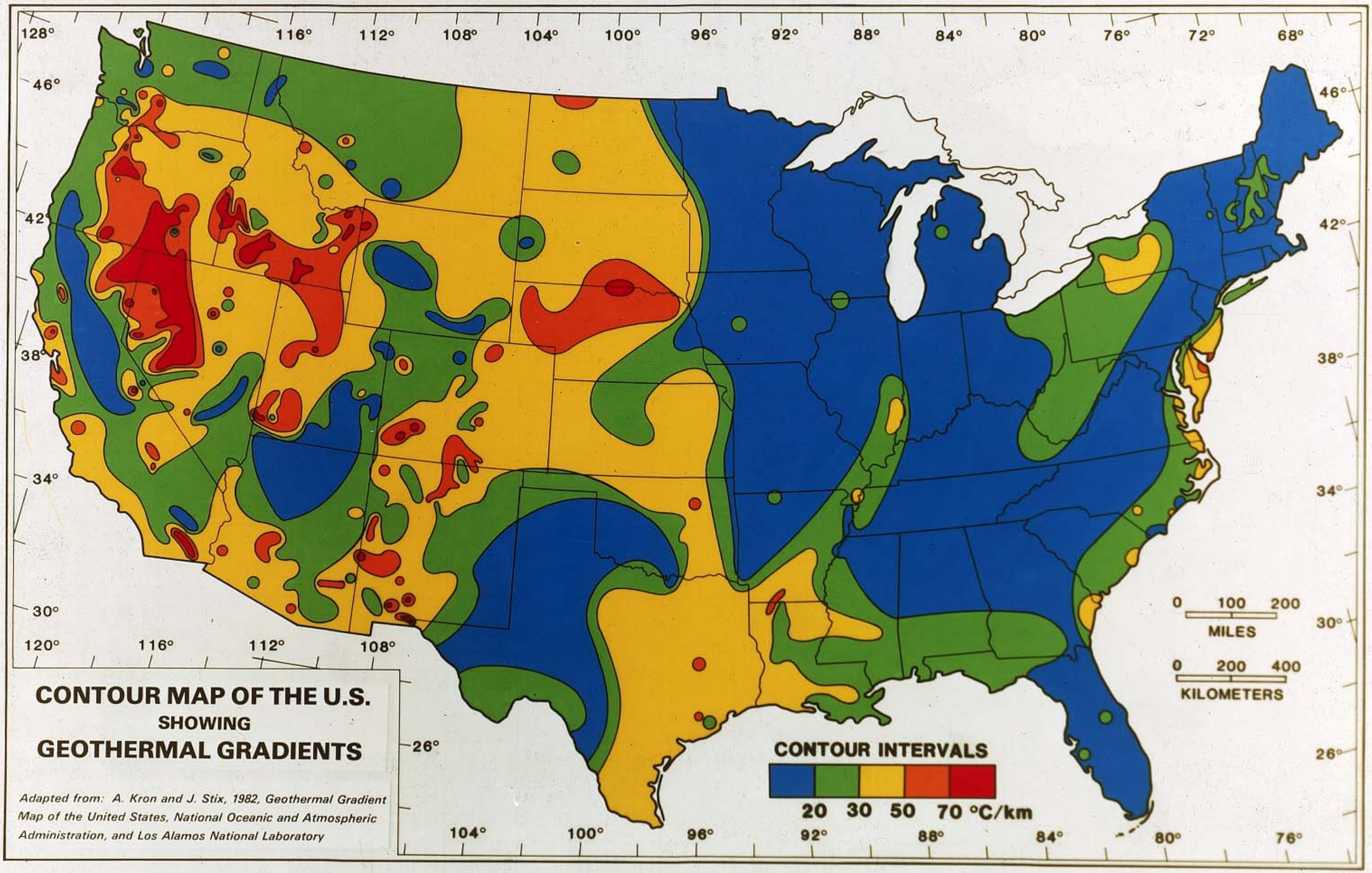


Courtesy of Los Alamos National Laboratory.

Hot Dry Rock [HDR or EGS]

- Resource characteristics
- Reservoir properties
- Energy conversion and end use
- Economics





CONTOUR MAP OF THE U.S.
SHOWING
GEOTHERMAL GRADIENTS

Adapted from: A. Kron and J. Stix, 1982, Geothermal Gradient Map of the United States, National Oceanic and Atmospheric Administration, and Los Alamos National Laboratory

Critical Elements for Heat Mining

- ☐ **Resource quality**
  - average geothermal gradient -- ∇T
  - geotechnical “compliance” and stability of rock formations
- ☐ **Reservior performance**
  - size – active volume and/or surface area

    <V> and/or <A>
  - flow resistance or impedance

    $I = (\Delta P - P_{buoyancy})/$ (mass flow rate)
  - temperature – availability and fluid quality
- ☐ **Economic factors**
  - Well drilling and completion costs
  - Surface plant and distribution costs

The “Laws” Geothermal Economics

1st Law -- Completed well cost increases exponentially with depth

2nd Law -- Power plant cost decreases linearly with temperature

3rd Law --As resource quality decreases drilling costs dominate

Basic Economics of Heat Mining

Cost = C(well system) + C(power plant) + C(O&M)

$\text{Cost} = f(\,T_{gf}(\nabla T,\ depth),\ T_o,\ <V>\ or\ <A>,\ m_{gf}(\text{☟}P,\ I))$

C(well system) = f (number of wells, cost per well, T&D)

C(power plant) = Power x $f\,(T_{gf},\ T_o\,)$

Basic Economics of Heat Mining

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$$C(\text{power plant}) = \text{Power x}\ f\,(T_{gf}, T_o\,)$$

where

T_{gf} = the initial geothermal fluid temperature

m_{gf} = mass flow rate thru single reservoir = $\Delta P/I$

n_{wells} = number of wells = Power / $m_{gf}\ \eta_u\ \Delta B$

∇T = average geothermal gradient in °C/km

$<V>$ and $<A>$ = volume and area or reservoir

I = flow impedance, Pa s/kg ; ΔP = pressure drop across system, Pa

$\eta_u\ \Delta B$ = recoverable fraction of thermodynamic availability, J/kg

Unique Heat Mining Tradeoffs

1. **Drill deeper to increase temperature**
    - lowers surface plant costs
    - increases individual well cost
    - reduces number of wells needed
    - may reach a geochemical limit

2. **Drill shallower to lower temperature**
    - raises surface plant costs
    - decreases individual well costs
    - increases the number of wells needed

Unique Heat Mining Tradeoffs

3. **Connection between reservoir size and energy extraction rate**
   - Finite thermal drawdown is needed for optimal economic performance
   - Larger reservoir <volumes> or <areas> require higher mass flow rates
   - Parasitic pressure losses must be considered as well

Constrained optimization problem $T_{min} < T_{rock} < T_{max}$

Costs for Heat Mining depend on

1. Resource grade
2. Reservoir production rates
3. Drilling costs
4. Power plant costs

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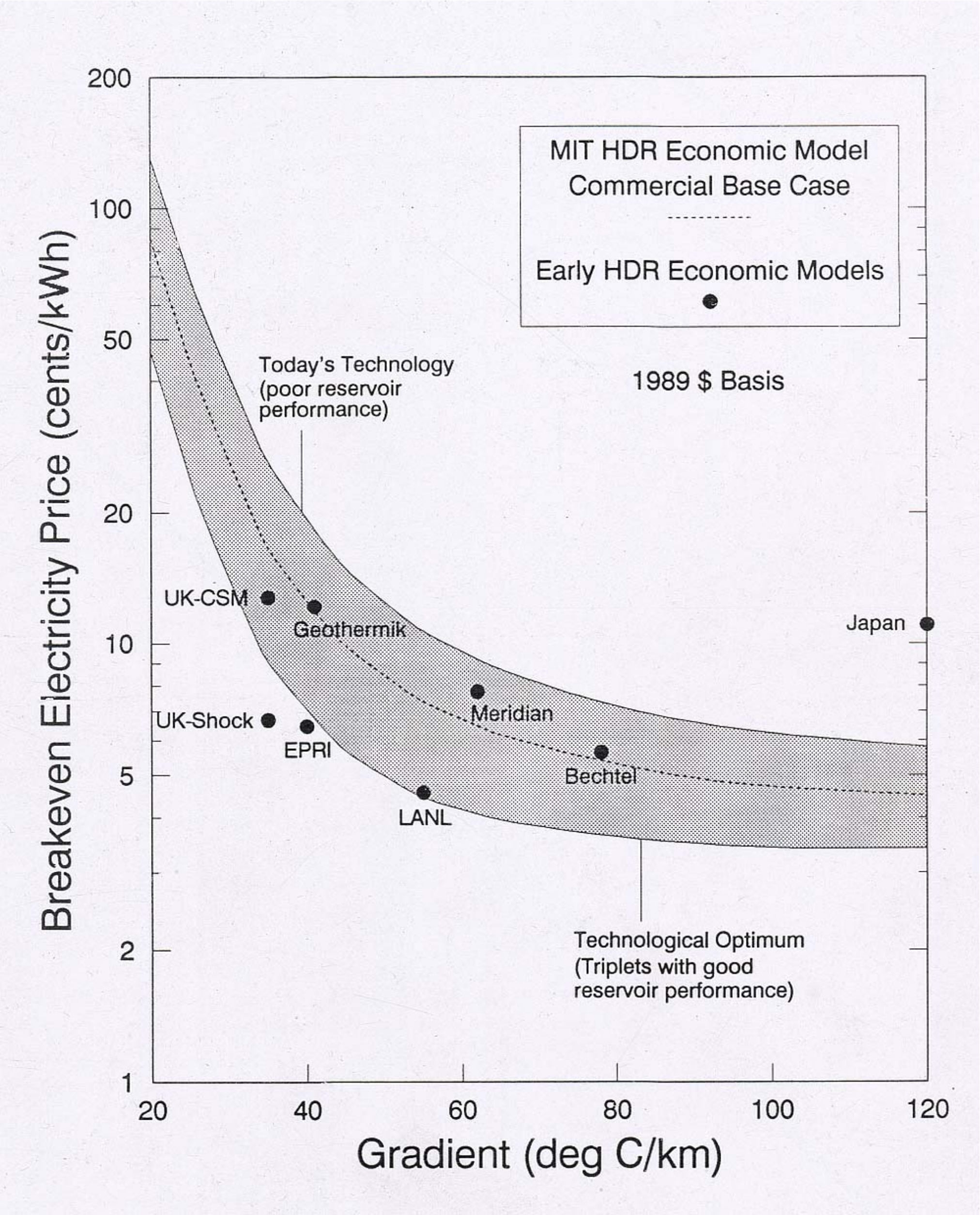
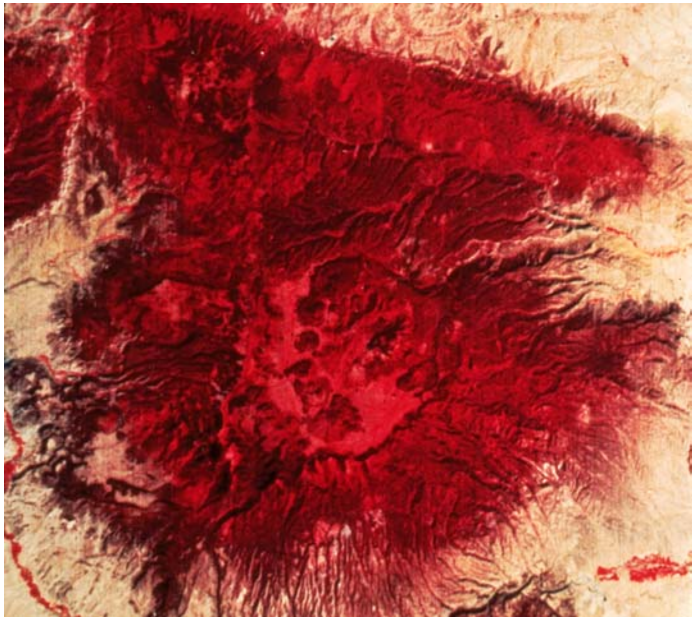


The Fenton Hill Los Alamos experiment

High grade, volcanic resource in crystalline rock



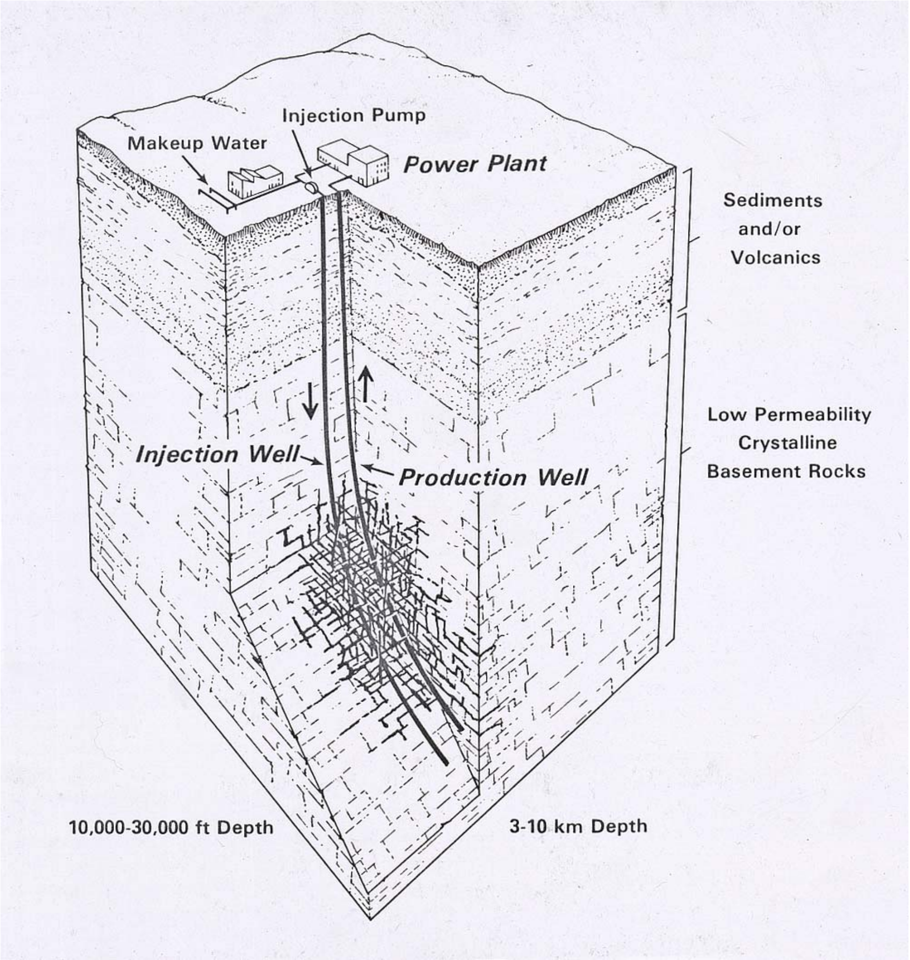


Photo courtesy of NASA.

Fenton Hill – a 25+ yr Los Alamos experiment

- ☐ HDR concept born at Los Alamos as a subcomponent of Subterrene - 1970
- ☐ Fenton Hill Test hole drilling GT1 – 1971
- ☐ Phase I field test - 1973 –1979
  - ▪ GT-2B – EE-1 , 2-well connected system
  - ▪ 3 km (10,000 ft), 200°C
  - ▪ prototype reservoir ca 10,000 m^2
- ☐ Phase II field test - 1980 – 1990
  - ▪ EE-1 – EE-2 , 2-well connected system
  - ▪ 5 km (15000 ft), 300^{+} °C
- ☐ Post –phase II testing – 1991 – 1999
- ☐ Site decommissioning - 2000

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$180 million total about 50% on infrastructure

Fenton Hill facts – the Phase I experiment

Phase I field testing from 1975 –1981 was successful
in demonstrating the technical viability of the HDR concept

- Hydraulic stimulation of low-matrix permeability granitic system demonstrated
- Seismic and tracer mapping achieved verifying fractured reservoirs approaching 1 km^3 in volume
- Water quality good with small diffusive losses and declining as predicted from theory
- Thermal hydraulic testing and modeling successfully identified critical parameters for sizing reservoirs
- Parasitic pumping requirements are acceptable but flow impedance too high

Fenton Hill facts – the Phase II experiment

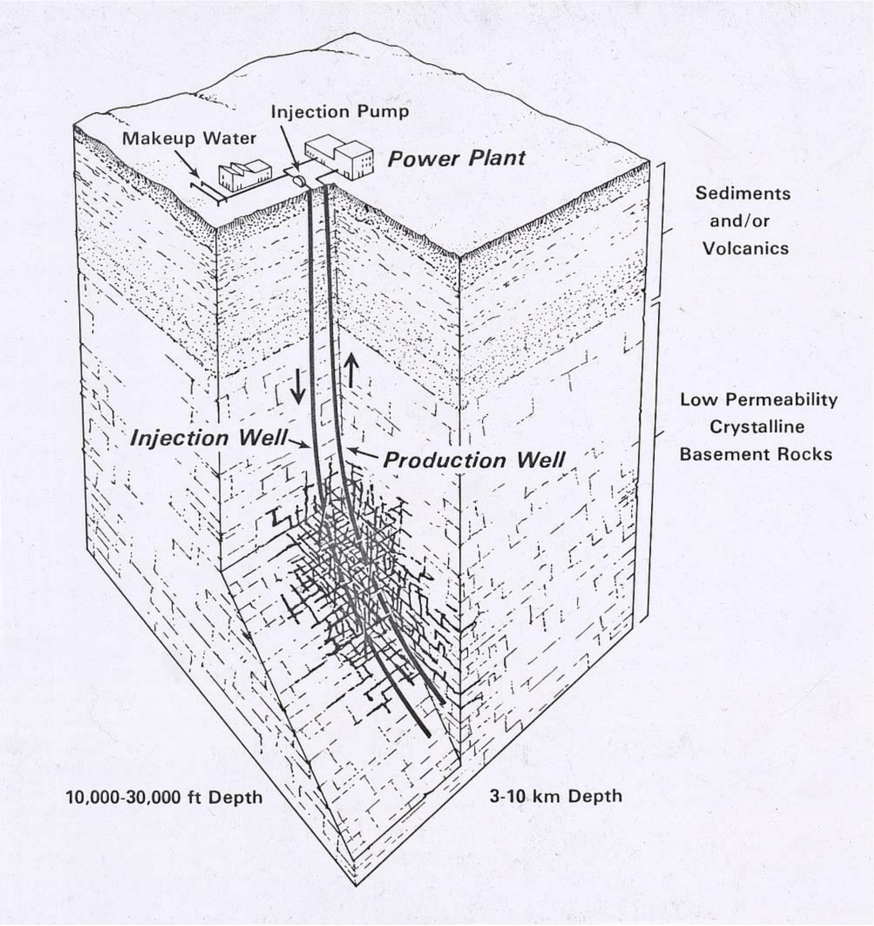
- Because the heat extraction capacity of the Phase I reservoir was too low by about a factor of 10, the Phase II demonstration focused on constructing a larger, hotter reservoir.
- Although adequate funding occurred from 1975 until 1987, the project was severely underfunded from 1987 thru 1999 during Phase II
- As a result of this shortfall, funds were not available to upgrade and test the Phase II system in an adequate manner and project goals and milestones were not met
- The credibility of the Los Alamos approach and its scientific team was compromised

Summary of Geothermal Heat Mining

- Relative to fossil energy, HDR is a low-grade, dilute energy source requiring high mass flow rates
- Typical fluid production temperatures of 200 to 300 ^{o}C are needed to maintain reasonable electric conversion efficiencies of 10 to 20 %
- Significantly higher performance results from direct use and cogeneration applications
- Although early tests at Fenton Hill and elsewhere have achieved much in terms of technical feasibility, they did not demonstrate an operational commercial-sized reservoir
- More field tests of enhanced geothermal systems (EGS) are needed for commercialization to occur.

Achieving Universal Heat Mining

There are many engineering science issues that could make a difference



Engineering Science Opportunities

Key technical improvements needed for Universal Heat Mining

- ☐ improved diagnostics for resource characterization
- ☐ improved methods for forming reservoirs
- ☐ better understanding thermal hydraulic behavior of fractured, porous media (CFD-poroelastic models…)
- ☐ better chemical and physical methods of altering reservoir properties and fluids
- ☐ ultra-deep drilling capability to supercritical conditions at reasonable costs

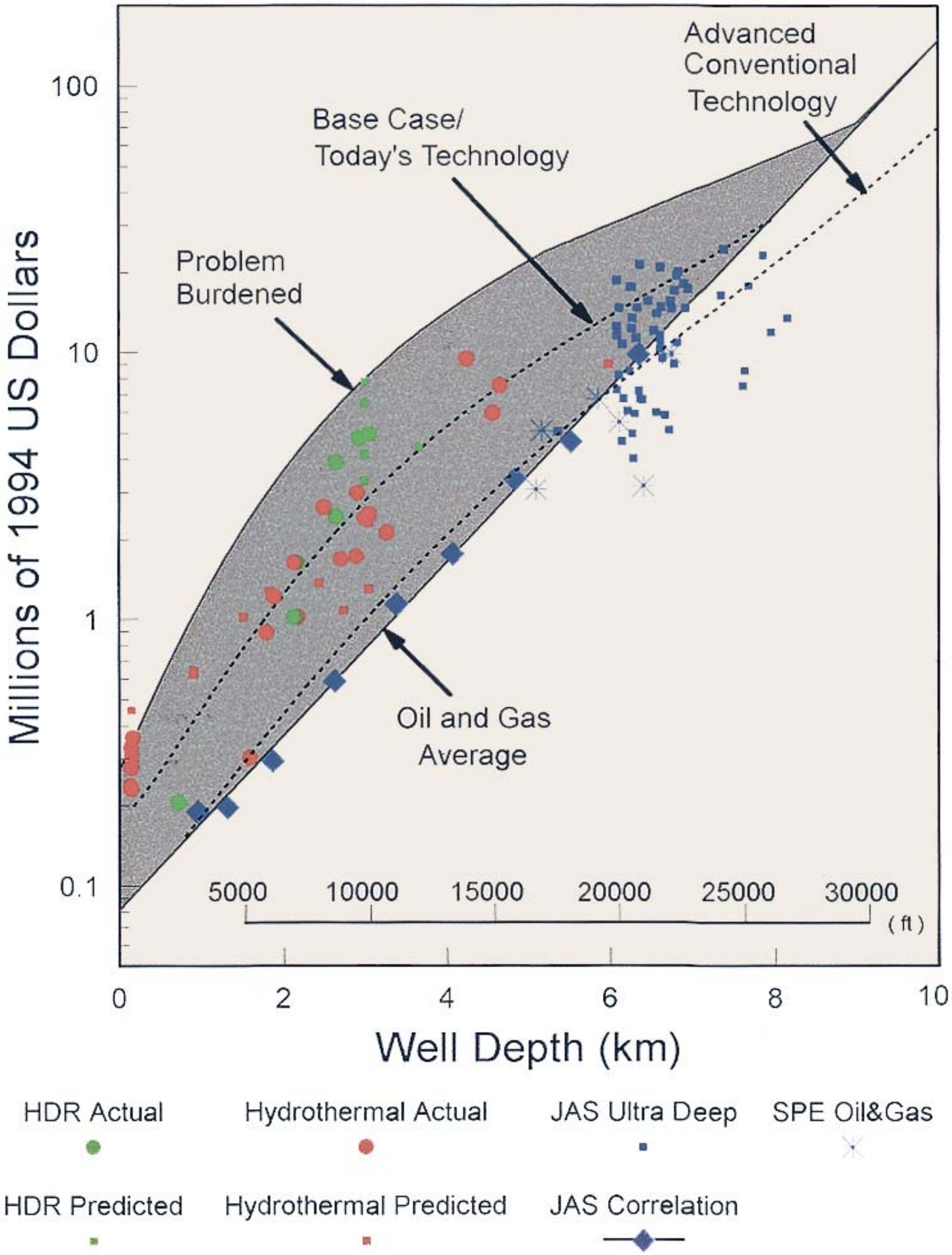
Geophysical aspects of universal heat mining

- ☐ Locating good prospects with high certainty
- ☐ Real time drilling diagnostics with look-ahead and borehole stability prediction capability
- ☐ Characterization of formations during deep drilling and stimulation
- ☐ High resolution characterization of rock fabric to define fluid flow paths within reservoir
- ☐ Continuous characterization of reservoirs during energy extraction

The future in subsurface geophysics

- Develop ultra-high resolution 4D in situ seismic diagnostics in the deep earth at depths of 10 to 20+ km
- Develop in situ measurement and monitoring capabilities for stresses, fracture patterns, fluid flow and composition, resistivity, etc. at similar depths
- High resolution gravity measurements and mapping using solid state technology

Conventional drilling costs scale exponentially with depth



Current limitations of drilling technology

- Well costs scale exponentially with depth
- Maximum depth capability to 42,000 ft (12 km)
- Under-reaming diameter capability less than 2X
- Hole stability and lost circulation is still a big problem in some formations
- Drill bits have been improved to increase penetration rates but the entire system is still prone to wear and failure with crushing as the primary mechanism
- Working downhole temperatures less than 250^{o}C

A new method of drilling is needed

A revolutionary approach that avoids the inherent limitations of conventional rotary drilling would provide significant opportunities for heat mining by removing current size, depth, and cost restrictions of well drilling and completion

A new method of drilling is needed

- Avoids “1st law” limitations of exponential drilling costs
- Neutrally buoyant drill string greatly reduces rig size and capacity demands
- Provides vertical and directional drilling capability to total drilled depths > 60,000 ft (>20 km)
- Under-reaming capability for creating subsurface infrastructures to at least 5 X base well diameter
- Built in hole stabilization with glassy liners and casing formed in place

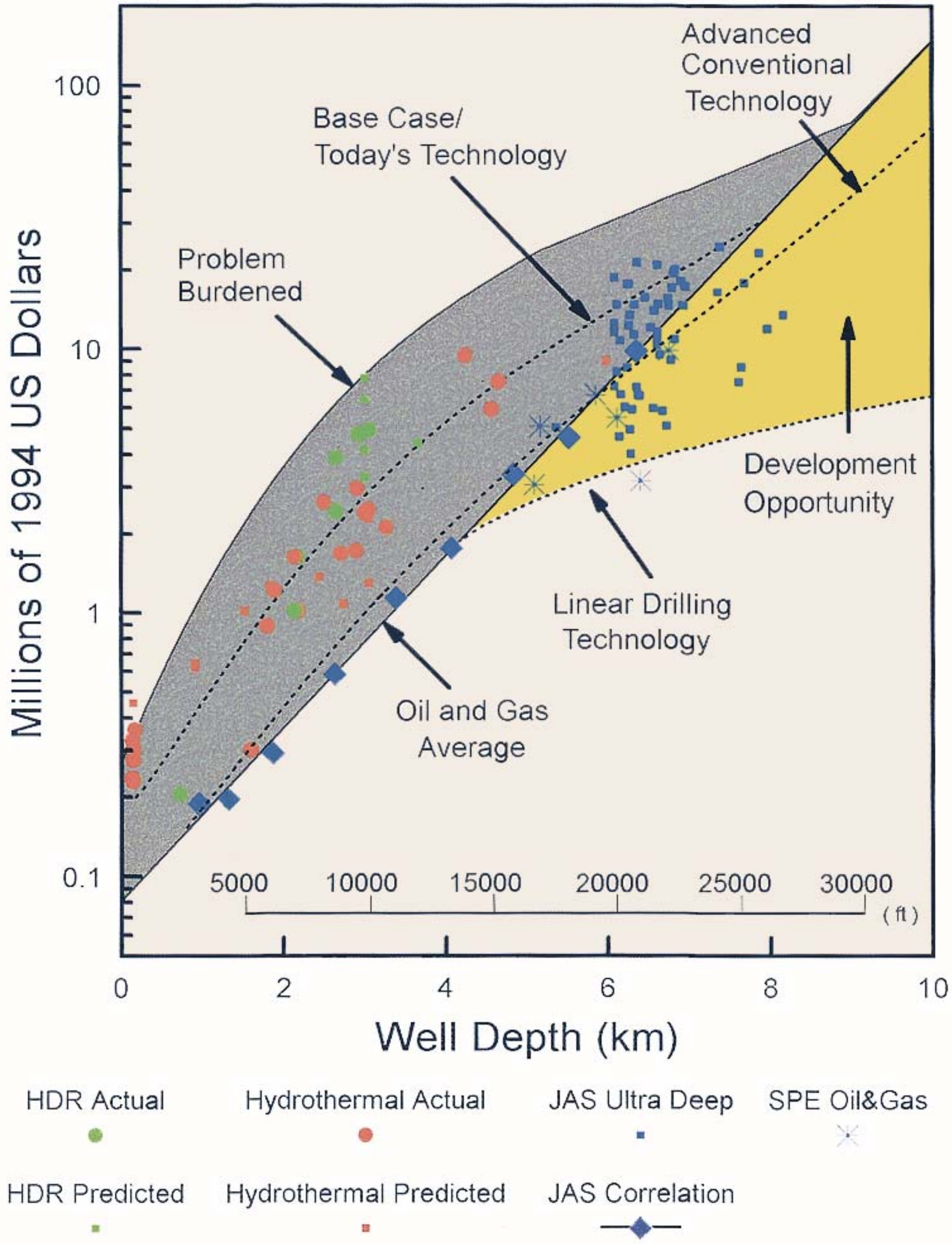
Thermal spallation and fusion drilling

- controllable rapid, ultra-deep drilling and under-reaming capability
- for producing stable sub-surface infrastructures for fluid production, downhole processing and monitoring

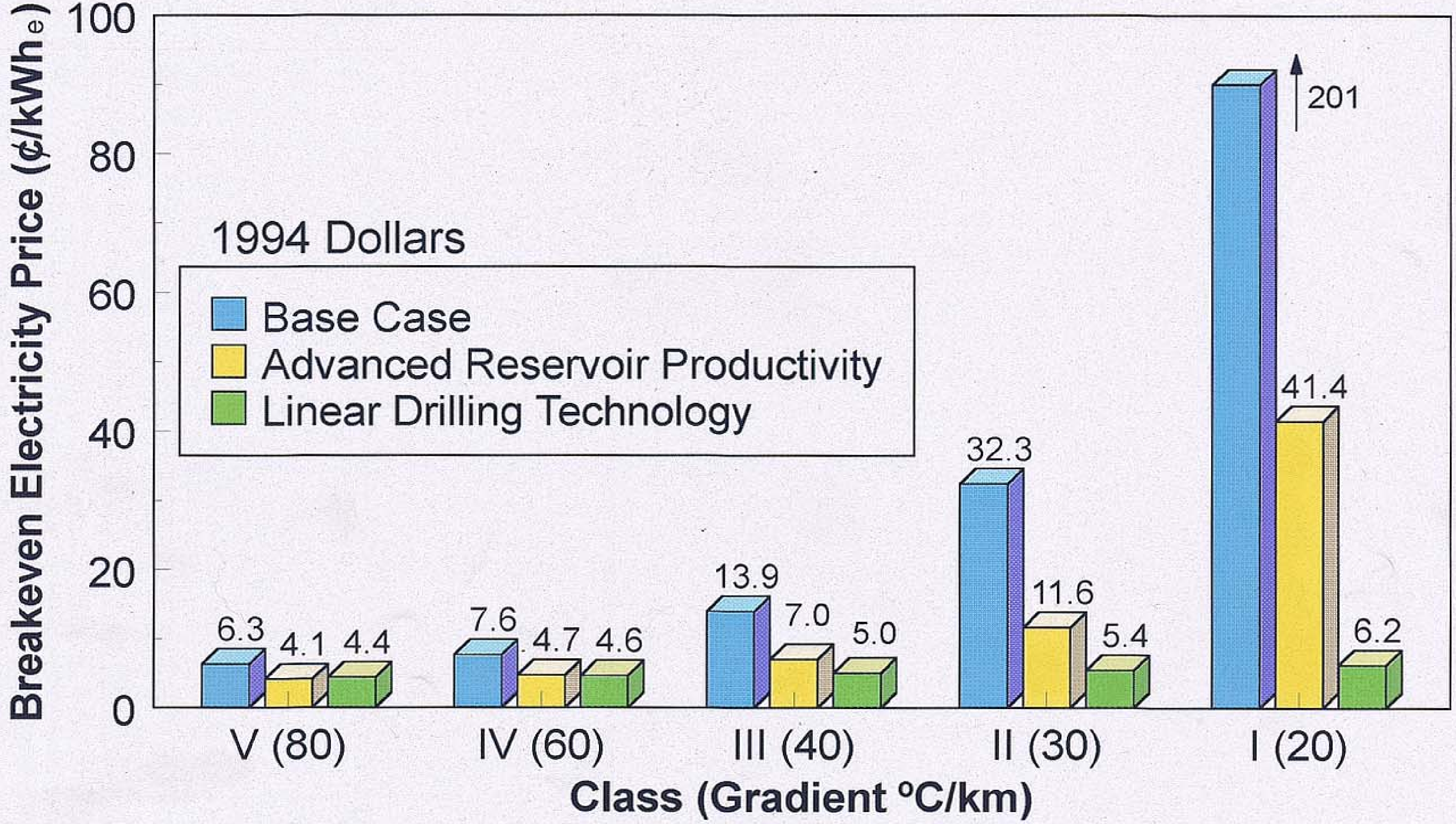
First generation flame jet spallation drill

Drilling Costs for Completed Wells

Linear drilling can be achieved with thermal spallation and fusion methods



HDR Cost Scenarios by Class



A recommended 10-year RD^2 program for heat mining – key elements

Goal – to develop enabling technologies for deploying 10,000 MW of HDR/EGS geothermal energy by 2020 and 100,000 MW by 2050

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1. Geoscience research effort focused on resource and reservoir characterization
2. Engineering science effort aimed at understanding the behavior of subsurface rock to develop effective heat mining methods
3. Advanced drilling research to scale-up spallation and fusion and other promising technologies
4. Field testing and demonstration at multiple US sites with different geologic characteristics

A recommended 10-year RD^2 program for heat mining

Funding requirement -- $60 million per year
or $600 million total

Approximate distribution of effort

1. Geoscience -- $ 10 million/yr
2. Engineering Science -- $10 million/yr
3. Advanced Drilling -- $10 million/yr
4. Field testing -- $30 to 60 million/yr

Assets generated by 2020 $ 20 billion
by 2050 $200 billion

MIT documentation on heat mining

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The End