Geothermal Resource Group

TAPPING THE EARTH'S ENERGY

DRILLING AND TESTING GEOTHERMAL WELLS

A Presentation for The World Bank

July 2012 Geothermal Training Event

Geothermal Resource Group

TAPPING THE EARTH'S ENERGY

- Geothermal Resource Group, Inc. was founded in 1992 to provide drilling engineering and supervision services to geothermal energy operators worldwide. Since it's inception, GRG has grown to include a variety of upstream geothermal services, from exploration management to resource assessment, and from drilling project management to reservoir engineering. GRG's permanent and contract supervisory staff is among the most active consulting firms, providing services to nearly every major geothermal operation worldwide.

Geothermal Resource Group

TAPPING THE EARTH'S ENERGY

Services and Expertise:

- Drilling Engineering
- Drilling Supervision
- Exploration Geosciences
- Reservoir Engineering
- Resource Assessment
- Project Management
- Upstream Production Engineering
- Training

Worldwide Experience:

- United States, Canada, and Mexico
- Latin America – Nicaragua, El Salvador, and Chile
- Southeast Asia – Philippines and Indonesia
- New Zealand
- Kenya
- Turkey
- Caribbean

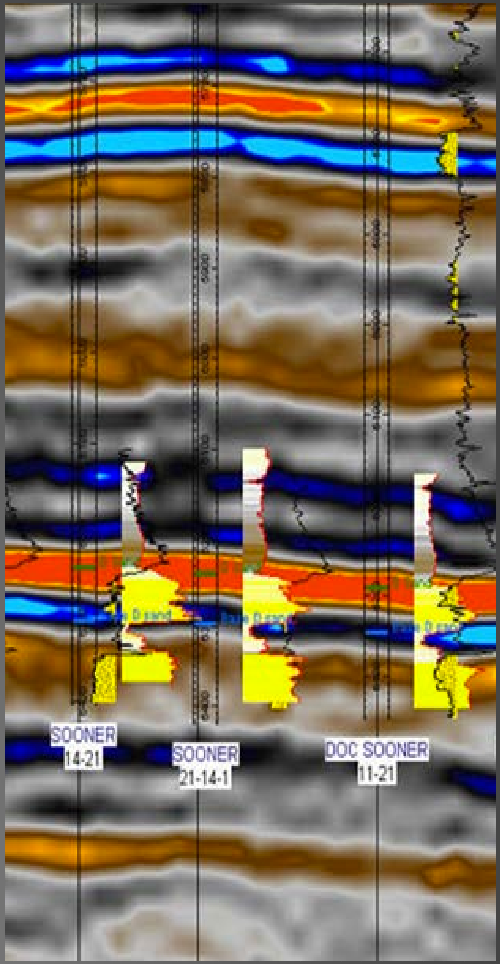
EXPLORATION PROCESS

The exploration process is the initial phase of the project, where the resource is identified, qualified, and delineated. It is the longest phase of the project, taking years or even decades, and it is invariably the most poorly funded.

EXPLORATION PROCESS

Begins with identification of a potential resource

- Visible System – identified by surface manifestations, either active or inactive
- Blind System – identified by the structural setting, geophysical explorations, or by other indicators such as water and mining exploration drilling.



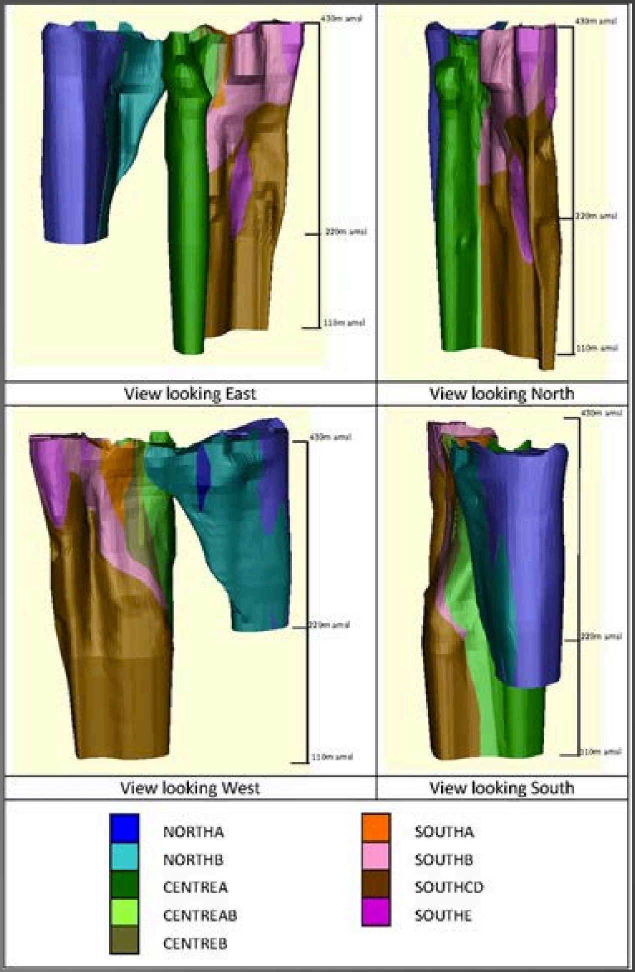
EXPLORATION PROCESS

Primary personnel

- Geoscientists
  - Geologists – structural mapping, field reconnaissance, conceptual geological models
  - Geochemists – geothermometry, water & gas chemistry
  - Geophysicists – geophysical exploration, structural modeling
- Engineers
  - Drilling Engineers – well design, rock mechanics, economic oversight
  - Reservoir Engineers – reservoir modeling, well testing, economic evaluation, power phase determination

EXPLORATION METHODS

- Pre-exploration research. Site history and field literature, including:
  - Well logs
  - Geological maps
  - Previous investigations, particularly from oil & gas exploration
- Mapping – structural and petrographic
- Water and gas sampling
- Surface geophysics, including:
  - Gravity
  - Magnetotellurics
  - Seismic
- Exploratory drilling



EXPLORATION MODEL

- Create a conceptual model to determine if the project is worth developing
- Establish the resource potential (MW) and cost of development
- Identify external influences, including potential customers, transmission requirements, and regulatory limitations
- Create preliminary designs and cost estimates for drilling
- Perform a feasibility study, to include:
  - Engineering, construction, and development costs
  - O&M costs
  - Revenue potential

DRILLING AND TESTING - TOPICS

- Types of geothermal wells
- The products of each type of well
- Testing each class of well
- Differences between geothermal drilling and oil & gas drilling
- Planning, risk, and O&M considerations

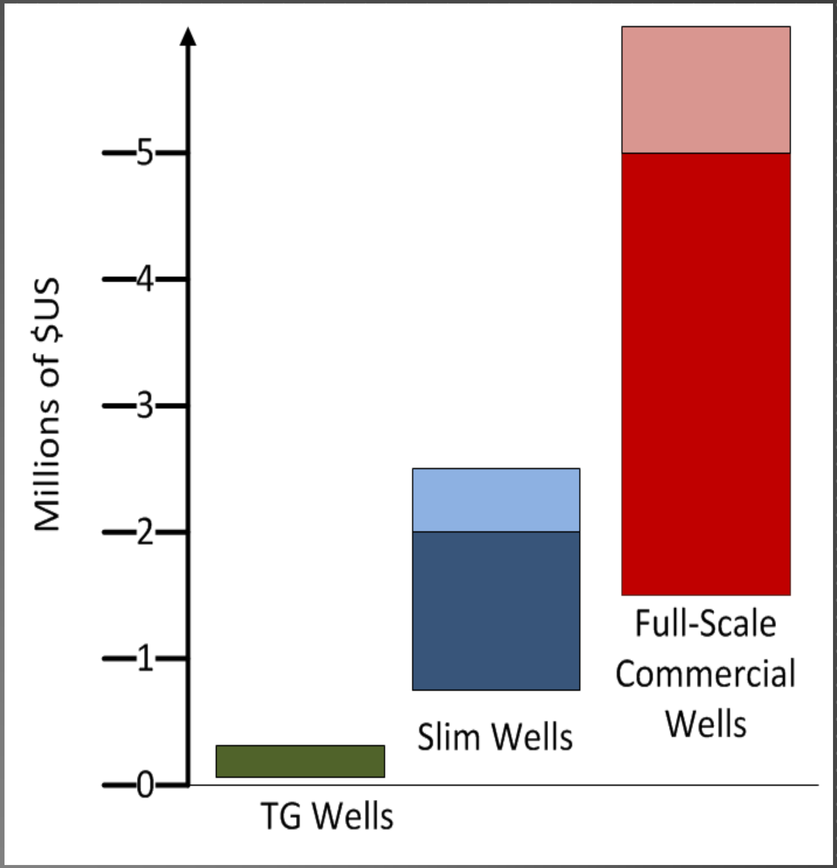
THREE *TYPICAL* CATEGORIES OF GEOTHERMAL WELLS

Temperature Gradient (TG) Wells
Stratigraphic or "Slim" Wells
Commercial Grade Wells

The types of wells are described as *Typical* because in reality there are no clear distinctions. Depending on the design and operator requirements, wells may be intended to serve multiple purposes.

COMPARING COSTS

- TG wells are inexpensive – typically around 10-20% of the cost of a slim well
- Slim wells are inexpensive relative to the cost of a full-scale commercial well – commonly 30-50% of the cost
- Full-scale, commercial grade geothermal wells are very expensive, ranging from a minimum $1.5M to in excess of $5M
- The most expensive commercial grade wells may exceed $10M to drill and complete



TEMPERATURE GRADIENT (TG) WELLS

- First wells drilled on a project
- Used to delineate the heat anomaly, and to establish the geothermal gradient
- Not capable of being produced

TG WELL FEATURES

- Shallow
  - Less than 500 meters
  - Most often 150 meters or less
- Small diameter
- Drilled with light truck-mounted rotary or diamond core rigs
- Drilled without BOPE – Drilling *STOPS* when flow line temperatures reach 75C

TG WELL DRILLING

- A surface hole is drilled
- Surface casing is cemented or a conductor is driven

TG WELL DRILLING

- A smaller diameter hole is drilled
- Small diameter tubing is run back to surface
- Driven surface conductor is pulled

TG WELL DRILLING

- Cement is pumped through tubing back to surface
- A wiper plug is pumped to displace cement in tubing

TG WELL DRILLING

- A valve is installed to give access to the tubing for survey tools
- Tubing is filled with water, with the top 10 meters filled with vegetable oil or antifreeze

TWO PRODUCTS OF TEMPERATURE GRADIENT WELLS

- Geology of the shallow subsurface
- Temperature data subsequent to drilling
  - Short-term conductivity data
  - Long-term TG data
  - Seasonal effects

DESIGN ADVANTAGES

- Inexpensive, can be drilled with locally-available rigs
- Fully cemented tubing equilibrates rapidly
- Large scale surface production equipment not necessary
- Testing involves simple temperature-logging equipment
- Well abandonment is simple

DISADVANTAGES OF DESIGN

- Not producible
- Provides only minimal data

STRATIGRAPHIC OR "SLIM" WELLS

- Larger diameter than TG wells
- Normally drilled into the reservoir
- Drilled using BOP equipment with light-medium range oilfield rigs

SLIM WELLS

- Drilled during the intermediate exploration phase
- Drilled to establish resource viability
- Provide information about:
    - Reservoir fluid chemistry
    - Structural data
    - Lithological data
    - Deep temperature gradient data

SLIM WELL DRILLING

- A conductor is cemented in place
- Surface hole is drilled
- Surface casing is set and cemented back to surface

SLIM WELL DRILLING

- A temporary wellhead is installed, along with blowout prevention equipment
- An intermediate hole is drilled
- Geophysical logs are run, (SP, Gamma, Resistivity), and
- Casing is set and cemented back to surface

SLIM WELL DRILLING

- The permanent wellhead is installed, with a master wellhead valve
- An open (uncased) hole is drilled
- Geophysical logs are run, (often including imaging logs), and
- A perforated liner is set on bottom
- Finally, a flange with a small valve is installed on the wellhead, providing access to the wellbore for future logging

ADVANTAGES OF SLIM WELL DRILLING

- Inexpensive relative to commercial grade wells – typically 30% to 50% of the cost of a full sized well
- Intentionally designed and constructed to be inexpensive, and special casings and cement slurries are not normally required
- Smaller footprint may be advantageous in environmentally sensitive areas
- Yield most of the same data that a commercial grade well provides
- May be useful as disposal wells during subsequent production testing
- Useful as reservoir monitoring wells

DISADVANTAGES OF SLIM WELL DRILLING

- Requires much heavier equipment than can normally be obtained locally
- Because the wells are not built to be as robust as commercial grade wells, they are shorter-lived and must be abandoned after only a few years
- Normally not commercially producible except in cases of very good, hot resources

TESTING SLIM WELLS IS A 4-STEP PROCESS

- Pressure/Temperature logging
- Flow/pump testing
- Injection testing while Pressure/Temperature/Spinner logging
- Falloff or Buildup testing

FLOWING WELLS ARE MEASURED USING:

- An atmospheric separator with a weir
- A lip pressure measurement (James Method)
- Flow line temperature
- Gas sampling
- Pressure/Temperature logging tool suspended in wellbore
- Orifice measurements in vapor dominated systems

PUMPED WELLS ARE MEASURED USING

- Pump output charts
- Ammeter
- Flow measurement device – orifice plates, ultrasonic flow sensor, annubar, etc.
- Flow line temperature
- Gas sampling
- "Bubbler" tube attached to the pump column

PRODUCTIVITY MEASUREMENTS

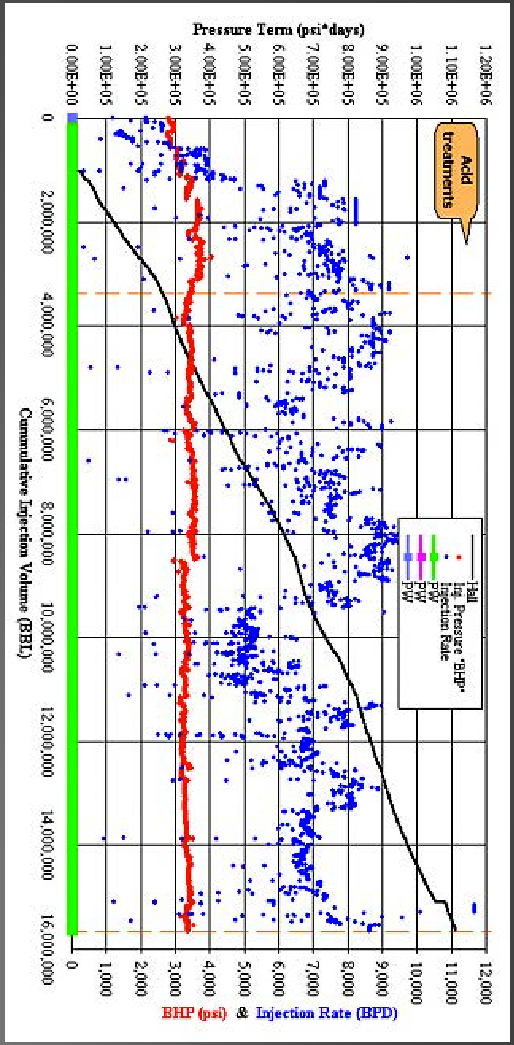
- Both flow and pump tests determine volumetric *productivity* within the limits of the wellbore and/or the pumping equipment. Measuring bubbler tube pressure while pumping determines *drawdown*. Measuring bubbler tube pressure subsequent to pumping aids in determining rates of *recharge*.

PRESSURE/TEMPERATURE LOGGING

- Establishes a baseline temperature and fluid density profile

INJECTION TESTING WITH PTS LOGGING

- Establishes *Injectivity* based on
  - Rate of injection
  - Surface pressure & injection temperature or with a PT tool in the well.
  - Wells in a highly productive reservoir will accept a large volume of fluid before reaching capacity. Smaller diameter slim holes reach capacity more rapidly, thus PTS may be even more important when testing slim wells
- PTS logs delineate permeable intervals by a comparison of all three data sets – pressure, temperature, and flow past the spinner



FALLOFF / BUILDUP TESTING

- Performed in the interval immediately after injection testing
- Establishes rate of recharge equilibrium
- Reservoir margins (boundary conditions) may be detected by examining pressure transients

COMMERCIAL GRADE WELLS

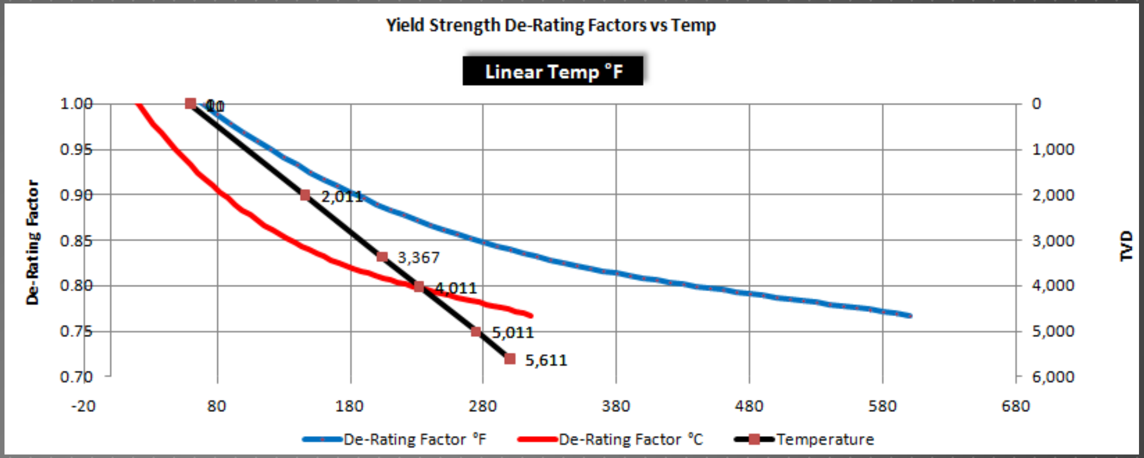
- Two Primary Categories
  - Production
  - Injection
- Designed to be very robust and long-lived
- Often use the same design, especially early in well field development. It is not always clear early in the wells which service the well will be used for

HOW GEOTHERMAL WELLS DIFFER FROM OIL & GAS WELLS

- Geothermal wells are typically much larger in diameter
- Geothermal casing strings are fully cemented
- High temperature materials and tools must be used
- Casing cycles between compression and tension states with temperature changes
- Fractured formations lead to major loss of circulation
- Less "kick tolerant" due to altered formations and soluble gases, often resulting in the setting of more casing strings than are needed in oil & gas wells

THE DESIGN PROCESS - INPUTS

- Lithological and structural information
- Reservoir fluid chemistry
- Temperature data
- Downhole targets
- Offset well data

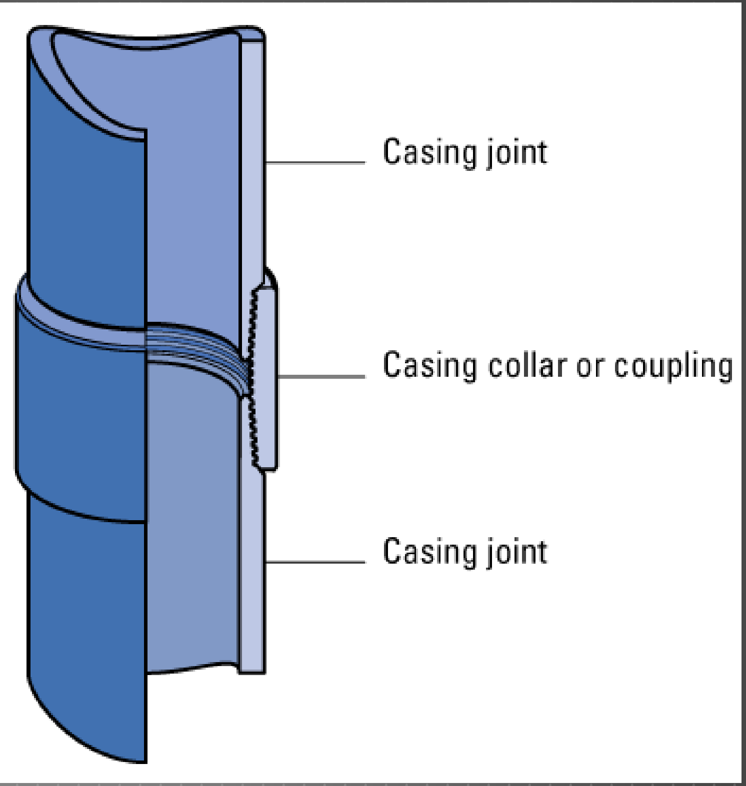


THE DESIGN PROCESS – WELL DESIGN

- Casing and grades are selected based on
  - Reservoir fluid chemistry
    - Corrosion due to acidity or redox reactions
    - Erosion due to suspended solids
    - Scaling
  - Structural strength requirements in order to avoid collapse and to support wellhead equipment

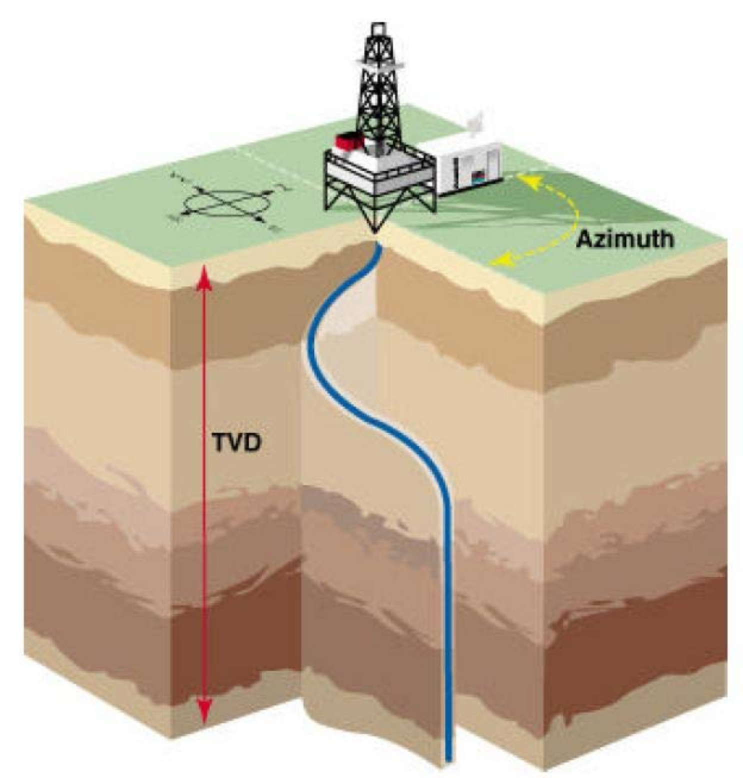
CASING THREADS ARE SELECTED BASED ON

- Reservoir temperature
- Compressive strength
- Annular clearance between casing strings



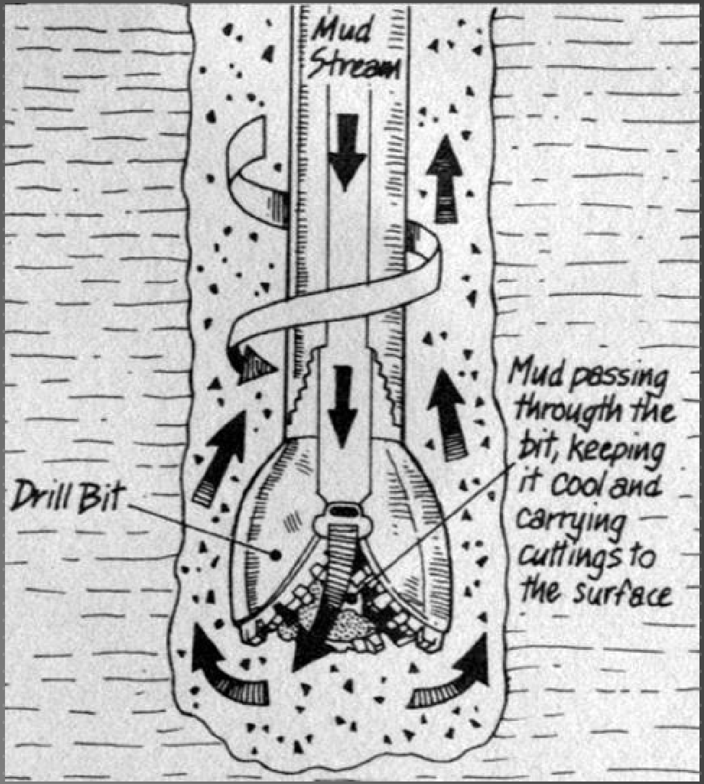
CASING SETTING DEPTHS ARE BASED ON

- Lithological and structural data
- Planned wellbore geometry
- Need for "Kick Tolerance"



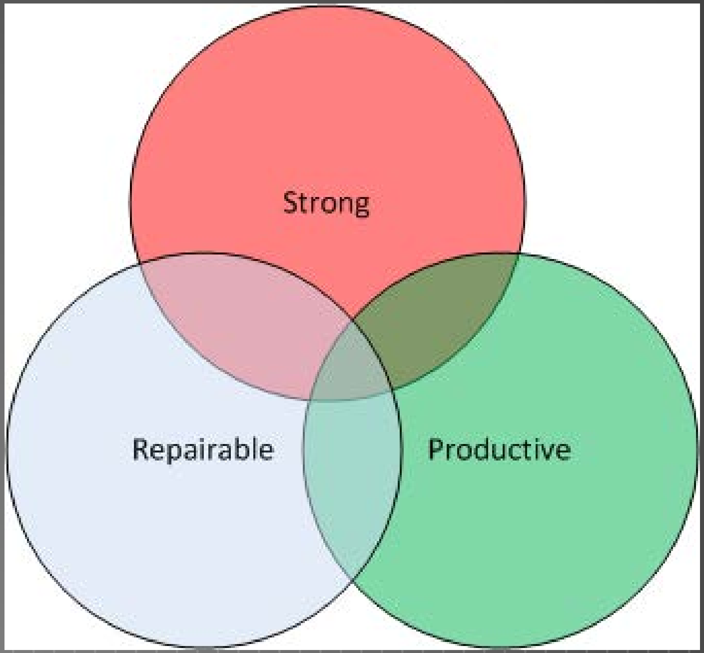
OTHER DESIGN ISSUES

- Cement slurries
- Drilling fluids
- Pump setting requirements
- Wellbore flashing
- Production phase (liquid or vapor)



DESIGN PHILOSOPHY - WELLS SHOULD BE DESIGNED TO BE:

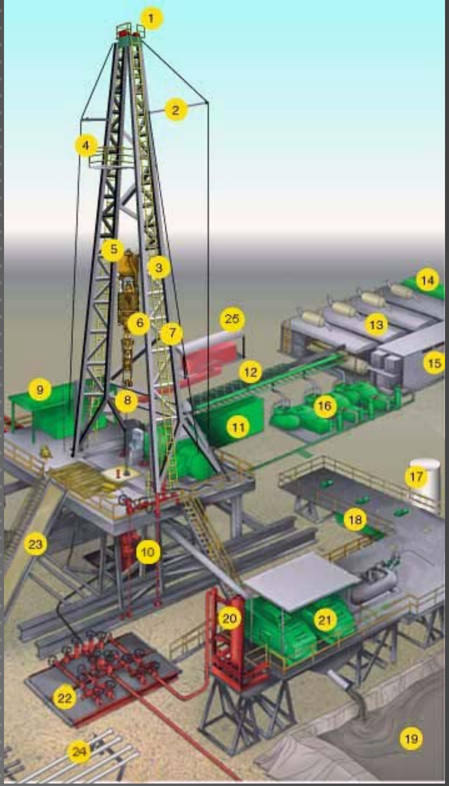
- Strong, to be long-lasting and withstand the rigors of repeated thermal cycling and exposure to reservoir fluids
- Able to be "worked over" – that is to be repaired, re-drilled, and cleaned out
- Productive and not have the well design limit the capacity for production



Commercial grade wells are drilled using oilfield rigs capable of drilling large diameter holes and handling large diameter strings of casing

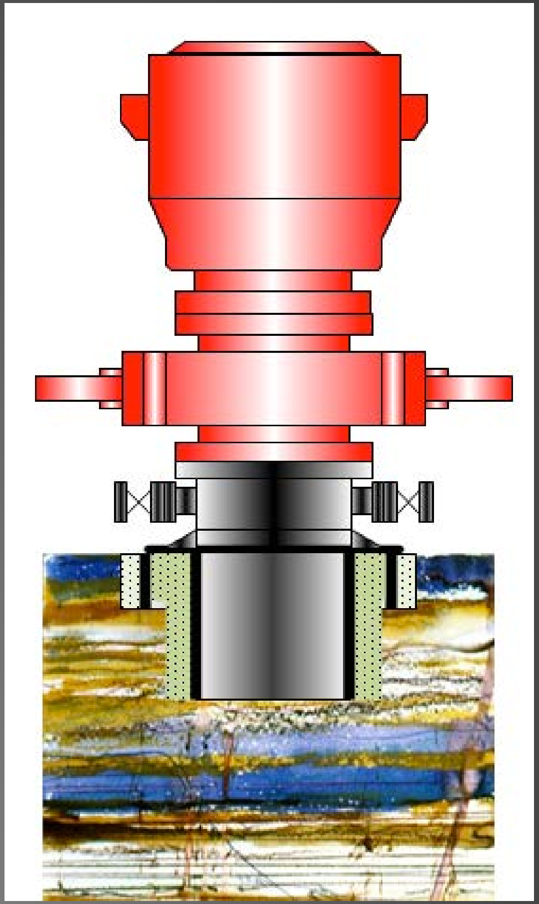
RIGS MUST HAVE

- Tall substructures to place BOP equipment under the rig floor
- Large capacity mud pumps to clean the large diameter hole
- A substantial mud storage volume in order to fight lost circulation
- A high capacity hoisting system to handle large diameter tools and casing
- A large diameter rotary table or master bushing, for the same reason



PRODUCTION WELL DRILLING

- A conductor is cemented in place
- A large diameter surface hole is drilled using bentonite-based mud or air
- Surface casing is installed and the annulus is fully cemented
- A temporary wellhead is installed
- BOP equipment is installed and tested



PRODUCTION WELL DRILLING

- An intermediate hole section is drilled
- Intermediate casing is installed and the annulus is fully cemented
- The process may be repeated if more than one intermediate casing string is required, or liner strings may be set, saving the cost of running a full string to surface and cementing it. Liners are also advantageous on wells that are pumped.
- The permanent wellhead is installed, along with the master valve

PRODUCTION WELL DRILLING

- A hole is drilled into the reservoir
- Water/polymer drilling fluid in liquid-dominated reservoirs
- Air or foam in vapor-dominated reservoirs
- The well is logged and a perforated liner is run. Some hard rock reservoirs only need a liner in wells that are used for injection.

TESTING COMMERCIAL GRADE WELLS

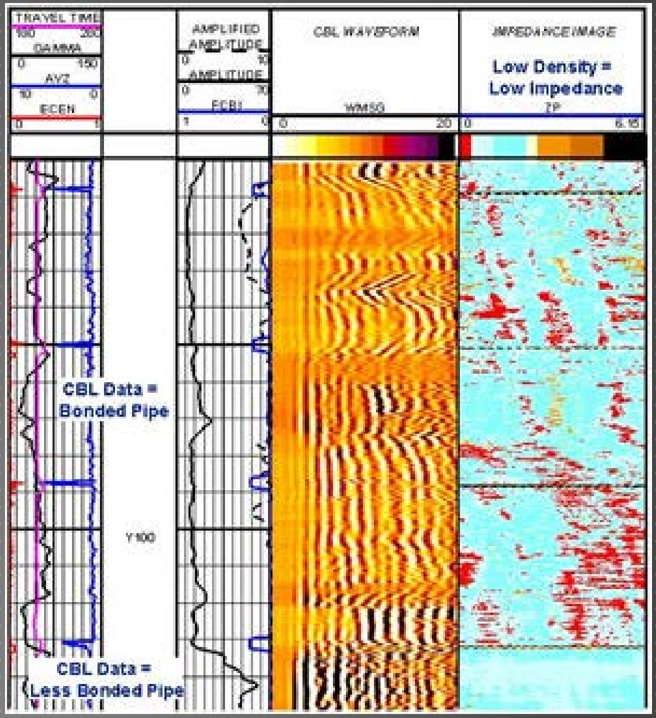
Production and injection wells are tested in the same manner as slim wells.

- Pressure/Temperature logging
- Flow or pump testing
- Injection testing while Pressure/Temperature/Spinner logging
- Falloff or wellhead pressure buildup testing

INJECTION WELL TESTING

Injection wells may also be tested for mechanical integrity, demonstrating that injected fluid is not flowing into surface water zones. MIT's include:

- Temperature and noise logs
- Casing caliper logs
- Cement bond logs
- Ultrasonic casing imaging logs



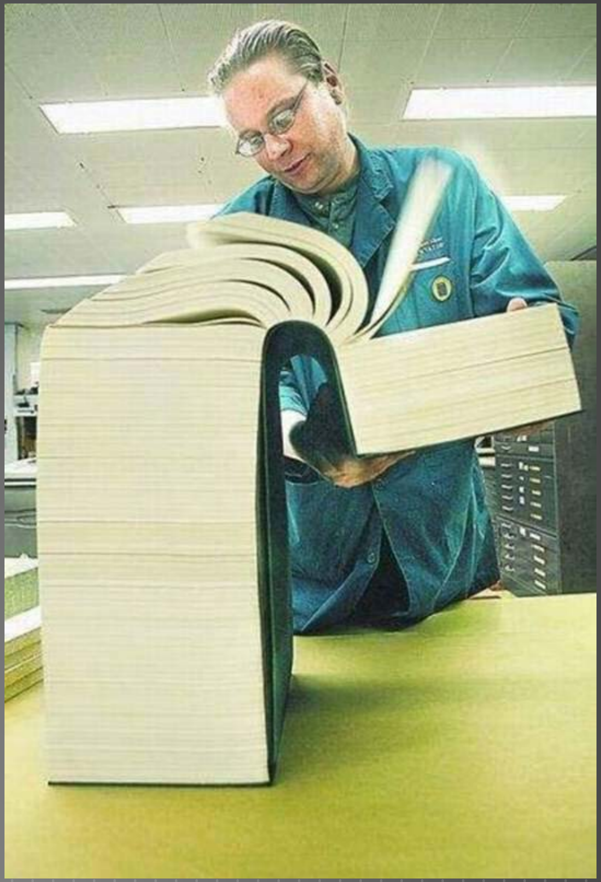
PLANNING, RISK, LONG-TERM CONSIDERATIONS

Planning is the single most effective way to reduce drilling and reservoir risk. Operators who short-change planning inevitably spend far more in lost rig time, fishing operations, equipment delays, and other unplanned operations than are ever saved in planning session costs.

THE DRILLING PROGRAM

The drilling program should include:

- Section by section procedure
- Casing and cementing program
- Drilling fluids program
- Directional program
- Vendors list
- Well logging
- Geological sampling
- Drilling data acquisition
- Testing procedures
- Communications, procurement, EHS



RISK IDENTIFICATION AND MITIGATION

Must account for the factors that make geothermal wells unique:

- Lost circulation
- Low fracture gradients
- Hole cleaning problems
- Stuck pipe concerns
- Large and complex cementing operations
- Well control

Must include mitigation techniques

LONG-TERM WELL FIELD CONSIDERATIONS

- O&M costs:
  - Scale control
  - Reservoir management, testing, and monitoring
  - Wellhead and production equipment maintenance and replacement
  - Well cleanouts and work-overs
- Costs related to reservoir decline, leading to make-up and replacement drilling

Geothermal Resource Group

TAPPING THE EARTH'S ENERGY

Thank you for your kind attention. We at Geothermal Resource Group are proud of our part in helping to produce clean geothermal energy. We are also very happy to be a resource to the World Bank in the development of this form of energy worldwide. Please feel free to contact us at any time with your questions or comments.

Best Regards

Alan Bailey

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