Innovative Drilling and Production Technology for Deep Geothermal Wells

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RESERVOIR DEVELOPMENT SERVICES
Gaffney, Cline & Associates, reservoir engineering and simulation, geological modeling and analysis, software

DRILLING and EVALUATION
Drill bits, directional drilling, formation evaluation, coring, surface logging, wireline, drilling fluids

COMPLETION and PRODUCTION
Completion, intervention, intelligent production systems, artificial lift, completion fluids, oilfield chemicals

PRESSURE PUMPING
Cementing, hydraulic fracturing, acidizing, stimulation, coiled tubing

INDUSTRIAL SERVICES
Refining, water management, petrochemical, process and pipeline services, polymers and well service products

About Baker Hughes
- Revenues: $24.6 billion
- R&D: $613 million
- 62,000 employees
- Facilities in 72 countries
- Operations in 90+ countries

*FY 2014: Baker Hughes
Motivation & Projects Goals

– Reduction of Cost per kWh „Stromgestehungskosten“

– Reduce non-productive time
– Reduce planning risks
– Improve safety and reliability

– Improved productivity over time
Ways

- Innovative Wellbore Construction
- Drilling Process Control and Automation
- Advanced Drilling BHA
- Alternative Drilling Technologies
- Innovative Production Systems
Innovative Wellbore Construction
Well Designs

Standard Design

- Conductor Pipe 28"
- Hole 24" Casing 20"
- Hole 18" Casing 16"
- Hole 14.3/4" Casing 13.3/8"
- Packer
- Hanger
- Hole 12.1/4" Liner 10.3/4"
- Open Hole 8.3/4"
- Shoe 800m
- Shoe 2700m
- LK 3400m
- Shoe 3500m
- Shoe 4500m

Expandable Design

- Conductor Pipe 16"
- Hole 12.1/4" Casing 10.3/4"
- Reamed 12" Liner 10.1/2"
- Reamed 12" Liner 10.1/2"
- Reamed 12" Liner 10.1/2"
- Reamed 12" Liner 10.1/2"
- Open Hole 9.1/2"
- Shoe 800m
- Shoe 1800m
- Shoe 2700m
- Shoe 3500m
- Shoe 4500m
- Open Hole 4800m
Well Bore Construction Cost Analysis Workflow

- Well Bore Design
  - Bore hole, casing, etc.
- Time
  - Drilling, tripping, etc.
- Cost
  - Drilling service, rig, fluid service, completion service, etc.
  - Condensed Cost
Innovative Monobore Wellbore Construction Cost Savings

Standard Design
14.7 Million EUR

- Contract Rig: 26%
- Casing / Liner / Expandable: 18%
- Drilling Fluid Services: 10%
- Completion: 9%
- Directional Drilling Services: 7%
- Electric Wireline Logging: 6%
- Drilling Bits: 6%
- Cementing Services: 4%
- Well Planning / Preparation: 4%
- Electric Wireline Logging: 4%
- Waste Management: 3%
- Personnel Cost: 2%
- Coring Equipment Services: 2%

Expandable Design
12.8 Million EUR

- Contract Rig: 29%
- Casing / Liner / Expandable: 11%
- Drilling Fluid Services: 10%
- Completion: 8%
- Directional Drilling Services: 7%
- Drilling Bits: 7%
- Cementing Services: 7%
- Well Planning / Preparation: 6%
- Directional Drilling Services: 6%
- Waste Management: 3%
- Personnel Cost: 3%
- Coring Equipment Services: 2%
Innovative Monobore Wellbore Construction Process

http://www.dea-group.com/de/technologie/bohrung/expandable-tubular-verrohrung
Innovative Monobore Technologies for Geothermal Applications

High Temp Metal to Metal Hanger/Packer

Monobore Installation

Expansion System

Welded Connections

VAM
Expandable Welding Technology

Magnetic Impelled Arc Welding

- Short welding times
- High level of automation
- Combinations of materials
- High welding quality
- High temperature gas tight

Welded 9.5/8” N80 Tubular at Leibniz University Hannover
Drilling Process Control and Automation
Drilling Systems Automation

OBJECTIVES

- Reduce Well Delivery Costs
- Reduce Operational Risk

<table>
<thead>
<tr>
<th>Automation Level</th>
<th>Automation Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The computer offers no assistance: human must take all decision and actions.</td>
</tr>
<tr>
<td>2</td>
<td>The computer offers a complete set of decision/action alternatives, or</td>
</tr>
<tr>
<td>3</td>
<td>narrows the selection down to a few, or</td>
</tr>
<tr>
<td>4</td>
<td>suggests one alternative, and</td>
</tr>
<tr>
<td>5</td>
<td>executes that suggestion if the human approves, or</td>
</tr>
<tr>
<td>6</td>
<td>allows the human a restricted time to veto before automatic execution, or</td>
</tr>
<tr>
<td>7</td>
<td>executes automatically, then necessarily informs humans, and</td>
</tr>
<tr>
<td>8</td>
<td>informs the human only if asked, or</td>
</tr>
<tr>
<td>9</td>
<td>informs the human only if it, the computer, decides to.</td>
</tr>
<tr>
<td>10</td>
<td>The computer decides everything and acts autonomously, ignoring the human.</td>
</tr>
</tbody>
</table>

* 10 levels of automation following Sheridan & Verplank
Conventional vs. Automated Drilling Systems Control

Field Engineer

Driller

<<recommend>>

<<feedback>>

<<action>>

<<monitor>>

Service Company Displays

Rig Sensors:
- RPM
- WOB
-...

Controller (PLC)

<<actuate>>

in-the-loop control

<<measure>>

Conventional

drill

Automation

Controller

Rig Actuators:
- Drawworks
- Top drive
- Mud pump

Driller

Advisor App

Monitor App

Control App
Advanced Drilling Technology
Advanced Drilling BHA with integrated GaugePro™ Echo Reamer and AutoTrak Steering Unit

MWD/LWD

Steering Unit

Near Bit Gamma +5 ft.

Pass Thru Size

Enlarged Hole Size

8 ¼" BHA, 10 5/8" x 12 ¾"
Alternative Drilling Technology Future
Bit Example

6" Electrode – Granite drilling test in Water under atmospheric pressure
High Pressure Performance Feasibility

Electro Impulse Research Lab and Team
TU Dresden and TU Freiberg

Drilling Simulator of TU Clausthal in Celle

500 Bar (~7k psi)
Granite Test-samples
System Concept:
TU Bergakademie Freiberg and TU Dresden
Innovative Production Systems
Innovative and Reliable Production Systems

- Geothermal ESP
- Heat Exchanger Design
- Tubular Connection
- High Temperature Packer
- Scaling and Corrosion Monitoring
- Reservoir Monitoring
- Self-driving after initiation?
Baker Hughes, Geothermal ESPs

ESP swap at Unterhaching

None Public Picture
Challenges of Geothermal Applications

Combination of

- High motor power requirements (voltage max. 6,5kV)
- Frequent speed adjustments / power cycles
- Frequent thermal cycles
- High fluid flow, high flow velocities
- Temperatures > 140° C
- Shallow installation depth (low ambient pressure)
- Scales from thermal water (calcium carbonate)
ESP-Development in Celle

Team of 5 conducts

- Lab and field testing
- Failure investigation, materials examination

- Reliable motor bearing development
- Scale resistant pump development
- Geothermal seals development for reliable oil containment
- 175°C ESP-gauge electronics development with failure prediction

geothermal pump prototypes (100 l/s, 200 l/s)

board layout for 175°C gauge electronics
Hi-Tempemperature Test-Bench: „HotLoop“

High temp pressure vessel

control room

High-flow pump-test-bench
"Thermal cycle" tests

- automated thermal cycle testing (5 cycles/day)
- increased stress on insulation materials
- increased load for length and oil compensation
- permanent temperature measurement on outer face seal

Water temperature:
- Pre-heat: 65°C
- 1 cycle: 140°C
- Stopp / Start:
  - First: 60Hz
  - Second: 38Hz
  - Third: 60Hz

Resistance & insulation measurement
FLEX- ESP Development

High Power FLEX-pumps developed for:

- Wider, more flexible, flow operating range for power plant demand adjustment from 75 – 100% => 40 – 100%

- Optimized power efficiency from 79 => 82%

Operational Flexibility in Liter/second
Design Improvement of Pump Bearings

- Scaling on bearings after short time
- Bearings get blocked, ESP shafts twist off

- Improved and tested design
- No failures after implementation in 7 wells
Long Term Corrosion Investigation in North German Brine

<table>
<thead>
<tr>
<th>Ions</th>
<th>(mg/L)</th>
</tr>
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<tbody>
<tr>
<td>Cu²⁺</td>
<td>8.3</td>
</tr>
<tr>
<td>K⁺</td>
<td>2750 - 3130</td>
</tr>
<tr>
<td>Na⁺</td>
<td>37700 - 38700</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>54000 - 56500</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>390 - 550</td>
</tr>
<tr>
<td>NH₃⁺</td>
<td>125 - 200</td>
</tr>
<tr>
<td>Fe³⁺</td>
<td>60 - 200</td>
</tr>
<tr>
<td>Mn²⁺</td>
<td>250 - 260</td>
</tr>
<tr>
<td>Ba²⁺</td>
<td>25 - 40</td>
</tr>
<tr>
<td>Li⁺</td>
<td>197 - 230</td>
</tr>
<tr>
<td>Sr²⁺</td>
<td>1485 - 1550</td>
</tr>
<tr>
<td>Pb²⁺</td>
<td>96 - 225</td>
</tr>
<tr>
<td>Zn²⁺</td>
<td>60 - 160</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>150000 - 167000</td>
</tr>
<tr>
<td>Br⁻</td>
<td>150 - 300</td>
</tr>
<tr>
<td>I⁻</td>
<td>50 - 160</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>43 - 94</td>
</tr>
<tr>
<td>H₂SiO₃</td>
<td>80 - 190</td>
</tr>
<tr>
<td>CO₃⁻ (dissolved)</td>
<td></td>
</tr>
</tbody>
</table>
Our Purpose: enabling safe, affordable energy, improving people’s lives.

Martin Craighead, Chairman and CEO