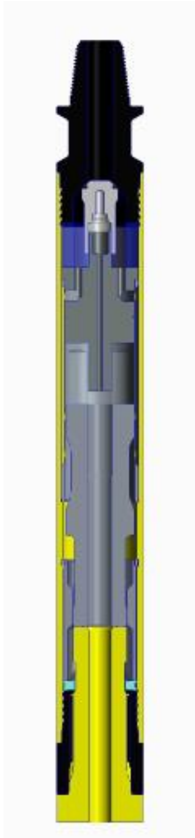
Atlas Copco



Sandia National Laboratories

Advanced Percussive Drilling Technology for Geothermal Exploration and Development

Project Officer: Michael Weathers

Total Project Funding: $3.2M

May 13, 2015

Principal Investigator

Dale Wolfer

ATLAS COPCO SECOROC, LLC

HRC

Relevance/Impact of Research

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- Purpose: To develop percussive hammer technology capable of operating in high-temperature geothermal formations
- Percussive hammers have the potential to reduce overall well construction costs by significantly improving the penetration rate.
  - Example: 3000 m well, Rig costs $50K/day
    - Conventional method: Avg. ROP 7 m/hr ; Time 429 hr ; Cost $900K
    - HTDTHH method: Avg ROP 21 m/hr ; Time 143 hr ; Cost $300K
- Technical Barriers and Challenges
  - Find alternative design solutions to conventional polymer components
  - Find alternative design solutions to conventional elastomeric seals
  - Eliminate the need for hydrocarbon based lubricants
  - Find alternative solutions to metal parts with low temperature heat treatment
  - Develop laboratory testing facilities capably of validating the design at the target temperature

Relevance/Impact of Research

- Success within this project will impact the Geothermal Technologies Office's goals by:
  - Reducing geothermal well drilling costs, thereby reducing the overall cost of a project, thereby reducing LCOE
  - Driving industry deployment by making proposed projects more economically attractive
- Technical Targets
  - Achieve 3X drilling rate vs. conventional rotary drilling methods
  - Capability to drill to 3000 meters depth and formation temperature of 300 C
  - Develop percussive hammer design to operate reliably within the expected temperature range
  - Develop viable internal sealing systems at HT
  - Identify and develop lubricating strategies at HT
  - Insure material properties are sufficient for reliable operation in high temperature, corrosive drilling environment

Scientific/Technical Approach

- Phase 1: Proof of Concept
  - Requirements definition for operating conditions
  - Thermodynamic cycle computational modeling of proposed DTH cycles
  - Finite Element Analysis (FEA) of structural components and systems
  - Systems solution and configuration definition
  - HT percussive hammer design, analysis and evaluation
  - Materials selection, qualification and testing along with review of technical literature for identification of potential materials and/or processes
  - Coupon level environmental coatings and bulk property testing

Scientific/Technical Approach

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- Phase 2: Component and System Level Testing
  - Establish baseline prototype hammer performance at the Atlas Copco Roanoke test facility
  - Provide Proof-of-Concept (POC) validation via laboratory testing of representative design features.
  - Build full-scale prototype hammers based on design and material selection from Phase 1
  - Test and characterize prototype hammers under ambient conditions at the Atlas Copco Roanoke test facility
  - Identify options and test requirements for high-temperature test facility
  - Design, build and test high-temperature test facility
  - Validate performance of prototype HT hammer at temperatures up to 300° C on the high-temperature facility

Accomplishments, Results and Progress

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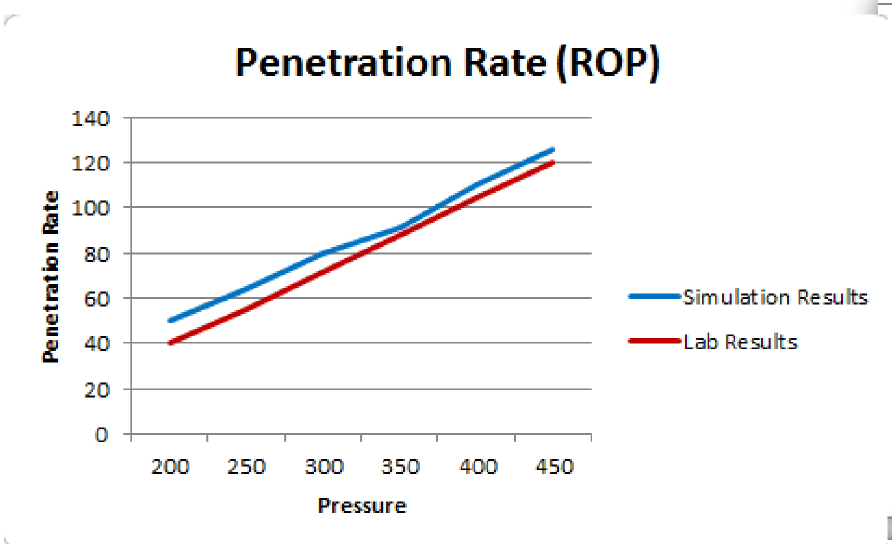
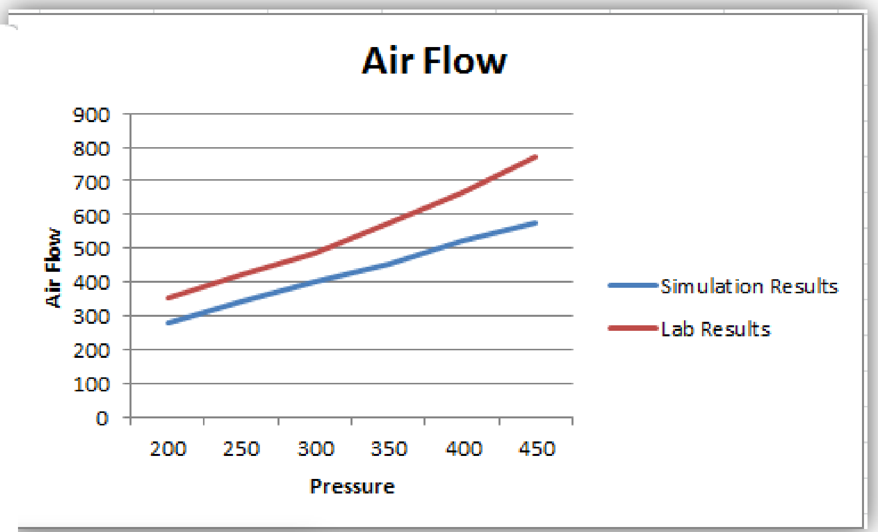
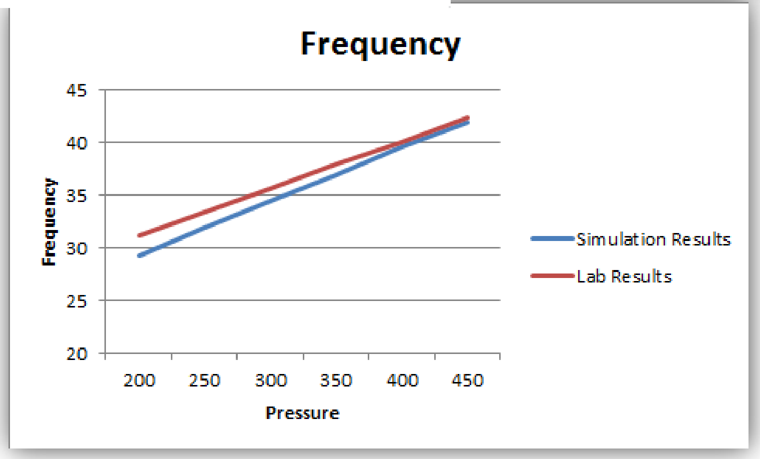
- Flow / Counterflow modeling of deep hot borehole
- Requirements defined for drilling environment and operational specifications
- Establish baseline DTHH performance
- Design and build full scale Proof of Concept DTHH
- Computational modeling of performance for full scale POC DTHH
- Identify current materials and identify candidate materials and coatings for qualification testing
- Analyze and test bit button retention for hot drilling environment
- Construct prototype DTHH for low temperature component and system level lab testing
- Complete material and coating qualification testing
- Select materials and coatings for HT prototype
- Validate selected materials and coatings by bench-scale testing
- Complete low temperature component and prototype testing and cycle optimization
- Identify options for internal sealing at high temperature
- Design and build prototype for high temperature testing.
- Design and construct test facility for high temperature testing of HTDTHH prototype, including process gas heater, hammer heater, rock sample positioning, feed and rotation system, controls and instrumentation.
- Begin low temperature validation of HT prototype vs LT prototype results.

Simulation vs Prototype Results





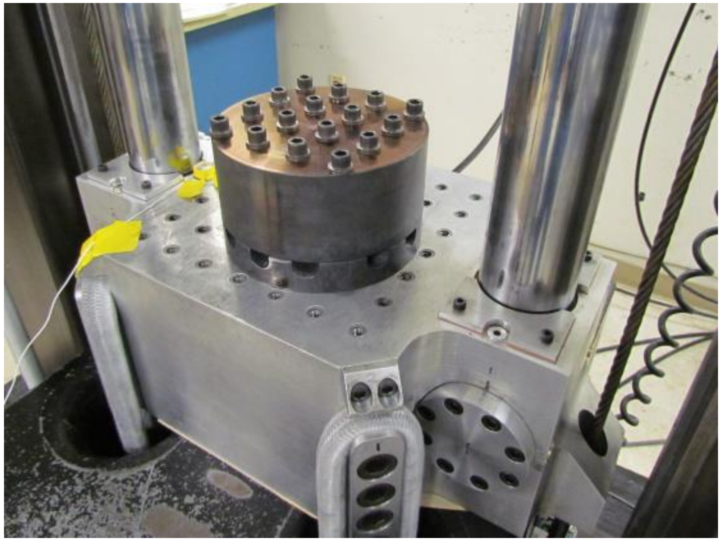


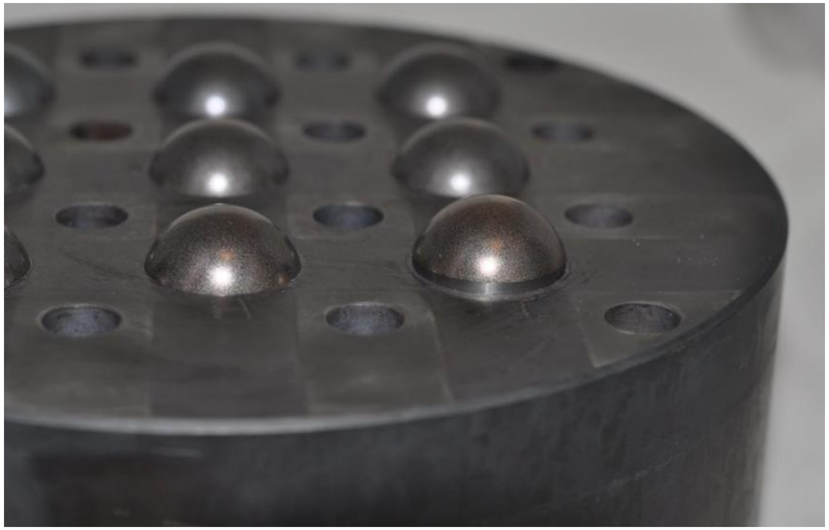
Internal Sealing

- Initial testing showed internal leakage between the Air Distributor and Cylinder dramatically limited hammer performance
- Low temperature testing using a conventional Buna –N o-ring showed that effective sealing would correct the problem
- Alternatives for High Temperature sealing
  - Interference fit
  - Permanent joining of Air Distributor and Cylinder
  - High temperature, graphite filled valve packing seal
  - High temperature elastomer
- Evaluated valve packing and Kalrez o-ring
  - Valve packing provided fair sealing performance, more development is necessary
  - Kalrez o-ring is a drop in replacement for standard elastomers and is fully capable of performing satisfactory in the target environment (Max. temperature rating 327 C)

Button Retention Testing

- Impact testing up to 12,000 g
- Varying interference fits to simulate button hole expansion due to temperature
- Two buttons with the least interference began shifting at 10,000 g
- All other buttons remained in place up to 12,000 g
- Conclusion: current interference fit is suitable to retain buttons in a bit, up to 600 F





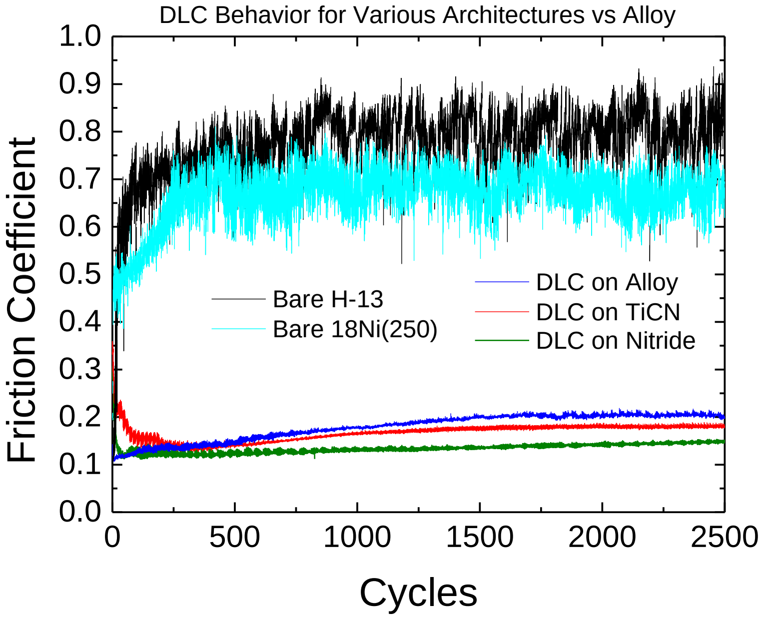
Material Selection

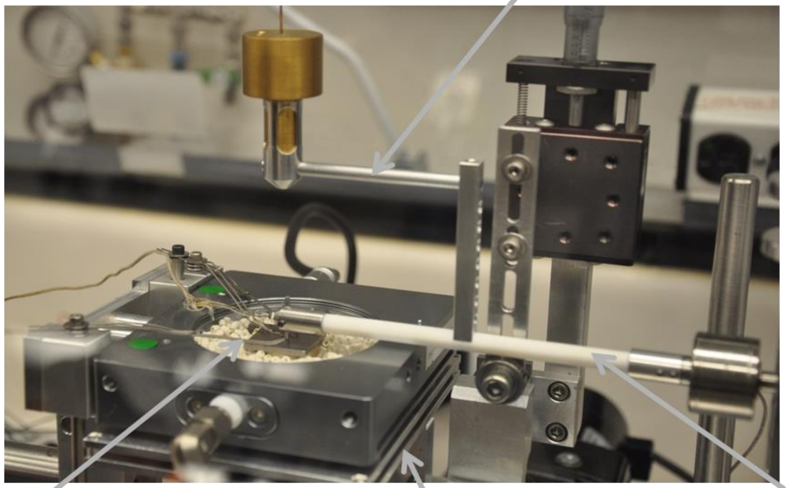
- Focus on Casing, Air Distributor, Piston, Bearing
  - Conventional parts are tempered below the target geothermal operating temperature
  - Fatigue resistance is a key property
  - Corrosion resistance is important
- Selection Process
  - Literature search to determine properties of current materials and identify candidate materials with good physical properties at 300 C
  - Qualification testing of candidate material, including
    - Tensile strength
    - Charpy impact toughness
    - Fatigue
    - Abrasion resistance
    - Friction and wear characteristics
- Results
  - No candidate material showed better properties than the existing casing material. Surface hardening will be omitted from part specifications
  - A precipitation hardening stainless steel was selected for the piston
  - A hot working tool steel was selected for the Air Distributor and Bit Bearing

Lubricious and Wear Resistant Coatings

- Thermal Spray Coatings
  - Four (4) commercially available coatings tested
  - Addition of hBN or MoS_2 was also evaluated
  - Testing Conducted:
    - Hardness
    - Abrasive wear
    - Friction
    - Tensile adhesion of coating
    - Impact fatigue resistance
- Vapor Deposition Coatings
  - Two (2) candidate coatings evaluated
    - Diamond Like Coating (DLC) with ceramic barrier level
    - DLC with multiple barrier layers (TiCN nanolaminate and ceramic barrier layer)
  - Tested for friction and wear properties at 300 C
    - Multiple layer sample developed cracks and delaminated
    - DLC with single SiO barrier layer showed good friction resistance and no delamination

Coatings Friction and Wear Testing





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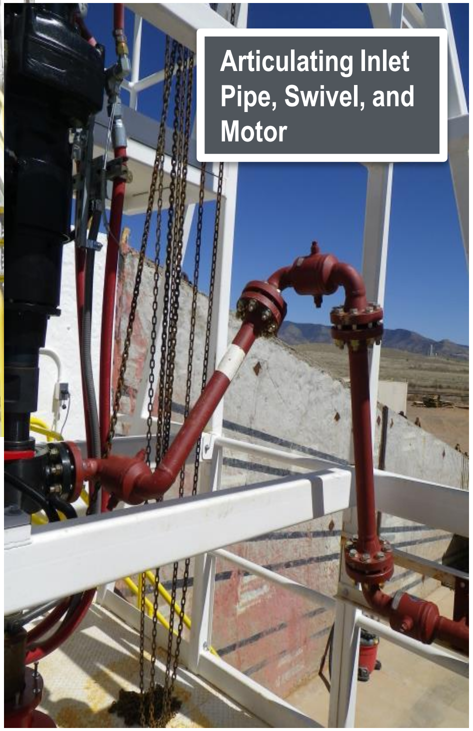
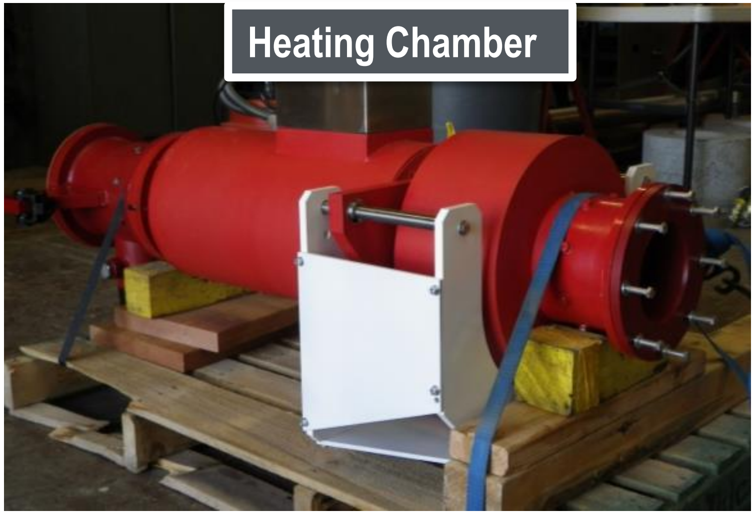
High-Temperature Test Facility

- Capability to simulate high-temperature drilling conditions (up to 300^0C)
- Evaluate effects of thermal shock on hammer components
- Evaluate effectiveness of coatings and materials in simulated geothermal conditions
- Enabling features for safely testing at high-temperatures
  - Pneumatic operation
  - Dual-stage air filtration system for process gas
  - High-temperature swivel
  - Atlas Copco pneumatic motor
  - Articulating feed pipe joint
  - Rock positioning system



High Temperature Test Cell

- Capacities
  - Weight on Bit (WOB) – to 6000 lbf
  - Rotation speed – up to 60 rpm
  - Rotation torque – up to 2500 ft -lbf
  - Feed Rate - up to 100 ft/hr
  - Hammer heater – up to 300 C (9kW heater)
  - Process gas heater – up to 300C (190 kW heater)



Future Directions

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- Future Work and Directions
  - Conduct ambient temperature testing to validate HT Prototype - Complete March 31, 2015
  - Qualification testing of HT test apparatus – Complete by April 30, 2015
  - Conduct HT testing of HT DTHH and validate results – Complete by December 31, 2015
  - Prepare and submit Final Report for Project

Summary

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- Conclusions to Date
  - Low temperature prototype testing shows ROP target can be met.
  - Low temperature test results compare favorably with computational model predictions.
  - Current interference fit of cutting elements in the bit body can successfully retain them at target operating temperature.
  - Laboratory based material and coating testing show selected materials and coatings can be effective in a high temperature drilling environment