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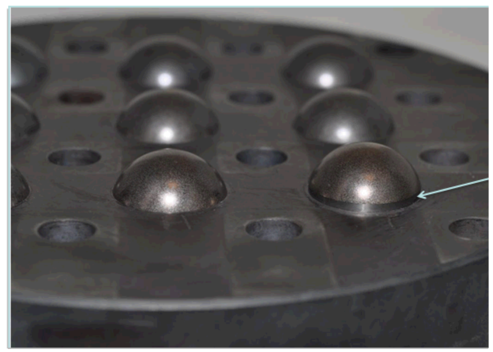

Advanced Percussive Drilling Technology for Geothermal Exploration and Development

Jiann Su, David Raymond, Somuri Prasad

Sandia National Laboratories

Dale Wolfer

Atlas Copco Secoroc

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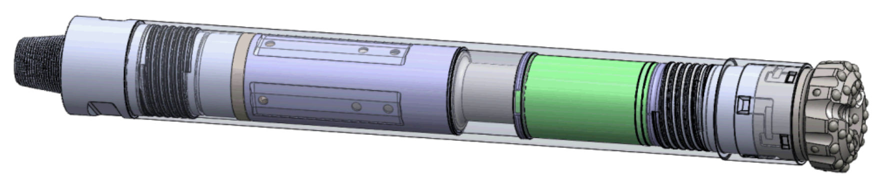
Atlas Copco Partnership

- Headquartered in Stockholm, Sweden
- Industrial group with products and services for mining and construction
  - Compressed air and gas equipment
  - Industrial tools and assembly systems
  - Down the hole hammers suited for geothermal environments
- Production facilities in more than 20 countries
- $~12 B revenue in 2016

- Prior SNL DARPA work showed promise for hammers in harsh environments
  - Efficient at drilling hard rock
  - Very durable
  - Low weight on bit and torque requirements
- Current work result of competitive bid process for DOE Funding Opportunity Announcement
  - Funded separately by DOE
  - Atlas Copco has cost share
- Established a broader CRADA including others at Sandia
- Synergy between other Sandia work and Atlas Copco needs

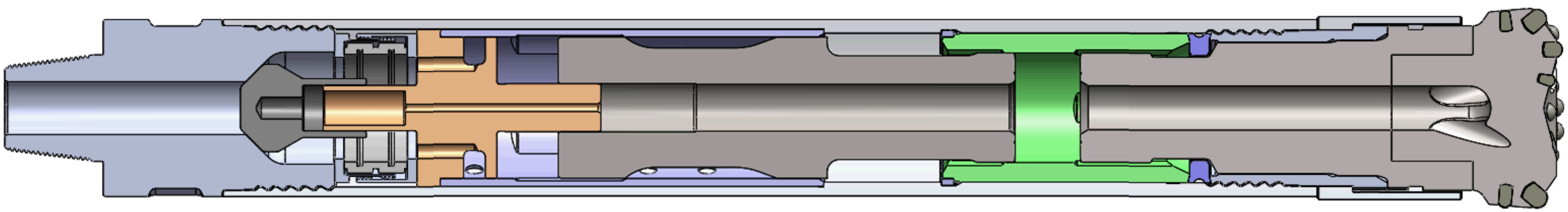


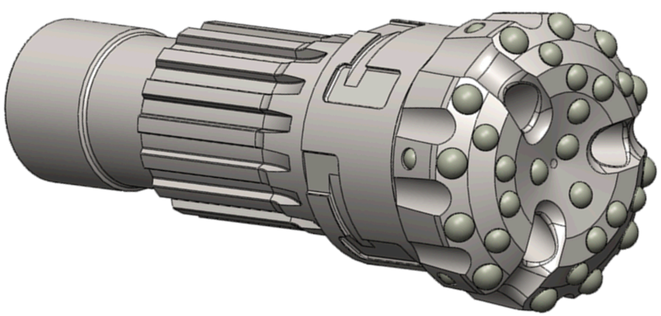
Project Objectives

- To construct the conceptual definition of a High Temperature (HT) pneumatic percussive hammer.
- Identification, testing, evaluation and qualification of constituent materials for this hammer.
- Perform computational modeling of the available power delivery of conceptual designs.
- Provide Proof-of-Concept (POC) validation via laboratory testing of representative design features.
- Implement prototype hardware development of a high temperature pneumatic percussive hammer.
- Conduct laboratory drilling tests to validate performance of prototype hardware at conventional temperatures.
- Perform laboratory drilling tests to validate performance in a high temperature test cell simulating a geothermal drilling environment.

Proof of Concept Hammer

- Valveless cycle
- No polymeric or elastomeric parts or seals
- No fluid lubrication
- Performance comparable to current commercial DTHH

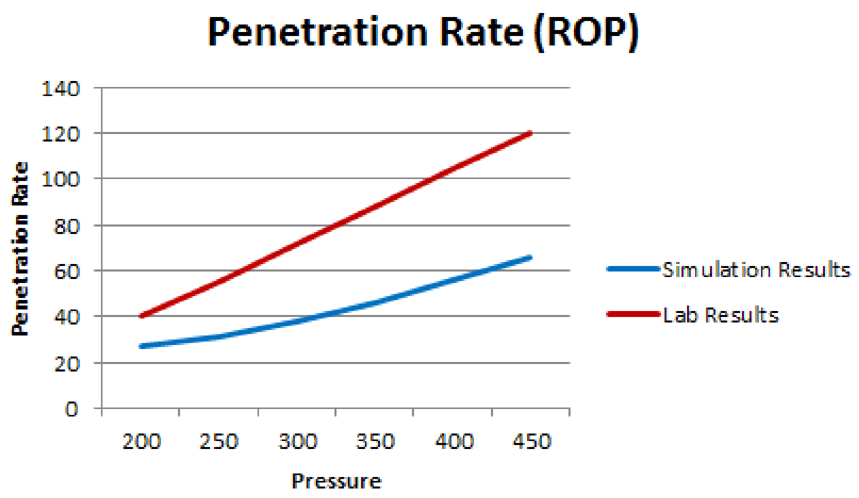


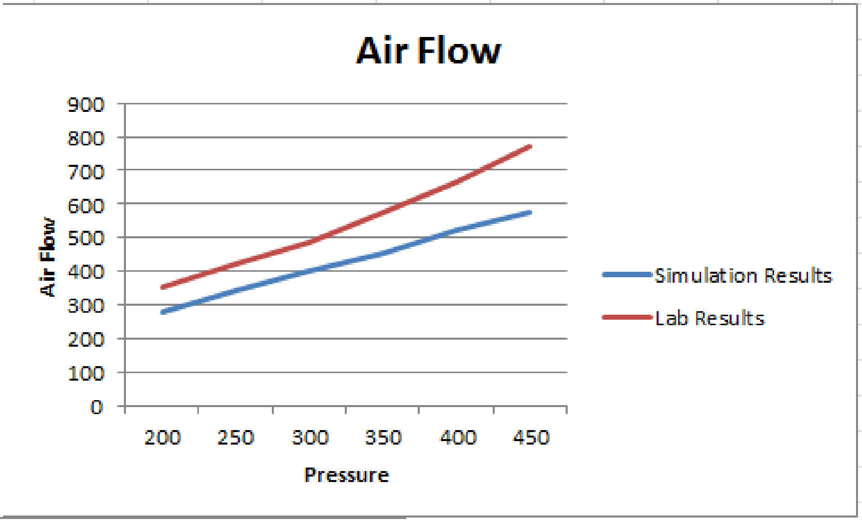


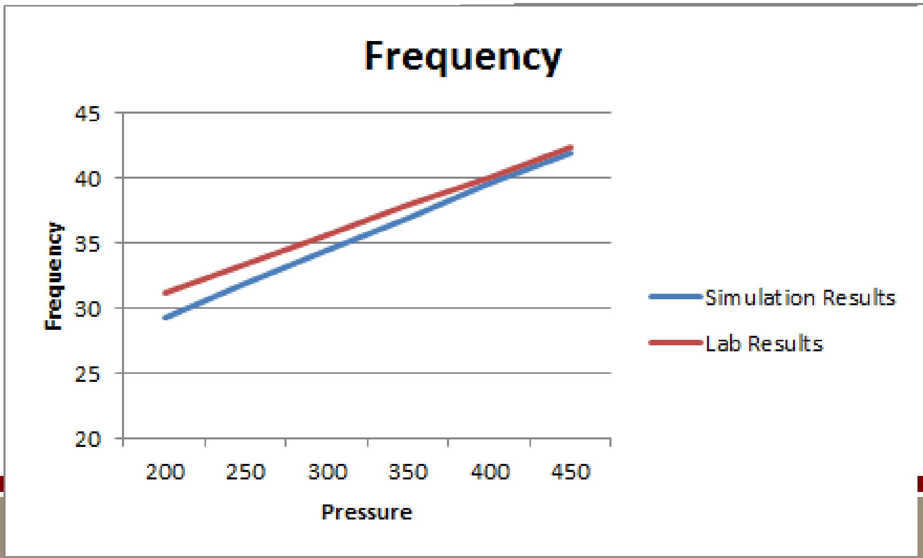
Scientific/Technical Approach

- 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
- 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
  - Design, build and test high-temperature test facility
  - Validate performance of prototype HT hammer at temperatures up to 572 F on the high-temperature facility

Simulation vs Prototype Results





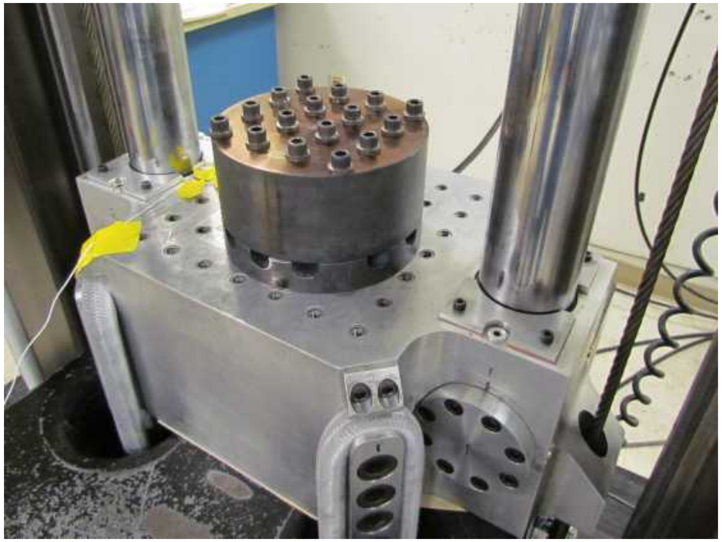


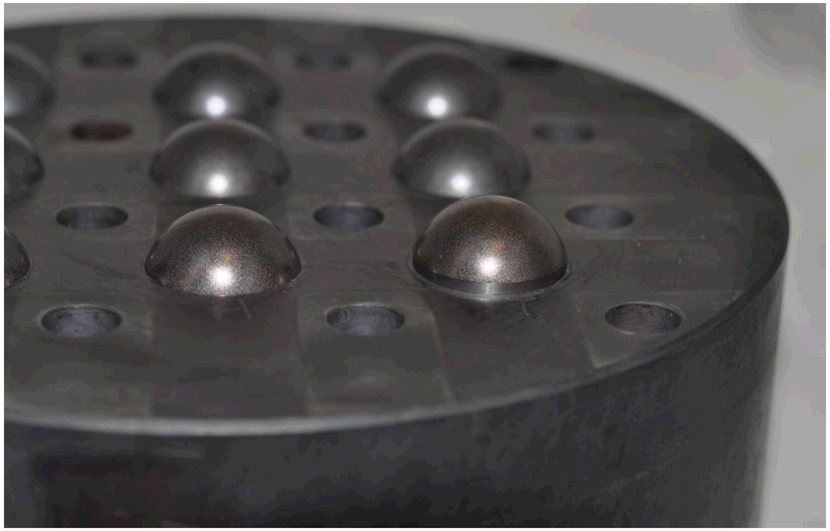
Internal Sealing

- 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



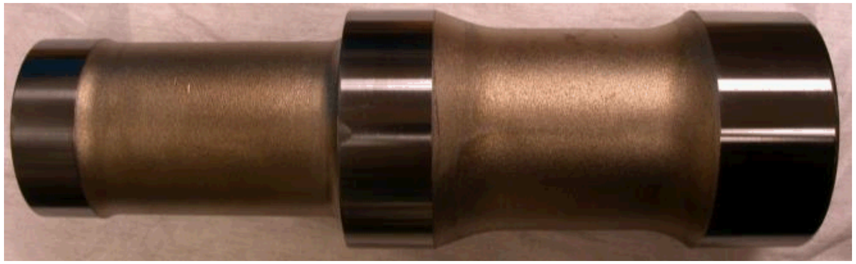


Material Selection

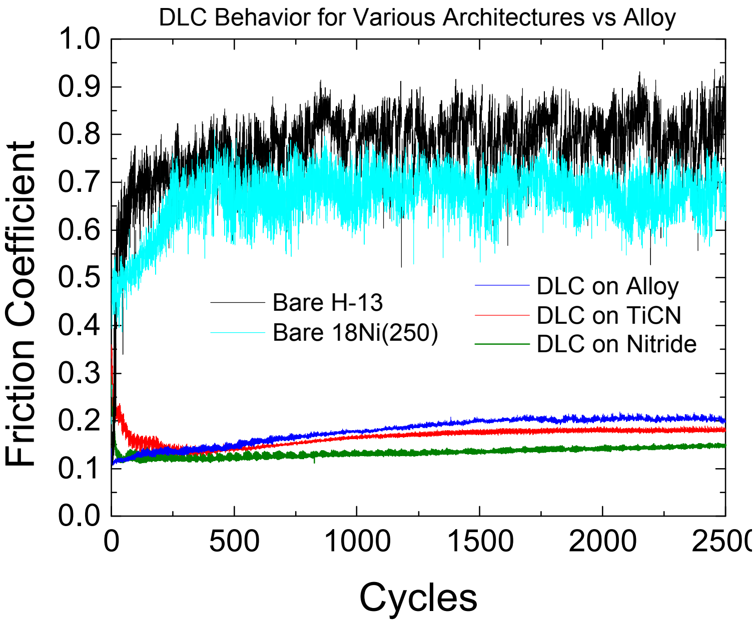
- Focus on Casing, Air Distributor, Piston, Bearing
  - Conventional parts are tempered below the target geothermal operating temperature
  - Fatigue resistance is a key property
  - Corrosion resistance is important
- Selection Process
  - Literature search to determine properties of current materials 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

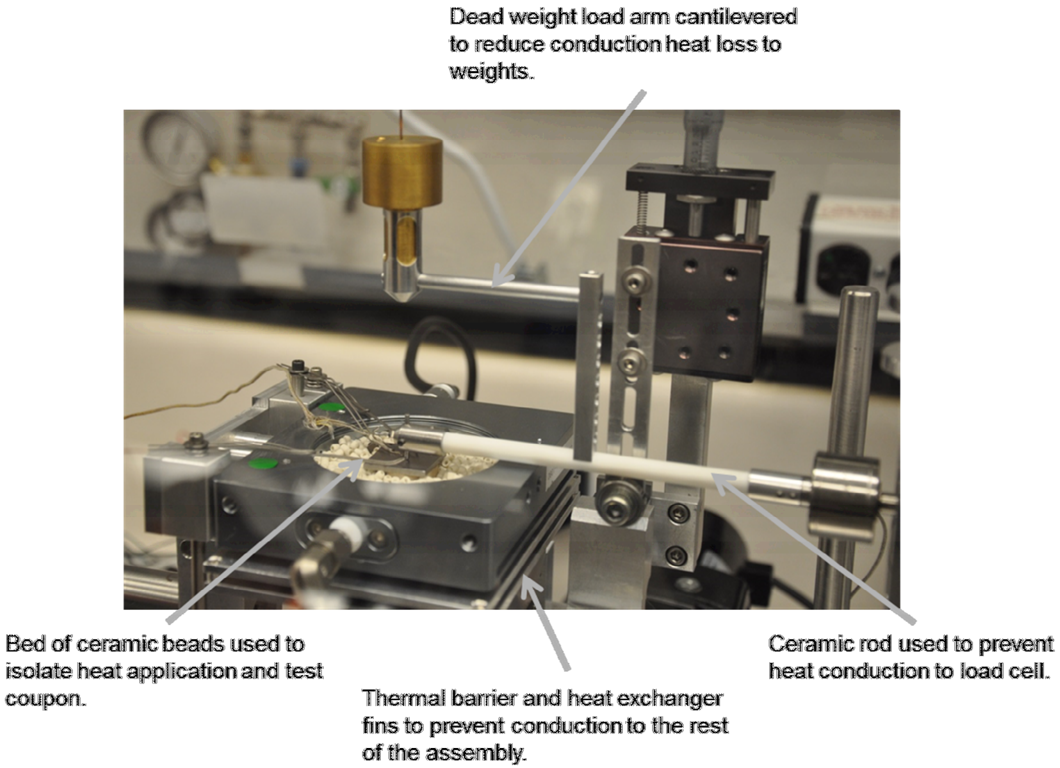
Lubricious and Wear Resistant Coatings

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

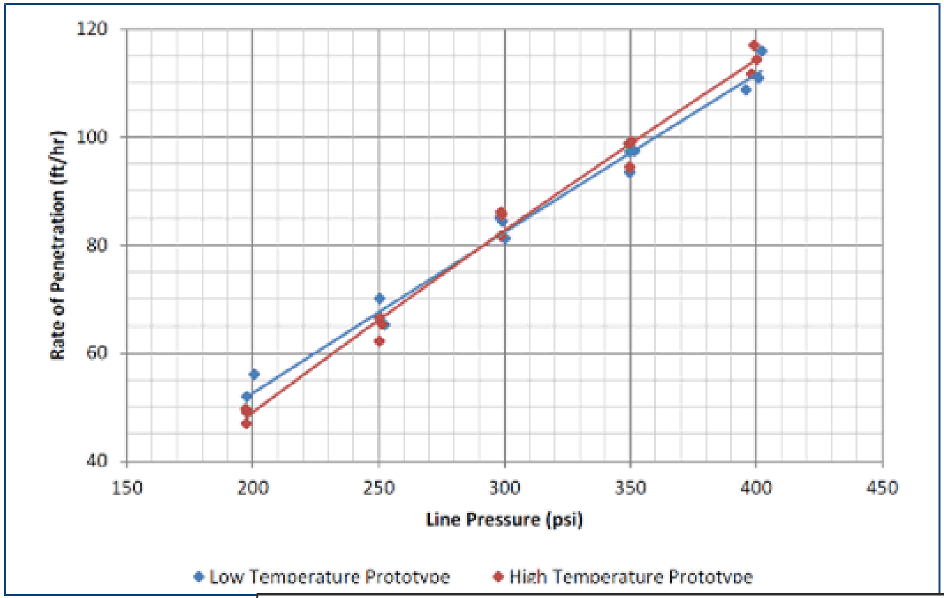


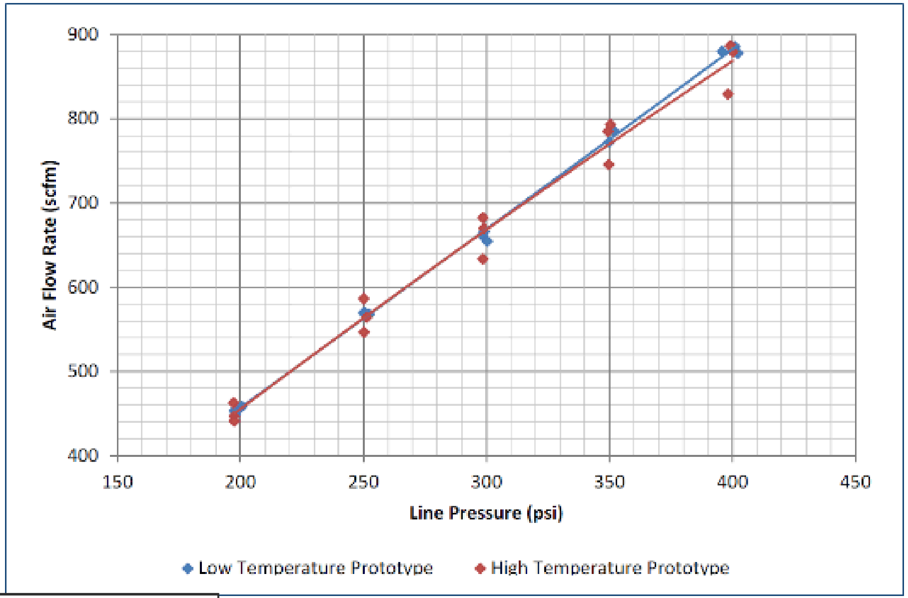
Coatings Friction and Wear Testing

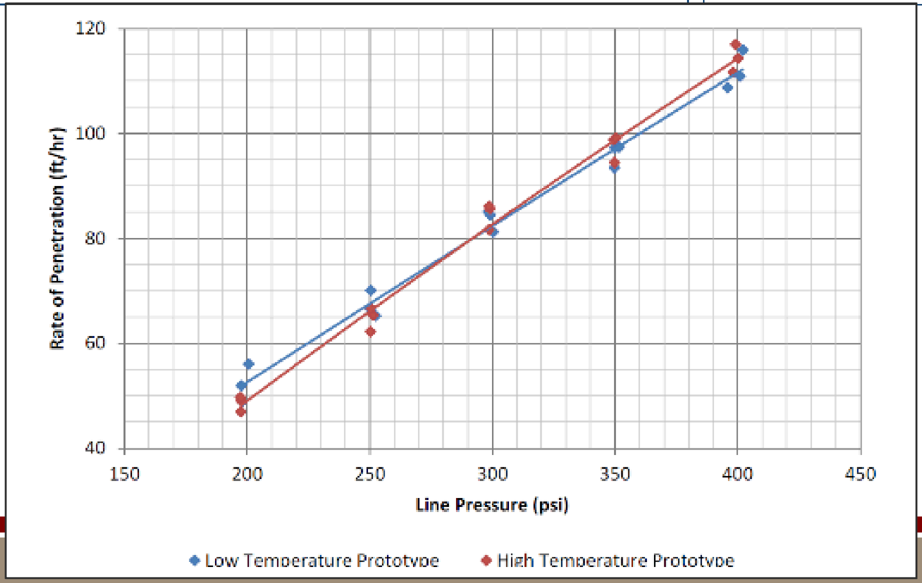




Baseline Results







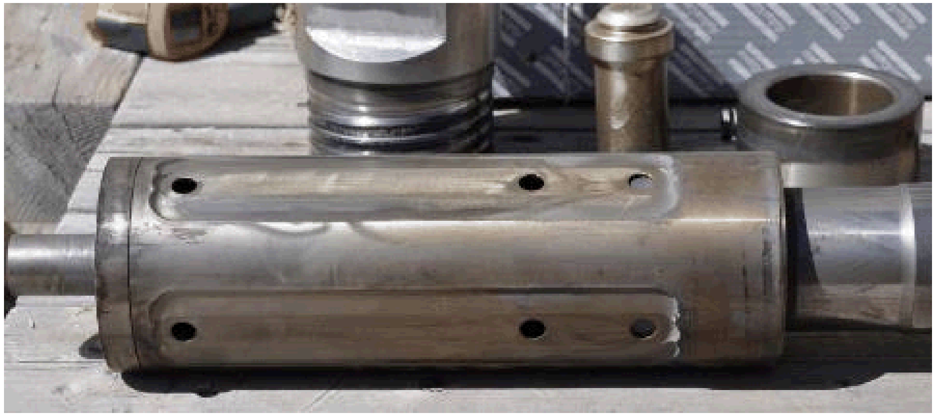
Conducted at A-C test cell

High Operating Temperature Facility

- Capacities
  - Weight on Bit (WOB) – to 6000 lbf
  - Rotation speed – up to 60 rpm
  - Rotation torque – up to 2500 ft -lbf
  - Hammer heater – up to 300 C (9kW heater)
  - Process gas heater – up to 300C (190 kW heater)
- Features
  - Remote operation
  - Automated drilling
  - Automated rock positioning
  - Closed-loop control of drilling parameters
  - Cuttings collection system with dust washdown
  - Two-stage air filtration

Preliminary HOT Facility Testing

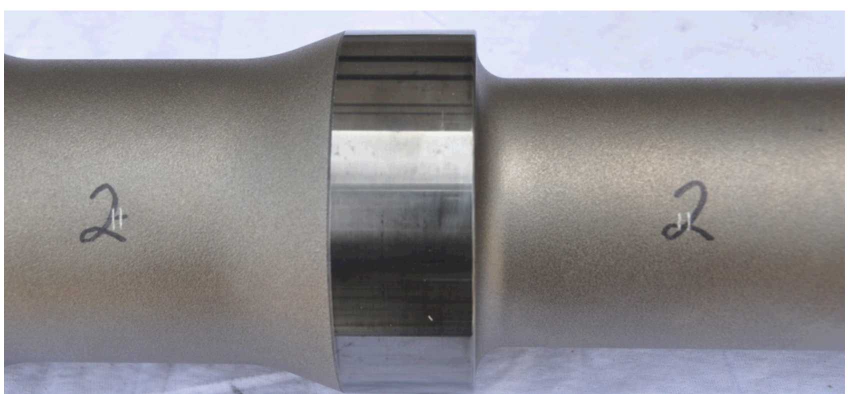
- Validate DAQ
- Verify control system
- Shakedown system



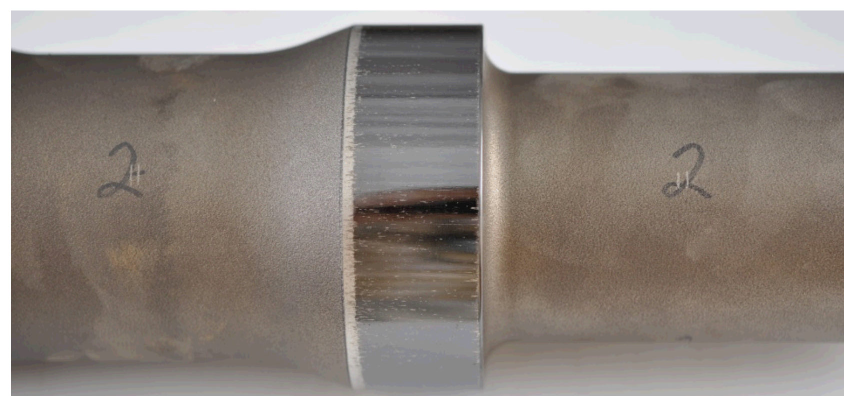
Residual assembly lube after heating to 400°F

Piston #1 (HT Material Candidate)

New

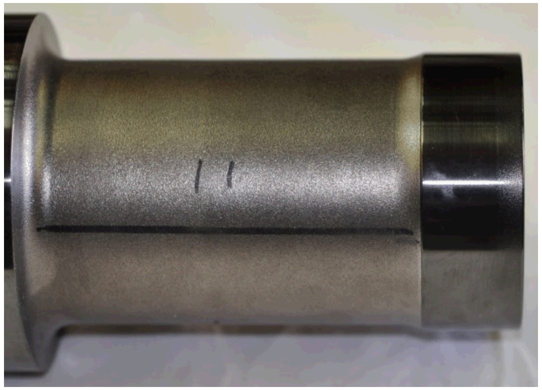


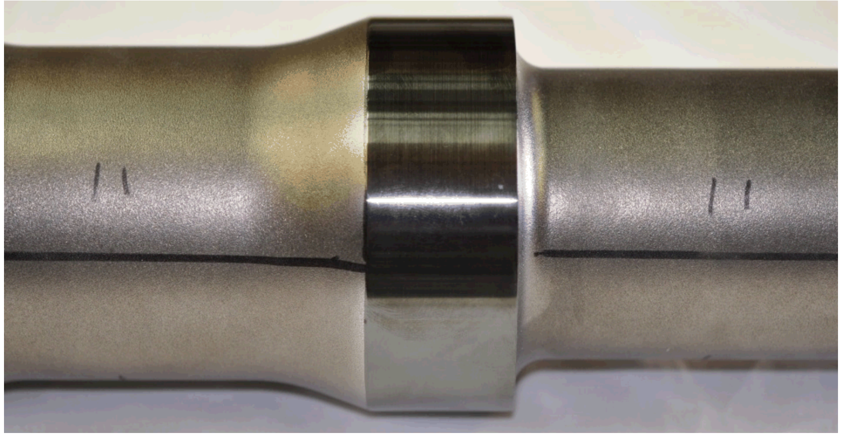
After ~39 ft



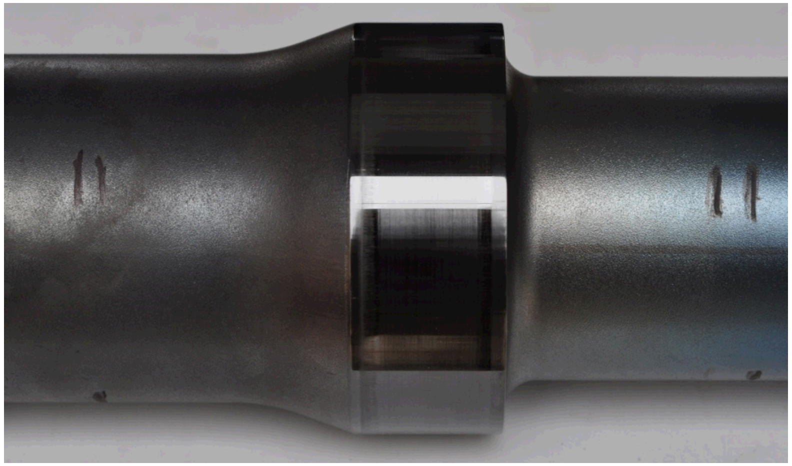
Piston #2 (Alternate Material)

New

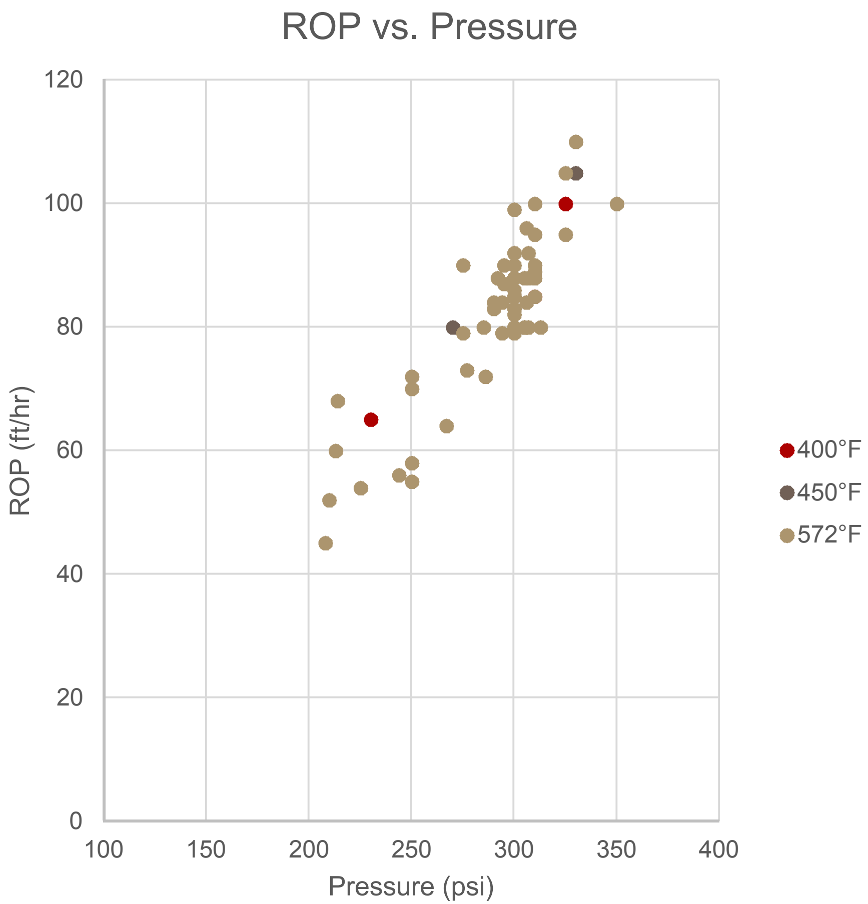


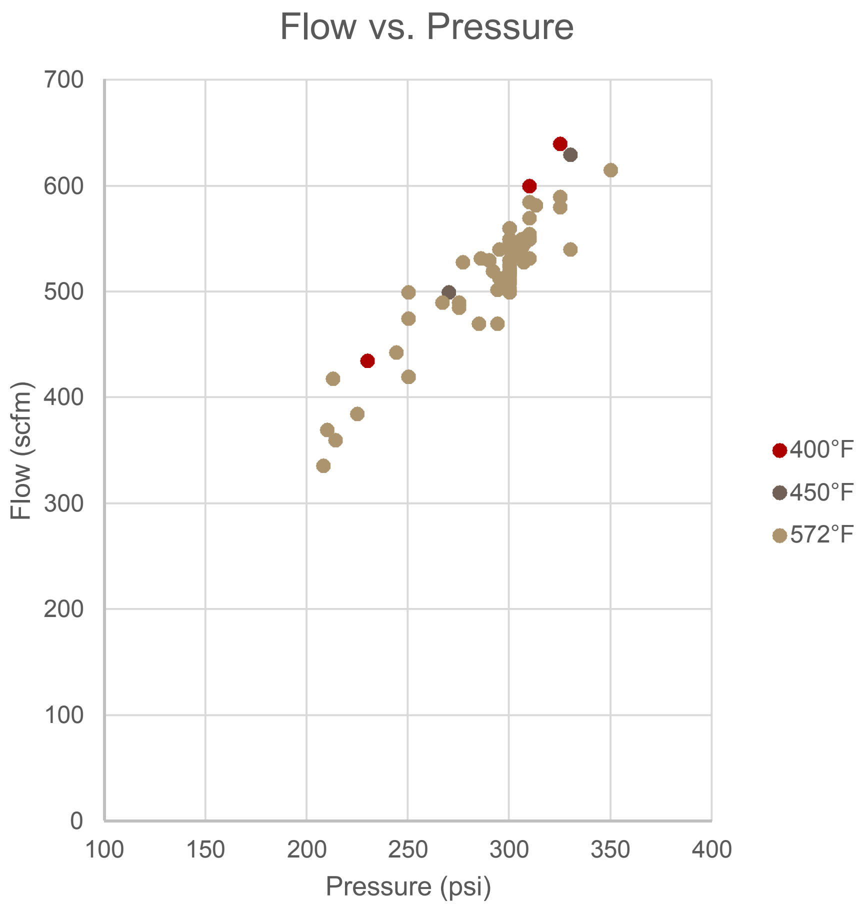


After ~200 ft



Overall HT Performance





Results

- Validated HOT Facility performance with Atlas-Copco Roanoke test facility
- Drilling performance evaluated at temperature (~300 C)
- Drilling performance in line with expectations
- Achieved target rate of 100 ft/hr at temperature
- Over 200 ft drilled at temperature in lab environment
- Gradual progression of wear on piston stem
- Seeking opportunities to conduct additional field testing

Acknowledgements

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Questions?