U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
SAND2015-2661C

High Temperature Downhole Motor

Project Officer: Lauren W.E. Boyd

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Sandia National Laboratories

Track 3 – EGS1

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Relevance/Impact of Research

- Objectives
  - Develop technology for a new downhole motor for geothermal drilling
  - Design power section and demonstrate viability with a proof of concept demonstration
  - Enable high temperature downhole rotation solution for directional drilling and eventual rotary steerables contributing to multi-lateral completions

- Barriers - Geothermal drilling hampered by downhole rotation capabilities
  - Temperature limitations: Positive Displacement Motors - 350F (177C) max
  - Performance limitations: Mud Turbines – High speed, low torque
  - Limits options for multi-lateral completions in geothermal well construction

- Impact
  - Technology is needed that improves ROP and capable of drilling to depth
  - Multi-lateral completions will allow improved resource recovery, decreased environmental impact, and enhanced well construction economics
  - Development of a high temperature motor is an EGS enabling technology

Work Scope

- Task 1 - Project Management
- Task 2 - Requirements Definition
  - Compile / evaluate results from survey of current motor product offerings
  - Compare results to requirements for fixed cutter bits drilling geothermal formations
- Task 3 & 4 – Preliminary & Detailed Engineering Design
  - Design power section concepts for downhole motor applications in HT environments
- Task 5 - Computational Modeling & Analysis
  - Conduct engineering modeling and analysis to validate concepts
  - Evaluate flow conditions through rotor, ports & chambers
  - Develop operational performance predictions for fluid / power section interaction
- Task 6 - Prototype Hardware Development & Testing
  - Develop and test prototype hardware in controlled laboratory test fixtures to demonstrate and validate available performance
- Task 7 - Field Testing
  - Placeholder for subsequent fiscal years

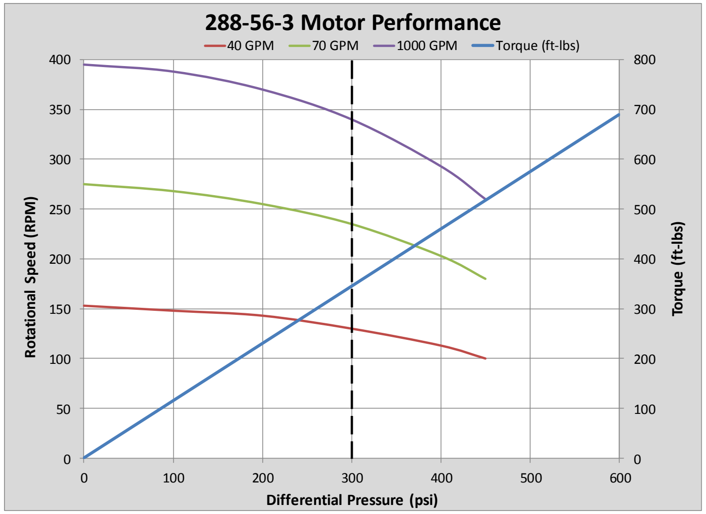
Accomplishments, Results and Progress
- Task 2 / Requirements Definition

Limitations of positive displacement motors

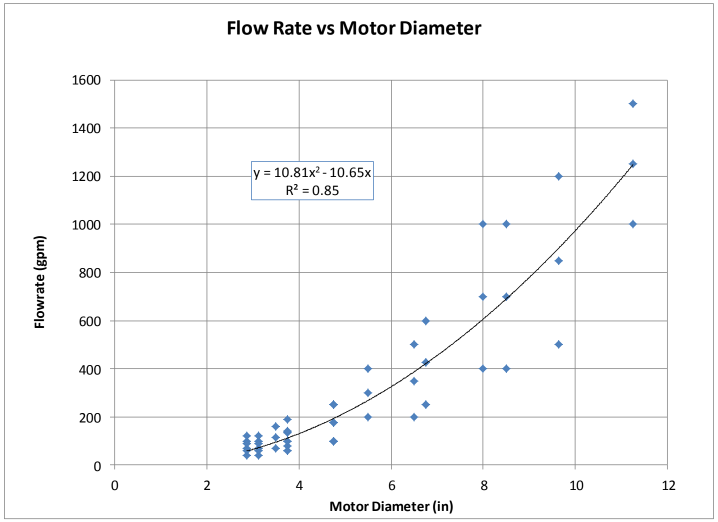
- PDMs introduce rotation via rotor "nutation"
- Temperature limit: 350 F /177 C max
- Introduce lateral vibration to BHA

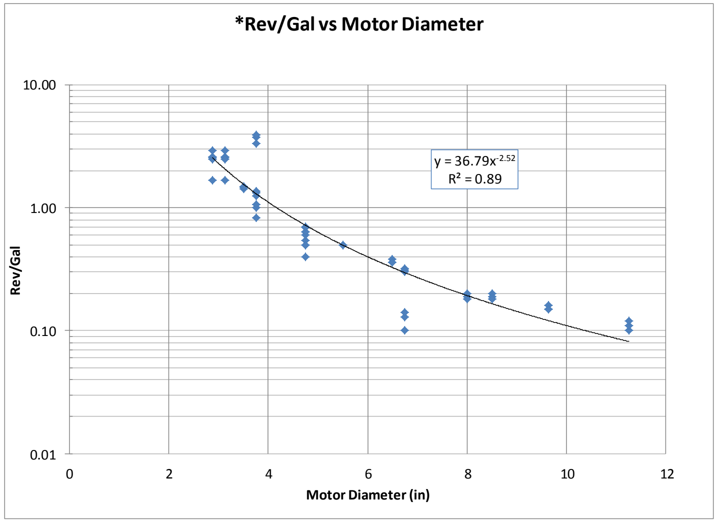
Evaluate for geothermal formation suitability

- Use catalog surveys to map performance
- Compare to fixed cutter bit requirements to validate applicability



PDM Motor Data per Toro, Cavo & Bico Catalogs





PDM Motor Stator

Accomplishments, Results and Progress- - Task 2 / Requirements Definition

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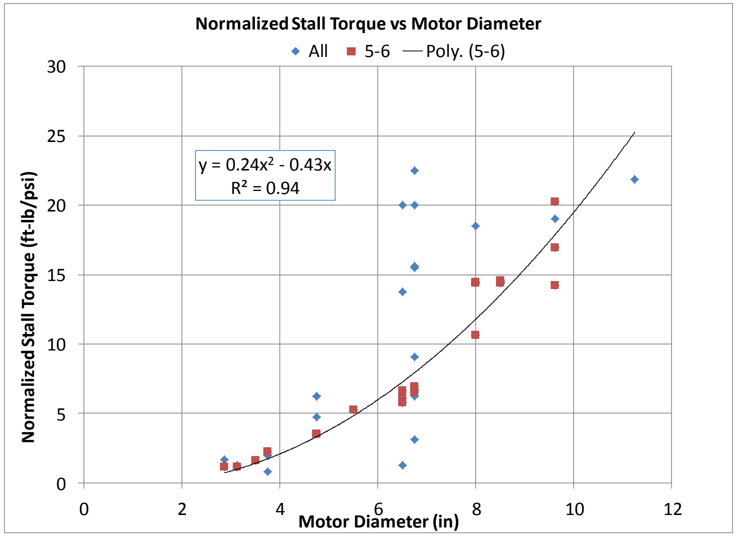
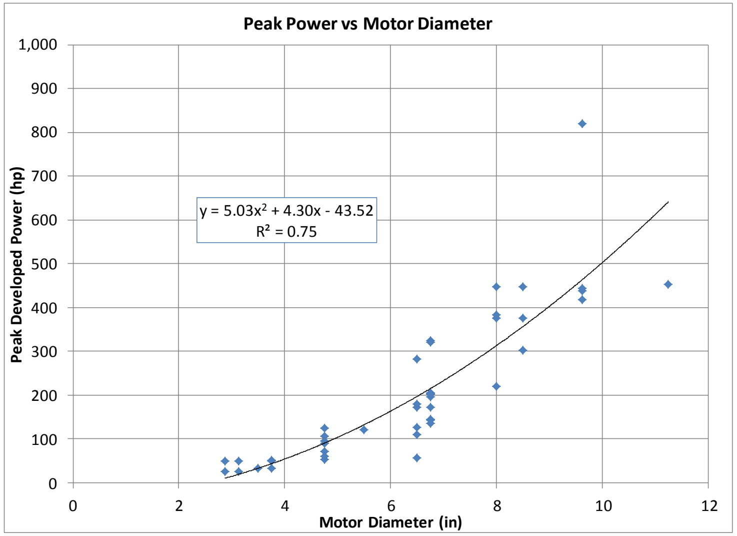
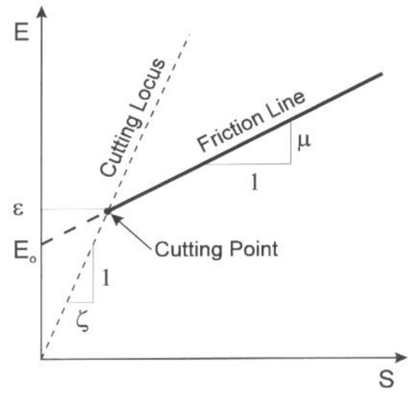
PDM Motor Survey of Torque & Power



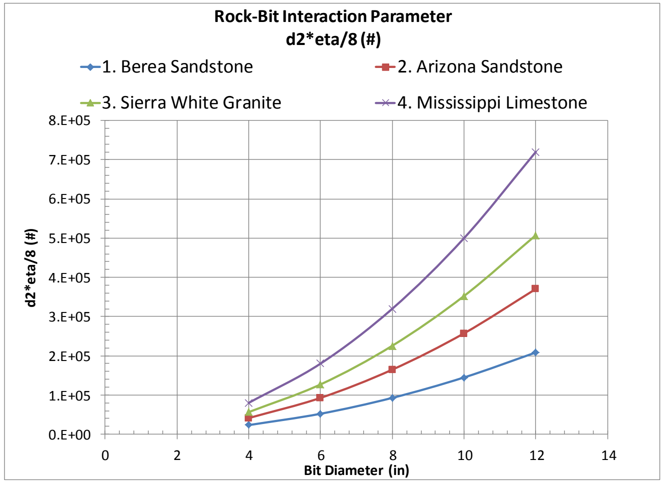


Rock Bit Interaction Analysis for formation suitability

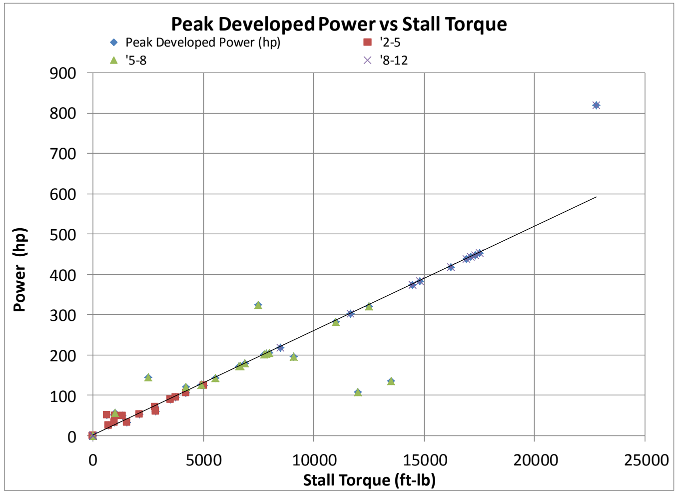
(Ref: Detournay, 1992)



$$E = \frac{2T}{r^2\delta} \qquad S = \frac{W}{r\delta}$$



NOV/Sandia Test Bit, Dec 2011



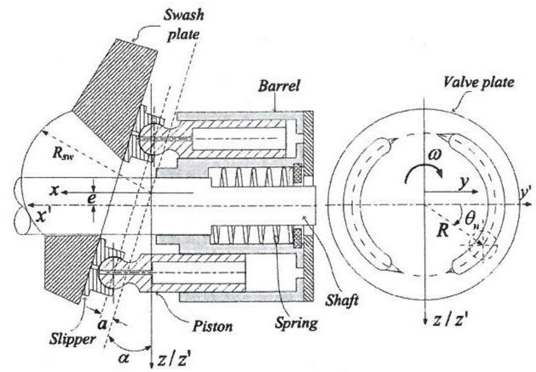
Accomplishments, Results and Progress - Task 3 / Power Section Design

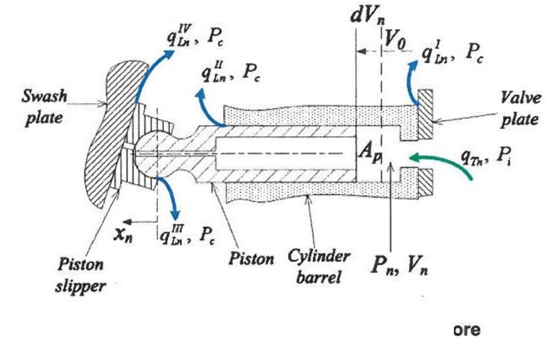
Approach

- Develop linear piston motor with functionality analogous to swash-plate type axial piston motors & pumps used in hydraulic systems

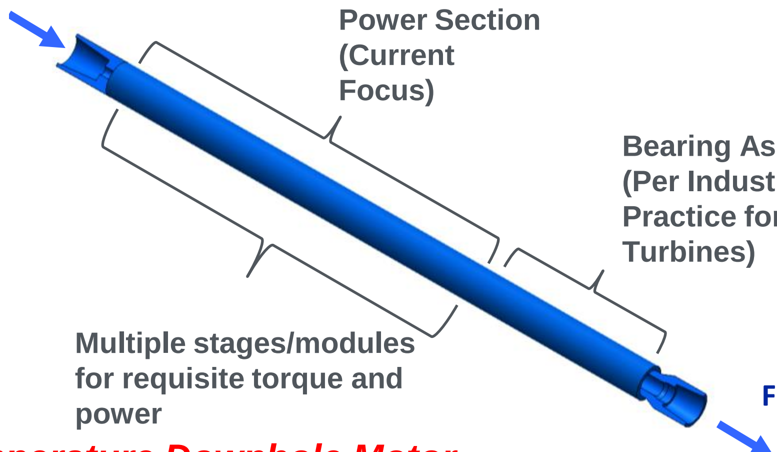
Progress

- Prototype Concept Developed





Above figures per "The Analysis of Cavitation Problems in the Axial Piston Pump," S. Wang, Eaton Corp., ASME Journal of Fluids Engineering, July 2010.



Sandia High Temperature Downhole Motor

Conventional Hydraulic Axial Piston Motor

U.S. Patent Application No. 14/209,840, filed 3/13/2014; CIP of U.S. App. No. 14/298,377, filed 05/05/2014 and U.S. Provisional Patent Application No. 62/142,837, filed 4/3/2015.

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Progress – Prototype Power Section Developed and Demonstrated

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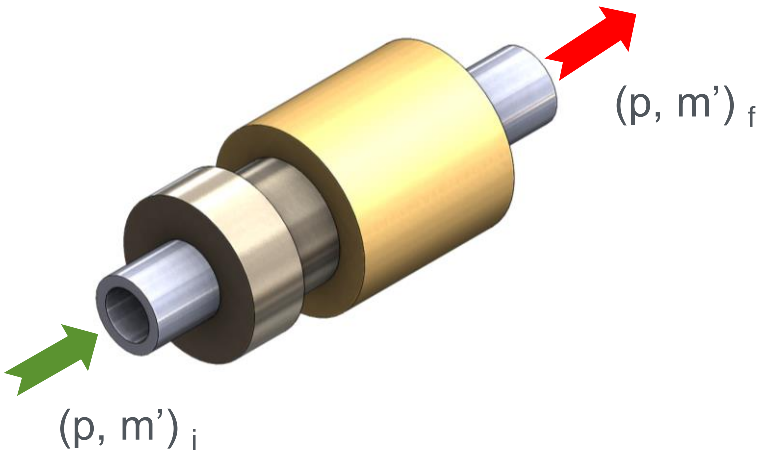
Power Section Design Description

- Fluid Power Cycle
  - Piston oscillation generated by hydraulic flow through tool
  - Requires alternating pressure on piston lands for reciprocation
- Harmonic drive coupling converts axial piston force / motion to rotor torque / rotation
- Requires multiple pistons
  - Continuous rotation
  - Torque generation
  - Overcome dwell points
- Allows fluid leakage / no seals
- Low friction surfaces at piston interfaces



Assembly

- Removable Rotor Assembly
- Case/Rotor Design Integration
- Pressure/Exhaust Manifold Integration
- Piston Motion / Valve Port Integration

Sandia High Temperature Downhole Motor

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Fluid-End / Power-End Separation:

- Isolated
- Open
- Metered

Material Considerations & Selection

- Triplex pump cup-seal pistons with mud pump liners for low temperature proof of concept
- Abrasion Resistant Chromium or Zirconia Liners
- Migrate to HT/Abrasion Resistant materials
  - Tungsten Carbide
  - Silicon Nitride
  - Others

Accomplishments, Results and Progress
- Task 5 / Computational Modeling & Analysis

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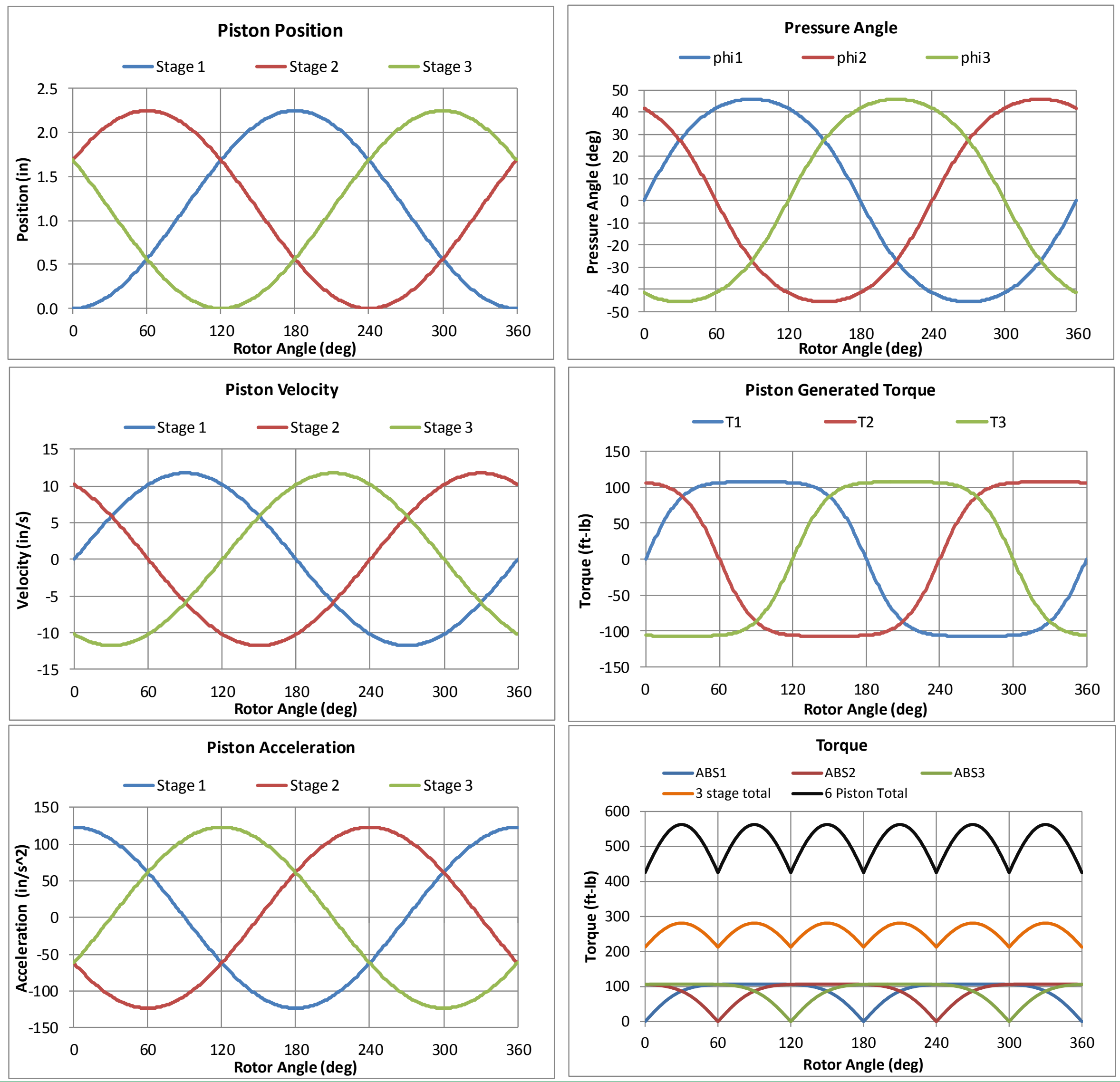
Approach

- Evaluate piston mechanics
- Couple with fluid interaction

Results

- Range of conditions evaluated
- Preferred stroke for motor diameter
- Design for performance metrics

3" Piston Motor at 100 RPM & 600 psi Differential Pressure



Progress – Piston Motor concept designs validated against PDM Performance

Nominal Motor Size (in)	PDM			Piston Motor				
	PDM Motor Configuration	Peak Torque Differential Pressure (psi)	PDM Stall Torque (ft-lb)	Piston Motor Configuration	Peak Torque Differential Pressure (psi)	Piston Diameter (in)	Stroke (in)	Piston Motor Stall Torque (ft-lb)
3-1/8	3-1/8", 5:6 lobe, 3 stage	600	692	6 piston	600	2.6	2.3	514
6-1/2	6-1/2", 5:6 lobe, 4 stage	800	4,910	6 piston	800	5.0	4.3	4,507
8	8", 5:6 lobe, 6 stage	1200	12,500	6 piston	1200	6.0	5.0	11,840
11-1/4	11-1/4", 3:4 lobe, 4 stage	800	17,500	6 piston	800	8.0	9.5	21,826

<u>Dynamics Model</u>

- Used to address coupling between fluid mechanics and reciprocating pistons
- Allows investigation of influence of valve geometry and timing on overall motor performance
- Preliminary results obtained
- Results to be compared to Task 6 Prototype Testing

Accomplishments, Results and Progress - Task 6 / Prototype Demonstrations - Dynamometer

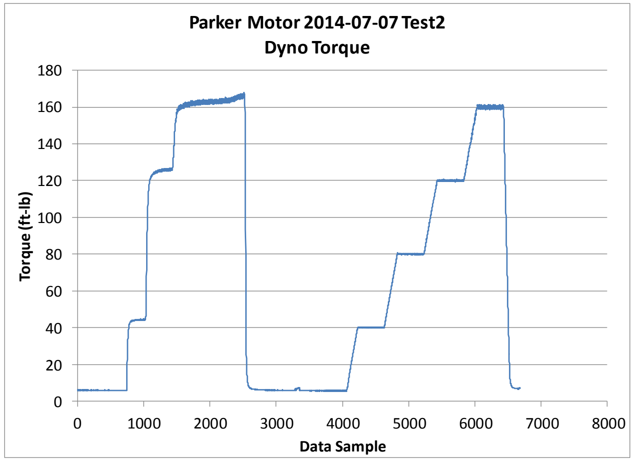
Approach

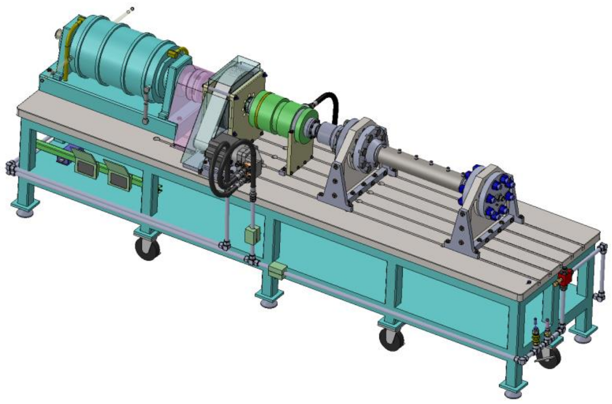
- Develop load testing capability to evaluate prototype motors
- Use for single & multi-stage motor testing

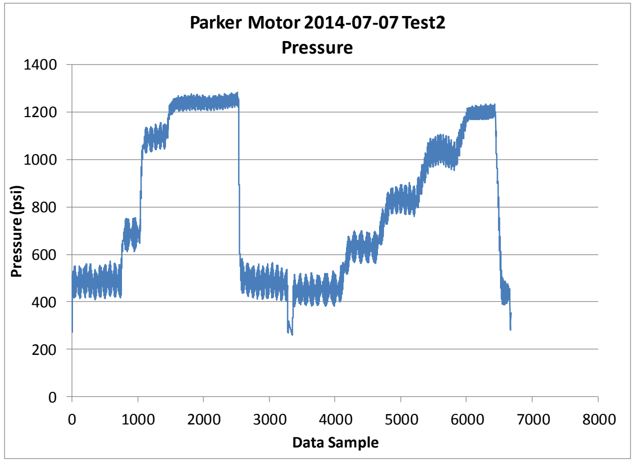
Results

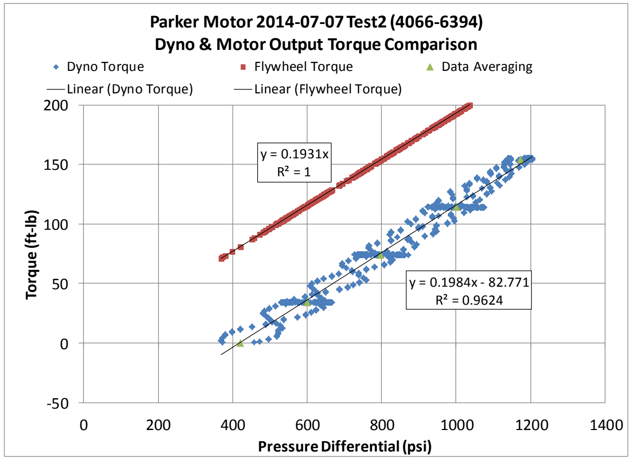
- Dynamometer Test Station developed using Powder Brake Dynamometer
- Sized to provide braking load for proof of concept motor
- Pressure vessel, rotating head, & swivel qualified and operational
- Qualified on commercially-available piston motor

Parker Motor Test at 100 RPM









Accomplishments, Results and Progress
- Task 6 / Prototype Demonstrations - Motor

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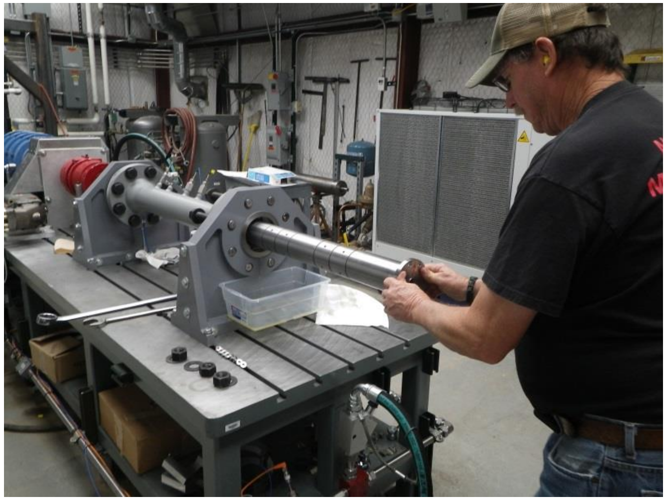
Approach to Prototype Motor Demonstration

- Geothermal typically completed 8-1/2” D
- Full scale not reasonable for POC
- Develop scaled version compatible with existing infrastructure
  - Validate motor concept on hydraulic power source
  - Offset material selections to later program date
  - Allows focus on power section mechanics & fluid power / component interaction

Results

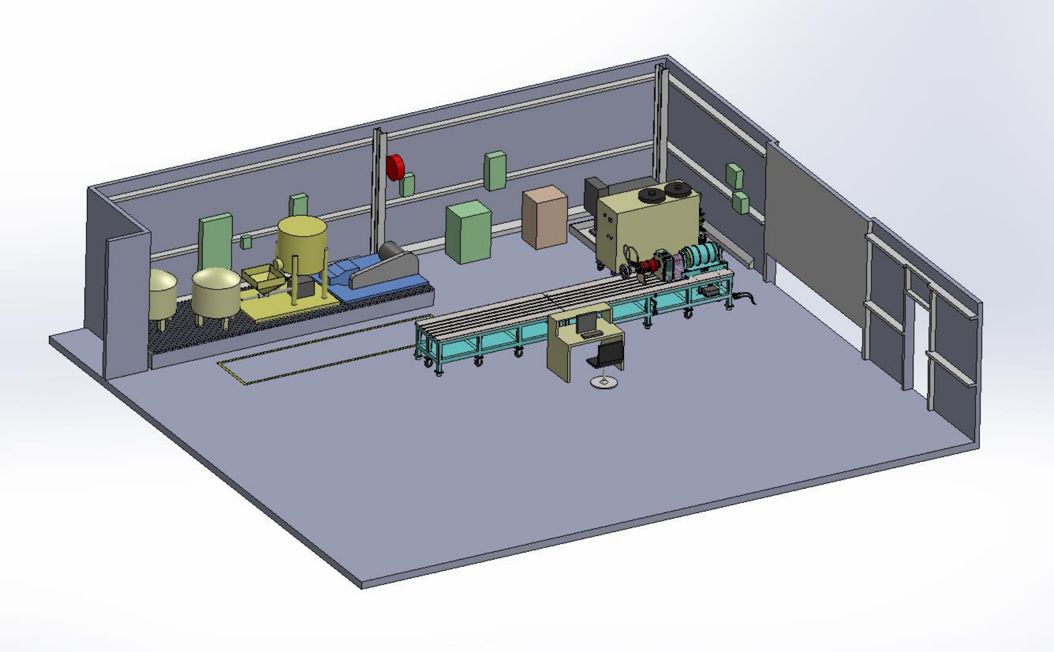
- Single and multi-stage functionality demonstrated
- Full power section testing underway
- Testing has highlighted importance of
  - Relative deflections in members
  - Assembly preload
  - Harmonic drive stress concentrations
  - Material compatibilities



Accomplishments, Results and Progress - Task 6 / Prototype Demonstrations – Flow Loop

Approach

- Use hydraulic fluid power to prove motor developments
- Validate abrasion resistance of material selections on drilling fluids
- Migrate to HT validations in FY16



Results

- Dynamometer Test Station in service
- Fluid Power Upgrades Underway
  - Drilling Fluid Flow Loop
    - Designed, fabrication underway
    - Triplex Pump – on order
    - Mud Mixer - received
    - PDM Motor 288-56-3 – Received, use to qualify flow loop
  - Nitrogen System – designed, components ordered
  - Use to qualify components & overall design

Accomplishments, Results and Progress

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Conceptual, Preliminary and Detailed Power Section Design	Performance requirements identified for 3" diameter Proof of Concept (POC) motor	11/01/12
	Preliminary/prototype design developed for 3" diameter, 3 piston motor incorporating key features in eventual downhole piston motor concept	03/01/13
	Conceptual design approach developed for Fluid-End/Power-End separation	11/20/13
	Performance requirements for geothermal drilling identified by rock bit interaction analysis	09/14/14
	Operational performance requirements for various motor sizes identified by survey of existing downhole motor products	03/31/15
Test Platform Design & Development	Preliminary dynamometer test system in place to accommodate laboratory evaluations	01/31/12
	Compressed air (Nitrogen) test system designed; develoment underway	03/17/14
	Dynamometer Test Station proven on industry standard piston motor	07/07/14
	Hydraulic fluid power flow loop developed with pressure vessel/motor housing, rotating head and swivel	07/08/14
	Water-based drilling fluid test system designed; development underway	03/26/15
Prototype Development, Demonstration and Validation	Prototype hardware fabricated, assembled, bench-top tested with ongoing testing on the hydraulic test system	07/08/14
	Conceptual design approach demonstration pending for Fluid-End/Power-End separation	pending
	Candidate coatings identified; treatments pending	12/01/13
Critical Function Evaluation	Critical function evaluation underway with preliminary testing of prototype on DTS/ hydraulic fluid power fluid	pending
	Critical function evaluation pending on compressed air (nitrogen)	pending
	Critical function evaluation pending on water-based drilling fluid	pending

Future Directions

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- Planned milestones and go/no-go decisions for FY15 and beyond:

Milestone or Go/No-Go	Status & Expected Completion Date
- In FY15, motor design features will be evaluated using water-based mud and compressed air (nitrogen) as the drilling fluid power medium with test capability added to the Dynamometer Test Station to accommodate these fluids.	On-Track 9/30/15
- In FY16, development will commence on a high temperature compatible power section incorporating results of the drilling fluid critical function evaluations with the Dynamometer Test Station upgraded for high temperature evaluation.	On-Track 9/30/16
- In FY17, a prototype motor will be developed via design integration of the concept power section with a bearing pack to produce a fully-functioning downhole motor and tested in a laboratory drilling configuration for BHA readiness.	On-Track 9/30/17
- In FY18, field testing will commence to demonstrate motor performance under the rigors of geothermal drilling.	On-Track 9/30/18

Summary
High Temperature Downhole Motor

- Reliable downhole motors do not exist for geothermal drilling
  - PDM temperature limitations / Mud Turbines performance limitations
  - Steering options are limited requiring compromises in drilling plans and well completions
  - Directional drilling can be used to enable multi-lateral completions from a single well pad to improve well productivity and decrease environmental impact

- This project will develop and demonstrate a high temperature downhole rotation concept that can enhance geothermal drilling
  - Prototype Power Section designed, developed, demonstrated & critical function evaluation underway
  - Pathway to abrasion resistant, high temperature operation identified
  - Project on track to produce full-scale downhole motor for geothermal drilling by FY18