U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

High Temperature Downhole Motor

Project Officer: Lauren Boyd
Total Project Funding: $3,349k
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Sandia National Laboratories

Track 3 - EGS Tools

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Relevance to Industry Needs and GTO Objectives

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- 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
  - Positive Displacement Motors
    - Temperature limitations: 350F (177C) max
    - Introduce lateral vibration to BHA
    - Possible torque limitations for hard rock
  - Mud Turbines – Performance limitations: 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

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Project Overview

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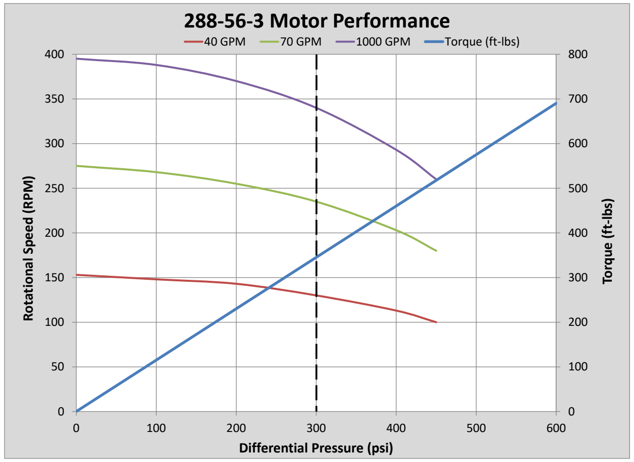
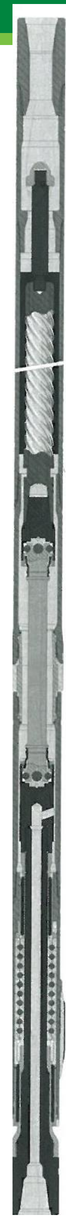
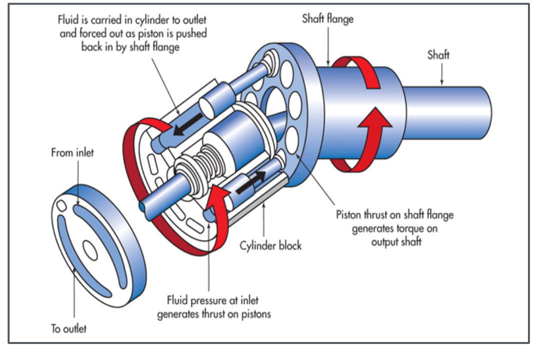
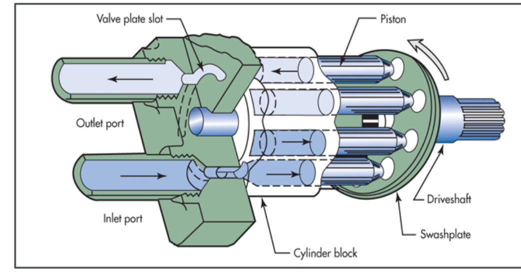


PDM per Toro Downhole Tools

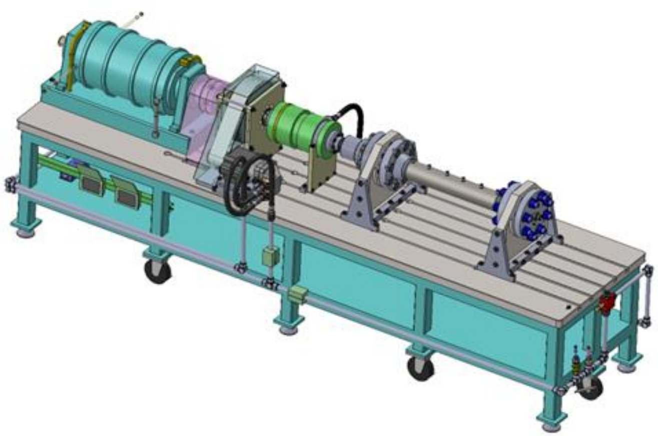


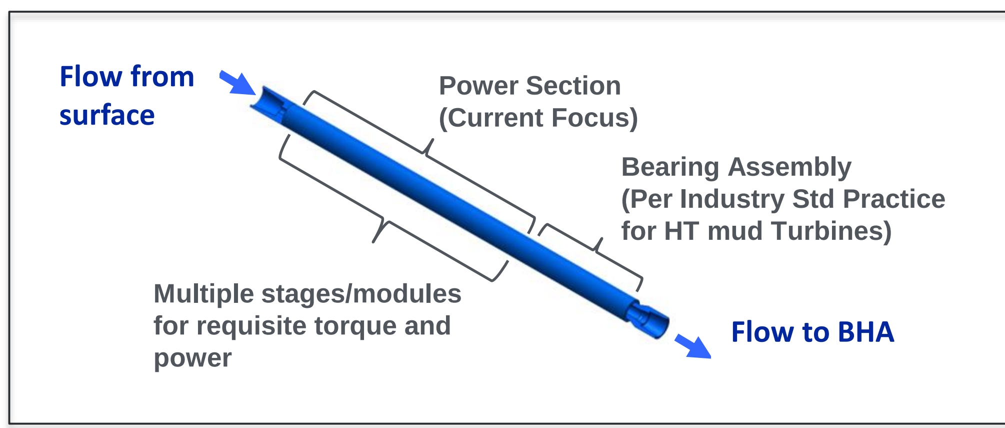




Bent-axis and inline swashplate hydraulic motor per Hydraulics & Pneumatics.com

Sandia Prototype Motor Concept **(U.S. Patent 9,447,798 B1)**





[Axial Motor Hardware Video]

Methods/Approach

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Work Scope

- Task 1 - Project Management
  - Stewardship of DOE/EERE funding towards developmental motor concept
  - Facilitate industry partnerships and commercial licensing opportunities
- 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

Technical Accomplishments and Progress:
Task 2 / Requirements Definition

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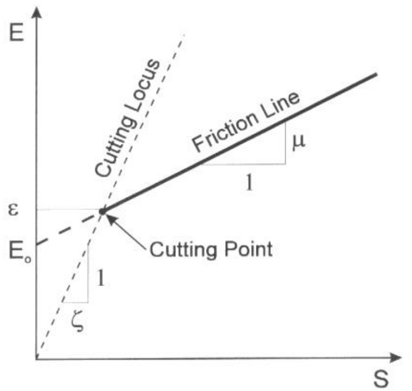
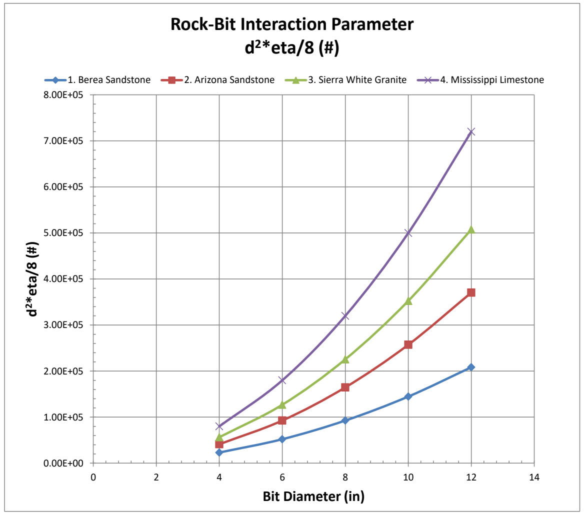
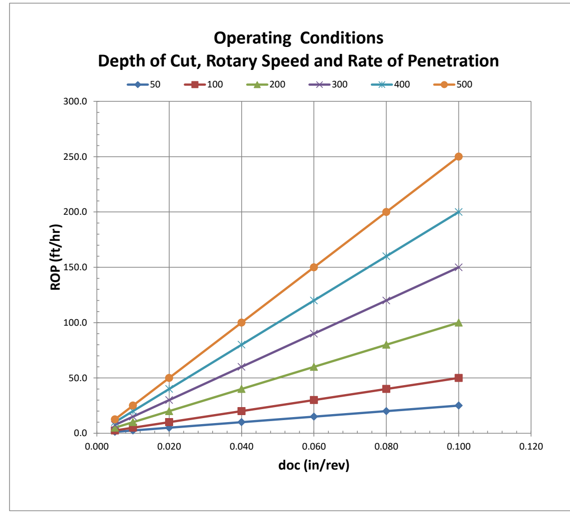
Rock Bit Interaction Analysis for formation suitability

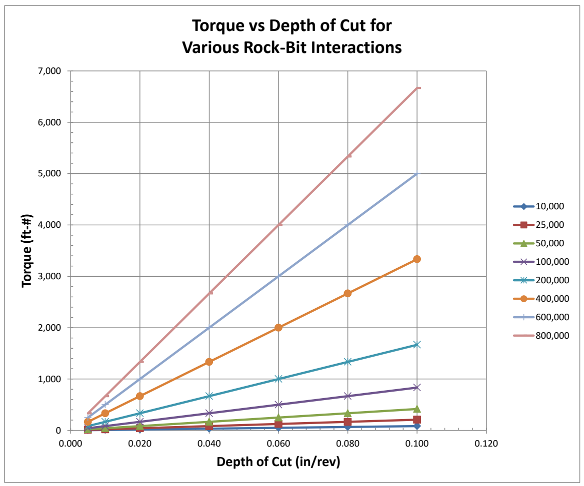
(Ref: Detournay, 1992)

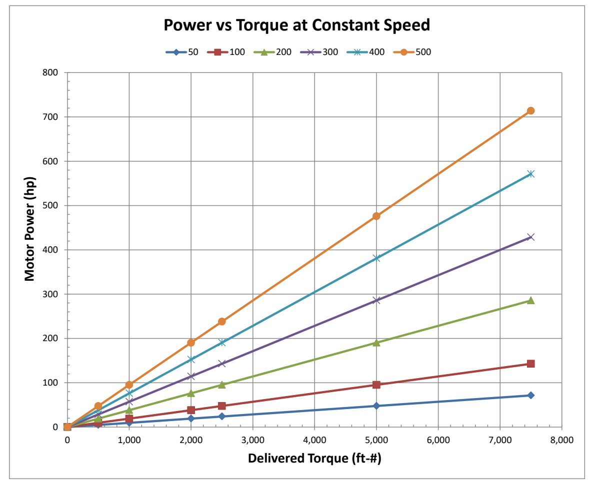


$$E = \frac{2T}{r^2\delta} \qquad S = \frac{W}{r\delta}$$







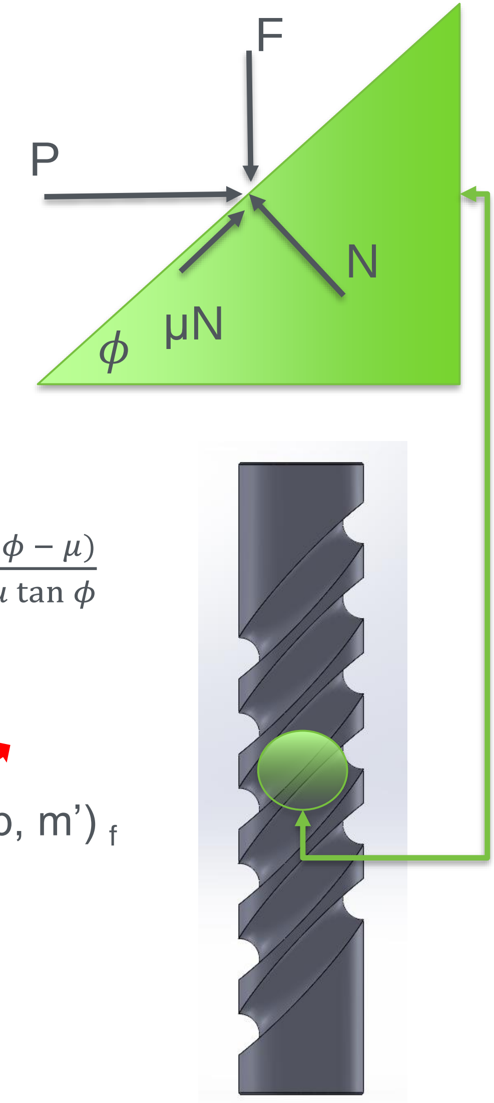


NOV/Sandia Test Bit, Dec 2011

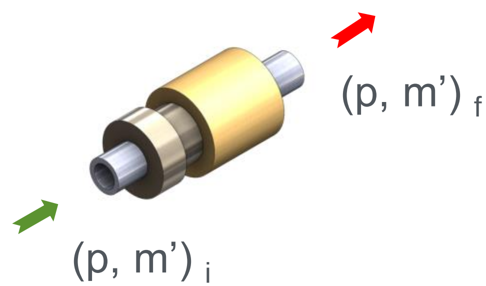
Compare to Survey of existing PDM Motors Torque & Power Profile

Prototype Power Section Developed and Demonstrated

- 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
  - Design Intent
    - Allow fluid leakage / no seals
    - Low friction surfaces at piston interfaces
    - Removable Rotor Assembly
    - Case/Rotor Design Integration
    - Pressure/Exhaust Manifold Integration
    - Piston Motion / Valve Port Integration



$$T = Pr = Fr \frac{(\tan\phi - \mu)}{1 + \mu \tan\phi}$$

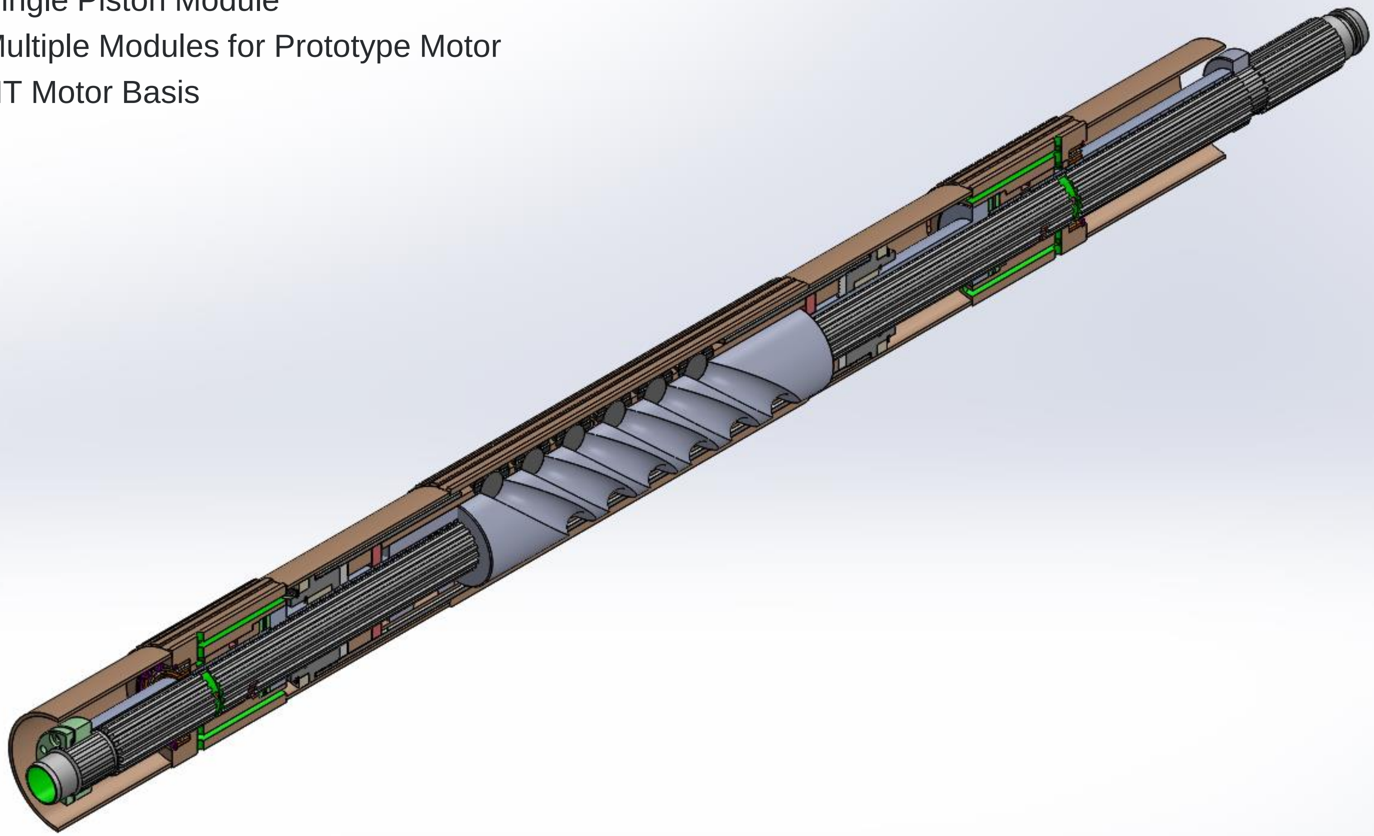


U.S. Patent 9,447,798B1 from U.S. Patent Application No. 14/209,840, filed 3/13/2014; CIP of U.S. App. No. 14/298,377, filed 05/05/2014 and U.S. Provisional Patent Application No. 62/142,837, filed 4/3/2015.

Technical Accomplishments and Progress:
Task 3 & 4 / Power Section Design

AXIAL PISTON PROTOTYPE MODULE

- Module Design - Axial Piston Configuration
  - Single Piston Module
  - Multiple Modules for Prototype Motor
  - HT Motor Basis



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Technical Accomplishments and Progress:
Task 3 & 4 / Power Section Design

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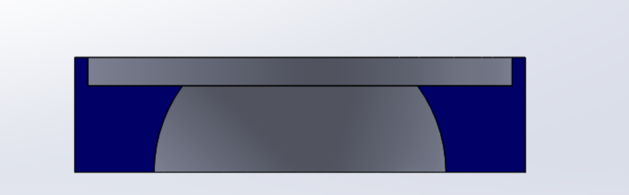
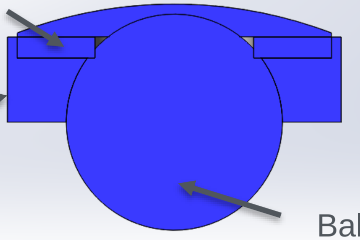
Ball Transfer

- Allows retainer to remain centralized in Piston/Ring
- React side loads from single harmonic system
- Centralize retainer with respect to harmonic drive rotor
- Tungsten Carbide PCD Die
- PCD on Rotating Ball Surface (μ=0.1)



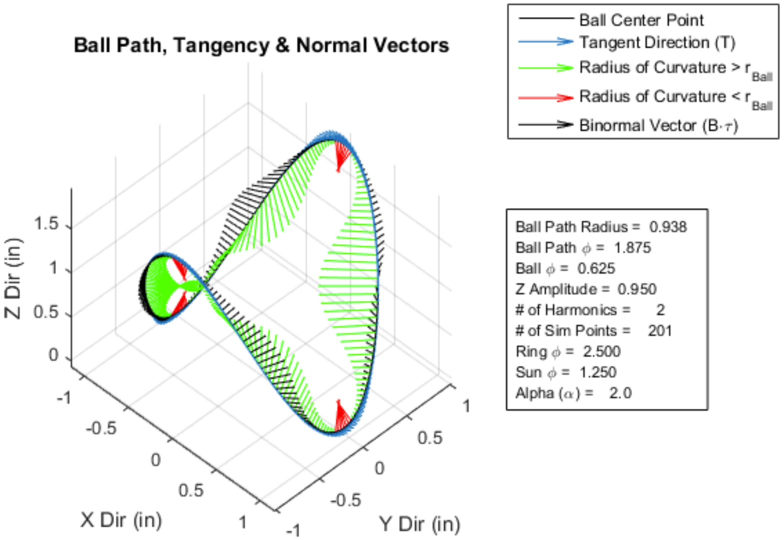
PCD Wire Die



Patent Pending
U.S. Patent App. No. 15/15726506, Ball Transfer Mechanism with Polycrystalline Diamond Bearing Support

Advanced Harmonic Drive (AHD)

- Specify ball track on rotor and piston/ring for ball rotation with no slipping
- Developed Frenet-Serret frames for analysis
- Identify design constraints between harmonic amplitude, ball & track diameters



Patent Pending
SD-14556 - Harmonic Drive for Converting Reciprocating Axial to Continuous Rotary

Technical Accomplishments and Progress:
Task 3 & 4 / Power Section Design

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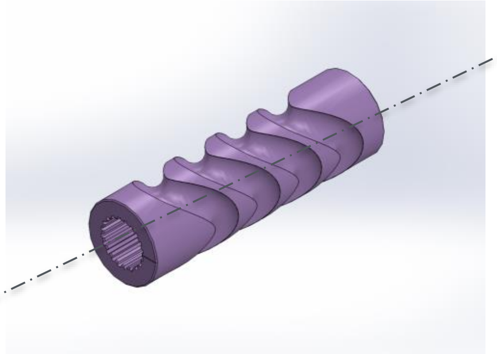
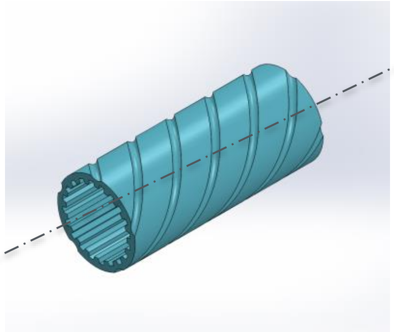
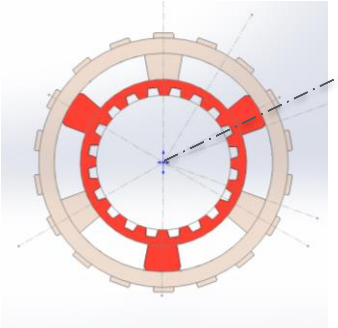
ROTARY PISTON PROTOTYPE MODULE

- Rotary Piston Configuration with Torque Inverter
  - Accommodates drilling fluids
  - Generates high torques
  - Dual Rotor System
  - Single Stage Module
  - Serial Connect Multiple Modules for Full
  - HT Prototype Motor Basis







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Technical Accomplishments and Progress:
Task 5 / Computational Modeling & Analysis

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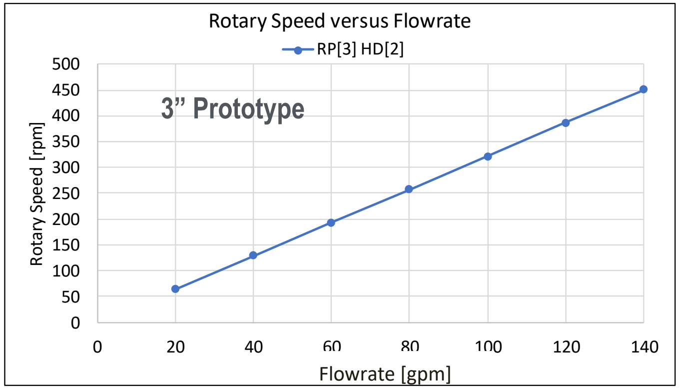
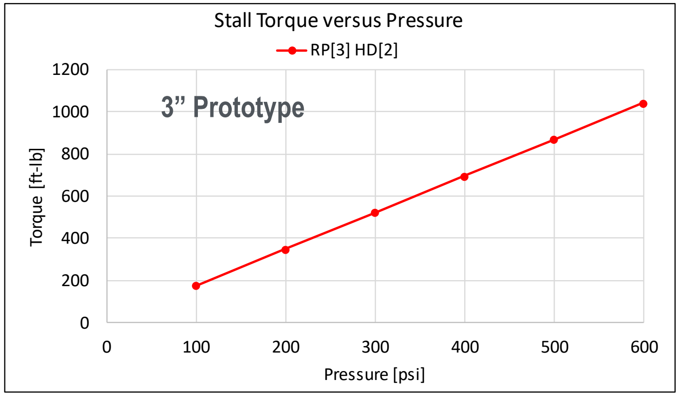
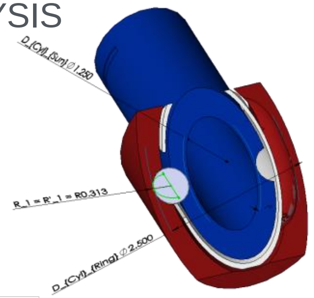
TORQUE & ROTARY SPEED ANALYSIS





CONTACT STRESS ANALYSIS



If:

E_* – Elastic Modulus of Material for Body 1 or 2

v_* – Poisson's Ratio of Material for Body 1 or 2

R_* – Principal Radii of curvature of Body 1 and 2

R'_* –Radii of curvature of Body 1 and 2 in a direction orthogonal to R_x

F_s – Total applied load

Geometrical Constant:

$$K_{d_1} = \frac{1.5}{\frac{1}{R_{1_1}} + \frac{1}{R'_{1_1}} + \frac{1}{R_{Cyl\,1}} + \frac{1}{R_{2'1}}}$$

Material Constant:

$$Ce_1 = \frac{1-\nu_{1_1}^{\;2}}{E_{1_1}} + \frac{1-\nu_{2_1}^{\;2}}{E_{2_1}}$$

θ describes the degree of contact between the two bodies:

$$\cos\Theta = \frac{K_d}{1.5}\cdot\sqrt{\left(\frac{1}{R_1}-\frac{1}{R'_1}\right)^2 + \left(\frac{1}{R_{Cyl}}-\frac{1}{R'_2}\right)^2 + 2\cdot\left(\frac{1}{R_1}-\frac{1}{R'_1}\right)\cdot\left(\frac{1}{R_{Cyl}}-\frac{1}{R'_2}\right)\cdot\cos\left(2\cdot\phi\right)}$$

cos(θ) is used to calculate the size of the elliptical contact (c & d)

$\cos\theta$	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.75	0.80	0.85	0.90	0.92	0.94	0.96	0.98	0.99
α	1.000	1.070	1.150	1.242	1.351	1.486	1.661	1.905	2.072	2.292	2.600	3.093	3.396	3.824	4.508	5.937	7.774
β	1.000	0.936	0.878	0.822	0.769	0.717	0.664	0.608	0.578	0.544	0.507	0.461	0.438	0.412	0.378	0.328	0.287
λ	0.750	0.748	0.743	0.734	0.721	0.703	0.678	0.644	0.622	0.594	0.559	0.510	0.484	0.452	0.410	0.345	0.288

$$c = \alpha\cdot\left(\frac{F\cdot K_{d_1}\cdot Ce_1}{1}\right)^{\frac{1}{3}}$$

$$d = \beta\cdot\left(\frac{F\cdot K_{d_1}\cdot Ce_1}{1}\right)^{\frac{1}{3}}$$

Maximum Contact Pressure:

$$\sigma_{c\,max} = \frac{1.5\cdot F}{\pi\cdot c\cdot d}$$

Solution of the above for the 2nd generation prototype geometry (0.688" diameter ball) and tungsten carbide mating materials results in a maximum contact load of 4460 lbf.

Control Volume – Conservation of Mass

The instantaneous mass within the piston bore is

$$M = \rho V$$

The fluid mass time rate of change is

$$\frac{dM}{dt} = \frac{d\rho}{dt} V + \rho \frac{dV}{dt}$$

where

$$\frac{dM}{dt} = \rho\, Q = \dot{m}_{in} - \dot{m}_{out}$$

From the definition of Bulk Modulus,

$$\beta = \rho \frac{dP}{dp}$$

then,

$$\frac{dM}{dt} = \rho\, Q = \frac{\rho}{\beta} \frac{dP}{dt} V + \rho \frac{dV}{dt}$$

$$\frac{\rho}{\beta} \frac{dP}{dt} V = \rho\, Q - \rho \frac{dV}{dt} = \rho\left(Q - \frac{dV}{dt}\right)$$

$$\frac{dP}{dt} = \frac{\beta}{V}\left(Q - \frac{dV}{dt}\right)$$

Using $\omega = \frac{d\theta}{dt}$ and the chain rule for $\frac{dV}{dt} = \frac{dV}{d\theta}\frac{d\theta}{dt}$

Then the pressure on the piston as a function of rotary angle is

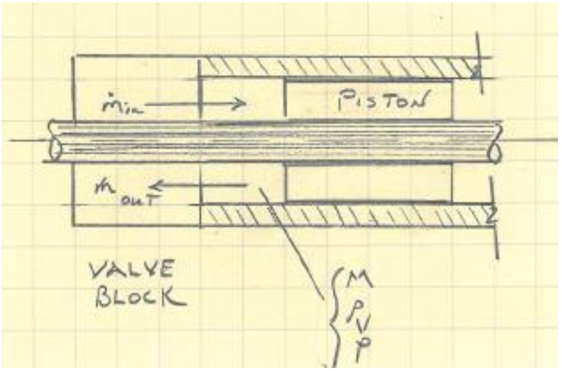
$$\frac{dP}{dt} = \frac{dP}{d\theta}\frac{d\theta}{dt} = \frac{\beta}{V}\left(Q - \frac{dV}{d\theta}\frac{d\theta}{dt}\right)$$

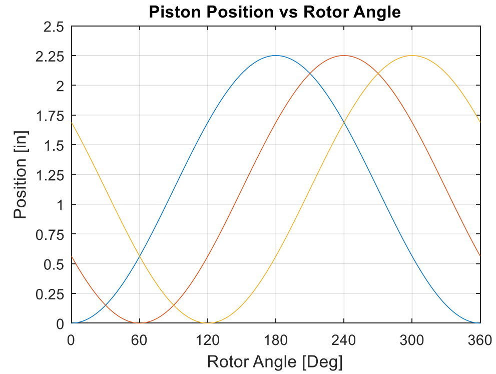
and

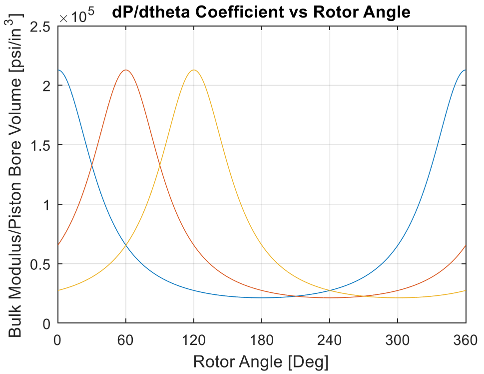
$$\frac{dP}{d\theta} = \frac{\beta}{V}\left(\frac{Q}{\omega} - \frac{dV}{d\theta}\right)$$

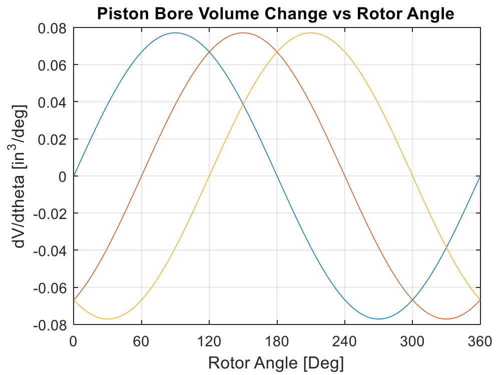
Fluid Power Cycle Modeling

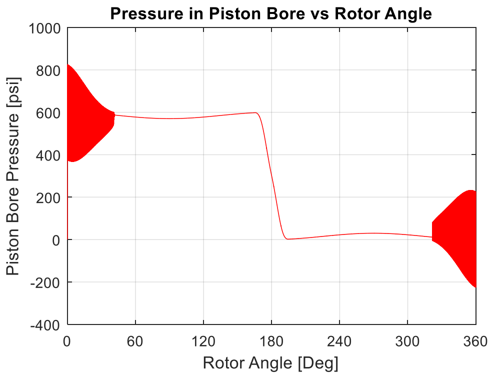
- Use to address coupling between fluid mechanics and reciprocating pistons
- Investigate influence of valve geometry and timing on motor performance











Task 6 / Prototype Demonstrations

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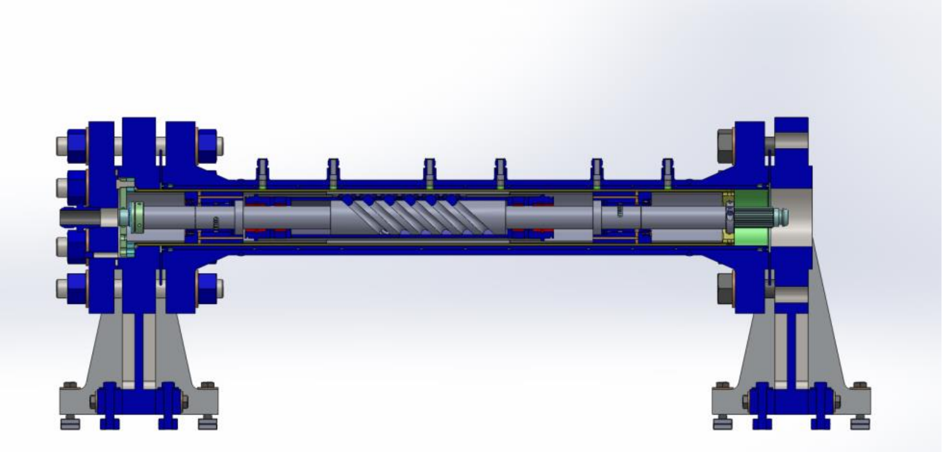
Approach

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

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
- Prototype Motors
  - 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
- PDM to be tested for side- by-side comparison with prototype motor



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Technical Accomplishments and Progress

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Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Conceptual, Preliminary and Detailed Power Section Design	Performance requirements for geothermal drilling identified by rock bit interaction analysis	Pre-FY16
	Operational performance requirements for various motor sizes identified by survey of existing downhole motor products	
	Preliminary/prototype design developed for 3" diameter axial piston motor incorporating key features in eventual downhole piston motor concept	
Power Section developed for Fluid-end/Power-end separation.	Complete	3/31/2016
Qualified design of Advanced Harmonic Drive for Critical Function Evaluation (CFE) and Proof of Concept (POC) Demonstration	Complete - additional static/dynamic characterization underway	3/31/2017
Test Platform Design & Development	Preliminary dynamometer test system in place to accommodate laboratory evaluations	Pre-FY16
	Dynamometer Test Station proven on industry standard piston motor	
	Hydraulic fluid power flow loop developed with pressure vessel/motor housing, rotating head and swivel	
	Compressed air (Nitrogen) test system designed and developed	
	Water-based drilling fluid test system designed; development underway	
Water-based drilling fluid test system commissioned.	High Pressure pump on order; flow loop comissioning pending	pending
Prototype Development, Demonstration and Validation	Prototype hardware fabricated, assembled, bench-top tested with ongoing testing on the hydraulic test system	Pre-FY16
	Conceptual design conceived; demonstration pending for Fluid-End/Power-End separation	
	Prototype design developed including material formulations, assembly methods and operational specifications	
SMART Milestone - Demonstrate a motor performance metric of 250 ft-lb of torque delivery at a 600 psi pressure differential and 90 RPM of rotary speed at 20 gallons per minute flow rate when running the 3 inch diameter prototype section on water-based drilling fluids on the Dynamometer Test Station.	Prototype hardware released for fabrication - testing will commence in early FY18	pending
Complete component fabrication, sub-assembly checkout and assembly integration of prototype power section with Advanced Harmonic Drive	Pending - AHD will be integrated into helical drive following prototype demonstration using ball transfers	pending
Critical Function Evaluation	Preliminary testing of first generation prototype on DTS using hydraulic fluid power fluid	Pre-FY16
Critical Function Evaluation of Power Section on Hydraulic Fluid, H2O & N2 including sub-assembly compatibility evaluation with water-based mud	CFE on Hydraulic Fluid, H2O and N2 pending completion of prototype hardware POC	pending
Critical Function Evaluation of power section on water-based drilling fluid.	Commence following integration of diamond bearings in FY18	pending
High Temperature Proof Of Concept Demonstration of prototype power section operating on N2 power fluid with representative drilling brake horsepower applied	Complete following CFE of diamond bearings in FY18	pending

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Research Collaboration and Technology Transfer

- Industry and/or academic engagement
  - Radigan Engineering, Design Services & Analytical Support
  - US Synthetic
    - Ball Transfer Direct Sintering
    - PCD Bearings

- Opportunities or efforts currently underway to transition technology to the private sector
  - Marathon Oil - Technical Interchange Meetings
  - Technology To Market (T2M) Initiative

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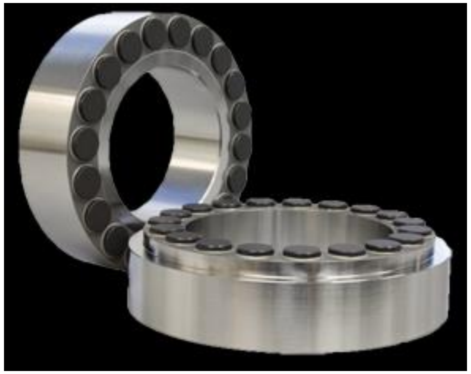
Future Directions

- FY18
  - Demonstrate prototype axial and rotary piston module/motor on hydraulic fluid
  - Upgrade motor with diamond bearings & evaluate using water-based fluids and compressed air (nitrogen) with test capability added to Dynamometer Test Station to accommodate these fluids
- Long-Term / Out-years
  - Critical function evaluation of power section with the Dynamometer Test Station upgraded for high temperature evaluation
  - Develop prototype downhole motor via design integration of prototype power section with a bearing pack & test in laboratory drilling configuration for BHA readiness
  - Field testing to demonstrate motor performance under rigors of geothermal drilling



Diamond Bearings per US Synthetic

Milestone or Go/No-Go	Status & Expected Completion Date
Qualified design of Prototype Power Section incorporating diamond bearings	1/31/2018
Complete component fabrication, sub-assembly checkout and assembly integration	3/31/2018
Critical Function Evaluation of Power Section using diamond bearings on Hydraulic Fluid, H20 & N2	9/30/2018

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Summary

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- Reliable downhole motors do not exist for geothermal drilling
  - PDM temperature/vibration limitations; Mud Turbines performance limitations
  - An improved motor concept is needed:
    - overcome temperature limitations
    - mitigate drillstring vibrations
  - 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 introduce a high temperature downhole rotation concept
  - Prototype Power Section designed, developed, demonstrated & critical function evaluation underway
  - Pathway to abrasion resistant, high temperature operation identified
  - Project will develop prototype to technology transfer level
  - Work with commercial partner to produce full-scale downhole motor for geothermal drilling

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