Two-Speed Rotorcraft Research Transmission Power-Loss Associated with the Lubrication and Hydraulic Rotating Feed-Through Design Feature

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Topics

- **Background – why are we doing this?**
- **Modular inline concentric two-speed research transmission configuration**
- **Rotating Feed-Through (RFT) design feature**
    - **RFT System (Shaft and RFT) in the two-speed transmission**
    - **Isolated RFT power loss experiment and results**
    - **Conclusions and future RFT development**

Background

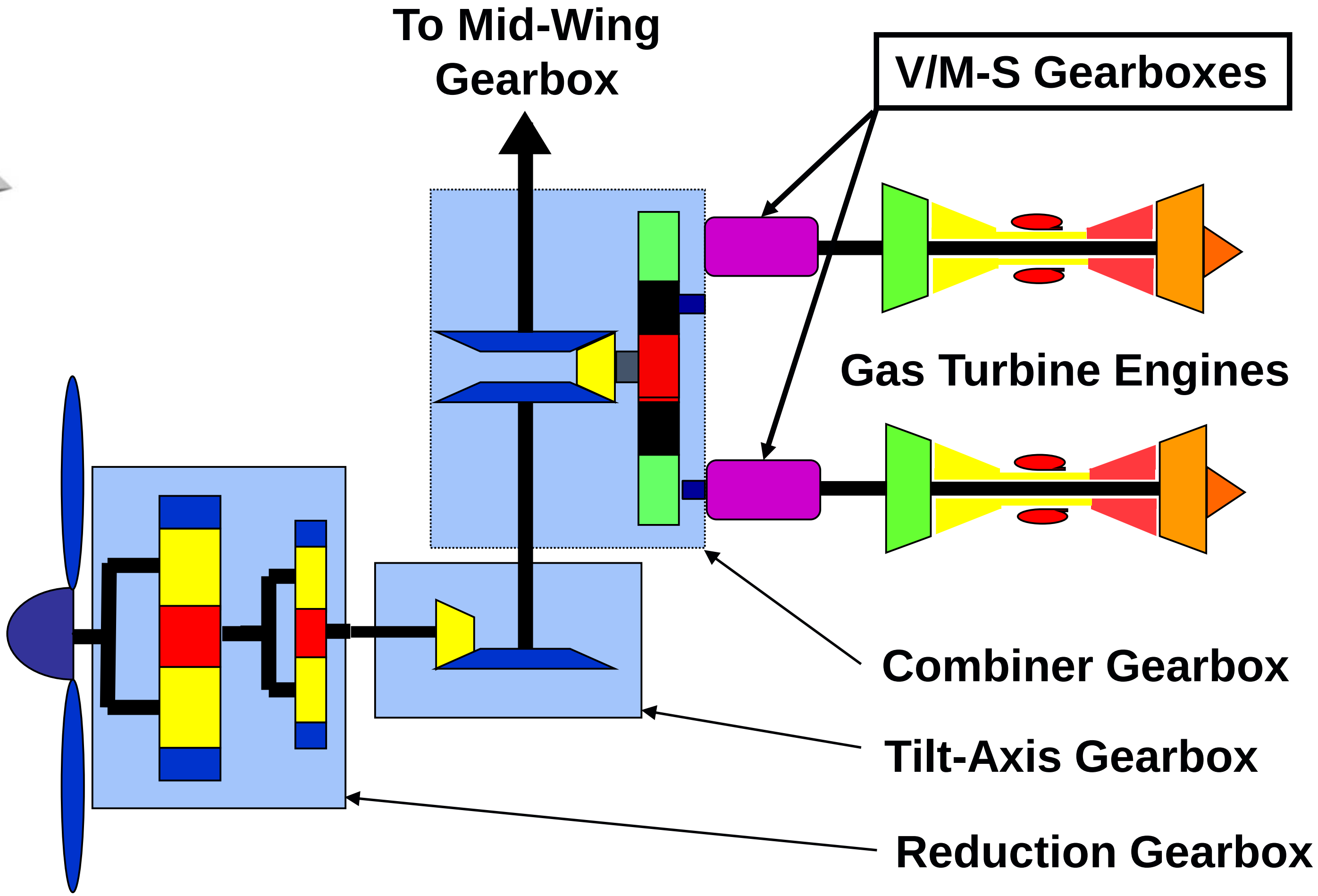
- **Advances in rotorcraft propulsion systems require increased efficiency, power, and enhanced capabilities**

- **Studies show that *variable/multi-speed rotors* are required for:**
  - **Enhanced capabilities: increased speed, payload, and range**
  - **Reduction in noise**

Advances require varying rotor speed up to 50%.

<u>Present Limitations</u> ~15% via engine output shaft speed control.

Future Rotorcraft Propulsion System Configuration, Variable/Multi-Speed Gearbox Application



Hover Ratio 131.4 : 1 Cruise Flight Ratio 243.6 : 1

Two-Speed Research Transmission Design Requirements

- 250 HP nominal (200 HP facility capacity)
- Inline concentric configuration
- Input Speed 15,000 rpm
- Output Speeds 15,000 rpm (hover), 7,500 rpm (cruise)
- Lubricant: DOD-PRF-85734A, synthetic ester-based oil
- Drive should fail safe to the high-speed (hover) mode
- Employ straight spur gear geometry
- [a] Provide high-speed positive drive locking-element
- [a] Light-weight rotating components (flight like)
- [b] Housing design (modular, possibility of windage shrouds)

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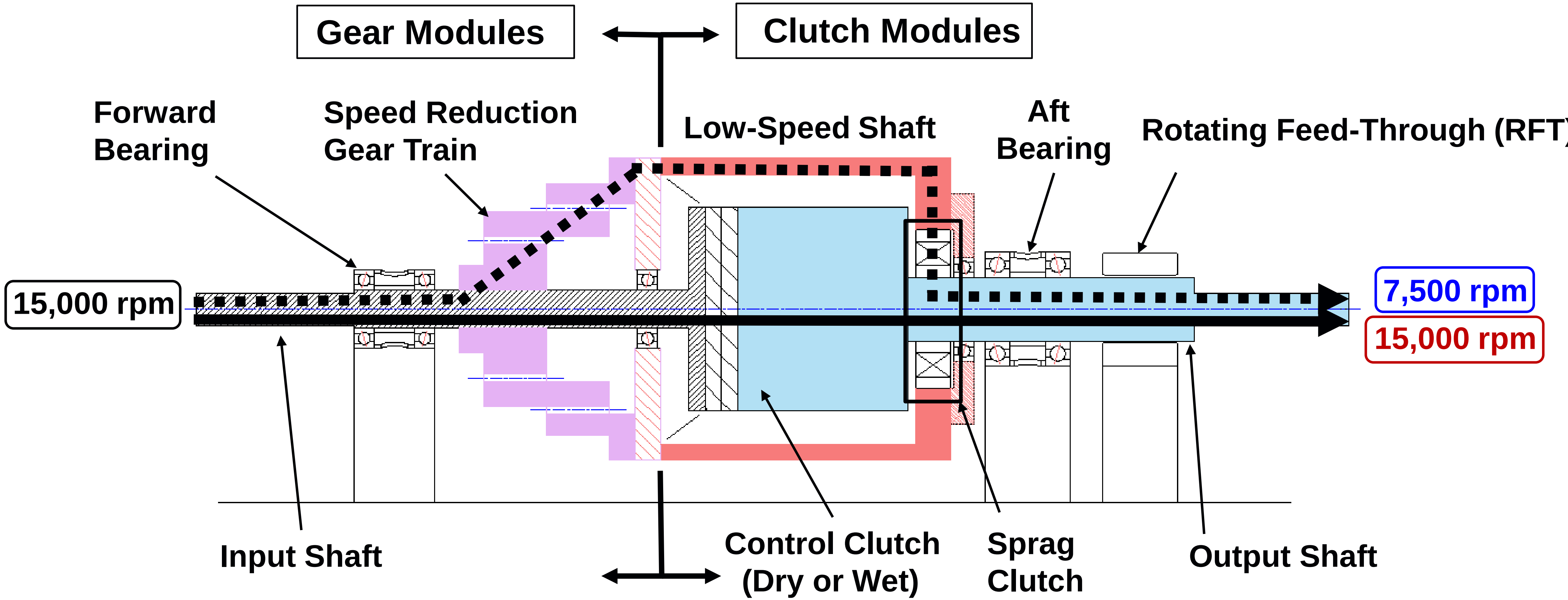
[a] *requirement dropped*

[b] *not an original requirement*

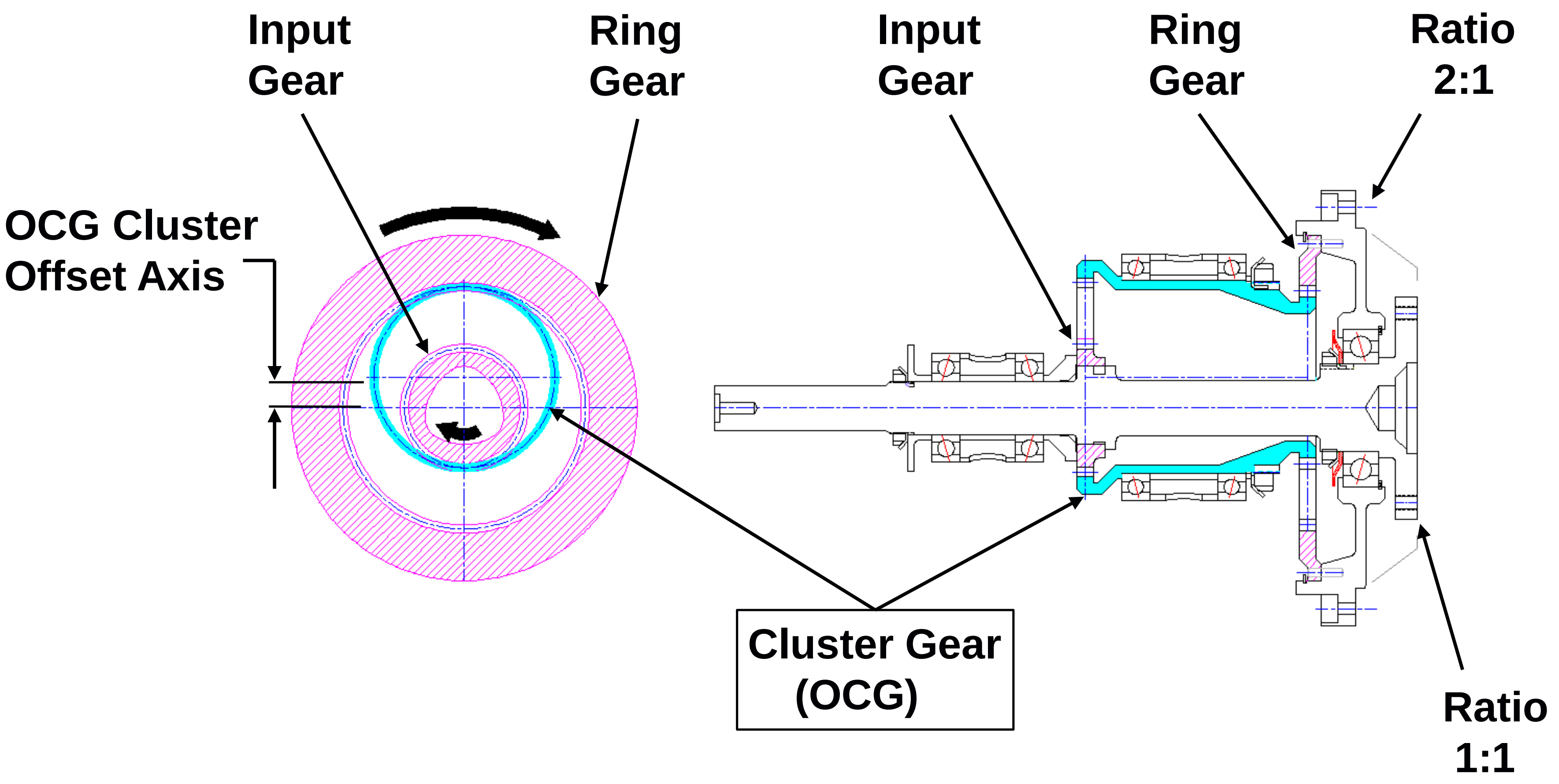
Research Transmission Modules: Gear & Clutch



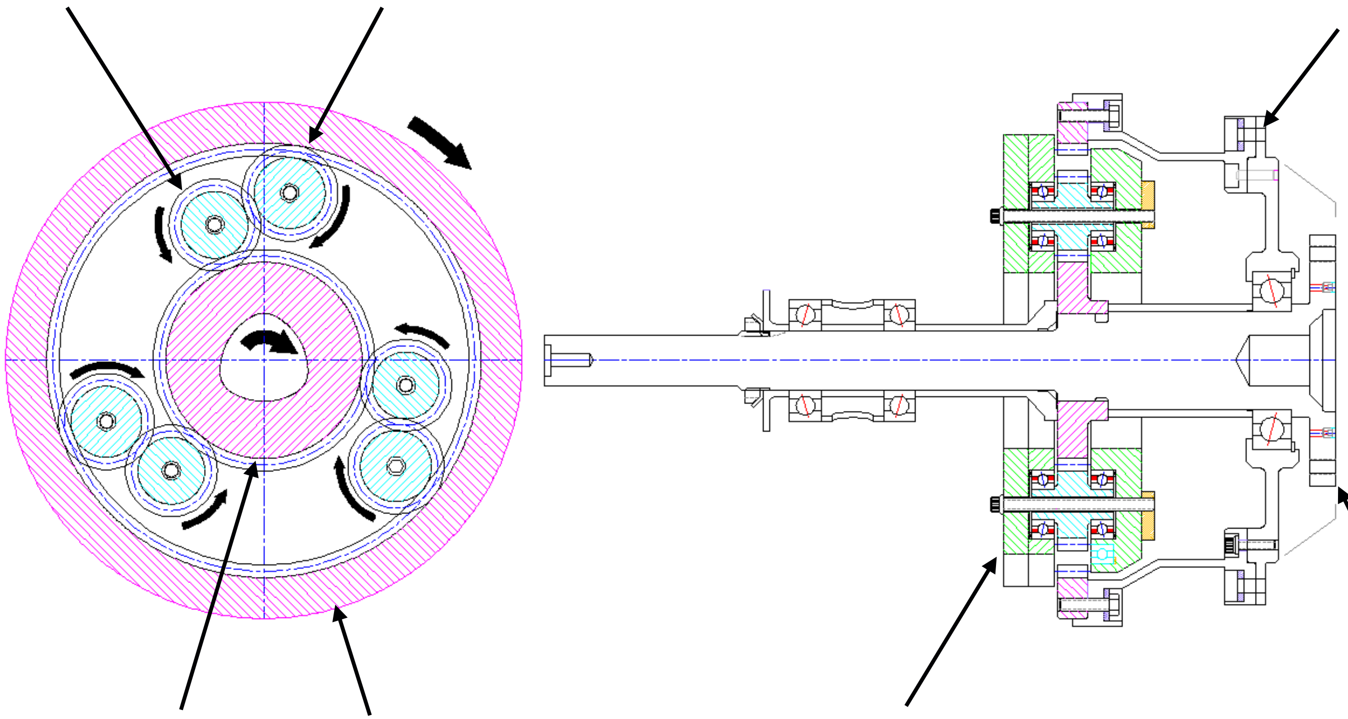
1:1 Direct Drive (Hover Mode)
Control Clutch Engaged

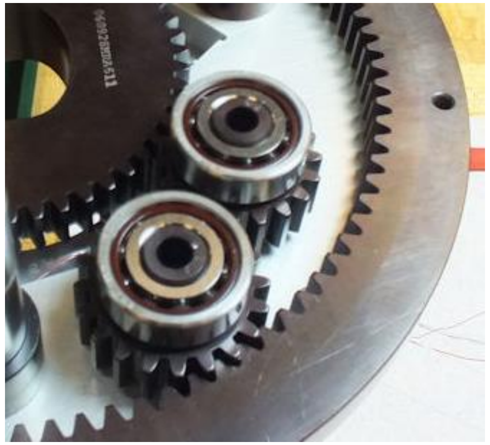
2:1 Reduction Drive (Cruise Mode)
Control Clutch Disengaged

Gear Module 1: Offset-Compound Gear (OCG)

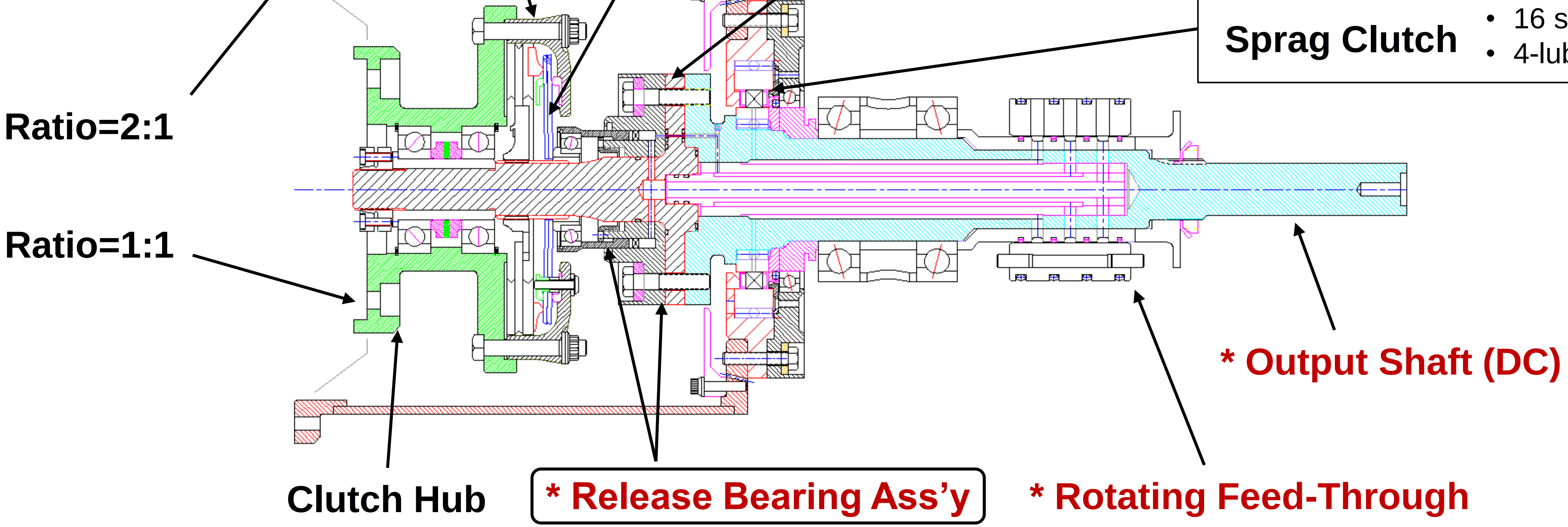


Gear Module 2: Dual Star-Idler Planetary (DSI)





Clutch Module: Dry-Clutch (DC)

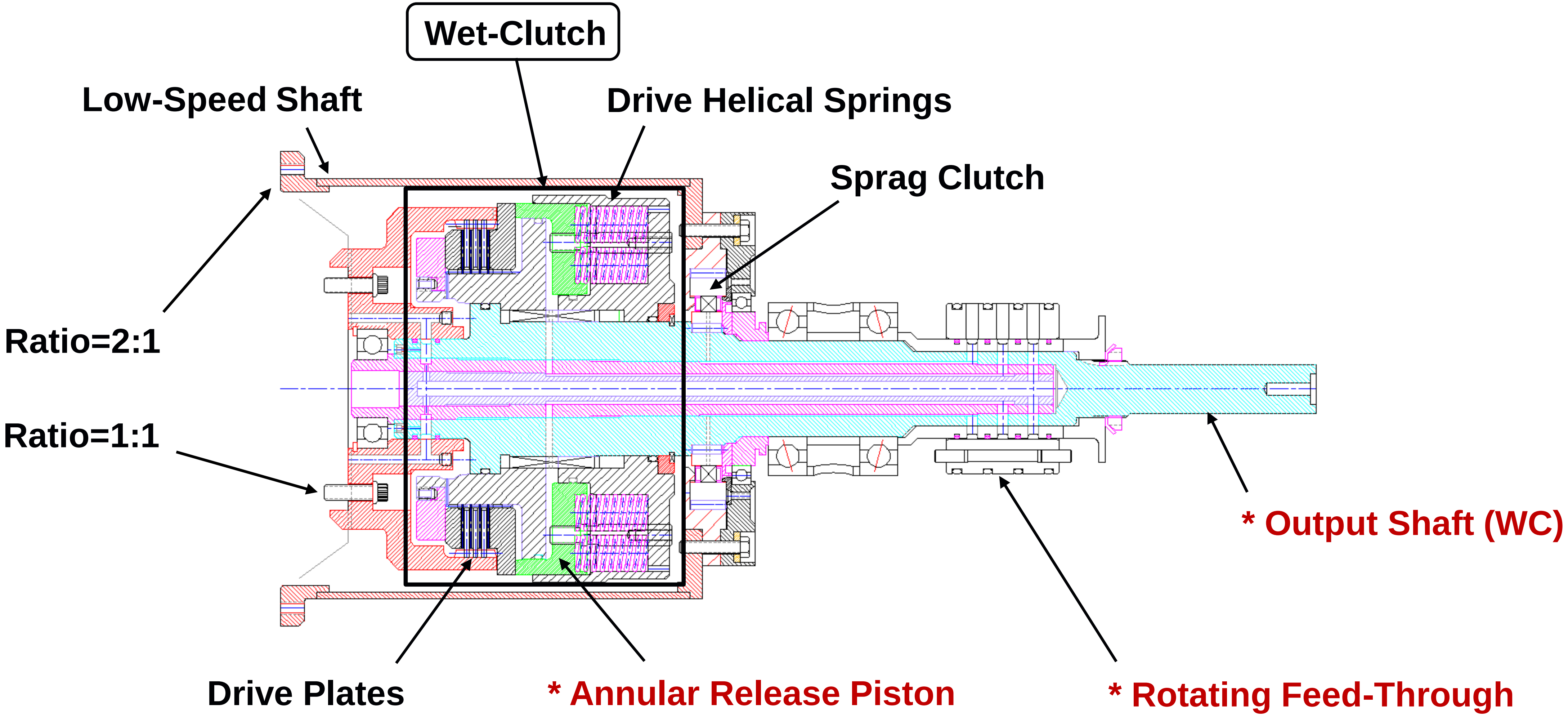


Sprag Clutch

- 16 sprag elements
- 4-lube inlets/drains

* Unique hardware necessary to meet the inline design requirement

Clutch Module: Wet-Clutch (WC)



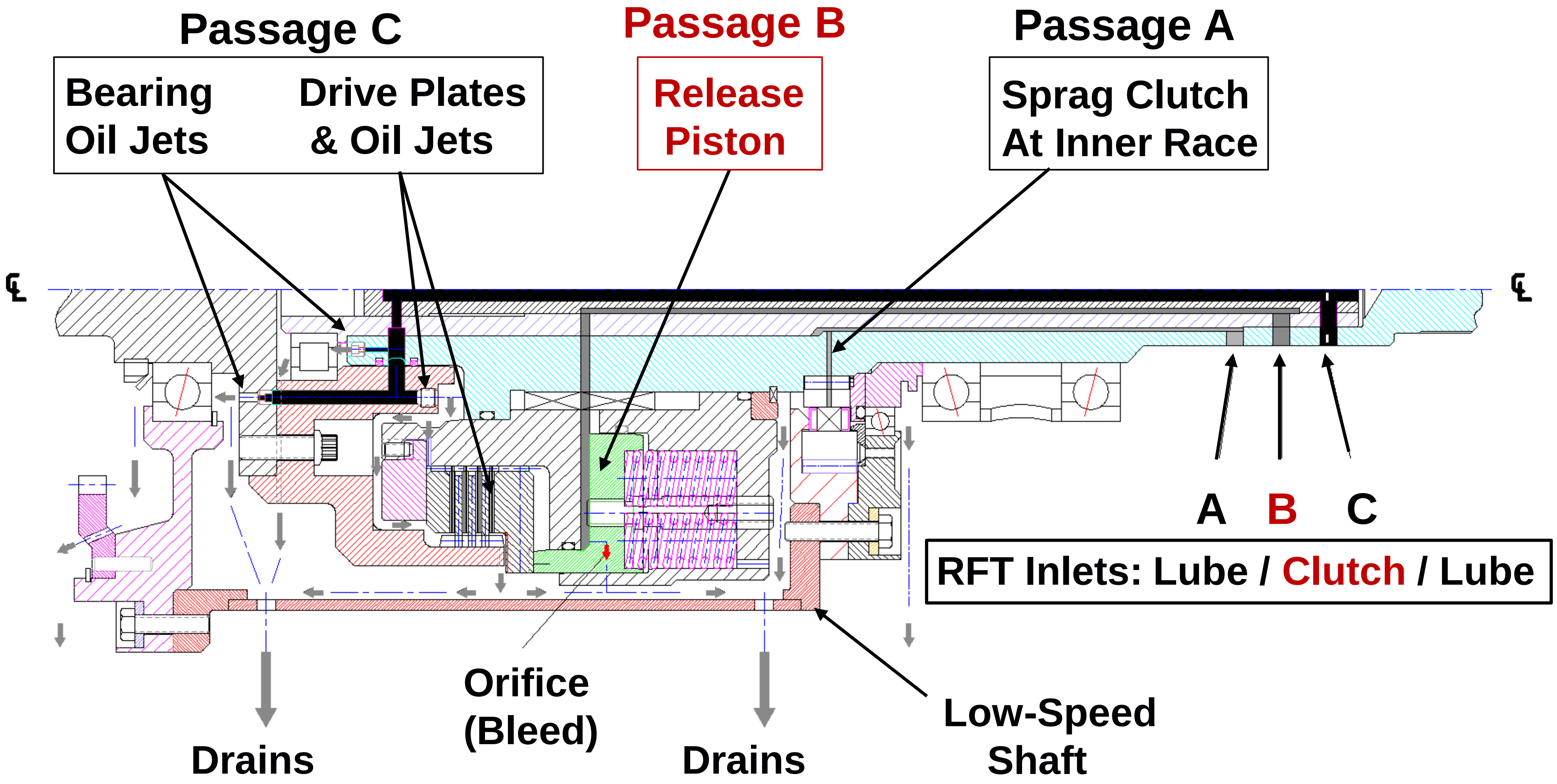
* Unique hardware necessary to meet the inline design requirement

Rotating Feed-Through (RFT) Design Feature

Output Shaft and RFT in the Two-Speed Transmission
Power Loss Experimental Setup
Power Loss Experimental Results

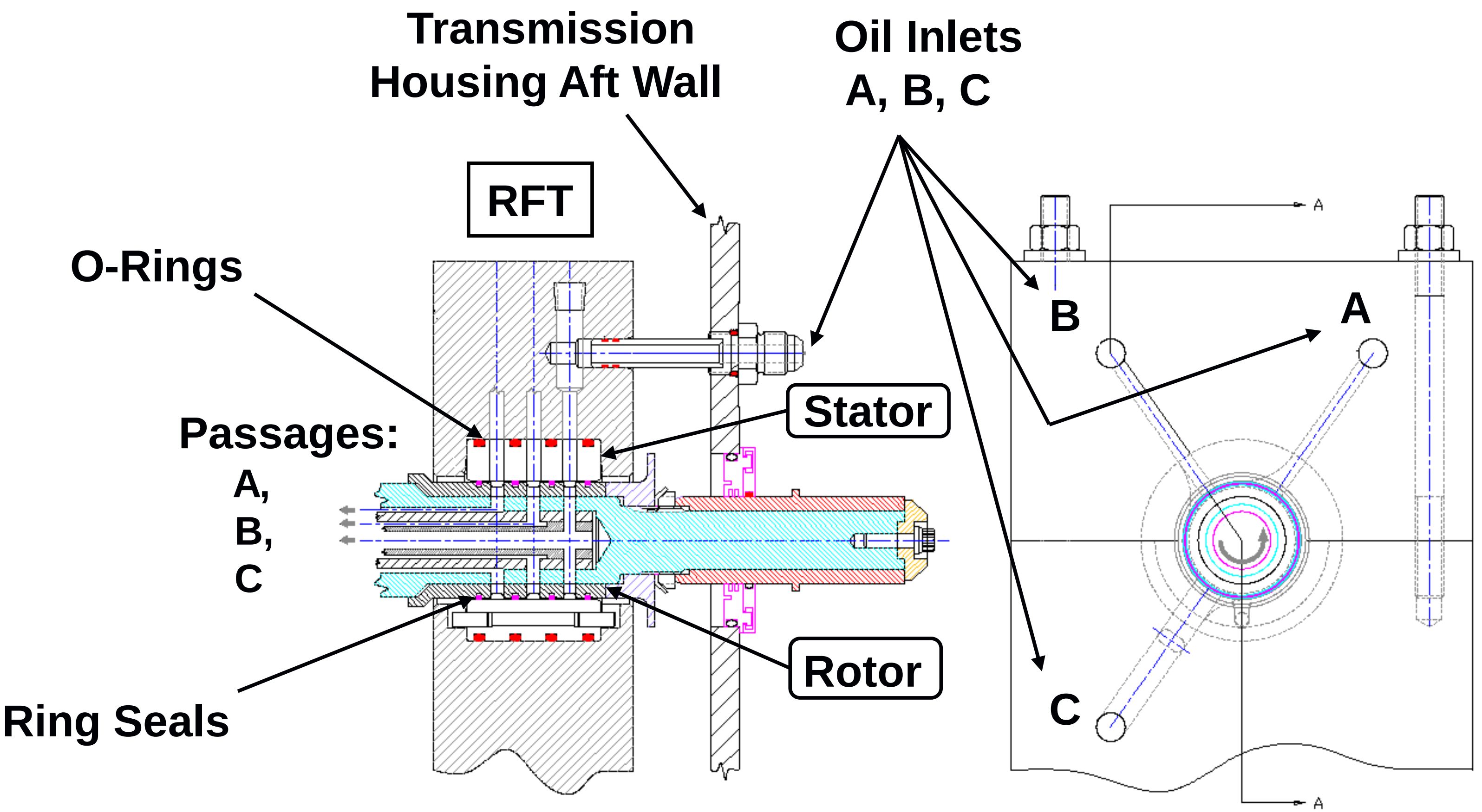
Output Shaft* - Hydraulic & Lubrication Passages

(Wet-Clutch Shown)

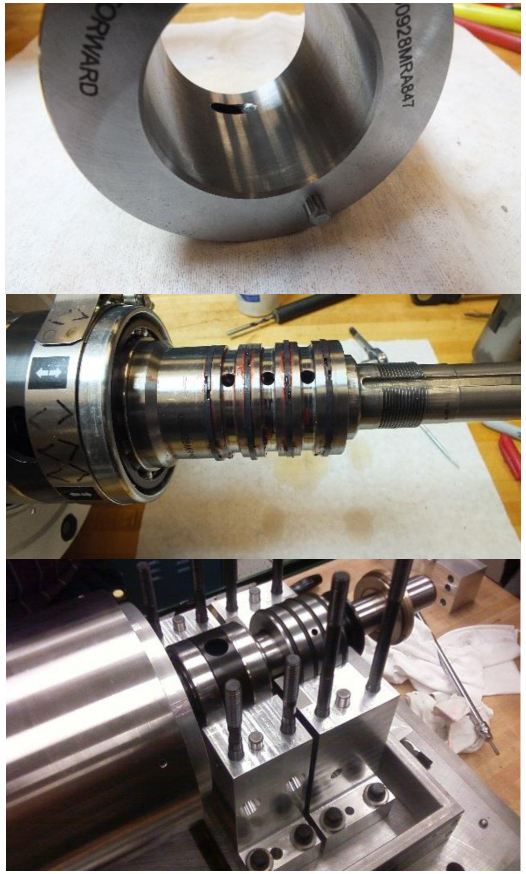


* Unique hardware necessary to meet the inline design requirement

Hydraulic/Lubricant Rotating Feed-Through (RFT*)

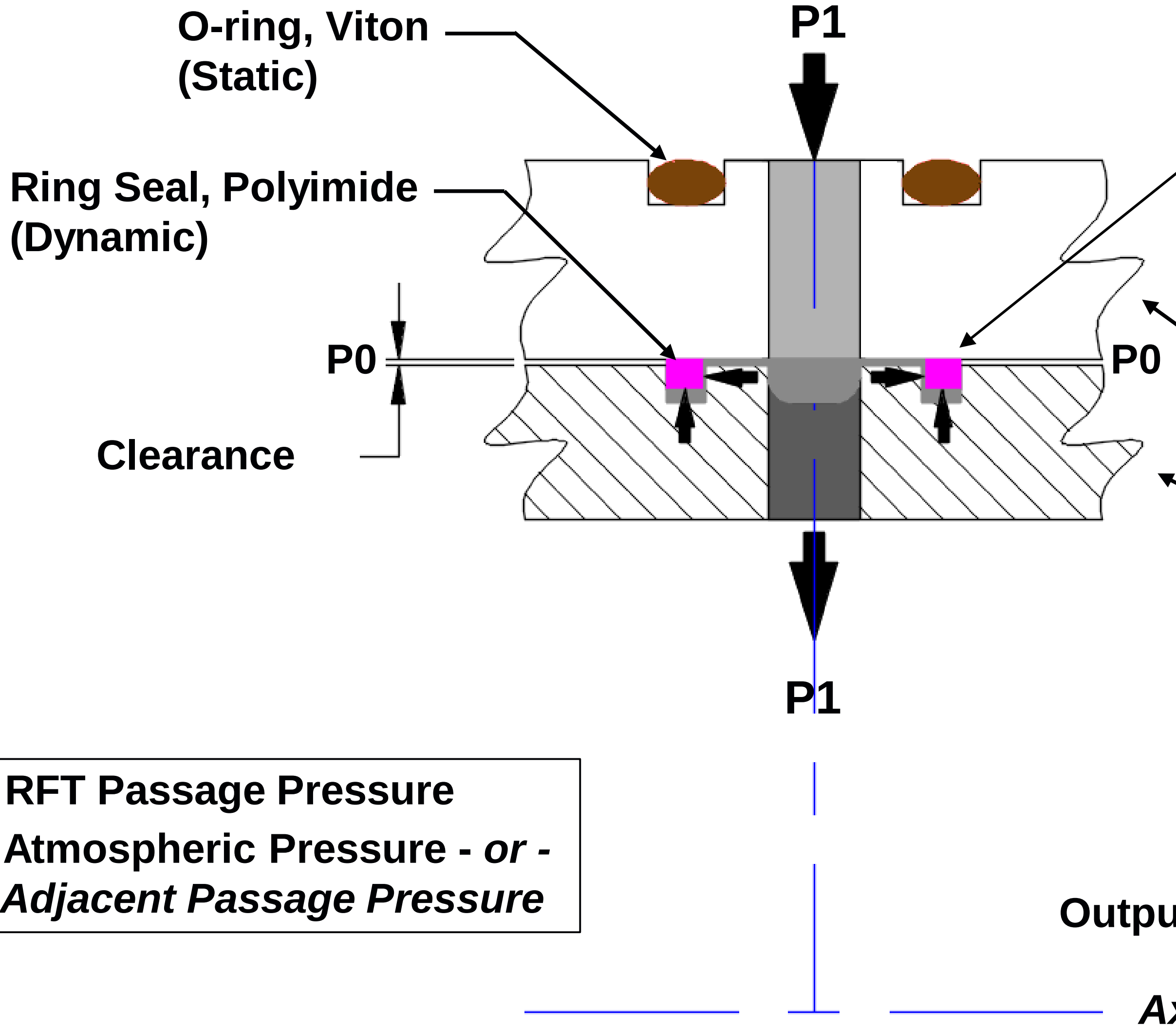


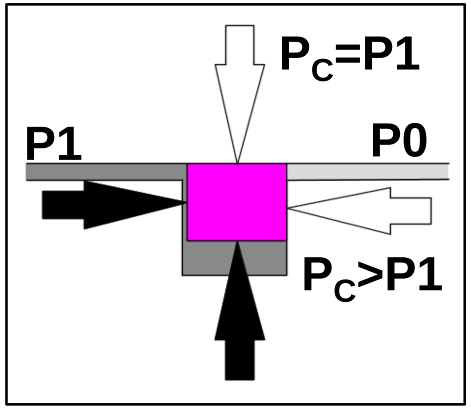
- Ring Seals
- 15,000 rpm Max



* Unique hardware necessary to meet the inline design requirement

RFT Example Single Passage Pressures, Speeds, Velocities





Pressures & Reactions

Stator **0 rpm**

Rotor **15,000 rpm Maximum Shaft Speed**

1,571 in/s (40 m/s) Ring Seal Side Surface Velocity

(Ref: 2 inch nominal diameter)

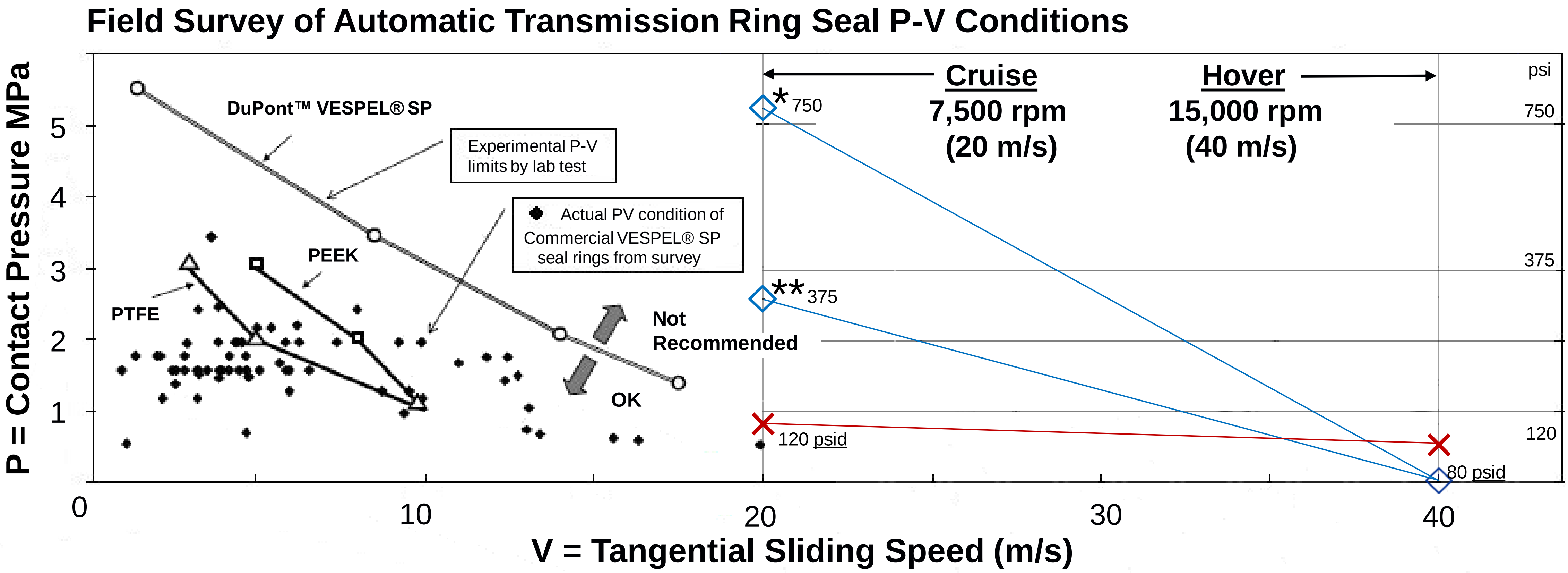
P1 – RFT Passage Pressure

P0 – Atmospheric Pressure - *or - Adjacent Passage Pressure*

Output Shaft Not Shown

Axis of Rotation

RFT Seal Pressure and Speed Operating Points

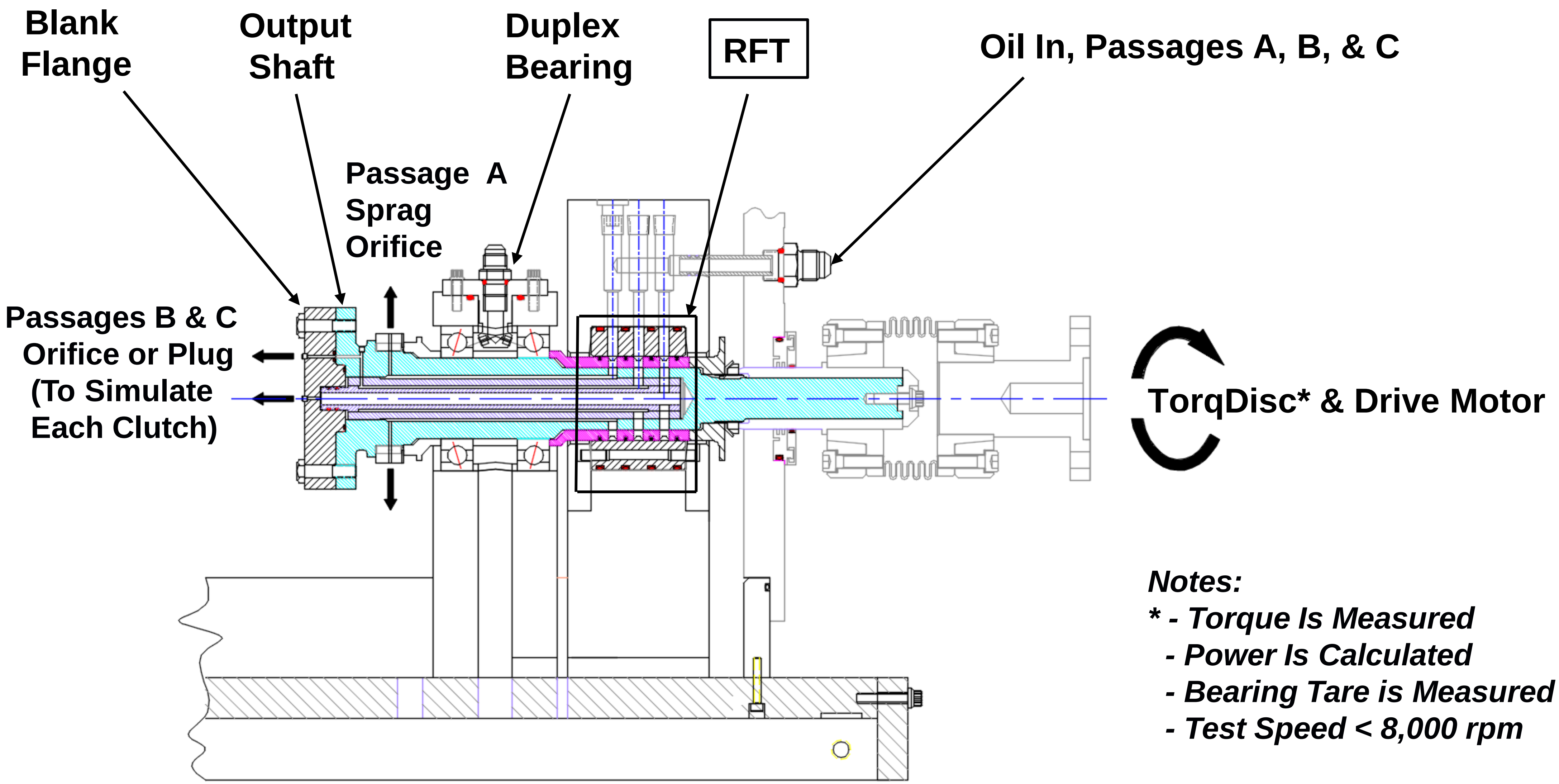


RTF Ring Seal Conditions at Cruise and Hover:

- ◇ Dry-Clutch control (initial* & modified** design)
- ✕ Wet-Clutch control (0-200 psi)

Ref. 9: Graphic Basis (0 - 20 m/s); RFT operation (20 - 40 m/s)

RFT Isolated Power Loss Experiments

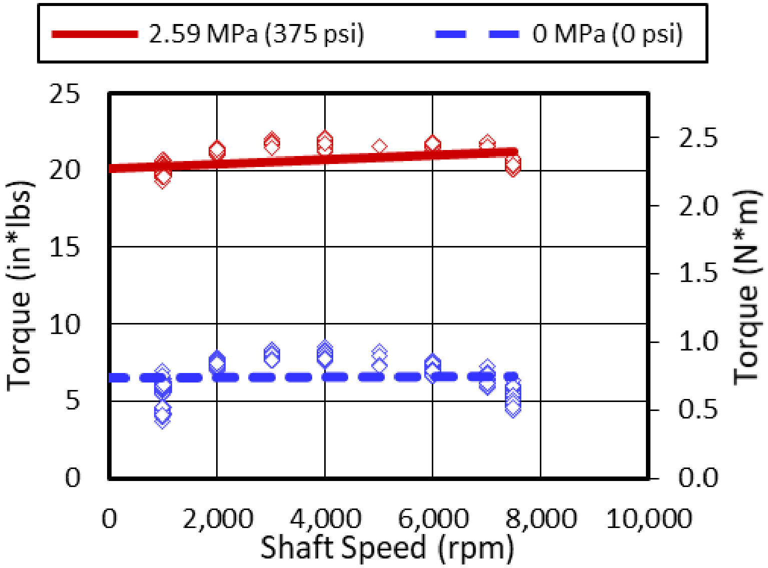


Notes:
**** - Torque Is Measured***
- Power Is Calculated
- Bearing Tare is Measured
- Test Speed < 8,000 rpm

RFT Experiment Ring Seal Torque Drag Vs. Speed

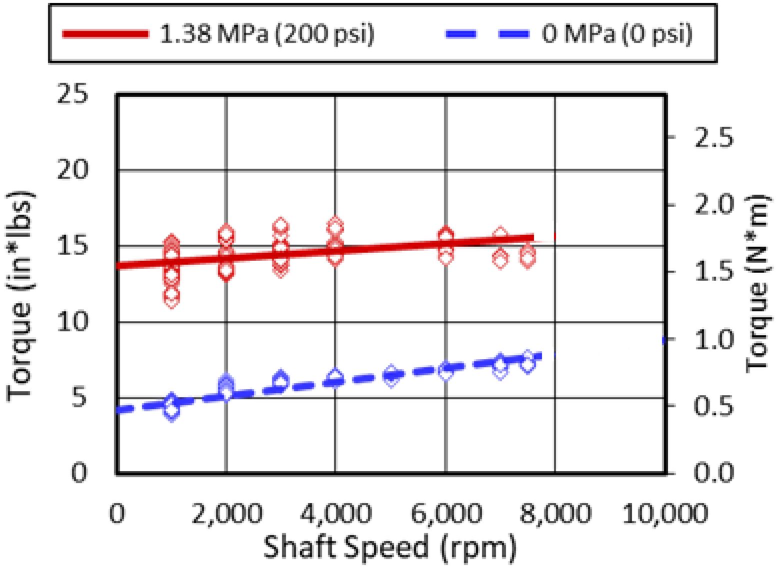
Dry Clutch Configuration

Clutch disengaged at 2.59 MPa (375 psi)
Clutch engaged at 0 MPa (0 psi)



Wet Clutch Configuration

Clutch disengaged at 1.38 MPa (200 psi)
Clutch engaged at 0 MPa (0 psi)



Experimental data linear trend line correlation coefficients, r^2	Dry Clutch	Engaged $r^2 = 0.0008$; Disengaged $r^2 = 0.2$
	Wet Clutch	Engaged $r^2 = 0.9$; Disengaged $r^2 = 0.2$

Note: Torques shown above is for the RFT ring seal drag less the duplex bearing torque measured separately.

Note: Speed range limited due to rotor dynamic response of experiment setup.

RFT Power Loss Trend Line Equations

Dry-Clutch disengaged (cruise)

| 80 psi (sprag) | 375 psi (clutch) | 375 psi (clutch) |

Torque (in-lb) = $1.4E\text{-}4 \times \Omega + 20$
Power (hp) = $2.4E\text{-}9 \times \Omega^2 + 3.2E\text{-}4 \times \Omega$
Torque (N-m) = $1.6E\text{-}5 \times \Omega + 2.3$
Power (Watts) = $1.7E\text{-}6 \times \Omega^2 + 2.4E\text{-}1 \times \Omega$

Wet-Clutch disengaged (cruise)

| 80 psi (sprag) | 200 psi (clutch) | 80 psi (bearing lube) |

Torque (in-lb) = $2.4E\text{-}04 \times \Omega + 14$
Power (hp) = $3.9E\text{-}09 \times \Omega^2 + 2.2E\text{-}04 \times \Omega$
Torque (N-m) = $2.8E\text{-}05 \times \Omega + 1.5$
Power (Watts) = $2.9E\text{-}06 \times \Omega^2 + 0.16 \times \Omega$

Dry-Clutch engaged (hover)

| 80 psi (sprag) | 0 psi (clutch) | 0 psi (clutch) |

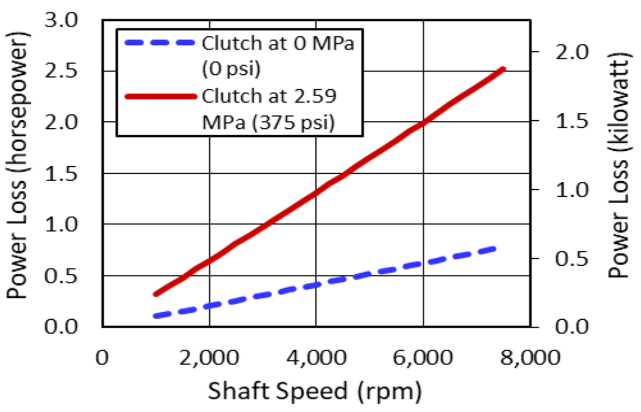
Torque (in-lb) = $1.2E\text{-}5 \times \Omega + 6.5$
Power (hp) = $1.9E\text{-}10 \times \Omega^2 + 1.0E\text{-}4 \times \Omega$
Torque (N-m) = $1.4E\text{-}6 \times \Omega + 0.73$
Power (Watts) = $1.4E\text{-}7 \times \Omega^2 + 7.7E\text{-}2 \times \Omega$

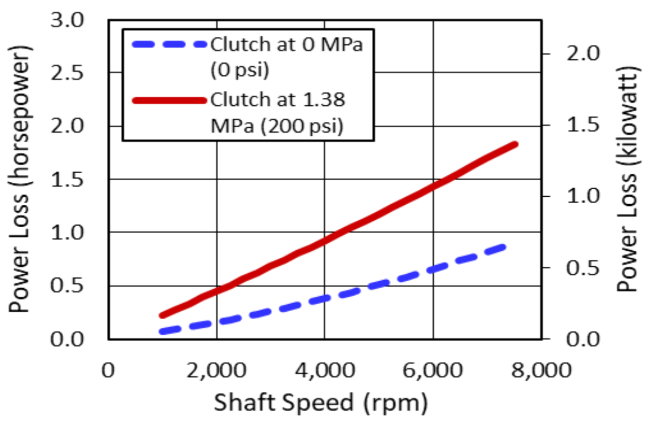
Wet-Clutch engaged (hover)

| 80 psi (sprag) | 0 psi (clutch) | 80 psi (bearing lube) |

Torque (in-lb) = $4.7E\text{-}04 \times \Omega + 4.1$
Power (hp) = $7.4E\text{-}09 \times \Omega^2 + 6.5E\text{-}05 \times \Omega$
Torque (N-m) = $5.3E\text{-}05 \times \Omega + 0.46$
Power (Watts) = $5.5E\text{-}06 \times \Omega^2 + 4.9E\text{-}02 \times \Omega$

Where Ω is shaft speed in rpm





Note: RFT torque and power loss shown above is less duplex bearing torque and power loss.

Generalized Ring Seal Power Loss Equations

Torque (in-lb) = (5.8E-07 × Ω + 2.8E-02) × ΔP
Power (hp) = (9.2E-12 × Ω^2 + 4.5E-07 × Ω) × ΔP where: Ω is rpm and ΔP is psi

Torque (N-m) = (6.6E-08 × Ω + 3.2E-03) × ΔP
Power (W) = (6.9E-09 × Ω^2 + 3.4E-04 × Ω) × ΔP where: Ω is rpm and ΔP is MPa

Comparison of Power Loss from Experimental Data Trend Line Equations with Power Loss Estimates from the Generalized Ring Seal Power Loss Equation

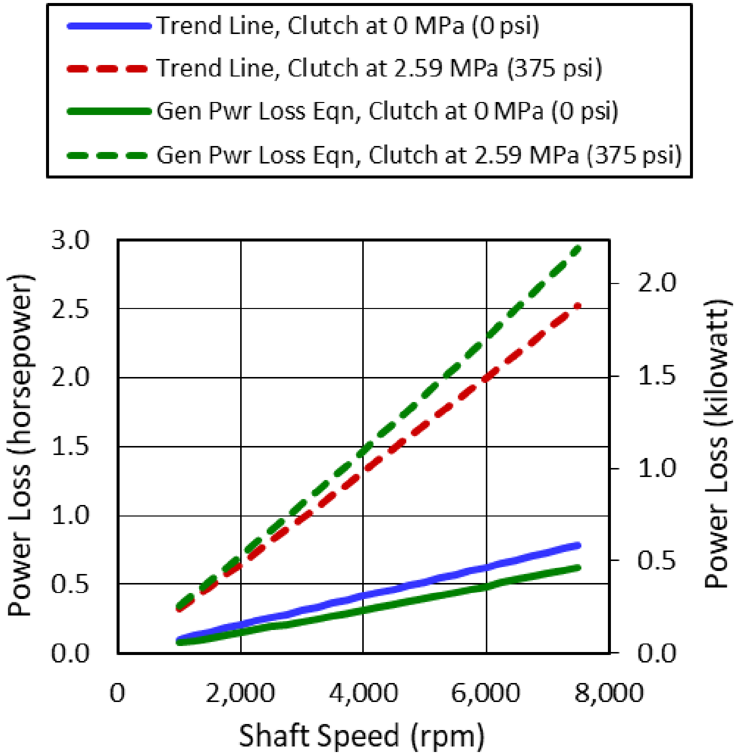
Clutch Drive Ratio	RFT Passage Pressure			Summed Seal ΔP Pressure Differentials (psi)	% Error	
	A (psi)	B (psi)	C (psi)		1,000 rpm	7,500 rpm
Dry Clutch 1:1	80	0	0	160	-28 %	-20 %
Dry Clutch 2:1	80	375	375	750	7.8 %	16 %
Wet Clutch 1:1	80	0	80	320	103 %	34 %
Wet Clutch 2:1	80	200	80	400	-16 %	-15 %

Estimating RFT Power Loss

Comparison of Experimental RFT Power Loss Data Linear Trend Lines versus the Generalized Ring Seal Power Loss Equation

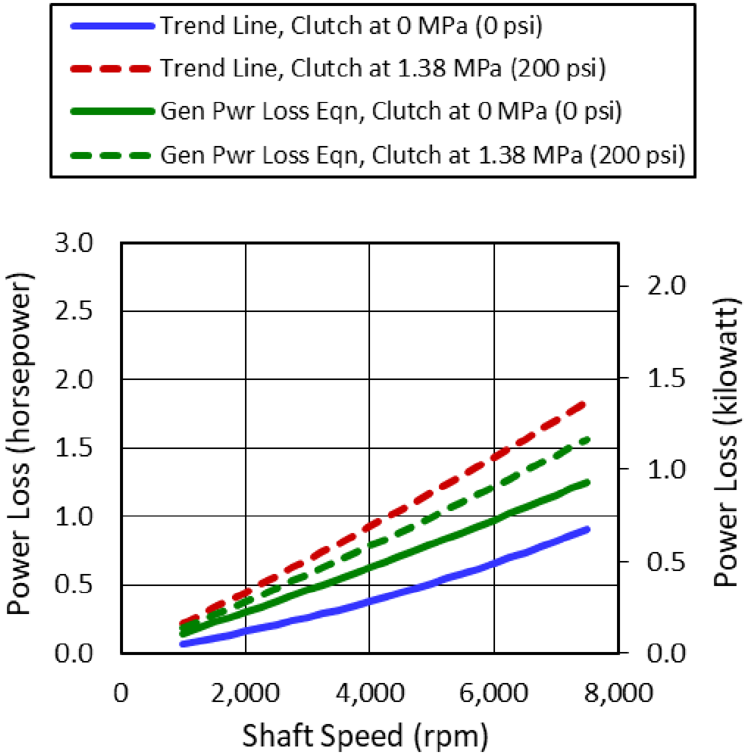
Dry Clutch Configuration

| 80 psi (sprag) | Clutch psi | Clutch psi |



Wet Clutch Configuration

| 80 psi (sprag) | Clutch psi | 80 psi |



RFT Conclusions & Future Considerations

Conclusions

- **The RFT power loss at ~80 psid is low and is a reasonable option to provide lubrication internal to a rotating system provided that seals are not required to be leak free.**
- **The RFT power loss does not scale with system power, but does increase when designs require larger shaft diameters, higher speeds, or higher pressure.**
- **The RFT and total transmission power loss can be minimized by designing any components supplied through the RFT with the lowest required pressures necessary for proper function.**
- **The polyimide ring seals performed well for the experimental time accumulated.**
- **All experimental data and results are valid only for polyimide ring seal materials.**

Future Considerations

- **Test all ring seal materials under consideration as friction coefficients vary considerably.**
- **The RFT design used standard ring seals and installation geometry. Future design should consider thermal expansion with respect to operating temperatures.**
- **The RFT rotor geometry should be optimized:**
  - Outside diameter: Increase seal sliding contact area.
  - Groove width: Increased width ensures pressure is applied radially outward.

Questions?