# Air-Riding Seal Technologies for Advanced Gas Turbines

University Turbine Systems Research Workshop

October 22, 2014

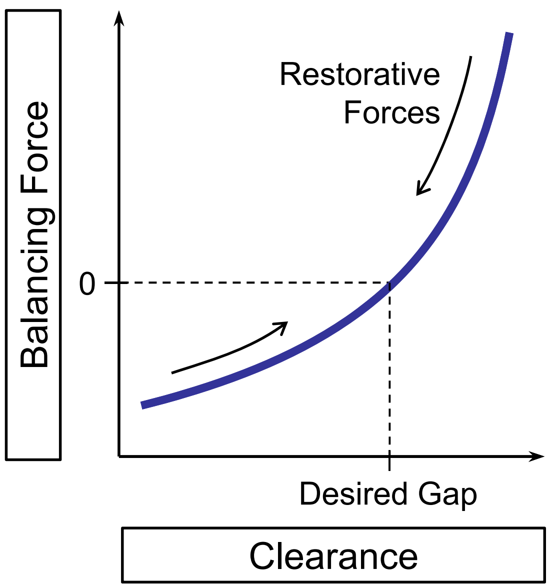
Jake Mills
Senior Systems Design Engineer
Florida Turbine Technologies, Inc.
561-427-6439
jmills@fttinc.com
www.fttinc.com

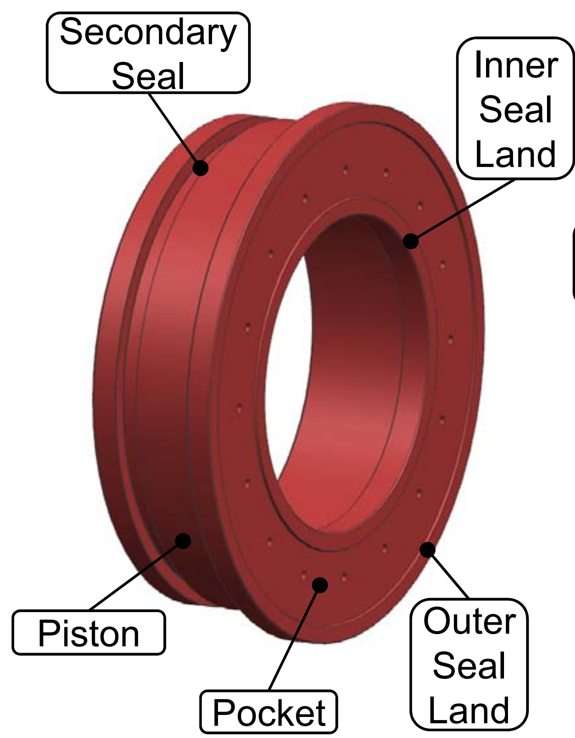
# Outline

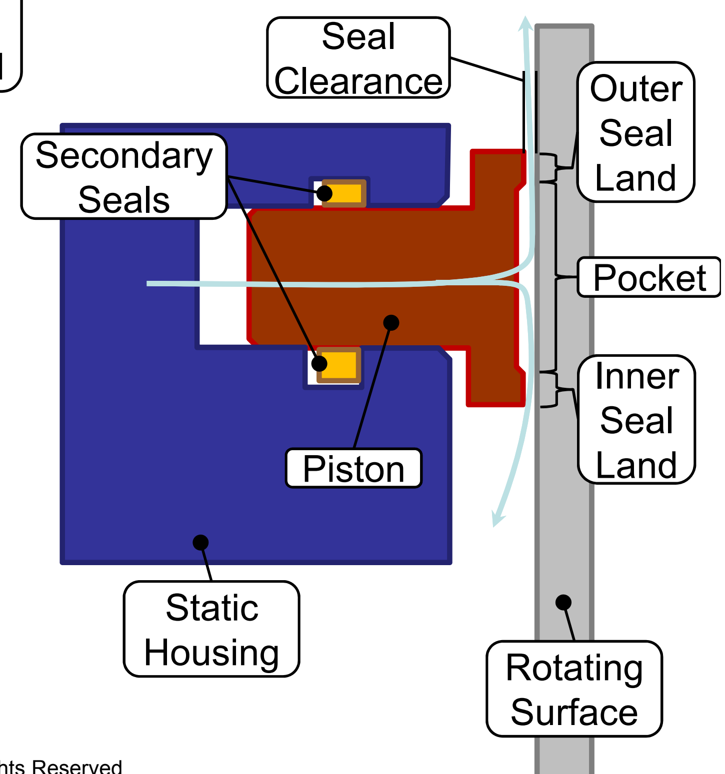
- Air Riding Seal Concept
- Phase I
  - Design
  - Testing
- Application
- Future Development

# Concept

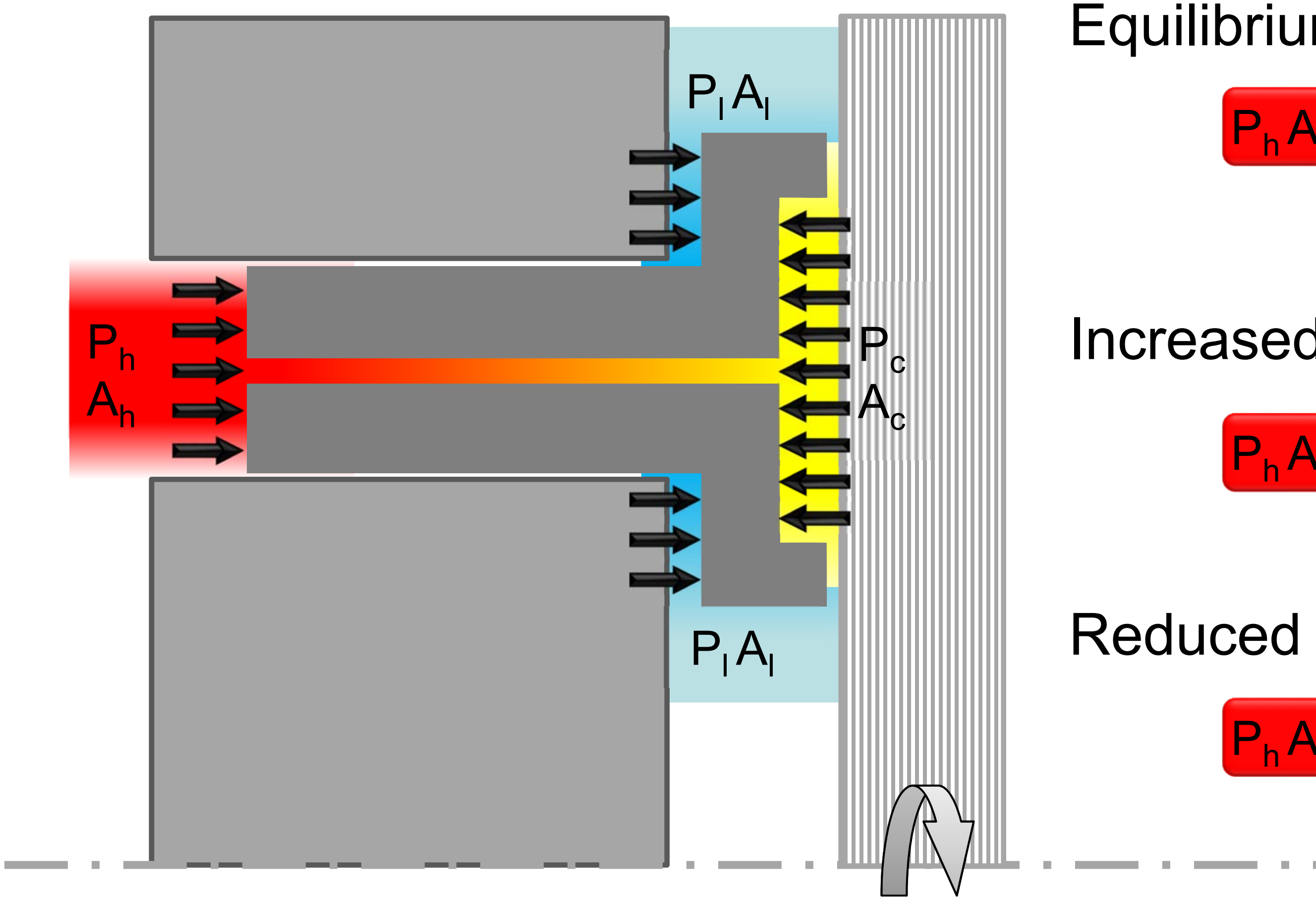
- Non-contacting static to rotating seal
- Hydrostatic balance of forces
- Ability to follow rotor to maintain close clearances



# ARS Concept




Equilibrium $\Sigma F_x = 0$

$P_h A_h + P_l A_l = P_c A_c$

Increased Clearance $\Sigma F_x = \rightarrow$

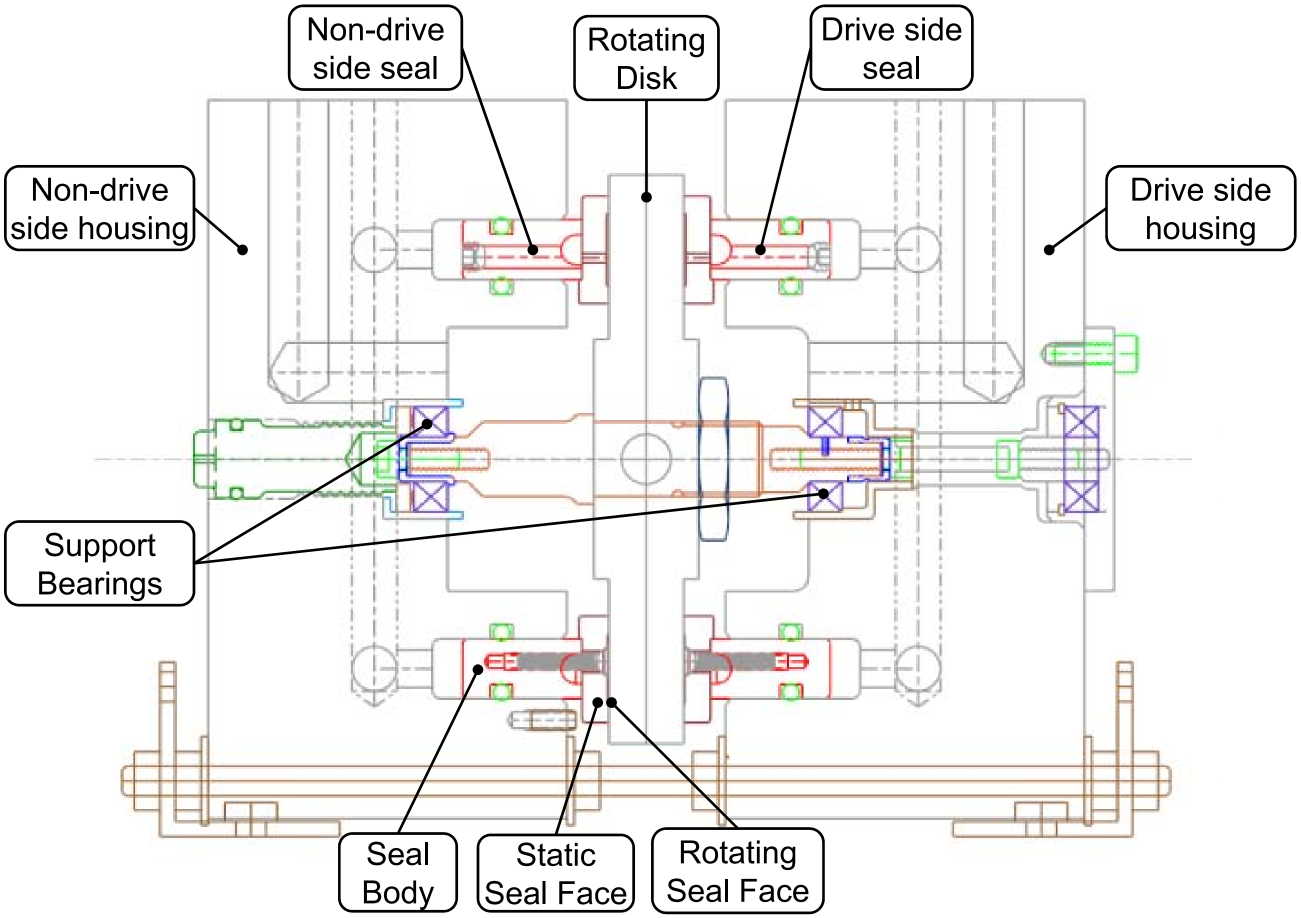
$P_h A_h + P_l A_l > P_c A_c$

Reduced Clearance $\Sigma F_x = \leftarrow$

$P_h A_h + P_l A_l < \mathbf{P_c A_c}$

# Phase I

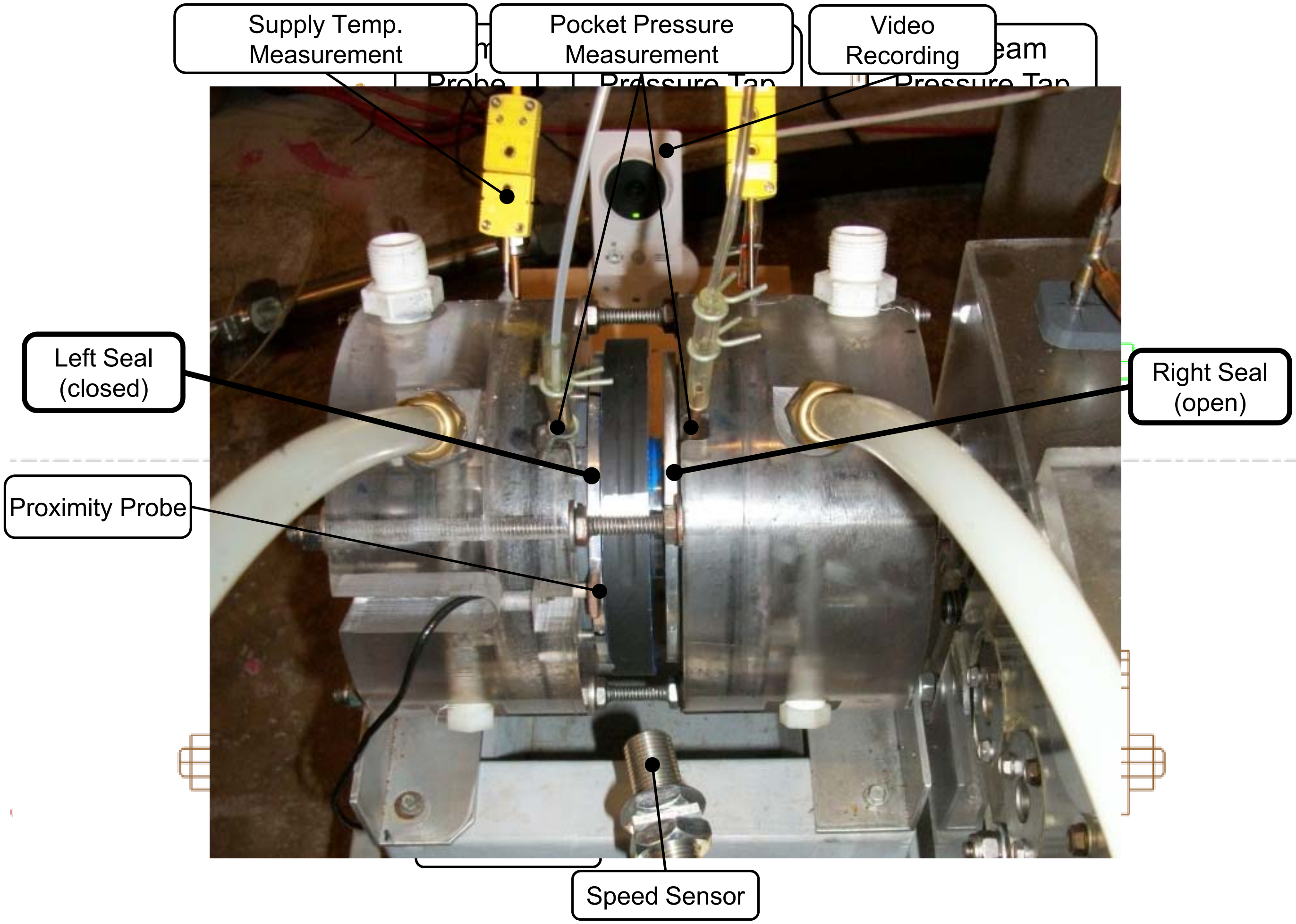
**Rig Design** | Analytical Models | Seal Testing




Simple low cost rig used for initial evaluation of the ARS seal concept

# Phase I

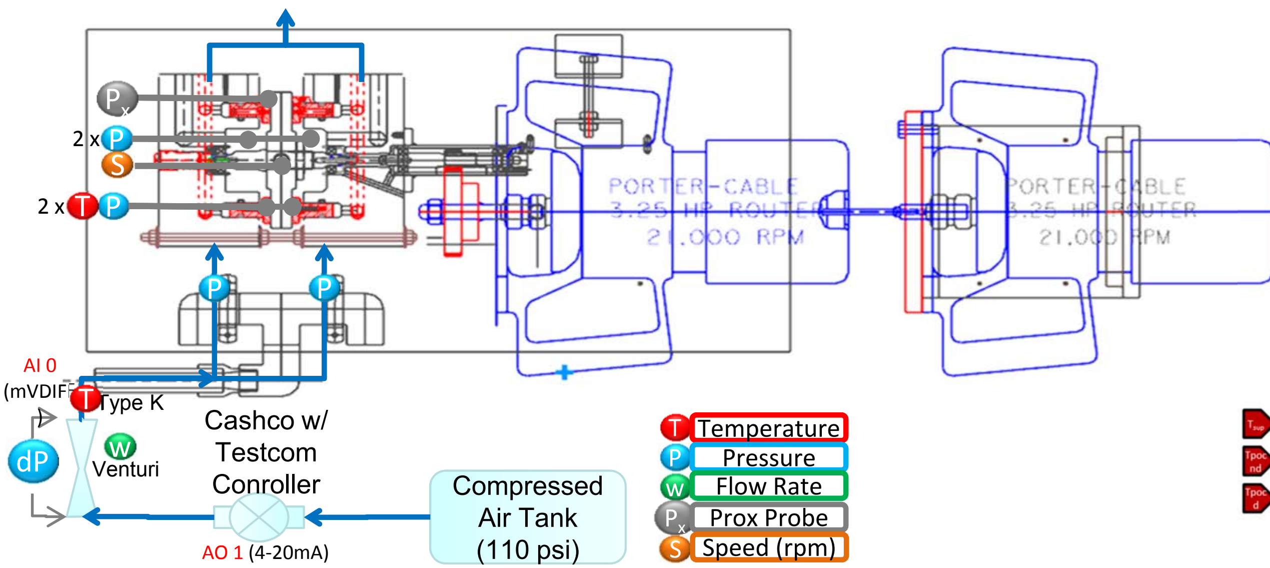
Rig Design | Analytical Models | Seal Testing

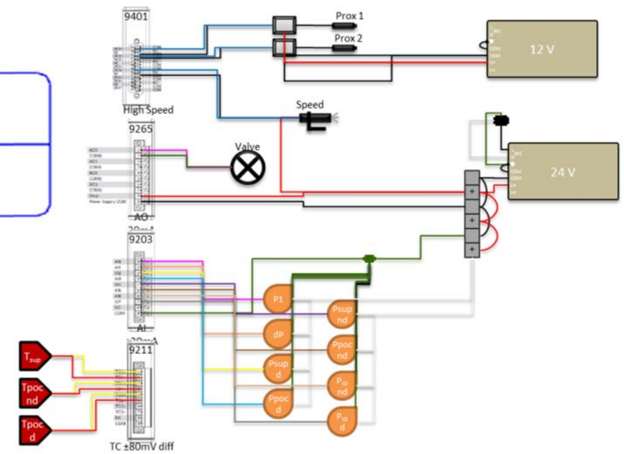



Simple low cost rig used for initial evaluation of the ARS seal concept

# Phase I

Rig Design | Analytical Models | Seal Testing



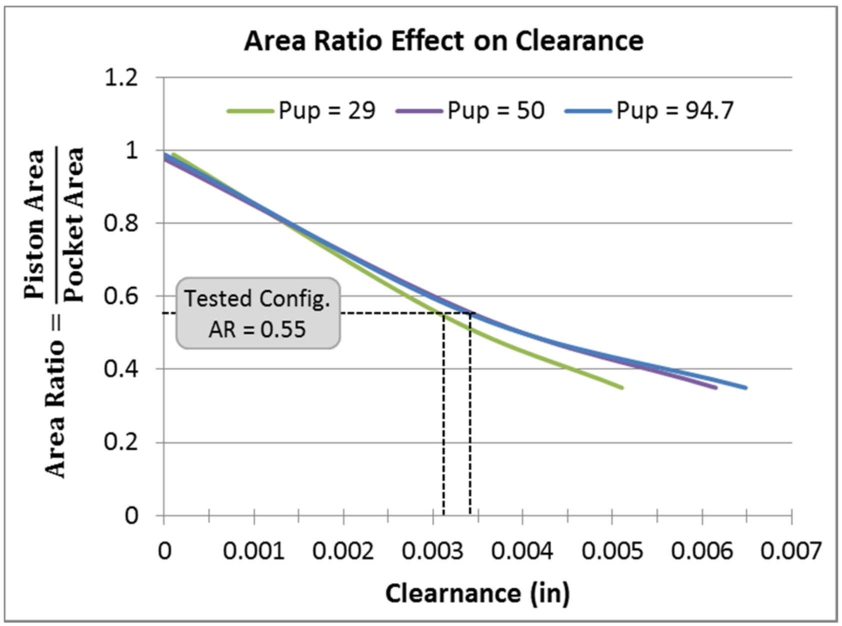



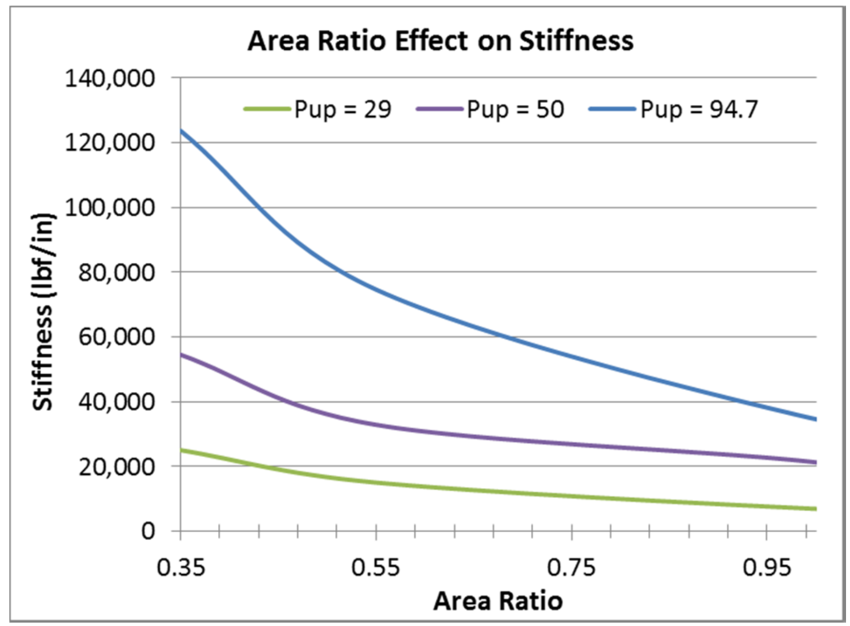

**15 pieces of instrumentation used to accurately measure seal performance**

# Phase I

Rig Design | **Analytical Models** | Seal Testing

- Simple 1D models used to study design variables
- More complex CFD models used for more accurate physical representation
- Analytical models then anchored to test data



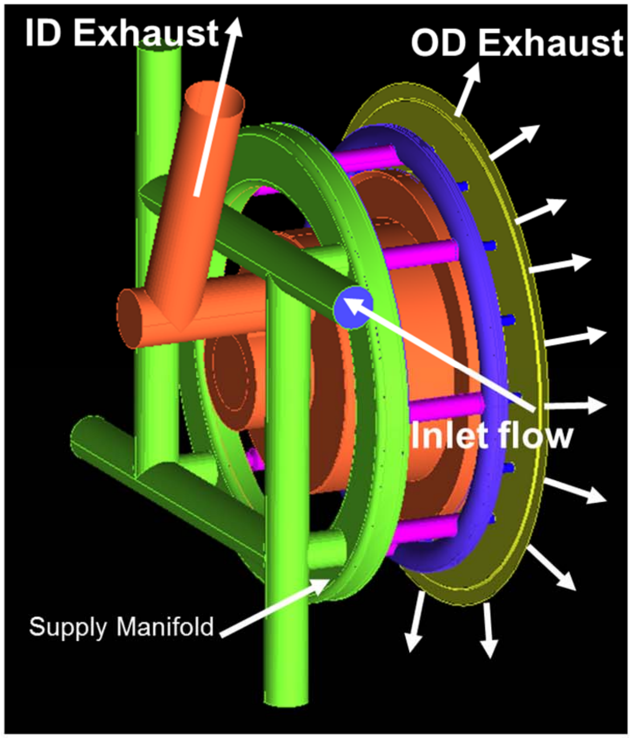



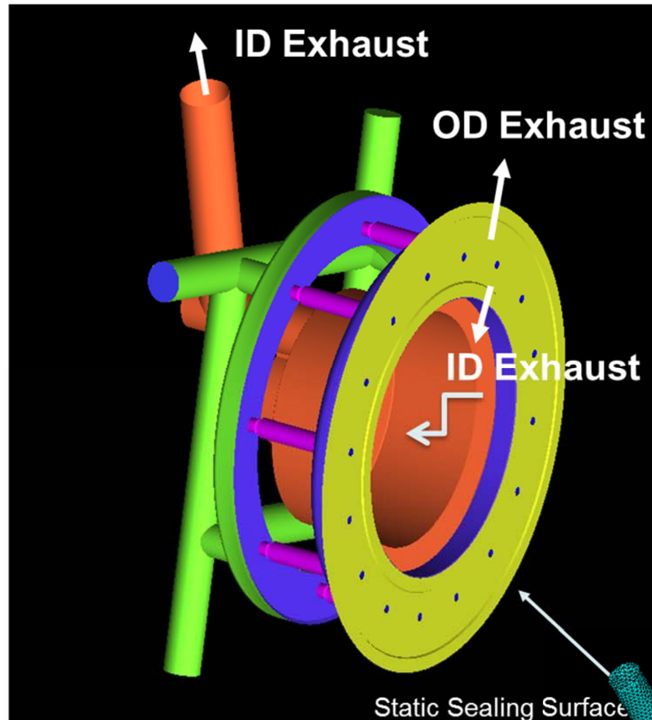

**Predicted seal clearance is 0.0030” to 0.0035”**

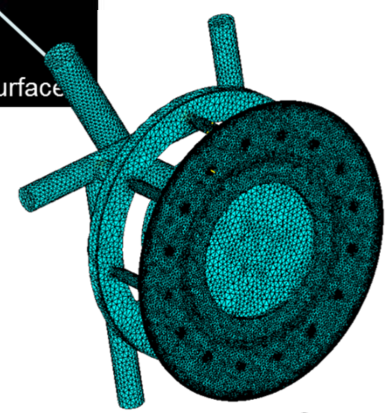
# Phase I

Rig Design | Analytical Models | Seal Testing

- CFD Model



Tetrahedral grid with prism layers to resolve boundary layer

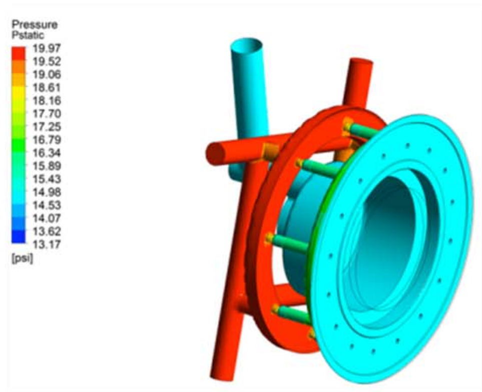
- ❑ Cells = 1.3E6
- ❑ Shear Stress Transport (SST)
  - Heat Transfer
- ❑ Total Energy
  - Adiabatic walls
  - Advection Scheme

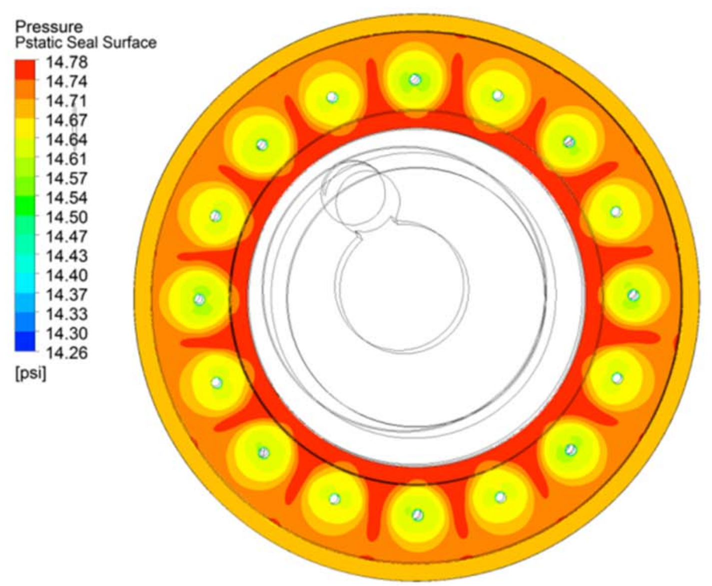
# Phase I

Rig Design | Analytical Models | Seal Testing

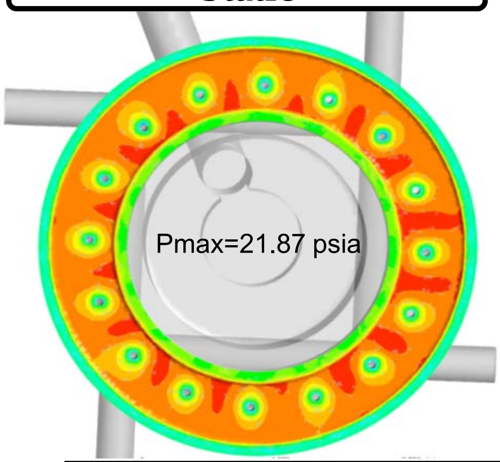
- CFD Model

Static Pressure Distribution::

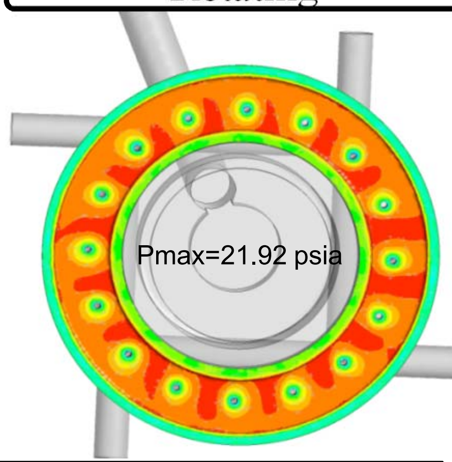



Static




Rotating




Results are periodic, a simplified sector model can be used

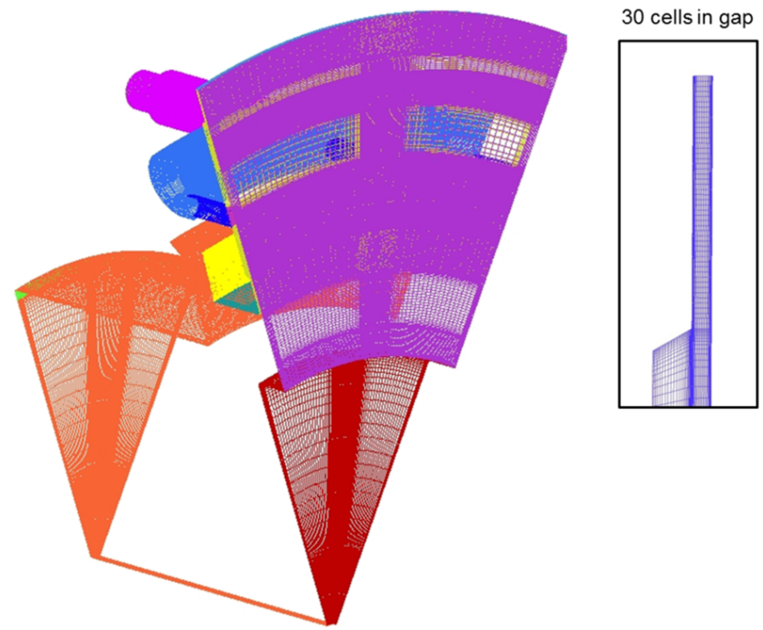
Seal is fundamentally hydrostatic

# Phase I

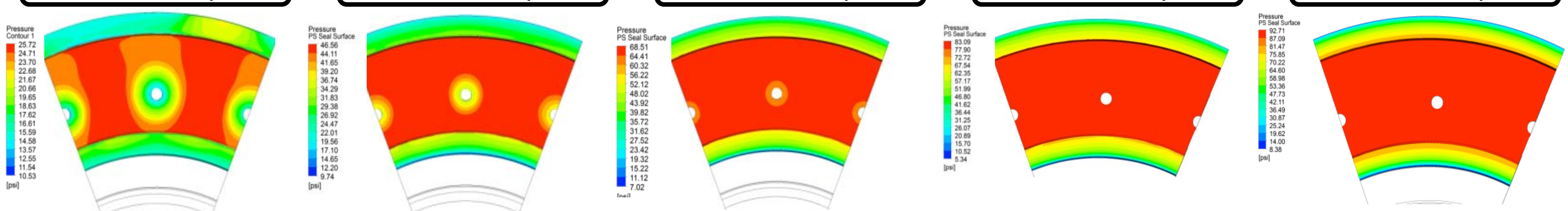
Rig Design | **Analytical Models** | Seal Testing

- 3D Periodic CFD Model
  - Studied clearances
    - 0.001”
    - 0.002”
    - 0.003”
    - 0.005”
    - 0.010”
  - Inlet pressures
    - 95 psi
    - 50 psi
    - 20 psi

Model Statistics:
- ❑ Structured hexahedral grid
- ✓ Nodes = 5.41e06
- ✓ Cells = 5.58e06
- ✓ Cells in axial gap =30
- ✓ Expansion=1.2
- ✓ Near wall cell = 9e-05 m
- ❑ Turbulence Model
- ✓ Shear Stress Transport
- ❑ Heat Transfer
- ✓ Total Energy
- ✓ Adiabatic walls
- ❑ Advection Scheme
- ✓ High resolution




0.010” Gap | 0.005” Gap | 0.003” Gap | 0.002” Gap | 0.001” Gap

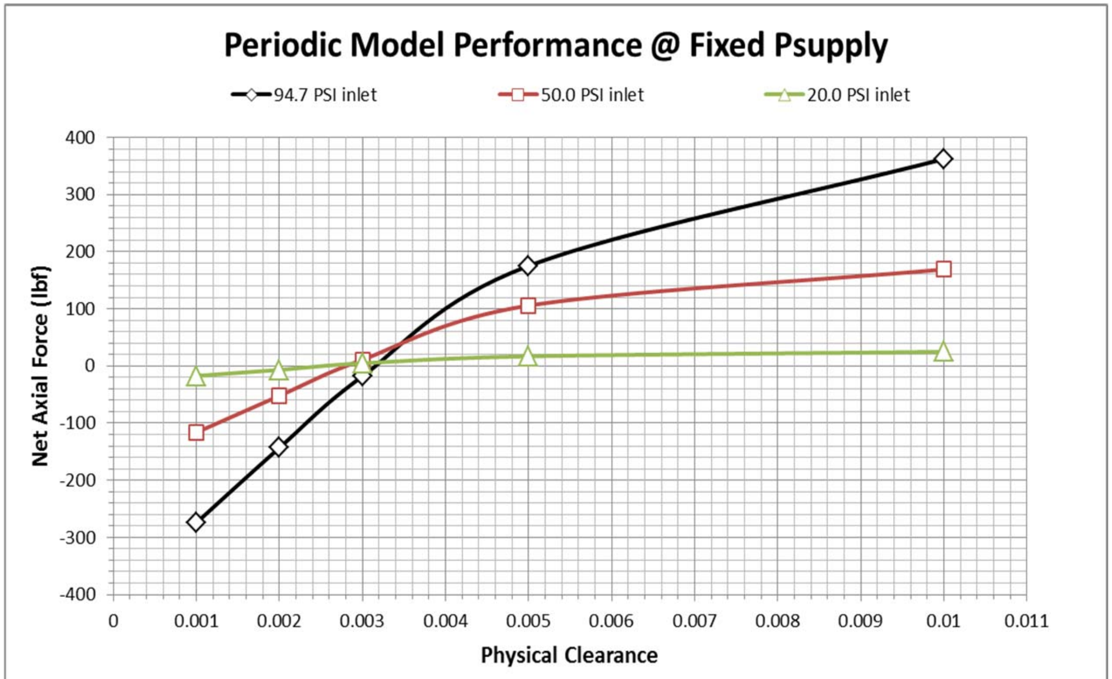


**On the rig, clearance of 0.005” and less led to uniform pocket pressures**

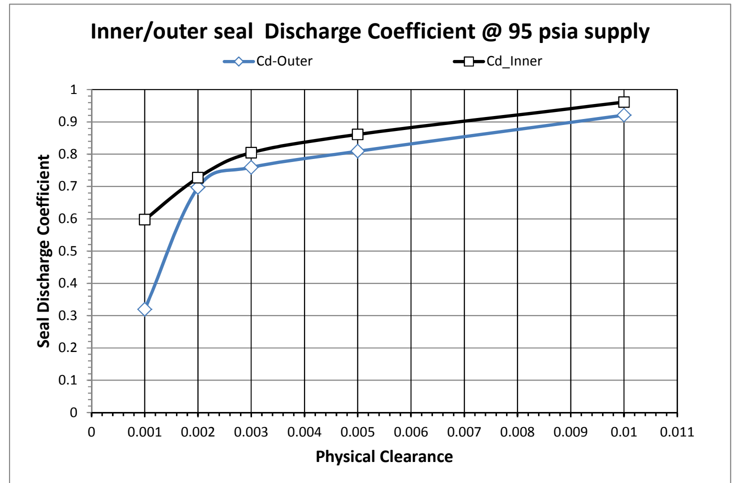
# Phase I

Rig Design | Analytical Models | Seal Testing

- CFD Model
  - Manually run for the five clearances at the three inlet pressures




CFD predicted seal clearance is 0.0030” to 0.0033”




CDs from CFD model used to improve the accuracy of the 1D model

# Phase I

Rig Design | Analytical Models | **Seal Testing**

- Test matrix developed to measure seal performance over a range of speeds and pressures
- For each test speed the supply pressured was varied from atmospheric to 95 psig while holding the downstream pressure at atmospheric

| | Test Number | Shaft Speed (rpm) | Face Speed (ft/s) | ΔP (psid) |
|---|---|---|---|---|
| Low Speed | 01a | 0 | 0 | 20 |
| | 01b | 0 | 0 | 40 |
| | 01c | 0 | 0 | 60 |
| | 01d | 0 | 0 | 80 |
| | 02a | 10,450 | 200 | 20 |
| | 02b | 10,450 | 200 | 40 |
| | 02c | 10,450 | 200 | 60 |
| | 02d | 10,450 | 200 | 80 |
| | 03a | 20,900 | 400 | 20 |
| | 03b | 20,900 | 400 | 40 |
| | 03c | 20,900 | 400 | 60 |
| | 03d | 20,900 | 400 | 80 |

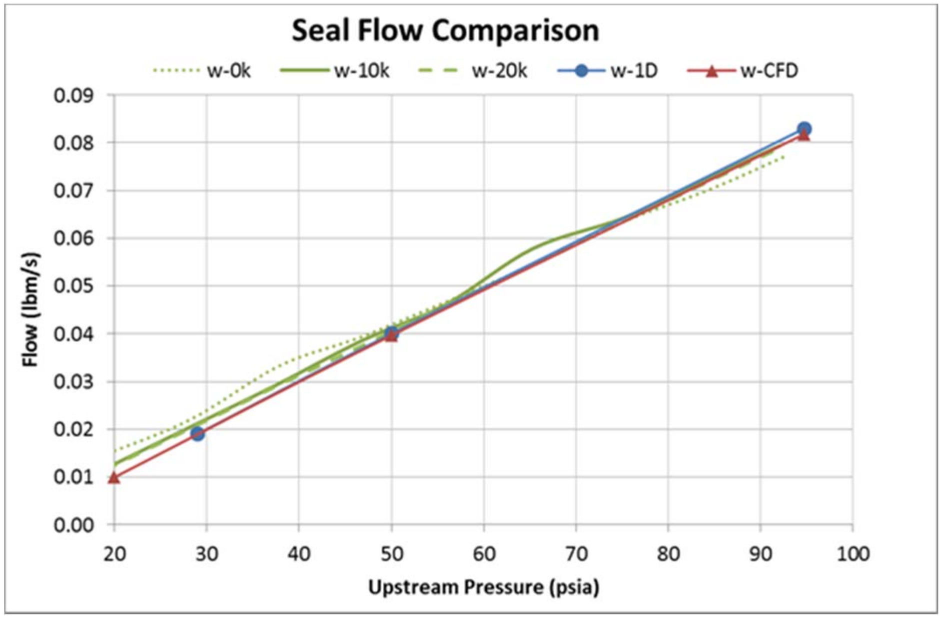
| | Test Number | Shaft Speed (rpm) | Face Speed (ft/s) | ΔP (psid) |
|---|---|---|---|---|
| High Speed | 04a | 31,350 | 600 | 20 |
| | 04b | 31,350 | 600 | 40 |
| | 04c | 31,350 | 600 | 60 |
| | 04d | 31,350 | 600 | 80 |
| | 05a | 41,800 | 800 | 20 |
| | 05b | 41,800 | 800 | 40 |
| | 05c | 41,800 | 800 | 60 |
| | 05d | 41,800 | 800 | 80 |

Rig failure occurred during high speed testing. However low speed data indicates seal performance is independent of speed

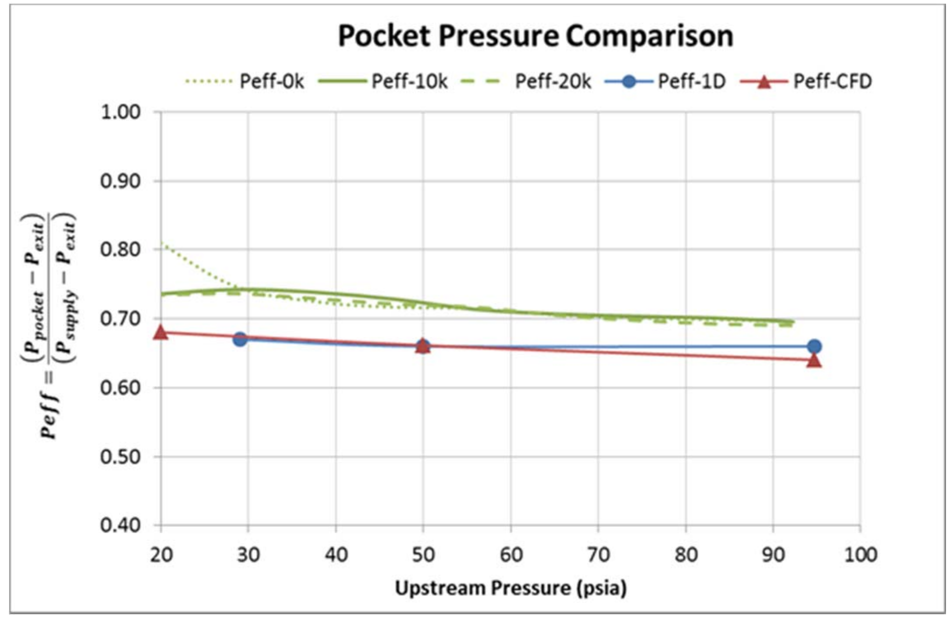
# Phase I

Rig Design | Analytical Models | Seal Testing

- Test data compares favorably to analytical predictions



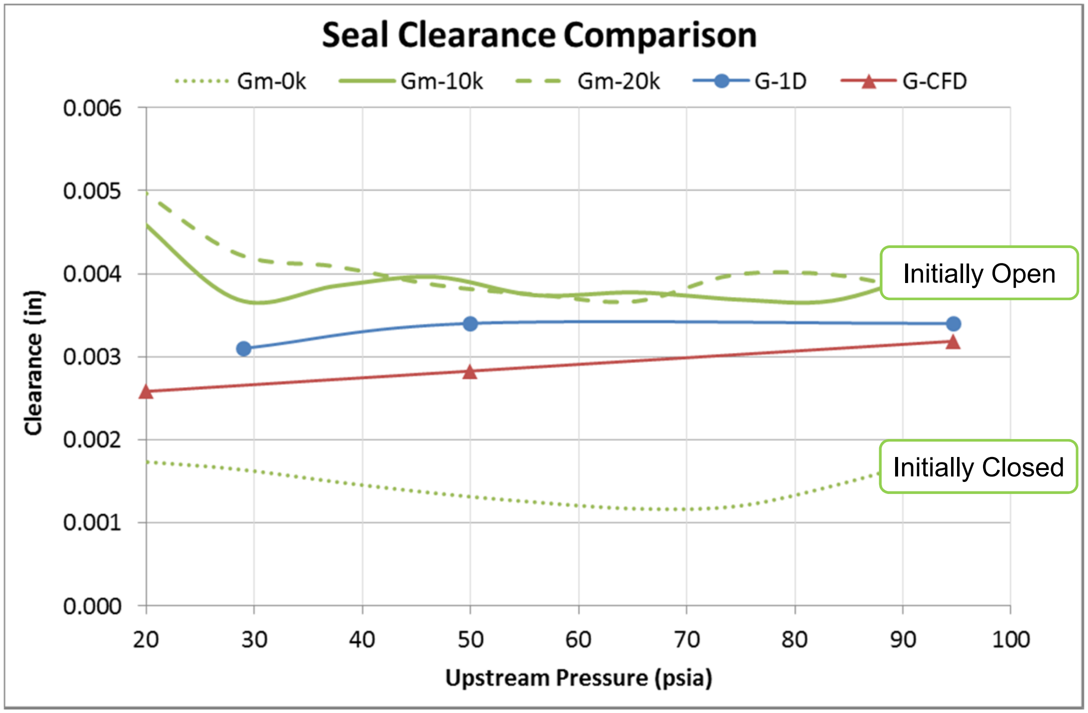

Linear relationship between supply pressure and flow rate




Non-dimensionalized pressure remains constant for a given design

# Phase I

Rig Design | Analytical Models | Seal Testing

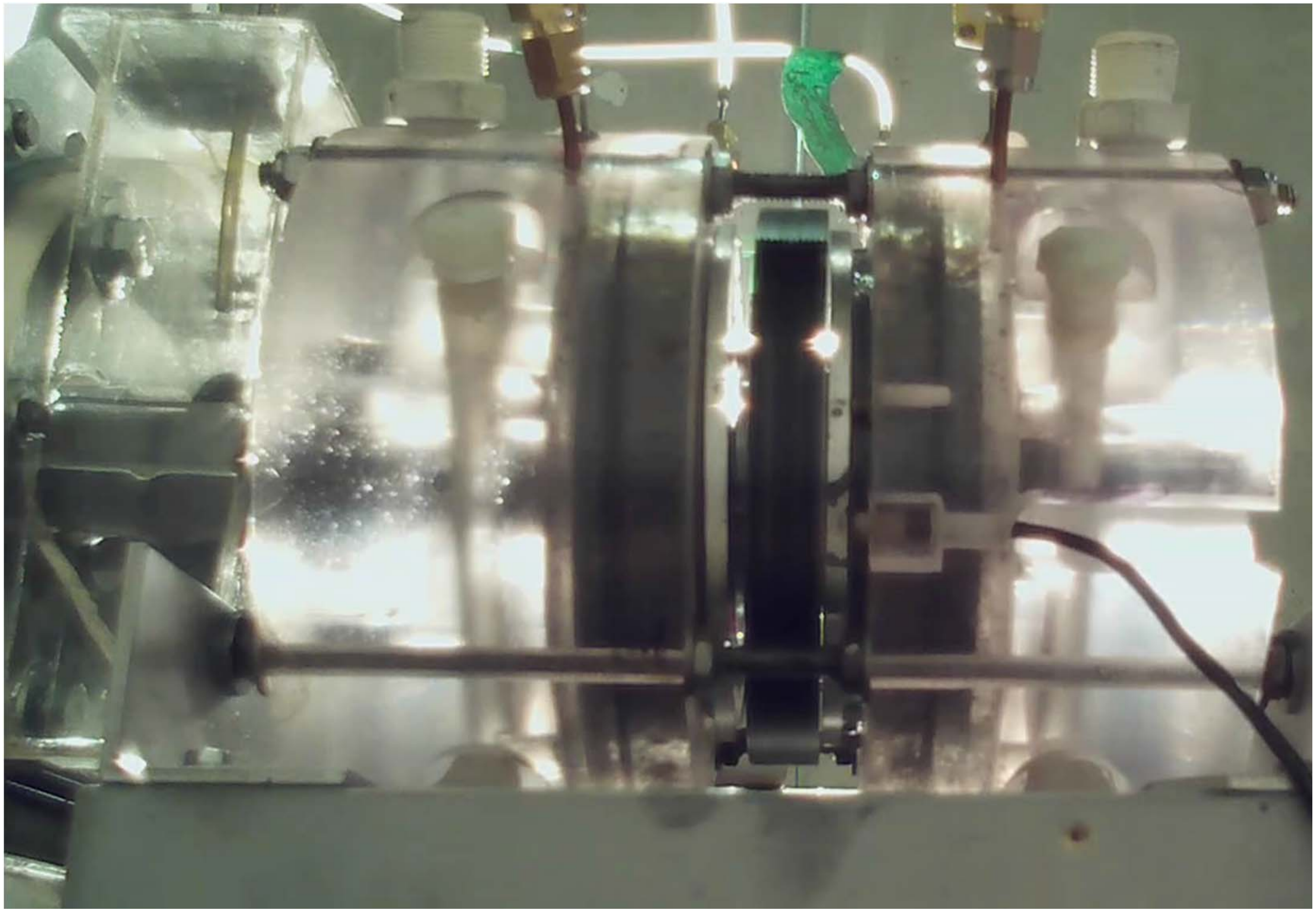



- Friction plays a role in the steady state operating clearance
- Seal design should minimize friction forces

**Analytical models provide an accurate representation of the seal**

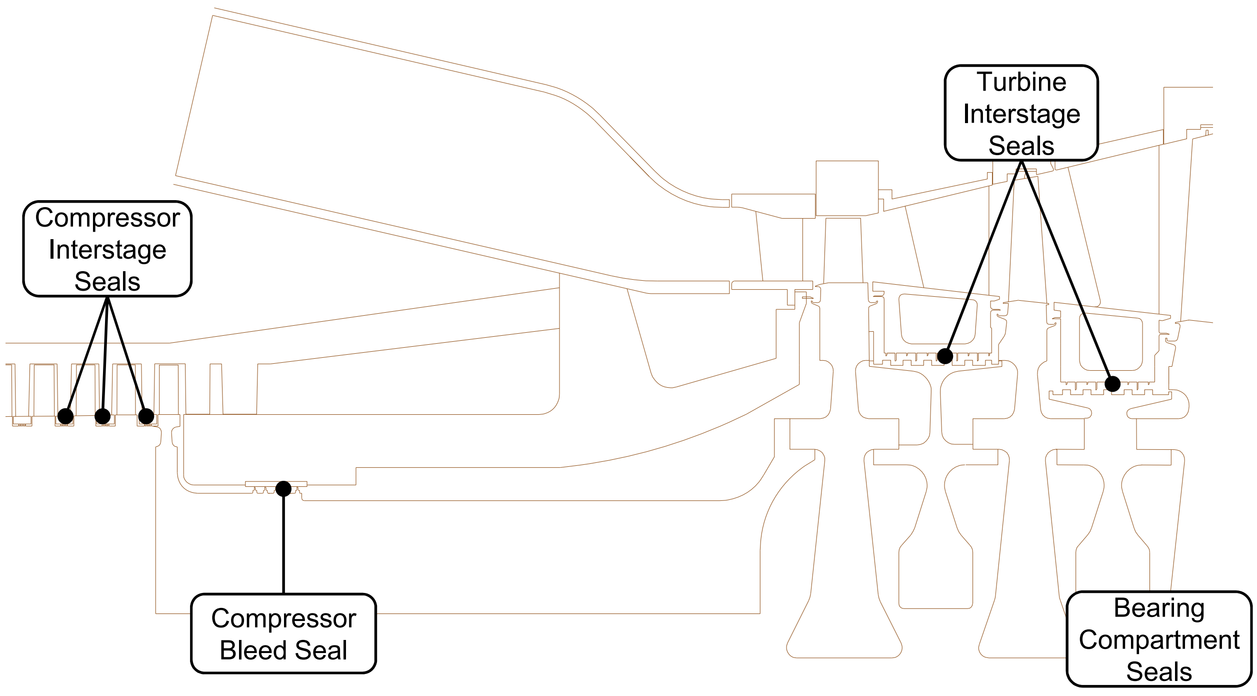
# Phase I

Rig Design | Analytical Models | Seal Testing



# ARS Application

- ARS technology applicable to a variety of rotating to static seals



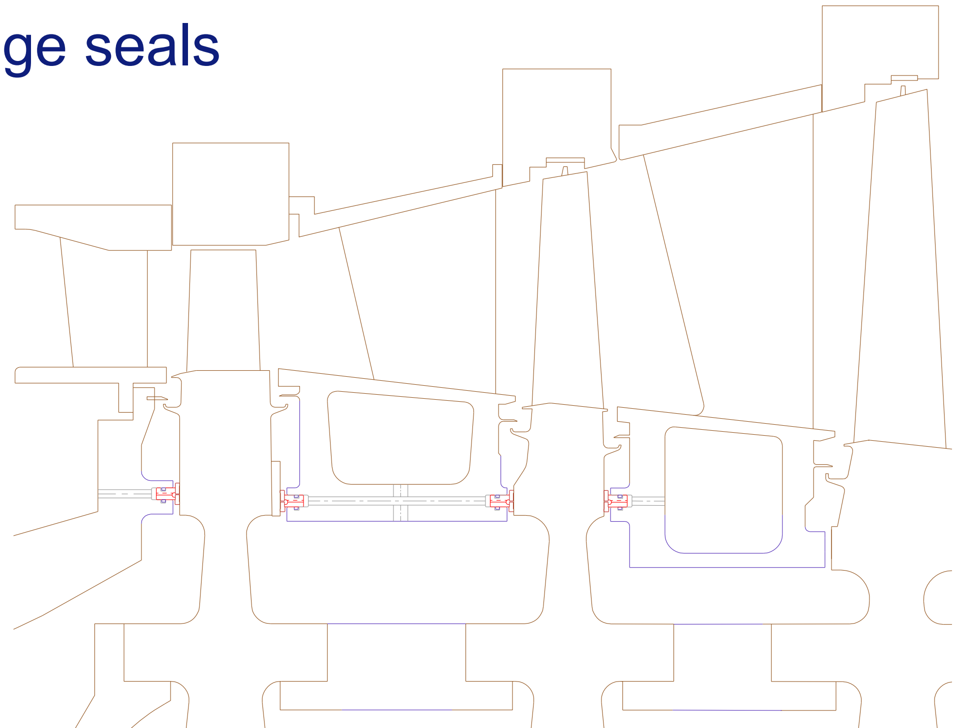

- Large utility scale engine performance model created to assess benefits of retrofitting an engine with the ARS technology [1]

# ARS Application

- ARS replacing labyrinth interstage seals

## Benefit in the Turbine

| Leakage Location | Baseline |
|---|---|
| Rotor 1 Upstream | 1.903% |
| Rotor 1 Downstream | 0.755% |
| Rotor 2 Upstream | 0.769% |
| Rotor 2 Downstream | 1.019% |
| Rotor 3 Upstream | 0.175% |
| **Total Key Leakages** | **4.621%** |



| | |
|---|---|
| Additional Power Output | 11910 kW |
| Operating Hours per Year | 6000 hr |
| Average Florida Residential Electricity Rate | 0.12 $/kWh |
| **Additional Annual Revenue per Engine** | **$8,574,725** |

| | |
|---|---|
| Power Revenue | $8,574,725 |
| Fuel Expense | $1,370,743 |
| **Net Annual Profit per Engine** | **$7,203,982** |

| | Baseline | T&C ARS |
|---|---|---|
| Normalized $CO_2$ Emissions per kilowatt-hour (lb $CO_2$/kWh) | 0.784 | 0.773 |

## Benefit in the Compressor

- Increased compressor efficiency estimated from data correlating stage efficiency increase due to reduced leakage [2]
- Stage efficiency benefit weighted by pressure ratio to arrive at on overall compressor efficiency increase
- Potential increase of compressor isentropic efficiency of 0.34% points

# Continued Development

## Technology Maturation Items

- Design variations
  - Tolerances, surface finish
- Operating anomalies
  - Rotor coning, non-symmetrical BCs
- System response

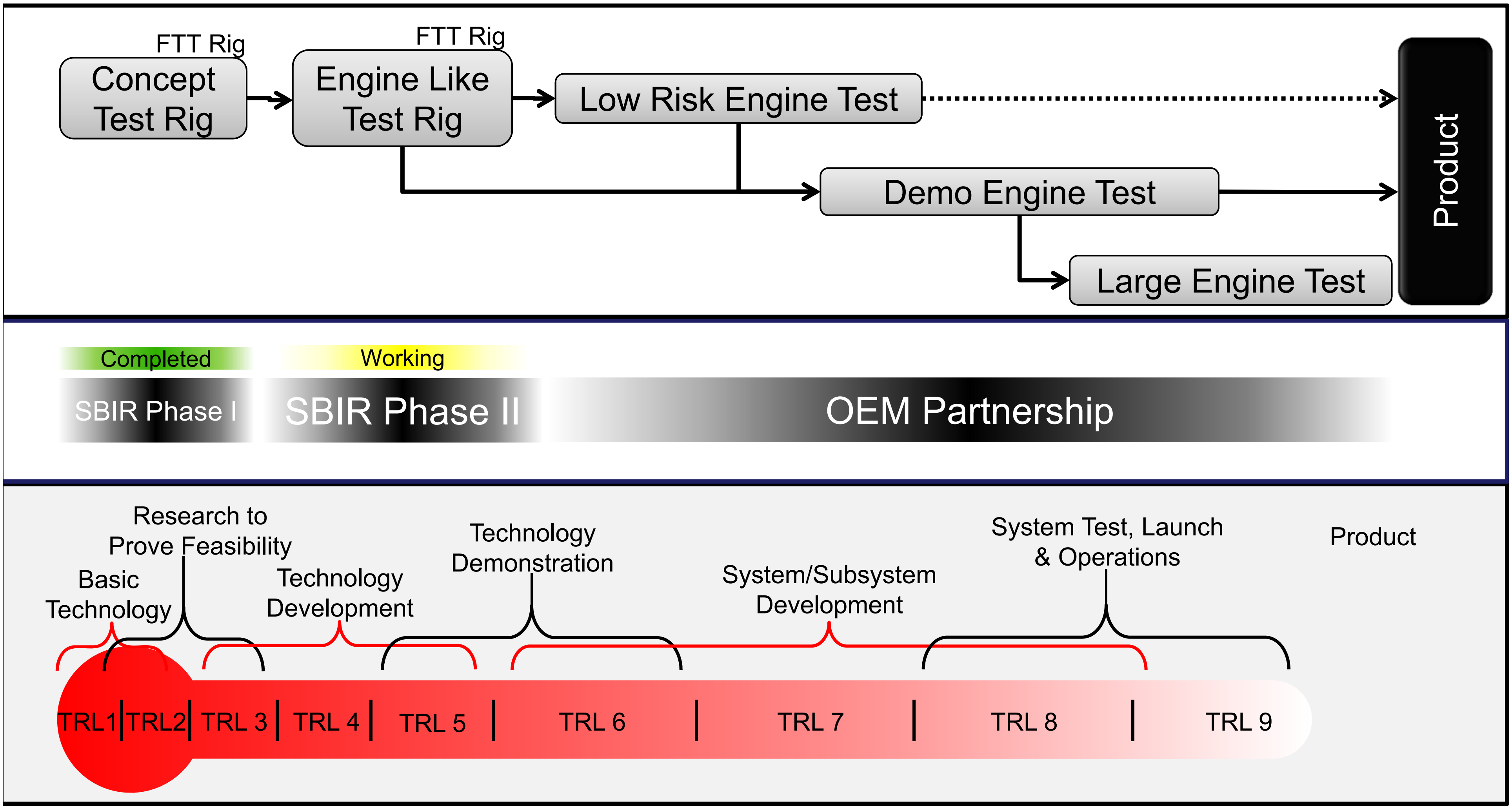
## Phase II SBIR

- Design for specific engine application
- Rig test in engine-like environment

## Beyond Phase II

- Partner with OEM
- Conduct engine testing

# Technology Development Roadmap



# Acknowledgments

Travis Shultz – DOE Program Manager

Todd Ebert – CFD and Sealing Expert
Justin Cejka – Performance Engineer

## References

[1] Pequot Publishing Inc., "Gas Turbine World 2005 Performance Specs", January 2005, Vol. 34 No. 6
[2] Lakshminarayana, B. (1970). Methods of Predicting the Tip Clearance Effects in Axial Flow Turbomachinery. *ASME: Journal of Basic Engineering*, 92(3), 467-480.