University Turbine Systems Research (UTSR) Workshop
Atlanta, Georgia, November 3-5, 2015

Turbomachinery Technology Development at FTT

3 November 2015

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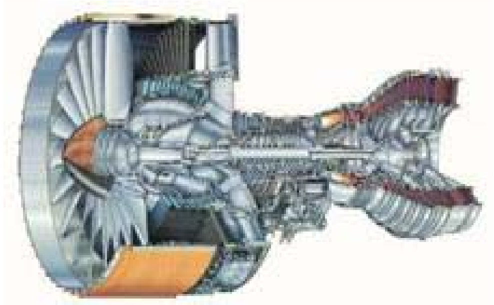
Outline

- FTT company overview
- DOE-sponsored turbomachinery technology programs at FTT
- Opportunities for collaboration with UTSR universities

OEM Capability – Innovation Emphasis

Independent Know-How of Industry Systems (Industrial and Aero)

- Design practice, design criteria, and lessons learned
- Fast iteration conceptual design
- Detailed design know-how
- Expert knowledge of material systems and manufacturing processes



Calibrated Analysis Tools and Design System

- Internal and external software
- Continuously improved with new information/data

Technology Portfolio

- Intellectual property
- Government-sponsored technology programs

Proven Supply Chain for Prototype Hardware

- Manufacturing engineering to support delivery

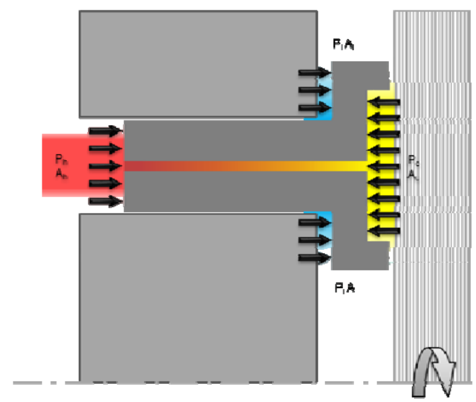
Validation and Field Experience

- Production as-manufactured hardware verification
- Field issue root cause
- Power producer engineering support

DOE-Sponsored Technology Programs

- TurboGT™ Gas Turbine with ARTICReturn™ Cooling (FE-0023975)
  - 18 month Phase I program
    Wraps-up early next year

- Air Riding Seal Technologies for Gas Turbines (DE-SC0008218)
  - 2 year program
    Concludes next year



DOE Advanced Turbines Program

R&D Activities to Accelerate Turbine Performance and Efficiency Beyond Current SOA and Reduce the Risk to Market for Novel and Advanced Turbine-Based Power Cycles

Goals:

- Efficiency – High, 65% (LHV) or Greater in Combined Cycle
- Operability – Support Load Following Capabilities to Meet Demands of Modern Power Grid
- Higher Firing Temperatures (1700°C/3100°F)
- Emissions – Low NO_x and other Criteria Pollutants
- Cost – ? … FTT Primary Goal = Lower Cost

Ref: DOE NETL Web Site

Path to High Efficiency Goal

Combined Cycle Power Plant

A lot of pieces, but the efficiency is predominantly driven by the gas turbine(s)

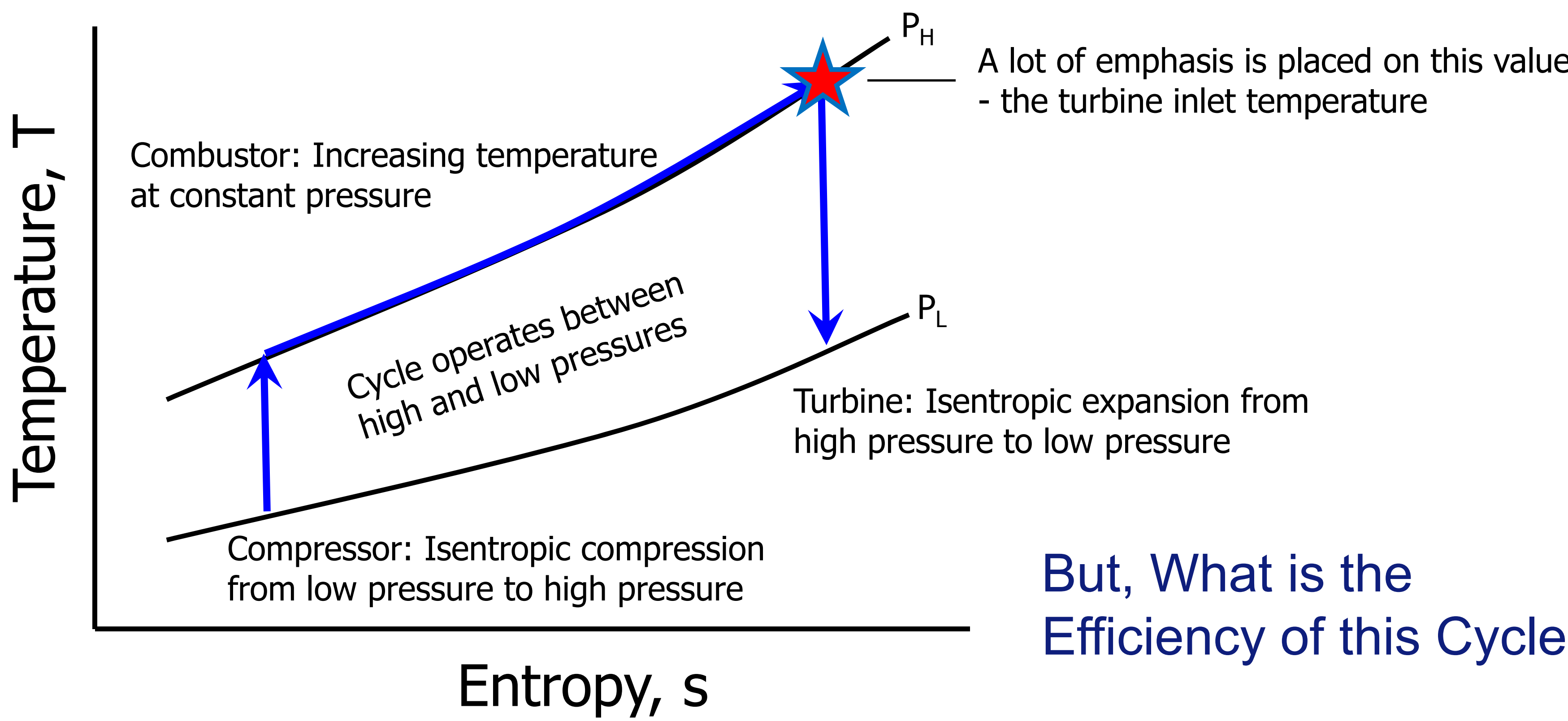
Ref:http://tse1.mm.bing.net/th?&id=OIP.Meed81da2ead7c689b2dbf71a16d1f9b6o0&w=300&h=300&c=0&pid=1.9&rs=0&p=0

→ Focus here is on gas turbine performance

Gas Turbine Performance

What's the Limit? How Good Can it Get?

Understanding the fundamentals of the ideal thermodynamic cycle:



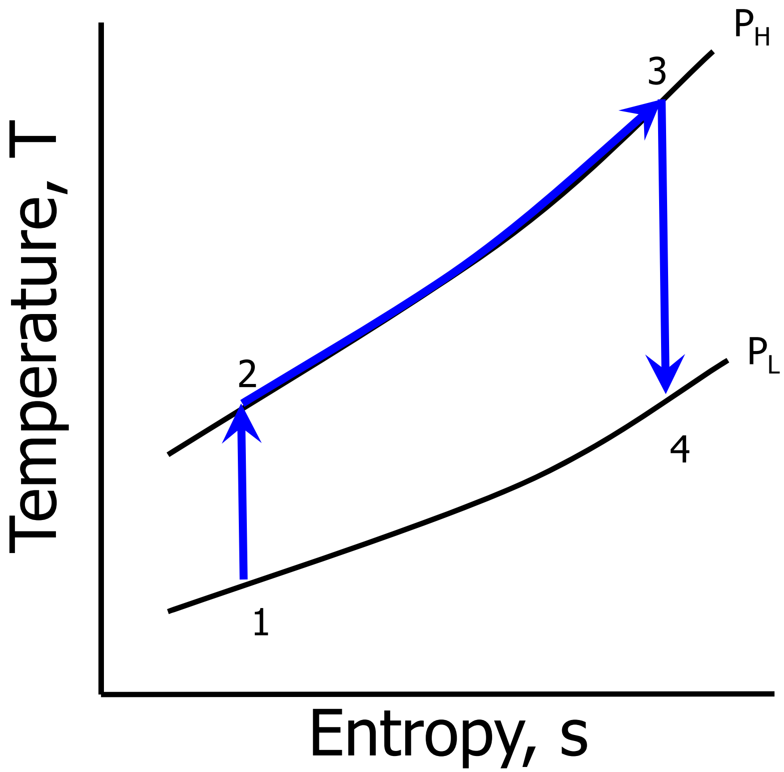
But, What is the Efficiency of this Cycle?

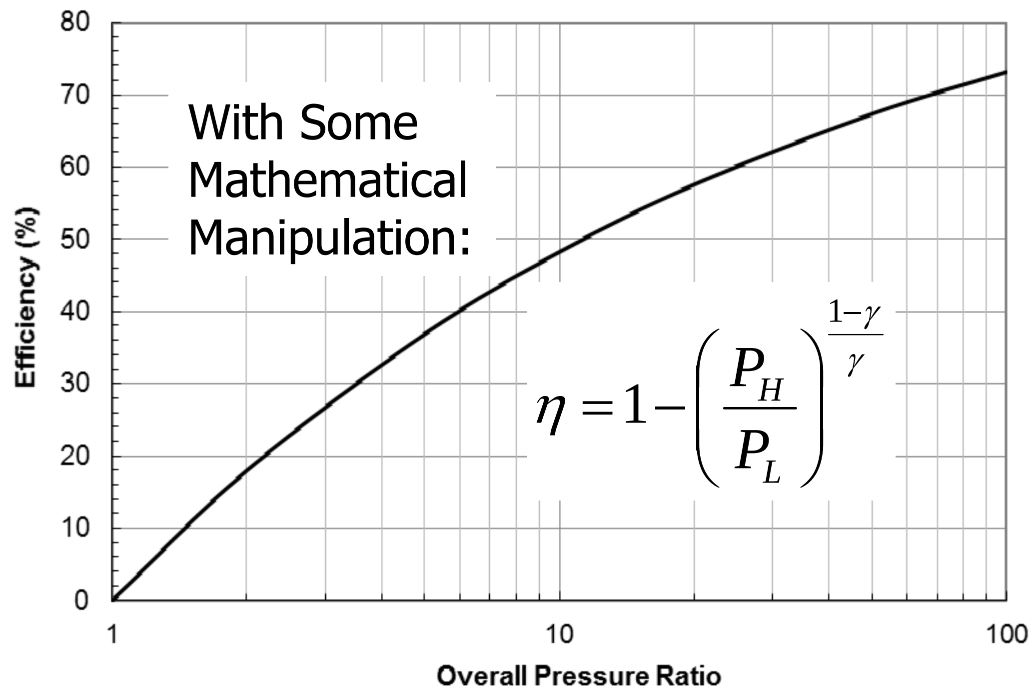
Gas Turbine Performance

Ideal Simple Cycle Efficiency – As Good as it Gets

$$\text{Efficiency } (\eta) = \frac{\text{Useful Output}}{\text{Total Energy Input}}$$

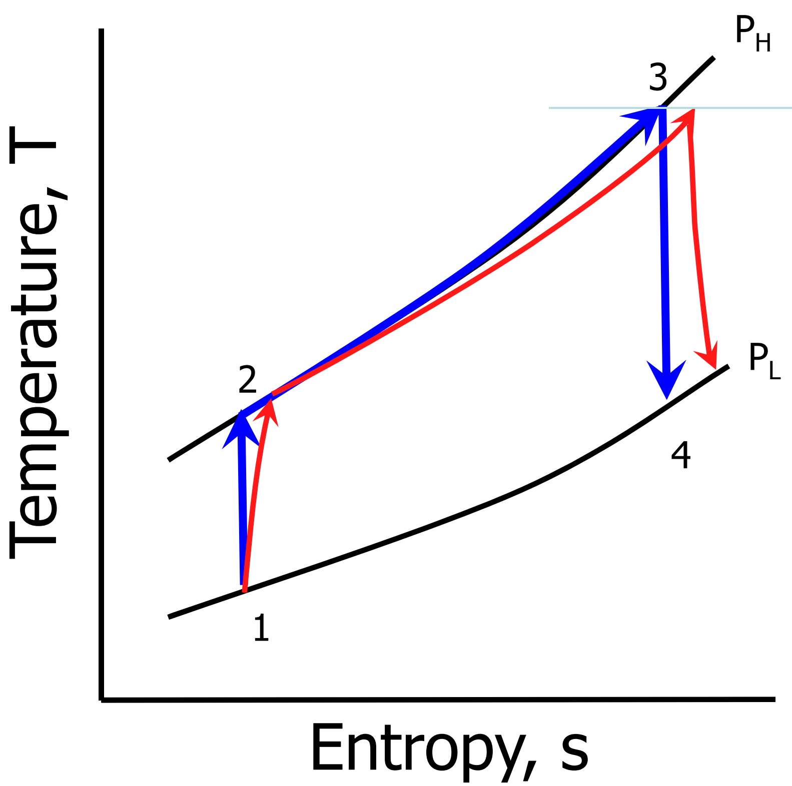
$$\approx \frac{(T_3 - T_4) - (T_2 - T_1)}{(T_3 - T_2)}$$

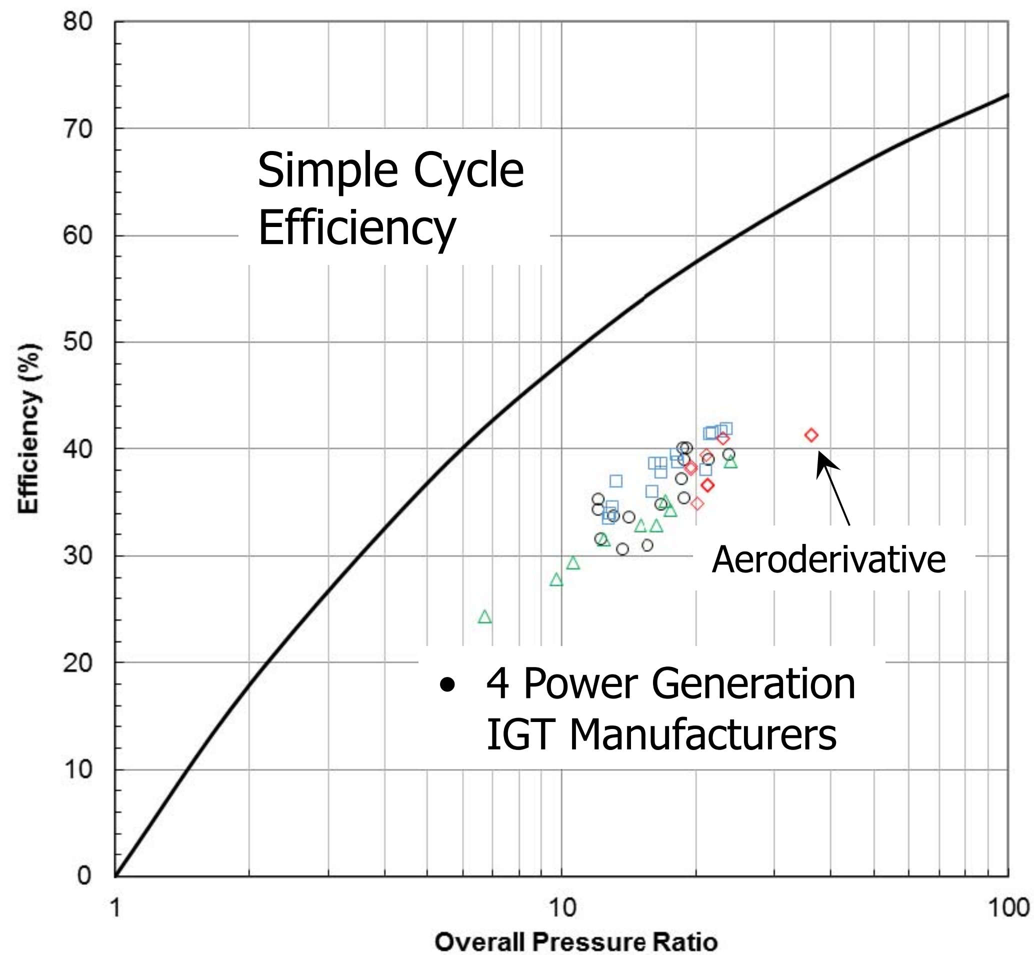




Gas Turbine Performance

Reality √ – Real Component Performance Reduces Efficiency





Gas Turbine Performance

Increased Pressure Ratio Needed to Reach Goals

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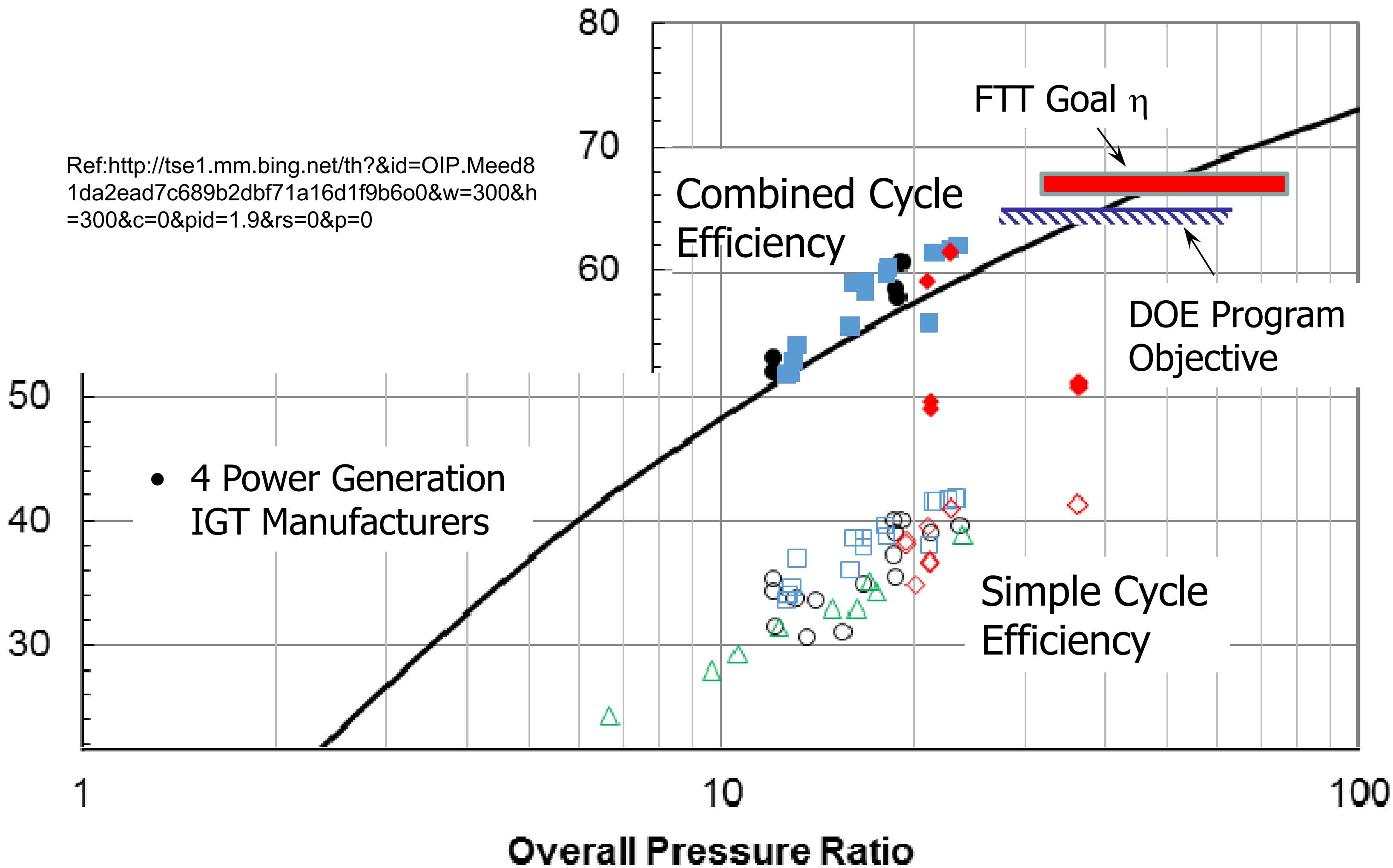


Turbomachinery Technology Development at FTT

FTT Design Solutions

Problem – For Single Shaft Architecture, High Pressure Ratios Decrease the Size of the Core Hardware … Reduces Component Efficiencies

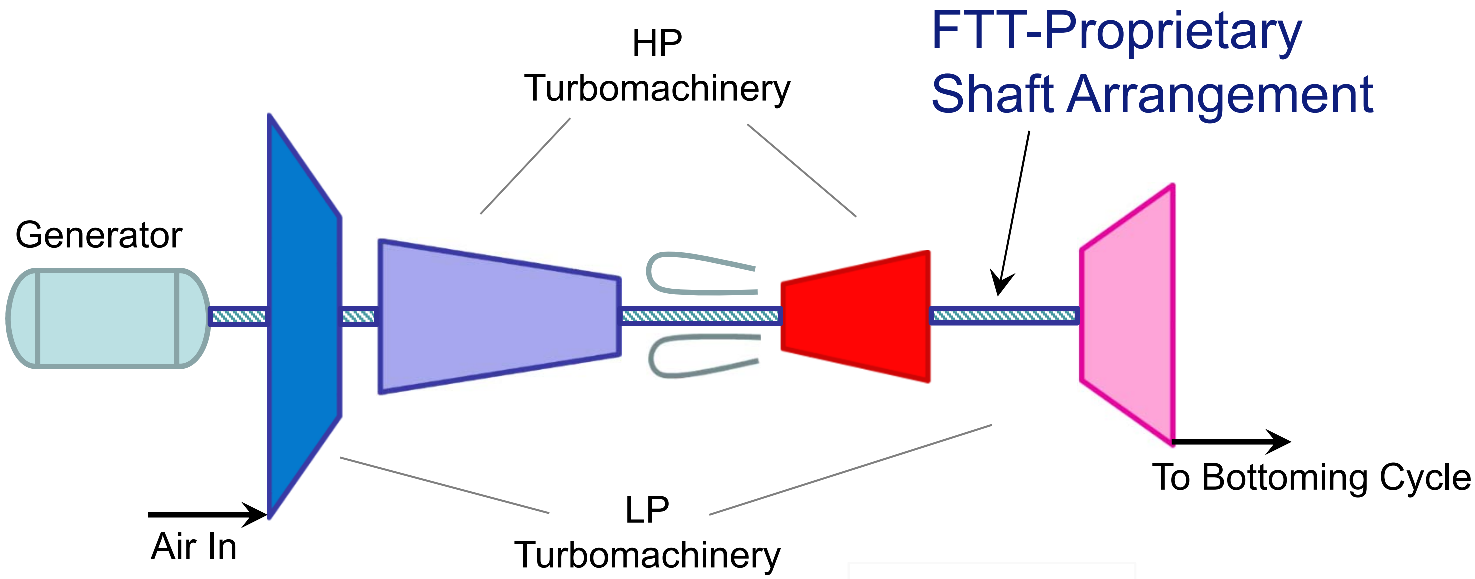
http://www.netl.doe.gov/scng/projects/end-use/at/images/at31176HseriesTurbine.jpg

- Today's IGT operates on a single shaft
- Size is limited due to last stage turbine blade pull stress as quantified by AN^2

- Requires Innovation to Mitigate Effects of Shrinking Core Size
- FTT Offers New Solutions to Historical IGT Problems

FTT Innovation

Aircraft Engine-Derived Multi-Shaft Architecture – TurboGT™



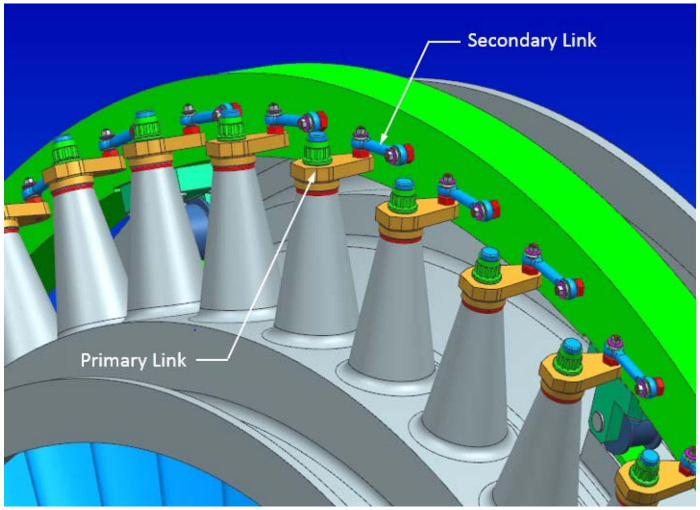
FTT Patents Pending

- 2X pressure permits 2X flow through expensive core parts
- Extended operability
  - Downturn to 10% power

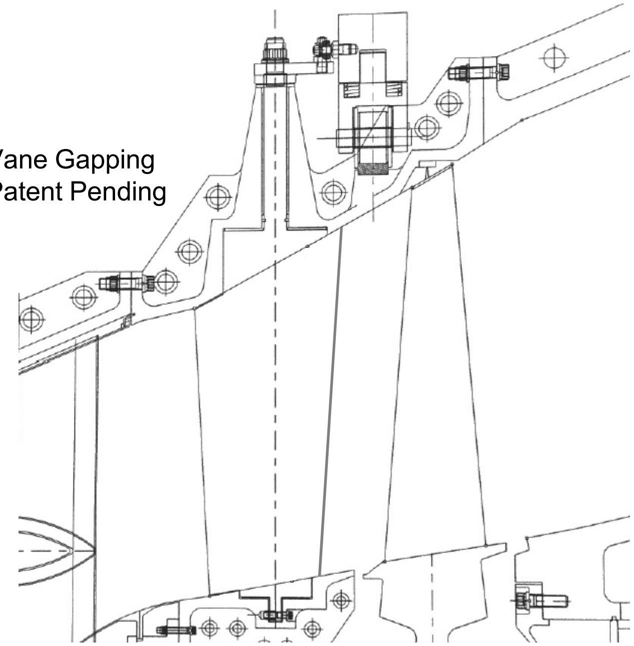
Operability

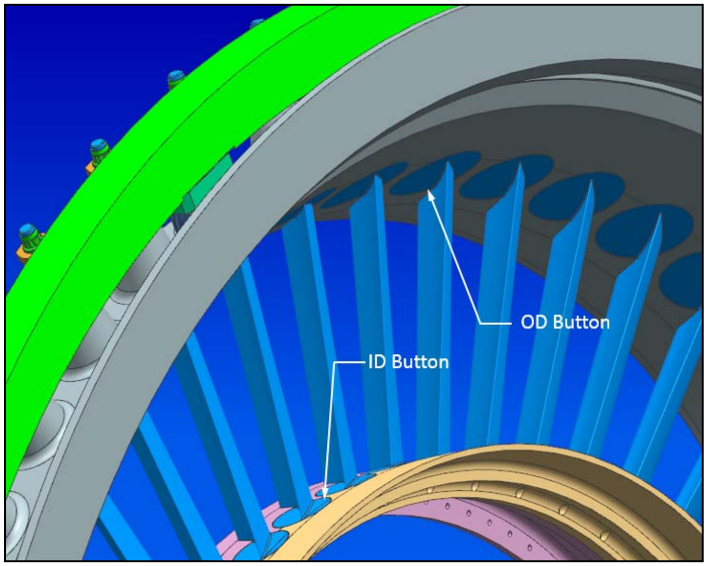
Variable Turbine Geometry

- Improves responsiveness to intermittent power demands caused by increased use of renewables
- Enables substantial expansion of turn-down envelope



Vane Gapping
Patent Pending

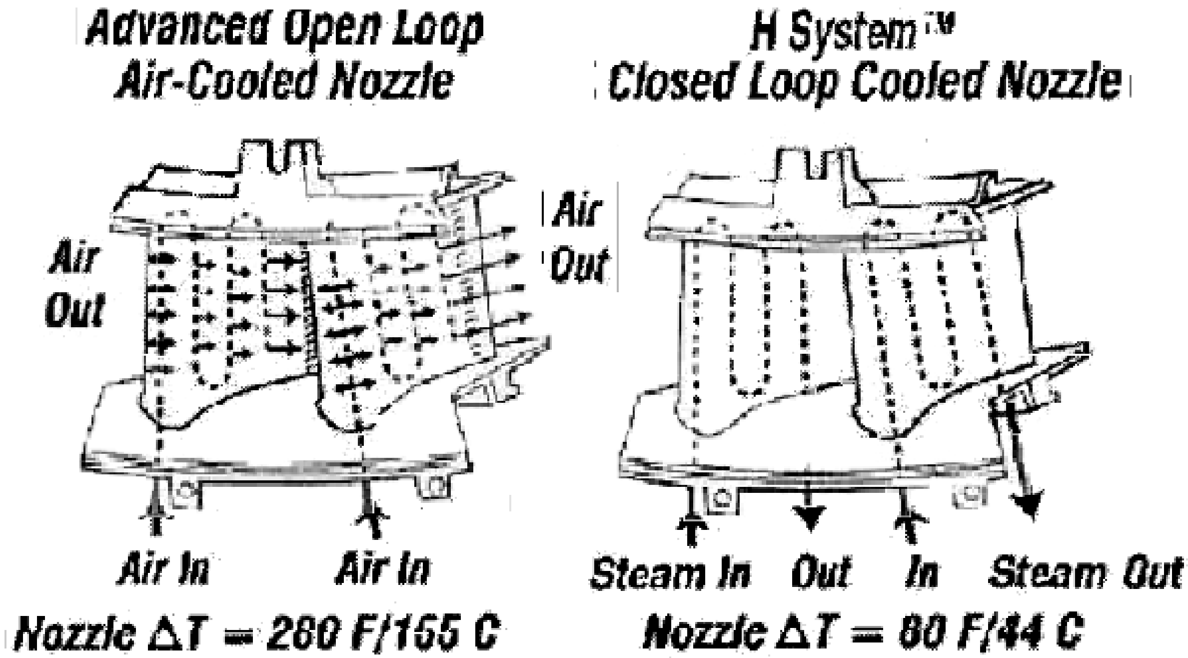




Turbine Cooling

Problem: C/A Dilution Increases Turbine Inlet Temperature

Independent Assessment/Conclusion:



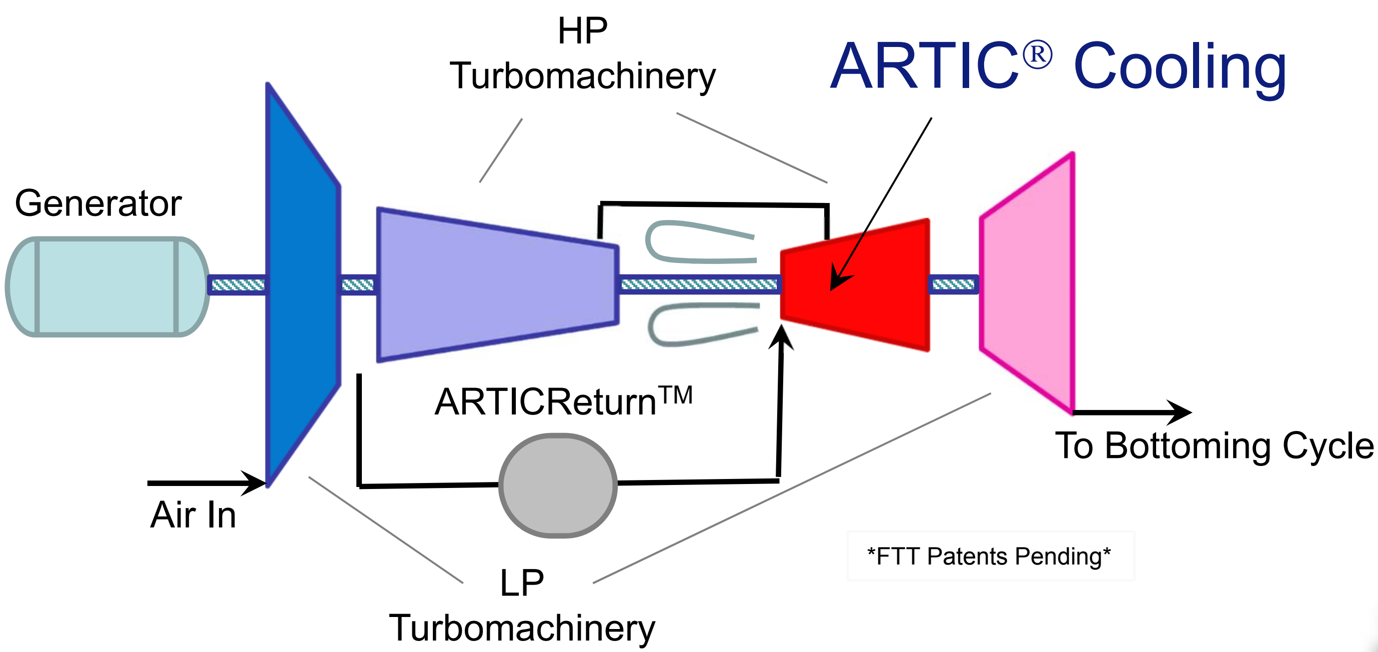
- Enables rotor inlet temperature to be increased 200°F/111°C
- Mitigates emissions impact

⇒ Benefits of Internal Convection Cooling are Well-Established

Ref: GE ATS Final Report, June 2001

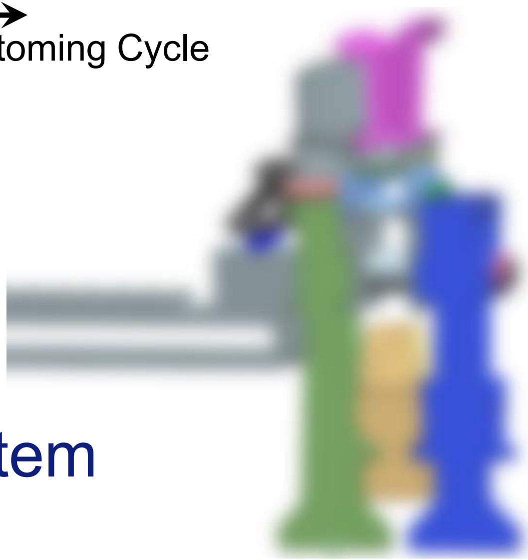
Turbine Cooling

Enhanced Cooling to Address Increased Turbine Inlet Temperature



FTT Patents Pending

Iteration #1 Geometry



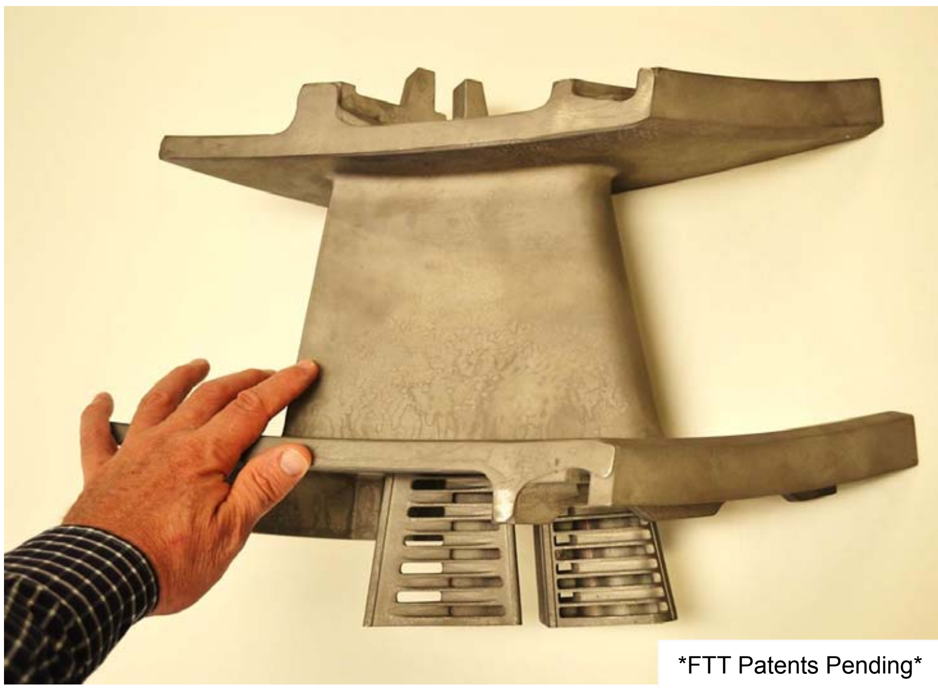
ARTICReturn™ Cooling System

Turbine Cooling

Fundamentals of ARTIC® Vane 1 Cooling Technology Demo'd Under DOE Contract DE-FE0006696

Demonstrator Hardware Produced

- Rapid prototype technologies



FTT Patents Pending

Demonstrated in Full-Scale IGT

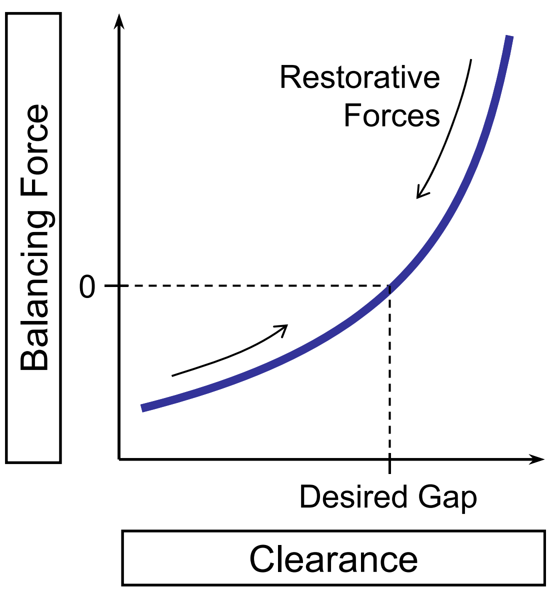
- Engine ran from March to April, 2014 with ARTIC™ parts installed
- Total estimated run time ~ 115 hours
  - ~25 hours at maximum power temperature rating
- Total estimated number of cycles ~ 50
- All objectives of planned test campaign were completed

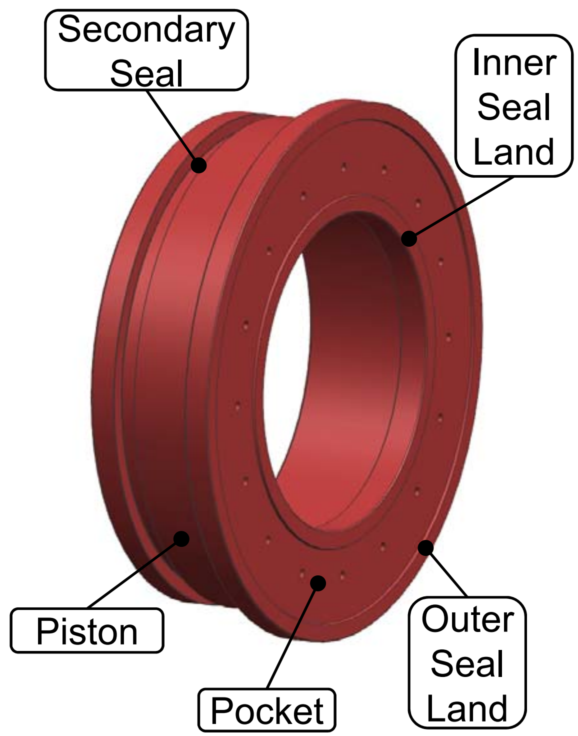
→ New Application in TurboGT™ as ARTICReturn™

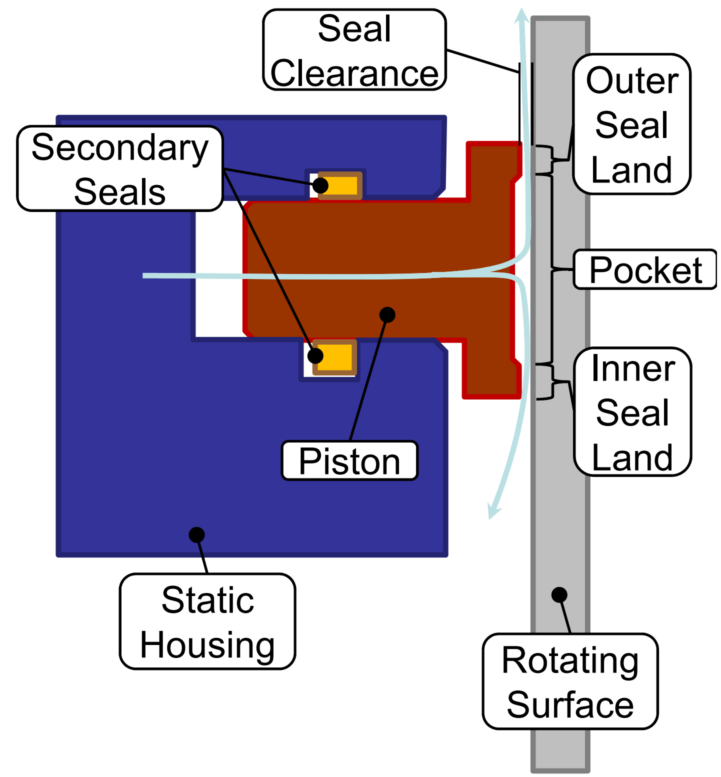
Advanced Leakage Control Technology

Air Riding Seal Concept (Jake Mills, Principal Investigator)

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

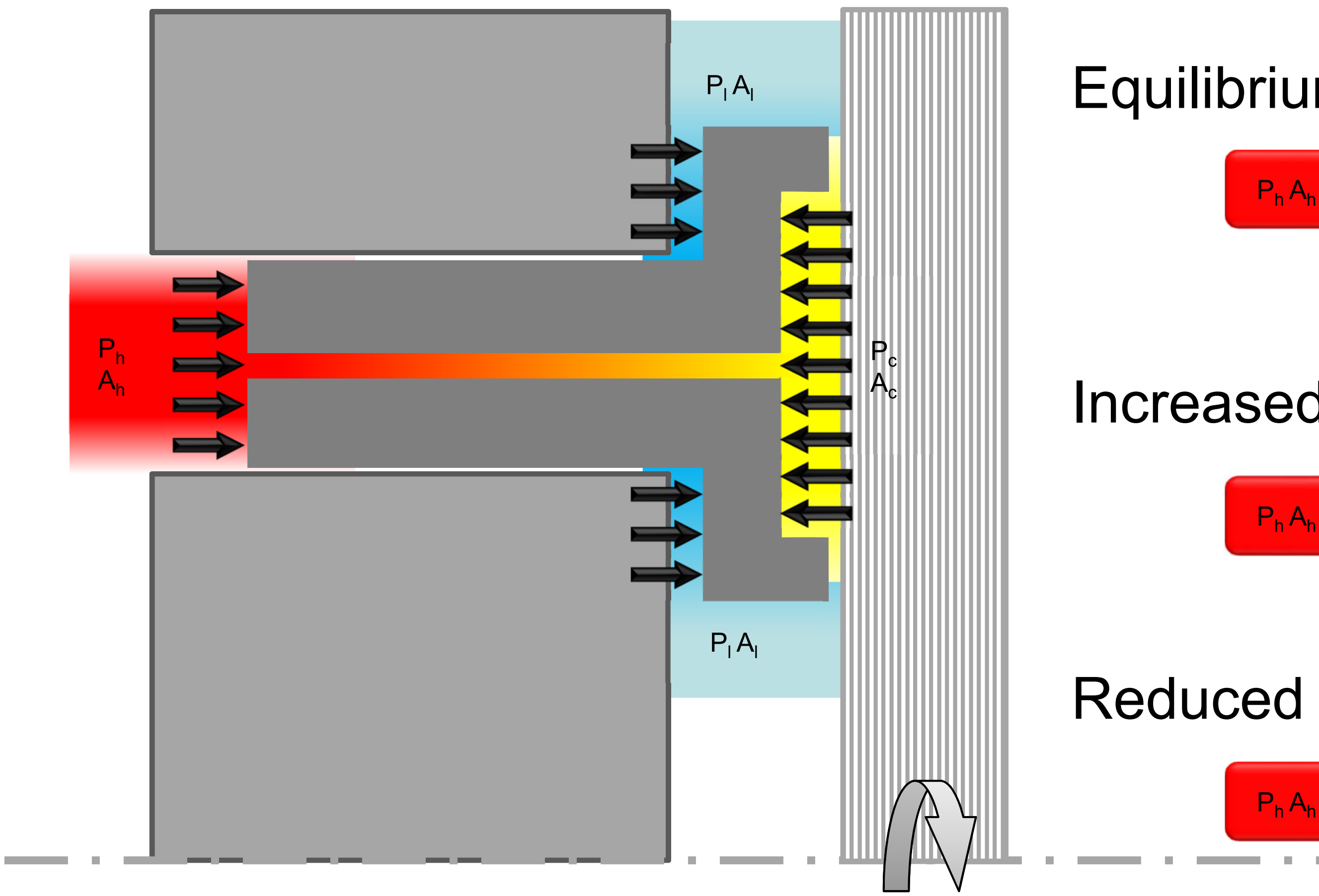






Advanced Leakage Control Technology

Air Riding Seal (ARS) Concept



Equilibrium $\Sigma F_x = 0$

$P_h A_h + P_l A_l = P_c A_c$

Increased Clearance $\Sigma F_x = \rightarrow$

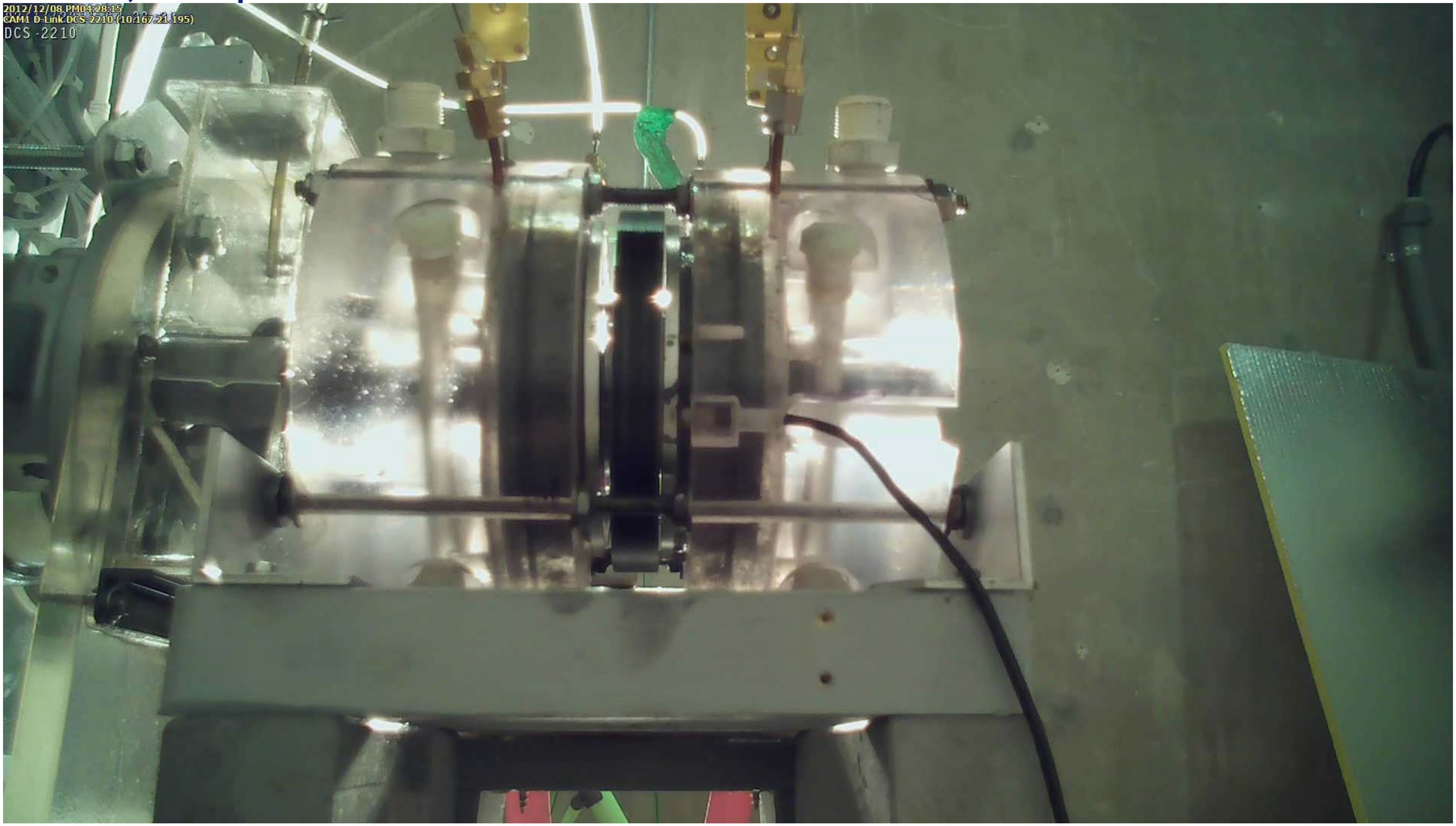
$P_h A_h + P_l A_l > P_c A_c$

Reduced Clearance $\Sigma F_x = \leftarrow$

$P_h A_h + P_l A_l < P_c A_c$

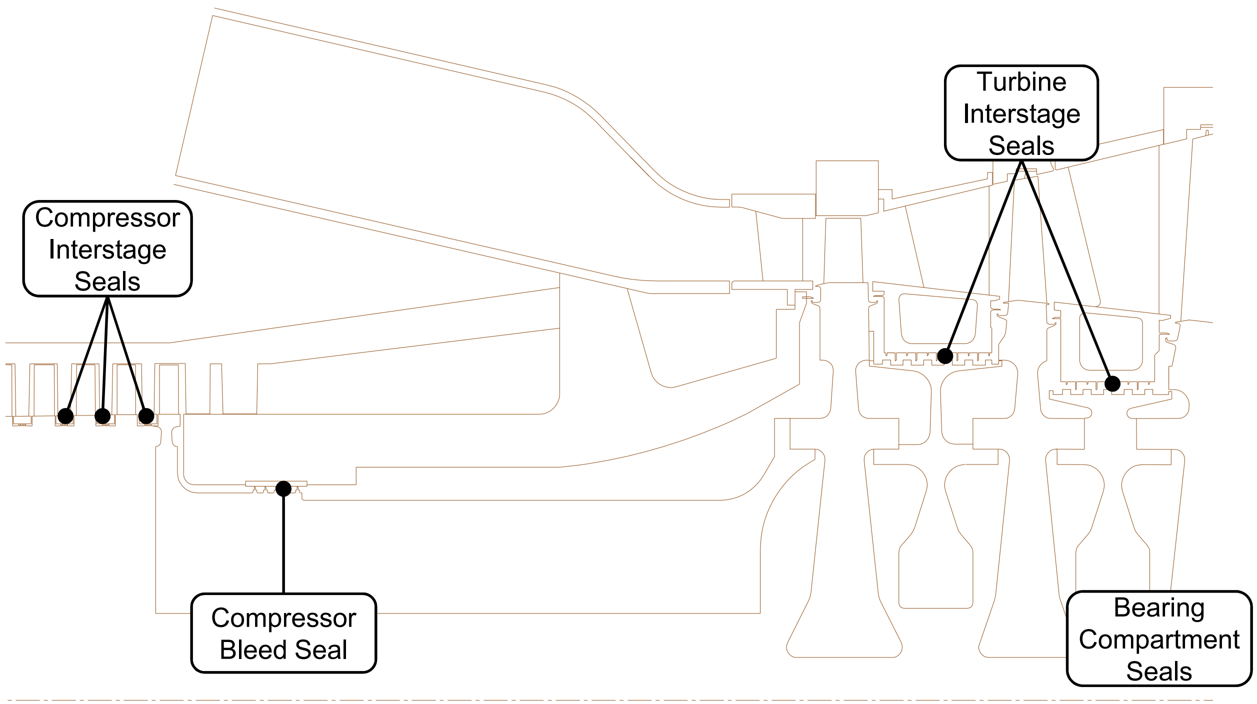
ARS Technology Demo'd in Phase I

20,000rpm Seal Pressurization/Activation



ARS Application

ARS technology applicable to a variety of rotating to static seals

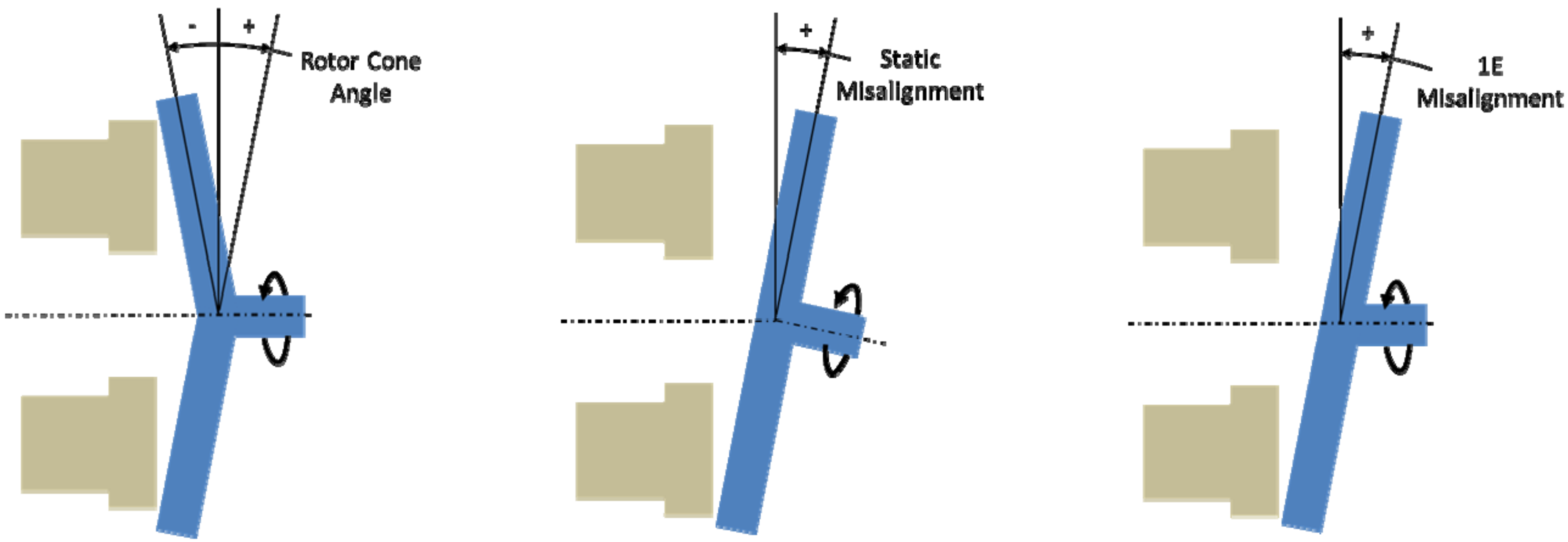


- Large utility scale engine performance model created to assess benefits of retrofitting an engine with the ARS technology

Rig Testing

Design-to-Test Operating Considerations

- Testing centered around engine operating conditions
- Rig allows for variation of a variety of design variables to understand the ARS design space and to calibrate/validate the analytical tools.



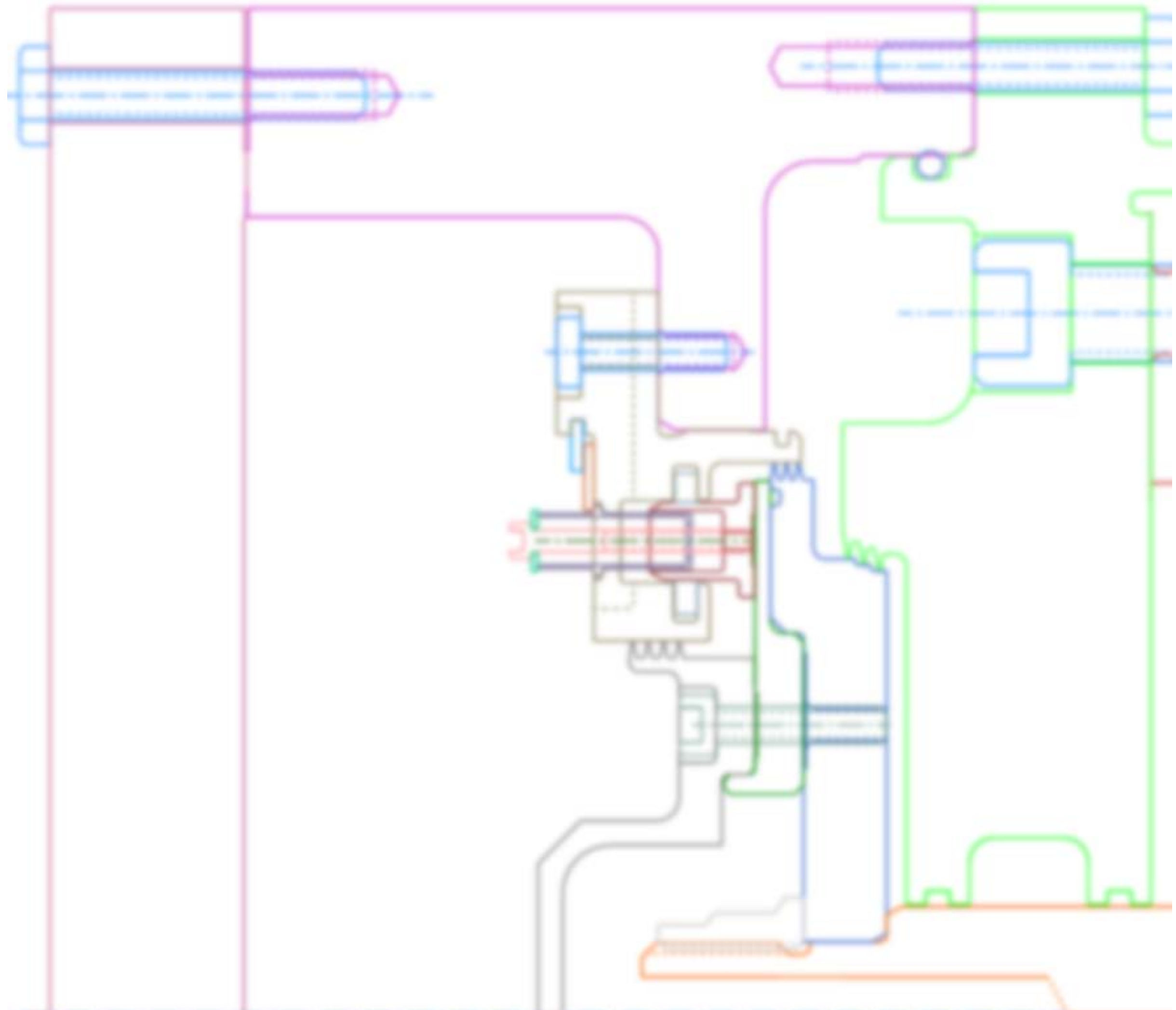
Future ARS Engine Testing

- To reduce cost and risk for future engine testing, the initial application of the ARS has been designed for the 501K
  - The ARS will be tested in a rig at engine conditions under the Phase II contract
  - Rig hardware has been designed to integrate into the engine

- ARS replaces the 'thrust balance seal' upstream of the first stage turbine

Project Overview

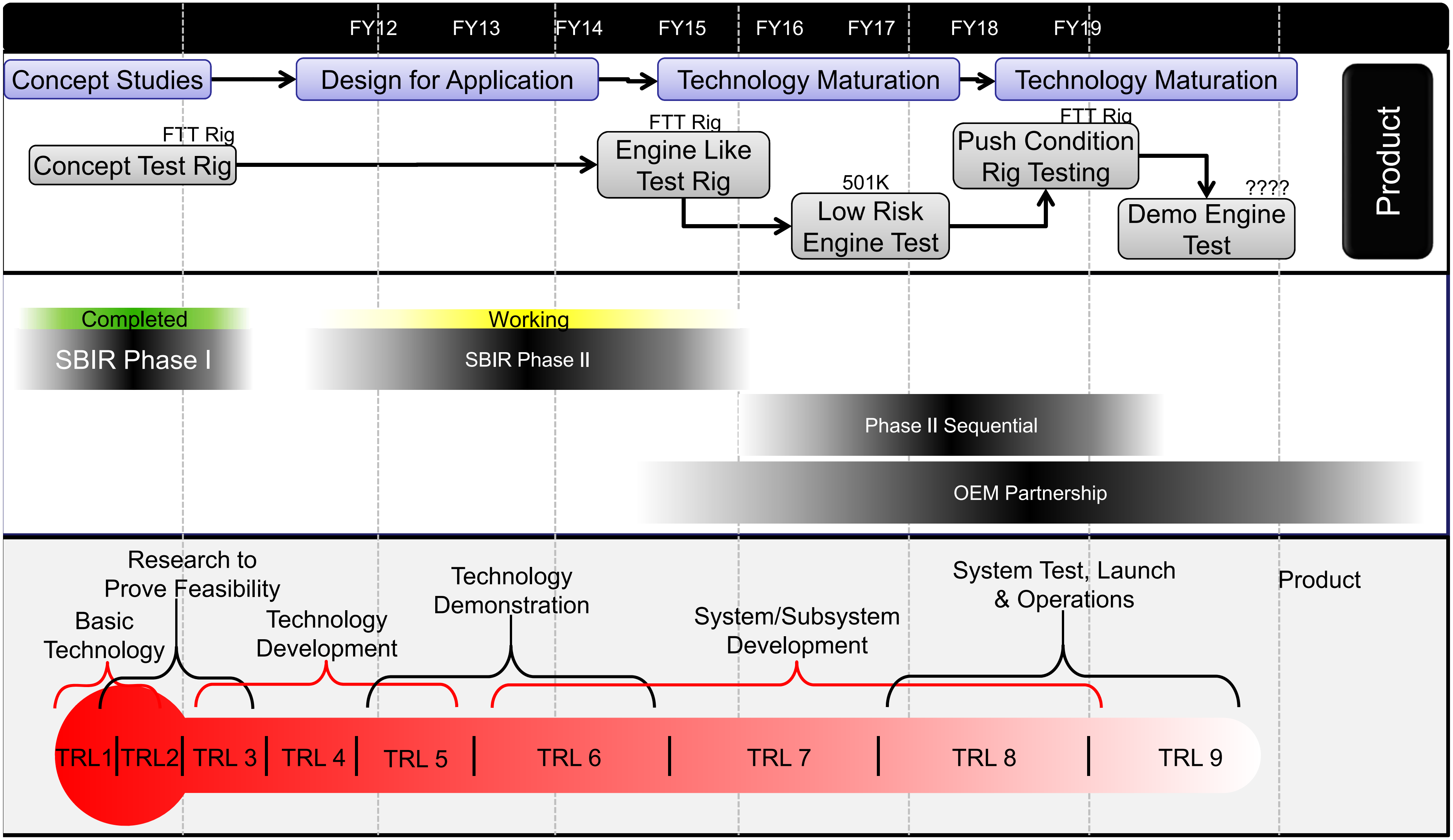
Rig



Rig

- Designed around engine hardware
- Design requirements and test objectives established from engine OEM
- Designed to establish a large design space centered around engine conditions

ARS Tech, Development Roadmap



TurboGT™ Conceptual Design Status

- Thermodynamic Performance Model for *TurboGT™* has been Created Using GateCycle Software

- High Fidelity Based On:
  - FTT's fast-Iteration conceptual design system with:
    - Calibrated aerodynamic and turbine design codes
    - Compressor aerodynamics (Component efficiencies and diffuser pressure losses)
    - Turbine aerodynamics (Stage pressure ratios and efficiencies in HPT and LPT)
    - Fast FEM
    - Completed analysis: Rotor dynamics, Thrust balance, SAS
    - Incorporation of cooling and leakage flow rates and pressure losses based on latest mechanical arrangement
- Over past 12 months, design elements have been balanced to achieve a robust conceptual design which will be reviewed with the DOE in coming weeks

TurboGT™ Cost Impact

Multi-Pronged Approach to Reduce COE

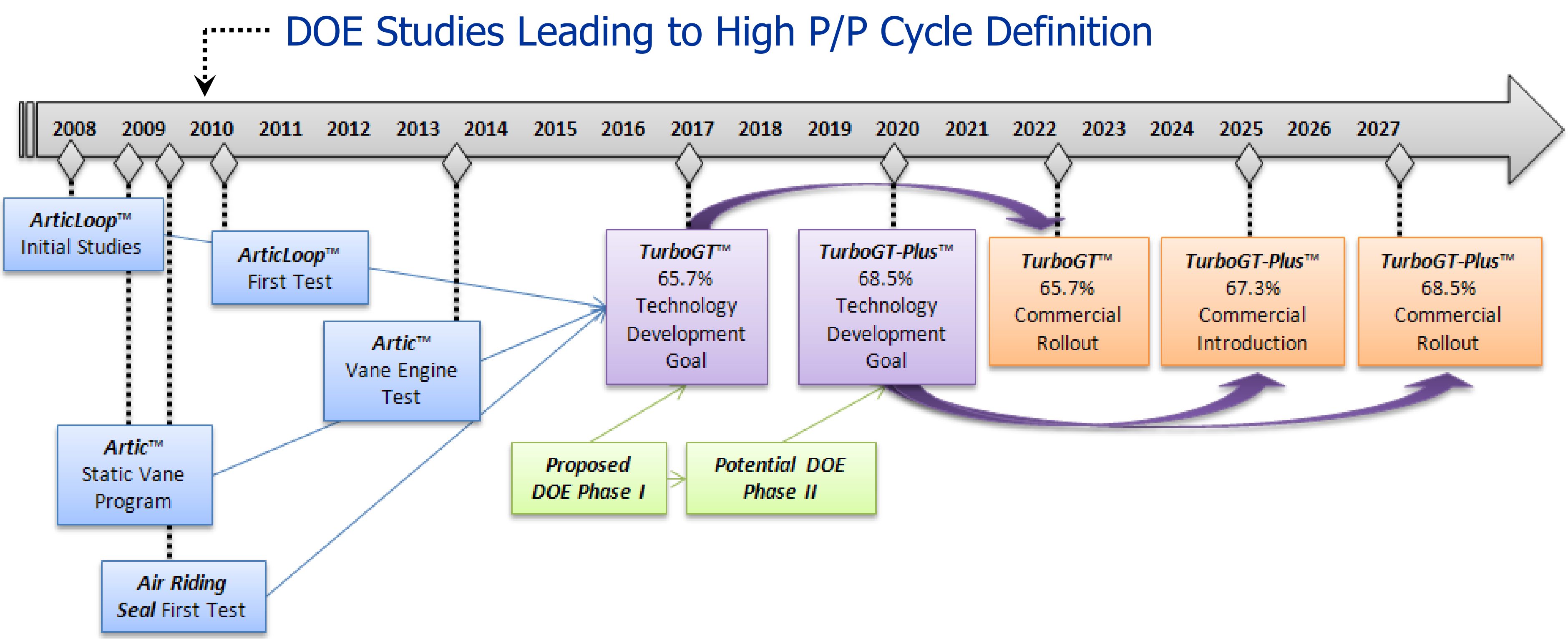
- Low Equipment First Cost
  - More Steel, Less Nickel, per Megawatt
- Low Operating Cost
  - High Efficiency Maintained Over Wide Operating Range
  - Increased Utilization (Turn-Down to 10% Load)

➢ On Track For:

- CC cost reduction > 25%
- SC cost reduction > 30%

TurboGT^{TM} Development Roadmap

Goal is for Technology Development of a 65% Combined Cycle to be Complete by 2017, with Commercial Rollout by 2022



Opportunities for UTSR Collaboration

- System-Level
  - Operability and controls validation
  - Controls logic development
- Component-Level
  - High pressure low NOx combustion using gaseous fuels
  - Emissions control over wide range of operating conditions
  - Coatings for high pressure environment
  - Cooling technology development
  - Seal durability test opportunities

Summary

- TurboGT™ Addresses All of the Advanced Turbines Program Goals
  - Affordability
  - Efficiency
  - Operability
  - Increased Temperatures
- Leverages Prior Successful FTT/DOE Component Development Experience
- Following Demonstration/Validation Test Phase, Commercial Rollout Could Be Realized by 2022
- Many Opportunities for Collaboration with UTSR Universities

Acknowledgements

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Thank You & Questions?