Dan Frias
05/02/2018

HONEYWELL CLEEN II

Open Discussion – May 2018

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Agreement Number: DTFAWA-15-A-80017
Contractor Name: Honeywell International Inc.
Address: 111 S. 34th Street
Phoenix, Arizona 85072-2181

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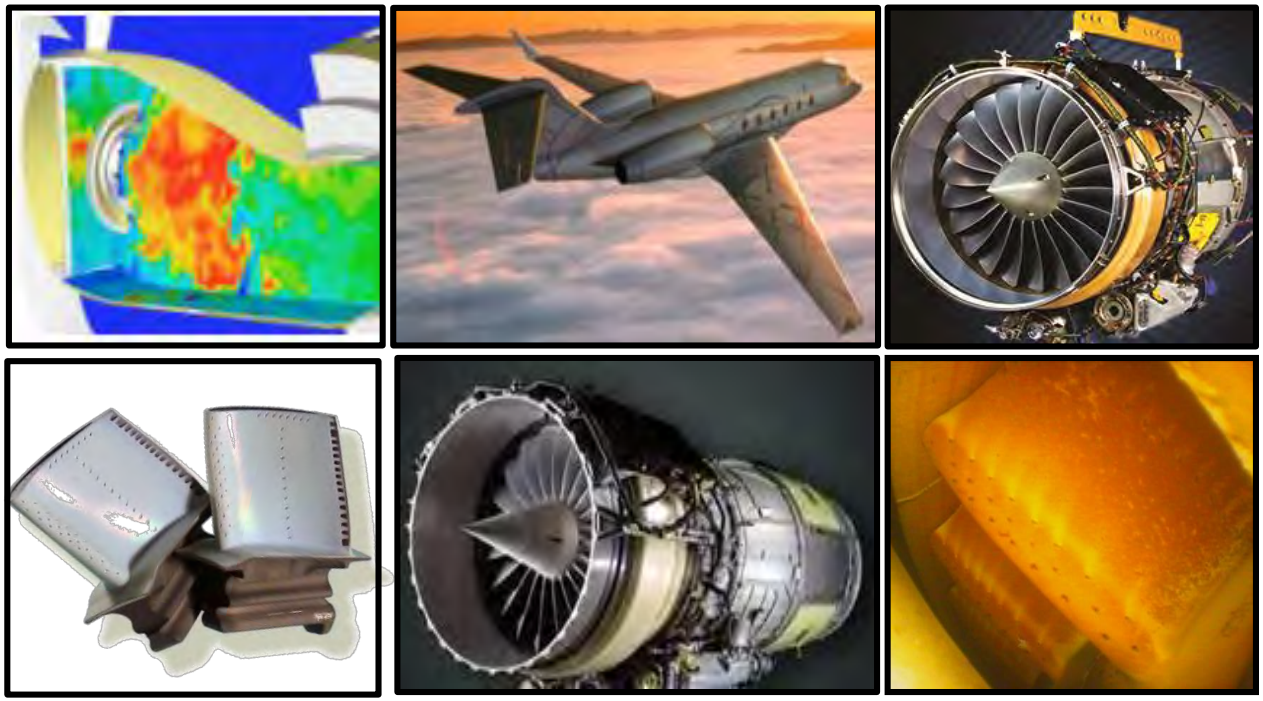
Agenda

- Elevator Speech
- Honeywell's Products and CLEEN II
- CLEEN II Technologies
  - Challenges, Benefits and Opportunity Costs
- Technology Maturation Approach and Program Schedule
- Engine and Aircraft Systems Analysis Status
- Technologies Status – Compact Combustor
- Technologies Status – Blade Outer Air Seal (BOAS)
- Future Plans
- Summary

CLEEN II Elevator Speech

- Honeywell's CLEEN II program is maturing advanced combustor and turbine technologies to reduce weight, fuel burn and emissions



Honeywell's Broad Base of Commercial & Military Turbine Products

APUs

100 to 1400 hp for commercial and military aircraft

Turbofan Engines

3,000 to 10,000 lb thrust for commercial and military aircraft

Turboprop Engines

575 to 1,600 shp for commercial and military aircraft

Turboshaft Engines

500 to 5,000 shp for tanks, commercial and military rotorcraft

B08-147

Over 150,000 Turbine Engines Delivered – Large Installed Base

Next Gen Turbofan Can Benefit from CLEEN Technologies to Reduce Fuel Burn and Emissions

- State-of-the-art performance
- Industry leading dispatch reliability
- Quantum leap in value: cost and durability
- Versatile technology: 7000-10000 lbs thrust
- Five aircraft applications to date
  - > 1000 engines in service
  - > 2 million flight hours

HTF7000 Series

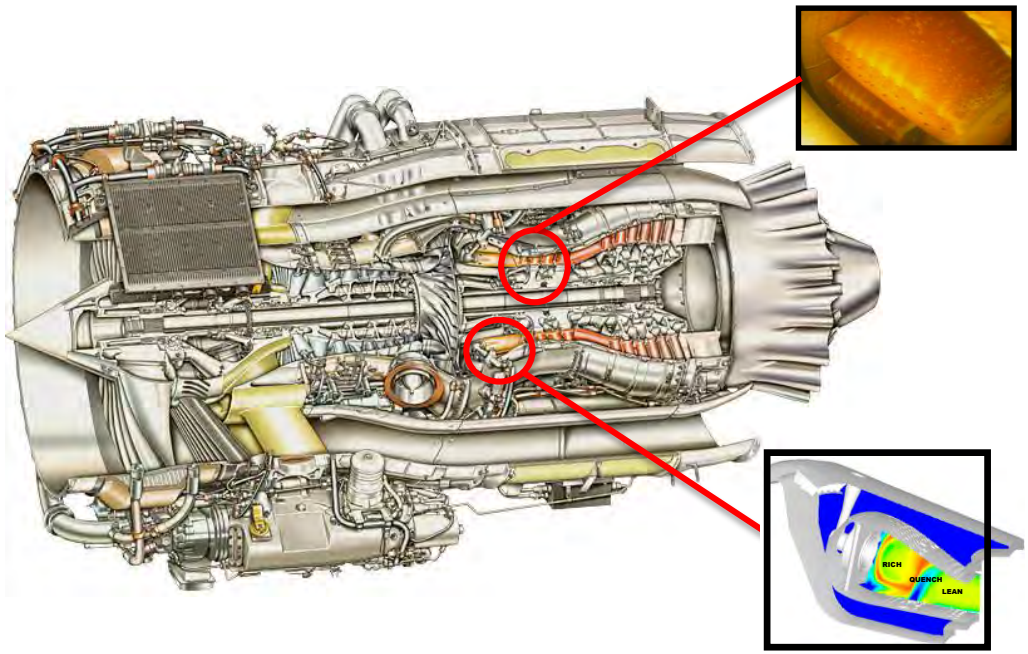
Engine	Platform
HTF7000	Bombardier Challenger 300
HTF7350B	Bombardier Challenger 350
HTF7250G	Gulfstream G280
HTF7500E	Embraer Legacy 450/500
HTF7700L	Cessna Citation Longitude

CLEEN Technologies Enhance Future Product Capabilities

Honeywell CLEEN II Technologies

- Under CLEEN II Honeywell is developing and demonstrating advanced Combustor and Turbine technologies.

Blade Outer Air Seal



Compact Combustor

The advanced ***Turbine BOAS*** increases high pressure turbine efficiency, resulting in reduced fuel burn.

Compact Low Emissions Combustor *integrates* advanced aerodynamics and fuel injection technologies to reduce engine NO_X emissions and weight, contributing to reducing fuel burn.

Honeywell CLEEN II Technology Challenges

CLEEN Technology	Technical Challenge	Technical Approach
Compact Combustor System	NOx	Optimize Primary Zone Aerodynamics, fuel placement and reduce residence time. Validate at full engine conditions.
	Operability	Improve atomization and fuel placement. Validate at altitude relight conditions in test rig.
Advanced Turbine BOAS System	High Temperature and Weight	Select advanced light weight, high temperature materials and coatings.
	Leakage	Design to minimize leakage between shroud and advanced turbine blade tip for improved turbine efficiency.

CLEEN II Technology Summary

CLEEN Technology Name	Goal Impact	Benefits, Applications and Collateral Benefits
Compact Combustor System	**Emissions**	• **Goal to reduce NOx emissions to >50% margin to CAEP/8**, for next generation super mid-sized class business jet turbofan engines for 2025 entry into service (EIS)

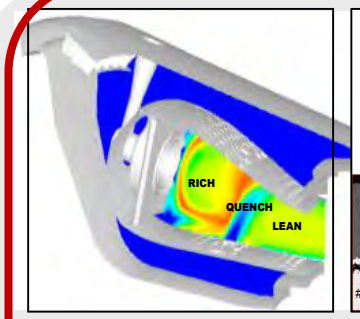
Advanced Turbine BOAS System
 	
Compact Combustor
	Fuel Burn	• **Goal to reduce turbofan engine fuel burn >22%** relative to the Baseline Engine for next generation turbofan, turboshaft, turboprop engines and large auxiliary power units (APUs) for 2025 entry into service (EIS)
		
		Collateral Benefits
		• FAA CLEEN programs support validation of Low-K TBC and Alloy-10 Powder Metal Super-alloy.
		  • Currently being evaluated by major aerospace and industrial Engine OEMs.
		  • Applied to current and future turbine propulsion and industrial engines should increase fuel efficiency and lower operating costs

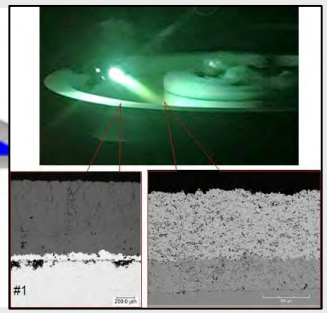
CLEEN II Value and Opportunity Cost

Technology	CLEEN II Value	Opportunity Cost *(If FAA had not funded…)*
Fuel Burn	Enables >22% fuel burn improvement over baseline engine through an advanced engine architecture with high efficiency turbine technologies	Likely delays technology development and implementation of advanced fuel burn technologies impacting near term reductions in fuel burn and CO2 emissions.
Emissions	Enables > 2x improvement in NOx margin over Honeywell state-of-the-art combustor through integration of advanced combustor aerodynamics, fuel placement and materials	Achieving ultra-low emissions is very challenging and requires major investment. Without FAA support, level of internal investment reduced and level of current customer/regulatory requirements, will result in delayed implementation of ultra low emissions technologies.

Technology Maturation Approach

TRL 3 TRL 4 TRL 5 TRL 6





Analysis and Technology Demonstration Testing

Component / System Development Testing

Engine Demonstration and Validation Testing

May 2018 Status

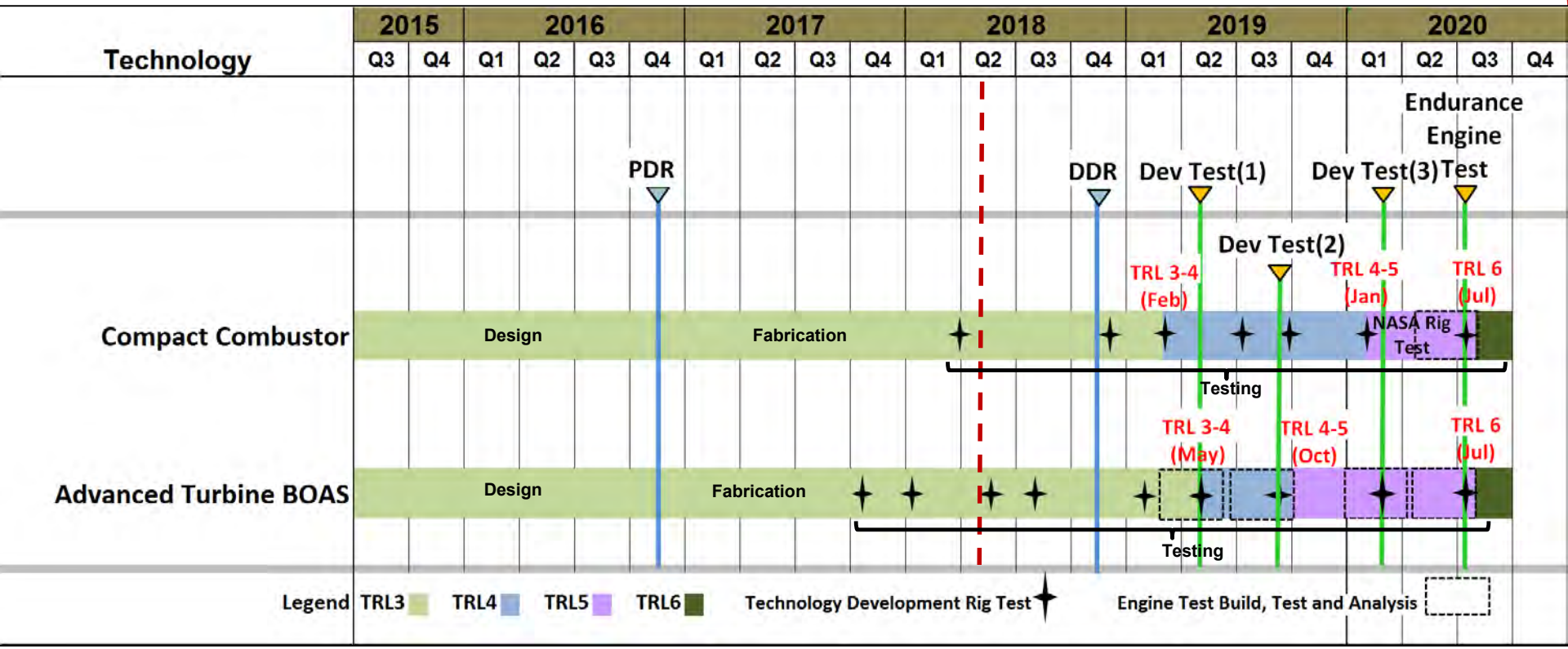
Progressive Approach to Validate Technology and Reduce Risk

Progress and Achievements

- **Engine System Level Risk Assessment complete**
- **Preliminary Design Reviews (PDRs) complete**
  - Engine System Architecture and Cycle Defined
  - Compact Combustor Design
  - Blade Outer Air Seal (BOAS) Design
- **Blade Outer Air Seal Development**
  - Material Characterization complete
  - Air Plasma Spray (APS Thermal Barrier Coating (TBC) Process Down-select complete
- **Combustor Development**
  - Multiple design configurations analyzed and rig testing complete
- **Communicated Progress ~ Monthly Reports and Consortiums**

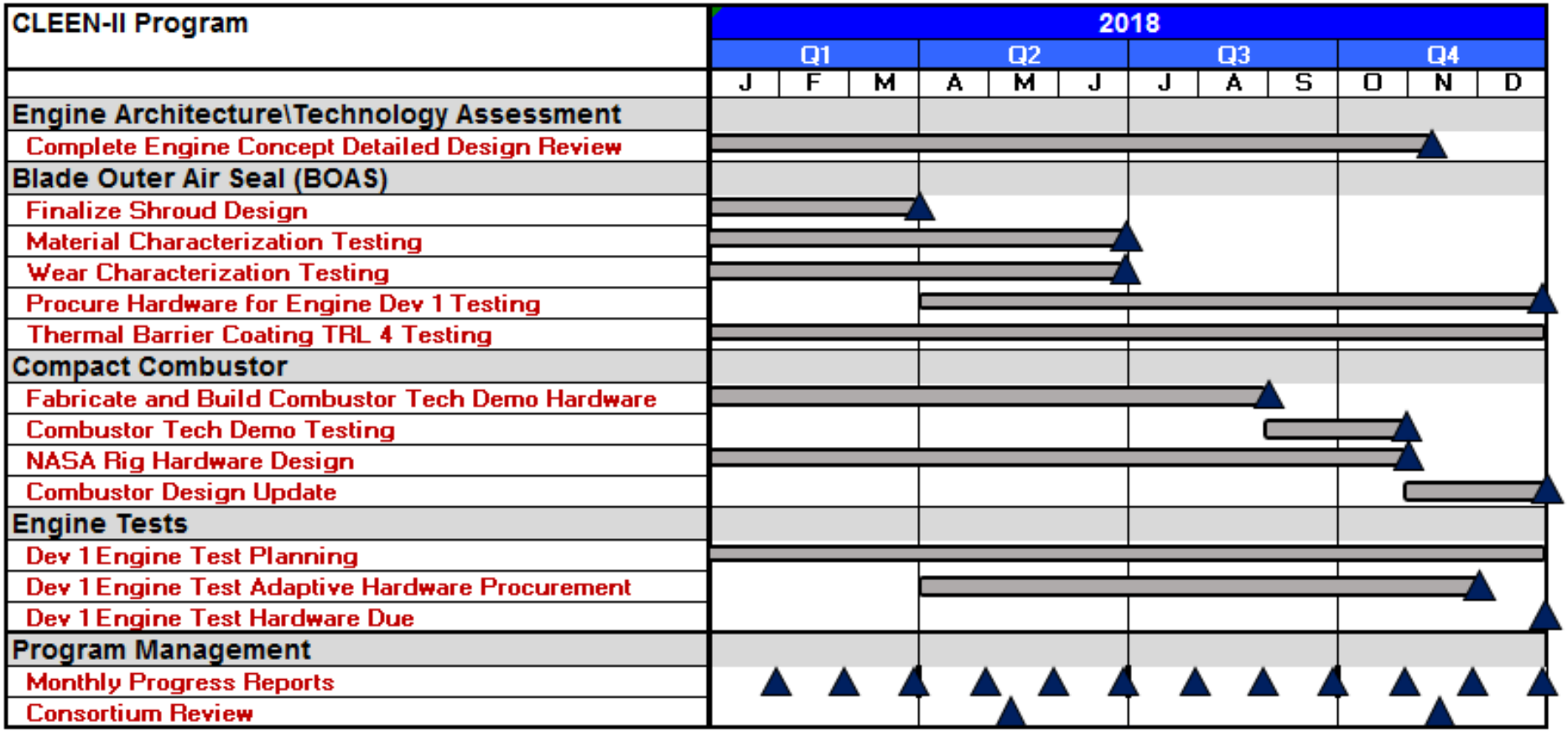
Next Steps to Refine and Validate Technology Designs

Overall Program Schedule

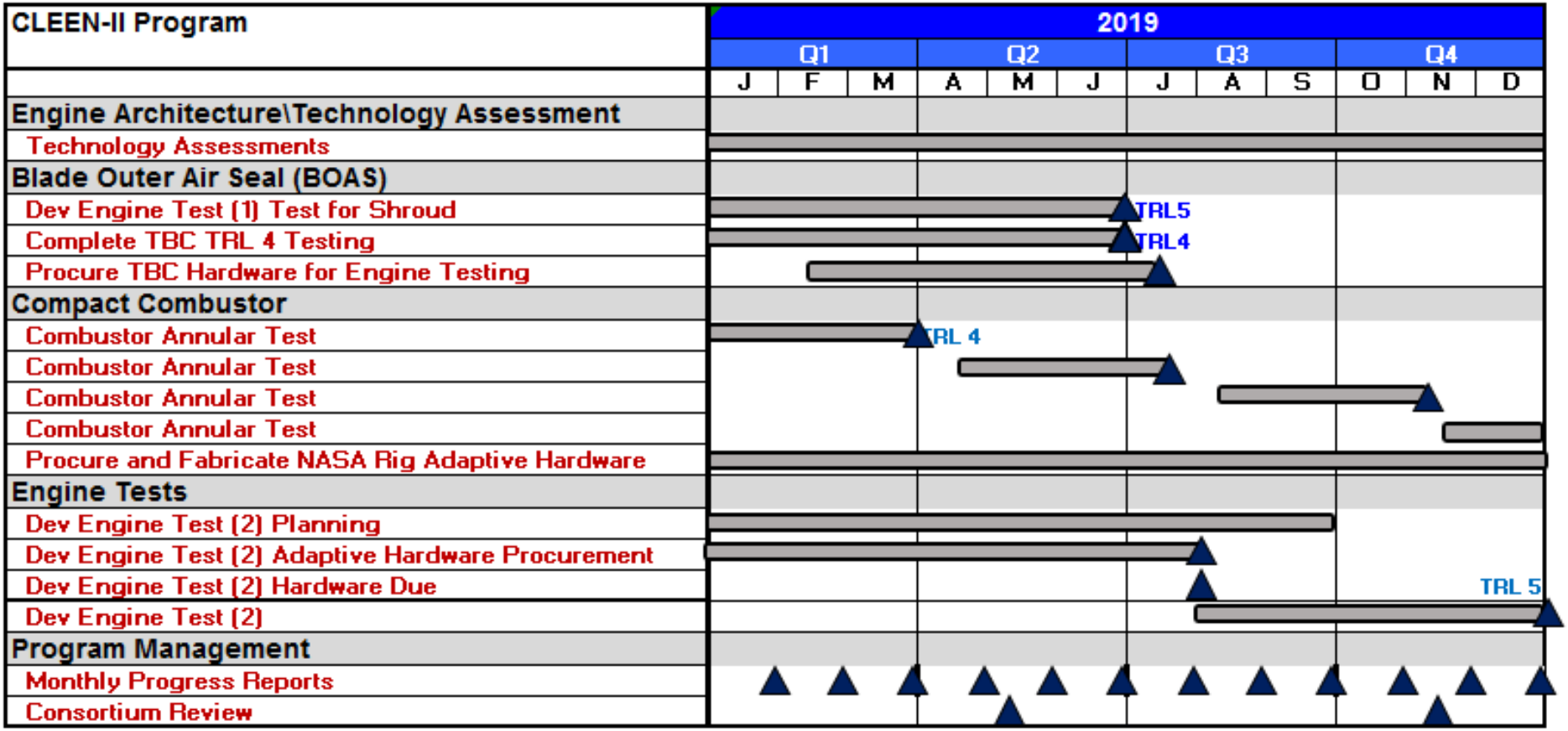


TRL = Technology Readiness Level

2018 Project Schedule

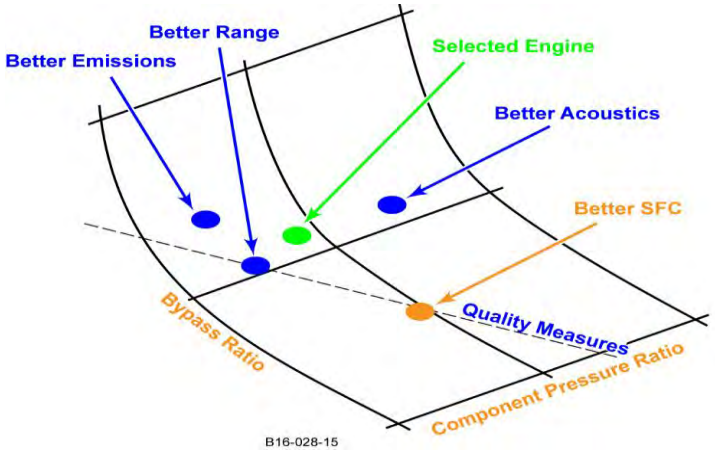


2019 Project Schedule



Engine and Aircraft Systems Analysis Status

Engine and Aircraft Systems Analysis



Benefits

- Reduced engine thrust specific fuel consumption (TSFC)
- Improved power-to-weight ratio
- Reduced fuel burn and NOx emissions

Risks/Mitigations

- Insufficient aircraft fuel burn assessment/work with Gulfstream and Georgia Tech

Objectives

- Define a 'CLEEN II' engine with advanced technologies that enable reduction in fuel burn and NOx emissions.

Work Statement

- Perform Engine Preliminary and Detail Engine Concept Reviews along with independent assessments of the technology benefits.

Accomplishments/Milestones

- Engine Preliminary Concept Design Review complete
- Gulfstream Assessment complete

Technology Schedule

CLEEN II	2015	2016	2017	2018	2019	2020
System Analysis		▲		▲		
Task 1 - PDR		▲		▲		
PDR			◆			
Task 2 - DDR			▲		▲	
DDR					◆	

Engine and Aircraft Systems Analysis Accomplishments and Next Steps

Accomplishments

- Completed Gulfstream quantitative assessment of mission fuel burn for engine/aircraft integration
- Continued work with Georgia Tech to perform independent assessment of fleet-wide impact. Established data plan required from Honeywell

Next Steps

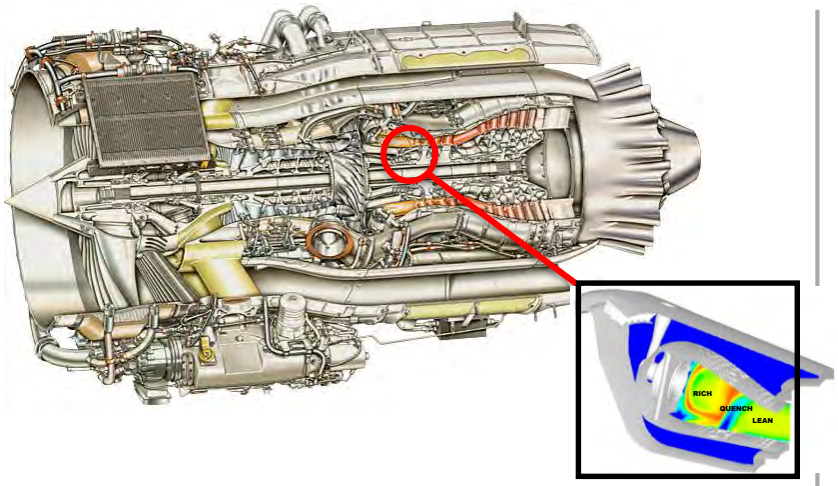
- Complete Engine Detailed Design Review (DDR)
- Honeywell to provide assessment information to Georgia Tech

Systems Analysis Progressing Well to DDR in Q4 2018

CLEEN II Technologies Status

Compact Combustor

Combustor System Technology



Benefits

- Reduction in fuel burn
- Lower engine emissions

Risks/Mitigations

- Operability - Rig test validation at Altitude cond.
- Emissions - Test validation at full engine cycle operating conditions in NASA facility
- Combustor Durability - Demo Engine cyclic test

Objectives

- Reduce NOx emissions
- Reduce combustor weight

Work Statement

- Develop and demonstrate a low emission compact combustor for improved NOx and fuel burn in a an engine.

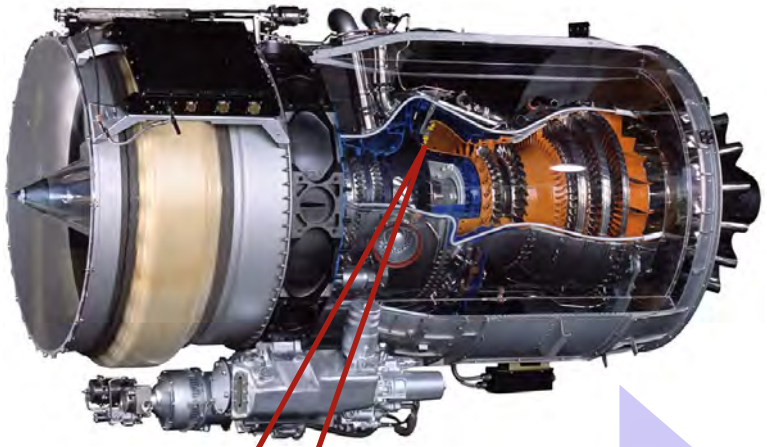
Accomplishments/Milestones

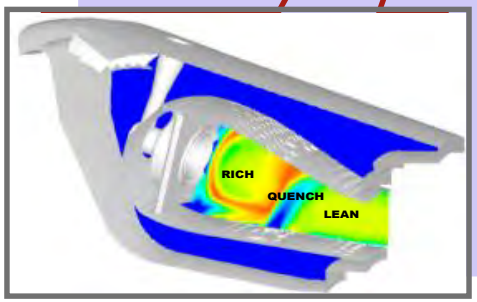
- Completed Preliminary Rig Design
- Initial Tech Demo Combustor Rig Test complete
- Redesign for Nest Tech Demo complete

Technology Schedule

Compact Combustor	2015	2016	2017	2018	2019	2020
Technology Demo						
Comb System Devel						
Dev Engine Tests						
NASA Rig Testing						
Engine Test (TRL 6)						

Compact Combustor Technology



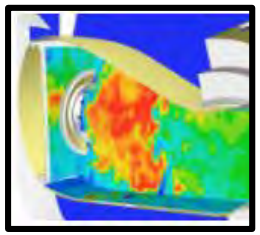


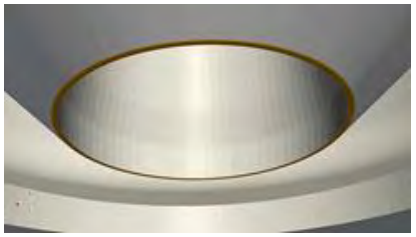
Compact Combustor

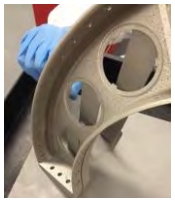
is an advanced combustor design that integrates state-of-the art aerodynamic design, advanced material selection & coatings and improved fuel control.

Compact Combustor Attributes

- Improved aerodynamic design
- Advanced cooling and materials
- Improved durability enabling higher temp cycle to reduce fuel burn
- Reduced weight







Combustor Technology Progressing to TRL 4 in Q2 2019

Compact Combustor Accomplishments

Accomplishments

- Completed Initial Technology Demonstration testing to refine design for next design iteration
  - Technology demonstration testing evaluated fuel ignitor and aerodynamic design features to optimize performance, emissions and wall cooling

- Completed go-forward concept definition for next Technology Demonstrator Test and for Demo Engine combustor system

Preliminary Designs Complete, Testing Underway

Compact Combustor Next Steps

- Refine design based on learning from analysis and initial test results
- Complete Second Technology Demo test in Q4 2018

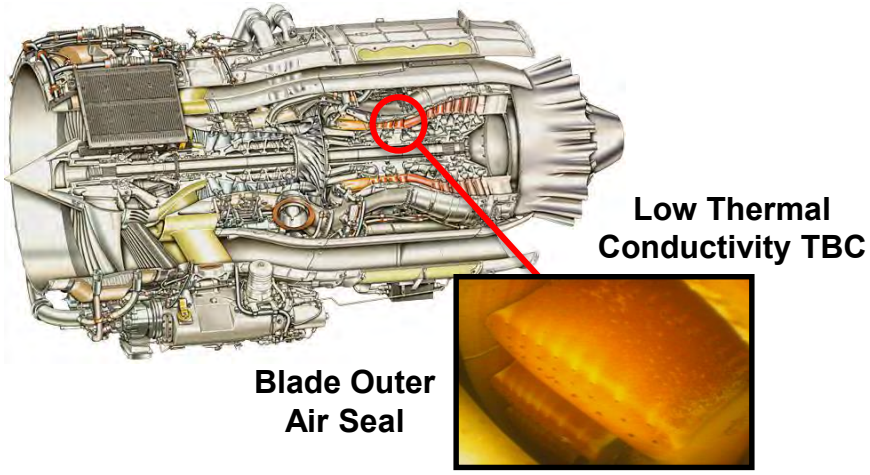
- Complete design of all adaptive rig hardware to support validation testing at NASA test facility Q1 2020

Honeywell Rig Testing

NASA ASCR Testing

Several Compact Combustor Tests Planned in Year 3

Advanced Turbine BOAS System Technology



Benefits

- Fuel burn reduction

Risks/Mitigations

- Insufficient material durability/rig and engine test
- Insufficient performance/alternate BOAS design

Objectives

- Improve High Pressure Turbine (HPT) efficiency

Work Statement

- Develop and demonstrate a BOAS System that improves HPT efficiency in an engine.

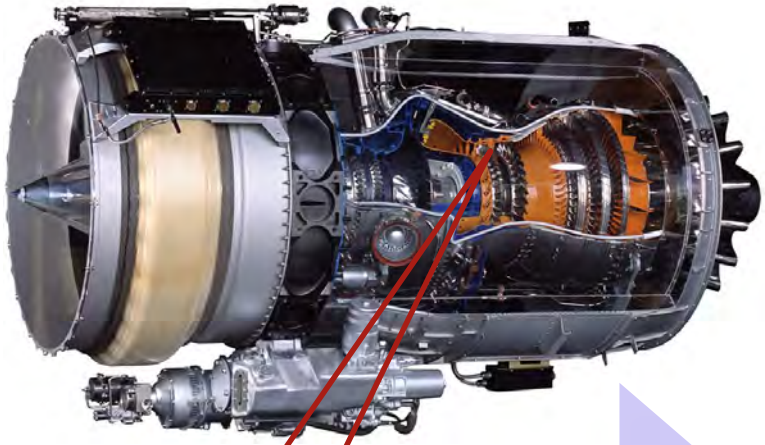
Accomplishments/Milestones

- HPT Shroud design complete and in process of being procured for development engine testing
- APS Low-k TBC Processing down-selected

Project Schedule

BOAS	2015	2016	2017	2018	2019	2020
Design & Analysis		▲	▬	▲		
Material Testing			▲	▬	▲	
BOAS Rig Test				▲	▬	▲
Dev Engine Tests					◆	▬ ◆
Engine Test (TRL 6)						◆

BOAS Technology

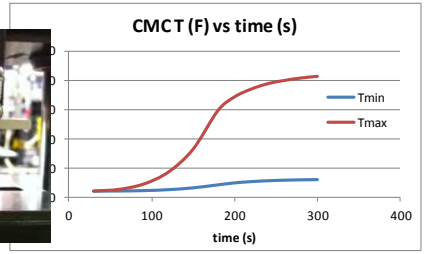


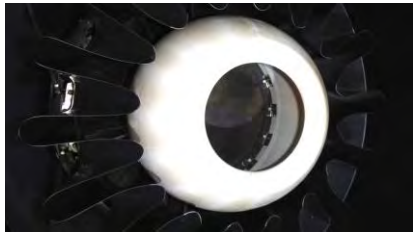
Blade Outer Air Seal

is an advanced turbine system design that addresses blade-to-shroud interaction, high temperature capability and durability.

BOAS Attributes

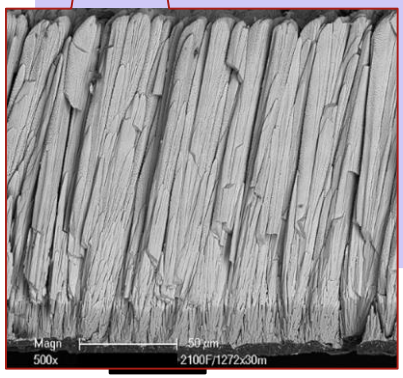
- Increased Temperature Capability
- Reduced Leakage
- Effective Tip Clearance
- Improved Durability
- Reduced Weight





BOAS Technology Progressing to TRL 4 in Q2 2019

Honeywell's Next Gen EB-PVD TBC Technology

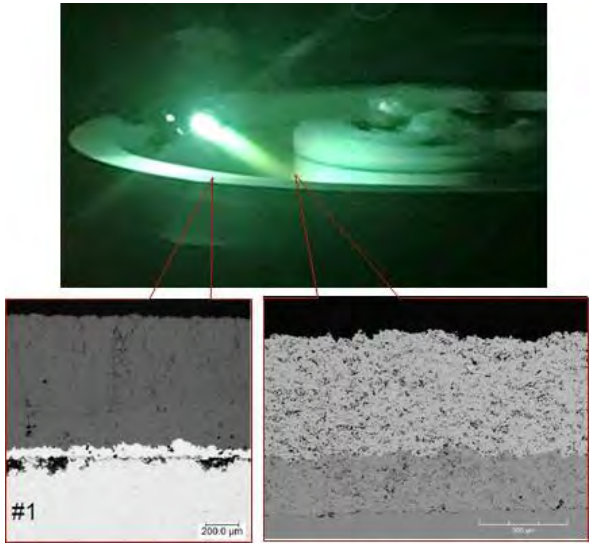


Lower Thermal Conductivity TBC

is a protective ceramic coating applied to the external surface of air-cooled turbine airfoils to insulate the component, and inhibit oxidation and hot corrosion.

Low-K Thermal Barrier Coating (TBC) Attributes

- 33% lower conductivity
  - > 2x component rupture life
  - > 4x TBC spallation life
- 2x higher toughness
- 4x sintering resistance
- Phase stable above 2,800°F
- EB-PVD validated in CLEEN I
- Air plasma spray (APS) validation in CLEEN II



Air Plasma Spray Technology Progressing to TRL 4 in Q2 2019

Advanced BOAS System Accomplishments

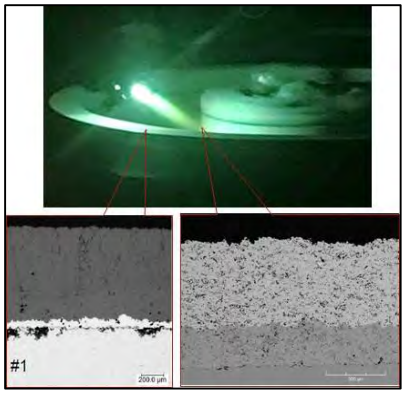
- **Shroud**
  - Material Mechanical Testing complete
  - Shroud Design complete
  - Material Thermal Characterization testing nearing completion
  - Advanced Blade processing has been down-selected

- **APS Low-K TBC**
  - Identified most promising processing route for APS low-K TBC
  - Developed viable coating systems
  - Preliminary durability testing to down-select coating system well underway to include engine hardware

BOAS to Achieve System TRL 4 in Q2 2019

Future Plans – TRL Maturation

- **TRL 4 – 2019**
  - **Blade Tip** Mechanical Testing
  - **APS LowK TBC** Process Optimization
  - Annular **Compact Combustor** Testing



- **TRL 5 – 2019-2020**
  - **Development Test(1) – Q1 2019**
    - **HPT Shroud** Technology Assessment
  - **Development Test(2) – Q3 2019**
    - **HPT BOAS Technology** assessment
  - **Development Test(3) – Q1 2020**
    - **Compact Combustor** liner wall temperature assessment

- **TRL 6 - 2020**
  - **NASA Combustor System Testing – Q1/Q2 2020**
  - **Endurance Engine Test – Q3 2020**
    - Engine Emissions assessment
    - Endurance Engine test to support TRL 6 validation of **Compact Combustor and BOAS Technologies**

Summary

- **Honeywell CLEEN II program is progressing well to mature the Compact Combustor and the Advanced Turbine BOAS to reduce fuel burn and NOx emissions**
  - **Engines and Aircraft Systems Analysis**
    - Completed Preliminary Engine Concept Design Review
    - Gulfstream Assessment complete
  - **Compact Combustor**
    - Completed Preliminary Rig Design
    - Initial Combustor Rig Testing complete, refining design for 2nd test
    - Continue design of NASA combustor rig test configuration
  - **Turbine BOAS**
    - Shroud design complete
    - APS Low-k TBC processing down-selected
    - Engine Test planning and preparation underway

Honeywell is building a smarter, safer,
and more sustainable world

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