# Rolls-Royce CLEEN II Low Emission Combustion Technology

Brad Belcher

8 May 2019

CLEENII Consortium Public Day

| Jurisdiction | Export Control Classification (Rating) | Date |
|---|---|---|
| US | No Technical Data | 4-5-2019 BDB |

**Public Release No. V191046**
**May 1, 2019**

## CLEEN Technologies

| CLEEN Technology Name | Goal Impact | Benefits and Application |
|---|---|---|
| Advanced RQL Low NOx Combustion System | NOx Reduction | Develop and demonstrate significant NOx reduction with advancing combustion technology that is suitable for emerging high pressure ratio, small core engines |

Rolls-Royce Low NOx Combustion Program

# Elevator Speech

The Rolls-Royce CLEEN II Low NOx Combustor Program will advance the state of the art in Rich-Quench-Lean (RQL) combustor performance, enabling significant reduction in NOx pollution for advanced engine platforms with aggressive turbine entry temperatures.

The comprehensive approach incorporates advanced fuel injection and wall cooling technologies coupled with implementation of enhanced mixing methodology.

A rigorous development plan with progressive validations through component rig and system-level testing will mitigate risk and develop a combustion platform for engine evaluation.

We will build upon prior Rolls-Royce development to demonstrate emission reductions in two phases with a near-term configuration targeting NOx emission levels 40% below CAEP/8 limits and a final configuration with NOx levels 65% below CAEP/8.

Rolls-Royce Low NOx Combustion Program

# Program Objectives

- Define cycle efficiency improvement and emissions reduction technologies that work together in future engine architectures to provide significant contributions toward the CLEEN II goals
- Develop RQL combustion technology capabilities through the application of advanced technologies, new design methods, and research of fundamental principles
- Demonstrate through component and full-scale system testing LTO NOx emissions 65% below CAEP/8 requirements, while limiting or reducing other gaseous and particle emissions
- Conduct TRL6 engine testing to demonstrate viability for next-generation production application and fleet engine retrofit opportunities

Rolls-Royce Low NOx Combustion Program

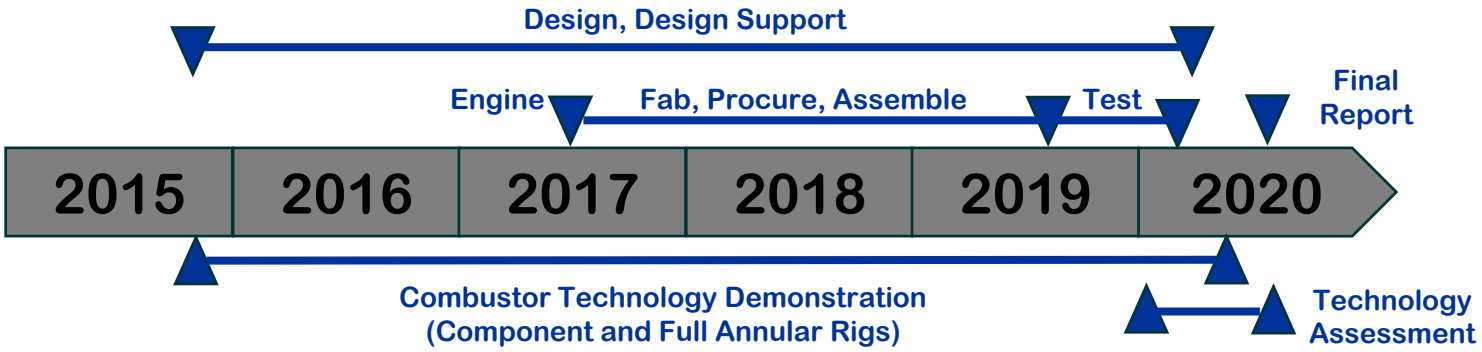
# Program Approach

- Integrate low-emission enabling technologies in Rich-Quench-Lean (RQL) combustion system
  - Innovative fuel injection to improve uniformity and dispersion
  - Novel mixing aerodynamics to minimize NOx formation
  - Advanced wall cooling to improve cooling effectiveness
  - Optimized combustor shape to reduce residence time
- Conduct progressive development and demonstration of combustor performance
  - Combustion design guided by high fidelity CFD analysis
  - TRL3 rigs used for component technology development
  - TRL5 rigs used to demonstrate system performance
  - Engine testing to demonstrate integration and viability in the engine environment (TRL6).
  - Phased approach to incorporate prior results and lessons-learned into ultimate low-NOx configuration.

# Program Schedule

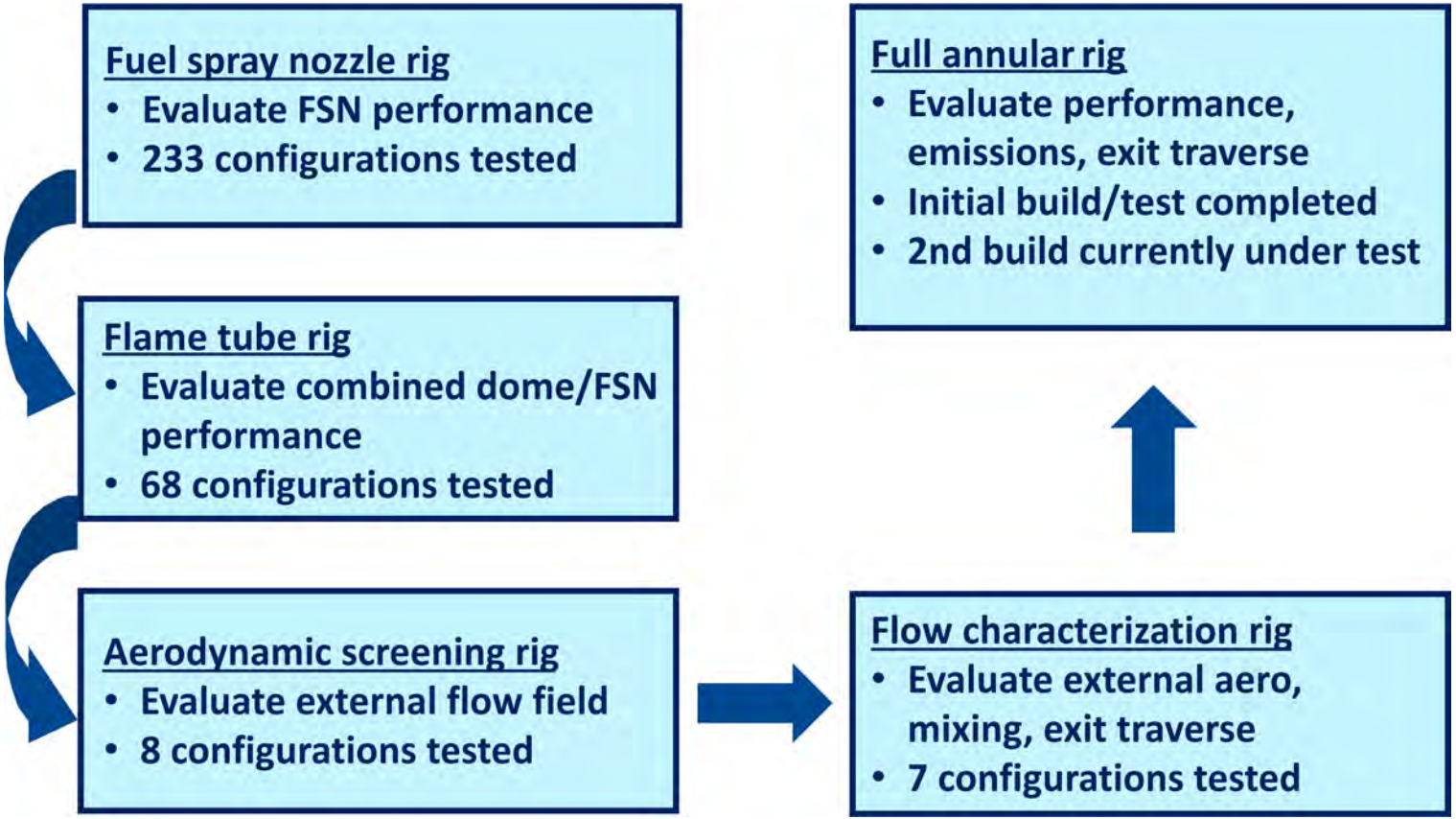
**Rolls-Royce Low NOx Combustion Program**

**Advanced RQL Low NOx Combustion System Development**



# Combustion Rig Progression

**Rolls-Royce Low NOx Combustion Program**



Rolls-Royce Low NOx Combustion Program

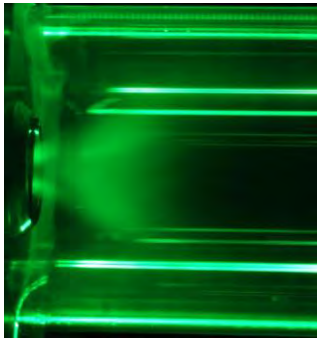
# Past 18-month Achievements

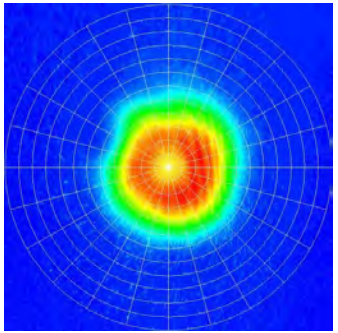
- FANN Rig Testing (TRL5) on the Gen2 and 2a combustion systems
  - Full-annular combustor rig delivery, assembly, and checkout
  - Combustor operability assessed, exit temperature distribution quantified, and wall temperatures mapped
  - Gen2 combustor cleared for engine demonstration
  - Gen2a combustor testing currently underway
- Completed TRL3 activities to support Gen3 combustor definition
  - Fuel spray diagnostics identified fuel nozzle tip candidates for flametube combustion testing
  - Single-sector flametube evaluation at high pressure and high temperature to assess combustion performance of fuel injector candidates
  - Confirmed fuel nozzle tip configuration for Gen3 combustor
- Completed design of the Gen3 combustion system
  - High fidelity, system-level CFD analyses used to capture design details, generating flow field solutions and performance predictions
  - Incorporation of larger scale ALM structural elements
  - Compact design for low NOx performance

# TRL3 Activities to Characterize Fuel Injector and Assess Combustion Performance

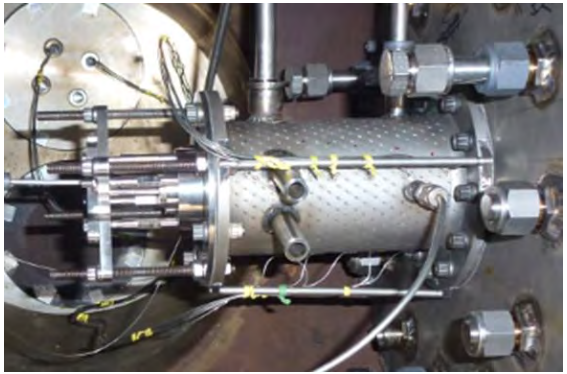
**Rolls-Royce Low NOx Combustion Program**

- Fuel Spray Diagnostics
  - Fuel spray quality
  - Liquid droplet dispersion
  - Transient spray effects
  - Spray visualization





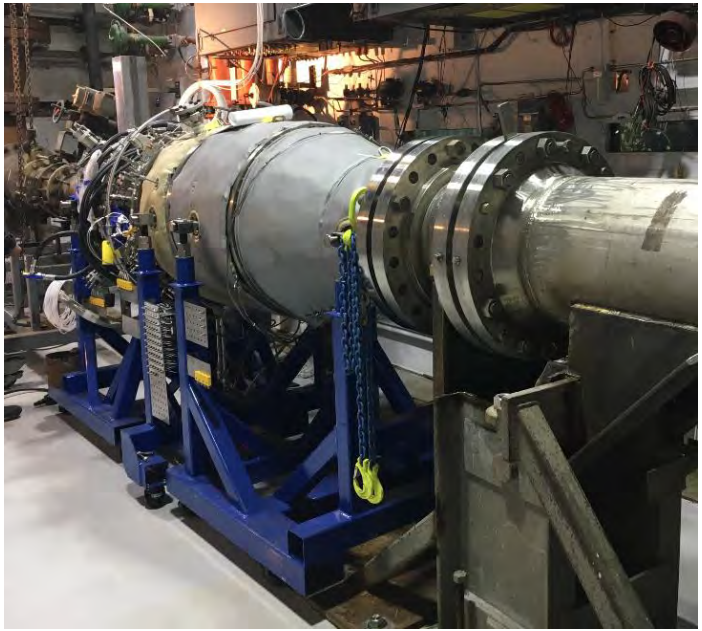
- Single Sector Flametube
  - High inlet temperature and moderate pressures
  - Emissions
  - Operability
  - Flexibility to assess multiple concepts



# Full Annular Combustor Rig

**Rolls-Royce Low NOx Combustion Program**

- Key objectives to characterize combustor exit temperatures, wall temperatures, emissions, and operability
- Will incorporate lessons learned into engine liner design
- Features rotating emission and temperature probes to map the combustor exit
- Maintains comprehensive aerodynamic similarity to the engine design
- Provides combustion system-level performance validation prior to installation into demo engine



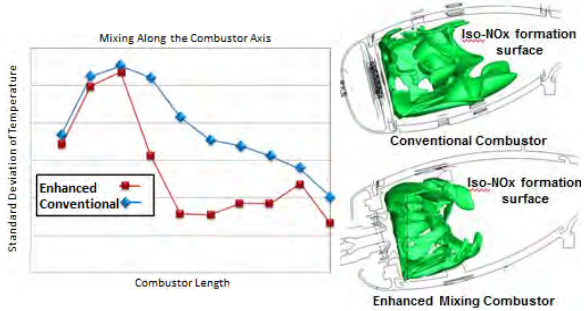
# Future Project Plans

**Rolls-Royce Low NOx Combustion Program is on Track to Deliver Program Objectives**

- Complete second full-annular rig build with testing of the Gen2a combustor
  - Includes testing with synthetic fuel at TRL5
- Complete fabrication of Gen3 combustor hardware
  - Expanded use of additive layer manufacturing
- Conduct full-annular rig testing of Gen3 combustion system
  - Characterize full system performance
  - TRL5 demonstration of advanced, low NOx combustion technology
- Conduct engine demonstration of Gen2 combustor
  - TRL6 validation of CLEEN II combustion technology
- Complete Gen4 combustor design and fabrication

# Advanced RQL Low NOx Combustion System

## Quad Chart




**Anticipated Benefits:**

- Significant NOx reduction
- Negligible operability impact
- Highly cost effective
- Technology capable of broad product insertion
- Advanced wall cooling and manufacturing technology

**Risks/Mitigation Plans:**

- Rigs are planned to manage risk and provide
  - Analysis benchmarking
  - Component and system development

**Objectives:**

- Demonstrate LTO NOx emissions 65% below CAEP/8 requirements, while limiting or reducing other gaseous and particle emissions
- Conduct TRL6 engine testing to demonstrate viability for next-generation production application and fleet engine retrofit opportunities

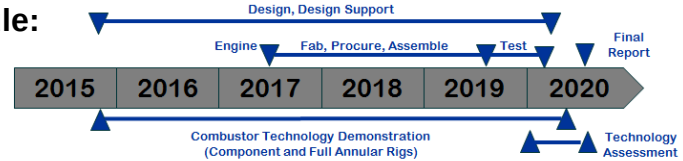
**Work Statement:**

- Integrate low emission enabling technologies in a Rich-Quench-Lean (RQL) combustion system and develop and demonstrate low emission performance

**Accomplishments / Milestones:**

- Conducted detailed fuel spray diagnostics (TRL2)
- Completed array of single-sector flame tube tests (TRL3)
- Aero rig testing to screen system configurations
- Design, fabrication, and validation test of combustion system to support engine demonstrator
- Design defined for lower NOx combustion system

**Schedule:**



# Rolls-Royce CLEEN II Sustainable Aviation Fuels

Brad Belcher

May 8, 2019

CLEEN II Consortium Public Day, Cleveland

| Jurisdiction | Export Control Classification (Rating) | Date |
|---|---|---|
| US | No Technical Data | 4-5-2019 EBW |

**Public Release No. V191047**
**May 1, 2019**

## CLEEN Technologies

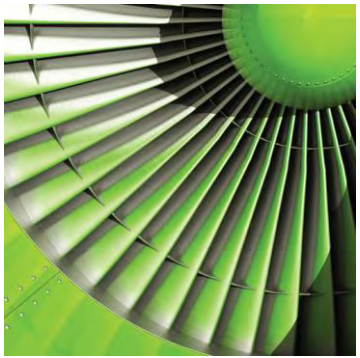
| CLEEN Technology Name | Goal Impact | Benefits and Application |
|---|---|---|
| Alternative Jet Fuel Test and Evaluation (Area A) | Alternative Fuels | Promotes the development and introduction of viable, renewable alternative fuels to achieve the NextGen Air Transportation System goals. Data will be shared with the ASTM Aviation Fuel Community to support international approval of a fully synthetic jet fuel. |

Rolls-Royce Sustainable Aviation Fuel Program

# Elevator Speech

The Rolls-Royce Sustainable Aviation Fuel Program is promoting alternative jet fuel development, approval & deployment, which contributes to the attainment of FAA NextGen Air Transportation System goals.  This robust evaluation program is characterizing a novel fully-synthetic fuel's performance under representative engine conditions. This goal is being accomplished through a series of "back-to-back" rig tests with conventional Jet A fuel to assess the fuel's impact on combustor performance and emissions. Elastomeric seal performance is also being assessed using the innovative Elastocon rig capability developed and demonstrated under CLEEN I. The data generated will be compared to prior work, assessed, and shared with the ASTM Aviation Fuel Community to support the International approval of a fully synthetic jet fuel.

## Rolls-Royce Sustainable Aviation Fuel Program



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# Program Scope

- Promotes the development and introduction of viable renewable alternative fuels to meet NextGen Air Transportation system goals
- A robust evaluation program that is characterizing a fully synthetic fuel's performance under representative engine conditions
- Accomplished through a series of "back-to-back" rig tests with conventional Jet A fuel
- Fuel chemistry/properties relationship upon fuel spray, combustor performance, operability, and emissions
- Elastomeric seal performance due to cyclic fuel switching under more realistic engine conditions
- Data generated can be shared with ASTM Aviation Fuel Community and aid in fuel certification process

Rolls-Royce Sustainable Aviation Fuel Program

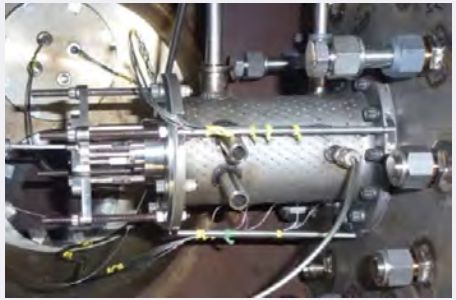
# Benefits

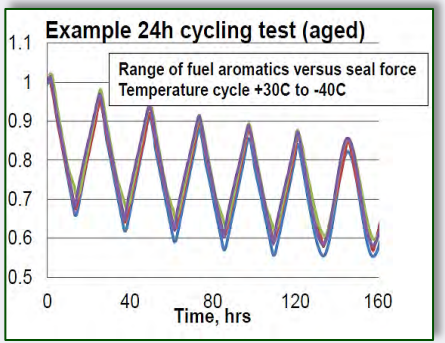
- The data generated will support the international approval of a fully synthetic jet fuel
- Enhanced methods for predicting fuel performance on engine systems to support reduced cost and timescale of approvals
- Greater data and test capability to support environmental benefits (i.e., local air quality, increasing regulations)
- Renewable, synthetic alternative jet fuel for aerospace gas turbine engine applications will provide reduced aerospace environmental impact and increased energy security

**The Purpose of the Test Program is to Ensure the Candidate Fuel will have No Negative Impact on Engine Safety, Durability, or Performance**

# Approach

- Proven sequential test program (“back-to-back” with Jet A)
  - Fuel requirements: 4100 gallons
  - Conduct laboratory and fit-for-purpose evaluation
  - Characterize fuel spray behavior
  - Utilize combustion rigs to assess fuel impact upon performance, operability, and emissions
  - Assess elastomeric seal performance using the innovative Elastocon rig
- Data generated will be compared to prior work, assessed, and reported to ASTM Aviation Fuel Community






No Technical Data

# Summary of ATJ-SKA Test Results

- Laboratory characterization:
  - Primarily iso-paraffinic composition
  - Acceptable volatility, fluidity, and thermal stability
- Overall spray performance similar to Jet A fuel, with only minor differences noted
- Combustion flame tube:
  - Lean stability deteriorated slightly
  - Emissions – NOx similar, but CO and UHC emissions are higher at certain conditions, leading to lower combustion efficiency
  - Combustion liner wall temperatures are similar

Sustainable Aviation Fuel Program

# Achievements

- **Complete**:
  - Laboratory and fit for purpose
  - Spray characterization
  - Elastocon rig modification
  - Flame tube testing
  - 2200 gallons of ATJ-SKA fuel received
- **Ongoing:**
  - FANN rig test underway
  - Elastocon-generating compression stress relaxation data for five seal materials

Program on track to deliver objectives

## Schedule

# CLEEN II Sustainable Aviation Fuel Schedule

| Rolls-Royce Sustainable Aviation Fuel Program | | 2016 | | | | 2017 | | | | 2018 | | | | 2019 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| Fuel Selection | | | | | | | | | | | | | | | | | |
| Test Program | | | | | | | | | | | | | | | | | |
| Draft Final Report | | | | | | | | | | | | | | | | | |

Program on track and on schedule

Sustainable Aviation Fuel Program

# Year 4 Objectives

- Complete FANN rig test
- Complete Elastocon work at Sheffield University
- Assess test results and provide preliminary results
- Deliver full draft technical report

## Quad Chart

# Sustainable Aviation Fuel Test and Evaluation

## Benefits:

- The data generated will support the international approval of a fully-synthetic jet fuel
- Enhanced methods for predicting fuel performance on engine systems to support reduced cost and timescale of approvals
- Greater data and test capability to support environmental benefits (i.e., local air quality, increasing regulations)
- Renewable, synthetic alternative jet fuel for aerospace gas turbine engine applications will provide reduced aerospace environmental impact and increased energy security

## Objectives:

- Promote the development and introduction of viable renewable alternative fuels - NextGen Air Transportation systems goals
- Improved tools for predicting fuel performance and scientific understanding
- Data generated will aid in ASTM fuel certification process

## Work Statement:

- Assess a fully synthetic jet fuel using low NOx combustion systems to determine fuel impact on performance, operability, and emissions
- Assess elastomeric seal performance using the innovative Elastocon rig

## Accomplishments/Milestones:

- Complete: Laboratory fit for purpose, spray characterization, and flame tube testing
- 2200 gallons of ATJ-SKA fuel received for the FANN rig test
- Ongoing: FANN rig test, Elastocon-generating compression stress relaxation data for five seals

## Schedule:

| Rolls-Royce Sustainable Aviation Fuel Program | | 2016 | | | | 2017 | | | | 2018 | | | | 2019 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| Fuel Selection | | | | | | | | | | | | | | | | | |
| Test Program | | | | | | | | | | | | | | | | | |
| Draft Final Report | | | | | | | | | | | | | | | | | |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