FAA CLEEN II Technologies

Rolls-Royce CLEEN II Low NOx Combustor Program, Unlimited Rights/Public

Presented to: CLEEN Consortium, Washington DC

By: Brad Belcher

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Jurisdiction	*Export Classification Rating*	*Date*
United States	NO TECHNICAL DATA	11-6-2017 by BDB

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Rolls-Royce

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

Elevator speech

The Rolls-Royce CLEENII 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 level 65% below CAEP/8.

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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, 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

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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 phased development approach to develop and demonstrate low emission performance
  - Lower TRL rigs used for initial technology development
  - TRL5 full annular rigs used to demonstrate system performance
  - TRL6 engine testing using to demonstrate viability in engine environment

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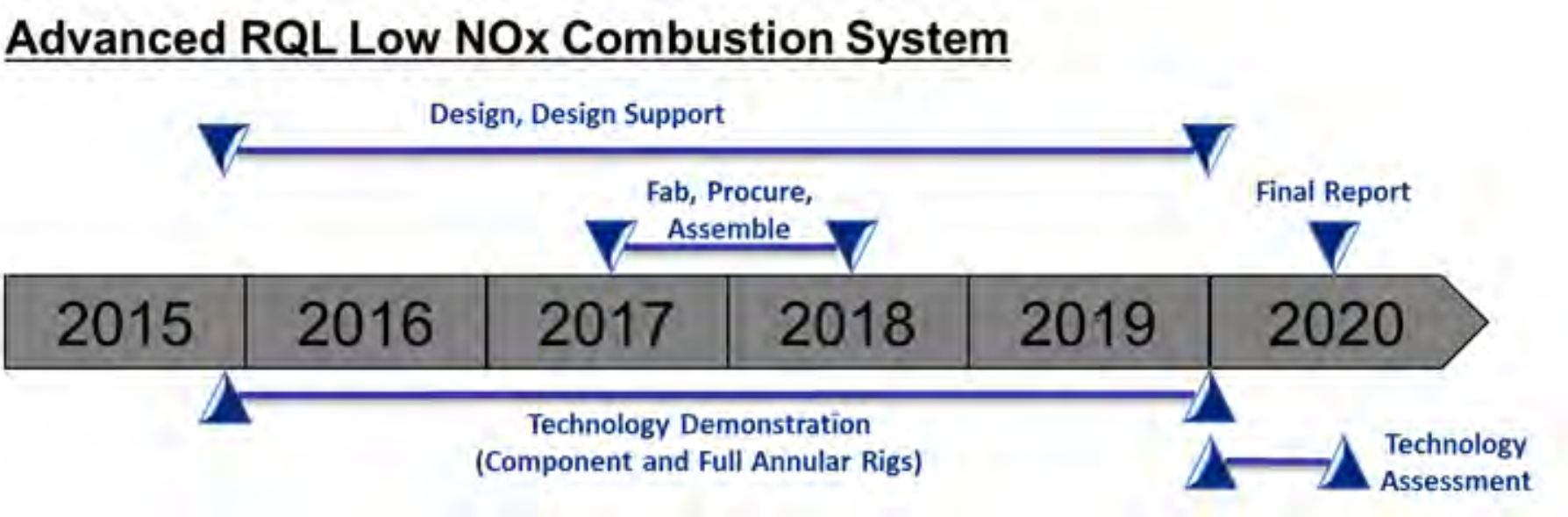
Program schedule



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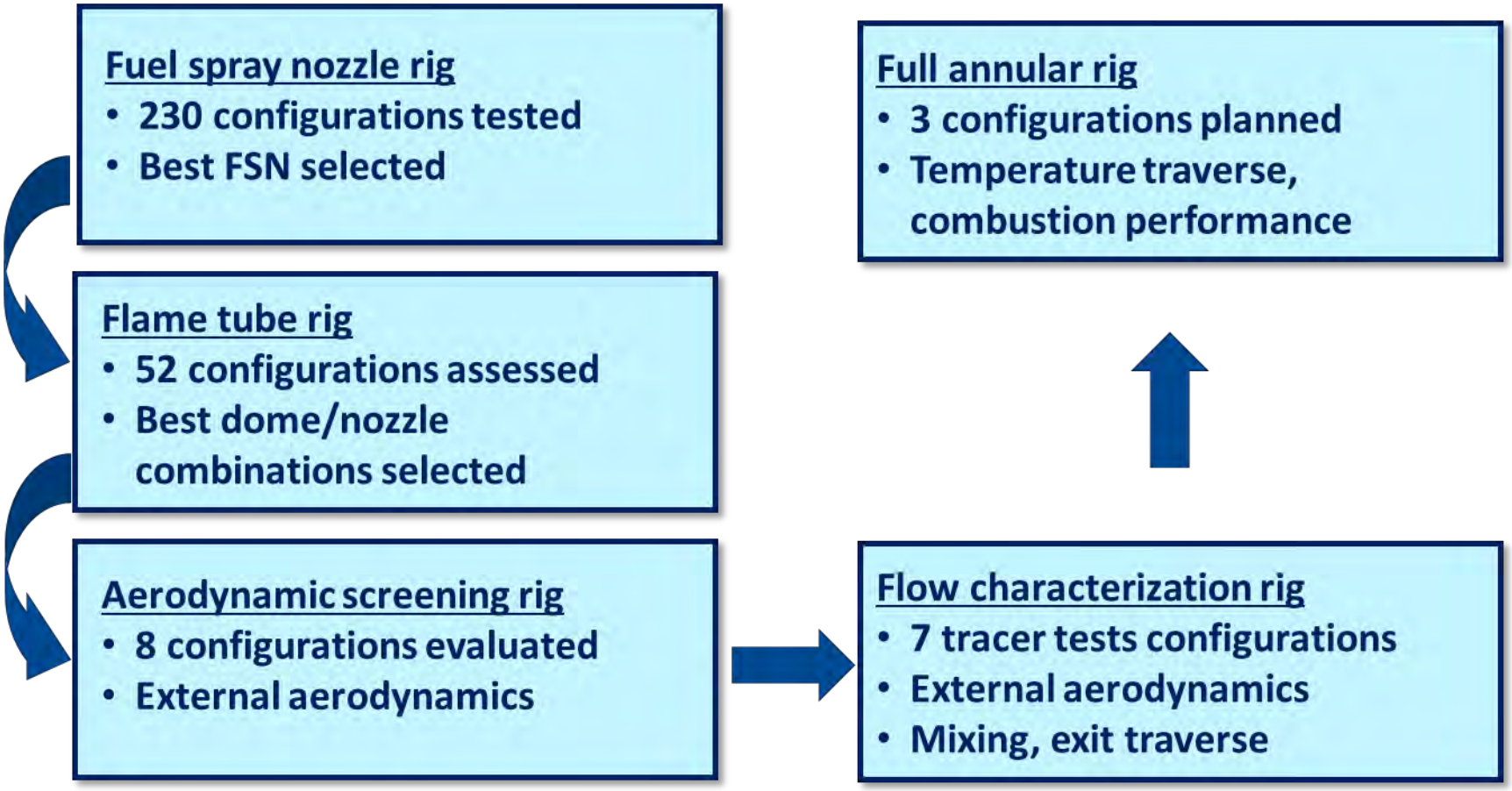
Development approach

- Combustion system design will be guided by CFD analyses and component rig validations
  - Atmospheric spray and combustion fuel nozzle rig to assess fuel injector designs
  - High pressure flame tube rig to assess stability and emissions
  - Atmospheric flow characterization rigs to assist in defining external aerodynamics, boundary conditions, and mixing performance
  - Full annular combustor rig for profile, pattern factor, and emissions.
  - CFD analyses benchmarked to rigs for design and development
- Engine combustor design will be informed by rig testing results

Combustion rig progression



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Past 18 months achievements

- Completed preliminary combustion system design and review
  - Selected system architecture and key technologies
- Completed TRL3 activities to support full annular combustor definition
  - Identified best fuel injector candidate design from fuel spray diagnostic testing
  - Single-sector combustion performance assessment of candidate fuel injector using moderate pressure flametube test vehicle.
  - Testing completed to support detail design and TRL5 activities.
- Conducted cold flow, aerodynamic rig testing to screen combustion system configurations
  - Results used to benchmark CFD tools and refine system design
  - Evaluate external aerodynamics, boundary conditions, and mixing performance
- Completed detailed combustion system design and review
  - Analytical verification completed, confirming detailed design definition meets demonstrator requirements with acceptable technical risk
- Delivery and Installation of full annular (TRL5) combustion rig
  - Combustion module emission, operability, and exit traverse performance

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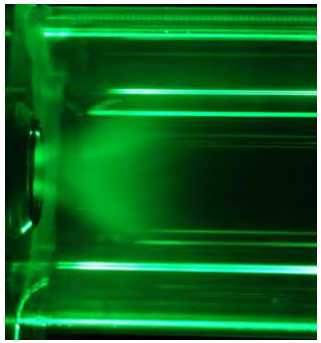
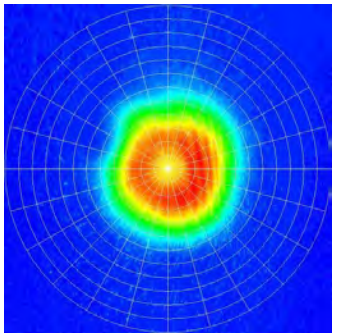
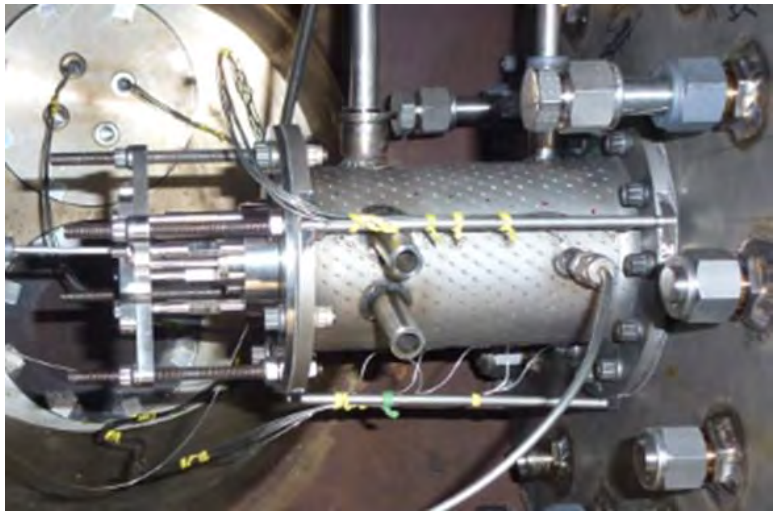
TRL3 activities to characterize fuel injector and assess combustion performance

- 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



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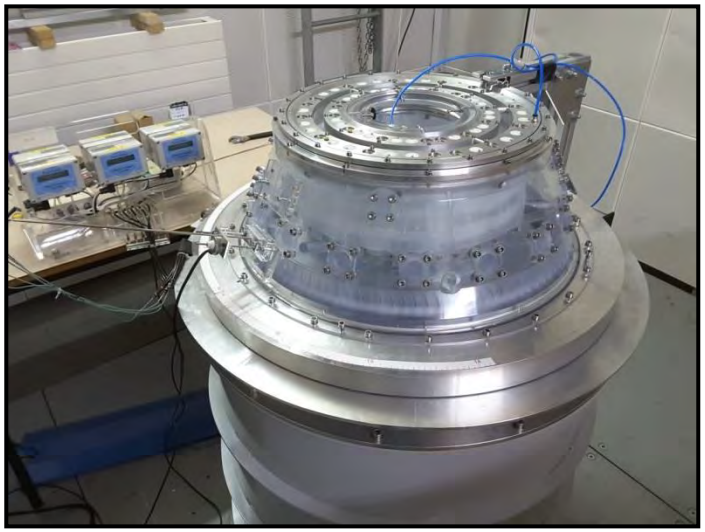
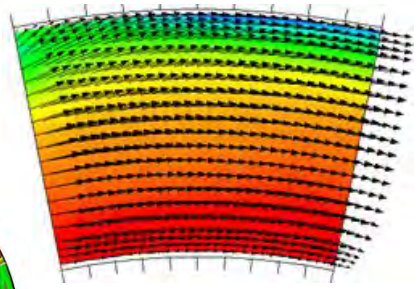
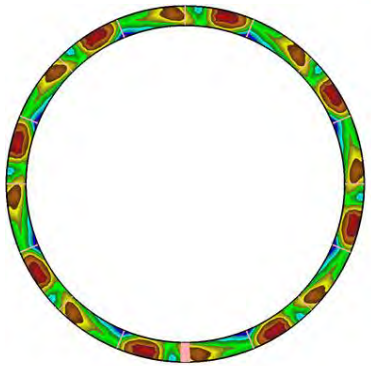
Aerodynamic characterization rig

- Simulates combustor inlet and exit conditions
- Measures system pressure losses
- Map aerodynamic flow field development in the combustion system architecture
- Establishes combustor port effective flow area for liner design
- Enables examination of liner flow near wall regions for response to disturbances
- First level assessment of exit mixing







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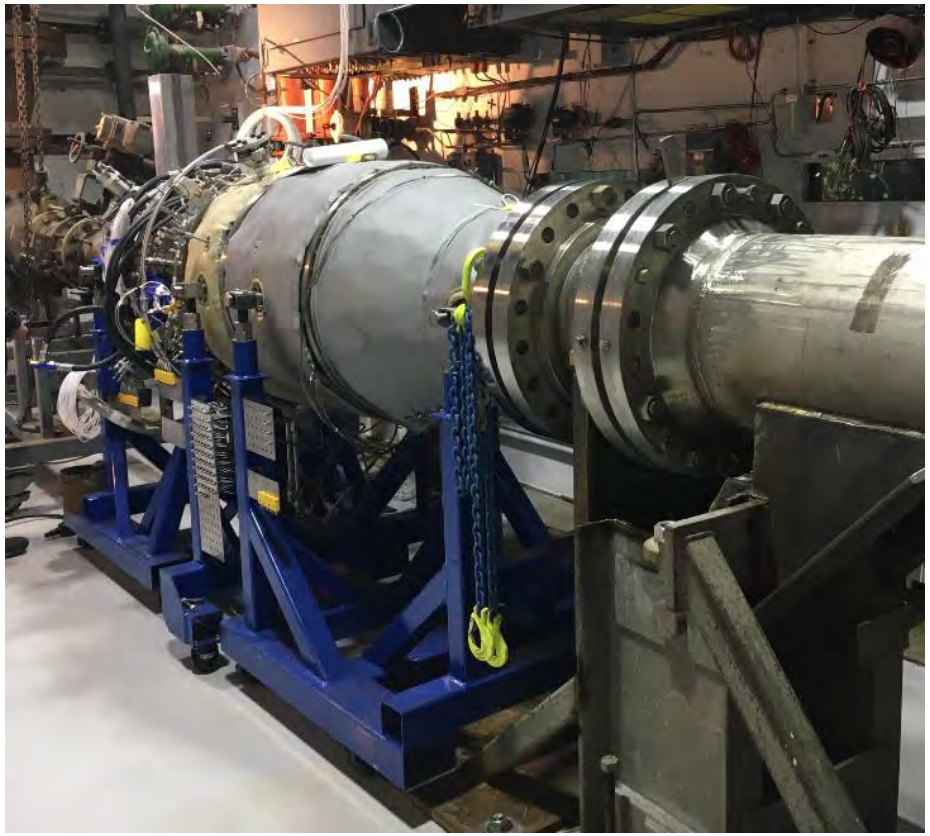
Full annular combustor rig

- Key objectives to characterize combustor exit temperatures, wall temperatures, emissions and operability
- Will incorporate lessons-learned into engine liner design
- Features rotating emissions probe for exit temperatures
- Maintains aerodynamic similarity to engine design



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Project plans for Year 3 into Year 4

- Launch full annular rig testing to support engine demonstrator
  - Testing commencing late 2017 and planned into project Year 3
- Development of next-gen fuel spray nozzle concepts
  - TRL3 spray and flametube testing of advanced concepts
  - Identify performance improvements
- Assemble and test technical demonstrator engine
  - TRL6 validation of Generation 2 CLEEN combustion technology
- Develop and rig test (TRL5) advanced combustion technology
  - Design and test hardware in program years 3 and 4.

CLEEN II activities on track to deliver program objectives

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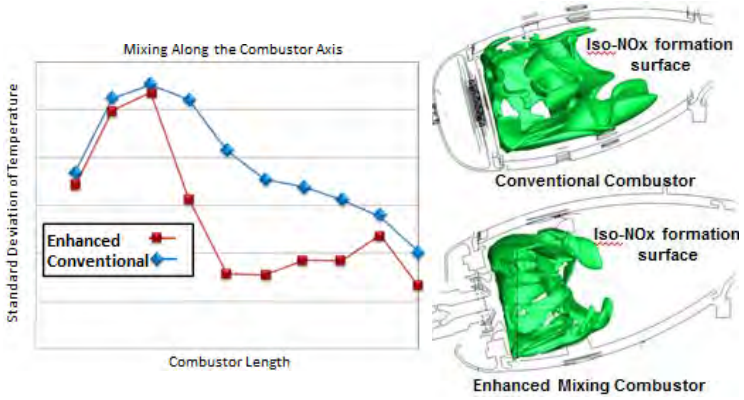
Advanced RQL Low NOx Combustion System



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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

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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

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Accomplishments / Milestones:

- Preliminary design of combustion system
- Initial fuel spray nozzle testing (TRL3)
- Initial flame tube testing (TRL3)
- Aero rig testing to screen system configurations
- Flow characterization rig testing
- Manufacturing trials of key system components

Schedule:

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NO TECHNICAL DATA

FAA CLEEN II Technologies

Rolls-Royce CLEEN II Alternative Fuel Program, Unlimited Rights/Public

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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.

Elevator speech

The Rolls-Royce CLEEN II Alternative Fuel Program will promote alternative jet fuel development, approval & deployment, which contributes to the attainment of FAA NextGen Air Transportation System goals. This robust evaluation program will validate a novel fully synthetic fuel's performance under engine conditions. This goal will be accomplished through a series of "back-to-back" rig tests with conventional Jet A fuel, to access the fuels' impact on combustor performance and emissions. Elastomeric seal material compatibility with the fuel will also be accessed 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.

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Program objectives

- Promote the development and introduction of viable renewable alternative fuels to meet NextGen Air Transportation system goals
- Test program data will support improved methods for predicting fuel performance and understanding:
  - Fuel chemistry/properties relationship upon fuel spray, combustor performance, operability and emissions
  - Seal performance due to cyclic fuel switching under more realistic engine conditions
- Data generated will shared with ASTM Aviation Fuel Community and aid in fuel certification process

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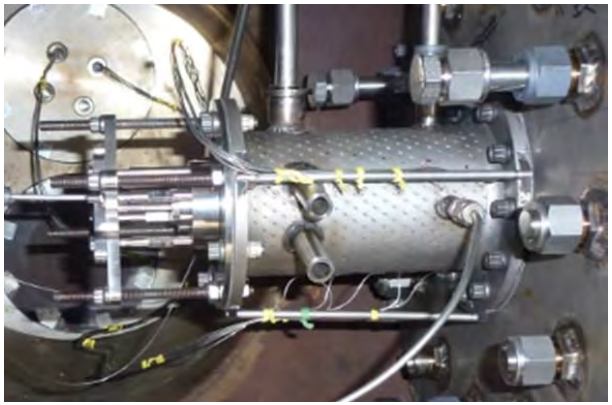
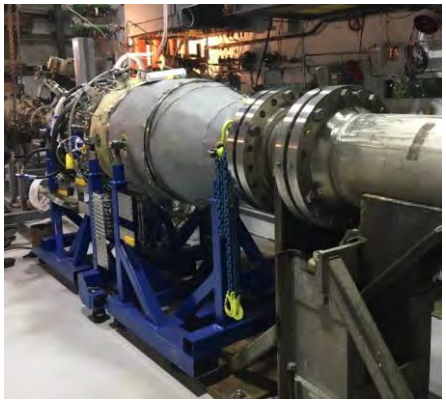
Approach

- Proven sequential test program ("back-to-back" with Jet A)
  - Fuel requirements: 11,000 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
  - Conduct "back-to-back" fuel testing in a technology demonstrator to further characterize performance and emissions
- Data generated will be compared to prior work, assessed and reported to ASTM Aviation Fuel Community





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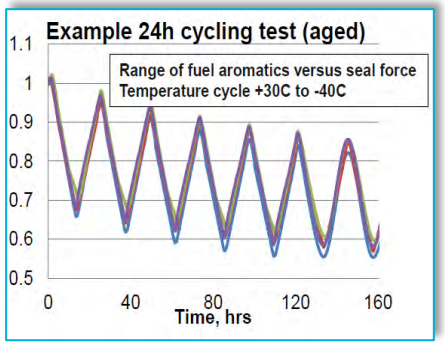

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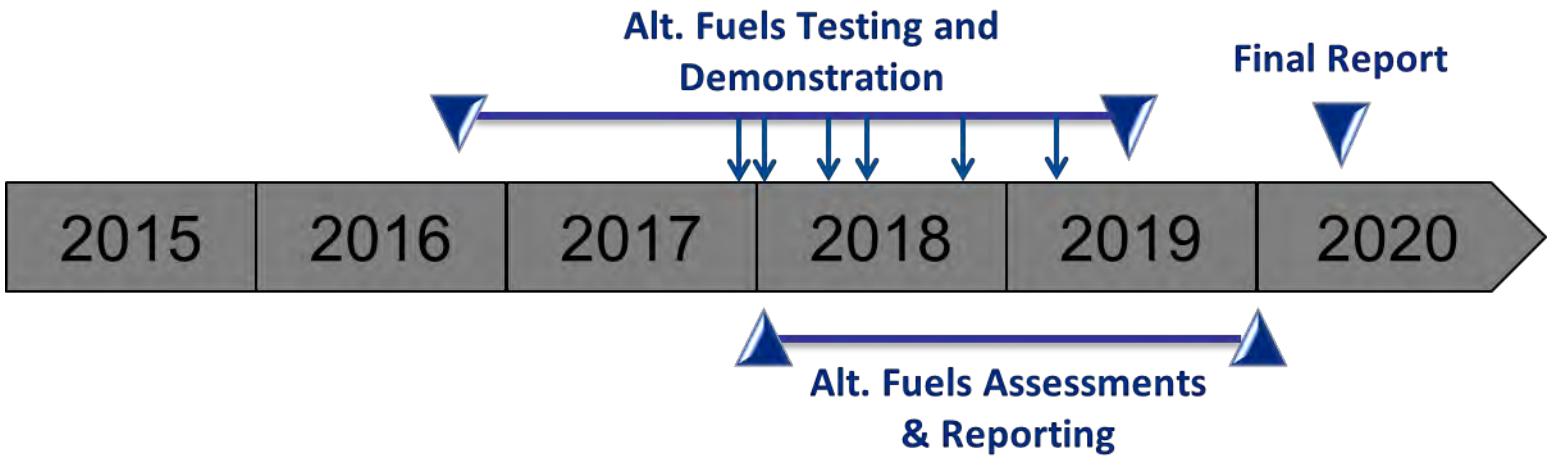
Program schedule



Aligned with technology demonstrator schedule

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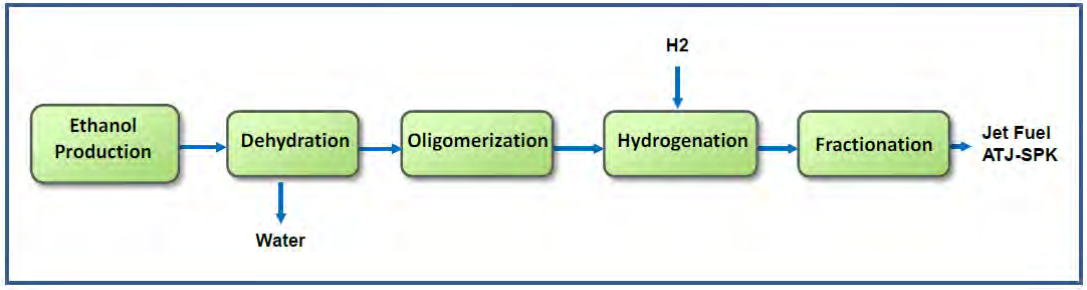
Achievements

- Established robust fuel test program that is aligned with the Rolls-Royce technology development schedule
- Down-selected fully synthetic alternative fuel (agreed with FAA)
  - Fuel is 90% LanzaTech LT/PNNL ATJ with 10%Swift mesitylene aromatic
  - Demonstrates suitability and commercial viability
  - LanzaTech commitment to fuel volumes on schedule
- First fuel order on track, with delivery planned Dec 2017



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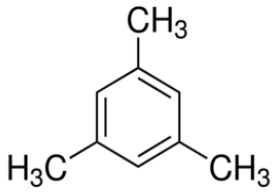

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Project plans for Year 3 into Year 4

- Receive first fuel shipment in December 2017
- Launch test phase of the program
  - Laboratory and fit-for-purpose
  - Rigs: flametube, spray, and full annular
- Launch Elastocon work at Sheffield University
- Assess test results and provide preliminary report

CLEEN II activities on track to deliver program objectives

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Alternative Jet Fuel Test and Evaluation

Anticipated Benefits:

- Supports International approval of fully synthetic fuel
- Enhanced methods for predicting fuel performance on modern engine systems to support reduced cost and timescale of approvals

Risk/Mitigation Plans:

- Test rigs are designed and installed to mitigate risk
- Fuel producer committed to supplying sufficient quantities.

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 certification process

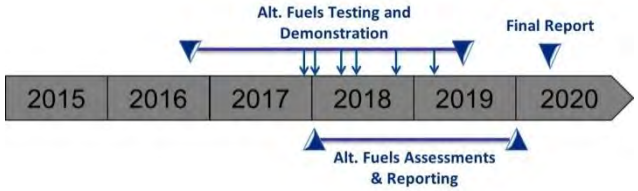
Work Statement:

- 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:

- Established robust fuel test program
- Screened several alt fuel candidates/producers
- Down-selected fully synthetic fuel: LanzaTech ATJ with Swift aromatic
- Launch test phase of program
- Begin Elastocon assessment
- Assess results and report

Schedule:



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