FAA CLEEN II Technologies

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

Presented to: CLEEN Consortium, Chula Vista, CA.
By: Brad Belcher
Date: 2 May 2018
<table>
<thead>
<tr>
<th>CLEEN Technology Name</th>
<th>Goal Impact</th>
<th>Benefits and Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced RQL Low NOx Combustion System</td>
<td>NOx Reduction</td>
<td>Develop and demonstrate significant NOx reduction with advancing combustion technology that is suitable for emerging high pressure ratio, small core engines</td>
</tr>
</tbody>
</table>
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.
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.
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
Program schedule

Advanced RQL Low NOx Combustion System

Design, Design Support

Fab, Procure, Assemble

Technology Demonstration (Component and Full Annular Rigs)

Final Report

Technology Assessment

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 tip 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

Fuel spray nozzle rig
• 233 configurations tested
• Best FSN selected

Flame tube rig
• 68 configurations assessed
• Best dome/nozzle combinations selected

Aerodynamic screening rig
• 8 configurations evaluated
• External aerodynamics

Flow characterization rig
• 7 tracer tests configurations
• External aerodynamics
• Mixing, exit traverse

Full annular rig
• 1 configuration assessed
• 2 configurations planned
• Temperature traverse, combustion performance
Past 18 Month Achievements

- Delivery and Installation of a full annular (TRL5) combustion rig
  - Combustion module level performance assessment
- Completed TRL5 rig testing on Gen2 combustion system
  - Combustor operability assessed, exit temperature distribution quantified, and wall temperatures mapped
  - Gen2 combustor cleared for Engine demo build
- Wrapping up TRL3 activities to support Gen3 combustor definition
  - Fuel spray diagnostics identified fuel nozzle tip candidates for flametube combustion testing
  - Single-sector flametube testing in progress for stability, and high pressure, high temperature combustion assessment of fuel injector candidates
  - Preparing for final downselect to define tip configuration to deliver to fuel nozzle fabricator
- Conducting design studies to define Gen3 combustion system design
  - High fidelity, system level CFD analyses used to capture design details, generating flow field solutions and performance predictions
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
Aerodynamic Characterization Rig

- Simulates combustor inlet & exit conditions
- Measures system pressure losses
- Maps 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
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 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
Project Plans for Year 4 into Year 5

- Complete Gen3 aerodynamic and mechanical design
  - Definitions for fuel nozzle manufacture and combustion liner fabrication.
- Employ full annular rig testing to characterize Gen3 combustion system design
  - Characterize full system performance
  - TRL5 demonstration of advanced combustion technology
- Assemble and test technical demonstrator engine
  - TRL6 validation of Generation 2 CLEEN combustion technology

CLEEN II activities on track to deliver program objectives
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:
- 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:
FAA CLEEN II Technologies

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

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By: Brad Belcher
Date: May 2, 2018

Jurisdiction | Export Classification Rating | Date
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## CLEEN technologies

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<th>CLEEN Technology Name</th>
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<tr>
<td>Alternative Jet Fuel Test and Evaluation (Area A)</td>
<td>Alternative Fuels</td>
<td>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.</td>
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Elevator speech

The Rolls-Royce CLEEN II Alternative 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 fuels’ 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 CLEEN II Alternative Fuel Program Scope

- Promote the development and introduction of viable renewable alternative fuels to meet NextGen Air Transportation system goals
- A robust evaluation program that will characterize 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 will be shared with ASTM Aviation Fuel Community and aid in fuel certification process
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
- Data generated will be compared to prior work, assessed and reported to ASTM Aviation Fuel Community
Alternative Fuel Program Schedule

<table>
<thead>
<tr>
<th>Task Name</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
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<tbody>
<tr>
<td>ALTERNATIVE JET FUEL DEVELOPMENT</td>
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<tr>
<td>Area A: Alternative Jet Fuel Test and Evaluation</td>
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<tr>
<td>WE1 - Project Management</td>
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<tr>
<td>WE2 - Alt Fuel Selection &amp; Testing</td>
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<tr>
<td>Fuel Selection</td>
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<td>Fuel Delivery (drums)</td>
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<td>Fuel Delivery (Tanker)</td>
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<tr>
<td>Fit For Purpose (FFP) Laboratory Testing # 1</td>
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<tr>
<td>Fit For Purpose (FFP) Laboratory Testing # 2</td>
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<tr>
<td>Fit For Purpose (FFP) Laboratory Testing # 3</td>
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<tr>
<td>Fuel Spray Rig (ERC)</td>
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<tr>
<td>Flametube Rig (Plt 8)</td>
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<tr>
<td>Full Annular Rig (Plt 8)</td>
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<tr>
<td>Elasticon Rig - Sheffield University</td>
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CLEEN II Activities on track to deliver program objectives
Achievements

• Selected fully synthetic fuel: 87% LanzaTech ATJ/13% Swift Aromatic
• Several fuel shipments received
• Fuel spray characterization complete – initial results look positive
• Test Elements currently underway:
  • Full laboratory analysis of fuel and fit for purpose properties
  • Combustion Flame tube testing
  • Sheffield University – Elastocon seal performance
Project plans for Year 3 into Year 4

- Complete laboratory and combustion flame tube testing
- Continue Elastocon work at Sheffield University
- Launch full annular combustion rig test
- Assess test results and provide preliminary report
Alternative Jet Fuel Test and Evaluation

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

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.

Accomplishments/ Milestones:
• First few fuel shipments received (87% LanzaTech/13% Swift)
• Spray characterization test complete – positive results
• Test Elements currently underway:
  • Full laboratory analysis of fuel properties
  • Combustion Flame tube testing
  • Sheffield University – Elastocon

Schedule:

NO TECHNICAL DATA