Rolls-Royce CLEEN II Low Emission Combustion Technology

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CLEENII Consortium Public Day

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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

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Elevator Speech

Rolls-Royce Low NOx Combustion Program

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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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, 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 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.

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Overall program time line

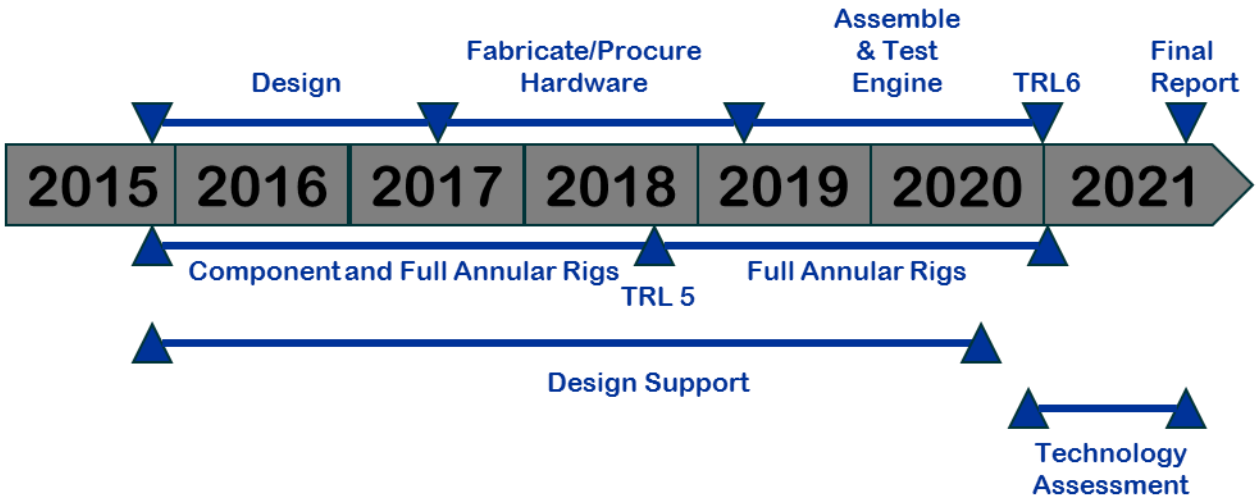
Low NOx Combustion Program key points

Program launched in October 2015

Component rig testing (TRL3) in 2016-17 used to inform combustor design

Full annular rig testing (TRL5) of designs began in 2018

Engine testing (TRL6) initiated in late 2019



Final phase of program is now underway

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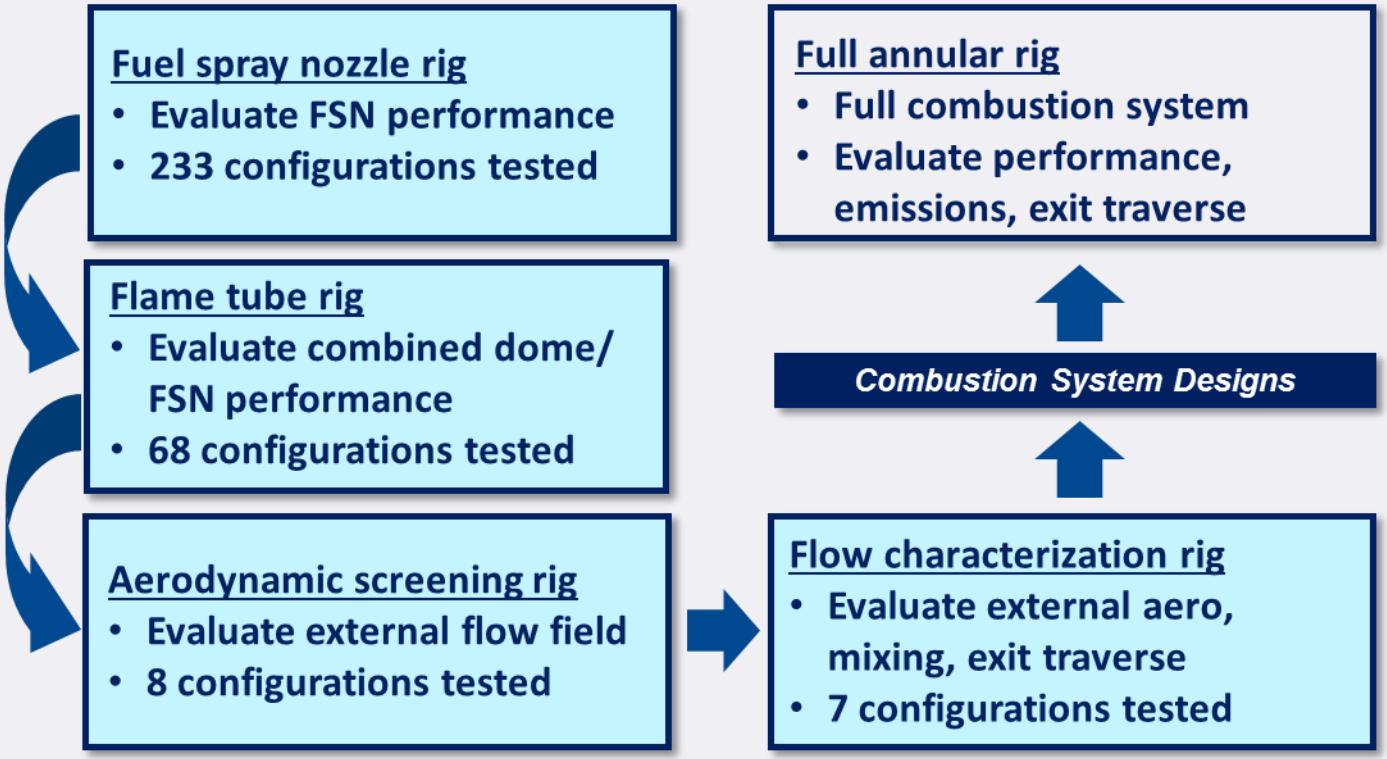
Low NOx Combustion Program key points

Progressive validation via component and system rigs to inform designs and down-select configurations

Combustion design validation & verification



Full annular rig testing informs engine test readiness

TRL3 Activities to Characterize Fuel Injector and Assess Combustion Performance

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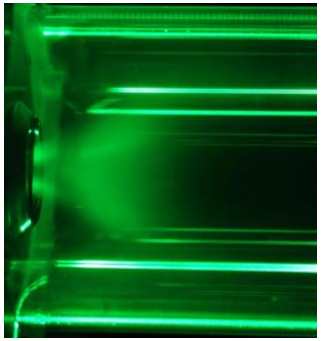
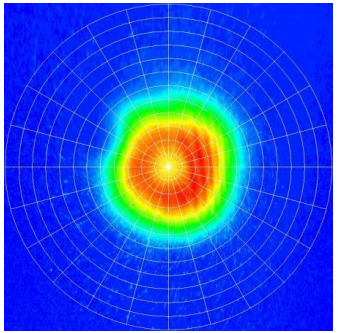
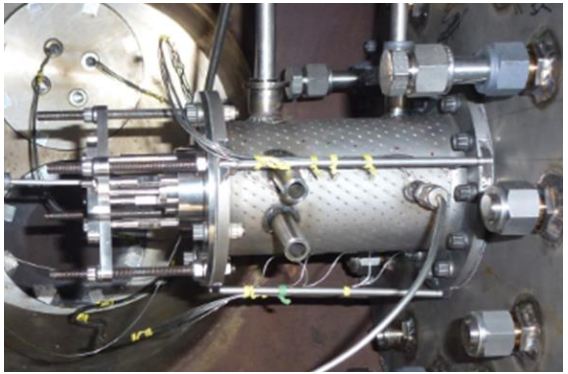
- Fuel Spray Diagnostics
  - Fuel spray quality
  - Liquid droplet dispersion
  - Transient spray effects
  - Spray visualization





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



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Full Annular Combustor Rig

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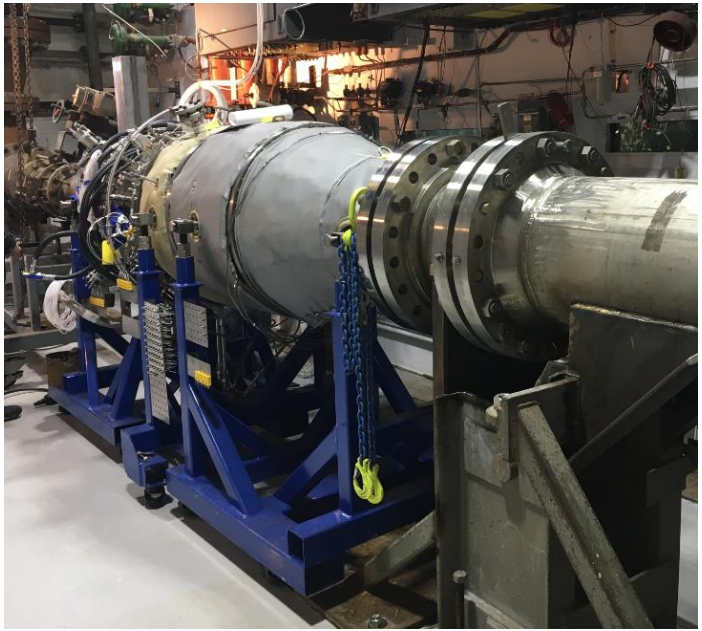
- Key objectives to characterize combustor exit temperatures, wall temperatures, emissions and operability
- Will incorporate lessons-learned into engine liner design
- Features rotating emission and temperature probes to map the combustor exit
- Maintains comprehensive aerodynamic similarity to the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



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Past 18 Month Achievements

- Combustion system design activities
  - Completed final design iteration for Gen2 combustor family
    - Utilized results of initial full annular rig testing to define design refinements
    - Completed design (aero and mechanical), and fabricated hardware for the Gen2c combustor assembly
  - Completed design, fabrication, assembly, and flow calibration for the Gen3 combustor
    - Incorporated design elements for reduced NOx
    - Expanded application of additive layer manufacturing
- Full annular rig testing (TRL5) activities
  - Conducted testing of three Gen2 combustors, including performance & operability, emissions, exit temperature distribution, and wall temperatures mapping
    - Initial Gen2 combustor cleared for initial engine demonstration
    - Latest Gen2c combustor cleared for second engine.
    - Gen2c achieved our FAA goal of 65% NOx margin to CAEP8.
- Engine testing (TRL6) activities
  - Combustor operation meeting all engine test objectives.

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Future Project Plans

- Complete full annular rig (TRL5) testing of the Gen3 combustor design
  - Rig final assembly underway in preparation for test cell installation.
  - Establish system performance and NOx emission reduction potential
- Continue engine demonstrations of Gen2 combustors
  - Engine sea level and altitude performance, emissions, and durability testing.

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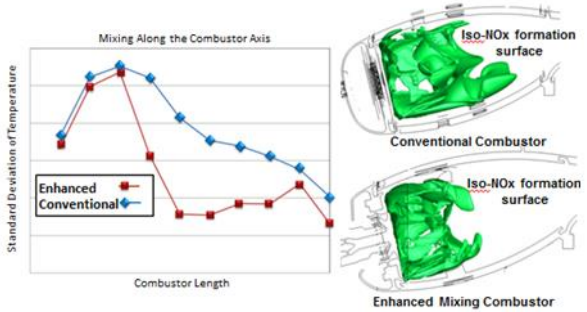
Advanced RQL Low NOx Combustion System

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

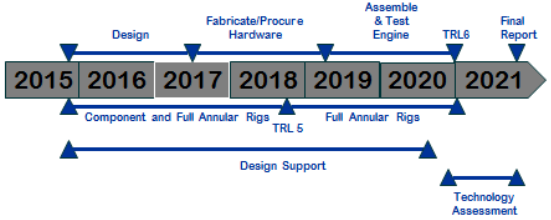
Work Statement:

- 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 TRL6 demonstration
- Design refinements to enhance performance, leading to goal attainment of 65% NOx margin to CAEP8.

Schedule:



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