FAA Continuous Lower Energy, Emissions, and Noise (CLEEN II) Technologies Program

Rolls-Royce CLEEN II Low NOx Combustor Final Report – Public Version

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Engineering Department Report (EDR)

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List of Acronyms and Abbreviations

3-D	three-dimensional
ALM	Additive Layer Manufacturing
CAEP	Committee on Aviation Environmental Protection
CAEP/8	Committee on Aviation Environmental Protection issue 8
CFD	computational fluid dynamics
CLEEN	Continuous Lower Energy, Emissions, and Noise
CO_2	carbon dioxide
dB	decibel
f/a	fuel-air
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
NOx	oxides of nitrogen
RQL	rich quench lean
SLA	stereolithography
TMF	thermomechanical fatigue
TRL	technology readiness level

1. Introduction/Overview

The goals of the Federal Aviation Administration's (FAA's) Continuous Lower Energy, Emissions, and Noise (CLEEN) II program were the development and demonstration of:

1. Certifiable aircraft technology that reduces aircraft fuel burn by 40% relative to 2000 best-in-class in-service aircraft, and/or supports the FAA goal to achieve a net reduction in climate impact from aviation;
2. Certifiable aircraft technology that reduces landing and takeoff cycle (LTO) nitrogen oxide emissions by 70% over the ICAO standard adopted in 2011 (CAEP/8), and/or reduces absolute NOx production over the aircraft's mission; This must be achieved while limiting or reducing other gaseous or particle emissions;
3. Certifiable aircraft technology that reduces noise levels by 32 dB cumulative, relative to the Stage 4 standard, and/or reduces the noise contour area in absolute terms;
4. The feasibility of use of drop-in alternative jet fuels in aircraft and engine systems, including successful demonstration and quantification of benefits; advancement of fuel testing capability; and support for fuel evaluation.

Under the CLEEN II program, Rolls-Royce initiated a program to develop combustion technology capable of achieving 65% margin to ICAO CAEP/8 NOx standards and to demonstrate the resulting combustion system to technology readiness level (TRL) 6. The details of the combustor development are included in the balance of this report.

Rolls-Royce targeted a rich burn combustion system for this program based on the need for emissions reduction in smaller gas turbine engines that cannot sustain the cost and complexity of staged lean burn combustion systems found on large engines. The selected approach combined innovative techniques and technologies including highly effective cooling schemes, novel combustor aerodynamics, and innovative fuel injection.

Candidate technologies and concepts were developed and screened in a systematic fashion using lower TRL rigs. Additive Layer Manufacturing (ALM) technology was utilized to deliver component definitions beyond the capability of standard fabrication approaches, and high temperature materials were employed to minimize cooling requirements.

A full-scale, full-annular TRL5 combustor rig was used to demonstrated system performance and emissions, and the combustor achieved TRL6 with engine testing in 2020. The Rolls-Royce CLEEN II combustion system ultimately demonstrated 68% margin to CAEP/8 NOx standards, and has performed well throughout engine testing, satisfying our program goals.

2. Combustion Module Development

To deliver the CLEEN II goal level of emissions reduction in a rich-quench-lean (RQL) combustion system, Rolls-Royce pursued several innovative design elements, techniques, and technologies. Advanced wall cooling and high temperature materials were incorporated to improve cooling effectiveness, enabled through additive layer manufacturing. Novel mixing aerodynamics and optimized combustor shape were defined to reduce residence time and minimize NOx formation. Finally, innovative fuel injection was developed to improve uniformity and dispersion at the smaller physical scale needed for a compact combustion system

The combustion system development approach incorporated a systematic evaluation of technologies to mature the technical elements individually followed by integration into the overall system. The specific elements are listed in Table 1, and each of the validation vehicles is discussed in the following separate subsections of this report.

Table 1. Combustion system development approach and rig vehicles.

Technical element	Validation vehicle(s)	TRL	Information acquired
Wall cooling	Thermomechanical fatigue rig	2	Material/design limitations with regards to thermal cycling
External aerodynamics	Aero screening rig	2	Early characterization of external pressure field
External aerodynamics	Cold flow rig	3	Detailed external pressure field mapping
Advanced mixing	Cold flow rig	3	Jet mixing efficiency as measured at exit of combustion liner
Fuel injection	Fuel spray nozzle rig	2	Fuel – air mixing characterization Atmospheric combustion showing flame development
Fuel injection, combustion performance	Flametube rig	3/4	Single combustion sector at high inlet pressure and temperature to investigate flame stability, and combustion properties
Advanced mixing, combustion performance	Full annular rig	5	Full-scale combustion module system level performance at high inlet temperature and pressure to determine combustor exit temperature characteristics and emissions

2.1 Thermomechanical Fatigue (TMF) Rig

Emission control is dependent upon having sufficient air quantity to facilitate reaction of the fuel and subsequent rapid mixing of the hot reactants to a temperature uniformity level consistent with the turbine mechanical design parameters. Therefore, a highly efficient wall cooling system is an enabling technology for low emissions. The CLEEN II combustion system incorporated advanced liner wall construction and improved material capability, produced by ALM, to provide the necessary cooling effectiveness. This construction and material system was assessed and validated in a thermomechanical fatigue rig before being integrated into the full-scale combustion liner hardware to ensure the required durability in engine operation.

The test consisted of passing a specimen through a hot vitiated airstream over multiple cycles to generate understanding of the crack initiation and crack growth properties of a design. Detailed mapping of the specimen surface at different time intervals and number of cycles provided a characterization of the material system with representative hardware features. This testing provided the necessary data to complete the mechanical design of the combustor liner and provide confidence in its durability in the actual operating environment.

2.2 Aerodynamic Screening Rig

The aerodynamic screening rig was used to provide an initial assessment of the engine architecture and concept configuration of the combustion system. The rig was full scale and simulated the combustion module from compressor diffuser section to the turbine inlet. The combustion liner was fabricated with a stereolithography (SLA) three-dimensional (3-D) printer and included all liner wall flow features and shapes as well as an integral fuel nozzle emulator. This rig was used to conduct a system-level assessment and characterize key design parameters prior to the more detailed cold flow characterization testing.

2.3 Cold Flow Characterization Rig

The cold flow aerodynamic characterization rig provided the mechanism to select key design parameters for an optimum engine system and provided basic performance data for benchmarking computational fluid dynamics (CFD) models. The results provided early definition of the pressure field for the combustion liner design with detailed measurement capability, providing increased confidence in the design definition.

The cold flow rig design was based on full-size scale combustion module hardware. Inlet air was supplied via a blower unit to pressurize the rig to the specified conditions. The rig, shown in Figure 1, included all details of the compressor exit diffuser and the combustion liner test article, including fully detailed shape and air openings and simulated fuel injectors. The combustion liner hardware for the cold flow rig was made from Perspex, a plastic type material, which provided optical access and reduced fabrication time. Multiple pressure measurement stations were included along the outer wall and inner wall. To get high resolution pressure measurements, the rig was mounted so it could be rotated 360 degrees.

Following external aerodynamic characterization, the cold flow rig was reconfigured for internal flow field and mixing characterization. The test setup was modified to include the instrumentation and inclusion of a flow path for a tracer gas in the fuel injector. There was no combustion, or chemical reaction in this rig. Rather, CO_2 was injected through a fuel injector as a tracer gas. This rig provided empirically quantification of the mixing sensitivity for different combustion liner geometries. Using these data, the position of mixing flow ports and the flow distribution among the individual ports was defined.

2.4 Fuel Spray Nozzle Rig

The small size of the CLEEN II combustor drives the fuel injector to be smaller as well, introducing design challenges as well as performance challenges. The injector performance for the combustion must be excellent, with the fuel dispersed in very small droplets across the reaction zone. Given the complex nature of fuel atomization, evaporation, and dispersion in a reacting flow field, the fuel nozzle tip was developed empirically as first principal modeling and computations are not available for such complex physical processes.

The fuel nozzle development approach utilized a combination of flexible hardware and screening diagnostics to evaluate the fuel spray quality and resultant low pressure flame structure. To do this, a modular fuel injector was designed with interchangeable airflow features. The fuel injector assembly was fabricated from high temperature materials to allow the same hardware to be used in this rig, which runs at atmospheric conditions, as well as in the flametube rig, which runs at high temperature, high pressure conditions. This allowed the spray performance as characterized via the fuel nozzle rig to be maintained precisely when moved to the flametube rig.

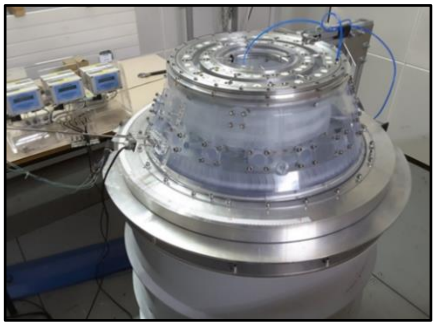

Figure 1. Cold flow aerodynamic characterization rig.

The fuel spray rig has capability to image the spray using laser light at atmospheric conditions. The spray is contained in an optically transparent cylinder that serves as a flametube to contain the flame and an igniter can be inserted to trigger a flame. Thus, ignition of the fuel and visual observation of the resultant flame structure as well as the liquid spray interaction with the flame can be accomplished for candidate injector hardware configurations. Figure 2 presents representations of the fuel spray nozzle rig visualization and patternation capabilities. This rig was utilized to examine a broad range of candidate fuel spray nozzle configurations and identify to the most promising candidates for further testing.

2.3 Flametube Rig

The flametube rig was the primary vehicle for downselection of the fuel spray nozzle functional design. The flametube was installed into a rig that can support testing at high temperature and pressure operation and incorporates aerodynamics suitable for assessing performance. These attributes plus the fact the flametube was designed to use a single fuel injector make it particularly suitable for fuel injector assessment since only one injector was needed for the evaluation rather than several as in a full annular system.

The flametube, shown in Figure 3, was instrumented with thermocouples and provides access ports for the ignition system as well as a gas sampling probe. The flametube had integral air ports with provisions for pressure loss, which mimicked the system-level differences in pressures found in the combustion system between the fuel injector and liner walls.

Testing was conducted over a range of the combustor's operating environment and fuel-air (f/a) ratios. This f/a ratio sweep provided a view of performance sensitivity to burner temperature rise at each specific inlet condition. Results of the flametube testing identified the most promising configuration for the CLEEN II combustion system. The selected combination of liner dome and fuel spray nozzle configuration performed well at low power inlet conditions with good flame stability and high combustion efficiency and maintained low NOx at high power conditions.

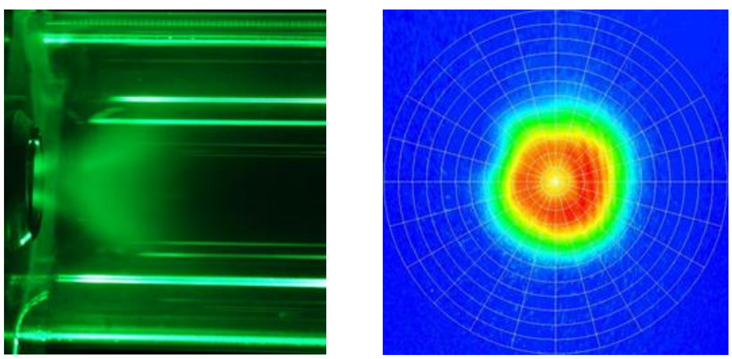

Figure 2. Fuel spray nozzle rig visualization and patternation results

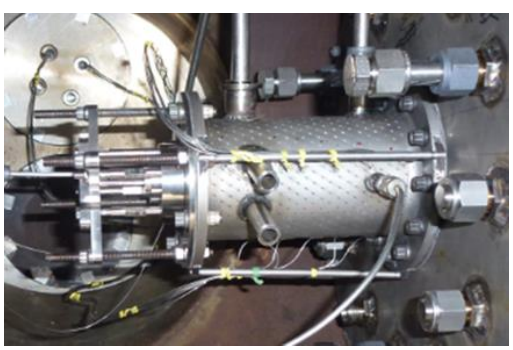

Figure 3. Flametube installed in high pressure rig

2.6 Full Annular Rig

Component rig development efforts assessed and established the wall cooling system, combustion aerodynamics, and the fuel injector configuration. This effort culminated in the full annular combustor rig. This rig was a full-scale, full-detail representation of the combustion module from compressor discharge to turbine inlet. The rig delivered high pressure, high temperature air to mimic compressor discharge conditions through a via a compressor flow-path simulator. The combustion test section hardware was designed for incorporation in a demonstrator engine upon successful rig test completion.

The full annular combustor rig contained special instrumentation to measure combustor discharge temperature and emissions, as well as a water quench system that cooled the hot combustor gases to a level they could be discharged safely. The rig was designed to accept 2 rakes at the exit of the combustor, mounted at 180-degree positions from one another. The rakes could be rotated so that a full 360-degree view of the combustor exit could be measured, with simultaneous measurement of gas temperatures and extraction of gas samples as the probes were swept. A view of the full annular rig in the Rolls-Royce test facility is shown in Figure 4.

The first CLEEN II combustor was tested in the full annular combustor rig in 2018. The measured performance of this combustor was in line with design intent in terms of exit temperature pattern, efficiency, and operability. Therefore, the combustor was cleared to progress to the initial engine demonstration. Emissions performance, while improved from our baseline configuration, did not meet our expectations. Therefore, a design iteration was conducted to target further improvements.

The second combustor incorporated adjustments to the combustion liner wall port sizes to redistribute the mixing air. This configuration was tested in the full annular combustor rig in 2019. The results of this testing found that mixing performance did not improve as intended, particularly at high power operation. This testing did, however, provide further guidance to define a third iteration of the combustor liner design.

Using the lessons learned from the first two iterations, a third combustor was defined with further modifications to liner wall port sizes and mixing air distribution. Full annular combustor rig of this configuration in 2020 found outstanding performance. Exit temperature pattern, efficiency, and operability met expectations, and as a result the combustor was cleared to

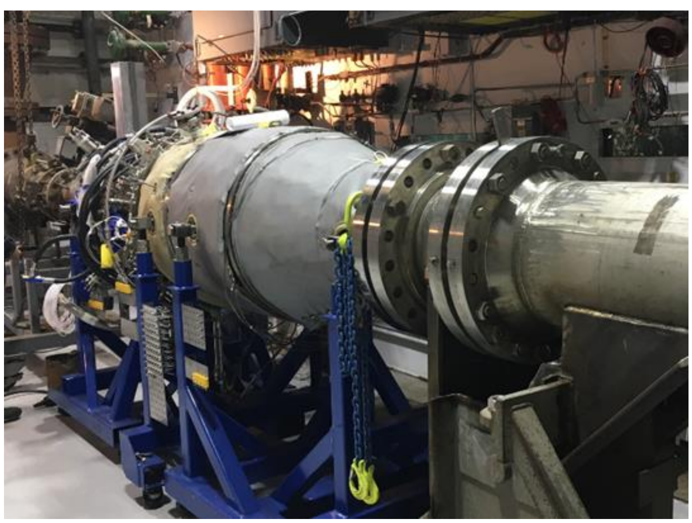

Figure 4. Full annular combustor rig installed in test stand

progress to engine demonstration. Emissions performance was excellent, with reductions in gaseous emissions and particulates in line with our program goals.

In parallel with this rig activity, an alternative combustor configuration had been defined with significant modifications to the liner configuration to target further NOx reductions. This design reduced combustor volume by 25% to minimize the residence time combustion products spend at high temperature and reduce overall NOx emission levels. This alternative design was also tested in the full annular combustor rig in 2020 with overall positive results. However, given the novelty of the design, further design assessment and rig testing was deemed necessary, and this design did not progress to engine test.

3. Engine Demonstration Testing

Having demonstrated the CLEEN II combustor's performance and emissions in the rig environment, the hardware was passed to the engine assembly for TRL6 demonstration. The first combustor module was assembled in the engine and passed to test in 2019. The combustor met all expectations during engine testing, with excellent performance, operability, and starting performance. The second combustor was assembled in the engine and passed to test in 2021. This combustor likewise met all expectations during engine testing. Over 200 hours of engine operation have been accumulated on the CLEEN II combustion system.

Post-test inspection of hardware from the first engine test found the combustor liner to be in excellent condition. Some carbon buildup was seen on the liner, but its thermal barrier coating was fully intact and no evidence of cracking during test was found. Light carbon buildup was observed on the fuel spray nozzles but no change in flow number was measurable. Inspection of the second combustor found it to be in similar excellent condition. Based on these test results, the CLEEN II combustion system has demonstrated TRL6 and is poised for introduction in the next generation of Rolls-Royce production offerings.

4. Future Product Engine Performance

A representative turbofan product engine was defined to quantify the benefits of the CLEEN II combustor technology in future aircraft applications. The selected configuration was based on a high pressure ratio core coupled with a high bypass ratio fan module to represent a likely next-generation application of this technology. Incorporating the emissions data acquired during testing of the CLEEN II combustion system, the predicted NOx emissions of this representative turbofan engine would be 32.0% of CAEP/8 standards or 68.0% margin to requirements.

5. Summary

Rolls-Royce has developed and demonstrated a high performance combustion system under the FAA CLEEN II program. The combustion system incorporated key technologies that were developed and demonstrated in a staged, systematic fashion to enable a combustor design that provide significant NOx reductions. Rig demonstrations with high fidelity measurements captured detailed combustor performance. Testing in the engine environment showed excellent performance and durability, achieving TRL6. Emissions measurements revealed the combustor would deliver a 68% margin to the CAEP/8 NOx standards in a future turbofan application.

The Rolls-Royce CLEEN II combustion system has fully demonstrated technology capable of supporting future product engines that will have superior performance while protecting the environment.

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