CLEEN Phase I and II Projects

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Aurora Flight Sciences

Aurora, under CLEEN Phase II, is developing and demonstrating composite airframe technologies that will enable an unconventional aircraft configuration with the potential to reduce fuel burn, emissions, and noise. The company is designing an all-composite fuselage for what is known as the double-bubble advanced aircraft concept, using materials and manufacturing processes that demonstrate configuration feasibility and weight benefits. The technologies developed under CLEEN Phase II will help enable fabrication of the fuselage of the double-bubble aircraft concept.

- In 2017, Aurora fabricated and load tested a set of manufacturing exploration elements in order to improve the manufacturing approach and validate Finite Element Method (FEM) models of key fuselage components. Aurora built and tested a key subsection of the double-bubble fuselage configuration to validate its structural performance.
- The double-bubble advanced aircraft concept is estimated to provide a 29 percent reduction in fuel burn and up to 16 EPNdB (Effective Perceived Noise level in dBs) cumulative noise reduction toward the CLEEN Phase II goals. These benefits represent the improvements this configuration change provides, on which additional technology benefits could be applied. This configuration with advancements in engine integration that could be realized beyond the CLEEN Phase II timeframe holds the potential for up to 56 percent fuel burn reduction and 42 EPNdB cumulative noise reduction.

Boeing

The technologies matured by Boeing during CLEEN Phase I included an Adaptive Trailing Edge (ATE) on the aircraft wing and a Ceramic Matrix Composite (CMC) acoustic engine exhaust nozzle. Boeing also conducted research jointly with the University of Dayton Research Institute to examine how sustainable aviation fuels effect aircraft fuel systems.

- In 2012, Boeing demonstrated that the ATE system provides up to a 2 percent reduction in aircraft fuel burn and reduces aircraft noise levels by 1.7 decibels (dBs). When used fleet-wide in the United States, a 2 percent reduction relative to 2009 fuel usage could save 340 million gallons of fuel with operating cost savings of $1.2 billion. Technologies from this project have since been adopted for use in commercial and defense products.
- In 2014, Boeing tested the CMC nozzle on a 787 aircraft. This technology can withstand higher temperatures, is made of lighter weight material, and lowers fuel consumption. The CMC nozzle technology can also accommodate acoustic treatments that reduce community noise. The CMC nozzle reduces fuel burn by up to 1 percent and provides up to a 2.3 dB noise reduction. This technology is being considered in trade studies for current development programs.

For CLEEN Phase II, Boeing is developing and demonstrating advanced aircraft wing technologies that could reduce aircraft fuel burn by up to 3.5 percent. The Structurally Efficient

Wing (SEW) provides large weight reductions through new manufacturing techniques and advanced composite material technology, resulting in a reduction of aircraft fuel burn. Over twenty years, this technology could result in an estimated 200 million tons of jet fuel savings and avoidance of approximately 660 million tons of CO_2 emissions. Boeing is also conducting design and test work on a compact nacelle inlet and thrust reverser design for ultra-high bypass engines. The technology is expected to reduce weight and allow for improved acoustic treatment.

- In 2018, Boeing completed a ground test campaign of compact nacelle technology at the Stennis Space Center Rolls-Royce engine test facility. Crosswind testing was conducted for a baseline and short inlet. The findings will be used to validate propulsion-aero design tools and inform future development programs.
- In 2019, Boeing completed full scale ground testing of the Wing Component Test Article. The structural test series was conducted at the National Institute for Aviation Research in Wichita, Kansas. Boeing is currently collecting additional test data and will submit a final report to FAA in Q2 CY2020.
- In 2019, Boeing initiated a follow-on CLEEN Phase II effort to develop acoustic treatment concepts for the aft duct of compact nacelle architectures. This work will culminate in a flight demonstration to validate design concepts for transition to new and existing products. A preliminary design review was completed in October 2019.

Collins Aerospace

Under CLEEN Phase II, Collins Aerospace is developing integrated propulsion system nacelle technology to reduce noise, fuel burn, and emissions. The company is advancing innovative acoustic treatment technologies and clean fan duct thrust reverser designs. The combined technology package is expected to provide a one percent reduction in fuel burn and 2 EPNdB reduction in noise, while also enabling the use of next generation quiet and efficient ultra-high bypass engines.

- In 2019, Collins completed a detailed design review for the acoustic ground test demonstrator. The ground test incorporates an advanced tailored acoustic design, including area maximization, zoned liner optimization, and low drag liner integration. The ground test is scheduled to occur in summer 2020.

Delta Tech Ops / MDS Coating Technologies / America's Phenix

Under CLEEN Phase II, the team of Delta Tech Ops, MDS Coating Technologies and America's Phenix is developing and demonstrating a protective leading edge coating for gas turbine engine fan blades. This coating protects against fan blade erosion, which degrades aerodynamic efficiency of in-service engines. The resulting retained efficiency will reduce fuel consumption over the life of the engine, estimated at up to 0.4 percent fuel savings during aircraft cruise and over 1 percent fuel savings at maximum power.

- In 2018, the team installed coated blades on-wing and began flight service evaluation. Multiple sets of coated blades are currently flying on revenue service MD-80 aircraft, with inspections occurring at periodic intervals. The flight test schedule will extend through 2020 with the goal of proving the robustness and benefits of the coating.

GE Aviation

Under CLEEN Phase I, GE developed and demonstrated several aircraft technologies that reduce fuel burn, emissions, and noise. These technologies are the open rotor engine, advanced engine combustor known as the Twin Annular Premixed Swirler (TAPS) II, Flight Management System-Air Traffic Management (FMS-ATM) System Integration, and Flight Management System-Engine Integration.

- In 2012, GE engine emissions tests of the TAPS II combustor demonstrated that the technology reduced NO_X emissions more than 60 percent below the 2004 ICAO CAEP NO_X standards, thus meeting the CLEEN Phase I goal. The TAPS II combustor subsequently entered into service in 2016 as part of CFM International's TAPS Leading Edge Aviation Propulsion (LEAP) engine, currently onboard Airbus 320neo, Boeing 737 MAX, and COMAC C919 aircraft.
- In 2012, GE also completed scaled open rotor wind tunnel tests, which resulted in a 15 dB reduction relative to the Stage 4 noise standards and a 26 percent fuel burn reduction relative to specific current jet engines.
- In 2013, GE demonstrated flight trajectory synchronization between aircraft and the En-Route Automation Modernization (ERAM) system. These technologies provide pilots and controllers with better predictability of an aircraft's location, enabling greater fuel savings through more efficient aircraft routing.
- In 2013, GE developed probabilistic advisory spacing and vertical flight path optimization technologies. These two technologies are anticipated to reduce fuel burn by 0.7 percent and 1 percent, respectively.
- In 2015, GE completed ground engine and flight tests of their Flight Management System-Engine Integration technologies, showing a significant reduction in aircraft fuel burn.

Under CLEEN Phase II, GE is developing four aircraft technologies and undertaking one sustainable aviation fuel (SAF) project.

- More Electric Systems and Technologies for Aircraft in the Next Generation (MESTANG) is an integrated aircraft power system being designed by GE to support future "more-electric" aircraft architectures. The MESTANG technologies under CLEEN Phase II may reduce fuel burn by up to 6 percent. GE is conducting detailed design work on new power extraction, generation, distribution, and conversion systems for the MESTANG program. In 2019, GE completed fabrication and initial load testing of a key subcomponent prototype. GE continues to conduct component and system level tests, culminating in a full system demonstration in 2020.
- GE is also developing the Twin Annular Premixing Swirler (TAPS) III low emissions combustor for the 777X's GE9X engine. In 2017, GE achieved TRL 6 emissions demonstration of TAPS III combustor fuel-air mixer technology that meets the CLEEN

NO_X goal. CLEEN Phase II supported extensive rig test validation and development of risk mitigation technologies for TAPS III, thus enabling the technology to meet the NO_X target. The technology is on target for implementation into a 2020 entry-into-service (EIS) production engine.

- GE is developing Flight Management System (FMS) software algorithms that will optimize aircraft performance during the cruise and descent phases of flight. This project is estimated to a fleet-wide average of 1 percent and up to 4 percent fuel burn savings relative to legacy systems. In 2019, GE matured their FMS algorithms and Electronic Flight Bag prototype to TRL 6. GE delivered a final report to FAA, concluding their work under CLEEN Phase II. GE is currently working to incorporate these technologies in future FMS products.
- GE is developing novel acoustic liner and fan noise source strength reduction technologies to combat the reduced noise treatment area available in low fan pressure ratio engines. This work is targeting a 3 EPNdB cumulative noise reduction with no adverse impact to fuel burn. In 2019, GE tested novel liner designs in the NASA Langley Grazing Flow Impedance Tube and conducted detailed aeroacoustic and mechanical design of the fan source strength reduction concept.
- GE has completed testing of 100 percent Alcohol-to Jet Synthetic Parraffinic Kerosene in support of the National Jet Fuel Combustion Program. GE will perform combustor rig testing of novel SAFs to support ASTM approval. GE is advancing the approval of “drop-in” fuels. GE has selected two SAFs for testing: a 100 percent synthetic fuel (Hydro-processed Esters and Fatty Acids [HEFA] Synthetic Paraffinic Kerosene [SPK] + Hydrodeoxygenated Synthetic Aromatic Kerosene [HDO-SAK]), and High Freeze Point HEFA (HFP-HEFA). Testing will focus on operability of these fuels in a lean combustion system to further their potential for approval within the scope of the ASTM process. In 2019, GE completed combustor rig operability testing and data analysis for HFP-HEFA and HDO-SAK. The testing revealed no adverse impact on operability for the selected SAFs.

Honeywell

Under CLEEN Phase I, Honeywell developed and demonstrated engine core technologies that increase engine efficiency and reduce engine weight. Honeywell also tested sustainable aviation fuels.

- In 2011, Honeywell completed testing of HEFA fuel that expedited its international approval by ASTM International for use by commercial aviation.
- In 2015, Honeywell completed final engine core and engine endurance testing of all of its CLEEN Phase I technologies, validating fuel burn reduction and maturity for those technologies. Together with complementary engine upgrades, the technologies offer a 15.7 percent overall reduction in fuel burn relative to current engine designs.

Under CLEEN Phase II, Honeywell is developing and demonstrating two technologies: a compact, low emissions combustor and an advanced turbine Blade Outer Air Seal (BOAS). The compact low emissions combustor uses advanced aerodynamics and fuel injection technologies to reduce engine NO_X and particulate matter emissions while reducing weight, and thereby reducing fuel burn. Honeywell's advanced turbine blade outer air seal increases high pressure turbine efficiency, resulting in reduced fuel burn. The two technologies contribute to an engine level improvement of greater than 22 percent fuel burn reduction relative to a baseline engine with a factor of two improvement in NO_X margin relative to Honeywell's state-of-the-art combustor.

- In 2019, Honeywell completed a rig test of their latest combustor design at the Honeywell Phoenix Combustor Test Laboratory. Honeywell also completed the rig design and final test plan for their planned NASA Glenn Advanced Subsonic Combustor Rig test, slated for Q3 CY2020.
- In 2019, Honeywell completed design of the turbine shroud for the BOAS system and received most of the hardware for a planned 2020 development engine test. The low conductivity thermal barrier coating is also on track for 2020 engine testing, having shown good results in performance and process optimization tests.

Pratt & Whitney

Under CLEEN Phase I, Pratt & Whitney developed and demonstrated an ultra-high bypass ratio Geared Turbofan™ (GTF) engine and associated advanced technologies. Pratt & Whitney also supported qualification of sustainable aviation fuels via combustor rig and auxiliary power unit testing.

- In 2015, Pratt & Whitney completed a series of tests in support of ASTM International approval of the following SAFs: Amyris Synthesized Iso Paraffins (SIP) Farnesane; Kior Hydrotreated Depolymerized Cellulosic Jet (HDCJ); Applied Research Associates (ARA) Catalytic Hydrothermolysis (CH), and Swedish BioFuel ATJ-SKA. In part because of these tests, one of these fuels have been approved for use (SIP) and another is nearing approval (CH).
- In 2017, Pratt & Whitney completed an ultra-high bypass engine test campaign, demonstrating aerodynamic performance, mechanical, and acoustic characteristics of advanced fan system technologies. Geared turbofan engine technologies contribute to a 20 dB aircraft noise reduction and a 20 percent fuel burn reduction because of increased engine efficiency.

Under CLEEN Phase II, Pratt & Whitney is developing and demonstrating technologies for the engine compressor and turbine to improve engine thermal efficiency and reduce fuel burn of the Pratt & Whitney GTF engines. The development work will focus on advanced aerodynamics, cooling, and durability optimization.

- In 2016, Pratt & Whitney completed a compressor rig test that demonstrated improved high pressure compressor efficiency and validated performance predictions. This compressor design is slated for a ground test in the near future. The Pratt & Whitney CLEEN Phase II compressor technologies are estimated to result in 0.8-1.0 percent fuel burn reduction relative to a state-of-the-art engine.

- In 2019, the CLEEN Phase II compressor aero design successfully completed ground and flight tests. The tools developed and knowledge gained on aero performance under CLEEN Phase II will be introduced into Pratt & Whitney's Geared Turbofan product line.
- In 2019, test facility upgrades were completed at the Pennsylvania State University Steady Thermal Aero Research Turbine (START) facility that will enable Pratt & Whitney to advance turbine aero-efficiency and durability technologies. Aero-efficiency testing of the baseline turbine blade was completed, with testing of the CLEEN Phase II technology blade to follow in 2020. The team also completed single element cascade testing to evaluate the effectiveness of different turbine blade cooling hole designs. The Pratt & Whitney CLEEN Phase II turbine technologies are estimated to result in 0.8-1.0 percent fuel burn reduction relative to a state of the art engine.

Rolls-Royce

Under CLEEN Phase I, Rolls-Royce developed and demonstrated Dual-Wall Turbine Airfoil and CMC Blade Track technologies aimed at increasing thermal efficiency in the turbine section of the engine, thereby reducing fuel burn. Rolls-Royce also conducted laboratory and engine component tests of advanced sustainable aviation fuels that could be approved for commercial use by ASTM International.

- In 2013 and 2014, engine testing of the CMC Blade Track validated the technology's performance and benefits.
- In 2015, Rolls-Royce completed testing of the Dual Wall Turbine Airfoil. The testing showed that the Dual-Wall Turbine Airfoil and CMC Blade Track technologies will realize a fuel burn reduction of up to one percent overall.
- In 2013, Rolls-Royce completed laboratory testing of new sustainable aviation fuels under development by nine fuel companies. Four of these fuels were tested in support of ASTM approval. One of the fuel candidates, HEFA, has been approved. ARA CH, Byogy ATJ-SKA, and Virent Synthesized Aromatic *Kerosene (*SAK) are currently in the ASTM International approval process.

Under CLEEN Phase II, Rolls-Royce is developing and demonstrating low emissions combustor technology and undertaking sustainable aviation fuels testing work. Rolls-Royce's advanced Rich-Quench-Lean (RQL) combustion system employs advanced fuel injection and mixing technologies that will provide significant emissions reduction while simultaneously enabling the increase in turbine entry temperature required by advanced engine cycles. The project will demonstrate a near-term configuration targeting NO_X emission levels 40 percent below CAEP/8 limits and a final configuration with NO_X levels 65 percent below CAEP/8, achieving significant progress toward the CLEEN Phase II NO_X goal. Rolls-Royce is also conducting SAF testing to support ASTM approval of novel fuels.

- In 2017, Rolls-Royce selected a fully synthetic fuel for the SAF test program after screening several candidates and producers. The selected fuel is a blend of 87 percent LanzaTech Alcohol-to-Jet fuel with 13 percent Swift Fuels mesitylene aromatic. In 2018, Rolls-Royce completed spray characterization; fit for purpose; emissions; and elastomeric seal performance phase one testing. They anticipate concluding full annular rig testing in 2020.

- In 2019, Rolls-Royce conducted full annular rig testing of their near-term combustor configuration. This combustor design has been cleared for an engine demonstration build. The team also completed design of a second phase configuration that is slated for full annular rig testing prior to engine demonstration.
- In 2020 Rolls-Royce will conduct a flight test demonstration of the Boeing compact nacelle technology, a follow-on from their collaboration with Boeing for ground test of the technology.