# REDAC Environment and Energy Sub-Committee

## Aircraft Technology Update

By: Levent Ileri and Arthur Orton
FAA CLEEN Program Managers

Date: March 18, 2020

# Agenda

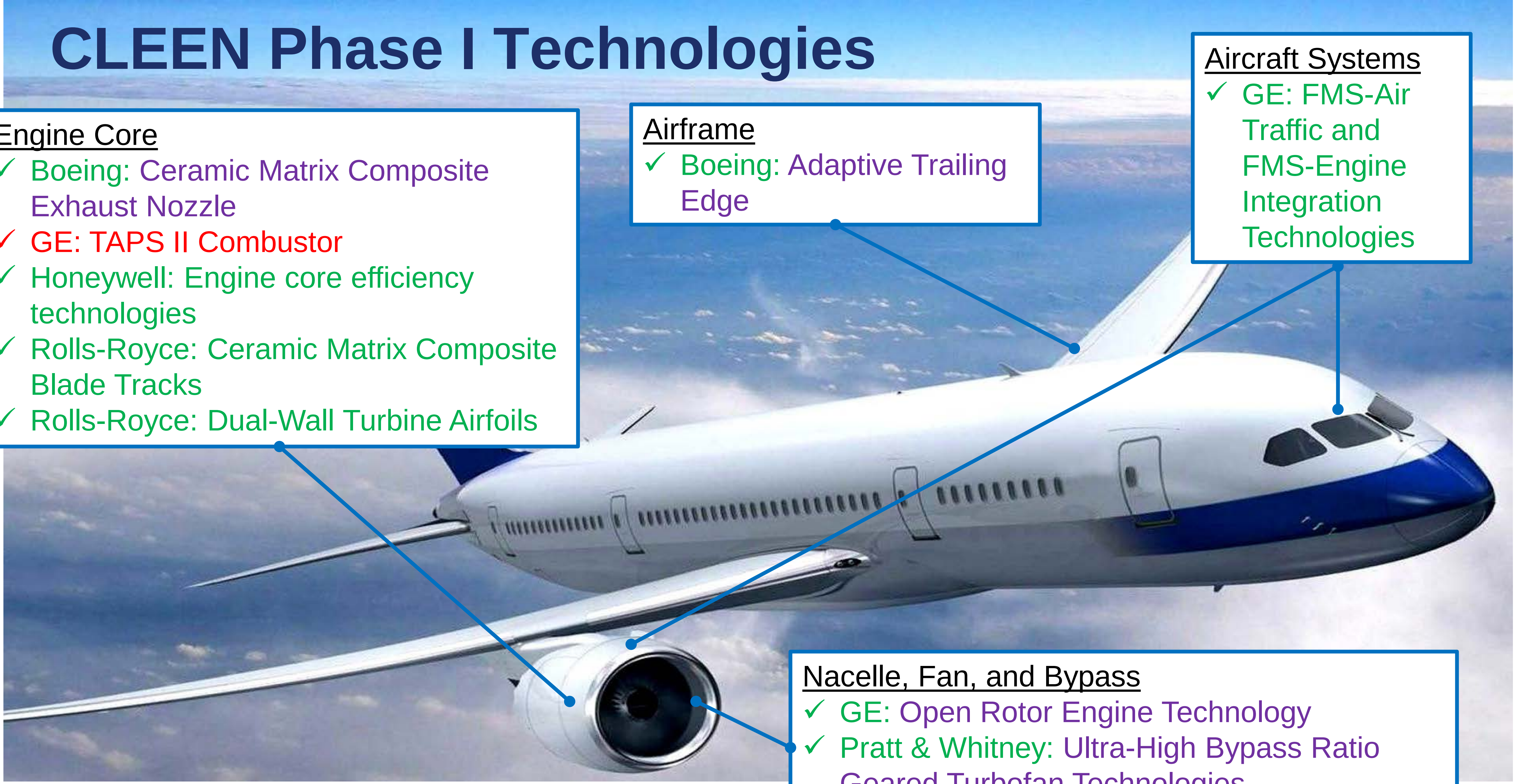
- **Continuous Lower Energy, Emissions & Noise (CLEEN) Program Overview**
  - CLEEN Phase II status
  - CLEEN Phase III update
- **Aviation Sustainability Center of Excellence (ASCENT) Technology Projects**

# Continuous Lower Energy, Emissions & Noise (CLEEN) Program

- FAA led public-private partnership with 100% cost share from industry
- Reducing fuel burn, emissions and noise via aircraft and engine technologies and alternative jet fuels
- Conducting ground and/or flight test demonstrations to accelerate maturation of certifiable aircraft and engine technologies

| | Phase I (Completed) | Phase II (Ongoing) |
|---|---|---|
| Time Frame | 2010-2015 | 2016-2020 |
| FAA Budget | ~$125M | ~$100M |
| Noise Reduction Goal | 25 dB cumulative noise reduction cumulative to Stage 5 | |
| Fuel Burn Goal | 33% reduction | 40% reduction |
| $NO_X$ Emissions Reduction Goal | 60% landing/take-off $NO_X$ emissions | 75% landing/take-off $NO_X$ emissions (-70% re: CAEP/8) |
| Entry into Service | 2018 | 2026 |

# CLEEN Phase I Technologies



**Engine Core**
- ✓ Boeing: Ceramic Matrix Composite Exhaust Nozzle
- ✓ GE: TAPS II Combustor
- ✓ Honeywell: Engine core efficiency technologies
- ✓ Rolls-Royce: Ceramic Matrix Composite Blade Tracks
- ✓ Rolls-Royce: Dual-Wall Turbine Airfoils

**Airframe**
- ✓ Boeing: Adaptive Trailing Edge

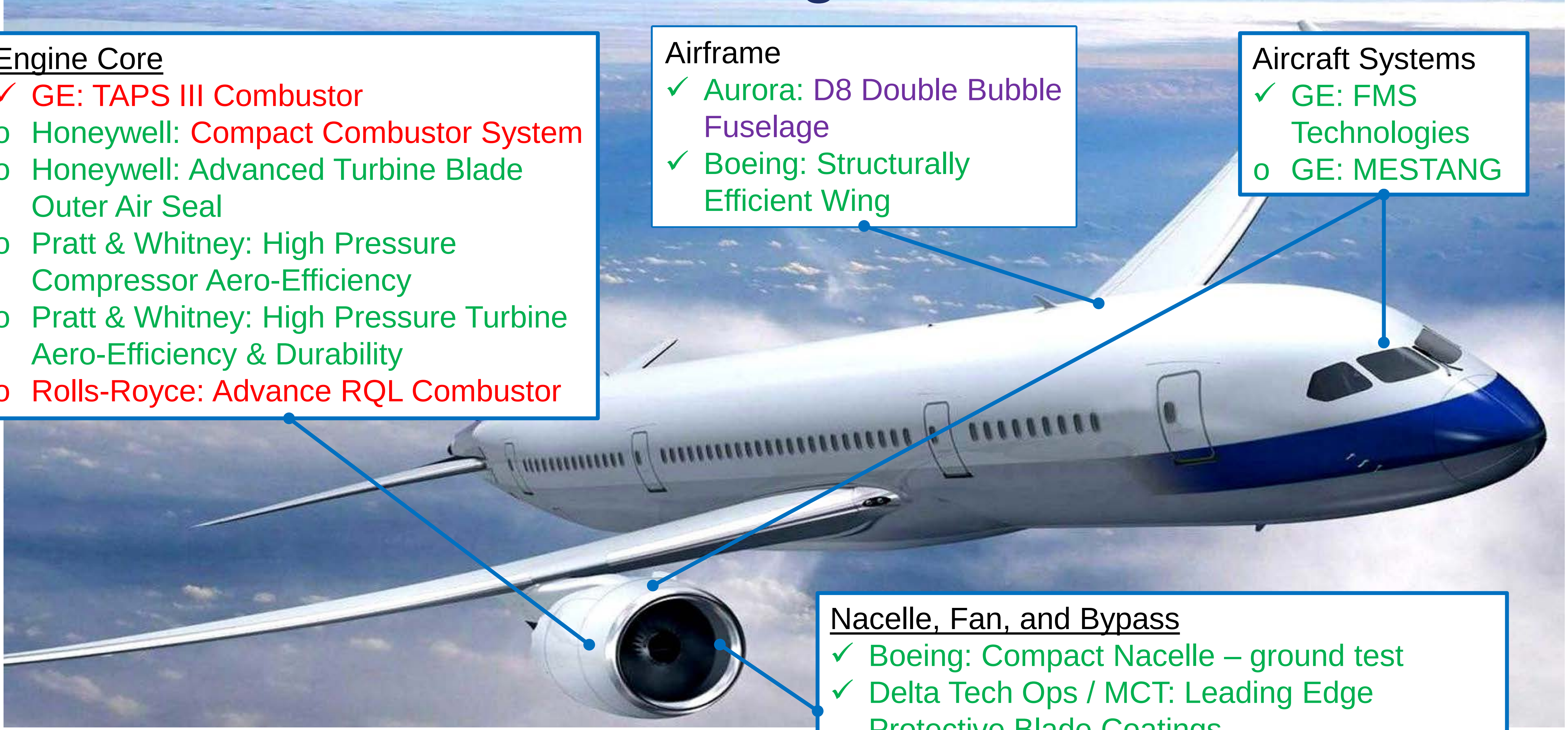
**Aircraft Systems**
- ✓ GE: FMS-Air Traffic and FMS-Engine Integration Technologies

**Nacelle, Fan, and Bypass**
- ✓ GE: Open Rotor Engine Technology
- ✓ Pratt & Whitney: Ultra-High Bypass Ratio Geared Turbofan Technologies

Fuel
$NO_x$
Noise

✓ Completed Effort

# CLEEN Phase II Technologies



**Engine Core**
- ✓ GE: TAPS III Combustor
- o Honeywell: Compact Combustor System
- o Honeywell: Advanced Turbine Blade Outer Air Seal
- o Pratt & Whitney: High Pressure Compressor Aero-Efficiency
- o Pratt & Whitney: High Pressure Turbine Aero-Efficiency & Durability
- o Rolls-Royce: Advance RQL Combustor

**Airframe**
- ✓ Aurora: D8 Double Bubble Fuselage
- ✓ Boeing: Structurally Efficient Wing

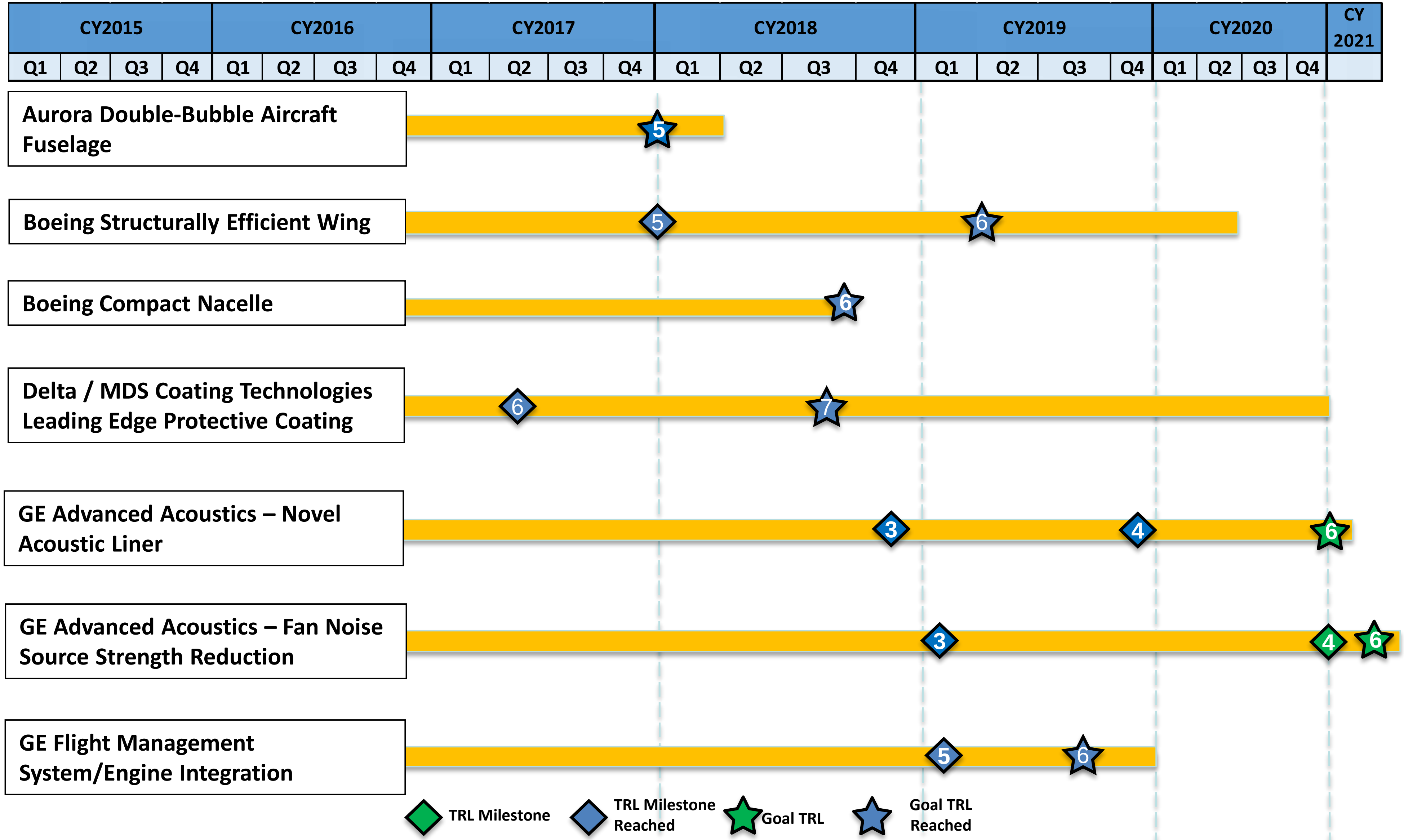
**Aircraft Systems**
- ✓ GE: FMS Technologies
- o GE: MESTANG

**Nacelle, Fan, and Bypass**
- ✓ Boeing: Compact Nacelle – ground test
- ✓ Delta Tech Ops / MCT: Leading Edge Protective Blade Coatings
- o GE: Low [illegible]re Ratio Advanced Acoustics
- o Collins Ae[illegible]e: Nacelle Technologies

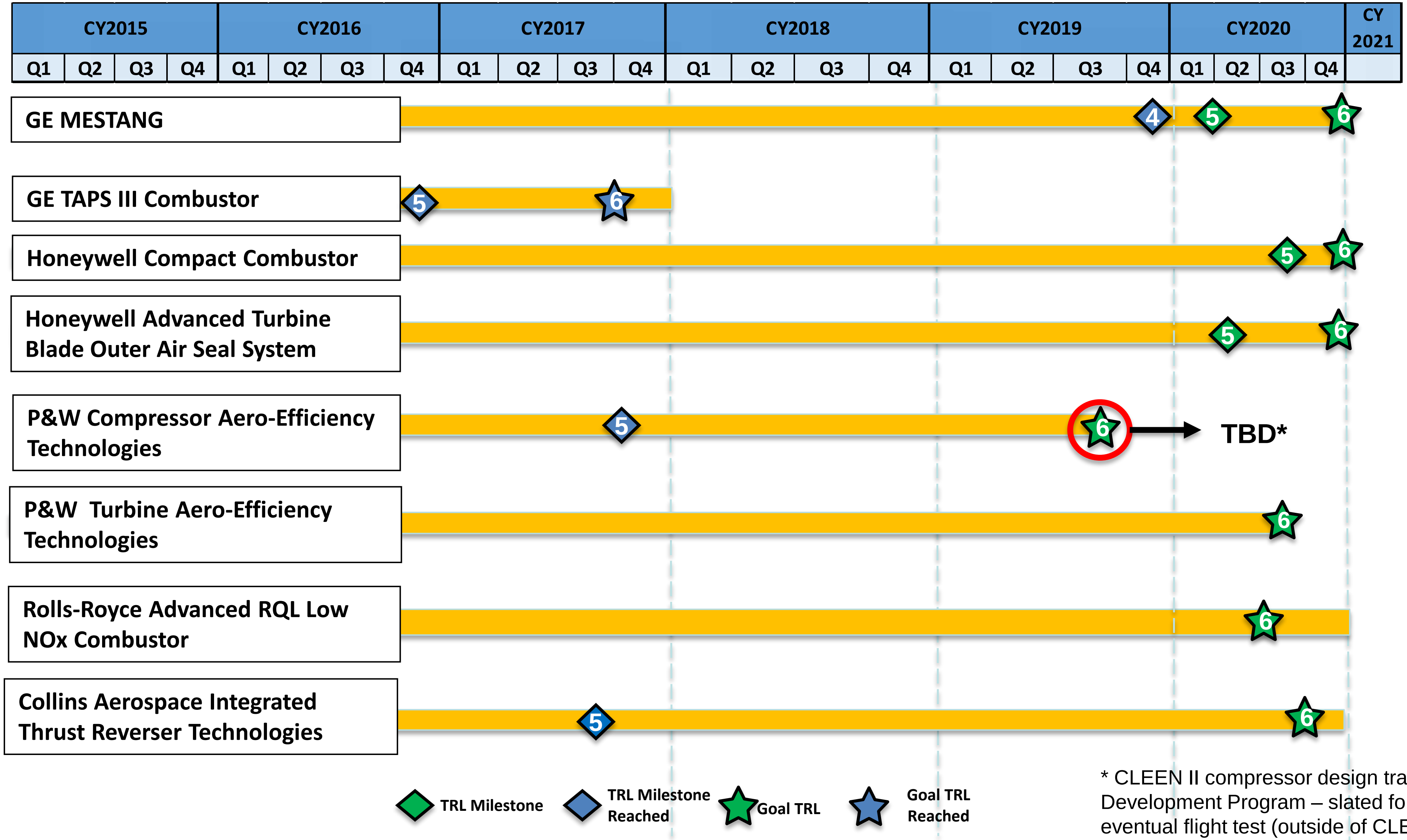
Fuel
$NO_x$
Noise

- ✓ Completed Effort
- o Continues in FY20

# CLEEN Phase II Technologies – TRL Milestones



# CLEEN Phase II Technologies – TRL Milestones cont.




* CLEEN II compressor design transitioning into Engine Development Program – slated for ground test and eventual flight test (outside of CLEEN-funded scope)

# Accomplishments - Second Half of 2019

- Boeing delivered Structurally Efficient Wing (SEW) Final Test Report (July 2019)
- Kicked off CLEEN Phase II Option for Boeing Acoustic Improvements in Aft Fan Duct (Oct 2019)
- Boeing completed Detailed Design Review for Acoustic Improvements in Aft Fan Duct (Jan 2020)

- Collins Aerospace conducted Detailed Design Review for Nacelle Technologies (Sep 2019)

- Delta TechOps / MDS Coating Technology reached > 2,000 flight service hours on two separate engines with coated fan blades (Nov 2019)

- GE completed detailed mechanical design review of fan source strength reduction technology (July 2019)
- GE completed second round of Grazing Flow Impedance Tube testing of novel liner panels at NASA Langley (Oct 2019)
- GE completed development of High Pressure Spool Starter Generator prototype (Oct 2019)
- GE matured FMS technologies to TRL 6, delivered final reports and briefing, and closed out CLEEN Phase II work (Dec 2019)

- Honeywell completed a full annular rig test of their counter-swirling injector air cap combustor configuration (Nov 2019)

- Pratt & Whitney completed baseline turbine blade aero-efficiency testing in the Penn State Steady Thermal Aero Research Turbine (START) rig (Nov 2019)

- Rolls-Royce completed full annular rig testing of multiple combustor configurations in preparation for engine test (Dec 2019)

# Upcoming CLEEN II Activities

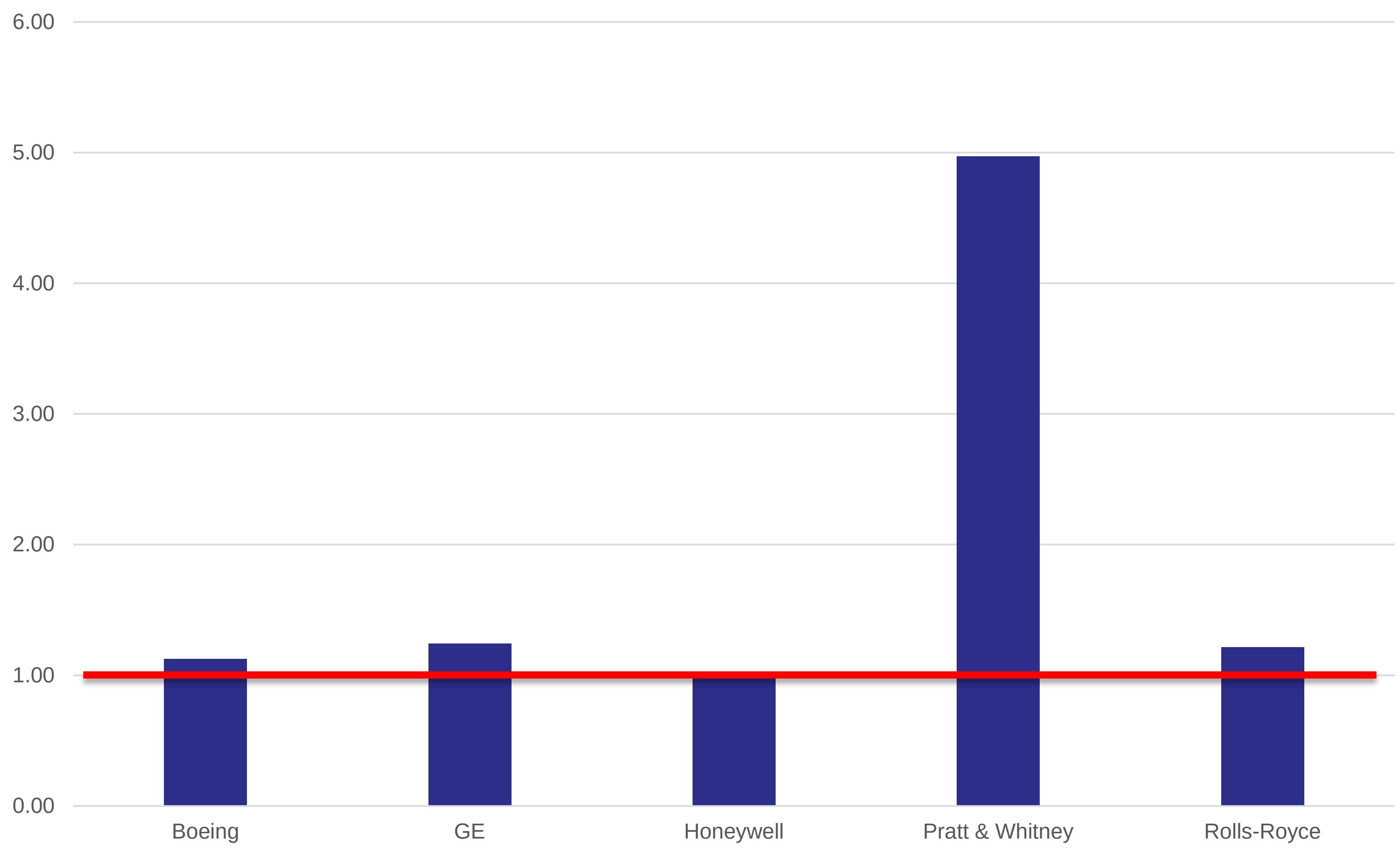
**Next 6 Months' Activities**

- Continued execution of CLEEN Phase II Options
- Boeing to deliver updated SEW final report
- Collins to hold clean fan duct demonstrator Test Readiness Review
- Pratt & Whitney to complete turbine technology blade testing on START rig
- Honeywell to begin blade outer air seal engine test as well as next rig test of next combustor configuration
- Rolls-Royce to initiate combustor full annular rig testing

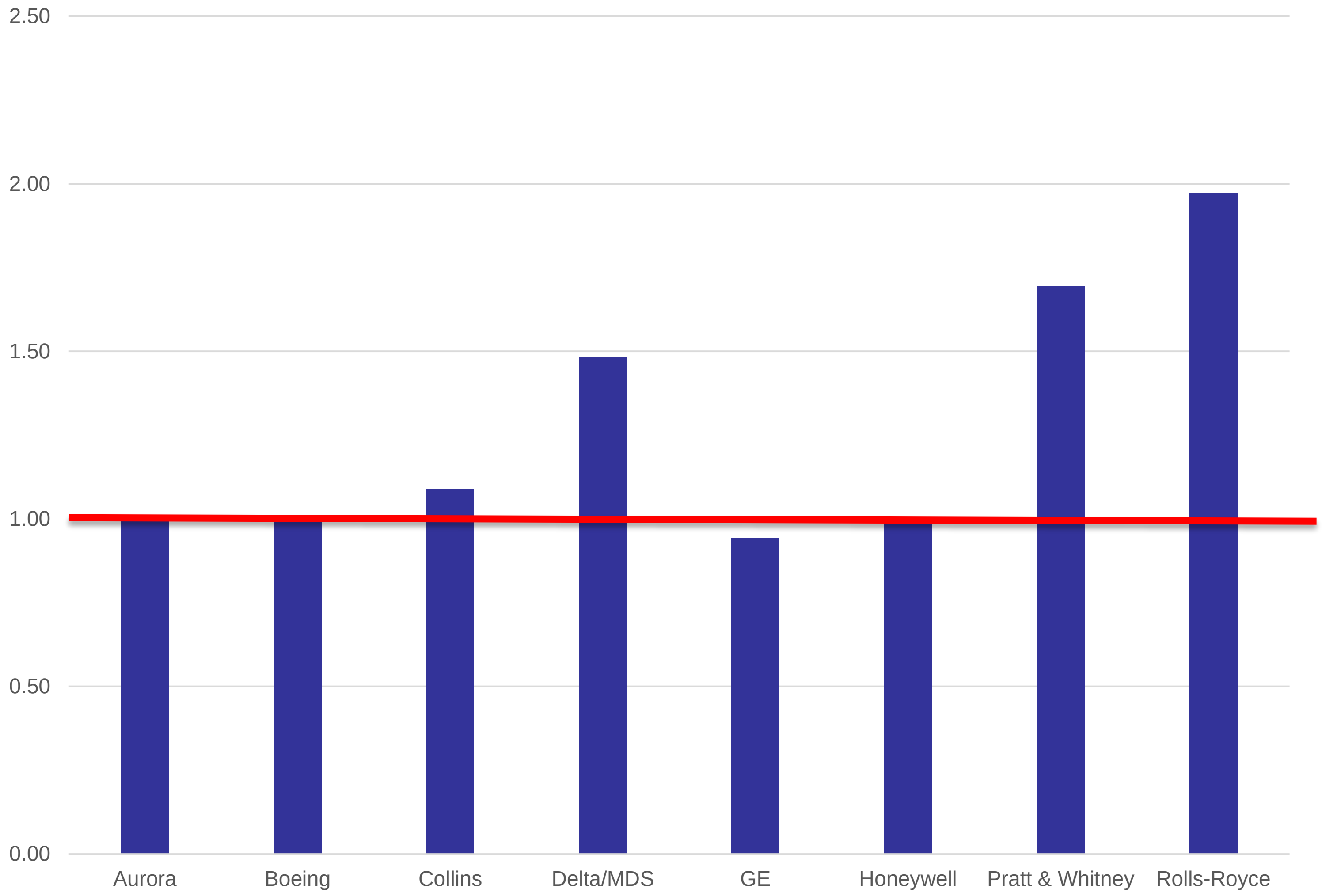
# Actions from Fall REDAC Meeting

- Cost-sharing factors
- CLEEN benefits paper

# CLEEN I – Cost Sharing Contribution Factors



# CLEEN II – Cost Sharing Contribution Factors



# CLEEN Benefits Paper

Continuous Lower Energy, Emissions and Noise (CLEEN) Program Benefits

The CLEEN Program is the FAA's principal environmental effort to accelerate the development of new aircraft and engine technologies. Through the CLEEN Program, the FAA has selected companies to cost-share development of technologies that reduce noise, emissions, and fuel burn. The benefits of CLEEN's investment is two-fold:

- CLEEN enables the aviation industry to expedite development and integration of these technologies into current and future aircraft to deliver benefits in operation for years to come.
- CLEEN leads to improved analysis and design tools that are improving every aircraft or engine product being made by these companies, well beyond individual technology applications.

CLEEN's acceleration of technology development has been successful. Technologies from CLEEN Phase I (2010-2015) have entered the fleet, and industry anticipates that additional technologies will enter into service in the coming years as opportunities arise for their insertion into new aircraft and engine designs. While maintaining continuous investment on advancing technologies to enter operational service, the program has also enabled development of supporting technologies with lower readiness level that may otherwise been left unsupported, such as developing viable manufacturing alternatives and advancing the state of the art for materials that can be used in various applications.

Highlighted technology benefits include:

- Boeing's Adaptive Trailing Edge and Ceramic Matrix Composite Nozzle technologies, developed under CLEEN Phase I, are expected to provide fuel burn reductions of 2% and 1%, while reducing noise by 1.7 decibels and 2.3 decibels, respectively. Technologies from the Adaptive Trailing Edge project have been adopted for use in commercial and defense products, and the Ceramic Matrix Composite Nozzle is currently being considered in trade studies for current development programs. Boeing's CLEEN Phase II technologies include the Structurally Efficient Wing, estimated to save 3.5% fuel burn, which has cleared testing that supports transition of many composites technologies into a broad set of current and future commercial and military applications.
- Delta and MDS Coating Technologies have partnered to successfully develop and begin operational test of an erosion-resistant fan blade coating. This coating, undergoing operational test on Delta flights, is estimated to provide retained efficiency equating to 0.4% to 1% fuel burn savings in different flight conditions over uncoated blades.
- GE Aviation's Twin Annular Premixing Swirler (TAPS) II combustor exceeded the NOx emission targets for CLEEN Phase I (60% target below CAEP/6 standard). The TAPS II is now in service on aircraft throughout the global fleet – installed on Airbus 320neo, Boeing 737 MAX, and COMAC C919 aircraft. GE's advanced combustor work has continued under CLEEN Phase II. The TAPS III combustion system will be implemented in the GE9X-powered Boeing 777X, expected to enter into service in 2020, and enables NOx emissions 30% below the more stringent CAEP/8 international standards.
- Honeywell's CLEEN Phase I technologies in jet engine cores achieved a 15.7% overall fuel burn reduction relative to baseline engine designs, as part of a package of complementary engine upgrades. Under CLEEN Phase II, Honeywell's engine core work has focused on turbine and combustor technologies which are targeting a combined 22% fuel burn reduction relative to their baseline engine while reducing NOx emissions 50% below CAEP/8 standards.
- Pratt & Whitney's Geared Turbofan developments under CLEEN have focused on enabling technologies for revolutionary high-bypass engine designs that provide 20% fuel burn reduction and 20 decibels noise reduction relative to current 737-800 aircraft.
- Rolls-Royce developed advanced-cooling turbine blades and ceramic matrix composite blade tracks under CLEEN Phase I, yielding 1% fuel burn reduction.

The work CLEEN has done on maturing individual environmentally beneficial technologies is expected to propagate into greater benefits on a fleet-wide scale. According to analysis done by Georgia Tech under the Aviation Sustainability Center of Excellence (ASCENT) the technologies matured in the first phase of CLEEN will reduce U.S. fleet-wide fuel burn by 2 percent from 2025 through 2050, representing a cumulative savings of 22 billion gallons of jet fuel. The associated $CO_2$ savings are the equivalent of taking 1.7 million cars off of the road over the duration of this 25 year period. It will also save airlines 2.75 billion dollars per year while contributing to a 14% decrease in the land area exposed to significant noise, as defined by a day-night noise (DNL) level of 65 dB. Alternatively, this noise reduction enables a 1.4x increase in operations while maintaining current noise levels.

CLEEN Phase II technologies are expected to enter operational service by 2026, providing further benefits to fuel burn, emissions, and noise. An ongoing assessment of CLEEN Phase II's projected fleet-wide benefits is expected to yield results in Fall 2020 and will show further benefits that will change the trajectory of aviation's environmental impacts for years to come.

Click here for full text version:

Microsoft Word Document

# CLEEN Phase III

# CLEEN Phase III Overview

| | Phase III* | |
|---|---|---|
| Time Frame | 2021-2025 | |
| Entry into Service | 2031 | |
| FAA Budget | TBD | |
| Vehicle Type | Subsonic | Supersonic |
| Noise Goal | 25 dB cumulative noise reduction cumulative to Stage 5 and/or reduces community noise exposure | Reduction during landing and takeoff cycle (LTO) |
| Fuel Burn Goal | -20% re: CAEP/10 Std | - |
| $NO_X$ Goal | -70% re: CAEP/8 Std (LTO) | Reduction in absolute $NO_X$ emissions |
| Particulate Matter Goal | Reduction rel: CAEP/11 Std (LTO) | - |

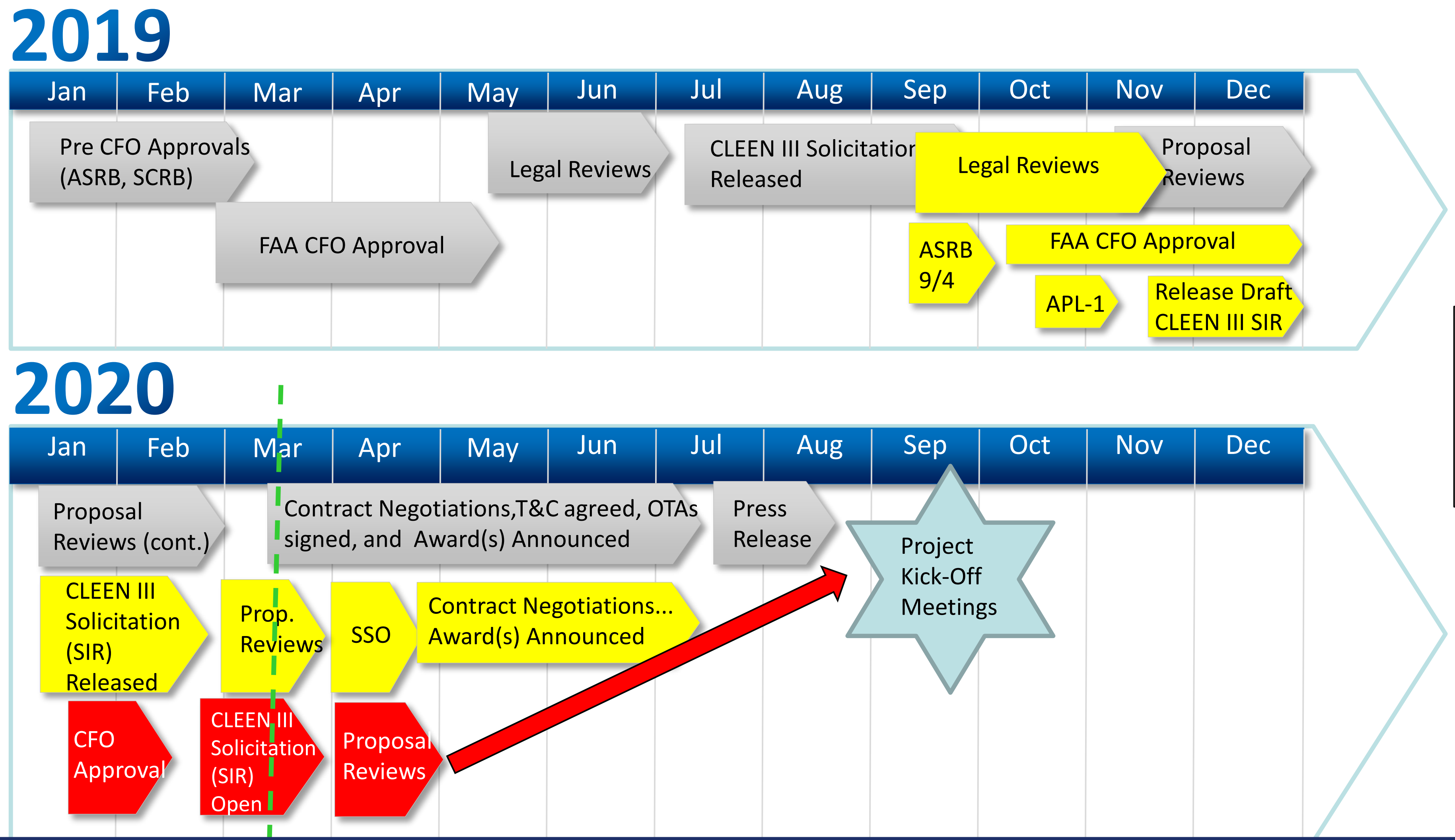
*** The information for the third phase of the CLEEN Program is notional as the FAA is in the process of developing the final solicitation.**

- **CLEEN Phase III: Follow-on to CLEEN Phase I and Phase II Programs focusing on aircraft noise, emissions and energy**
- **Purpose:**
  - Mature previously conceived noise, emissions and fuel burn reduction technologies for <u>civil subsonic and supersonic airplanes</u> from TRLs of 3-5 to TRLs of 6-7 to enable industry to expedite introduction of these technologies into current and future aircraft and engines
  - Assess jet fuels that could provide reductions in emissions or improvements in efficiency, including fuels that enable advancements in aircraft and engine design. This includes both conventional and alternative fuels.

The third phase of the CLEEN Program also aims to advance the development and introduction of hydrocarbon jet fuels for aviation that could enable improvements in fuel efficiency and reductions in emissions. This includes fuel blends. The CLEEN Program is interested in fuels that are drop-in compatible with the existing pipeline and airport fueling infrastructure, but have changes in their composition that could help an aircraft meet these CLEEN Program goals.

# CLEEN Phase III Acquisition Schedule

**FAA CLEEN Phase III Contracting Officer:**
Ryan Battad”
Ryan.M.Battad@faa.gov
(202) 267-7524




Legend
- Original Plan
- Slip As of Fall REDAC
- Actual

# General Updates

- CLEEN technology development and alternative fuels projects are progressing under CLEEN Phase II
- Next CLEEN II Consortium Meetings:
  – May 5-7, 2020: Phoenix, AZ (Honeywell)
  – Nov 16(7)-19(20), 2020: Washington, DC (location TBD)
  – May 4-6, 2021: (location TBD)
  – Nov 2-4, 2021: Washington, DC (location TBD)
- In the process of initiating CLEEN Phase III (2020-2025)
  – Market Survey was conducted in summer of 2018
  – Industry day took place on December 10, 2018
  – ASRB was approved September 4, 2019
  – CFO approval on January 30, 2020
  – ***Final SIR released February 25, 2020***
  – ***Proposals due by March 20, 2020***
- For more on CLEEN https://www.faa.gov/go/cleen

# ASCENT Technology Projects

- **Expanding environmental technology research portfolio into our Center of Excellence**
- **Provides complementary venue for University-led research to advance industry state-of-the-art and expand knowledge broadly**
  – Projects can be collaborations with industry, but data rights are generally more open than CLEEN
- **Themes:**
  – System-level modeling and design considerations (Projects 37, 52, 64)
  – Propulsion-airframe integration (Projects 50, 63)
  – Combustion (Projects 51, 55, 66, 67, 68, 70, 71)
  – Turbomachinery (Project 56)
  – Supersonics (Projects 10, 47, 59, 74) – *to be discussed in a dedicated session*

# System-Level Modeling and Design Considerations

# ASCENT Project 37: CLEEN Technology Modeling and Assessment

**Institution / PI:** Georgia Tech / Dimitri Mavris

**FAA PM:** Roxanna Moores

**Funding:** $240,000

**Objective:** Independently model and assess the benefits of the technologies that are being developed under the CLEEN program.

**Approach:** Directly coordinate, capture, and share data with the CLEEN II companies in order to accurately model the environmental benefits of each technology. Use these technology models in vehicle and fleet-level assessments of fuel burn, emissions and noise benefits from CLEEN.

**Impact:** Quantifies the benefits of the CLEEN Program's technology investments as they propagate into the fleet.

# ASCENT Project 52: Comparative assessment of electrification strategies for aviation

**Institution / PI:** MIT / Steven Barrett

**FAA PM:** Cecilia Shaw

**Funding:** $300,000

**Objective:** Compare the operational and economic feasibilty of “electro fuels” vs an all electric aircraft. Additionally, compare life-cycle emissions to conventional jet fuel powered aircraft.

**Approach:** Develop a system level engineering and economic model to estimate the lifecycle cost of each option.

**Impact:** Identify the conditions under which battery-powered aircraft or electrofuels are the more desirable electrification strategy for aviation from an economic and environmental perspective.

# ASCENT Project 64: Alternative Design Configurations to meet Future Demand

**Institution / PI:** Georgia Tech / Dimitri Mavris

**FAA PMs:** Fabio Grandi and Maryalice Locke

**Funding:** $250,000

**Objective:** Investigate alternative aircraft design approaches to meeting future air transportation demand while taking into consideration a variety of constraints.

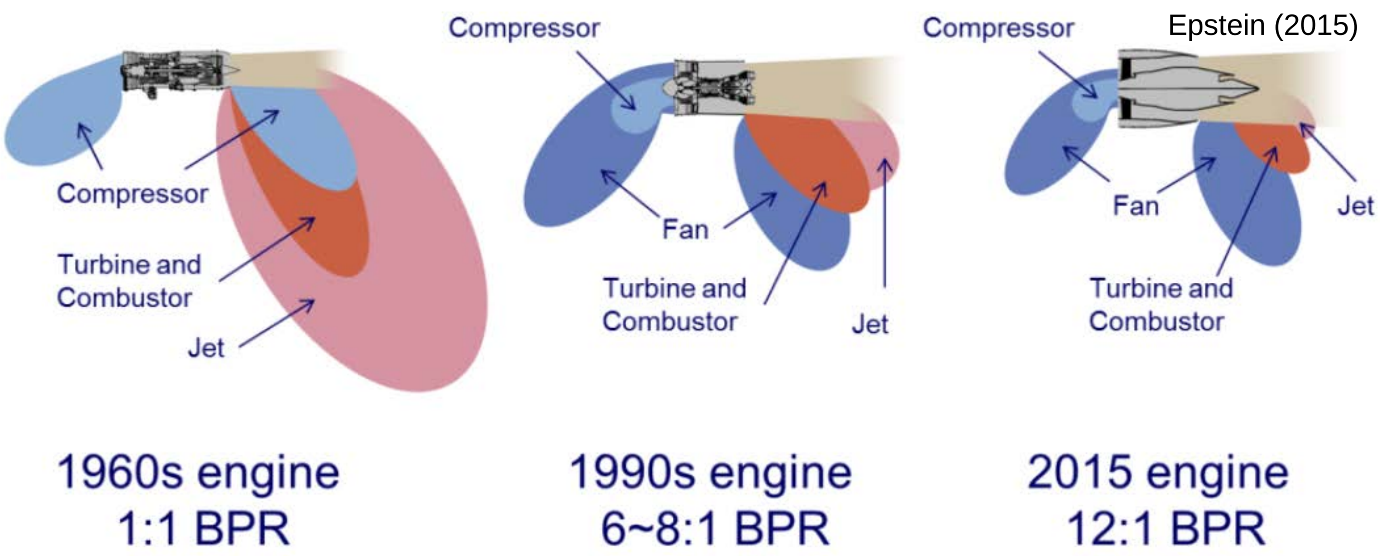
**Approach:** Consider constraints including real-world issues such as airport capacity constraints and desires for increased sustainability, while accounting for potential changes in aircraft design that result from advances in technology and changes in mission specifications and up-gauging.

**Impact:** Provide an understanding of the impacts of fleet turn-over trends and potential alternative design choices by the aircraft manufacturers to meet the growing passenger demand of the future. This project will identify the appropriate design requirements for new aircraft with available technologies of the future and assess how the use of these new aircraft designs will impact fuel burn, noise, and emissions.

*Pending*

# Propulsion-Airframe Integration

# ASCENT Project 50: Over-Wing Engine Placement Evaluation




**Institution / PI:** Georgia Tech / Dimitri Mavris

**FAA PM:** Chris Dorbian

**Funding:** $590,000 over two years;

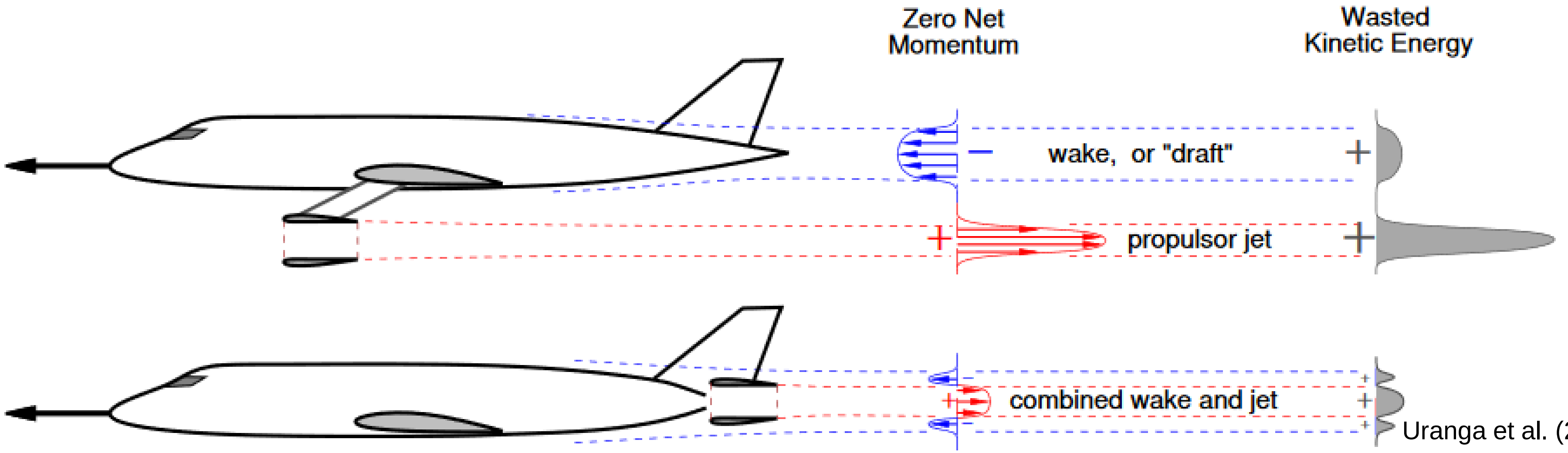
**Objective:** Over-wing nacelle (OWN) concept has potential noise benefits due to shielding and reduced landing gear height, but there is potential for fuel penalties from wing/propulsor aerodynamic interactions if not optimized. Project will deliver method to assess tradeoffs and optimize OWN configuration.


**Approach:** Leverage Georgia Tech experience with OWN, multidisciplinary analysis and optimization, and adaptive sampling to reduce computational cost of analysis. Build on past efforts to include noise shielding effects and analyze multiple flight conditions.

**Expected Impact:** Optimization of an OWN aircraft configuration over a mission with noise constraints will enable accurate tradeoffs between noise benefits and fuel burn. Informs FAA and industry on viability of OWN technology.

# ASCENT Project 63: Parametric Noise Modeling for Boundary Layer Ingesting (BLI) Propulsors

**Institution / PI:** Georgia Tech / Dimitri Mavris
**FAA PM:** Chris Dorbian
**Funding:** $300,000




Uranga et al. (2014)

**Objective:** Identify, develop, and validate a parametric fan noise module for a generic BLI propulsor. Provide assessment of noise implications of advanced vehicle concepts that employ BLI (e.g., D8, STARC-ABL).

**Approach:** Utilize lower order methods but seek to validate against higher fidelity approaches and any publicly available experimental data sets. Quantify turbulence ingestion, mean flow distortion, and shielding in a generic enough way that multiple classes can be captured.

**Expected Impact:** Tool that allows propulsor designers to identify potential noise related problem areas for BLI propulsion concepts early in the conceptual design process to further define solutions for mitigation of noise impacts. Integrate with ANOPP in the future.

# Combustion

# ASCENT Project 51: Combustion Concepts for Next-Generation Aircraft Engines

**Institution / PI:** MIT / Steven Barrett
**FAA PMs:** Roxanna Moores & Rangasayi Halthore
**Funding:** $300,000 (with additional year planned)

**Objective:** The purpose of this project is to identify future aircraft engine designs which increase the efficiency of future aircraft, while simultaneously reducing emissions.

**Approach:** conducting simulations on new jet engine combustor technologies

**Expected Impact:** This project will provide novel capabilities to efficiently evaluate the performance of aircraft engine designs, which involve co-optimization of fuel, combustor, and engine cycle.


**In this project, MIT plans to develop numerical models for engine concepts with promising new technologies**

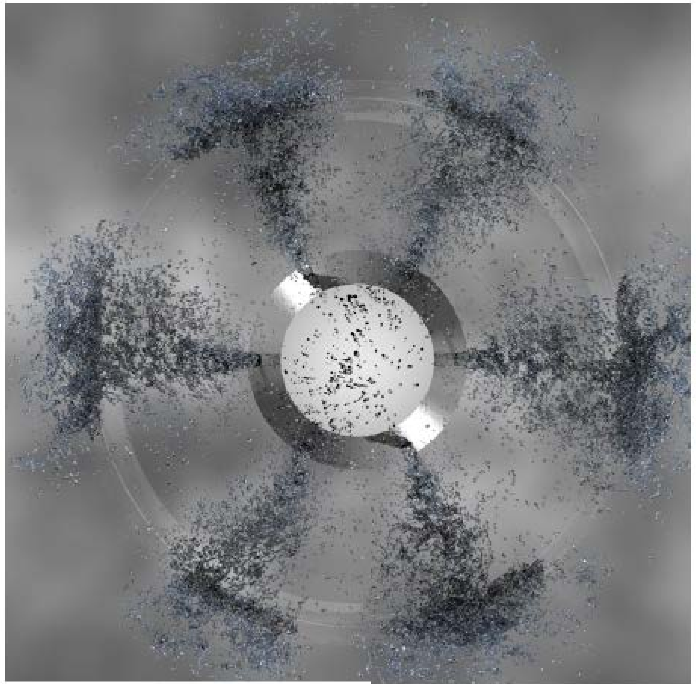
# ASCENT Project 55: Noise Generation and Propagation from Advanced Combustors

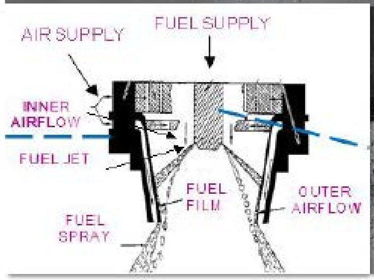
**Institutions / PIs:** Timothy Lieuwen (Georgia Tech) and Jeffrey Mendoza (UTRC)
**FAA PM:** Roxanna Moores
**Funding Level:** $1,499,984 (with additional year planned)

**Objective:** There is a need to reduce Jet engine combustor noise. This program will improve understanding of how combustion noise is generated, develop tools to predict noise levels and guide design decisions, and ultimately enable quieter aircraft engines.

**Approach:** Project will conduct simulations in various portions of the combustor. The project will conduct testing to validate the modelling results as well as create benchmark data.

**Expected Impact:** from this work are reduced noise pollution in the vicinity of airports and reduced development time/cost of new engines that meet future noise targets.






Accurate prediction of liquid fuel atomization is crucial for Large Eddy Simulation combustor noise prediction.

# ASCENT Project 66: Evaluation of High Thermal Stability Fuels

**Institution / PI:** University of Dayton / Josh Heyne
**FAA PM:** Anna Oldani
**Funding:** $184,997

**Objective:** Investigate potential improvements in jet engine fuel burn when fuels with high thermal stability are used as coolants or subjected to engine temperatures higher than currently realizable with typical conventional fuel thermal stability.

Improve understanding of what fuel components drive thermal stability properties.

**Approach:** Identify engine components that could benefit from cooling using high thermal stability fuels. Apply heat transfer models to these components to estimate energy recovery. Identify optimum cooling sequence to maximize heat recovery. Estimate resulting fuel efficiency gains from combined impacts of cooling improvement, heat recovery maximization, and reduced engine component weight.

**Impact:** Provide analysis of the benefits deriving from the usage of high thermal stability fuels as engine coolant.

# ASCENT Project 67: Impact of Fuel Heating on Combustion and Emissions

**Institution / PI:** Purdue / Robert Lucht

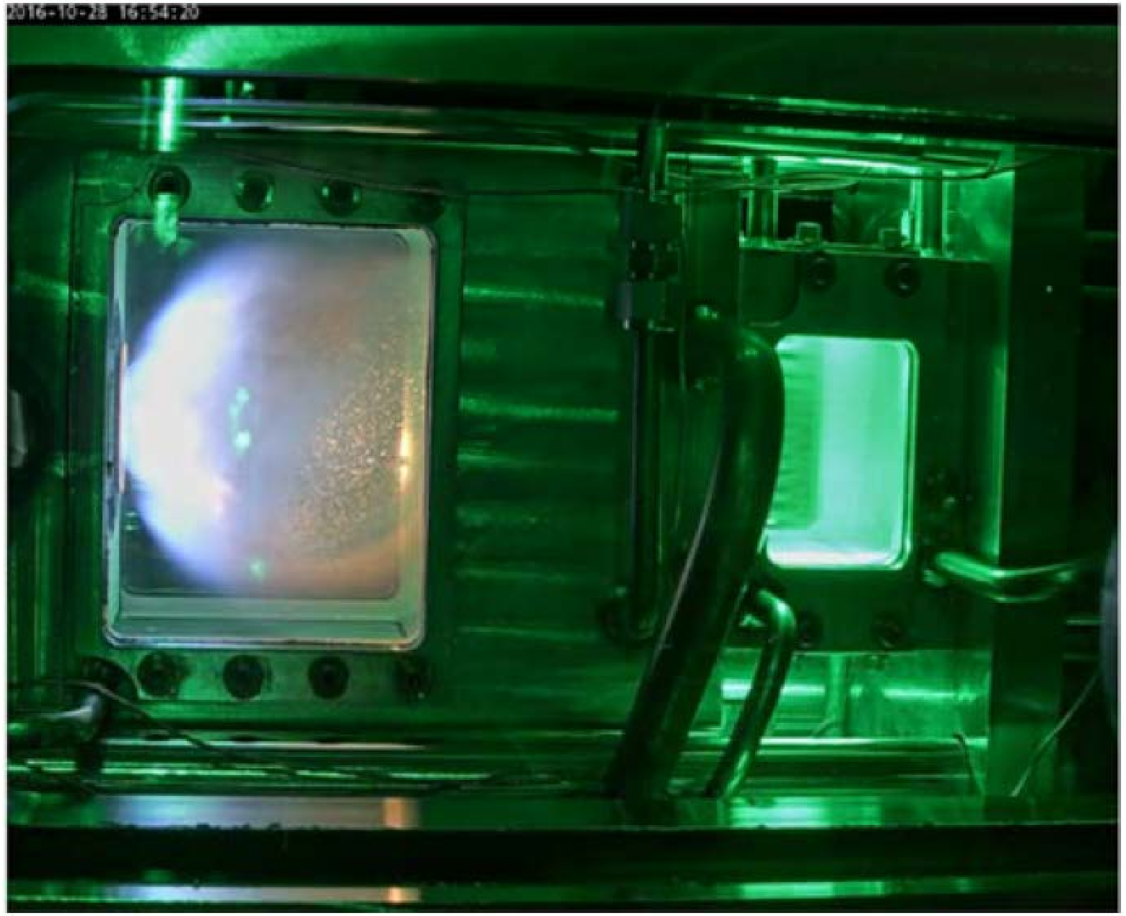
**FAA PM:** Cecilia Shaw

**Funding:** $250,000

**Objective:** Investigate the effects of hot fuel on combustion performance and the level of emissions for a lean burn combustor

**Approach:** The effects of heated fuel will be investigated using nonintrusive laser diagnostic methods and by physical probe sampling to monitor emissions and combustion efficiency.

**Impact:** Fuel can be used to support the increased thermal management load, enabling higher flight speeds.



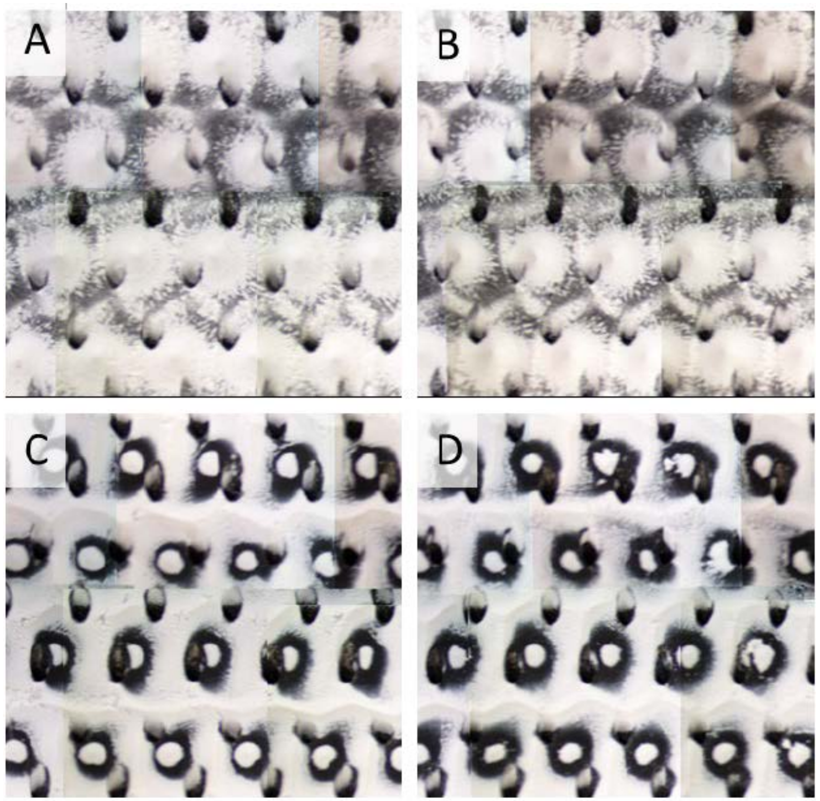
# ASCENT Project 68: Combustor Wall Cooling with Dirt Mitigation

**Institution / PI:** Penn State University / Karen Thole
**FAA PM:** Cecilia Shaw
**Funding:** $150,000

**Objective:** Develop new design to reduce dirt accumulation in the combustor cooling liner during operating conditions

**Approach:** Study a cooling design for combustor walls that is insensitive to dirt accumulation, as well as an improved understanding of why it is insensitive

**Impact:** Dirt mitigations will result in fuel burn reductions over a longer time period as well as allowing continued turbine operations while reducing turbine maintenance.



# ASCENT Project 70: Reduction of nvPM emissions from aero-engine fuel injectors

**Institution / PI:** Georgia Tech / Wenting Sun

**FAA PMs:** Daniel Jacob and Cecilia Shaw

**Funding:** $500,000 for two years

**Objective:** Investigate how jet fuel atomization affects the formation and oxidation of non-volatile particle matter (nvPM) in operating conditions and develop a model of novel fuel injector to reduce nvPM formation.

**Approach:** PI will use optical diagnostics to measure nvPM volume and flow field for a set of Honeywell injectors. Data will be used to develop CFD model to simulate nvPM formation oxidation

**Impact:** Enable the development of fuel injectors that have improved fuel atomization and reduced nvPM formation

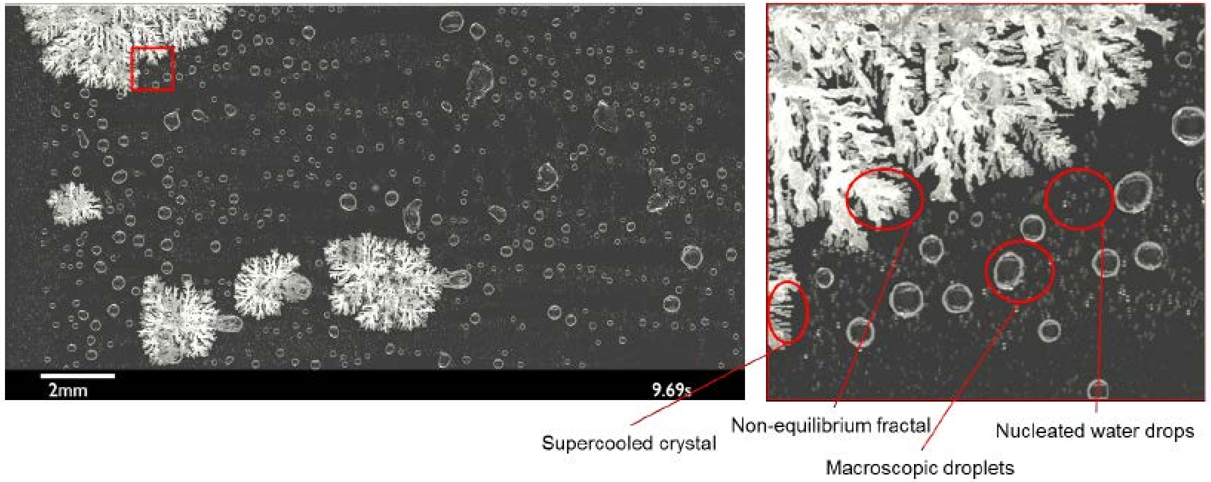
# ASCENT Project 71: Predictive Simulation of Sooting Flames

**Institution / PI:** Georgia Tech / Suresh Menon
**FAA PMs:** Roxanna Moores and Daniel Jacob
**Funding Level:** $500,000

**Objective:** This project will establish a new multiscale approach to predict soot formation in aircraft combustors. All modeling tools already exist with this GT team but a systematic coupling of these tools in multi-scale, multi-physics strategy has yet to be accomplished by anyone.

**Approach:** The project will conduct simulations for chemical kinetics mechanisms, will include new chemistry and new subroutines. Additionally CFD modelling will be conducted to assess the impact of turbulence.

**Expected Impact:** Improve knowledge of emissions formation should enable development of improved combustors with lower emissions characteristics.




**Snapshot of results using Metaphysics icing simulation capability which will be leveraged for a Monte Carlo simulation of post-inception mechanisms associated with soot formation and growth**

# Turbomachinery

# ASCENT Project 56: Reduced Fuel Burn through Double-Wall Cooling of Turbine Airfoils Made Possible through Additive Manufacturing

**Institution / PI:** Penn State University / Karen Thole

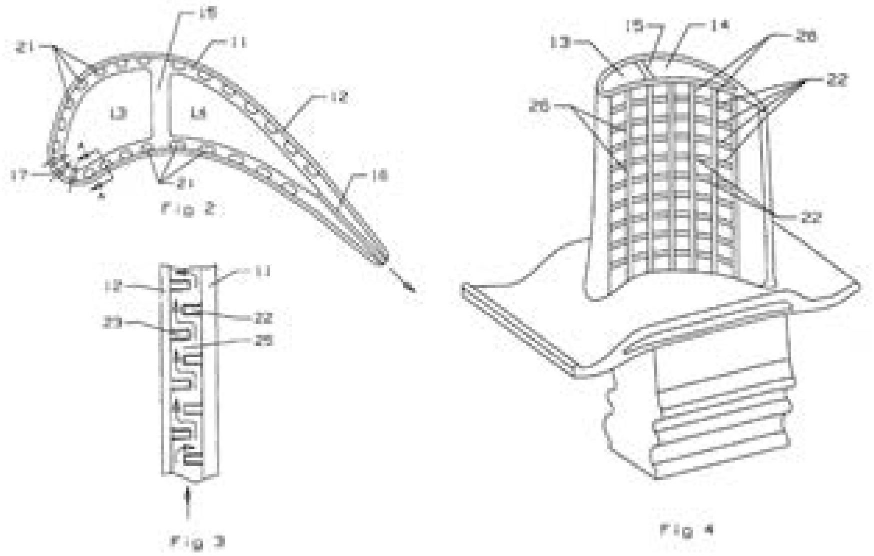
**FAA PM:** Cecilia Shaw

**Funding:** $400k for three years

**Objective:** Develop and fabricate potential thermal performance improvements to turbine airfoils using metal-based additive manufacturing.

**Approach:** PI will investigate the potential gains possible by manufacturing turbine airfoils using three-dimensional metal-based additive manufacturing (AM) and comparing them to traditional metal cast turbine airfoils

**Impact:** AM can improve cooling efficiency by exploring more complex cooling geometries.  Can lead to decrease in fuel burn and reduce thermal stresses.



# Conclusions

- **CLEEN Phase II is executing its fifth successful year**
  – Six technology projects have reached their maturation goals, with many more expected in CY2020
- **CLEEN Phase III will continue our efforts to accelerate maturation of environmental aircraft technologies into the fleet (2020-2025)**
  – Solicitation is open, with awards planned Q3 CY2020
- **New ASCENT projects are expanding our aircraft technology research portfolio**
  – Complementary to CLEEN, ASCENT is providing a venue for University-led research to advance industry state-of-the-art and expand knowledge broadly