REDAC Environment and Energy Sub-Committee

Aircraft Technology Research

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FAA CLEEN Program Managers

Date: March 10, 2021

Federal Aviation Administration

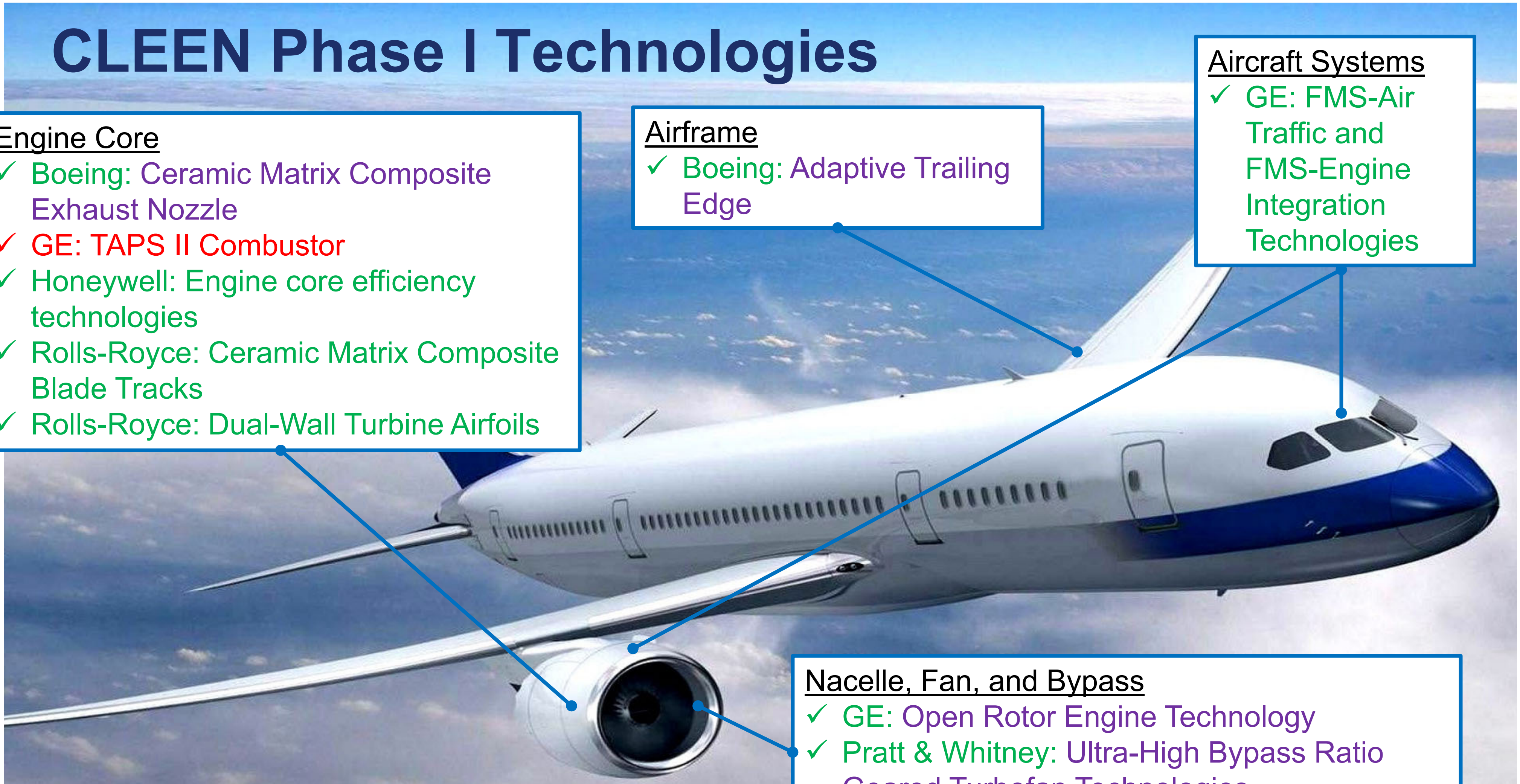
Agenda

- **Continuous Lower Energy, Emissions & Noise (CLEEN) Program Overview**
  - CLEEN Phase II status
  - CLEEN Phase III update
- **Aviation Sustainability Center of Excellence (ASCENT) Technology Projects**
- **ICAO CAEP Long Term Aspirational Goal Support**

Continuous Lower Energy, Emissions & Noise
CLEEN
Federal Aviation Administration

NextGEN

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

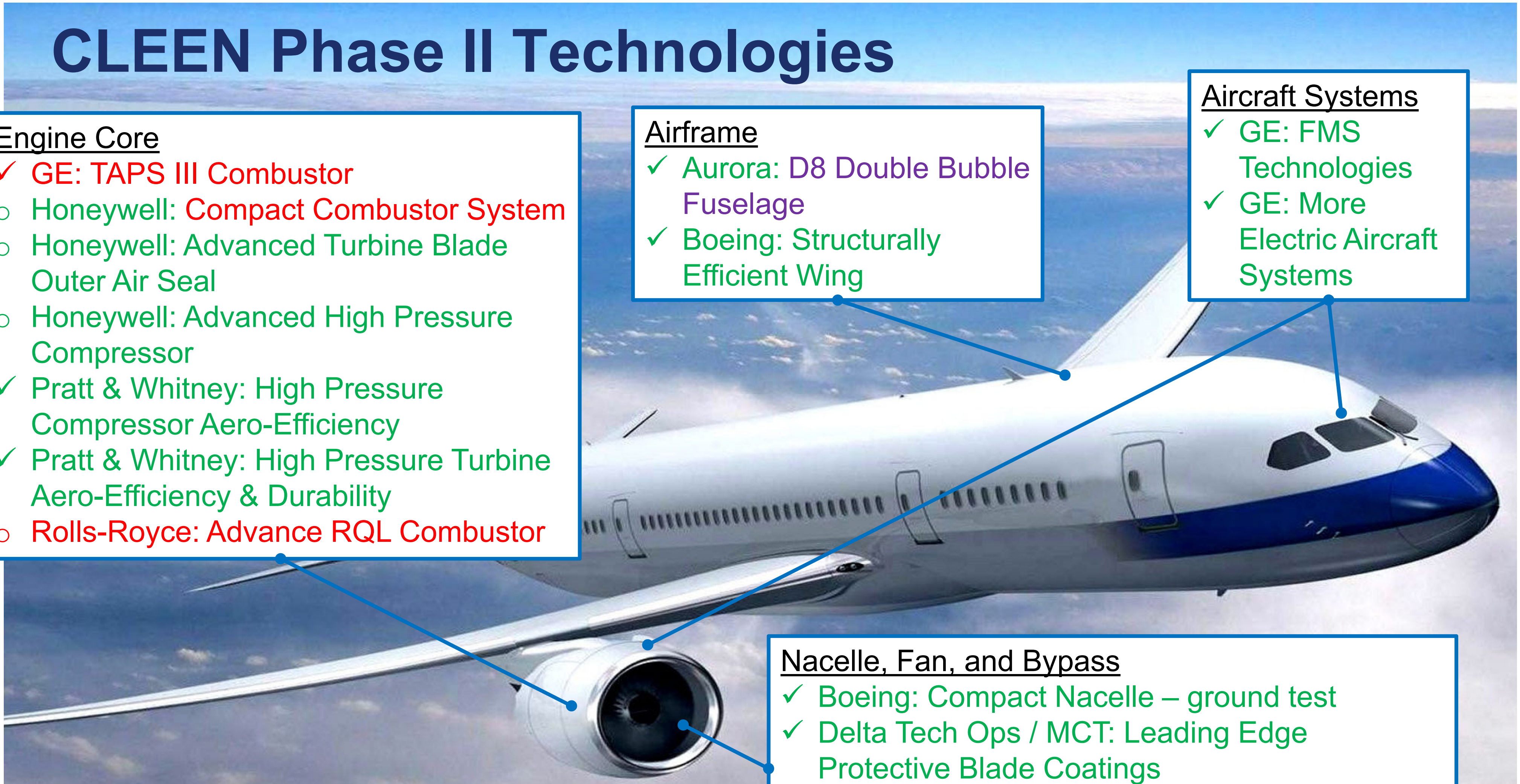
Nacelle, Fan, and Bypass

- ✓ 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
- ○ Honeywell: Compact Combustor System
- ○ Honeywell: Advanced Turbine Blade Outer Air Seal
- ○ Honeywell: Advanced High Pressure Compressor
- ✓ Pratt & Whitney: High Pressure Compressor Aero-Efficiency
- ✓ Pratt & Whitney: High Pressure Turbine Aero-Efficiency & Durability
- ○ Rolls-Royce: Advance RQL Combustor

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

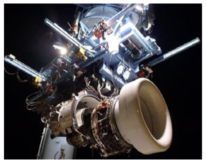
Aircraft Systems
- ✓ GE: FMS Technologies
- ✓ GE: More Electric Aircraft Systems

Nacelle, Fan, and Bypass
- ✓ Boeing: Compact Nacelle – ground test
- ✓ Delta Tech Ops / MCT: Leading Edge Protective Blade Coatings
- ○ GE: Low Pressure Ratio Advanced Acoustics
- ○ Honeywell: Advanced Acoustic Fan and Liners
- ✓ Collins Aerospace: Nacelle Technologies

Fuel
NO_x
Noise

✓ Completed Effort
○ Continues in FY20

CLEEN Highlights

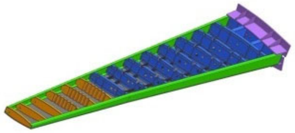


CLEEN Phase I

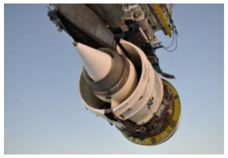
- GE TAPS II Combustor entered fleet in 2016 on LEAP engine; installed on Airbus 320neo, Boeing 737 MAX, and COMAC C919
  Exceeds CLEEN Phase I NO_X Reduction Goal
- Pratt & Whitney Gen 2 geared turbofan propulsor technology successfully engine tested
  Enables engine designs that provide 20% fuel burn reduction and 20 dB noise reduction
- Boeing CMC Nozzle flight tested on a 787 aircraft
  Up to 1% fuel burn reduction and 2.3 dB noise reduction

CLEEN Phase II

- Delta TechOps/MCT completed in-service flight evaluation of fan blade leading edge protective coating
  Retained efficiency equating to 0.4% to 1% fuel burn savings
- Boeing completed full scale ground test of Structurally Efficient Wing
  3.5% fuel savings through weight reduction



- Boeing completed ground engine test of Compact Nacelle technology
  1% fuel burn reduction; enables more efficient engine designs and improved acoustic treatments
- GE TAPS III combustion system will be implemented in the GE9X-powered Boeing 777X
  Enables NO_X emissions 30% below CAEP/8

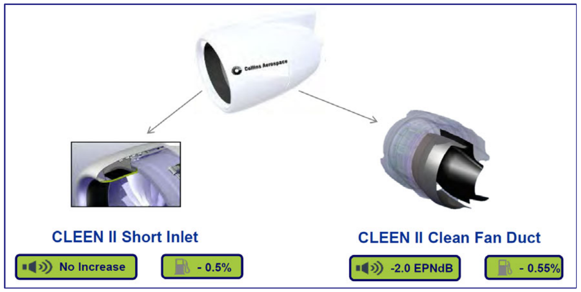


- GE completed TRL 6 demonstration of Flight Management System optimization algorithms, including electronic flight bag prototype
  1% fleet-wide average improvement in fuel burn
- P&W high pressure compressor completed ground and flight tests—learnings integrated into GTF product line
  0.8-1.0% fuel burn reduction relative to a state-of-the-art engine

Recent Accomplishments – Since Fall REDAC Sub-Committee

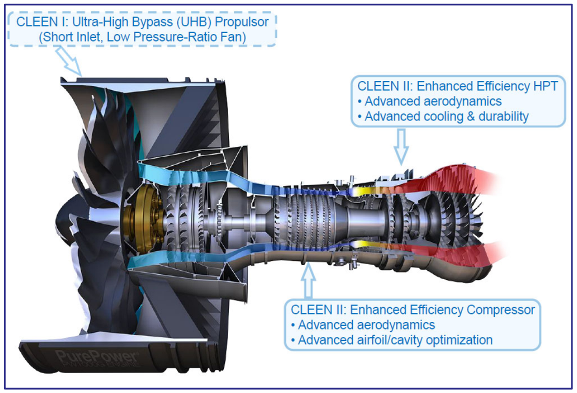
Project completion:

- Collins Aerospace completed CLEEN Phase II Program scope
  - Short Inlet and Clean Fan Duct technologies will provide a total of 1% fuel burn reduction and 2 EPNdB noise reduction
- Pratt & Whitney completed CLEEN Phase II Program scope
  - Compressor and Turbo Aero-Efficiency technologies will provide a total of 1.6-2.0% fuel burn reduction
- Public final reports will be posted to CLEEN website

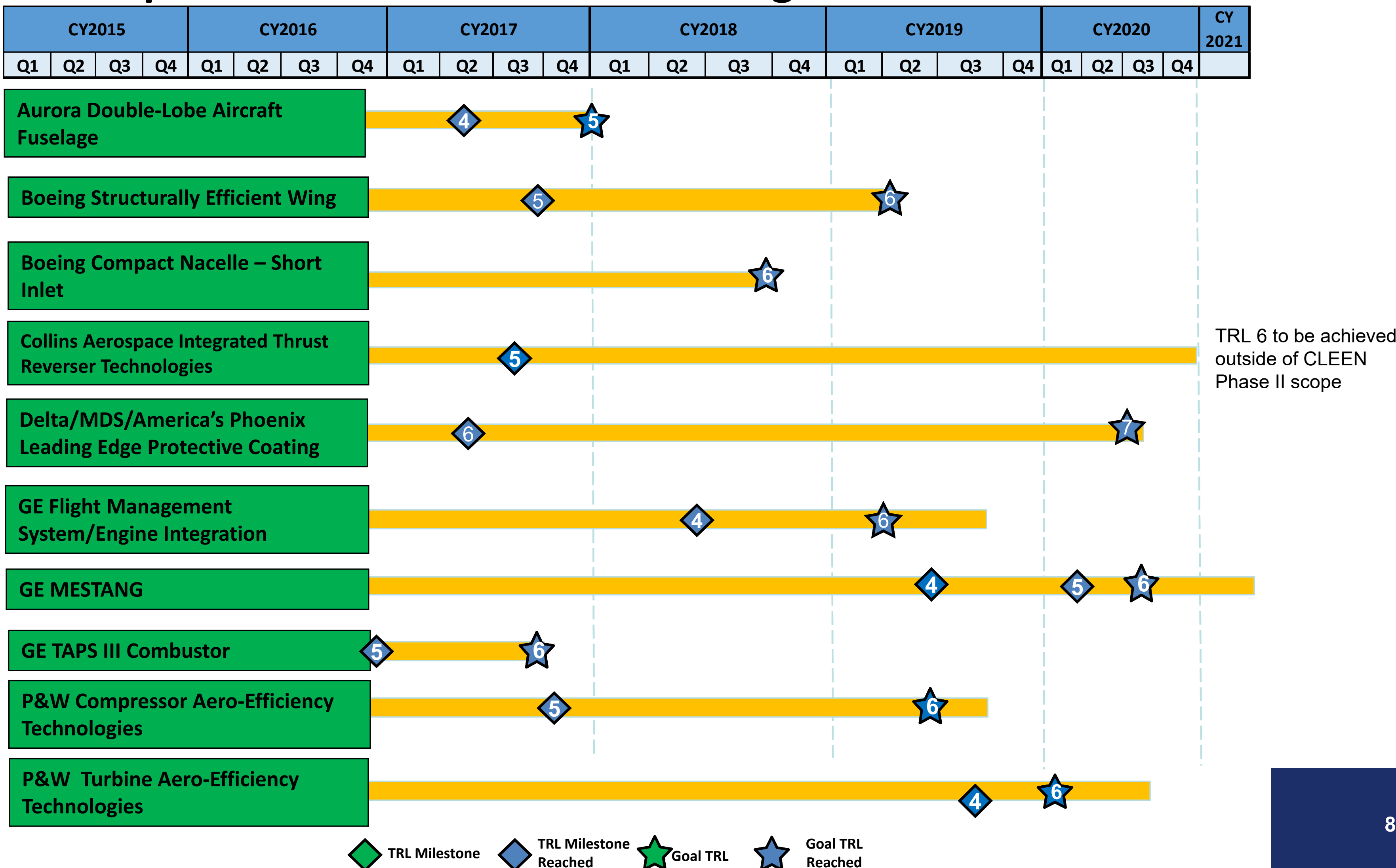


Major milestones:

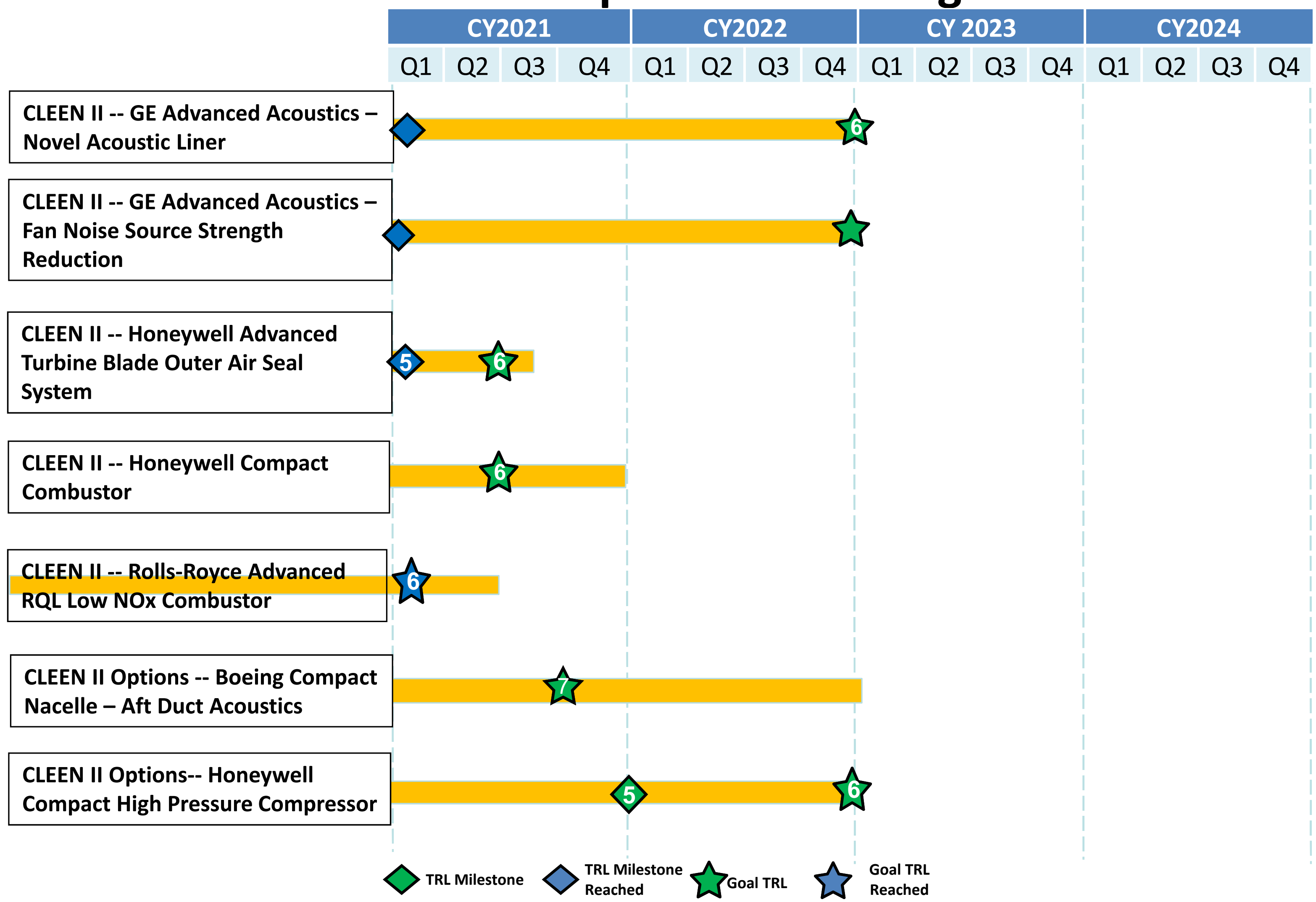
- Honeywell initiated engine tests of blade outer air seal and compact combustor technologies
- Rolls-Royce completed testing of advanced rich-quench-lean low-Nox combustor



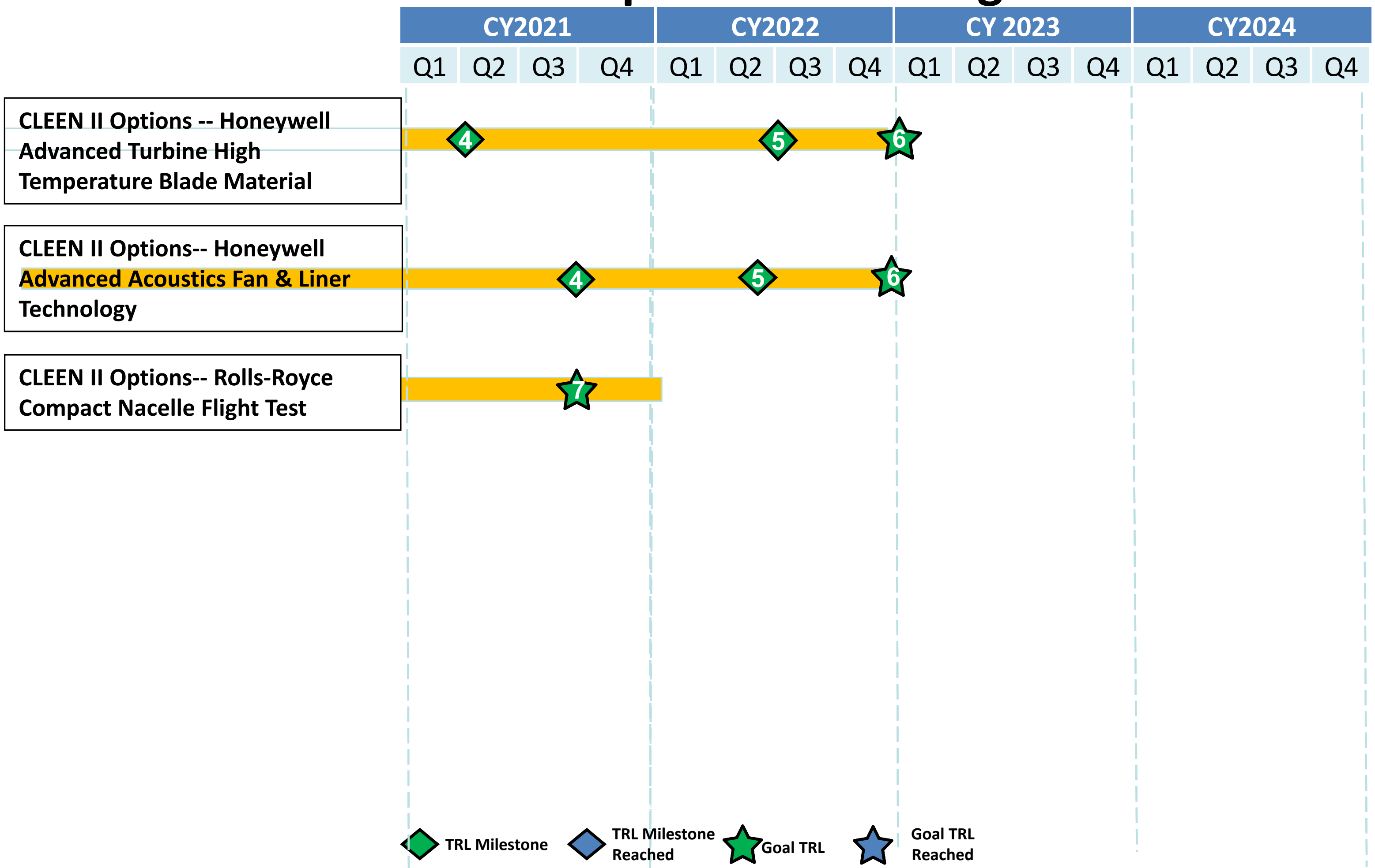
Completed CLEEN Phase II Technologies – TRL Milestones



CLEEN Phase II & CLEEN Phase II Options Technologies – TRL Milestones cont.



CLEEN Phase II & CLEEN Phase II Options Technologies – TRL Milestones cont.



Upcoming CLEEN II Activities

Next 6 Months' Activities

- Honeywell to conduct additional engine tests of blade outer air seal and combustor technologies
- Preparation for Rolls-Royce flight test of compact nacelle technology
- Preparation for Boeing flight test of aft duct acoustics technology
- Continued technology development on GE and Honeywell options technologies

Assessment of CLEEN Technologies

Analytical Evaluation:

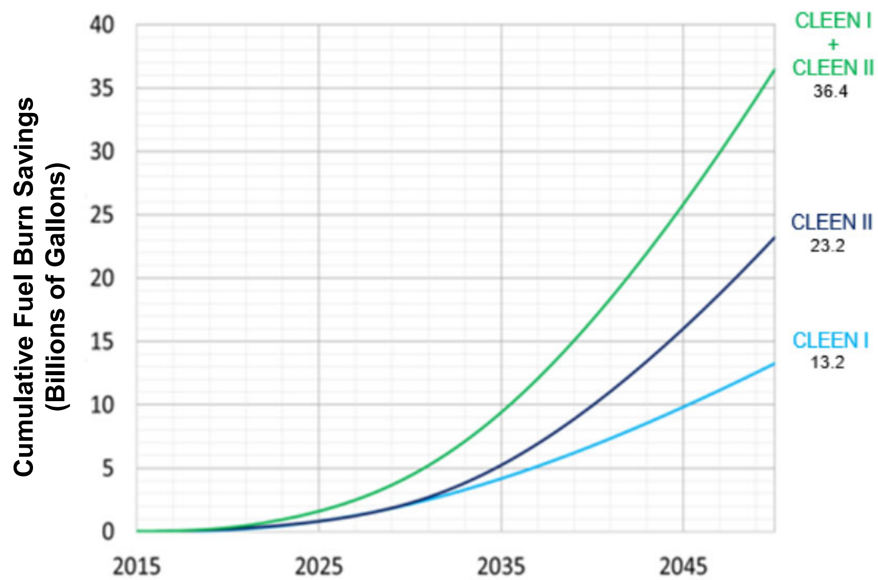
- Conducted by Georgia Tech through ASCENT COE Project 37
- Evaluating impact on fuel burn and noise out to 2050
- Have completed modeling of CLEEN Phase I technologies and all CLEEN Phase II fuel burn reduction technologies

Fuel Burn Benefit:

- 36.4 billion gallons of fuel saved cumulative by 2050 from CLEEN Phase I and II
- CO_2 emissions reduced by 424 million metric tons over this time period – the equivalent to removing 3 million cars from the road from 2020 to 2050

Noise Benefit:

- CLEEN Phase I Contributes to 14% decrease in the land area exposed to DNL 65 dB and greater
- CLEEN Phase II noise benefits assessment ongoing



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 relative 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)	-

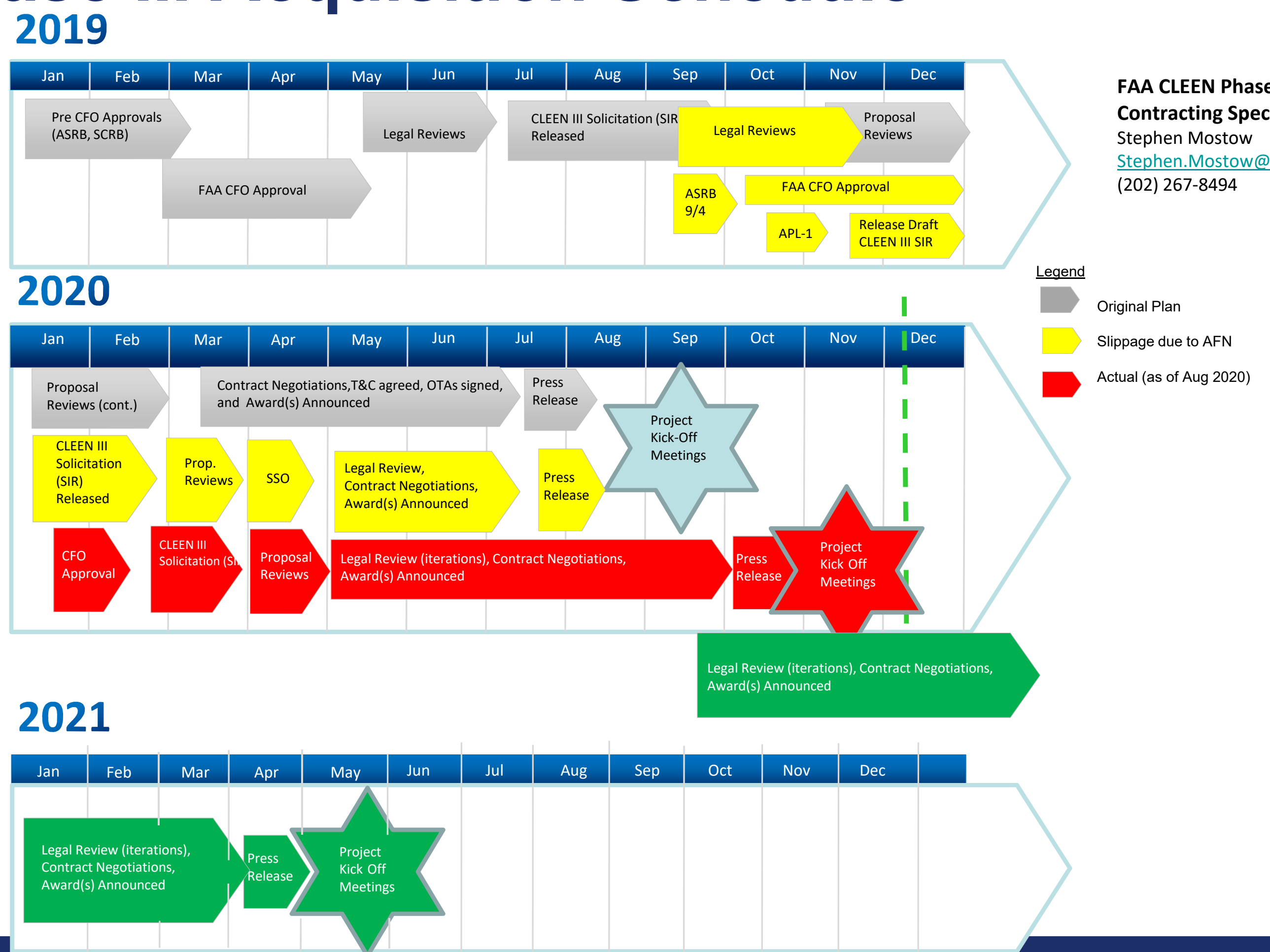
*** The information for the third phase of the CLEEN Program is notional as the FAA is in the process of developing the final solicitation.**

- **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 civil subsonic and supersonic airplanes 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.

**Solicitation has closed and evaluation is complete.
Expect to make awards in coming months.**

CLEEN Phase III Acquisition Schedule



FAA CLEEN Phase III Contracting Specialist:
Stephen Mostow
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CLEEN Program - In Summary

- CLEEN technology development and alternative fuels projects are progressing under CLEEN Phase II, managing COVID-19 impacts

- Next CLEEN II + CLEEN III Consortium Meetings:
  - May 4-6, 2021: VIRTUAL
  - Nov 2-4, 2021: Washington, DC (location TBD – pending COVID restrictions)

- In the process of executing CLEEN Phase III awards (2020-2025)
  - 8 awardees with multiple technology options planned

- For more on CLEEN https://www.faa.gov/go/cleen

ASCENT Technology Projects

- **Continue execution of the environmental technology research portfolio in our Center of Excellence**
- **Provides complementary venue for University-led research to advance industry state-of-the-art and expand knowledge broadly**
- **Themes:**
  - Noise reduction technology modeling and development
  - System-level modeling and design considerations
  - Propulsion-airframe integration
  - Combustion
  - Turbomachinery
  - Supersonics (covered in separate session on supersonics)
- **Overview of projects now available on ASCENT website:** https://ascent.aero/topic/Aircraft-Technology/

Technology Projects Summary

Noise reduction technology modeling and development

75	Improved Engine Fan Broadband Noise Prediction Capabilities
76	Improved Open Rotor Noise Prediction Capabilities
79	Novel Noise Reduction Liners Enabled by Advanced Manufacturing

New - Planned for Award in FY21

System-level modeling and design considerations

37	CLEEN Technology Modeling and Assessment
52	Comparative Assessment of Electrification Strategies for Aviation
64	Alternative Design Configurations to Meet Future Demand

Propulsion-airframe integration

50	Over Wing Engine Placement Evaluation
63	Parametric Noise Modeling for Boundary Layer Ingesting (BLI) Propulsors

Plan to discontinue after year 1

Combustion

51	Combustion Concepts for Next-Generation Aircraft Engines
55	Noise Generation and Propagation from Advanced Combustors
66	Evaluation of High Thermal Stability Fuels
67	Impact of Fuel Heating on Combustion and Emissions
68	Combustor Wall Cooling with Dirt Mitigation
70	Reduction in nvPM Emissions from Aero-Engine Fuel Injectors
71	Predictive Simulation of nvPM Formation in Aircraft Combustors

Technology Projects Summary (Contd.)

Turbomachinery

56	Turbine Cooling Through Additive Manufacturing

Supersonics

10	Aircraft Technology Modeling and Assessment
47	Clean Sheet Supersonic Engine Design and Performance
59	Jet Noise Modeling and Measurements to Support Low Noise Supersonic Aircraft Technology Development
74	Low Emissions Pre-Mixed Combustion Technology for Supersonic Civil Transport

Noise Reduction Technology Modeling and Development

ASCENT Project 75: Improved Engine Fan Broadband Noise Prediction Capabilities

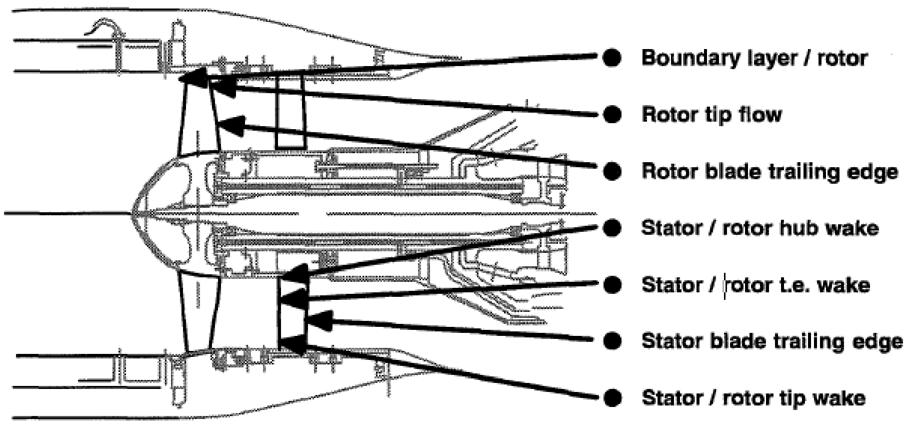
Institution: Boston University

Funding: $300,000/yr. for 3 years; Second year planned for award in FY21

Objective: Accepted methods for predicting, controlling, and treating fan tonal noise have existed for years, but less so for broadband noise. This work will develop a fan broadband noise prediction method that addresses the gaps in currently used lower-order models.

Approach: Researchers will leverage past experience with low-order model development, machine learning, and training data (some of which is on hand and some of which will need to be obtained/created) to build a fan-wake turbulence surrogate model. The team will also seek to make improvements to the low-order method. Rig testing at UTRC will be considered.

Expected Impact: Aft fan broadband noise is an increasingly significant noise source in modern engines. With a faster, more applicable fan broadband prediction method, engine designers will be able to include this outcome as a design variable, which will result in better engine designs.



(Ganz et al., 1998)

ASCENT Project 76: Improved Open Rotor Noise Prediction Capabilities

Institution: Georgia Tech

Funding: $300,000/yr. for 3 years; Second year planned for award in FY21

Objective: The Contra-Rotating Open Rotor (CROR) system has promising fuel/emissions, but may come with noise penalties. The researchers will perform a sensitivity study on the design parameters of a CROR configuration to enable system design improvements for noise reduction.

Approach: Build on past efforts to reduce size of parameter space, then carry out high-fidelity computational aeroacoustics analyses to assess impact of parameters on noise. GE Aviation is a cost-share partner.

Expected Impact: Provide both the FAA and industry key insights necessary for design optimization of the CROR system in the future.

Image Source: NASA

ASCENT Project 79: Novel Noise Reduction Liners Enabled by Advanced Manufacturing

Institution: TBD

Funding: $300,000 first year planned for award in FY21; $900,000 second year

Objective: Explore new noise reduction liner designs that are made possible by novel designs dependent upon advanced/additive manufacturing techniques.

Approach: Design, prototype (including advanced manufacturing trials), and assess novel liner designs noise reduction and drag performance

Expected Impact: Provide both the FAA and industry key insights into potential for novel noise reduction liners enabled by advanced manufacturing

NEW

System-Level Modeling and Design Considerations

ASCENT Project 37: CLEEN Technology Modeling and Assessment

Institution: Georgia Tech

Funding: $240,000/yr.; Currently forward funded into FY22

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

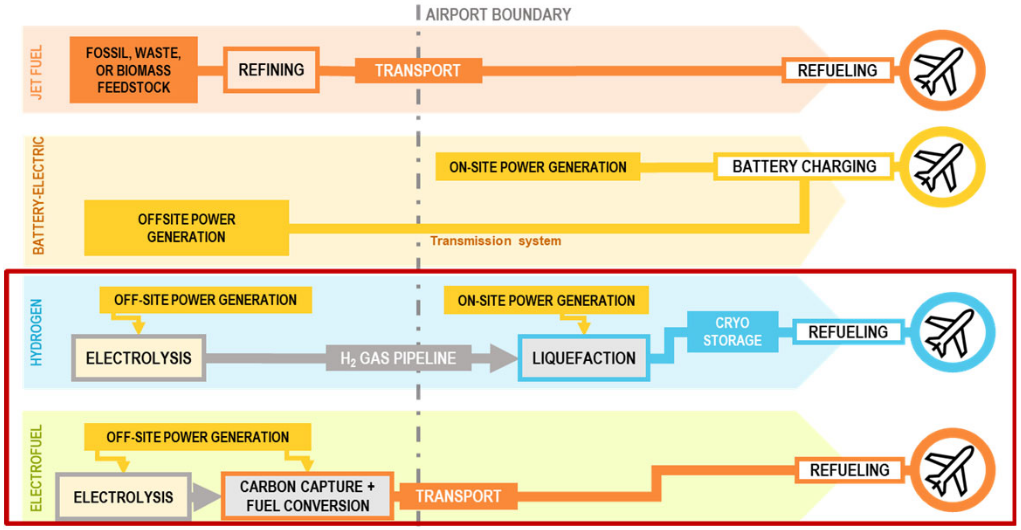
Approach: Directly coordinate, capture, and share data with the CLEEN Phase II ***and III*** companies in order to accurately model the environmental benefits of each technology. Use these technology models in vehicle and fleet-level assessments of fuel burn, emissions and noise benefits from CLEEN.

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: MIT

Funding: $300,000; Currently forward funded into FY22



Objective: Quantify costs, emissions and resulting impacts of different electrification approaches for commercial aviation. Electrification pathways include all-electric aircraft and conventional aircraft powered by hydrogen or electrofuels (aka power-to-liquid fuels) produced from electricity.

Approach: Develop system level engineering and economic models to estimate the lifecycle emissions, costs, and feasibility of each option. This includes a detailed assessment of infrastructure issues.

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

ASCENT Project 64: Alternative Design Configurations to meet Future Demand

Institution: Georgia Tech

Funding: $250,000 year 1; $1,200,000 year 2 planned to be awarded in FY21

Objective: Investigate the potential of future aircraft technologies and designs to reduce CO_2 emissions, in support of ICAO CAEP Long Term Aspiration Goal (LTAG) feasibility assessment.

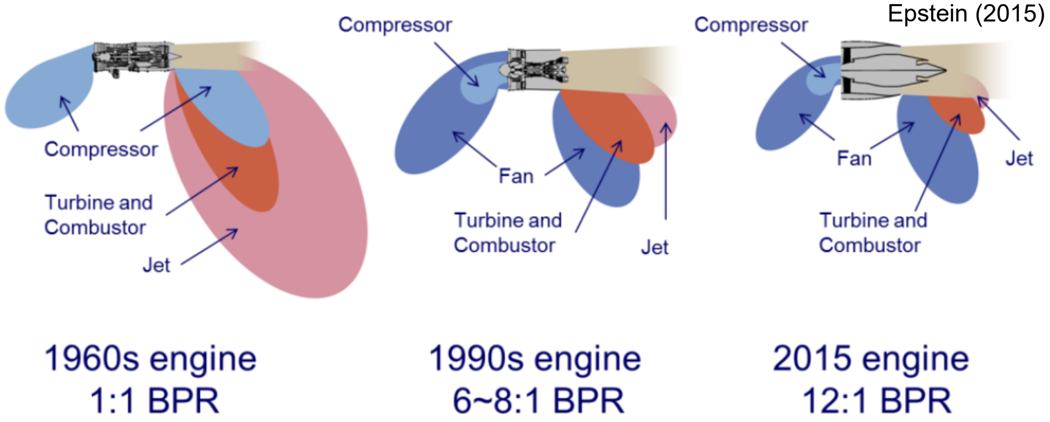
Approach: Gather data, model, and assess fuel burn / CO2 performance of future aircraft with integrated sets of technologies, including advanced tube and wing aircraft and advanced concept aircraft.

Impact: Provide an understanding of the impacts of aircraft technology on the potential evolution of CO_2 emissions from aircraft. Supply data as input to the larger LTAG analysis effort for these future aircraft to support the overall goal feasibility assessment.

Propulsion-Airframe Integration

ASCENT Project 50: Over-Wing Engine Placement Evaluation

Institution: Georgia Tech
Funding: $590,000 over two years;
Currently forwarded funded into FY22



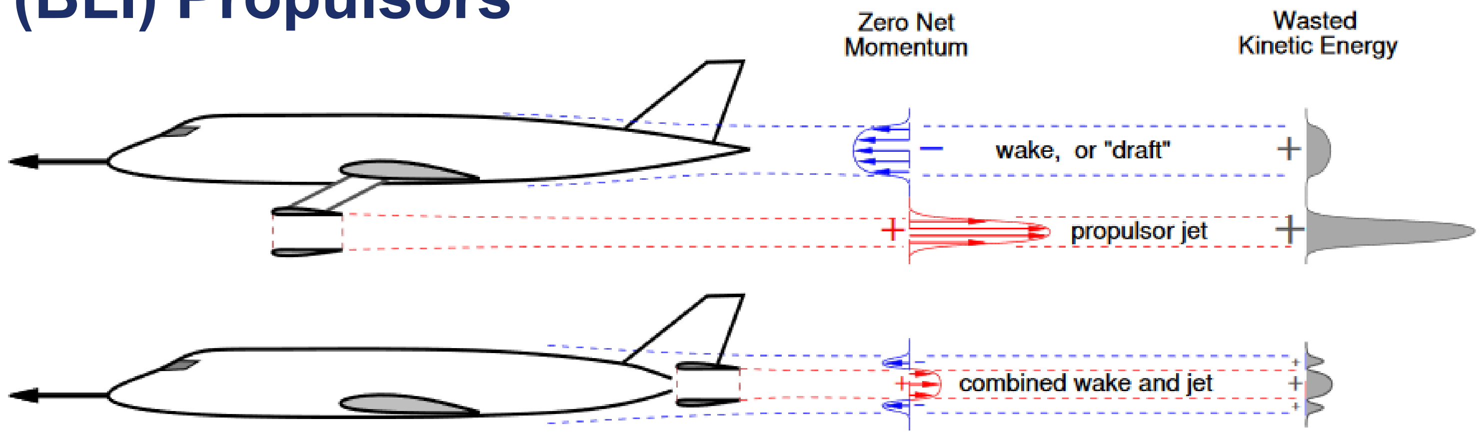
Objective: Over-wing nacelle (OWN) concept has potential noise benefits due to shielding and reduced landing gear height, but there is potential for fuel penalties from wing/propulsor aerodynamic interactions if not optimized. Project will deliver method to assess tradeoffs and optimize OWN configuration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

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: Georgia Tech
Funding: $300,000;
Planned to conclude after year 1 due to limitations on available data



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 with validation against higher fidelity approaches and any publicly available experimental data sets. Quantify turbulence ingestion, mean flow distortion, and shielding in a sufficiently generic 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

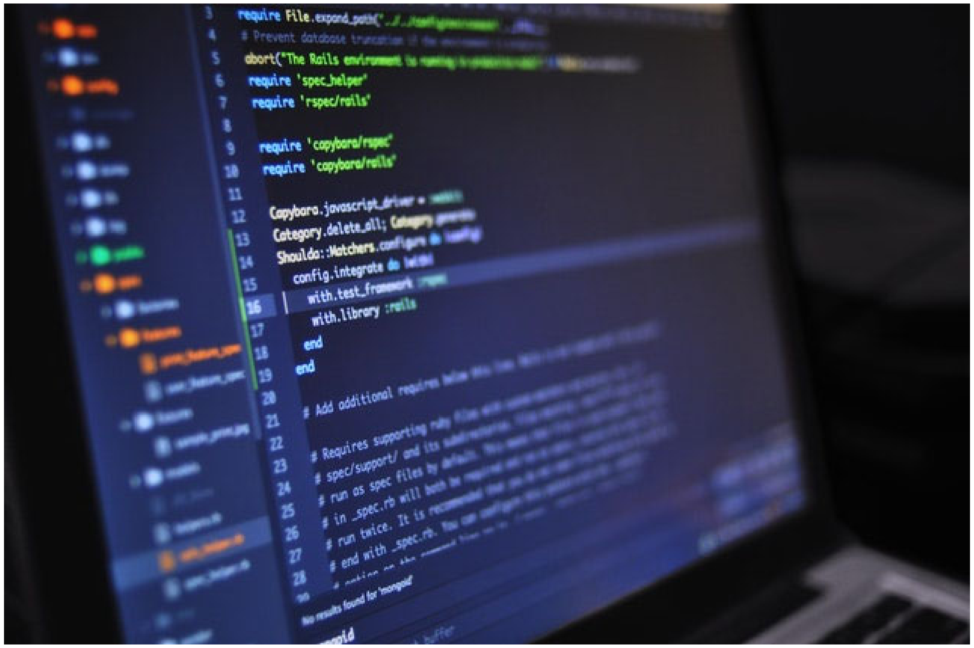
ASCENT Project 51: Combustion Concepts for Next-Generation Aircraft Engines

Institution: MIT
Funding: $300,000 for 2 years;
Currently forwarded funded into FY22

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

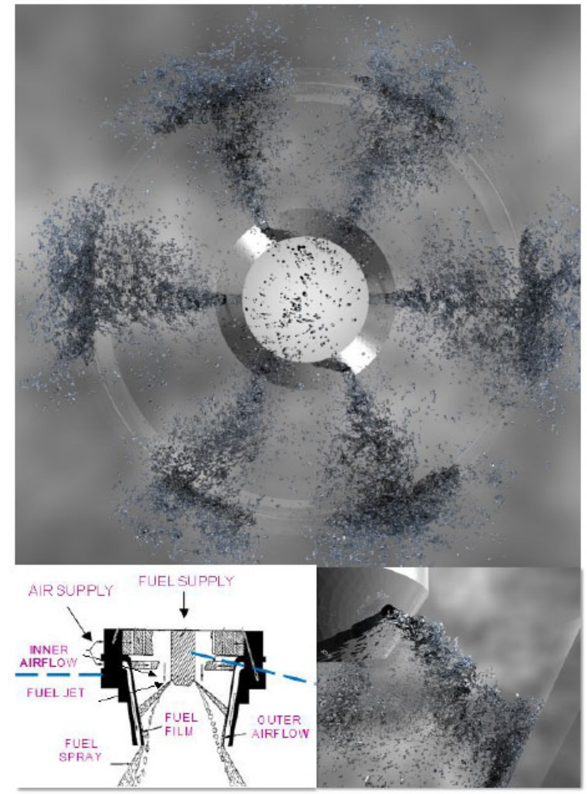
Institution: Georgia Tech

Funding Level: $1,500,000/yr. for 2 years;
Currently forwarded funded into FY22

Objective: Develop knowledge to enable the reduction of 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 parts of the combustor and conduct testing to validate the modelling results as well as create benchmark data for use by others.

Expected Impact: The knowledge from this project will enable the development of efficient gas turbine combustors that produce less noise. The result will be reduced development time and costs for new engines that meet future noise requirements.



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: University of Dayton
Funding: $184,997 first year; Planned for award of $100,000 second year beginning FY21

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

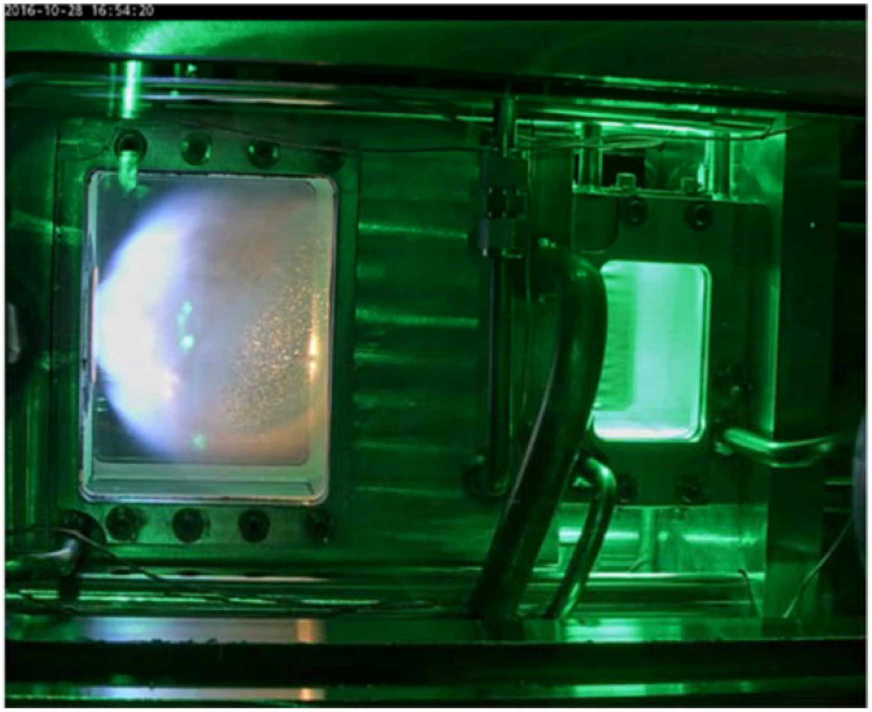
Institution: Purdue

Funding: $250,000/yr. for 2 years; Second year planned for award in FY21

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 increased thermal management load, enabling higher flight speeds or higher engine efficiencies..



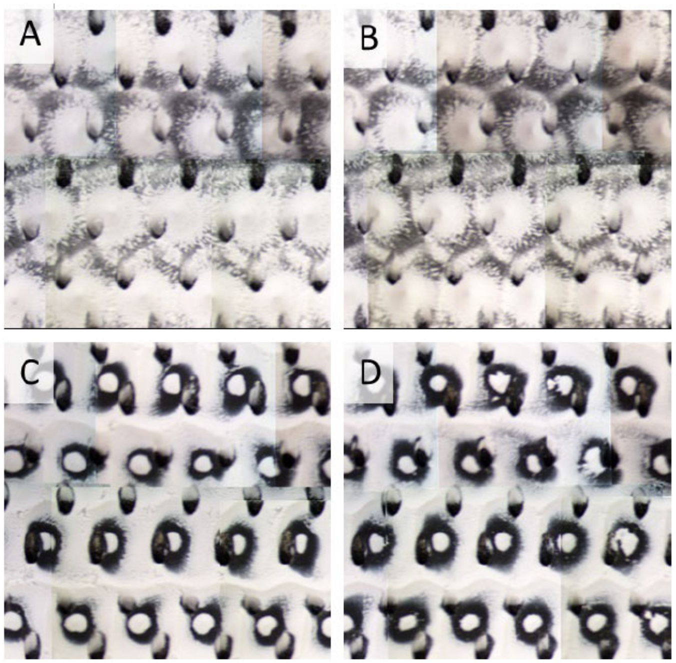
ASCENT Project 68:
Combustor Wall Cooling with Dirt Mitigation

Institution: Penn State University
Funding: $150,000 year 1; $150,000 year 2 planned for award in FY21

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: Georgia Tech

Funding: $500,000/yr.; Second year planned for award in FY21

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 a 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.

Particle Size (nm) from Decay Time Constant

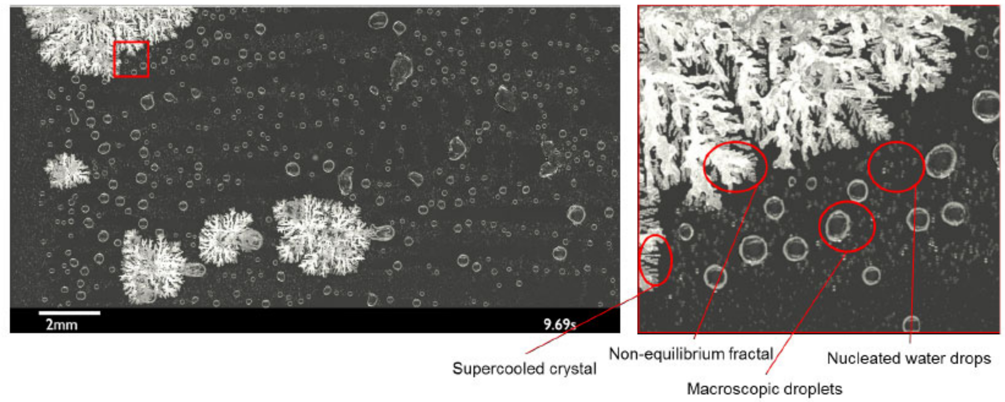
ASCENT Project 71: Predictive Simulation of Sooting Flames

Institution: Georgia Tech
Funding Level: $500,000/yr.; Second year planned for award in FY21

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

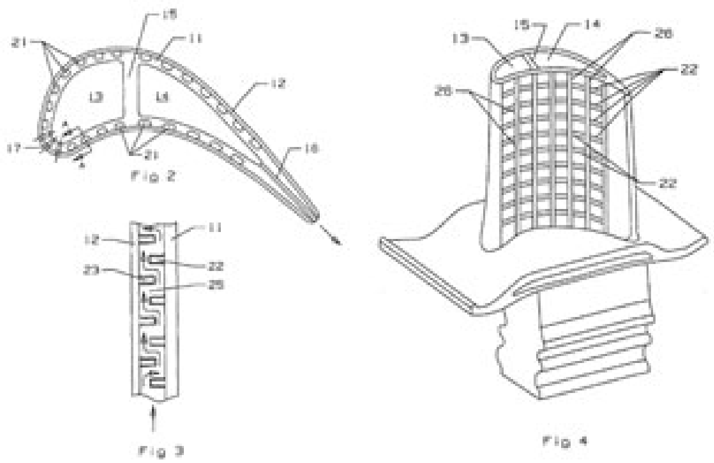
ASCENT Project 56: Reduced Fuel Burn through Double-Wall Cooling of Turbine Airfoils Made Possible through Additive Manufacturing

Institution: Penn State University

Funding: $400/yr. for three years; Currently forward funded into FY22

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 and comparing them to traditional metal cast turbine airfoils



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

ICAO CAEP Long Term Aspirational Goal (LTAG) Support

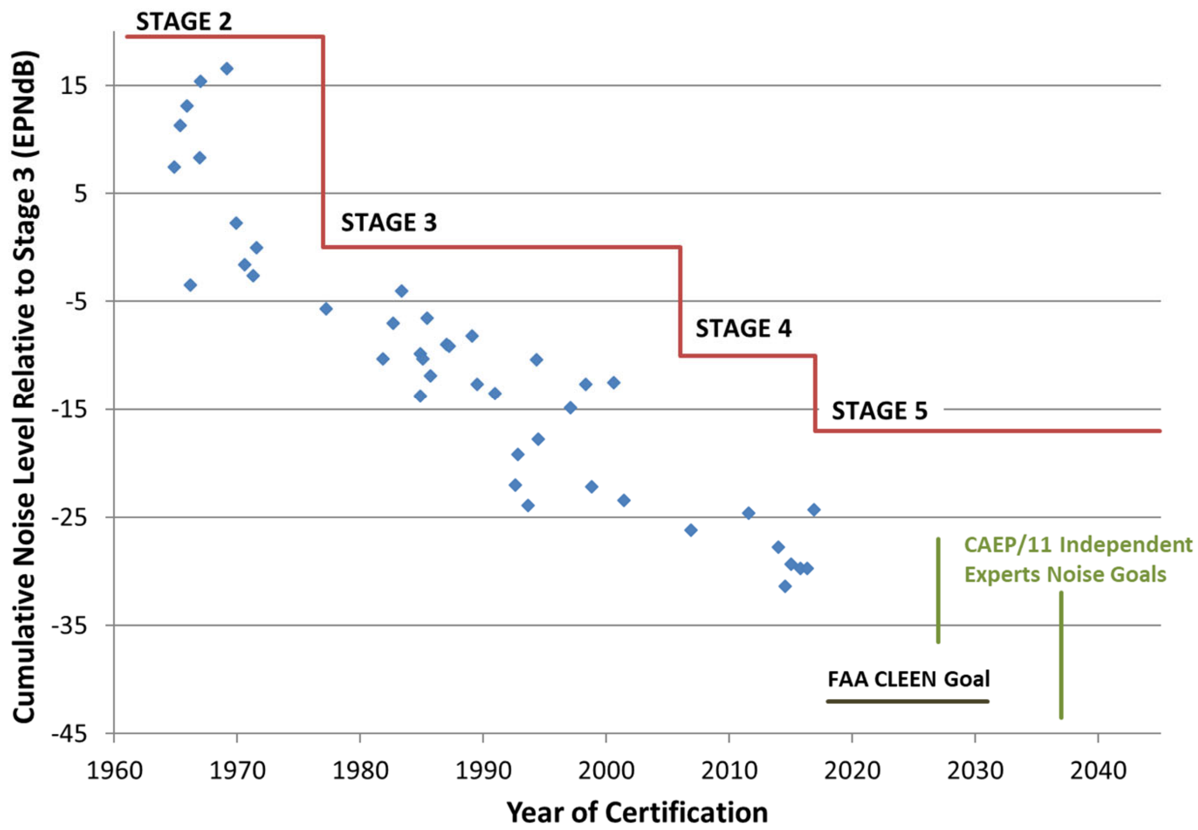
- FAA continues to provide staffing and researchers to support CAEP exploration of feasibility of a long term aspirational goal for CO_2 emissions from international aviation
- Engaging directly across all aspects of this work (tech, fuels, operations, scenarios) to support assessment of current, foreseen, innovative measures to contribute to CO2 reduction under various future scenarios
- Leveraging ASCENT Project 64 to provide analysis support for technology modeling/analysis/assessment
  - Feeds into larger assessment of feasibility of an aspirational goal

Conclusions

- **CLEEN Phase II is executing its fifth successful year**
  - Ten technology projects have reached their maturation goals, with many more expected in the next year, even after COVID impacts
- **CLEEN Phase III will continue our efforts to accelerate maturation of environmental aircraft technologies into the fleet (2020-2025)**
  - Eight awards planned Q2 CY2021
- **New ASCENT projects continue to expand our aircraft technology research portfolio**
- **Continuing to support CAEP LTAG work across several projects**

Backup Slides

CLEEN Noise Goal in Context



CLEEN Phase III Fuel Burn Goal in Context