U.S. Department
of Transportation
**Federal Aviation
Administration**

Office of the Administrator

800 Independence Ave., S.W.
Washington, DC 20591

January 11, 2024

The Honorable Maria Cantwell
Chair
Committee on Commerce, Science,
and Transportation
United States Senate
Washington, DC 20510

Dear Chair Cantwell:

This letter transmits the Federal Aviation Administration's (FAA) report to Congress under Section 742 of the FAA Reauthorization Act of 2018, Public Law 115-254. Section 742, titled "Technology Review," directs the FAA Administrator, in coordination with the Administrator of the National Aeronautics and Space Administration (NASA), to conduct a review of current and planned research on the use of advanced aircraft technologies, innovative materials, alternative fuels, additive manufacturing, and novel aircraft designs to increase aircraft fuel efficiency.

- FAA, in coordination with NASA, conducted this review and, per the legislative requirement, summarized projects and missions to examine a) the effectiveness of such technologies, materials, fuels, and aircraft designs to enhance fuel efficiency and aerodynamic performance and reduce drag, weight, noise, and fuel consumption; and b) the potential for novel flight pattern planning and communications systems to reduce aircraft taxiing and airport circling.

- Both FAA and NASA remain committed to advancing aviation technologies and operational procedures to improve fuel efficiency and reduce noise and emissions. The attached report highlights the research and development programs and collaborative efforts of FAA and NASA.

- In summary, in conducting this review, FAA found that research in the areas of aircraft technologies, innovative materials, alternative fuels, additive manufacturing, and novel aircraft designs enhances fuel efficiency and helps reduce noise and emissions. These technology development efforts are complemented by work to mature operational technologies and concepts that further reduce fuel consumption and improve operational efficiency. These key areas of research and development are showing great promise for increased fuel efficiency, as well as reduction of noise and exhaust emissions.

- The FAA's Continuous Lower Energy, Emissions, and Noise (CLEEN) Program is the centerpiece of the FAA's research and development efforts to improve aircraft fuel efficiency while reducing emissions and noise. The program partners with industry to develop certifiable aircraft and engine technologies that address these goals. Technologies developed by the CLEEN Program will result in a fleet of aircraft that generate less noise, use less fuel, and produce fewer emissions, thus supporting the overarching environmental performance goal for NextGen to achieve environmental protection that allows sustained aviation growth.

- FAA recommends that it continue to pursue technology development in the areas addressed in the attached report by using FAA's model of collaboration and coordination with NASA and industry to drive improvements in fuel efficiency. Currently, FAA is executing the third 5-year phase of the CLEEN Program.

We look forward to continued collaboration with your staff and would be happy to schedule time to brief you further if desired.

We have sent similar letters to the Ranking Member of the Senate Committee on Commerce, Science, and Transportation and to the Chairman and Ranking Member of the House Committee on Transportation and Infrastructure.

Sincerely,

Michael G. Whitaker
Administrator

Enclosure

U.S. Department of Transportation
Federal Aviation Administration

Office of the Administrator

800 Independence Ave., S.W.
Washington, DC 20591

January 11, 2024

The Honorable Ted Cruz
Ranking Member
Committee on Commerce, Science,
and Transportation
United States Senate
Washington, DC 20510

Dear Ranking Member Cruz:

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800 Independence Ave., S.W.
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January 11, 2024

The Honorable Sam Graves
Chairman
Committee on Transportation and Infrastructure
U.S. House of Representatives
Washington, DC 20515

Dear Chairman Graves:

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Michael G. Whitaker
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U.S. Department
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Office of the Administrator

800 Independence Ave., S.W.
Washington, DC 20591

January 11, 2024

The Honorable Rick Larsen
Ranking Member
Committee on Transportation and Infrastructure
U.S. House of Representatives
Washington, DC 20515

Dear Ranking Member Larsen:

This letter transmits the Federal Aviation Administration's (FAA) report to Congress under Section 742 of the FAA Reauthorization Act of 2018, Public Law 115-254. Section 742, titled "Technology Review," directs the FAA Administrator, in coordination with the Administrator of the National Aeronautics and Space Administration (NASA), to conduct a review of current and planned research on the use of advanced aircraft technologies, innovative materials, alternative fuels, additive manufacturing, and novel aircraft designs to increase aircraft fuel efficiency.

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Michael G. Whitaker
Administrator

Enclosure

Federal Aviation Administration
Office of Environment and Energy

REPORT TO CONGRESS:

Technology Review

FAA Reauthorization Act of 2018 (Public Law No. 115-254) – Section 742. Technology Review

Executive Summary

This report responds to Section 742(b) of the Federal Aviation Administration (FAA) Reauthorization Act of 2018 (the Act).

Section 742, titled Technology Review, requires the FAA, in coordination with the National Aeronautics and Space Administration (NASA), to review current and planned research on the use of advanced aircraft technologies, innovative materials, alternative fuels, additive manufacturing, and novel aircraft designs to increase aircraft fuel efficiency. Specifically, Section 742(a) requires the review to include summaries of projects and missions to examine a) the effectiveness of such technologies, materials, fuels, and aircraft designs to enhance fuel efficiency and aerodynamic performance, and reduce drag, weight, noise, and fuel consumption; and b) the potential for novel flight pattern planning and communications systems to reduce aircraft taxiing and airport circling. Section 742 also requires identification of opportunities for additional public or private research and development to increase aircraft fuel efficiency, as part of the review.

The FAA, in coordination with NASA, conducted this review and found that current and planned research in the areas of advanced aircraft technologies, innovative materials, alternative fuels, additive manufacturing, and novel aircraft designs can lead to improved aircraft fuel efficiency, as well as reduced noise and emissions. These technology development efforts are complemented by work to mature operational technologies and concepts that further reduce fuel consumption and improve operational efficiency. These key areas of research and development are showing great progress in improving fuel efficiency, as well as reducing noise and exhaust emissions.

Section 742(b) requires the FAA Administrator to submit a report containing the results of the review mandated by Section 742(a). This report contains those results. The FAA and NASA collaborated on this report’s content. Both agencies remain committed to advancing aviation technologies and operational procedures to improve fuel efficiency and reduce noise and emissions. This commitment is captured in the technical content of this report, which highlights the research and development programs, and collaborative efforts of the FAA and NASA.

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Introduction

The FAA is pleased to submit this report pursuant to Section 742, which requires the agency to work in coordination with NASA to conduct a technical review of advanced aircraft technologies, innovative materials, alternative fuels, additive manufacturing, and novel aircraft designs that have the potential to increase aircraft fuel efficiency.

The FAA and NASA collaborated on this report covering fuel efficiency research and development based on multiple data sources and references, including but not limited to FAA and NASA research and development program reports and plans; FAA regulations and advisory circulars; aerospace industry consensus standards, recommended practices and informational reports; FAA and Foreign Civil Aviation Authorities technical reports; and peer-reviewed academic research.

Legislative Mandate

Section 742 of the Act states:

(a) REVIEW.—

(1) IN GENERAL.—The Administrator of the Federal Aviation Administration, in coordination with the Administrator of the National Aeronautics and Space Administration, shall conduct a review of current and planned research on the use of advanced aircraft technologies, innovative materials, alternative fuels, additive manufacturing, and novel aircraft designs, to increase aircraft fuel efficiency.

(2) SUMMARIES.—The review conducted under paragraph (1) shall include summaries of projects and missions to examine—

(A) the effectiveness of such technologies, materials, fuels, and aircraft designs to enhance fuel efficiency and aerodynamic performance, and reduce drag, weight, noise, and fuel consumption; and

(B) the potential for novel flight pattern planning and communications systems to reduce aircraft taxiing and airport circling.

(3) RECOMMENDATIONS.—The review conducted under paragraph (1) shall identify potential opportunities for additional research and development, public or private, to increase aircraft fuel efficiency.

(b) REPORT.—Not later than 1 year after the date of enactment of this Act, the Administrator of the Federal Aviation Administration shall submit to the appropriate committees of Congress a report containing the results of the review conducted under subsection (a).

Background

FAA and NASA Collaboration

The FAA's Office of Environment and Energy's Continuous Lower Energy, Emissions, and Noise (CLEEN) Program and NASA's Advanced Air Vehicle program collaborate and leverage aircraft technology research and development programs to improve aircraft fuel efficiency and lower exhaust emissions.

This collaboration and coordination between the FAA and NASA on emissions reduction began in 2008. NASA, at the time as part of its Subsonic Fixed Wing (SFW) and Environmentally Responsible Aviation (ERA) projects, worked with the FAA to set goals for the first phase of the CLEEN Program, and subsequently on two projects to develop engine fan concepts that would result in significant fuel efficiency improvements and reduced noise. In collaboration with aircraft engine manufacturers, the two agencies funded multiple phases of fan efficiency and noise optimization research and conducted wind tunnel testing of the technologies at NASA's John H. Glenn Research Center. This report includes documentation on these two projects: the Pratt & Whitney Ultra-High Bypass Propulsion System Technologies project and the General Electric (GE) Open Rotor engine project.

This collaboration and coordination continues today, with constant exchange of information between the FAA and NASA on research plans, activities, and results. This coordination allows the two agencies' aircraft technology research and development efforts to be complementary, and for continued successful transition of the research findings to industry partners. Both agencies engage technical experts in program and project reviews to support evaluation of new program awards, and ensure proper alignment of the government-wide research portfolio.

This relationship continues to grow and maximizes the value of both agencies' research portfolios. For example, NASA subject matter experts are now engaging with aircraft technology research projects under the FAA's Aviation Sustainability Center of Excellence (ASCENT), as well as participating in the FAA's Research and Development Advisory Committee Environment and Energy Sub-Committee meetings, under which aircraft technology development work is reviewed and feedback is sought on the research portfolio. Similarly, FAA subject matter experts regularly engage with NASA aeronautics research projects support NASA in the annual review of its research portfolio. Additionally, FAA collaborates on the NASA-led Sustainable Flight National Partnership (SFNP) aimed at demonstration of the promising technologies for energy efficient aircraft as down selected from initial development over the last decade.

The FAA's role in aircraft-related research and development supports the certification and approval of aircraft designs, which aircraft and engine manufacturers transition into future aircraft products. While the FAA does not implement new aircraft designs or technologies directly, it collaborates with NASA, aircraft manufacturers, and academia through research and development efforts to drive innovation and accelerate new technologies for implementation by industry. In addition to advancing aviation technologies, these efforts provide the FAA with the necessary understanding of critical elements of these technologies so that the FAA can make informed safety decisions in its role as a certificating authority when these new technologies are incorporated into aircraft designs.

FAA CLEEN Program

In partnership with industry, the FAA's CLEEN Program[1] is developing certifiable aircraft and engine technologies that reduce noise and emissions while increasing fuel efficiency. Technologies developed by the CLEEN Program will result in a fleet of aircraft that produce less noise and fewer emissions, and use less fuel. These technologies support the overall environmental performance goals of the FAA's Next Generation Air Transportation System (NextGen) to achieve environmental protection that allows sustained aviation growth.

Historically, advances in aircraft technology have been the primary source of reduction in aviation's environmental impacts. Technological advancements have resulted in a 95 percent reduction in the number of people exposed to significant noise, and more than a 70 percent improvement in aircraft fuel efficiency over the last 50 years. The majority of these gains in fuel efficiency and noise reduction are due to enhancements in engine and airframe design. However, factors such as the increase in the overall number of operations and the implementation of new flight procedures lead to continued community concerns about noise. In addition, the continued growth of aviation results in the need for increased emissions reduction and improved fuel efficiency.

Through the public-private partnership of the CLEEN Program, the FAA and industry are working together to develop technologies that will enable manufacturers to create aircraft and engines with less noise, fewer emissions, and improved fuel efficiency. The technologies being accelerated by the CLEEN Program have relatively large technological risk but also enhanced benefits. Government resources help mitigate this risk and incentivize aviation manufacturers to invest and develop these high reward technologies which might otherwise not be pursued. By cost-sharing the development with the FAA, industry is willing to accept the greater risk and can better support a business case for these technological developments. Once these risks are addressed and the technology is matured via the CLEEN Program, the CLEEN companies apply these technologies to their future aircraft and engine products, leading to noise, fuel burn, and emissions benefits throughout the fleet for years to come. In addition to these benefits, the CLEEN Program has resulted in better analysis and design tools that

[1] More information about the CLEEN Program is available at http://faa.gov/go/cleen

improve the aircraft or engine product produced by these companies, well beyond the benefits provided by individual technology applications.

The CLEEN Program is implemented in five-year phases, and has goals for noise, fuel burn, and emissions. The first phase of CLEEN was executed from 2010 to 2015. In those five years, technologies were matured and demonstrated in major ground and flight test demonstrations, paving the way for introduction in future aircraft. Since then, a number of these technologies have successfully transitioned into new aircraft and engines that are flying today.

Based on the success of this program, the second phase of CLEEN was initiated in 2015 for a five-year term. Following subsequent successes under the second phase, the third phase of the CLEEN Program was launched in 2021. To receive funding from CLEEN, each industry partner has to match or exceed the FAA's contribution to the partner's awarded work in the program. This report covers accomplishments in Phases I and II, as well as the current work ongoing under Phase III.

FAA CLEEN Program Goals

All three phases of the CLEEN Program have targeted reductions in aviation noise, emissions and fuel burn. Table 1 summarizes these goals. As industry meets the program's goals, the FAA has made the goals for successive phases of the program increasingly more stringent. Further, additional goals have also been added over time. For the third phase of the CLEEN Program, the additional goals include reduction in community noise exposure to complement the existing certification noise goal, and an expanded emissions goal to include both aircraft engine nitrogen oxide (NO_X) emissions and particulate matter emissions.

The CLEEN Program demonstrates the continued commitment of the FAA toward reducing the noise, emissions, and fuel burn of the fleet of aircraft operating in the National Airspace System.

	Phase I	Phase II	Phase III
Time Frame	2010-2015	2015-2020	2021-2026[2]
FAA Contribution	~$125M	~$100M	~$125M+
Noise Reduction Goal	25 dB cumulative noise reduction cumulative to Stage 5		25 dB cumulative noise reduction relative to Stage 5 and/or reduction in community noise exposure
Fuel Burn Goal	33% reduction (relative to year 2000 best-in-class in-service aircraft	40% reduction (relative to year 2000 best-in-class in-service aircraft	-20% reduction relative to the CAEP[3]/10 CO_2 emissions standard
NO_X Emissions Reduction Goal	60% landing/take-off NO_X emissions reduction relative to the CAEP/6 standard	70% landing/take-off NO_X emissions reduction relative to the CAEP/8 standard	
Particulate Matter Emissions Reduction Goal			Reduction relative to CAEP/11 standard
Targeted Year for Technology Entry into Service	2018	2026	2032

Table 1: Timeframe, Funding, Goals, and Entry into Service for the Three Phases of the CLEEN Program (Listed goals are for subsonic aircraft)

While the CLEEN Phase I and II fuel burn reduction targets were defined in terms of reductions relative to year 2000 best-in-class in-service aircraft, for CLEEN Phase III, the goal is articulated as a 20 percent reduction relative to the International Civil Aviation Organization (ICAO) Committee for Aviation Environmental Protection's (CAEP) CO_2 emissions standard adopted in 2017.[4] Figure 1 represents the CLEEN Phase III goal (the red line) relative to the CAEP CO_2 emissions standard (the blue line). Figure 1 also shows the goals which, in 2019, an ICAO CAEP Independent Experts

[2] Timelines here are intended to reflect the reality of the executed work. Note that some projects were extended, resulting in overlapping execution of the phases.

[3] CAEP refers to the International Civil Aviation Organization's Committee for Aviation Environmental Protection

[4] CO_2 emissions and fuel efficiency are directly linked and scale proportionally.

panel (IEP) set for CO_2 emissions reductions in 2027 and 2037 across a range of aircraft size classes.[5] These targets were based upon a review of current and planned aircraft fuel efficiency technologies and designs. The third phase of the CLEEN Program is conducting aircraft technology development from 2021 through 2026 and targeting 2032 for applications of the technologies to enter into service. The fuel burn reduction goal is targeted appropriately between the 2027 and 2037 IEP goals for CO_2 and fuel efficiency.

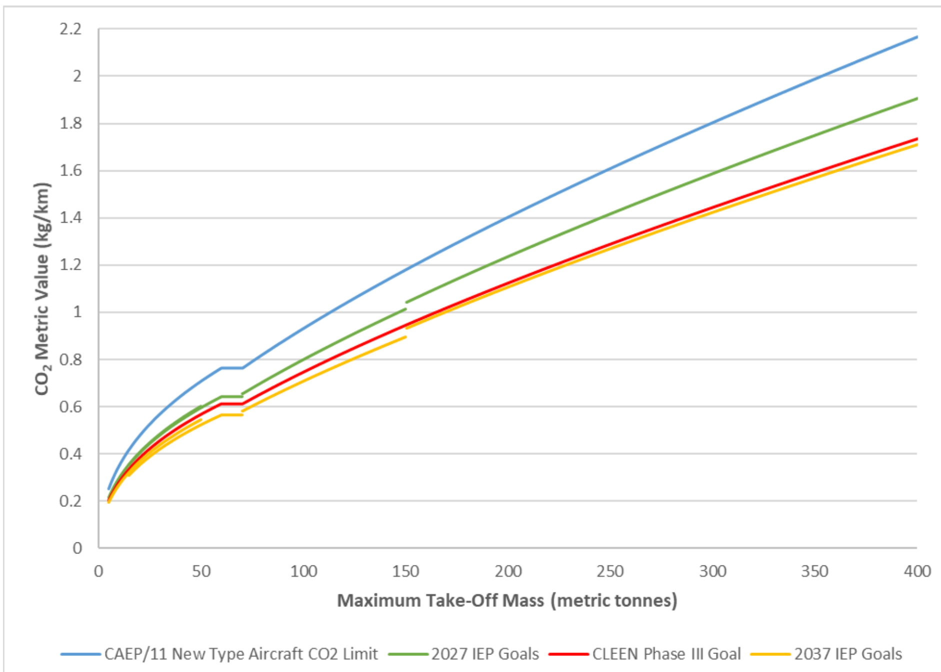

Figure 1: CLEEN Phase III Goal (red line) Relative to the CAEP CO_2 Emissions Standard (blue line)

[5] A summary of the findings of the Independent Experts panel is attached in this package addressing Section 742, entitled "Aviation and the Environment: Outlook"

Figure 2 shows the CLEEN noise reduction goal in context of previous and current noise standards. The CLEEN noise reduction goal is to reduce aircraft noise 25 decibels below the Stage 5 standard cumulatively at the three noise certification measurement points. This is represented by the black horizontal line between 2020 and 2030 in Figure 2 below. This figure illustrates the increasing stringency of the United States' Stage 2, 3, 4, and 5 noise standards, represented by the stepped red line. The blue data points in the figure represent the noise levels of previously certificated aircraft in their year of certification. In addition, the figure compares the FAA noise standards and CLEEN goals to projections made by the ICAO CAEP IEP in 2019. The green vertical bars represent the range of noise levels that the IEP set as goals for 2027 and 2037 across a range of aircraft size classes. In context, the CLEEN goal is aggressive, but is important to seek as a goal to reduce community noise exposure in the United States.

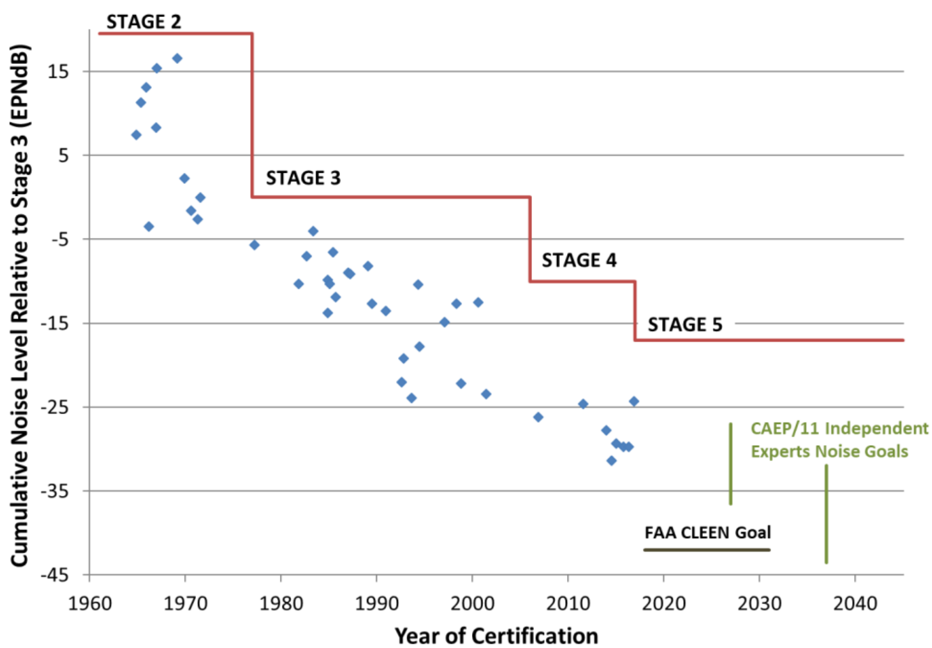

Figure 2: CLEEN Noise Reduction Goal in Context of Previous and Current Noise Standards

While the first two phases of CLEEN focused on subsonic civil aircraft, CLEEN Phase III is open to technologies for both subsonic and supersonic aircraft. The third phase of CLEEN includes goals for technologies that could reduce noise during the landing and takeoff phases of flight and/or reduce NO_X emissions throughout the flight of supersonic aircraft, in addition to the program's subsonic goals.

Alternative Jet Fuels

The first two five-year phases of CLEEN, as well as the ASCENT Center of Excellence[6] and the Commercial Aviation Alternative Fuels Initiative (CAAFI),[7] have been instrumental to the certification of alternative jet fuels for safe use by civil transportation via ASTM International.

For the purposes of this report, alternative jet fuels are fuels approved by ASTM International for use in gas turbines that are not produced from conventional petroleum. Sustainable aviation fuels (SAF) are a subset of alternative jet fuels produced from renewable and waste feedstocks that meet rigorous sustainability requirements.

At present, the FAA is supporting the certification of new fuels through the ASCENT Center of Excellence D4054 Clearing House at the University of Dayton Research Institute.[8] The Clearing House supports coordinated testing, evaluation, and review of alternative fuels for approval by ASTM International. These combined efforts have led to the approval of seven fuel types for use by civil aviation. These fuels are all drop-in compatible with today's aircraft and fueling systems and can be made from a variety of biomass, waste, and fossil resources. Given their similar composition to today's jet fuel, these alternative fuels do not result in a substantial change in fuel volume used; however, their use can result in a substantial (i.e., more than 50 percent reduction) in non-volatile particulate matter.

CLEEN Phase III continues to support testing and qualification of new alternative jet fuels, with a focus on supporting greater than 50% blends of these fuels with conventional petroleum-based jet fuel. These efforts are in line with the SAF Grand Challenge[9] and reflect the desire of the aviation industry to use 100% SAF without the need to blend with conventional jet fuel.

Benefits from the CLEEN Program

The CLEEN Program has successfully developed technologies that its industry partners have introduced to the fleet, and industry anticipates that additional technologies developed under the program will enter into service in the coming years as opportunities

[6] For more information on the ASCENT Center of Excellence, please visit https://ascent.aero/. For a list of sustainable aviation fuel projects in ASCENT, please visit https://ascent.aero/topic/alternative-fuels/

[7] For more information on CAAFI, please visit http://caafi.org/

[8] For more information on the ASCENT Center of Excellence D4054 Clearing House at the University of Dayton Research Institute, please visit https://ascent.aero/project/alternative-jet-fuels-test-and-evaluation-a/

[9] For more information on the SAF Grand Challenge, please visit https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/

arise for their inclusion in new aircraft and engine designs. Additionally, the knowledge gained from the development of these technologies is leading to improved design codes and fabrication methods that are being applied throughout these companies' product lines, leading to improved environmental performance across the industry.

Some of the technologies matured by the CLEEN Program are entering the fleet in large numbers. For example, GE's unique lean-burn combustion system, Twin Annular Premixing Swirler (TAPS), is designed to pre-mix air and fuel prior to combustion for leaner burn and fewer emissions than conventional combustion systems. In 2016, the TAPS combustion was introduced on the GEnx engine for the Boeing 787 Dreamliner and the 747-8 aircraft. TAPS was enhanced under the first phase of the CLEEN Program, and the resulting TAPS II combustor is now in operation in CFM International's LEAP engine for narrow-body aircraft. This engine currently has 8,000 orders. Under CLEEN Phase II, GE further developed the next generation TAPS combustor and demonstrated the TAPS III's reduced emissions via engine testing. The TAPS III combustion system will be implemented in the GE9X-powered Boeing 777X, the aircraft set to replace the GE90-powered Boeing 777. The 777X is expected to enter into service in 2025, resulting in NOx emissions 30 percent below international CAEP standards.

Under CLEEN Phase II, GE Aviation enhanced its Flight Management System (FMS) which automates a wide variety of in-flight tasks, enabling the pilots to more efficiently fly an aircraft from its origin to its destination, accounting for traffic, weather, aircraft performance, and required arrival time, while optimizing performance. The FMS uses a variety of sensors to determine its current position and sends guidance commands to the aircraft control systems to guide the aircraft along its approved flight plan. GE's CLEEN Phase II FMS technologies result in a one percent average improvement in fuel burn. GE is currently working to incorporate these technologies in future products.

Under CLEEN I, Boeing developed its Adaptive Trailing Edge (ATE) technology, which has been adopted for use in commercial and defense products. Similar to Boeing, other companies used their technologies developed under the CLEEN Program to incorporate into other commercial and defense programs. The security sensitivity of the defense programs do not allow these technologies' applications to be discussed publicly.

The CLEEN Program also aids industry in developing the analytical tools necessary to create aircraft and engine designs that result in lower noise, emissions, and fuel use. For example, the data and lessons learned from the CLEEN Phase I fan development work completed by Pratt & Whitney has been incorporated into the analytical tools that they use to design new engines. As such, this investment will lead to noise and fuel burn reductions from every new Geared Turbofan engine that is developed by Pratt & Whitney.

Low emissions combustion development work, conducted under CLEEN Phases I and II across GE, Honeywell, and Rolls-Royce projects, resulted not only in emissions reductions for the specific combustors developed under the program, but enhances each company's ability to design and optimize all future engine combustion systems for low emissions.

Collins Aerospace, in conjunction with NASA, developed low drag acoustic fan duct technology and new analytical tools that will be used in future nacelle designs that support ultra-high bypass ratio engines. Additionally, these efforts have generated new databases for low drag acoustic surfaces and material properties for novel acoustic structures. In particular, Collins has begun introducing the use of the newly generated databases to assist the definition of acoustic specifications on near-term applications.

An additional benefit of the CLEEN Program is that, while maintaining continuous investment in advancing technologies for entering fleet service, the program has enabled development of supporting technologies with lower maturity level that may otherwise have been unsupported. These are technologies such as developing viable manufacturing alternatives and advancing the state of the art for materials that can be used in various applications.

According to analysis done by Georgia Tech in 2021,[10] the technologies matured in the first five-year phase of CLEEN will reduce U.S. fleet-wide fuel burn by 1.4 percent by 2030 and 2.6 percent by 2050,[11] providing a cumulative savings of 9.3 billion gallons of jet fuel. The CO_2 savings from reduced fuel burn are the equivalent of taking 781 thousand cars off of the road from 2020 to 2050. In addition to saving airlines 18.7 billion dollars on fuel, technologies from the first phase of CLEEN will contribute to a 14% decrease in the land area exposed to significant noise, as defined by a day-night noise level (DNL) of 65 dB.[12]

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 has estimated that the program will reduce fuel consumption 2.4 percent by 2030 and 8.9 percent by 2050, bringing the contribution of CLEEN Phase I and II to 11.5 percent fuel burn reduction in the fleet by 2050.[8]

Cumulatively, CLEEN Phases I and II are estimated to reduce consumption of fuel by 34.7 billion gallons by 2050, saving airlines $69.5 billion,[13] and reducing CO_2 emissions by 404 million metric tons. These CO_2 reductions are equivalent to removing 2.9 million cars from the road from 2020 to 2050.

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10 https://ascent.aero/project/cleen-ii-technology-modeling-and-assessment/

11 Compared to a reference fleet scenario which includes evolutionary technology advancements

12 For more information on the DNL metric, please visit https://www.faa.gov/regulations_policies/policy_guidance/noise/community

13 Based on $2 per gallon assumed price of jet fuel. Computed October 2021.

Assessment of the other benefits of CLEEN Phase II are ongoing. A final update to the fuel burn and CO_2 emissions benefit assessment as well as quantification of the program's fleet-level noise and NOx emissions benefits are expected to be finalized in 2024.

Additional information on the CLEEN Program can also be found on the FAA website at www.faa.gov/go/cleen. This website will be updated on a periodic basis. The FAA also maintains an online version of this report at https://www.faa.gov/newsroom/continuous-lower-energy-emissions-and-noise-cleen-program?newsId=22534.

Response to Section 742

This report provides a review of current and planned research on the use of advanced aircraft technologies, innovative materials, alternative fuels, additive manufacturing, and novel aircraft designs intended to enhance aircraft fuel efficiency and aerodynamic performance, and to reduce drag, weight, noise, fuel consumption and emissions. This review is followed by an examination of the potential for novel flight pattern planning and communications systems that could reduce aircraft taxiing and airport circling.

1. Advanced Aircraft Technologies

Continuing advances in wing aerodynamics and structures have proven effective in reducing fuel burn from the fleet over time.

a. FAA CLEEN Wing Technologies

The FAA CLEEN Program has been working with NASA and Boeing to develop wing technologies that will reduce fuel burn and noise.

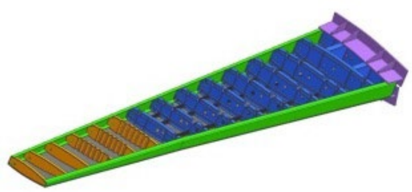
Structurally Efficient Wing (SEW)	Description:	Benefit:
	Under CLEEN Phase II, Boeing developed and demonstrated advanced aircraft wing technologies. The SEW provides large weight reductions through new manufacturing techniques and advanced composite material technology, resulting in a reduction of aircraft fuel burn.	**Fuel:** 3.5% reduction

Figure 3: Structurally Efficient Wing

For CLEEN Phase II, Boeing developed and demonstrated 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. In November 2019, Boeing completed full scale ground testing of the Wing Component Test Article at the National Institute for Aviation Research in Wichita, Kansas. The SEW has cleared testing that supports transition of its advanced composite technologies into a broad set of current and future commercial and military applications.

Adaptive Trailing Edge	Description:	Benefit:
	Under CLEEN Phase I, Boeing developed and demonstrated a prototype Adaptive Trailing Edge (ATE) system capable of tailoring wing performance to reduce noise and fuel burn at different flight conditions.	**Fuel:** Up to 2% reduction **Noise:** 1.7 decibels (dB) reduction

Figure 4: Adaptive Trailing Edge

The technologies matured by Boeing during CLEEN Phase I included an Adaptive Trailing Edge (ATE) for the aircraft wing. 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 the ATE project have been adopted for use in commercial and defense products.

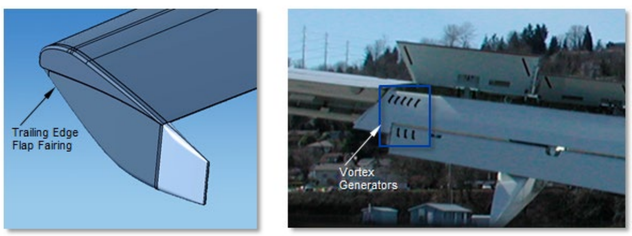
Quiet High-Lift System	Description:	Benefit:
	Under CLEEN Phase III, Boeing is developing flap edge fairings and vortex generators for wing high-lift devices in order to minimize noise.	**Noise:** Up to 0.5 EPNdB noise reduction

Figure 5: Quiet High-Lift System

Under CLEEN Phase III, Boeing is developing a quiet high-lift system, utilizing flap edge fairings and vortex generators to reduce aircraft noise. The technologies will be prototyped and demonstrated in flight.

b. NASA Ultra-Efficient Wing

NASA’s research and development of novel aerodynamic, structural, and control technologies is intended to enable a substantially higher span wing/lower friction for reduced drag without offsetting weight increases, resulting in an overall fuel efficiency benefit. The Advanced Air Vehicles Program (through its Advanced Air Transport Technology project) is addressing the multidisciplinary technical challenges associated with advanced wings, including addressing viscous and induced drag with the objective of enabling a 1.5 to 2 times increase in the aspect ratio of lightweight wings. This advanced wing research includes focus on multiple technologies including:

- *Performance adaptive aeroelastic wings*: Also known as mission adaptive wings, they take advantage of structural adaptation to alleviate loads and save weight, and continuously optimize cruise drag and save fuel. Flight tests of the X-56 test aircraft have focused on active flutter suppression of highly flexible wings and wind tunnel tests have focused on active trailing edge concepts to reduce loads and drag.
- *Passive aeroelastic tailored (PAT) wings:* PAT wings focus on alleviating critical off-design loads through passive, tailored design of composite wings to increase span and reduce weight. A large-scale ground test of a 39-ft semispan PAT wing was designed and recently completed testing with positive results. This research continues.
- *Active flow control*: Research has focused on enabling mechanically simpler high lift systems to reduce wing weight and cost. A wind-tunnel test was completed in fiscal year (FY) 2019 demonstrating effective active flow control systems for this purpose. Research will continue with refinement of the best concepts.
- *Natural Laminar Flow:* Research focuses on new design approaches to passively reduce drag for higher sweep/speed wings. Recent wind tunnel tests at high Reynolds numbers have demonstrated the feasibility of the approach, and plans are proceeding to validate the design method through flight test under the Integrated Aviation Systems Program Flight Demonstrations and Capabilities Project.
- *Transonic Truss Braced Wing (TTBW):* TTBW is a key aero-structural technology applicable to multiple vehicle classes. Research has focused on single aisle transport aircraft and has included multiple wind tunnel tests and high-fidelity computational studies. Fuel burn estimates for the TTBW technology are 8-10 percent below that of an equivalent advanced technology conventional configuration airplane. Transonic and high-lift integration tests of a Mach 0.80 design were completed in 2019 to 2021 with additional design and tests planned to further mature the technology.

NASA has also conducted research for reducing airframe noise with minimal or no impact on fuel burn. This research included efforts examining unconventional acoustic liner concepts, characterization of core/combustion and fan noise, concepts to reduce high-lift system and landing gear noise, and improvements in propulsion airframe aeroacoustics to reduce noise. Examples of specific research include open rotor as well as characterization of unique acoustic challenges for supersonic aircraft, highlighted by ongoing development of the X59 aircraft (currently in construction) to demonstrate low boom supersonic flight. Additionally, a modern single-aisle transport aircraft flight test was completed in FY18 demonstrating noise and drag reduction with a NASA-developed novel acoustic liner inside the engine nacelle. Continued research allowing better source characterization of new engines and advanced airframes will provide better estimates of noise for future aircraft designs.

c. FAA CLEEN Fuselage Technologies

The FAA CLEEN Program has supported unconventional airframe technologies that have the potential to enable step changes in fuel burn and noise. The origins of this concept started in 2008 under NASA funded N+3 studies with Aurora Flight Sciences (Aurora) and the Massachusetts Institute of Technology. Aurora worked under CLEEN Phase II to advance composite airframe technologies that would enable an unconventional aircraft configuration.

Double Bubble D8 Fuselage	Description:	Benefit:
	Under CLEEN Phase II, Aurora developed and demonstrated composite airframe technologies that will enable an unconventional aircraft configuration	**Fuel:** 29% reduction **Noise:** 16 EPNdB (Effective Perceived Noise level in dBs)

Figure 6: Double Bubble D8 Fuselage

Aurora, under CLEEN Phase II, developed and demonstrated composite airframe technologies that will enable an unconventional aircraft configuration with the potential to reduce fuel burn, emissions, and noise. Aurora designed an all-composite fuselage for what is known as the double bubble advanced aircraft concept, a more aerodynamically efficient shape, using materials and manufacturing processes that demonstrate configuration feasibility and weight benefits. The technologies developed under CLEEN Phase II will help enable economical fabrication of the fuselage while ensuring durability 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 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 decibels) cumulative noise reduction toward the CLEEN Phase II goals. These benefits represent the improvements that this fuselage configuration change provides, on which additional technology benefits could be applied. This configuration, combined with advancements in engine integration that could be realized beyond the timeframe for entry into service of applications of CLEEN Phase II, holds the potential for up to 56 percent fuel burn reduction and 42 EPNdB cumulative noise reduction; however, additional measurements are needed to confirm the noise reduction.

d. FAA CLEEN Aircraft Propulsion Technologies

Advances in propulsion system technologies historically have contributed to the majority of the fuel burn, emissions, and noise reductions for new aircraft. More efficient engines resulted from the continuing drive for higher bypass ratio and higher overall pressure ratio engines, combined with the development of ultra clean combustion systems to reduce emissions. Engines still have not reached the maximum level of efficiency possible under the technological limits of the Brayton thermodynamic cycle.

Engine Fan, Nacelle, and Nozzle Technologies

The FAA CLEEN Program is working with a number of industry partners to develop technologies to reduce fuel burn and noise through improvements in the engine fan, nacelle, and nozzle. Some of the efforts have also considered advanced engine geometries to achieve a step change in fuel efficiency.

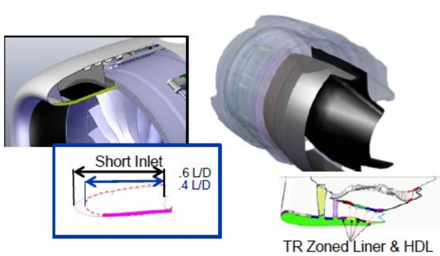
Integrated Propulsion System Nacelle Technologies	**Description:**	**Benefits:**
	Under CLEEN Phase II, Collins Aerospace developed an integrated propulsion system nacelle technology to reduce noise, fuel burn, and emissions. The company is advancing innovative acoustic treatment technologies and clean fan duct thrust reverser designs.	**Fuel:** 0.46% reduction aligned to 2025 Middle of Market **Noise:** 2 EPNdB reduction aligned to 2025 Middle of Market

Figure 7: Integrated Propulsion System Nacelle Technologies

Under CLEEN Phase II, Collins Aerospace developed integrated propulsion system nacelle technology to reduce noise and fuel burn. The company advanced innovative acoustic treatment technologies and clean fan duct thrust reverser designs. The combined technology package is expected to provide a 0.46 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 design and analysis and achieved Detailed Design Review approval for a ground test demonstrator that will incorporate acoustic technologies into a modified production thrust reverser. Collins Aerospace concluded its work under CLEEN Phase II in 2020 following the impacts from COVID-19 pandemic on its work plan for the project. Collins plans to complete Technology Readiness Level (TRL) 6 engine demonstration of the technologies in future years outside of the CLEEN Program. However, selected technologies from the program such as low drag surfaces and zoned liner configurations have successfully reached production-ready status and have been incorporated into current production nacelle applications.

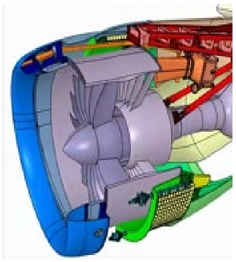
Compact Nacelle	**Description:**	**Benefit:**
	Under CLEEN Phase II, Boeing conducted design and test work in collaboration with Rolls-Royce on a compact nacelle inlet and thrust reverser design for ultra-high bypass engines. The technology is expected to reduce weight and allow for improved acoustic treatment.	**Fuel:** 1% reduction **Noise:** Enables improved acoustic treatment solutions

Figure 8: Compact Nacelle

For CLEEN Phase II, Boeing conducted 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. Flight testing of the compact nacelle was completed in 2022 on the Rolls-Royce 747 Flying Test Bed.

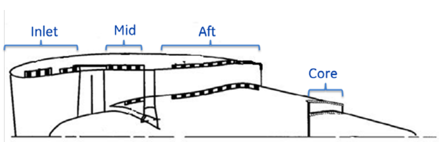
Low Pressure Ratio Fan Advanced Acoustic Technologies	**Description:**	**Benefits:**
	Under CLEEN Phase II, GE developed novel acoustic liner and fan noise source strength reduction technologies to combat the reduced noise treatment area available in low fan pressure ratio engines.	**Noise:** 3 EPNdB cumulative noise reduction with no adverse impact to fuel burn

Figure 9: Low Pressure Ratio Fan Advanced Acoustic Technologies

Under CLEEN Phase II, GE developed novel acoustic liners and fan noise source strength reduction technologies to combat the reduced noise treatment area available in low fan pressure ratio engines. This work targeted a 3 EPNdB cumulative noise reduction with no adverse impact on fuel burn. In 2019, GE tested novel liner designs in the NASA Langley Grazing Flow Impedance Tube and conducted detailed aeroacoustic design of the fan source strength reduction concept. Follow-on work to test and demonstrate the acoustic technology is planned to take place under CLEEN Phase III.

Ultra-High Bypass Propulsion System Technologies

Description:
Under CLEEN Phase I, Pratt & Whitney completed an ultra-high bypass engine test campaign, demonstrating aerodynamic performance, mechanical, and acoustic characteristics of advanced fan system technologies that would contribute to the overall benefits provided in a new geared turbofan engine.

Benefits:

Fuel: 20% fuel burn reduction compared to the Boeing 737-800/CFM56-7B

Noise: 20 dB aircraft noise reduction compared to the Boeing 737-800/CFM56-7B

Emissions: 60% NOx reduction compared to the Boeing 737-800/CFM56-7B

Figure 10: Ultra-High Bypass Propulsion System Technologies

Under CLEEN Phase I, NASA and Pratt & Whitney developed and demonstrated an ultra-high bypass ratio Geared Turbofan™ engine and associated advanced technologies. 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.

Ceramic Matrix Composite Acoustic Nozzle

Description:

Under CLEEN Phase I, Boeing designed, fabricated and demonstrated an acoustic ceramic matrix composite (CMC) primary exhaust system. The advanced material system enables lighter, quieter, more efficient engines. The CMC nozzle was flight tested on the Boeing 787 ecoDemonstrator.

Benefit:

Fuel: Up to 1% fuel burn reduction compared to 787 aircraft

Noise: Up to 2.3 dB noise reduction compared to 787 aircraft

Figure 11: Ceramic Matrix Composite Acoustic Nozzle

The technologies matured by Boeing during CLEEN Phase I included a Ceramic Matrix Composite (CMC) acoustic nozzle for the engine exhaust. 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. Rolls-Royce provided engines and technical support for this effort.

Open Rotor Engine	**Description:**	**Benefits:**
	Under CLEEN Phase I, GE and NASA developed open rotor designs for efficiency and low community noise. GE leveraged computational fluid dynamics, computational aero-acoustics, and rig scale testing to generate designs that achieved significant noise reductions well beyond what was attained in the 1980's while retaining cruise performance.	**Fuel:** 26% reduction relative to CFM56-7B powered narrow body aircraft **Noise:** 15-17 EPNdB reduction relative to Stage 4

Figure 12: Open Rotor Engine

Under CLEEN Phase I, GE also completed scaled open rotor wind tunnel tests with NASA, 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. The results proved instrumental in helping the U.S. negotiate the international agreement on a noise standard at the 9th meeting of the International Civil Aviation Organization (ICAO) Committee for Aviation Environmental Protection in 2013 which was promulgated domestically as the Stage 5 noise standard.

Advanced Acoustic Fan and Liners	**Description:**	**Benefits:**
	Under CLEEN Phase II, Honeywell is developing a lightweight fan that reduces rotor noise, along with novel acoustic liners that target reductions in both broadband and tonal noise from the fan.	**Fuel:** 1.5% reduction on top of other CLEEN Phase II Honeywell technologies **Noise:** 2.5 EPNdB reduction

Figure 13: Advanced Acoustic Fan and Liners

Under an optional expansion of their work scope for CLEEN Phase II, Honeywell developed a weight-reduced fan rotor that simultaneously reduces noise. Honeywell combined this technology with novel noise reduction liners in the fan case and bypass stream of the engine. Design work and final engine tests were completed in 2022, reaching TRL 6 for these technologies.

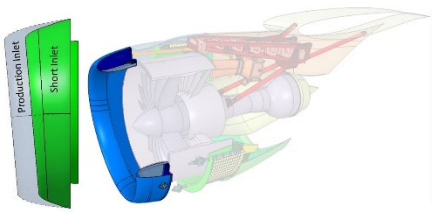
Advanced Nacelle: Next Generation Inlet	Description:	Benefit:
	Under CLEEN Phase III, Boeing is developing a new inlet architecture that will reduce weight, drag and noise.	**Noise:** Up to 1.5 EPNdB **Fuel:** 2% fuel burn reduction

Figure 14: Advanced Nacelle: Next Generation Inlet

Under CLEEN Phase III, Boeing is developing an engine inlet with novel structural and systems architecture that will reduce weight and drag, and improve acoustics relative to existing “short inlet” designs. The new inlet will be prototyped and demonstrated in flight. This work builds upon prior work under CLEEN Phase II conducted by Boeing.

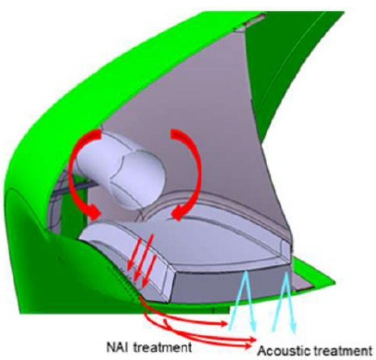
Acoustic Air Inlet Lip Skin	Description:	Benefit:
	Under CLEEN Phase III, SAFRAN Nacelles is developing additional acoustic treatment on the inlet lip of the nacelle while supporting de-icing functionality.	**Noise:** Improved acoustics for short inlets. **Fuel:** Enable benefits of short inlet (high bypass ratio)

Figure 15: Acoustic Air Inlet Lip Skin

SAFRAN Nacelles is seeking to increase the acoustic performance of the nacelle by adding an acoustic surface into the D-Duct area of the inlet. Under CLEEN Phase III, SAFRAN Nacelles is conducting testing to ensure de-icing performance is maintained under this new configuration and that engine operability is not impacted from the ingestion of heating air film. SAFRAN Nacelles also will demonstrate acoustic performance and manufacturability of the inlet technology.

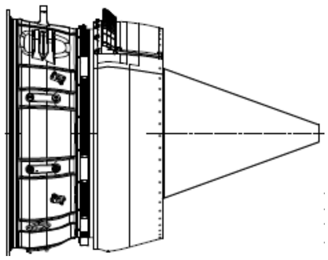
Large Cell Exhaust Acoustic Technology	**Description:**	**Benefit:**
	Under CLEEN Phase III, Collins Aerospace is developing a novel exhaust noise attenuation feature involving a “large cell” cavity treatment in the exhaust structure.	**Noise:** Lower noise by 0.9 to 1.5 EPNdB

Figure 16: Large Cell Exhaust Acoustic Technology

Under CLEEN Phase III, Collins Aerospace is developing large cell noise attenuation technology for application to the engine exhaust nacelle structure. This noise attenuation technology is primarily aimed at reducing combustion noise with application to current and future commercial aircraft. Collins Aerospace expects to reach TRL 6 by 2025 using a ground engine test in collaboration with Pratt & Whitney.

Highly Efficient Fan Module	**Description:**	**Benefit:**
	Under CLEEN Phase III, Honeywell is developing over-the-rotor acoustic treatment, a high efficiency booster, and optimizing the fan exit guide vanes and booster stators for combined noise and efficiency benefits**.**	**Noise:** 1.5 EPNdB **Fuel:** 1.5% fuel burn reduction

Figure 17: Highly Efficient Fan Module

Under CLEEN Phase III, Honeywell is developing a suite of technologies that it collectively calls the highly efficient fan module. Honeywell will leverage prior fan rig testing from a collaborative effort with NASA to inform development of noise reducing over-the-rotor acoustic treatment, a high efficiency booster with optimized stators, and improved fan exit guide vanes. The technologies will be fan rig tested and engine tested in the later years of the project to prove out their noise and fuel burn benefits.

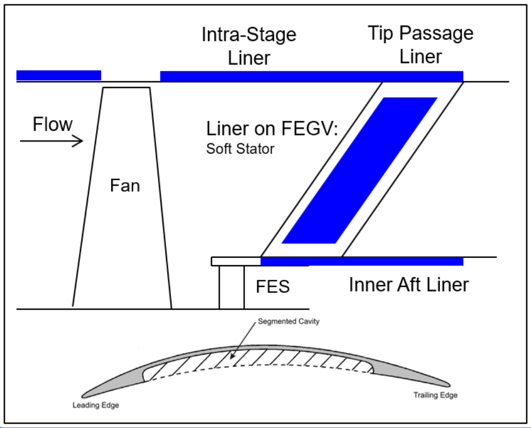
Ultra-Quiet Reduced-Loss Fan Stage	Description:	Benefit:
	Under CLEEN Phase III, Pratt & Whitney is developing a quieter, more efficient fan module including additively manufactured low-loss acoustic liners and reduced solidity, reduced-loss, lower noise fan exit guide vanes. Areas of interest for the advanced acoustic treatment are highlighted in blue.	**Noise:** Target 3 EPNdB noise reduction combined with P&W combustor technology **Fuel:** 0.8% fuel burn as part of package with P&W combustor technology

Figure 18: Ultra-Quiet Reduced-Loss Fan Stage

Under CLEEN Phase III, Pratt & Whitney is developing a reduced noise, higher efficiency fan system focused on reducing aerodynamic losses while reducing noise through new acoustic liners and optimized fan exit guide vanes. These technologies continue to be matured through rig and engine tests.

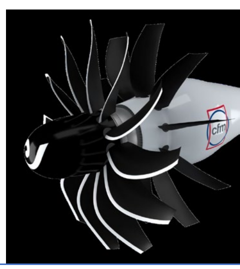
Open Fan	Description:	Benefit:
	Under CLEEN Phase III, GE Aviation is developing an unducted single fan architecture optimized for noise and fuel burn reduction.	**Noise:** 13 EPNdB cum margin relative to Stage 5 **Fuel:** 10+% reduction relative to current LEAP engine

Figure 19: Open Fan

Under CLEEN Phase III, GE Aviation is developing an open fan technology that delivers propulsive efficiency while seeking to overcome historical issues with complexity, weight, and flight speed limitations of this propulsion configuration. GE is focused on the aerodynamics and acoustics aspects of the propulsive fan. GE will bring fan blade and vane designs into a rig test program, culminating in high fidelity wind tunnel test validation that will allow for noise and performance measurements as well as projection to a full scale next generation narrow-body aircraft application.

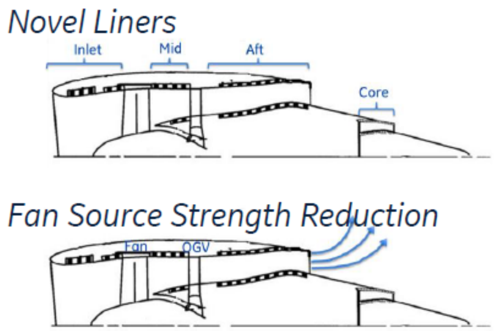
Advanced Acoustics	Description:	Benefit:
	Under CLEEN Phase III, GE Aviation is developing advanced fan duct acoustic liners and fan/outlet guide vane (OGV) technologies to reduce noise.	**Noise:** 2 EPNdB cum. reduction from novel liners, 1 EPNdB cum. reduction from fan/OGV designs

Figure 20: Advanced Acoustics

Under CLEEN Phase III, GE Aviation is developing novel acoustic liners and fan source strength reduction designs to reduce noise for future engine architectures. This work builds on work conducted under CLEEN Phase II to prototype these acoustic elements. Under CLEEN Phase III, GE will conduct subscale wind tunnel testing of the fan and outlet guide vane design to evaluate source noise reduction.

Engine Core Turbomachinery Technologies

The FAA CLEEN Program has been working with a number of industry partners to develop technologies to reduce fuel burn, emissions, and noise through improvements in turbomachinery and the use of novel materials used in the engine core.

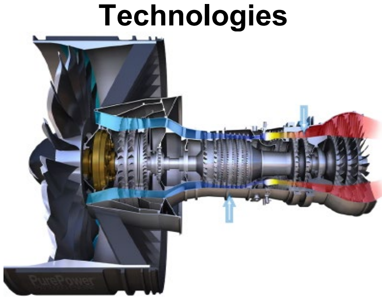
High Pressure Compressor and Turbine Aero-Efficiency Technologies	Description:	Benefits:
	Under CLEEN Phase II, Pratt & Whitney developed and demonstrated technologies for the engine compressor and turbine to improve engine thermal efficiency and reduce fuel burn for Pratt & Whitney geared turbofan engines. The development work focused on advanced aerodynamics, cooling, and durability optimization.	**Fuel**1.4% reduction relative to a state-of-the-art engine

Figure 21: High Pressure Compressor and Turbine Aero-Efficiency Technologies

Under CLEEN Phase II, Pratt & Whitney developed and demonstrated technologies for both the engine compressor and turbine to improve engine thermal efficiency and reduce fuel burn of the Pratt & Whitney Geared Turbofan engines. The development work focused 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 has been incorporated into an engine for both ground and flight test

demonstrations. In 2019 and 2020, Pratt & Whitney completed testing of the turbine technologies at the Pennsylvania State University Steady Thermal Aero Research Turbine facility. Combined, the Pratt & Whitney CLEEN Phase II compressor and turbine technologies are estimated to result in 1.4 percent fuel burn reduction relative to a state-of-the-art engine.

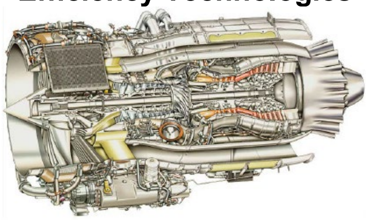
Honeywell Engine Core Efficiency Technologies	**Description:**	**Benefits:**
	Under CLEEN Phase I, Honeywell developed and demonstrated engine core technologies that increase engine efficiency and reduce engine weight. The technologies include a high temperature impeller, low leakage air seals, and advanced materials.	**Fuel:** 15.7% overall reduction in fuel burn when combined with complementary engine upgrades.

Figure 22: Honeywell Engine Core Efficiency Technologies

Under CLEEN Phase I, Honeywell developed and demonstrated engine core technologies that increase engine efficiency and reduce engine weight. 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 that were developed outside of the CLEEN Program, the technologies offer a 15.7 percent overall reduction in fuel burn relative to current engine designs.

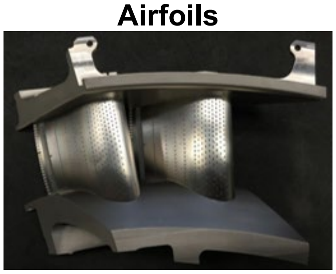
Dual Wall Turbine Airfoils	**Description:**	**Benefits:**
	Under CLEEN Phase I, Rolls-Royce developed and demonstrated Dual-Wall Turbine Airfoil technology aimed at increasing thermal efficiency in the turbine section of the engine. Dual-wall turbine airfoils are projected to provide 20% or more reduction in cooling and increased operating temperature capability.	**Fuel:** Greater than 0.3% reduction

Figure 23: Dual Wall Turbine Airfoils

Under CLEEN Phase I, Rolls-Royce developed and demonstrated Dual-Wall Turbine Airfoil technologies aimed at increasing thermal efficiency in the turbine section of the engine, thereby reducing fuel burn. 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.

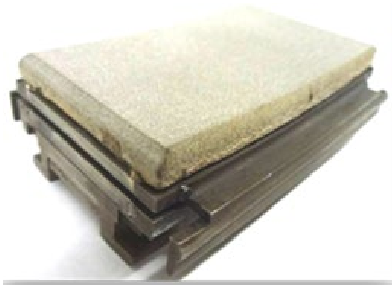
CMC Turbine Blade Tracks	Description:	Benefits:
	Under CLEEN Phase I, Rolls-Royce developed and demonstrated CMC Black Track technology aimed at increasing thermal efficiency in the turbine section of the engine. The blade tracks offer more than a 50% reduction in engine cooling and weight savings compared to a metallic design.	**Fuel:** Greater than 0.4% reduction

Figure 24: CMC Turbine Blade Tracks

Under CLEEN Phase I, Rolls-Royce developed and demonstrated CMC Blade Track technologies aimed at increasing thermal efficiency in the turbine section of the engine, thereby reducing fuel burn. In 2013 and 2014, engine testing of the CMC Blade Track validated the technology's performance and benefits.

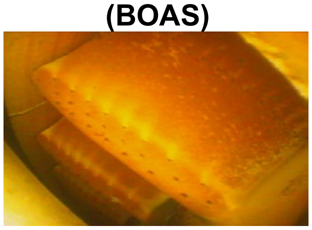
Advanced Turbine Blade Outer Air Seal (BOAS)	Description:	Benefits:
	Under CLEEN Phase II, Honeywell's advanced turbine BOAS increases high pressure turbine efficiency, resulting in reduced fuel burn. The technology leverages advanced light-weight, high-temperature materials and coatings and is designed to minimize leakage between shroud and advanced turbine blade tip.	**Fuel:** 22% reduction when combined other technologies

Figure 25: Advanced Turbine Blade Outer Air Seal

Under CLEEN Phase II, Honeywell developed and demonstrated an advanced turbine BOAS. Honeywell's advanced turbine blade outer air seal increases high pressure turbine efficiency, resulting in reduced fuel burn. The BOAS and advanced combustor technology (described below) contribute to an engine level improvement of greater than 22 percent fuel burn reduction relative to a baseline engine. In 2020, Honeywell initiated ground engine test of the turbine shroud for the BOAS system. Final engine testing of a high temperature capable blade alloy was completed in 2022.

Advanced High Pressure Compressor	Description:	Benefits:
	Under CLEEN Phase II, Honeywell is developing advanced axi-centrifugal high pressure compressor technologies. These include high efficiency axial stages and an expanded temperature capability impeller (building upon CLEEN Phase I successes).	**Fuel:** Additional 1% reduction on top of other CLEEN Phase II Honeywell technologies

Figure 26: Advanced High Pressure Compressor

Under an optional expansion to its CLEEN Phase II work, Honeywell developed and demonstrated advanced high pressure compressor technologies for both the axial and centrifugal stages of its compressor. These technologies aim to improve the efficiency of the axial stages and the temperature capability of the centrifugal stage (impeller). The impeller work built upon successful development of improved components under CLEEN Phase I. These technologies completed a final TRL 6 engine test in 2022.

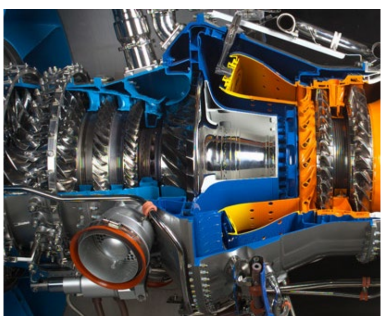
Efficient Green High Pressure Core	Description:	Benefit:
	Under CLEEN Phase III, Honeywell is developing advanced high pressure compressor, low emission combustor, and efficient high pressure turbine technologies for next generation business jet aircraft	**Noise:** 3 EPNdB reduction **Fuel:** 8.3% fuel burn reduction **Emissions:** 70% margin to CAEP/8 NO_X standard and 70% reduction in nvPM

Figure 27: Efficient Green High Pressure Core

Under CLEEN Phase III, Honeywell is maturing a suite of engine core technologies under the efficient green high pressure core project. For the high pressure compressor, this includes co-optimization of aero-efficiency and noise characteristics. The combustor is being designed to reduce both NOx and nvPM emissions, addressing both CLEEN Phase III emissions goals. Finally, advances in the high pressure turbine will improve efficiency and reduce weight using aerodynamic design techniques and improved materials. These technologies will be matured through ground engine test in the later years of the program.

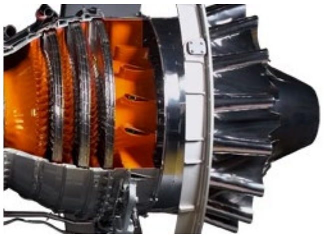
High Work High Lift Low Pressure Turbine (LPT)	Description:	Benefit:
	Under CLEEN Phase III, Honeywell is developing technologies for a reduced weight, more efficient and quieter low pressure turbine for future business jet class aircraft.	**Noise:** 0.5 EPNdB **Fuel:** 2.5% fuel burn reduction

Figure 28: High Work High Lift LPT

Under CLEEN Phase III, Honeywell is maturing technologies to support an engine LPT with improved efficiency, reduced weight, and reduced noise. Application of new advanced aerodynamic and acoustic designs will support these environmental objectives. Honeywell's approach will build from rig testing to full ground engine test, aligning with the other Honeywell CLEEN Phase III technologies.

Low Emissions Combustors

The FAA CLEEN Program has been working with a number of industry partners to develop improved combustor technologies to reduce engine emissions while avoiding negative impacts on fuel efficiency.

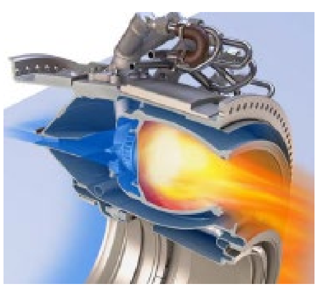
Twin Annular Premixing Swirler (TAPS) II Combustor	Description:	Benefits:
	Under CLEEN Phase I, GE's TAPS combustor concept is a low emissions, lean burn system. For TAPS II, GE scaled TAPS wide-body technology to narrow-body applications, made additional design improvements to meet the CLEEN NOx emissions goal, and demonstrated the design in full annular and core engine testing.	**Emissions:** More than 60% below CAEP/6 NO_X standard

Figure 29: Twin Annular Premixing Swirler (TAPS) II Combustor

GE's unique lean-burn combustion system, TAPS, is designed to pre-mix air and fuel prior to combustion for leaner burn and fewer emissions than conventional combustion systems. The TAPS combustion was introduced on the GEnx engine for the Boeing 787 Dreamliner and the 747-8 aircraft. GE adapted and enhanced this combustor to create TAPS II for CFM International's LEAP engine in narrow-body aircraft. 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 and exceeding the CLEEN Phase I goal.

Twin Annular Premixing Swirler (TAPS) III Combustor	**Description:**	**Benefits:**
	Under CLEEN Phase II, GE conducted extensive rig test validation and development of risk mitigation technologies for the TAPS III low emissions combustor, thus enabling the technology to meet the CLEEN II NO_x target.	**Emissions:** 35 percent reduction relative to CAEP/8 NO_X standard (55 OPR)

Figure 30: Twin Annular Premixing Swirler III Combustor

Under CLEEN Phase II, GE further developed the next generation TAPS combustor, TAPS III, and achieved TRL 6 emissions demonstration of the TAPS III combustion system. The TAPS III combustion system is being implemented in the GE9X-powered Boeing 777X, replacing the GE90-powered Boeing 777, expected to enter into service in 2025, and enables NOx emissions to be 30% below international CAEP standards. The GE9X with the TAPS III combustor was successfully certificated in 2020.

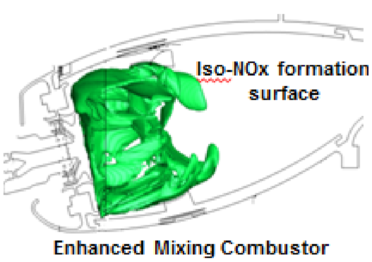
Advanced Low NOx Combustion System	**Description:**	**Benefits:**
	Under CLEEN Phase II, Rolls-Royce's advanced Rich-Quench-Lean (RQL) combustion system employs advanced fuel injection and mixing technologies that will provide significant emissions reduction while simultaneously enabling the increase in turbine entry temperature required by advanced engine cycles.	**Emissions:** 40 to 65% below CAEP/8 NO_X standard

Figure 31: Advanced Low NOx Combustion System

Under CLEEN Phase II, Rolls-Royce has developed and demonstrated low emissions combustor technology, while also testing alternative fuels. Rolls-Royce's advanced 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 engines' thermodynamic cycles. The project demonstrated 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 also conducted alternative fuels testing to support ASTM approval of novel fuels. In 2020 and early 2021, final testing of the third generation combustor design was completed.

Compact Core – Low Emissions Combustor	Description:	Benefit:
	Under CLEEN Phase III, GE Aviation is developing combustor technology that will result in reduced NOx emissions.	**NO_X:** Targeting NOx reduction for a future high overall pressure ratio engine cycle, equivalent to 70% margin to CAEP/8 standard at 30 OPR.

Figure 32: Compact Core – Low Emissions Combustor

Under CLEEN Phase III, GE Aviation is developing combustor technology to achieve a reduction in NOx emissions while also reducing non-volatile particulate matter emissions. Engine manufacturers will need to balance these environmental goals with next generation narrow-body objectives for operability, cruise efficiency, and component durability. GE will manufacture and conduct component rig tests to evaluate operability, performance, and emissions of different combustor technology designs.

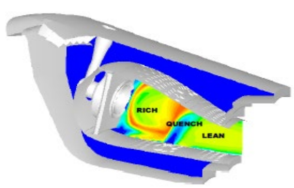
Compact Combustor System	Description:	Benefits:
	Under CLEEN Phase II, Honeywell is developing a compact low emissions combustor that uses advanced aerodynamics and fuel injection technologies to reduce engine NO_x emissions while reducing weight, which reduces fuel burn.	**NO_X emissions:** improved NO_X emissions of 2X relative to current state-of-the-art **Fuel:** 22% reduction when combined with other fuel burn technologies

Figure 33: Compact Combustor System

Under CLEEN Phase II, Honeywell is developed and demonstrated a compact, low emissions combustor. The compact low emissions combustor uses advanced aerodynamics and fuel injection technologies to reduce engine NO_X and particulate matter emissions while reducing weight, which reduces fuel burn. The BOAS and advanced combustor technology (described above) contribute to an engine level improvement of greater than 22 percent fuel burn reduction relative to a baseline engine. Additionally, the advanced combustor technology achieves a factor of two improvement in NO_X margin relative to Honeywell's state-of-the-art combustor. In 2021 and 2022 Honeywell completed engine testing of the advanced combustor design, as well as combustor rig testing with NASA.

The low emissions combustor development work, conducted under CLEEN Phases I and II across GE, Honeywell, and Rolls-Royce projects, results not only in emissions reductions for the specific combustors developed under the program, but enhances each company's ability to design and optimize all future engine combustion systems for low emissions.

TALON X+ Combustor	Description:	Benefit:
	Under CLEEN Phase III, Pratt & Whitney is developing an advanced combustion system based on the TALON X that will simultaneously reduce noise and emissions, while improving the temperature pattern factor and enabling improved high pressure turbine design and efficiency.	**Noise:** Target 3 EPNdB noise reduction combined with P&W fan technology **Fuel:** 0.8% fuel burn as part of package with P&W fan technology **NO_X Emissions:** deliver 50% margin to CAEP/8 standard

Figure 34: TALON X+ Combustor

Under CLEEN Phase III, Pratt & Whitney, is optimizing its TALON X+ combustion system using new swirler designs and cooling design alternatives. The technology will reduce combustor noise, reduce emissions and provide improved pattern factor to the high-pressure turbine, yielding fuel burn benefits. Pratt & Whitney will mature this technology through rig and engine tests.

Protective Engine Coatings

The FAA CLEEN Program has been working with an airline and a coatings manufacturer to develop new coatings to keep engine components at higher efficiencies for longer periods of time, reducing fuel burn from the current fleet.

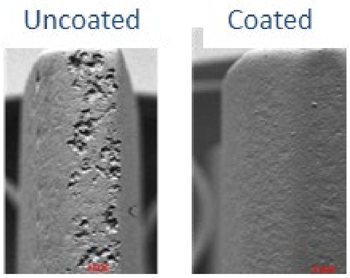
Leading Edge Protective Blade Coatings	**Description:**	**Benefits:**
	Under CLEEN Phase II, MDS Coating Technologies, America's Phenix, and Delta TechOps developed and demonstrated a protective leading edge coating for gas turbine engine fan blades. This coating protects against fan blade erosion, a source of lost aerodynamic efficiency in engines in service.	**Fuel:** up to 0.4% fuel savings during aircraft cruise and over 1% savings at maximum power

Figure 35: Leading Edge Protective Blade Coatings.

Under CLEEN Phase II, MDS Coating Technologies, America's Phenix, and Delta TechOps worked as a team to develop and flight test a protective leading edge fan blade coating to reduce erosion and maintain fuel efficiency. The team installed coated blades on-wing and conducted a flight service evaluation of the technology, accumulating thousands of operational hours that confirmed the coating's significant benefits.

Particulate & Fluid Erosion-Resistant Fan Blade Coating for Expanded Applications	Description:	Benefits:
	Under CLEEN Phase III, the team of Delta TechOps, GKN Aerospace, MDS Coating Technologies and America's Phenix, is developing erosion resistant fan blade coatings for various engine applications. The coatings protect the fan blade's leading edge against particulate and fluid erosion; thus, retaining engine performance, reducing fuel consumption and lowering emissions over an engine's operational tour.	**Fuel:** 1% or greater fuel burn reduction and corresponding reduction in greenhouse gas emissions via retaining engine performance over an engine's operational tour.

Figure 36: Particulate & Fluid Erosion-Resistant Fan Blade Coating for Expanded Applications

Under CLEEN Phase III, the team composed of Delta TechOps, GKN Aerospace, MDS Coating Technologies, and America's Phenix is building upon the successes of the CLEEN Phase II test and evaluation and flight demonstration program to expand the coating application to new, used and repaired fan blades across airline fleets. The coating applications will include high and low aspect ratio fan blades, both solid and hollow fan blades, and blades with titanium leading edge strips. The team will demonstrate the coating at TRL-7 by applying the coating on a production-type basis. During flight demonstration, the team will monitor up to three engines for each of the various turbofan blade configurations previously described. The coating's ability to protect the turbofan blades' leading edge helps maintain engine performance throughout an engine's operational tour, resulting in reduced fuel consumption of 1% or greater with corresponding reductions in greenhouse gas emissions.

e. NASA Gas Turbine Propulsion Technology

NASA's Advanced Air Vehicles Program's Advanced Air Transport Technology Project is focused on advancing gas turbine power generation efficiency while reducing the physical core size. The reduced size facilitates efficient propulsion/airframe integration for conventional or electrified aircraft propulsion systems and results in increased energy efficiency and reduced emissions. The research conducted addresses the challenges of enabling reduced size/flow high pressure compressors and high temperature disk/seals that are critical for 50+ overall pressure ratio (OPR) gas generators with minimal impact on noise and component life. Specific research is targeting hot section materials (1500 degrees Fahrenheit for hybrid disk and coatings, and non-contacting seals) and high pressure compressor technologies for high OPR engines targeting rear block designs and casing treatments. These technologies will contribute to advancing compact gas-generator core architectures and component technologies enabling bypass ratio (20+) growth by minimizing core size for thermally efficient, high OPR (50+) engines to reduce fuel burn and emissions.

The research also directly addresses the challenges of low NOx, fuel-flexible combustion with concepts and technologies focused on reducing NOx emissions from fuel-flexible combustors to 80 percent below the CAEP6 standard with minimal impacts on weight, noise, and component life. The research focuses on lean-burn combustion concepts suitable for small core engines, and exploration of active combustion control. The advanced core engine technology will be critical in both gas-turbine and electrified (hybrid or turboelectric) propulsion futures.

The NASA research has been advancing technology readiness and setting the stage for upcoming integrated engine system demonstrations.

f. FAA CLEEN Aircraft Engine System Integration

The FAA CLEEN Program has been working with GE to develop technologies to reduce fuel burn through better integration of the engine and electric systems with the flight management system enabling the aircraft to perform more efficiently through the entire mission.

More Electric Systems and Technologies for Aircraft in the Next Generation (MESTANG)	Description:	Benefits:
	Under CLEEN Phase II, MESTANG is an integrated aircraft power system designed to support future “more-electric” aircraft architectures that optimizes new power extraction, generation, distribution, and conversion systems.	**Fuel:** up to 6% reduction for single-aisle aircraft on short flights

Figure 37: More Electric Systems and Technologies for Aircraft in the Next Generation

Under CLEEN Phase II, GE developed More Electric Systems and Technologies for Aircraft in the Next Generation (MESTANG), an integrated aircraft power system designed to support future “more-electric” aircraft architectures. The MESTANG technologies under CLEEN Phase II may reduce fuel burn by up to 6 percent for single-aisle aircraft. In 2020, GE completed a full scale ground test of the system, reaching TRL 6 and completing technology maturation for this project.

MESTANG III	Description:	Benefit:
	Under CLEEN Phase III, GE Aviation is developing more electric aircraft systems that will reduce fuel burn by requiring reduced engine bleed air.	**Fuel:** 3-6% reduction for mid-size aircraft

Figure 38: MESTANG III

Under CLEEN Phase III, GE Aviation is developing a third phase of the MESTANG technology. The objective of this effort is to replace pneumatic systems with electric powered systems that reduce fuel burn by reducing bleed air requirements on the engine. This project will focus on maturing a 90kW starter/generator, building off of prior work conducted under CLEEN Phase II. GE will conduct requirements definition, design, and manufacturing of a first prototype starter/generator targeting regional, turboprop, and business jet applications.

Hybrid Electric Integrated Generation	Description:	Benefit:
	Under CLEEN Phase III, GE Aviation is developing an integrated electric power generation system within the engine to enable flexibility in electric power generation and optimize engine performance.	**Fuel:** 3-4% reduction

Figure 39: Hybrid Electric Integrated Generation

Under CLEEN Phase III, GE Aviation is developing integrated electric power generation systems within the engine to enable flexibility in electric power generation and optimize engine performance. This will enable significant operating benefits to the engine including improved operability, improved engine performance, and increased flexibility in off-design operating modes. Under CLEEN Phase III, GE will conduct trade studies to determine the optimal location for a motor/generator and will build a prototype.

Advanced Thermal Management	Description:	Benefit:
	Under CLEEN Phase III, GE Aviation is developing advanced thermal management and waste heat recovery systems to facilitate compressor and turbine temperature increases, thereby improving cycle efficiency and reducing fuel burn.	**Fuel:** Up to 3% reduction relative to traditional architectures

Figure 40: Advanced Thermal Management

Under CLEEN Phase III, GE Aviation is developing advanced thermal management systems such as cooled cooling air and heat recuperation. GE will complete conceptual mechanical and thermal design work for the system elements including a fuel de-oxygenation system, heat exchangers, a thermal transport bus, modern controls, and an associated fuel system. This design work will be conducted in support of future demonstration in a static engine test.

g. More Electric Aircraft

Current aircraft use hydraulic systems that are based on mature technology. Potential improvements to the efficiency of these systems would be negligible compared to the improvements from electrical technology. The hydraulic system uses central electric pumps that generate hydraulic pressure through tubing that stretches from the engine nacelles, across the firewall, through the pylons, and into the wheel wells, wings, and throughout the entire fuselage. Each of the hydraulic systems requires pressure and return lines plus a case drain for the pumps. These systems are usually triple-redundant, with the tubing protected against the flammable liquids within the hydraulic system. All of this protection, redundancy, and tubing adds weight to the aircraft.

To improve aircraft efficiency, reliability, and maintainability, the aerospace industry has found that progressive electrification of on-board services reduces or removes the need of the hydraulic, mechanical, and the bleed air/pneumatic systems. This concept, called more electric aircraft, involves the introduction of electromechanical actuators and electro-hydraulics actuators for the actuation of the flight surfaces of wide-body aircraft, moving from fly-by wire to the power-by wire concept. The more electric aircraft enables simpler structural solutions with fewer heat shields and less flammable-fluid protection needed throughout the airplane. This simplification results in lighter aircraft, lower complexity, and fewer certification requirements for the structure of the plane.

The resulting step change in aircraft electrical loading will have far-reaching implications for the electrical generation system. Considerable effort is directed towards realizing the so-called more electric engine, which foresees an integration of the electrical generator directly inside the main gas turbine engine. Also, the entire electrical distribution system is subject to radical revisiting, with a trend that is leaving the constant frequency alternating current energy distribution in favor of variable frequency or direct current solutions. The more electric aircraft trend increases the technical challenges and research topics for the electrical engineering in the aeronautic applications.

h. NASA Electrified Aircraft Propulsion

Advanced electric systems synergistically integrated with gas turbine engines can provide electrical power for a portion of aircraft thrust, resulting in increased energy efficiency and reduced emissions. NASA is placing significant emphasis on advancing electrified aircraft propulsion from small, vertical flight aircraft through transport class aircraft. The goal is to enable a paradigm shift from pure gas-turbine technology to electric technology, and enable new benefits in fuel/energy consumption, emissions, noise, and other considerations such as maintenance costs.

NASA research and development continues to focus on a range of hybrid gas-electric and turbo-electric propulsion challenges including propulsion system conceptual design, integrated subsystems, high efficiency/power density electric machines, flight-weight power systems and electronics, and enabling materials. The focus is on megawatt-class hybrid systems, including 2-3MW powertrains, for mid-term (2025-35) application with near term spin-offs, and far term research targeting 5-10 MW hybrid gas-electric propulsion systems.

NASA's research bridges gas turbine and electrified aircraft propulsion by developing an understanding of high power extraction from a dual spool turbine engine. NASA is focused on developing technologies that will enable its use for electrified airplanes – whether for use in propulsion or other aircraft systems.

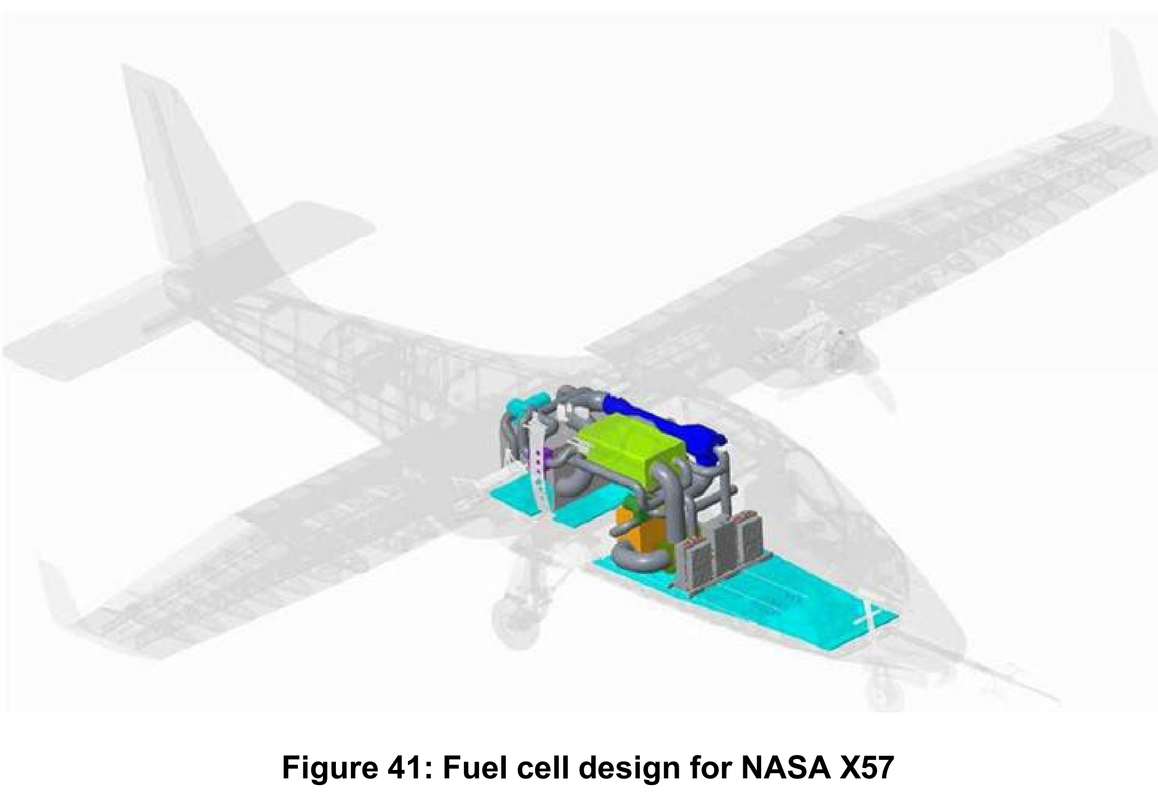


Figure 41: Fuel cell design for NASA X57

NASA is developing and testing the all-electric X57 Maxwell aircraft A Tecnam P2006T.

The aircraft is being converted into the first manned X-plane to feature a distributed electric propulsion system. Much is being learned and shared with the aviation community from the electrical component level, to thermal management and electromagnetic interference to aircraft level integration. All of the research results are public information, and are being used by standards setting committees to address this new technology. Additional plans also include partnerships with industry to flight test integrated hybrid-electric propulsion systems on larger aircraft to study and demonstrate system level integration challenges in flight and advance technology readiness level for regional to single aisle transport aircraft applications.

NASA has also developed and made operational a unique test facility known as the NASA Electric Aircraft Testbed (NEAT) facility. The NEAT is being used by NASA, industry, and other government agencies for component to system integration level research, development, test, and evaluation, in addition to risk reduction prior to flight tests. The NEAT facility continues to expand in capability.

i. FAA CLEEN Aircraft Systems Technologies

Flight Management System (FMS) Technology	Description:	Benefit:
	Under CLEEN Phase I, GE completed ground engine and flight tests of FMS-Engine integration technologies that use knowledge of aircraft state and engine health to optimize performance. Under CLEEN Phase II, GE's FMS software algorithms will optimize aircraft performance during the cruise and descent phases of flight.	**Fuel:** CLEEN Phase I - up to 2.5% reduction CLEEN Phase II - Up to 3.5% reduction relative to legacy systems

Figure 42: Flight Management System Technology

Under the first phase of CLEEN, GE developed a suite of controls and engine health management technologies that leverage the information from various engine and aircraft states (e.g., engine condition, flight stages, and external conditions) to improve aircraft fuel efficiency. These technologies have a potential to reduce fuel consumption by more than 1 percent in current and future aircraft engines. Some of these technologies are implemented into the CFM LEAP-powered Airbus A320neo and the Boeing 737 MAX and the Passport 20-powered Bombardier Global 7500. One of these technologies will be implemented on the GE9X-powered Boeing 777X, replacing the GE90-powered Boeing 777, expected to enter into service in 2025. These technologies are also implemented in various military applications.

Under CLEEN Phase II, GE Aviation developed new control policies for the Flight Management System (FMS) to optimize aircraft trajectories. These enhancements incorporate detailed weather forecast data to develop fuel-optimal fight profiles and provide guidance to pilots and the FMS on how to execute them, resulting in a potential one percent fleetwide average improvement in fuel burn. GE currently is working to incorporate these technologies in future products.

Quiet Landing Gear	Description:	Benefit:
	Under CLEEN Phase III, Boeing is developing acoustically treated landing gear doors and aerodynamic shields to reduce aircraft noise**.**	**Noise:** Up to 0.5 EPNdB noise reduction

Figure 43: Quiet Landing Gear

Under CLEEN Phase III, Boeing is developing acoustically treated landing gear doors, and aerodynamic shields for landing gear structures to reduce aircraft noise. The technologies will be prototyped and demonstrated in flight.

Intelligent Operations	Description:	Benefit:
	Under CLEEN Phase III, Boeing is developing noise-optimized flight path algorithms with integration into the Air Traffic Management System.	**Noise:** 3-5 dBA peak noise reduction **Fuel:** 2% fuel savings during take-off; 5% during approach phase

Figure 44: Intelligent Operations

Under CLEEN Phase III, Boeing is developing new “intelligent operations” with real-time, noise-optimized flight path algorithms derived from on-board, and ground-based inputs through the FAA Data Communications system. New algorithms for departure and arrival flight paths will be implemented and demonstrated in flight.

2. Innovative materials

Advanced materials and manufacturing technology enable lighter weight structures. This can enable more aerodynamically efficient airframe structural shapes than conventional cylindrical fuselages without an offsetting weight increase, resulting in fuel efficiency benefits.

Many of the advanced aircraft technology projects explained in section 1 leverage innovative materials to realize benefits in specific technical applications. The efforts described here are complementary and focused specifically on advancing the state of the art for composites and advanced metallics.

a. Composites

The FAA and NASA have collaborated on NASA's advanced composites program. The project focuses on reducing the time to develop and certify composite materials and structures, helping American industry retain a global competitive advantage in aircraft manufacturing with a goal to reduce product development and certification time by 30 percent. The program focuses on advanced tools and processes for existing material systems and addresses the following areas:

- **Accurate Strength & Life Prediction**: Develop validated strength and life prediction tools with known accuracy for complex composite structures and standardized procedures for their reliable use.
- **Rapid Inspection & Characterization**: Develop and demonstrate systems and enabling technologies to fully inspect and rapidly disposition findings in complex composite structures.

Efficient Manufacturing Process Development: Develop and demonstrate new computational methods to relate manufacturing parameters to defect formation, and also connect to commercial design and analysis software to allow structural optimization while resolving predicted manufacturing issues.

NASA has recently initiated the new high-rate aircraft composites manufacturing project (HiCAM) to focus on faster development of composite aircraft with a focus on manufacturing rate, along with weight and cost. The project will down select to the most promising technology for a large-scale demonstration and transfer the results to industry.

b. Advanced Metallics

FAA and NASA are also conducting research and development for advanced metallics. These projects include:

- **Advanced Alloys:** In the last five years, over 20 new aluminum-lithium (Al-Li) alloys (third generation) have been introduced and qualified for major airframe applications, having lower densities and improved properties over conventional metallic alloys. These weight saving aluminum alloys will help in the overall fuel efficiency of future aircraft designs.

- **Advanced Welding and Joining:** Advances in welding and joining are providing many opportunities for improved structural performance and weight savings with the reduction of bolted or riveted joints in aircraft structures. In particular, the friction welding process allows for many combinations of metallic alloys and the ability to build damage tolerant hybrid structures or so-called functionally gradient materials. Laser beam welding is being used in the construction of skin-stringer panels for the A319, A340, and A380 that improve corrosion resistance and reduce manufacturing cost and weight by 20 percent and 10 percent, respectively. As with monolithic structures, there are concerns with the lack of multiple separate load paths and crack-arrest features, which may reduce damage tolerance compared to the conventional built-up structure.

- **Bonded and Hybrid Structures:** Fiber-metal laminates have demonstrated better fatigue crack growth performance compared to conventional aluminum alloys. Adhesive-bonded metallic structures offer many advantages to riveted assemblies, including reduced weight and cost, improved fatigue resistance, and efficient aerodynamics. The program objectives are to characterize the fatigue and damage tolerance performance of bonded repairs subjected to a simulated service load and to evaluate the limit load capability of a typical composite wing panel of transport category aircraft with a failed repair.

3. Alternative Jet Fuels

The first two 5-year phases of CLEEN, along with the ASCENT Center of Excellence[14] and the CAAFI, [15] have been instrumental to the certification and qualification of alternative jet fuels for safe use by civil transportation. This testing and evaluation process is conducted in coordination with ASTM International, which manages specifications for jet fuels used by the industry. These combined efforts have led to the approval of seven fuel types for use by civil aviation.

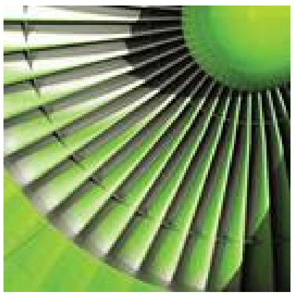
Alternative Jet Fuels	Description:	Benefits:
	Boeing, Honeywell, GE, Pratt & Whitney, and Rolls-Royce have evaluated a range of Alternative Jet fuels under the first and second phases of the CLEEN Program, demonstrating viability and acceptability of these fuels as alternatives to petroleum derived jet fuel.	Promotes the development, approval, and deployment of viable renewable alternative fuels for aerospace gas turbine engine applications. Offers potential to reduce aerospace environmental impact and increase energy security.

Figure 45: Alternative Jet Fuel Projects

Fuel characterization and qualification testing for alternative jet fuels under CLEEN and ASCENT consists of fuel property evaluations and component, rig, and engine tests covering material compatibility, combustion performance, and full engine operability.

At present, the FAA is supporting the certification of new fuels through the ASCENT Center of Excellence D4054 Clearing House at the University of Dayton Research Institute.[16] The clearing house supports coordinated testing, evaluation, and review of alternative fuels for approval by ASTM International. This includes efforts being done by industry through the CLEEN Program as well as other projects on fuel testing being done by the ASCENT COE.[17]

[14] For more information on the ASCENT Center of Excellence, please visit https://ascent.aero/.

[15] For more information on CAAFI, please visit http://caafi.org/

[16] For more information on the ASCENT Center of Excellence D4054 Clearing House at the University of Dayton Research Institute, please visit https://ascent.aero/project/alternative-jet-fuels-test-and-evaluation-a/

[17] For a list of sustainable aviation fuel projects in ASCENT, please visit https://ascent.aero/topic/alternative-fuels/

CLEEN Phase I and II Alternative Jet Fuel Activities

Under CLEEN Phase I, Boeing, Honeywell, Pratt & Whitney, and Rolls-Royce supported evaluation, fuel characterization and qualification testing for alternative jet fuels.

In 2011, Honeywell completed testing of Hydro-Processed Esters and Fatty Acids (HEFA) fuel, which expedited its approval through ASTM International. HEFA was added to the ASTM International fuel specification in July 2011 for use up to a 50% blend level with conventional jet fuel.

In 2013, Boeing completed evaluations on the effects of HEFA and HEFA blends with conventional jet fuel on non-metallic materials used in commercial aircraft fuel systems. This testing focused on the effects of HEFA on seals within fuel systems, furthering the understanding of key fuel properties that ensure new fuels are drop-in ready with existing and future aircraft fuel systems.

In 2015, Pratt & Whitney completed a series of tests in support of ASTM International approval on a range of alternative jet fuels including: Amyris Direct Sugar to Hydrocarbon Farnesane, Kior Hydrotreated Depolymerized Cellulosic Jet, Applied Research Associates (ARA) Catalytic Hydrothermolysis Jet, and Swedish BioFuel alcohol-to-jet synthetic kerosene with aromatics. This effort tested fuels produced from a wide range of feedstocks, supporting the desire to have a diverse supply of fuels. The data from these tests contributed to the approval of two new alternative jet fuel pathways to the ASTM International specification.

In 2015, Rolls-Royce completed rig testing to understand the performance of fuel system seals and materials in the presence of different jet fuels. The program characterized the impact that various alternative fuels, under realistic engine conditions, had on the sealing force performance of elastomers. The data generated supports the ASTM International approval of a fully synthetic jet fuel. Rolls-Royce’s work on seal performance has continued under CLEEN Phase II.

Under CLEEN Phase II, GE and Rolls-Royce have advanced the understanding of alternative jet fuels, with a focus on advancing additional fuel approvals, including exploration of fully-synthetic options.

GE has conducted combustor rig testing of alternative jet fuels under CLEEN Phase II. This included testing of alcohol to jet synthetic paraffinic kerosene (ATJ-SPK) produced by Gevo Inc., a blend of high freeze point hydroprocessed esters and fatty acids (HFP-HEFA) with petroleum jet fuel produced by Neste Oil, and Virent’s Hydro-deoxygenated Synthetic Aromatic Kerosene. Data from GE’s CLEEN Phase II testing supported the 2018 approval of higher blend levels for use of ATJ-SPK fuels. The results of GE’s SAF testing have also supported streamlining of the fuel approval process by validating that a non-proprietary combustor rig, developed under the National Jet Fuels Combustion Program and supported by ASCENT, can capture key characteristics of different combustion systems from various engine manufacturers.

Rolls-Royce’s robust evaluation program characterized the performance of a fully-synthetic Alcohol-to-Jet fuel under representative gas turbine engine conditions as a viable alternative to conventional jet fuel. This was accomplished through a series of laboratory and burner rig tests, ensuring the candidate fuel will have no negative impact on engine safety, durability, or performance. Rolls-Royce’s CLEEN Phase II efforts have helped advance the understanding of fully-synthetic alternative jet fuels.

CLEEN Phase III Alternative Jet Fuel Activities

CLEEN Phase III will continue supporting testing and qualification of new alternative jet fuels, with a focus on supporting greater than 50% blend levels of these fuels. These efforts reflect the desire of the aviation industry to use 100% alternative jet fuel without the need to blend with conventional jet fuel. The following sections describe planned alternative jet fuel activities under CLEEN Phase III. As these efforts are beginning, expected outcomes are provided and will be updated as the fuel testing efforts proceed.

Under CLEEN Phase III, Boeing is supporting qualification of alternative jet fuels through lab material compatibility evaluations and flight demonstration. This program will characterize selected new alternative fuel blends and provide test data in support of future ASTM International specifications. Through this effort, Boeing will support continued expansion of certified alternative fuel pathways to promote uptake and sustainability.

GE Aviation will also support alternative jet fuel testing under CLEEN Phase III through several valuable program thrusts. GE will support efforts to qualify new alternative jet fuels with unique chemical compositions, including highly cycloparaffinic fuels. Cycloparaffinic fuels have the potential to provide seal swell benefits that other paraffinic alternative jet fuels lack due to the absence of aromatic compounds. If cycloparaffinic fuels can be shown to provide the necessary seal swell performance as seen in conventional jet fuels, cycloparaffinic fuels would address one of the current barriers that limit paraffinic alternative jet fuels to a 50% blend volume limit. GE testing will characterize combustor operability and emissions impact of the fuels. The planned testing at GE for CLEEN Phase III aims to address additional barriers to support efforts in the alternative fuels community to increase the alternative jet fuel blending limits beyond 50%. Testing results and conclusions will be disseminated to the ASTM International D4054 fuel qualification panel as it provides critical data required as part of the fuel approval process. Additionally, GE Aviation will be exploring best ways to enable standardization of higher blend ratios including 100%.

NASA SAF Activities

In addition to FAA efforts, NASA-led research, development, test, and evaluation has advanced the understanding and use of sustainable alternative fuels. NASA has conducted research on alternative jet fuels in two primary areas. First, NASA has led flight research with national and international partners for the last decade by researching emissions from jet aircraft using a range of alternative fuels and comparing with conventional jet fuel. These tests have measured both gaseous emissions and particulate matter content on the ground and in flight at cruise altitudes using instrumented chase planes. The data gathering has been analyzed by the atmospheric science community and informed aviation regulatory organizations who are modifying and/or establishing new standards. The most recent test was a flight campaign led by DLR/Germany in 2018 that built on the last decade of NASA-led flight campaigns.

NASA has tested numerous types of alternative fuels in advanced fuel-flexible combustors in ground facilities to understand and characterize both performance and emissions benefits without losing combustor integrity and maintaining stability. This research has mainly been applicable to subsonic aircraft but a growing interest in supersonic aircraft is on the horizon. Moving forward, as new alternative jet fuels are coming to the market and are in need of certification for both subsonic and supersonic flight regimes, combustion research and testing still remains a need for the future of advancing smaller core, higher pressure ratio engines.

4. Additive Manufacturing

Parts manufactured using Additive manufacturing (AM), commonly known as 3D printing, can contribute to reducing aircraft and engine weight and performance by producing complex shapes that are lighter and with complex geometries that are difficult or impossible to duplicate using conventional manufacturing processes. Metallic AM has seen tremendous research and development investments by industry over the past decade and is incorporated in numerous products subject to FAA certification. While the current number of the AM parts introduced in critical applications on FAA certificated aircraft is limited, all major airframe and engine manufacturers are aggressively pursuing these technologies.

The number of aviation related parts produced using AM is projected to grow exponentially in the next 5 to 10 years. As reported by US Air Force Research Laboratory and industry experts, metal AM is considered to have over 100 process control variables that may affect the mechanical properties of a final part. Comparing it to approximately 10-15 parameters for traditional metal processes (castings, forgings, etc.) explains significant challenges in designing and certifying AM parts. Additionally, the 100+ variables are applied to each unique combination of material and the type of AM technology (laser powder bed, electron beam additive manufacturing, etc.). The AM technologies for metals can generally be broken down into several types by energy source and type of feedstock (e.g., powder vs. wire); however, there is an ever-increasing list of materials that can be used with each of these technology types, including several reinforced materials, effectively similar to composites.

The FAA's research program is focused on collecting data to address certification issues associated with the sources of variability in AM and processes to qualify AM materials, including development of public material databases. Industry is aggressively pursuing AM for critical applications, though no in-service history exists. The research is intended to help the FAA understand the variability of AM which will foster a better understanding of the process required to inspect and approve the materials ensuring the appropriate levels of product safety. For instance, this project will evaluate whether the introduction of special factors, similar to casting factors, is feasible and can sufficiently account for the variability of material properties produced under a publicly available AM specification. The project will also evaluate various AM-specific fatigue and damage tolerance methodologies that may be needed for certification of safety-critical AM parts. As the criticality of AM parts increases to include safety-critical components, the quantitative understanding of microstructural variability and material anomalies and their impact on component performance becomes especially critical, and needs to be reflected in the appropriate fatigue and damage tolerance (F&DT) framework tailored to AM materials. FAA research has helped fund development of the first public polymer AM database, and a new project that is co-sponsored by the FAA and DoD, with NASA involvement, will develop the first public metal AM database.

NASA's Advanced Air Vehicles Program/Advanced Air Transport Technology project has conducted metallic and composites research focused beyond the wing application, and beyond tool applications. Research has included additive manufacturing in the form of electron beam free form fabrication, and is starting to address metallic spin forming. As mentioned above, plans are now being implemented to include growth in advanced composite material systems for high rate, low cost, light weight manufacturing. Several NASA centers also conduct research and development for powder bed fusion materials and technologies.

Many of the advanced aircraft technology projects explained in section 1 leverage additive manufacturing to realize and enhance the benefits of specific technologies.

5. Novel Aircraft Designs

NASA has a long history of leading research to conceive, develop, and analyze advanced, integrated airplane concepts. These concepts typically serve as technology and system collectors investigating what is possible and identifying specific high-risk technology barriers. These vehicle system concepts are compared with current, baseline vehicles and with advanced technology reference vehicles of conventional configuration to help separate technology from configuration benefits. Integration of airframe and propulsion systems is a first-order challenge for advanced conventional and alternative airplane concepts.

Novel vehicle integration of airframe and propulsion systems enabled by subsystem advances leads to unconventional configurations both inside and out, and results in overall energy efficiency benefit and potential noise reduction. NASA continues to study a range of advanced subsonic transport concepts using noise, emissions, and fuel/energy consumption as primary metrics. Examples include:

- Hybrid-wing body class that includes versions with and without empennages, with over the body or over the wing propulsion installations with potentially substantial noise reductions through acoustic shielding.

- Transonic Truss Braced Wing based concepts that leverage the TTBW technology itself that offer fuel/energy/emissions/noise benefits, though noise benefits are less than typical for a hybrid-wing body aircraft. The truss-braced wing configuration does offer the potential of space for larger, more efficient engines, and manufacturing benefits associated with high wings.

Figure 46: TTBW Concept with Tailcone BLI

- Various concepts such as the Aurora D8 (double bubble) and the NASA Single-aisle Turboelectric Aircraft with an Aft Boundary-Layer (STARC-ABL) incorporate forms of Boundary-Layer Ingesting propulsion systems. There are challenges being addressed in configuration integration for BLI systems for overall benefit in addition to research focused on necessary distortion tolerant fans needed for such installations.

- Various concepts such as the NASA STARC-ABL are exploring the potential of aircraft designs enabled by electrified aircraft propulsion that may allow distributed propulsion concepts and multiple propulsors being driven by single core/power sources.

6. Novel Flight Planning

Section 742 (a)(2)(B) of the Act requires that the FAA review novel flight pattern planning and communications systems that may reduce aircraft taxiing and airport circling. While airport circling is no longer common practice in the U.S. National Airspace System (NAS), the FAA has numerous investments under the NextGen program which are focused on reducing flight delays, improving efficiency, and reducing taxi times.

a. Performance Based Navigation

Performance Based Navigation (PBN) flight procedures have been rolled out across the NAS, leveraging satellite-enabled aircraft technology to create precise, repeatable, predictable, and efficient 3-D flight paths. In many cases, PBN procedures save on distance flown, resulting in less fuel being used. Metroplex projects have completed implementation of airspace optimization in nine major metropolitan areas across the

U.S. In total, more than 9,600 PBN routes and procedures are now in place across the country.

b. Communications Systems Advancements

The FAA has deployed Data Communications (Data Comm) at 62 air traffic control towers in the NAS. Tower Data Comm provides a digital link between controllers' ground systems and the aircraft for communication of air traffic clearances, instructions, and a variety of other functions. Its use saves time, reducing delays and fuel consumption. As of January 2020, 1.4 million minutes of delay and 2.07 million minutes of communication time have been saved because of tower Data Comm's implementation.

A second phase of Data Comm provides digital communications between en route traffic controllers and aircraft, and is being rolled out across the NAS to deliver these benefits to the cruise phase of flight.

c. Surface Management Improvements

Terminal Flight Data Manager (TFDM) is a NextGen system that improves surface management efficiency on the airport surface. TFDM provides automation to current, manually-intensive operations and replaces critical, outdated systems in the NAS. TFDM shares electronic data between controllers, air traffic managers, aircraft operators, and airports. It enables stakeholders to more efficiently stage arrivals and departures and manage surface traffic flow. Rather than have airplanes push back early and wait in line on taxiways, TFDM will help manage constraints on the airport surface. It can advise an aircraft to remain at the gate and allow each airline to calculate predicted departure times and improve fuel consumption by reducing taxi time. TFDM is expected to be deployed across the NAS over the next few years.

d. NASA Airspace Technology Demonstrations

NASA-FAA collaboration extends to air traffic operational research as well. NASA's Airspace Operations and Safety Program has engaged in multiple Airspace Technology Demonstration (ATD) projects, working with the FAA and industry to develop cutting edge operational concepts for air traffic management. Most relevant to this review is ATD-2, in which NASA has developed an integrated arrival, departure, and surface (IADS) concept and technology to demonstrate the benefits of an IADS traffic management system for complex airport terminal environments.

NASA's ATD-2 IADS system has been demonstrated operationally at Charlotte Douglas International Airport, improving the efficiency of surface operations through time-based control of departures and improved sharing of flight operations information among the various airport surface stakeholders. ATD-2 research has been key to early development and risk reduction of the FAA TFDM system.

e. NextGen Benefits To Date

From 2010 to 2019, implemented NextGen capabilities accrued more than $7 billion worth of benefits from reduced accidents (5 percent), fuel savings (17 percent), other aircraft operating cost savings (21 percent), and passenger travel time savings (57 percent).[18]

Conclusion and Recommendation

The FAA and NASA continue to collaborate with the aviation industry and academia to advance innovations in aviation. The government's research on advanced aircraft technologies, innovative materials, alternative fuels, additive manufacturing, and novel aircraft designs offer improved fuel efficiency. This report has documented the results of a review of research on individual technologies, materials, fuels, and aircraft designs and their effectiveness to enhance aircraft fuel efficiency and aerodynamic performance, and reduce drag, weight, noise, fuel consumption and emissions. These technology development efforts are complemented by work to mature operational technologies and concepts that further reduce fuel consumption and improve operational efficiency.

These key areas of research and development have resulted in significant improvements in fuel efficiency, as well as reduction of noise and exhaust emissions. The two agencies' research portfolios are complementary, with much of NASA's research and early development setting the stage for demonstration in the FAA's CLEEN Program and in NASA demonstration projects as part of the Sustainable Flight National Partnership (SFNP).

The FAA recommends that it continue to pursue technology development in the areas covered in this report, including its successful coordination with NASA. This effort involves continued execution of the CLEEN Program, and pursuing planned research for a third phase of CLEEN, which began in 2021 and will run through 2026.

In addition to the aircraft-focused research described above, the FAA's NextGen portfolio of initiatives, including programs delivering new technology, airspace redesign to provide advanced air traffic procedures, and overall modernization of the NAS, are focused on delivering new capabilities that improve system efficiency which results in reduced fuel usage and emissions.

[18] https://www.faa.gov/nextgen/benefits/