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The Boeing CLEEN program exemplified a great working relationship between academia, industry, and the government, all working together toward a common goal of technology maturation aimed at realizing environmental benefits.

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1.0 Executive Summary

The Boeing Continuous Lower Energy, Emissions and Noise (CLEEN) program began in June 2010 and ended in December 2015. Over the course of 5 years, Boeing matured three promising environmental technologies, namely, Alternative Jet Fuels, Adaptive Trailing Edge (ATE), and Oxide Ceramic Matrix Composites (CMC) Nozzle. These technologies were pursued since they address the Federal Aviation Administration (FAA) CLEEN goals of reducing fuel burn emissions and noise, as well airplane/engine systems compatibility with alternative fuels.

Boeing's approach for CLEEN built on its extensive experience in environmental technology demonstration programs. The Boeing CLEEN program leveraged the Boeing Commercial Airplanes (BCA) ecoDemonstrator program for its ground and flight testing. This gave Boeing the unique opportunity to demonstrate environmental technologies on production aircraft.

Partnerships with the University of Dayton Research Institute (UDRI), Albany Engineered Composites (AEC), ATK Space Systems/COI Ceramics Inc. (ATK-COIC), and Rolls-Royce (RR) aided the technology advancement. The partnerships provided capabilities and expertise in alternative fuels, hardware fabrication, testing, and future use.

Boeing employed its Program Management Best Practices (PMBP) to manage cost, schedule, technical performance, and risk. A systematic "building block" approach maturation plan was put into action to progressively mature the technologies. This approach, along with appropriate milestones and reviews ensured readiness for flight demonstration.

Alternative Fuels aromatics testing was completed in 2011 and the cycloparaffin testing was completed in 2013. This testing enabled definition of fuel absorption and seal swell properties for blends up to 50%. The results supported the ASTM International D7566 Fuel Specifications in 2012 for synthetic fuel blends up to 50%. Overall, the technology maturation helped reduce the risks related to "drop-in" renewable fuel replacement strategies. The Alternative Fuels Public Report [1] in 2011 and an update in 2014 provides details of the technology development.

ATE technology enables tailoring wing aerodynamic performance which improves flight performance and thereby reduces noise and fuel burn. The ATE prototype system underwent a flight demonstration in 2012 utilizing an American Airlines 737-800 airplane. The prototype was a single slotted flap and a simulated mini-split flap. The flight testing validated failure modes and verified the acoustic and aerodynamic performance. The testing also demonstrated the viability of a mini-flap driven by the Shape Memory Alloy (SMA) rotary actuator with closed loop feedback control. Through CLEEN, ATE matured to Technology Readiness Level 7 (TRL7). The benefits and Technical Performance Metrics (TPMs) were identified for notional single-aisle and twin-aisle aircraft as part of a fleet-wide analysis. For these aircraft, a noise reduction range from 1.0 to 1.7 EPNdB CUM (Effective Perceived Noise in Decibels, Cumulative) was derived. Similarly, a fuel savings benefit ranging from 0.5% to 0.9% was derived. When accounting for system weight penalty, the fuel savings is 0.5%. The potential 2% reduction in fuel use for a specific aircraft and mission was previously identified but not analyzed here. Overall, ATE technology can enable more efficient wing architectures that can lead to greater benefits.

CMC Nozzle technology is a high temperature material system that enables lighter, quieter, and more efficient engines. A CMC nozzle and centerbody were demonstrated using a RR T1000 engine in an engine ground test in 2013, and then in a flight test in 2014, using a Boeing 787-8 airplane. Before CLEEN, the technology matured to TRL4, and through subcomponent, ground and flight test, CMC matured through TRL5 and TRL7. The testing validated: (a) thermal performance in excess of Inconel at a weight below titanium, (b) noise performance equivalent to or better than metallic designs, and (c) capability of oxide CMCs to operate at 1,500°F continuously. The benefits achieved were fuel savings up to 1.0%, noise reduction of 1.7 EPNdB with potential up to 2.3 EPNdB, and weight reduction > 20%. Overall, the CMC technology is a key enabler for future engine and nacelle architectures. The CMC Exhaust Public Report [2], provides details of the technology advancement.

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2.0 Program Background

2.1 CLEEN Overview

The FAA Office of Environment and Energy (AEE) sponsors and manages the CLEEN program. The CLEEN program is the FAA's principal NextGen environmental effort to accelerate the development of new aircraft and engine technologies and advance sustainable alternative jet fuels. The CLEEN Program is a key element of the NextGen strategy to achieve environmental protection that allows for sustained aviation growth.

At the technology level, CLEEN aimed to develop and demonstrate certifiable aircraft technology at TRL6-7. CLEEN also aimed to advance the use of drop-in alternative fuels in aircraft systems focusing on renewable options. Specifically, the defined technical goals are:

- Certifiable aircraft technology that reduces aircraft fuel burn by 33% relative to current subsonic aircraft technology and that reduces energy consumption and greenhouse gas (GHG) emissions.
- Certifiable engine technology that reduces Landing and Takeoff (LTO) cycle Nitrogen Oxide (NOx) emissions by 60% below the International Civil Aviation Organization (ICAO) standard adopted in 2004.
- Certifiable aircraft technology that reduces noise levels by 32 dB cumulative, relative to the Stage 4 standard.
- Drop-in sustainable alternative jet fuels, including quantification of benefits; drop-in alternative fuels will require no modifications to aircraft or fuel supply infrastructure.

The CLEEN program was a 5-year effort spanning 2010-2015, with total federal investment of approximately $125M. FAA awarded a 5-year agreement to Boeing, among other companies. The agreement required a minimum 1:1 cost share with industry. Authorization to Proceed (ATP) was on June 22, 2010. Boeing worked under the Other Transaction Agreement (OTA) DTFAWA-10-C-00030.

2.2 Boeing CLEEN Program Overview

Under CLEEN, Boeing investigated the effects of alternative jet fuels on aircraft fuel systems and developed and demonstrated two aircraft technologies: ATE and CMC acoustic nozzle. The objective of the ATE development was to develop and demonstrate a prototype ATE system capable of tailoring wing performance to reduce noise and fuel burn at different flight regimes. The objectives of the CMC development were to: (a) demonstrate a material system that can enable lighter, quieter, more efficient engines and (b) design, fabricate and demonstrate an acoustic CMC primary exhaust system. CMC technology also aimed at reducing fuel burn and noise. The selected technologies addressed the CLEEN environmental goals noted above.

Boeing's approach to CLEEN leveraged the extensive experience gained in similar previous environmental technology demonstration programs such as Quiet Technology Demonstrator 1 (QTD1) and QTD2, and multiple biofuel demonstrations since 2005. The Boeing CLEEN flight demonstrations were linked with the Boeing Commercial Airplanes (BCA) ecoDemonstrator program, which served as the framework for the engine ground testing and flight demonstration. This linkage gave Boeing the unique opportunity to demonstrate environmental technologies on aircraft from the Boeing production line. Boeing also leveraged its state-of-the-art laboratories, its extensive supplier relationships, its world-class experience in commercial transport design, integration, and certification, and its focus on technical innovation and rapid transition of technologies to products, to support the CLEEN program. Through disciplined technology maturation, demonstration, and program management, the program was a success.

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2.3 Technology Benefits

The benefits of the Boeing CLEEN technologies are summarized in Table 2-1. The discussion below provides further details on the benefits of each technology.

Table 2-1 – Benefits of the Three Technologies in the Boeing CLEEN Program

Technology	Goal / Impact		
	Fuel Burn	Noise	Drop in Alt Fuels
Alternative Fuels: Fuel system material swell & absorption	n/a	n/a	Support 2012 ASTM International Std for Synthetic blends up to 50%
Adaptive Trailing Edges	Up to 2% in some single-aisle and twin-aisle configurations	Up to 1.7 EPNdB CUM in some single-aisle and twin-aisle configurations	n/a
Ceramic Matrix Composite Nozzle	Up to 1.0% Weight Reduction > 20%	Nominally 1.7 EPNdB CUM (Parity or better with metallics) up to 2.3 EPNdB	n/a

The Alternative Fuels technology yields the benefit of potential fuel specification changes, which are likely to impose the testing needed before a future alternative fuel could be designated as jet fuel. The development can also help enable higher blend percentages, as well as communicate to industry the latest understanding of aromatics effects on various materials. At the completion of alternative fuels development, the study succeeded in supporting the 2012 ASTM International Standard for synthetic blends up to 50%.

The ATE technology provides benefits in fuel-burn reduction, greenhouse gas emissions reduction, and noise reduction. The fuel burn and emissions reductions are achieved through improved load distribution on the wing and, therefore, improved sectional performance and efficiency in cruise. Specifically, reduced fuel use is due to reduction in wave drag and induced drag. The reduced fuel use, in turn, yields reduced CO_2 emissions. With respect to noise reduction, ATE provides an increase in the lift-over-drag ratio of the airfoil, allowing for shorter runway length and improved climb performance. This reduces community noise by having the aircraft fly at higher altitudes as it departs the airport's envelope. The performance improvement can alternatively be used to alleviate thrust required for a given runway length, reducing jet noise emission. On landing, when airframe noise is dominant, the additional lift allows for a reduction in approach speed that strongly affects the emitted airframe noise. Conversely, the extra lift can be used to back off on the flap deflection to alleviate the flap edge noise-producing mechanism. Benefits were identified for notional single-aisle and twin-aisle aircraft as part of a fleet-wide analysis. For these aircraft, a noise reduction range from 1.0 to 1.7 EPNdB CUM was derived. Similarly, a fuel savings benefit ranging from 0.5% to 0.9% was derived. When accounting for system weight penalty, the fuel savings is 0.5%. The potential 2% reduction in fuel use for a specific aircraft and mission was previously identified but not analyzed in this study.

With the performance and environmental impacts, ATE aligns with, and is fully compatible with, the NextGen National Airspace System (NAS) initiative and its goal of more efficient, quieter aircraft and airport operations. ATE increases the maximum lift and performance during takeoff, approach, and landing. This expands the flight envelope and offers alternative flight control options, such as more efficient profile descents, improved, and more precise departure paths. The increased maximum lift can also allow operation from shorter runways, which decreases congestion at other airports or allows for more efficient routing. The improved takeoff and landing techniques can reduce fuel burn, emissions, and noise, meeting the NextGen environmental goals. By applying this concept to new aircraft from the beginning of the design process, even greater benefits in aircraft flight efficiency (noise, fuel-burn, emissions) can be realized.

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The CMC technology provides benefits in fuel-burn reduction, GHG emissions reduction, and noise reduction. Fuel burn and Carbon Dioxide (CO_2) reductions are achieved through reduced nozzle component weight enabled by high-temperature material properties and a structural sandwich design. The CMC also provides benefits due to fuel savings, maintenance cost avoidances, and reduced nozzle maintenance due to thermal and brake wear—all due to significant reductions in minimum and ground idle thrust levels. The reductions in thrust are achieved through the ability to achieve higher exhaust temperature limits without the adverse effect of oxidation. The overall benefit is an improvement in fuel savings of up to 1%. In addition, the CMC technology provides a converted weight benefit from noise reduction achieved through use of a ceramic bulk absorber as part of a CMC multifunctional lightweight structural-acoustic sandwich configuration. Thus, CMC enables the use of a lightweight liner that can operate at very high temperature flows, unlike current designs that require additional weight from thicker gage materials or the use of superalloys to utilize acoustic liners in high temperature flows. The overall effect on weight reduction is greater than 20%. The overall noise reduction result ranges from a nominal 1.7 dB CUM (i.e., parity or better compared with treated metallics) to as much as 2.3 dB. The higher noise reduction can be attained when the turbine component noise is significant relative to other engine noise sources. Then the CMC noise reduction, which is targeted for turbine noise becomes more impactful. Overall, CMC enables hotter, more efficient engine and nacelle architectures, as well as provides the ability to include acoustic treatment in hotter running engines that would not otherwise be possible with existing liner materials.

2.4 Program Management

The Boeing CLEEN program was led by Boeing Research and Technology (BR&T), the research and development unit of Boeing. BCA played a major role through the provision and coordination of key personnel, aircraft, and connection to its ecoDemonstrator program. Boeing Test and Evaluation (BT&E) provided the test support for the ground and flight tests. Together the business units performed as an integrated “best of Boeing” team to accomplish the CLEEN milestones and goals. Boeing employed its Program Management Best Practices (PMBP) to manage cost, schedule, technical performance, and risk in the program, and also ensure completion of all required elements of the Statement of Work (SOW). As part of the PMBPs, Boeing managed the subcontractors and suppliers.

2.5 Schedules/Milestones/Deliverables

An overview of the program’s 5-year schedule, including technical development, major milestones and deliverables is provided below in Figure 2-1. As noted in the figure, the program-level milestones in the schedule entailed:

- A low-speed wind tunnel test (WTT) in 2011 for ATE demonstration.
- A 737 flight test in 2012 for ATE demonstration.
- An engine ground test in 2013 and 787 flight test in 2014 for CMC Nozzle demonstration.

Accompanying these major program-level milestones were lower tier program milestones and technology-level milestones. Both flight-test programs were tied-to and integrated with Boeing’s ecoDemonstrator program and schedule. Upon maturation of preliminary designs, a Preliminary Design Review (PDR) and Critical Design Review (CDR) were conducted to ensure technology maturation appropriate for readiness for flight test.

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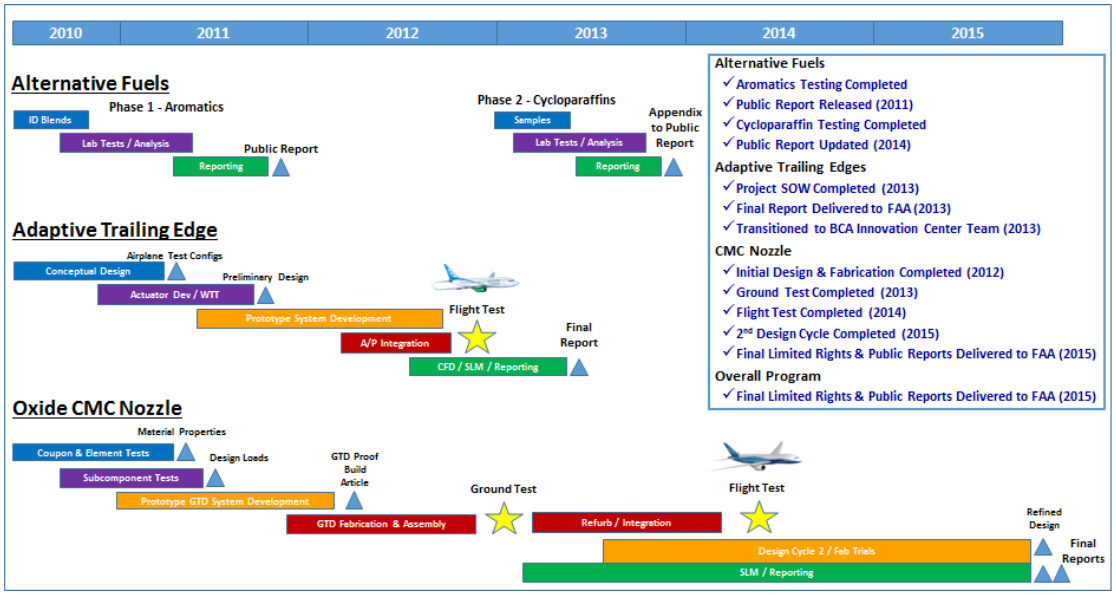

Figure 2-1 – Overview of the Boeing CLEEN Program Schedule/Milestones/Deliverables

Throughout the 5-year program, various types of deliverables were provided to the FAA. Table 2-2 provides an overview of the types of deliverables and their frequency.

Table 2-2 – Boeing CLEEN Program Deliverables to the FAA

Deliverable Types			
Task & Risk Plans	Informal Test Reports (GTD/FTD)	Monthly Technical and Schedule Reports	Design Review Presentation Packages (PDR/CDR)
Test and Instrumentation Plans	Final Test Reports (GTD/FTD)	Monthly Financial Reports	FAA Consortium Presentations

2.6 Technical Risk Management

Boeing executed a disciplined formal risk and opportunity management process. The process included steps to identify potential risk, analyze the level of risk, develop risk mitigation plans, and monitor risk mitigation status. The activities associated with risk mitigation were intended to improve the probability that the Alternative Fuels, ATE, and CMC technologies would meet the CLEEN goals. Boeing also engaged in opportunity analysis, an inverse of risk management in which opportunities were regularly identified, monitored, and reviewed with the customer to determine where coordination and leverage of the opportunities could benefit the program.

Each of the technologies in the program underwent an initial risks, issues, and opportunities (RIO) assessment to establish a reference. For each RIO, the evaluation criteria were defined in terms of likelihood and consequence. The CLEEN program RIOs were identified and characterized in the six major categories: (1) Project Management, (2) Schedule, (3) Cost/Finance, (4) Resources, (5) Technical, and (6) Flight Demonstration.

Once the initial reference was set, a systematic building block maturation plan was put into action, which was instrumental in reducing key technical risks, or barriers, for the ATE and CMC technologies. Without the reduction of these risks, ATE and CMC could not be considered viable technologies for aircraft programs.

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2.7 Technology Demonstrations Overview

Glasgow, Montana was the site of the ATE technology demonstration flight test from August 28 to September 6, 2012. The test airplane was a 737-800 from American Airlines. Figure 2-2 illustrates the flight test, which matured the technology to TRL7.

Moses Lake, Washington was the site of the CMC technology demonstration flight test from July 7 to July 23, 2014. The test airplane was a Boeing 787-8 fitted with a Rolls-Royce Trent 1000 engine. Figure 2-3 illustrates the technology flight test, which matured CMC technology to TRL7.

Figure 2-2 – ATE Flight-Test Demonstration

Figure 2-3 – CMC Flight Test Demonstration

2.8 Partners and Suppliers

Success of the program was in part due to participation from partners and suppliers with complementary capabilities. Boeing was the systems-level integrator of all technology development. BR&T Supplier Management (SM) supported engineering development and test efforts for Alternative Fuels, ATE, and CMC development. The BR&T Procurement System is ISO 9001:2000 and AS9100 approved. BR&T SM contracted with the following:

- UDRI to evaluate the impact of synthetic paraffinic kerosene (SPK) fuels and fuel blends on nonmetallic materials used in commercial aircraft fuel systems.
- Albany Engineered Composites (AEC) for CMC preforms.
- ATK Space Systems/COI Ceramics Inc. (ATK-COIC) for fabrication of CMC test parts, and ground test units.

Boeing also engaged academia, and government agencies in a collaborative manner. Rolls-Royce provided in-kind integration and resources. In addition to the FAA, Boeing worked with the Air Force Research Laboratory (AFRL), NASA, and Georgia Tech.

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3.0 Alternative Fuels

3.1 Technology Overview

The air transportation industry has an increasing need to: (1) reduce anthropogenic impact on the climate due to GHG emissions (primarily CO_2), (2) find alternative fuel sources to replace or supplement a decreasing and easily identifiable global oil supply, and (3) identify alternative fuel sources to provide more price stability during adverse oil price fluctuations. Due to the life cycle CO_2 emissions reduction it may provide, bio-derived jet fuel is a key component in the industry's strategy to address these challenges.

Boeing and its partners have made significant progress in the last few years toward identifying sustainable sources of plant-derived oils (triglycerides and free fatty acids). Progress has also advanced in processing methods that can efficiently produce SPK or bio-SPK that can then be used in commercial aircraft at a blend ratio of up to 50% with normal jet fuel (Jet A or Jet A-1). Bio-SPK is also known as Hydrotreated Renewable Jet (HRJ) fuel. The processing method to derive bio-SPK fuel is described in the Alternative Fuels Public Report [1]. Bio-SPK fuel contains the same types of molecules that are typically found in conventional petroleum based jet fuel, i.e., the same class of compounds of normal paraffins, iso-paraffins, and cyclic paraffins. Figure 3-1 shows that the bio-SPK carbon chain distributions match those of conventional jet fuel. Bio-SPK mimics physical properties of conventional aviation fuel like viscosity, boiling range, flash point, and the like. It is important to note that aromatics are not produced from the bio-SPK process. This is important because aromatics contribute to the density of the fuel and to the solvent characteristic of the fuel. Moreover, aromatics play an important role regarding the interaction of jet fuel with various fuel system components. This interaction is discussed below.

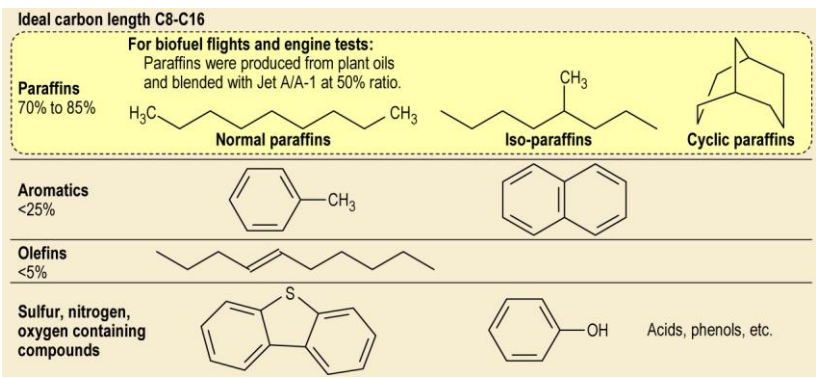

Figure 3-1 – Carbon Chain Distributions of Bio-SPK Matching Conventional Jet Fuel

Polymers used in modern aircraft fuel systems interact with the fuel. When a polymer, such as an O-ring seal, hose, or sealant, is exposed to fuel, it absorbs some of the fuel, causing it to soften and swell. It may also have soluble components such as plasticizers, solvents, or processing aids that are extracted by the fuel, which can cause it to shrink and harden. Once in service for a prolonged period, the fuel extractable components are removed and subsequent changes in the polymer physical properties (such as volume and hardness) will vary as the fuel composition varies over the normal lifespan of the component. In broad terms, the solvent characteristic of conventional aviation fuel lies in its aromatic content. In specific terms, the strength of interaction between the fuel and a specific polymer will depend on the material(s) involved and the specific aromatics present in the fuel. The strength of interaction between the fuel and polymer depends on the size and shape of the fuel molecules, the intermolecular bonding of the polymer, the intermolecular bonding of the fuel, and the intermolecular bonds that form between the polymer and the fuel penetrants.

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The aromatic content of conventional aviation fuel is required to be less than 25%v/v, while jet fuel tends to vary between 13% and 23%v/v. In contrast, SPKs typically have 0% aromatics. Therefore, SPKs have lower solvent characteristics than usual jet fuel. In a system that has been used with conventional aviation fuel in which all of the polymeric materials have been soaked with fuel and have softened and swollen because of that exposure, there may be some shrinkage and hardening when exposed to an SPK. This effect is of concern for polymeric materials in general, and O-ring seals in particular. Efforts are underway for SPKs to be blended with conventional aviation fuel. Within ASTM, it has been balloted that a blend may be used if it has an aromatic content of at least 8%v/v. The challenge of these approaches is that performance relative to the material compatibility of alternative fuels such as SPKs is not completely understood and there is little information available to place defensible restrictions on blending ratios or composition requirements. Such limits may unnecessarily restrict the future increased development and use of alternative fuels. It is conceivable that an alternative fuel could contain significant aromatics, yet still have a compatibility problem if the aromatics used prove to be inert. The aromatic specification could also exclude fuels that obtain solvent characteristic through components other than aromatics, such as the decahydronaphthalene found in some alternative fuels; these cause swelling similar to jet fuel, yet do not contain any aromatics.

The key is to address the aromatic content, as current systems are requiredto produce the necessary seal swell to prevent leaks and other fuel system issues. Maturing the scientific understanding of aromatics and materials compatibility publicly through laboratory testing of various fuels will also help enable higher blend percentages and communicate to industry the latest understanding of aromatics effects on various materials.

3.2 Testing Results and Analysis

In general, the CLEEN goal of transition strategies that enable drop-in replacement for petroleum-derived turbine engine fuels with no compromise in safety was addressed by assessing the readiness for use in aircraft systems and infrastructure. Also assessed was a variety of fuel testing needed to certify the use of fuels through bodies such as ASTM and United Kingdom Ministry of Defence (UKMOD) Defence Standard (DEFSTAN).

The testing helped to assess the composition-based needs for current aircraft system materials in use. The identification of these composition-based limitations will potentially result in future fuel specification changes, likely imposing the testing needed before a future alternative fuel could be designated as jet fuel. A composition-based fuels specification for higher blend percentages would need to identify the types of compounds that require testing and their allowable concentration (i.e., fuel provider tests that need to be accomplished). Herein, the work focused on testing of aromatics for its solvent characteristics. The volume swell and composition of the fuel absorbed by selected fuel system materials was measured using a variety of fuels. This established statistical bounds of the behavior of typical fuel system materials and helped determine which materials are problematic. UDRI accomplished a significant portion of the work, which was separated into the following tasks:

- Task 1 - Sample Selection and Preparation.
- Task 2 - Volume Swell of Reference Jet-A and SPK.
- Task 3 - Analysis of Absorbed Fuel.
- Task 4 - Volume Swell of 50% SPK/Jet-A Fuel Blends.
- Task 5 - The Behavior of SPK Blended with Selected Aromatics.
- Task 6 - Statistical Analysis and Reporting.

The materials that were tested are shown in Table 3-1 below. The reference fuels and test fuels are provided in Table 3-2 below. A high-level summary of the results and findings is also provided below. Further details on the technology development, testing, and results are provided in the alternative fuels public report [1].

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Table 3-1 – Test Materials for Alternative Fuels Technology Development

Component	Material	Sample ID
O-Rings	Nitrile Rubber	N0602
	Extracted Nitrile Rubber*	N0602e
	Fluorosilicone	L1120
	Low Temp Fluorocarbon	V0835
Sealants	Lightweight Polysulfide	PR 1776
	Polythioether	PR 1828
Coatings	Epoxy	BMS 10-20
	Epoxy	BMS 10-123
Films	Nylon (6,6)	Nylon
	Kapton	Kapton

* Nitrile rubber with its plasticizer extracted.

Table 3-2 – Reference and Test Fuels

Fuel	ID	Aromatics	Naphthalenes	Cycloparaffins	Notes
Jet-A	SRI-1	8.7%	0.2%	n.a.	Clay-treated JP-8
	4597	15.0%	1.9%	28%	Jet-A
	5245	15.5%	0.2%	30%	Jet-A
	3166	17.6%	2.5%	38%	Jet-A
	4598	17.6%	1.4%	n.a.	Jet-A
	4600	17.7%	1.3%	29%	Jet-A
	4658	17.7%	1.3%	30%	Jet-A
	4626	17.9%	0.6%	23%	Jet-A
	5661	18.1%	0.6%	40%	Jet-A
	4877	19.6%	0.4%	25%	Jet-A
	4599	19.9%	1.4%	29%	Jet-A
	3602	23.1%	1.1%	38%	Jet-A
Average		17.4%	1.1%	31%	Average Jet-A
SPK	SPK-1	0.0%	0.0%	2%	Jatropha

12 reference Jet-A fuels with 8.7%-23.1% aromatics and 23%-40% cycloparaffins
1 SPK blending stock (Jatropha) with 0% aromatics and 2% cycloparaffins
30% v/v was selected as the concentration of the cycloparaffins in the SPK

The overall response to the aromatic content of the fuel was found to be very material-dependent, with the greatest effect being shown by a nitrile rubber O-ring material and polythioether and polysulfide sealant materials. Although the volume swell of the test materials tended to increase with the aromatic of the fuel, only the nitrile rubber O-ring and the sealants showed a volume swell character in the SPKs that was lower than the range predicted for Jet-A based on the reference fuels used here. Only the nitrile rubber proved to be the most sensitive to aromatic content. It is important to note that this is not a prediction of success or failure, but merely a statistical prediction as to whether the volume swell of a given blend would fall within the predicted “normal” range for Jet-A. Based on recent testing (and ASTM D7566-11 approval of a minimum of 8% aromatics content) of up to 50% SPK blends, it is believed that fuel system materials can perform their intended functions when using fuel that provides lower volume swell than present in-service conditions. Beyond these recent approvals, more complete operational and engineering data of low aromatic fuels will likely be needed to determine how far outside the statistical bounds our present day experience can be extended. A summary of the volume swell and aromatic content for the testing is shown in Figure 3-2 below.

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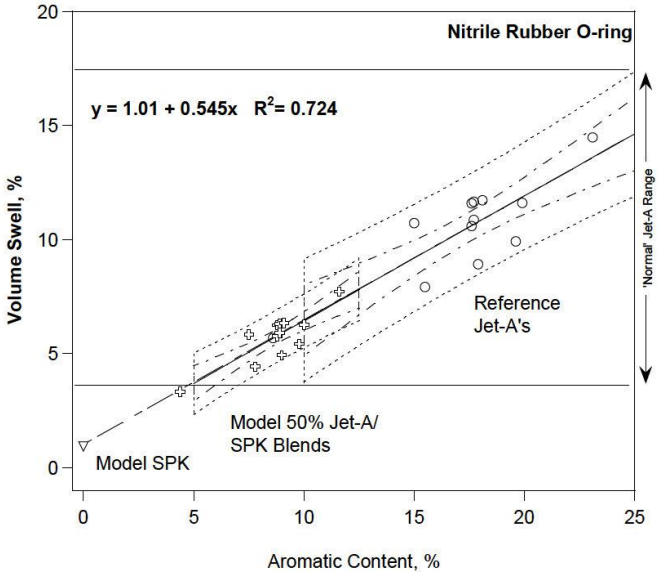

Figure 3-2 – Volume Swell vs. Aromatic Content for Test Fuels and Blends

Further highlights of the testing and results entail the following:

- Cycloparaffins obey the same basic rules as other fuel components.
- Volume swell increases as polarity increases and as molar volume decreases (cycloparaffins do not exhibit any hydrogen bonding character).
- Molar volume appears to be the main factor influencing the performance of cycloparaffins.
- Nonsubstituted cycloparaffins show a modest increase in activity with respect to substituted rings.
- The volume swell is weakly influenced by the substitution position with the 1, 2 substitution pattern being the preferred configuration.
- Overall, the results suggested that it might be possible to develop a fuel that is high in cycloparaffins with very low, or even zero, aromatic content.
- The addition of decalin at 30% to the SPK used here greatly improved the material compatibility of the 50% fuel blends used in this study.

With respect to decalin (selected cycloparaffin), we found the following:

- Decalin showed good overall performance, though not exceptionally high.
- Decalin lies well within the boiling range of Jet-A.
- Decalin showed good performance characteristics as a major fuel component (JP-900).
- Decalin can be produced from nonpetroleum sources (coal).
- Decalin is readily available in high purity and at a relatively low cost as an analytical chemical.
- Decalin has the added benefit of bringing significant density to the fuel, making it easier to meet the density specification.

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4.0 Adaptive Trailing Edge

4.1 Technology Overview

The ATE program combined recent advances in actuation with the aerodynamic understanding of transport aircraft wing design to demonstrate deployable and controllable trailing-edge elements that improve aircraft performance at all flight conditions. Small control surfaces (miniature flaps) that can be placed anywhere along the wing trailing edge represent a simple and effective way to alter an airfoil's performance characteristics and improve it over current fixed trailing-edge design. Detailed aerodynamic explorations into the potential benefit of these trailing-edge elements have identified the value of multiple configurations that vary with flight regime, for example, deploying for enhanced takeoff, cruise, and approach performance, and retracting when needed. This led to the development of a lightweight, novel, and robust SMA-based actuation system that controls deployment of the miniature flap surface. Figure 4-1 provides an overview of the ATE concept.

Figure 4-1 – Overview of ATE Concept

SMA actuation is an enabling technology for the ATE and maximizes the technology's benefits. SMA actuators provide actuation capability due to a thermally induced change in SMA microstructure resulting in a high-deflection, large-force macroscopic shape change. SMA tubes can be engineered to twist when heated and cooled, resulting in a highly weight efficient, compact, and easily integrated rotary actuator. Figure 4-2 below provides details of SMA actuators.

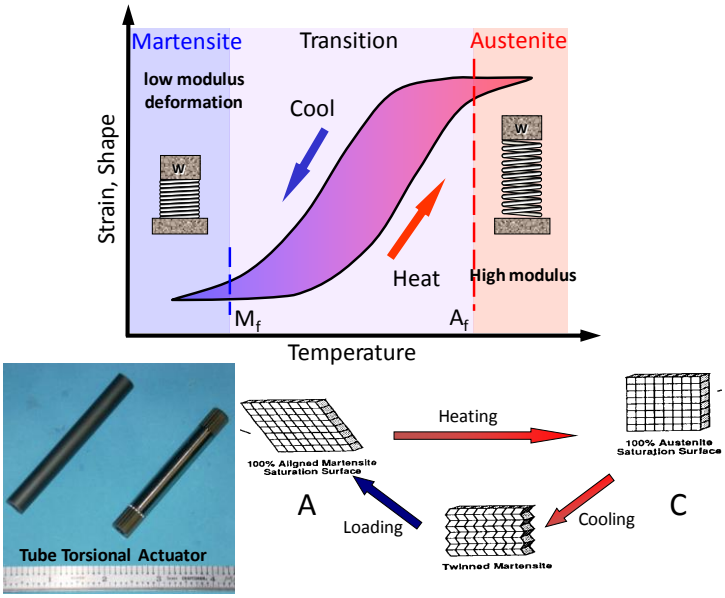

Figure 4-2 – SMA Actuation

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4.2 Technology Maturation

The ATE program technology maturation pulled together four key elements: aerodynamic and noise analysis and design, new actuation technology, unique system and integration solutions, and robust testing and validation. The design and implementation of the trailing-edge surface was based on thorough aerodynamic and noise analyses of current commercial airplanes. The actuation system was efficiently integrated into the 737-800 outboard wing section. The SMA rotary motor provided the drive for the trailing-edge wing surface and enabled the system to meet aerodynamic, noise, functional, and operational requirements. Extensive testing of the technology and its implementation was conducted in a wind tunnel and laboratory to validate the approach. These elements all came together with a flight test on a full-scale, fully functional ATE System on a 737-800. The program was divided into four phases: Technology Maturation, System Engineering and Integration, Technology Demonstration, and Technology Assessment.

4.2.1 Technology Maturation Phase

The Technology Maturation phase built critical understanding of trailing-edge devices and implementation options for commercial airplanes. The team explored viable low-speed and high-speed implementations of an ATE through steady and unsteady computational fluid dynamics analysis, WTT, and a technology survey of internal and external studies and tests of fixed trailing-edge elements. Miniature Split Flap (MSF) variables such as flap size, wing span distribution, deployment angle, and schedule, were evaluated. During this evaluation, the mini plain flap concept (MPF) was considered and performance and characteristics compared with the MSF. The down-select process for flight-test configurations concluded in February 2011 and included the MPF to complement the MSF. Subsequent WTT showed that the MPF has comparable function to the MSF, with some interesting advantages such as its ability to move up from the faired position to relieve loading on the wing. The flight down-select process resulted in the final flight-test configurations shown in Figure 4-3. At this point, preliminary design of the MSF and MPF actuation system was completed.

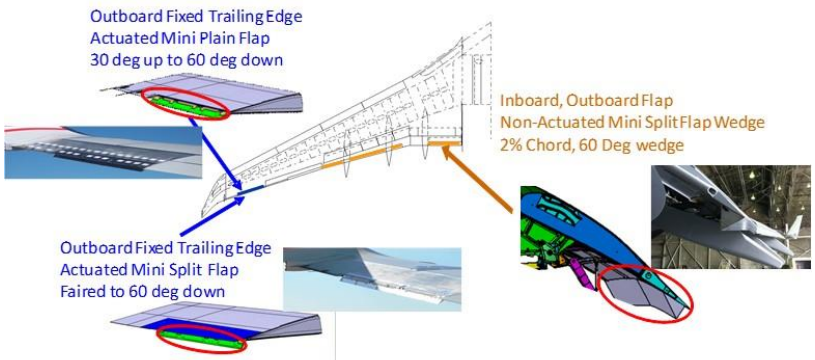

Figure 4-3 – ATE Flight-Test Elements: Outboard Wing Actuated Mini Split Flap and Mini Plain Flap, and One Fixed Wedge (2% of local chord 60-deg deflection) on Inboard and Outboard Aft Flap

4.2.2 System Engineering and Integration

The System Engineering and Integration phase included the design and fabrication of the flight-test components. One of the key areas of work included the outboard fixed trailing-edge structure that supported the actuated mini flap, actuation system, controls instrumentation, and flight-test instrumentation (shown in Figure 4-4). A series of CDRs were used to review the designs before initiating fabrication. Fabrication was accomplished through commercial airplane suppliers, new technology suppliers, and in-house fabrication capability. In support of the flight-

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test design and buildup of all ATE wing modifications, preflight testing was conducted in Puget Sound Boeing laboratories. In many cases, a rigorous testing process validated the design; for example, the SMA actuators were tested to show they met the limit and ultimate load requirements. Flight-test planning, which included coordination with the flight-test organization and preparation for airplane integration, was a significant effort. The integration of the technology onto the airplane was accomplished in phases as the commercial airplane moved from the production line to the flight-test organization. The ATE outboard wing structure was installed, followed by the miniature flap, actuation system, wiring, and instrumentation.

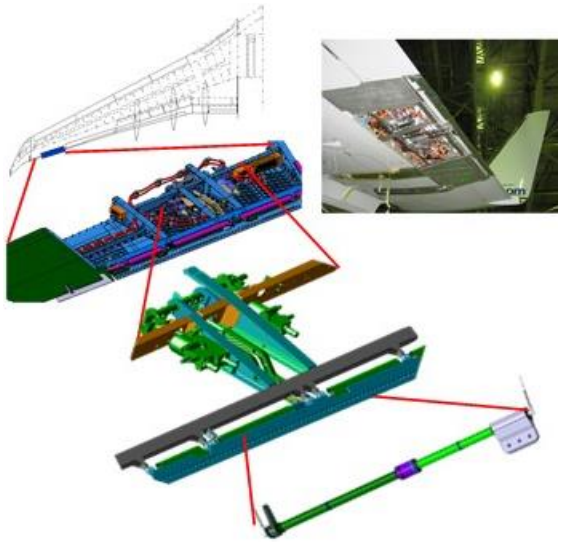

Figure 4-4 – Integration of SMA Actuator System and Miniature Flap Into 737-800 Wing

4.2.3 Technology Demonstration

The technology demonstration phase focused on the flight test, which occurred in August and September of 2012, at Moses Lake. The ATE technology was flight-tested on an American Airlines 737-800. Key facts and highlights of the test are provided in Figure 4-5. The actuation system, including the high-technology smart materials motor, reached TRL7.

Figure 4-5 – ATE Flight-Test Demonstration

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Flight-test preparation required considerable focus and coordination. The team completed the installation of the ATE actuation system components during and immediately after the airplane production flow. The actuation system and sensors were installed and calibrated in place. Extensive ground tests of the actuation system, control methods, and safety procedures were then accomplished. The final requirement was to demonstrate adequate actuation system endurance on the simulated flight-test mini-rig setup.

The flight-test elements included an outboard wing actuated mini-flap (4.2% of local wing chord, 66-in spanwise extent) tested as an MPF, an MSF, and inboard/outboard single-slotted flap with fixed wedge (2% of local chord, 60-deg deflection) simulating an MSF. All planned configurations were tested except for the MSF porosity noise testing, which was canceled when the expected tones were not measured on the ground for the baseline (nonporous) case. Figure 4-6 shows a sequence of MPF test conditions.

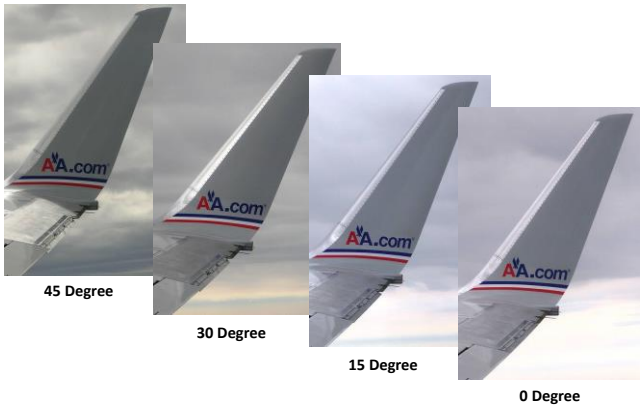

Figure 4-6 – Mini Plain Flap Low-Speed Aerodynamic Testing Sequence

All planned noise, low-speed aero, high-speed aero, loads, and actuation system control conditions were tested and high quality data was measured. The actuation control system operated flawlessly under high-speed and low-speed conditions in both MPF and MSF modes. Measurements included wing pressure distributions, flow visualization, community noise, and mini-flap control system parameters. Figure 4-7 illustrates the key instrumentation that supported the flight test. Instrumentation on the airplane included pressure measurements on the wing using low profile pressure belts, built-in flush-mounted pressure sensors, dynamic pressure Kulites, accelerometers on the MPF and MSF upper surface plate, thermocouples to monitor temperature of critical components, and strain gages to measure loading due to the mini-flap deployment. Flow cones were attached to key components for wing flow visualization. Figure 4-8 below shows the noise measurement instrumentation, including a ground-based phase array.

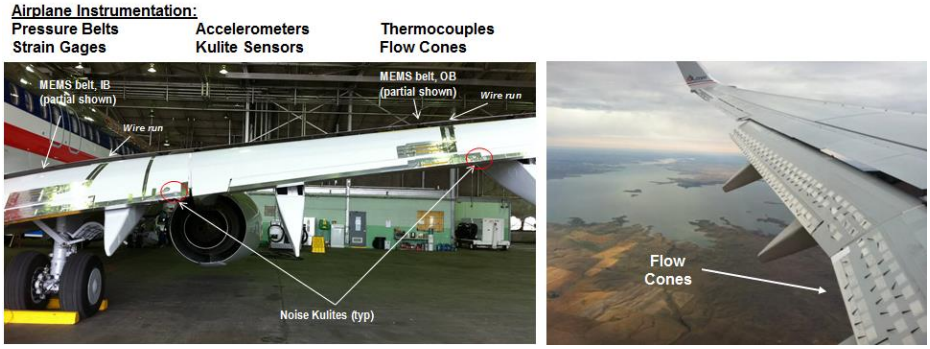

Figure 4-7 – ATE Flight-Test Instrumentation

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Figure 4-8 – The ecoDemonstrator 737-800 Flying Over the Phased Array at Glasgow

4.2.4 Technology Assessment

The Technology Assessment phase began immediately following the flight test. Performance data obtained by Aerodynamics, Loads, Noise, Stability and Control, Flight Controls, and SMA actuation groups supported the evaluation of the ATE for the assessment of the technology. Comparison of flight-test data and wind tunnel, laboratory testing, and modeling, including computational fluid dynamics, shows that across the disciplines, Boeing can make reasonable predictions of the performance and impacts of ATE type devices for commercial airplanes. Collaboration with Georgia Institute of Technology (Georgia Tech) under the Partnership for Air Transportation Noise and Emissions Reduction (PARTNER) Project 36 and the Aviation Sustainability Center of Excellence (ASCENT) Project 10, provided a fleet level assessment.

4.3 Testing Results and Analysis

The ATE program generated and analyzed data for multiple disciplines including high-speed and low-speed aerodynamics, noise, loads and dynamics, stability and handling, and actuation system. An overview of results from each discipline is provided.

4.3.1 High-Speed and Low-Speed Aerodynamics

The primary objective for testing the ATE at high-speed conditions was to validate incremental performance expectations based on past studies. Outboard wing pressure data were utilized in the validation exercise by comparing Computational Fluid Dynamic (CFD) results with the flight-test data across a range of ATE deflections and flight conditions. Figure 4-9 shows the high-speed aerodynamic test setup, including location of pressure sensors. Flight-test videos of the flow cones were used to evaluate how well CFD predicts trailing-edge flow characteristics.

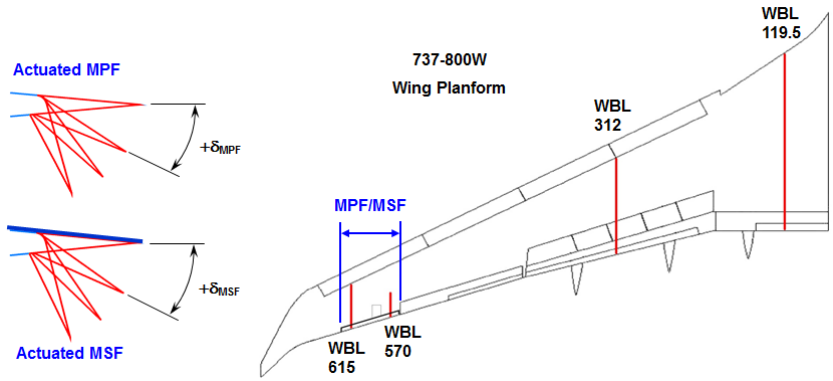

Figure 4-9 – High Speed Aerodynamic Test Setup

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The primary low-speed aerodynamic objective of the flight test was to gather a database of information on the incremental aerodynamic impact of ATEs that could then be compared with analogous results from CFD and the wind tunnel, the two primary tools used in aircraft development (Figure 4-10). The low-speed aerodynamic testing can be divided into three categories: MPF testing on the outboard fixed trailing-edge portion of the wing, MSF testing on the same portion of the wing, and simulated MSF testing across the full flapped span of the wing (see Figure 4-3 above).

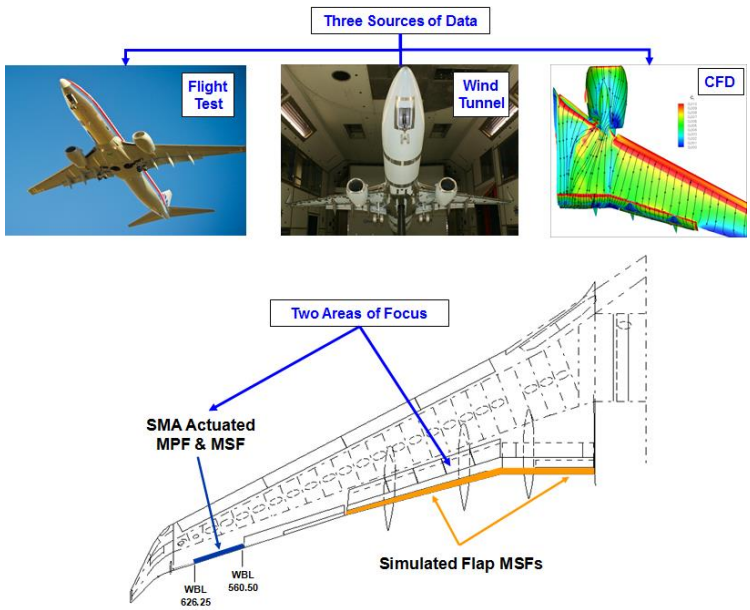

Figure 4-10 – Low-Speed Aerodynamic Test and Analysis

An evaluation of MPF and MSF devices from CFD, wind tunnel, and flight-test data show that these devices have similar effectiveness at low-speed conditions. At higher flap deflections, they reduce separation and therefore drag at a given lift. The wind tunnel and flight-test data provide an exceptional CFD reference dataset that can be used to validate CFD tools.

4.3.2 Noise

While the overall community noise benefit for an airplane outfitted with ATE devices comes primarily from engine noise due to improved low-speed performance, nonpropulsive (airframe) noise sources are also affected. Airframe noise reduction is realized in various ways depending on the spanwise location of ATE device deployment. On the outboard wing, the improved spanload distribution contributes to lower flap edge noise. When located on the flaps, the devices facilitate a simplified, and therefore quieter, trailing-edge architecture. Alternatively, any additional lift allows for lower approach speeds, which translate to lower noise from both the high-lift system along with other airframe sources such as the deployed landing gear.

In order to realize the above-mentioned community noise benefits, whether from improved performance or a lower airframe noise signature, a very different configuration from the ones tested during the CLEEN ATE flight-test program would be required. An overall noise benefit was calculated based on an applicable outboard wing ATE deployment as measured in the wind tunnel, combined with flight test validated performance increments as described in the low-speed portion of this report. Similarly, the airframe noise benefits from the use of optimized ATE devices were derived from wind tunnel data. The direct self-noise from the ATE devices were measured both in the wind tunnel and during the flight test, and were computationally predicted. These noise calculations were provided to Georgia Tech for System Level Modeling (SLM).

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WTT, numerical simulations, and the literature in general, show that ATE devices have a propensity for vortex shedding which, if strong enough, can translate to audible tones on the ground. Such tones, generally in the 100-300 Hz range for a practical aircraft implementation, can have a significant impact on certification levels and must be controlled or avoided for acceptable levels of community noise. Any benefit from improved performance could easily be cancelled out, or even reversed, in the case of tone-generation from the devices. The QinetiQ WTTs (see Figure 4-11) and computational effort both found ATE device perforations in various forms to be highly efficient in removing the tonal content produced by the device with a small decrease in lift (but increased lift to drag [L/D] ratio) as a result of the reduced effective area. The flight test demonstrated multiple ways to implement porosity on the trailing edge.

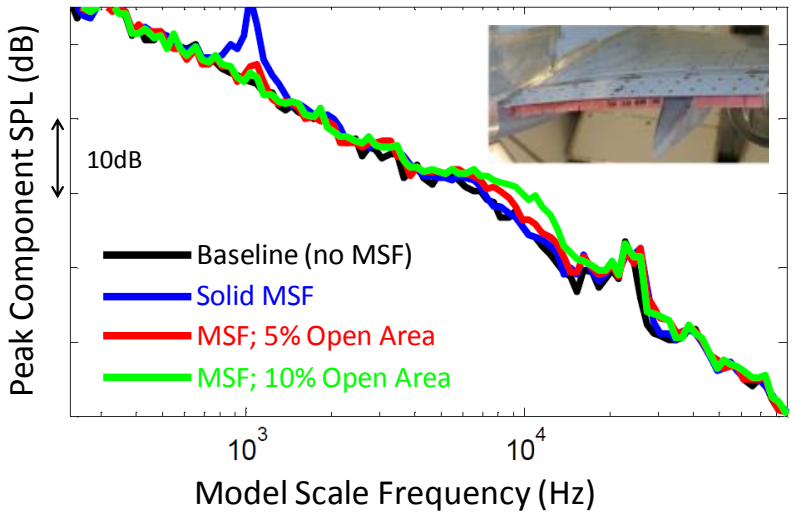

Figure 4-11 – QinetiQ Phased Array Spectral Data of Flap MSF (4%, 60° deflection) Tonal Behavior With and Without Slits; Wind Tunnel Model With the Perforated MSF Mounted on the Inboard Flaps

4.3.3 Loads and Dynamics

The goal of testing for the Loads and Dynamics organization was to create an aerodynamic database of data collected in-flight on full-scale airplanes and at-flight Reynolds numbers in order to compare with data produced by wind tunnels and CFD codes. This will allow for better flight-level predictions from Loads and Dynamics for future airplanes that use trailing-edge devices similar to MSFs and MPFs. Flight-test maneuvers were designed in such a way that they could be compared with CFD and wind tunnel data points at a wide range of airplane angles of attack (alpha). The onboard instrumentation was supplemented with additional CFD to create a useful aerodynamic database.

In order to get a wide range of airplane angle of attack, Loads required a “rollercoaster” or “pull up” maneuver. These maneuvers varied the load factor (vertical acceleration or “g’s”) of the airplane to the limits of the CLEEN configuration operating limitations, getting the highest maximum alpha range. As this was a dynamic maneuver, the speed, altitude, Mach, etc., tended to change throughout the condition.

4.3.4 Stability and Handling

No adverse handling characteristics were identified due to asymmetric deployment of the ATE flaps as MSF or MPF. Asymmetric deployment of the miniature flap was evaluated under multiple flight conditions and handling characteristics were measured.

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4.3.5 Actuation

The miniature flap actuation system including the SMA rotary actuator, see Figure 4-4, was tested extensively in the laboratory to ensure it was safe to fly, met test requirements, and provided a realistic test of the ATE concept on the 737-800. The performance of the ATE actuation system in-flight was impressive and the overall testing was very successful. Highlights include:

- Successful operation in all configurations and all flight-test conditions (MPF/MSF, HS/LS).
- SMA motor assembly actuated mini-flap in-flight at multiple altitudes, airspeeds, and temperatures.
- Successfully demonstrated the first closed-loop control of an SMA actuated flight controls surface on a commercial airplane.
- Evaluated three different SMA control schemes and various gain sets.
- Actuation system seamlessly controlled lock and motor element, providing fast-locking capability that complemented SMA motor performance.
- LabVIEW laptop control system with kill switches/circuit breakers worked as designed and successfully reduced the risk of system failures.

Figure 4-12 below shows the left and right wing MPF deflecting to 12 positions in support of aerodynamic and loads high-speed testing. The mini-flap was locked at each position while aerodynamic or loads data were collected.

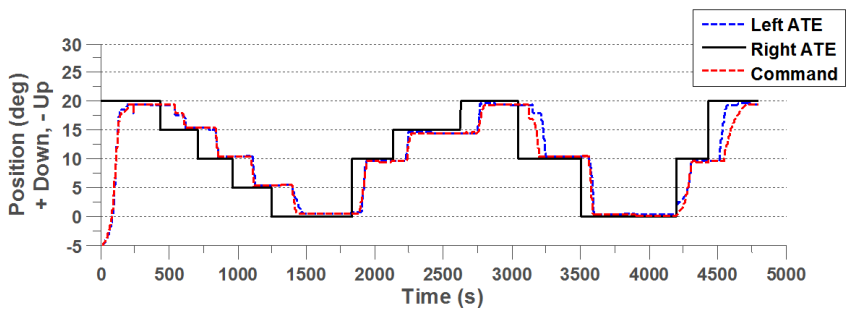

Figure 4-12 – MPF Actuation Sequence to 12 Positions in Support of Aerodynamic and Loads Testing

4.4 Technology Assessment and System Level Modeling

The ATE technology was assessed for implementation on commercial airplanes. One of the primary flight-test goals was to collect relevant performance data for different MPF and MSF configurations implemented on the wing and flown at key low- and high-speed conditions. This data was used to validate the design process of an ATE application on the Next-Generation 737 wing. Evaluation of the ATE technology and its value to the commercial aviation fleet was assessed using sources of data including wind tunnel, CFD, and the ATE flight test on a 737-800. The SLM was conducted with Georgia Tech under the Partnership for Air Transportation Noise and Emissions Reduction (PARTNER) Project 36 and the Aviation Sustainability Center of Excellence (ASCENT) Project 10.

Boeing and Georgia Tech collaborated to quantify the value of ATE technology on airplanes that could be rolled up to provide fleet-level benefits. The two airplanes considered were a narrowbody, single aisle (SA), representative of a 737NG-class airplane, and a widebody, twin aisle (TA), which is representative of a 777-class airplane. The analysis for both aircraft included cruise assessment for high-speed performance and high lift aerodynamic and noise performance.

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The high-speed impact of ATE on the representative aircraft was assessed, as shown in Figure 4-13. The fuel-burn change from the aerodynamic improvement of the ATE, the delta block-fuel weight penalty, and the overall fuel-burn change were isolated. The cruise Mach numbers for each vehicle were 0.78 and 0.84, respectively, for the narrowbody and widebody and each cruised between 31,000 ft and 39,000 ft, utilizing a 4,000-ft step cruise that was optimized for fuel burn. The results show that the aerodynamic benefit of the technology on the SA vehicle is 0.84% reduction in fuel burn. This reduction in fuel burn is then tempered by a 0.39% addition in fuel burn due to increased wing weight. The net reduction in fuel burn for the SA is -0.46%. By comparison, the net reduction in fuel burn for the TA is -0.26%, in which the differences are due to different max/peak L/D increases between the vehicles. In general, fuel reduction is highly dependent on airplane wing design, operation, and aircraft mission. This is the reason why the calculated fuel reduction does not match the TPM value of 2%, as the latter was based on a different aircraft and mission. Fuel burn can be improved by reducing the actuation system weight penalty through ongoing technology improvements.

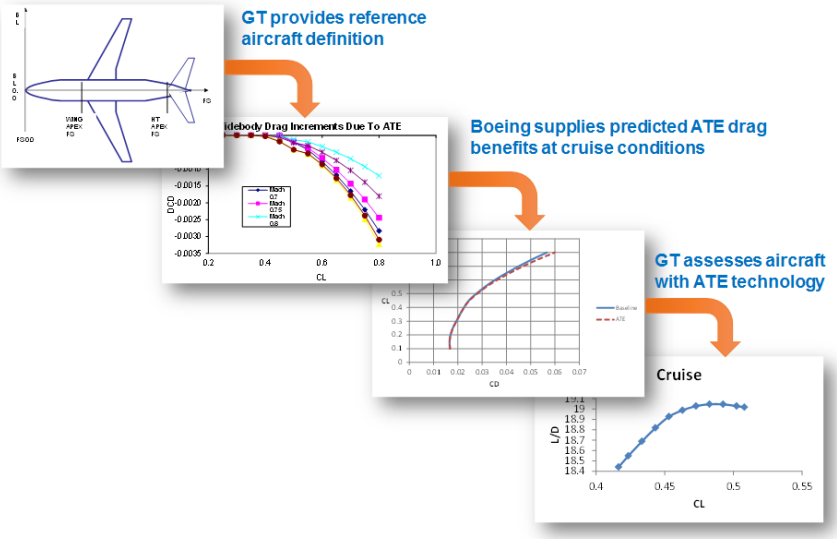

Figure 4-13 – ATE High Speed Modeling Process

The low-speed assessment provided the inputs necessary to assess certification noise benefits for the ATE using NASA's Aircraft Noise Prediction Program (ANOPP) with the Fink (FNK) airframe noise module. The SA vehicle was analyzed at flap 1 and flap 40 at takeoff and landing, respectively, while the TA vehicle was analyzed at flap 5 and flap 30, respectively. For both SA and TA aircraft at takeoff, the ATE provides increased lift at constant alpha, allowing for reduced thrust during the cutback segment. Vehicle airspeed is relatively unchanged. This reduced thrust during cutback leads to predicted 0.6 EPNdB and 0.25 EPNdB reductions for the SA and large TA aircraft, respectively. On approach, the ATE allows for reduced approach speed leading to a reduction in engine thrust. The effect on noise is two-fold, reducing engine thrust reduces jet and fan noise while reducing aircraft speed reduces airframe noise. Due to these effects, the reductions at approach are greater than those at cutback, leading to a 1.1 EPNdB reduction for the SA and a 0.7 EPNdB reduction for the large TA. Sideline noise is unchanged for both configurations since sideline is engine noise dominated. In total, a 1.7 EPNdB cumulative reduction is predicted for the SA and a 0.95 rounded to 1.0 EPNdB cumulative reduction is predicted for the TA in terms of cumulative noise. Note that 1.7 matches the TPM value.

The SLM of ATE on SA and TA aircraft showed the potential to improve both low-speed and high-speed phases of flight by improving L/D during cruise and reducing thrust requirements at cutback and landing, thereby reducing noise.

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5.0 Oxide Ceramic Matrix Composites

5.1 Technology Overview

Over the past two decades, fuel efficiency improvements and emission reductions have been realized through increased engine combustor temperatures and reduced cooling. With the advent of the next-generation high-bypass ratio engines, higher operating temperatures are outpacing the performance of nacelle exhaust washed structures including exhaust nozzles, as shown in Figure 5-1. State-of-art titanium exhausts are at their performance limits, and superalloy materials add weight (>30%). This has driven the need for alternative CMC high temperature materials for advanced nacelle packaging. By virtue of their specific strength and stiffness at temperature, these materials would be ideal for application in high-temperature environments over 1,000°F. Development of such materials would enable increases in engine temperatures resulting in improved operability and efficiency, lighter weight structures, reduced cooling and thermal management, extended life, and reduced noise and carbon footprint.

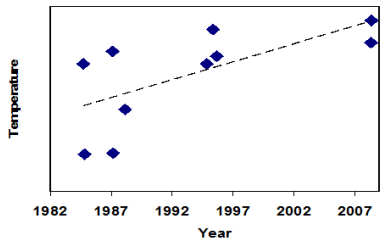

Figure 5-1 – Engine Exhaust Temperature (EGT) Variation Over Time

5.2 Technology Maturation

Within the CLEEN program, Boeing executed an aggressive CMC nozzle development and demonstration schedule that provided the near-term validation of FAA fuel burn and noise reduction goals. The technology maturation employed a building block approach to progress through the TRL levels, as illustrated in Figure 5-2.

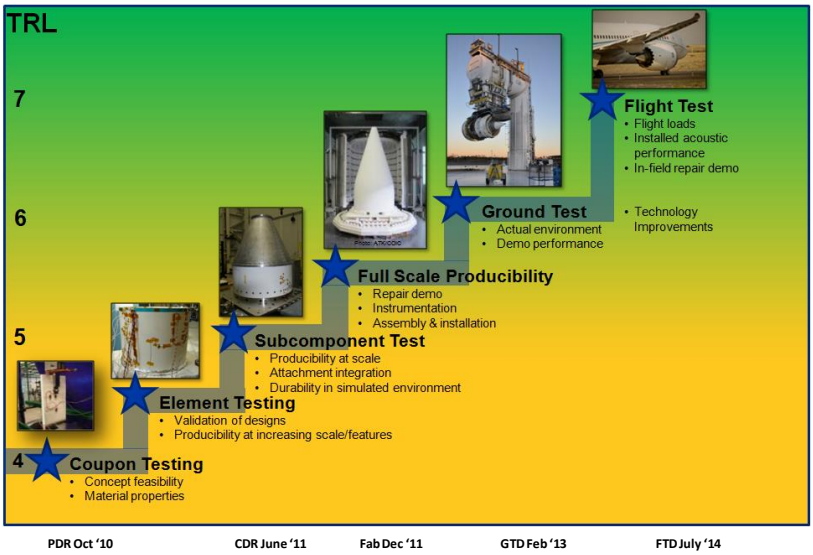

Figure 5-2 – Building Block Approach to TRL Maturation

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Technical maturity from TRL4 to TRL5 was achieved by the fabrication and test of a full-scale subcomponent article representing the entire forward hoop section of a major nozzle component. The structural integrity of the forward joint and adjacent high-stress areas was assessed under simulated worst-case flight loads. Producibility at scale and attachment integration were also validated. With the completion of the TRL5 technology maturation phase, sufficient risk was retired to commit to full-scale fabrication for the ground test. Leading up to the ground test, full-scale producibility was addressed, a repair demo was implemented, test instrumentation was readied, and installation trials were conducted. Upon completion of the full-scale nozzle and centerbody ground test demonstration (GTD), the technology was matured from TRL5 to TRL6 with CMC hardware exposed to the actual (flight relevant) thermal and vibration environments. The technology was finally matured to TRL7 through the flight-test demonstration (FTD) of the CMC nozzle and centerbody. The CMC hardware met or exceeded the technical targets defined for true-environment operation. Prior to the GTD and FTD, critical milestones were completed including a PDR, and a CDR. These reviews ensured successful completion and maturation of the technology before full-scale testing.

The CMC Design Cycle 2 (DC2) was initiated to capture lessons learned from efforts through ground and flight test. The overall goal of DC2 was to improve the TPMs of Weight, Life, Temperature, and Acoustic Attenuation, with the specific objective of rendering a CMC exhaust lighter and less expensive than SOA titanium. See CMC Exhaust Public Report [2] for details.

5.3 Testing Results and Analysis

Testing conducted during CMC technology development was fundamental to the building block approach to risk reduction for TRL maturation. This triad of testing, risk reduction, and TRL maturation, coupled with design, analysis, and fabrication, provided the complete technology development program. Five types of testing of increasing complexity were conducted: (1) Coupon Test, (2) Element Test, (3) Subcomponent Test, (4) Ground Test, and (5) Flight Test. The focus in this report is on the latter tests.

The static engine GTD completed in February 2013. The CMC centerbody and nozzle were mounted to a RR Trent 1000 engine and tested in the Rolls-Royce test facility at Stennis, MS as shown in Figure 5-3. Key facts of the ground test report are provided in the figure. The GTD verified structural integrity, validated thermal predictions, and proofed the hardware for flight testing. With the GTD, the technology was matured from TRL5 to TRL6, by addressing engine integration issues and subjecting the hardware to flight relevant thermal and vibration environments.

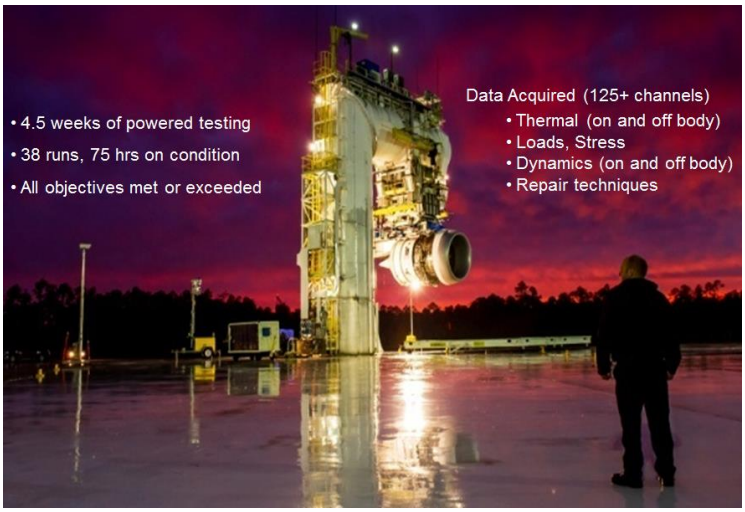

Figure 5-3 – CMC Ground Test Demonstration

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The FTD occurred in July of 2014, and advanced the technology to TRL7. The CMC centerbody and nozzle were installed on a Rolls-Royce Trent 1000 engine and flight-tested on the ecoDemonstrator 787 at Moses Lake. The GTD articles were refurbished and reused for the flight testing. Figure 5-4 shows the CMC hardware installed on the 787. Key facts and highlights of the test are provided in the figure.

Figure 5-4 – CMC Flight-Test Demonstration

CMC exhaust structural performance was demonstrated in a wide range of flight operations, significantly expanding the tested envelope, including engine starts, takeoff, climb, in-flight shutdowns and relights, high-g maneuvers, as well as thrust reverser actuation. Structural integrity was verified after test conditions were completed. Flight testing also enabled the measurement of full-scale installed, noise attenuation performance of the technology-validating-community noise benefits at the airplane level.

5.4 Technology Assessment and System Level Modeling

Detailed technology assessments were conducted, including the CMC structural response, structural integrity, dynamic response, thermal response, sonic fatigue response, and CMC acoustic performance. A subset is provided here as an overview of the technology assessment; SLM is discussed afterwards.

The technology assessment is based on performance relative to tailored Technical Performance Metrics (TPMs). The TPMs were used to capture requirements and constraints, drive technical progress, support business case decisions, and measure technology maturation. The TPMs delineated the expected benefit to engine performance in terms of temperature capability, noise reduction, weight reduction, and component life. Performance of the CMC nozzle design was evaluated relative to these TPMs, as well as cost metrics, to ensure timely TRL progression and performance.

The Weight technical performance metric (TPM) was defined as CLEEN weight goal of 20% less than acoustically treated SOA exhaust. The technology is projected to achieve up to the 20% goal compared to titanium and exceed it for Inconel. The Temperature and Life TPMs were satisfied with oxide CMC retaining strength at over 1,500°F. The Acoustic Attenuation TPM was defined as: Up to 2.3 EPNdB reduction with Spec Value 1.7 relative to hardwall exhaust. The goal was achieved in flight testing. Through the knowledge gained, future reductions can be attained.

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The ability of CMCs to operate at higher temperatures and provide as-good or better community noise treatments while operating at those higher temperatures (beyond that of metals) enables further engine operability at higher OPR. Cumulatively, these benefits can result in fuel savings up to 1.0% and up to 2.3 EPNdB reduction—average for a fleet of single and twin-aisle aircraft with comparisons to a non-acoustically treated exhaust, which was precluded by operational temperatures. Boeing's fuel efficiency assessment is conservative relative to Georgia Tech's fuel burn SLM because Boeing uses existing engines with lower OPRs than projected in Figure 5-7.

The discussion will now focus on Boeing noise modeling. This is followed by the SLM modeling conducted by Georgia Tech for fuel consumption and noise.

The CMC noise prediction model was calibrated with the flight-test results. The updated model was then used to support DC2 trade studies. Various CMC exhaust designs with varying acoustic lining parameters were investigated. The flight-test results with adjustment derived from DC2 yielded the noise reduction results depicted in Figure 5-5. As shown in the figure, 1.7 EPNdB noise reduction was achieved, equaling the noise reduction of the baseline design. This met the noise TPM of parity or better noise reduction than the baseline.

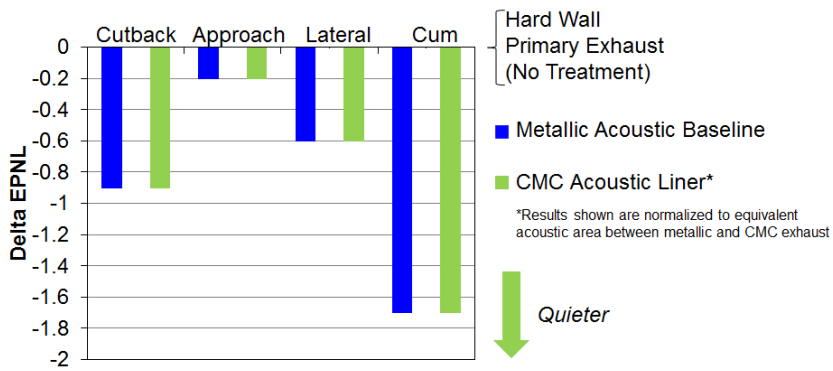

Figure 5-5 – CMC Noise Reduction

The fuel-burn system-level modeling that Georgia Tech conducted was based on engine horsepower and bleed-level inputs denoted in Table 5-1. These parameters are important because airplanes with electric power architectures require an increase in the power extraction from the engine. This, in turn, leads to higher exhaust temperatures. The higher temperature limits present a challenge to conventional titanium-based exhaust nozzles, and even for Inconel. In contrast, CMC is still viable at these high temperatures and can withstand even higher temperatures. The temperature limits for titanium, Inconel, and CMC are shown for comparison in Figure 5-6. The limits are shown for a hot day condition, for both the conventional engines and More Electric Aircraft (MEA), at an engine Operating Pressure Ratio (OPR) of 40, 50, and 70. As noted in the figure, Inco 718 provides a higher temperature limit at the expense of added weight and it may not provide enough temperature capability for very high OPR. Oxide CMC significantly reduces the temperature constraint for future growth, all the while at a reduced weight compared to the metals. The capability to operate at higher exhaust temperatures, coupled with an MEA, yields significant fuel efficiency benefits (reductions), as illustrated in Figure 5-7.

Table 5-1 – Horsepower and Bleed Modeling Inputs for Conventional and Electric Engines

Variable	Conventional		MEA	
	@ Idle	@ Cruise	@ Idle	@ Cruise
HPX (hp)	375	250	750	625
Bleed (pps)	3.0	3.0	0.0	0.0

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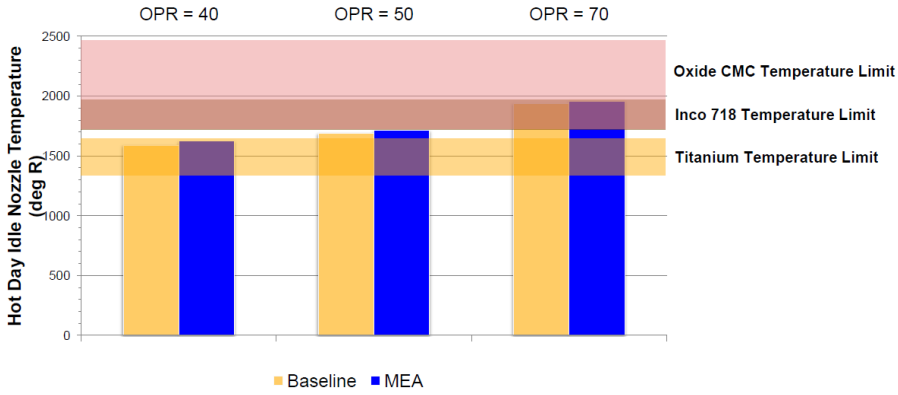

Figure 5-6 – Temperature Limits for Metals and CMC

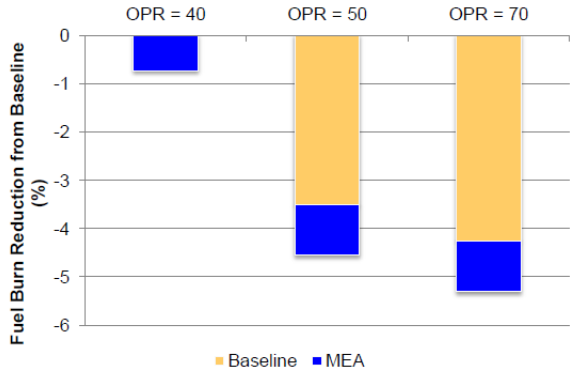

Figure 5-7 – Fuel-Burn Deltas for Baseline and MEA

The system-level noise modeling that Georgia Tech conducted was aimed at assessing the effect (impact) of the turbine noise on the total airplane-level system noise. The noise prediction tool was NASA's Aircraft Noise Prediction Program (ANOPP). A representative TA aircraft engine was utilized in the prediction. The existing ANOPP turbine noise prediction was adjusted in collaboration with Boeing in order to have a correct balance between the turbine noise and the other engine noise sources. With calibrated noise models, system-level noise prediction was carried out with and without a treated turbine for the baseline engine and engines with low, medium, and high OPR. The total aircraft (system) noise levels and the calculated benefits (noise reductions) are provided in Table 5-2.

Table 5-2 – SLM for Turbine Noise for Baseline/Low/Medium/High OPR

Baseline			
	With LPT	Without LPT	Difference
Cutback	93.92	92.99	0.93
Approach	98.81	98.05	0.76
Sideline	97.91	97.63	0.28
Cumulative	290.64	288.67	1.97

Low OPR			
	With LPT	Without LPT	Difference
Cutback	95.32	94.32	1
Approach	98.3	97.54	0.76
Sideline	99.05	98.82	0.23
Cumulative	292.67	290.68	1.99

Med OPR			
	With LPT	Without LPT	Difference
Cutback	94.35	93.21	1.14
Approach	97.72	96.67	1.05
Sideline	97.19	96.92	0.27
Cumulative	289.26	286.8	2.46

High OPR			
	With LPT	Without LPT	Difference
Cutback	93.87	92.5	1.37
Approach	97.58	96.47	1.11
Sideline	96.31	95.81	0.5
Cumulative	287.76	284.78	2.98

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6.0 Summary and Conclusions

The Boeing CLEEN program began in June 2010 and ended in December 2015. The program demonstrated a successful partnering among various stakeholders including industry, government, universities, and suppliers. Boeing and the FAA conducted a successful public relations campaign that showcased the CLEEN technologies at various venues and conveyed the environmental benefits. In conducting the program, Boeing adopted and followed the guidelines and strategies provided below.

- Open communication
- Methodical technology development
- Reduction of risks enabling technology transition
- Disciplined program execution, financial management, and risk management through the Boeing PMBPs
- Appropriate and timely technical and programmatic flexibility
- Identify learning/knowledge for future designs

All three technologies—Alternative Jet Fuels, ATE, and CMC Nozzle—had successful development programs. Technical maturation was achieved, all the while programmatic and technical risks were reduced, thereby promoting the technologies toward transition.

The Alternative Fuels testing was completed in 2011 for aromatics, and in 2013 for cycloparaffins. The testing was successful in defining the fuel absorption and seal swell properties for blends up to 50% for both aromatics and cycloparaffins. The results supported the ASTM D7566 International Fuel Specifications in 2012, and helped reduce the risks related to drop-in renewable fuel replacement strategies. The Alternative Fuels Public Report [1] in 2011 and an update in 2014 provides details of the technology development.

The ATE prototype system was demonstrated in-flight in 2012, on an American Airline Boeing 737-800. The prototype was a single-slotted flap and a simulated mini-split flap tested at low speed. The flight testing validated failure modes and verified the aerodynamic and acoustic performance of the technology. The testing also demonstrated the viability and capability for a mini-flap driven by SMA rotary actuator with closed-loop feedback control. The benefits and TPMs were identified for notional single-aisle and twin-aisle aircraft as part of a fleet-wide analysis. For these aircraft, a noise reduction range from 1.0 to 1.7 EPNdB CUM was derived. Similarly, a fuel savings benefit ranging from 0.5% to 0.9% was derived. When accounting for system weight penalty, the fuel savings is 0.5%. The potential 2% reduction in fuel use for a specific aircraft and mission was previously identified but not analyzed in this study Overall, the ATE technology will enable more efficient wing architectures.

The CMC was demonstrated in ground test in 2013, utilizing an RR T1000 engine and inflight test in 2014, utilizing a Boeing 787-8 airplane. The testing validated: (a) thermal performance in excess of Inconel at a weight below titanium, (b) noise performance equivalent to or better than metallic designs, and (c) capability for oxide CMC to operate at 1,500°F continuously. The benefits achieved were fuel savings up to 1.0%, noise reduction of 1.7 EPNdB with potential up to 2.3 EPNdB, and weight reduction > 20%. Overall, the CMC technology is a key enabler for future engine and nacelle architectures. The CMC Exhaust Public Report [2] provides details of the technology development.

Boeing is proud to have been part of the CLEEN program and thanks the FAA for the opportunity to work toward the goals of maturing and demonstrating promising, energy efficient, clean and quiet technologies, advancing sustainable alternative fuels for aviation, and assessing technology suitability for transition and implementation.

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7.0 Acronym List

Af	Austenite Finish Temperature
A/P	Airplane
AEC	Albany Engineered Composites
AEE	Office of Environment and Energy
AFRL	Air Force Research Laboratory
ANOPP	Aircraft Noise Prediction Program
ASCENT	Aviation Sustainability Center of Excellence
ATE	Adaptive Trailing Edge
ATK-COIC	ATK Space Systems/COI Ceramics Inc.
ATP	Authorization to Proceed
BCA	Boeing Commercial Airplanes
BDS	Boeing Defense, Space & Security
BR&T	Boeing Research and Technology
BT&E	Boeing Test and Evaluation
CDR	Critical Design Review
CFD	Computational Fluid Dynamics
CLEEN	Continuous Lower Energy, Emissions and Noise
CMC	Ceramic Matrix Composites
CO_2	Carbon Dioxide
CUM	Cumulative
DC2	Design Cycle 2
DDR	Detail Design Review
DEFSTAN	Defence Standard
EGT	Engine Exhaust Temperature
EO&T	Engineering, Operations & Technology
EPNdB	Effective Perceived Noise in Decibels
FAA	Federal Aviation Administration
FLIR	Forward Looking Infrared
FNK	Fink (ANOPP Airframe Noise Module)
FTD	Flight Test Demonstration
GHG	Greenhouse Gas
GTD	Ground Test Demonstration
HRJ	Hydrotreated Renewable Jet
HS	High Speed
ICAO	International Civil Aviation Organization

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ISO	International Organization for Standardization
L/D	Lift to Drag ratio
L/H	Length/Height (measure of acoustic treatment area)
LPT	Low Pressure Turbine
LS	Low Speed
LTO	Landing and Takeoff
Mf	Martensite Finish Temperature
MEA	More Electric Airplane/Aircraft
MPF	Mini Plain Flap
MSF	Miniature Split Flap
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System
NOx	Nitrogen Oxide
OPR	Operating Pressure Ratio
OTA	Other Transaction Agreement
PARTNER	Partnership for Air Transportation Noise and Emissions Reduction
PDR	Preliminary Design Review
PMBP	Program Management Best Practices
QTD	Quiet Technology Demonstrator
RIO	Risks, Issues, and Opportunities
RR	Rolls-Royce
SA	Single Aisle
SLM	System Level Modeling
SM	Supplier Management
SMA	Shape Memory Alloy
SOA	State of the Art
SOW	Statement of Work
SPK	Synthetic Paraffinic Kerosene
TA	Twin Aisle
Ti	Titanium
TO	Takeoff
TPM	Technical Performance Metric
TRL	Technology Readiness Level
UDRI	University of Dayton Research Institute
WBL	Wing Buttock Line
WTT	Wind Tunnel Test

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[2] C. A. Frankel, K. P. William, L. L. Lehman, E. Nesbitt, T. R. Pinney, M. P. Petervary and C. A. Wilsey, "CLEEN Oxide Ceramic Matrix Composite Exhaust Public Final Report," Boeing, December, 2015.

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