# CLEEN II Aft Fan Duct Acoustics Flight Demonstration Final Report (Public Version)

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## Acknowledgements

This report was prepared under Federal Aviation Administration (FAA) Other Transaction Agreement (OTA) DTFAWA-15-A-80011, Continuous Lower Energy, Emissions and Noise Technologies Program - Phase II (CLEEN II). It reflects the efforts associated with the second option awarded to Boeing under the CLEEN II Program: Aft Fan Duct Acoustics Flight Demonstration. The duration of this project was from October 2019 through December 2021.

Boeing thanks the FAA and the Office of Environment and Energy (AEE) for being selected to participate in the CLEEN II program and being awarded this additional project to further develop acoustics technologies in compact nacelle architectures.

The Boeing CLEEN II team thanks the following for their participation in making this program a success: Alaska Airlines for providing their 737 aircraft as part of the Boeing ecoDemonstrator Program; NASA for providing their Multi-Degree of Freedom (MDOF) Low Drag Liner Inlet; CFM International for providing their hardwall forward fan case liner; and Georgia Institute of Technology for their system level modeling efforts as part of the ASCENT program.

The Boeing CLEEN II team thanks several internal organizations within Boeing Commercial Airplanes (BCA) and Engineering, Operations & Technology (EO&T) for making this program a success.

The Boeing CLEEN II 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 program phase II (CLEEN II) began in October 2015 and ended in December 2021. The initial award of the CLEEN II program was for the Structurally Efficient Wing (SEW) project. The final reports for the SEW project were delivered in May 2020.

Subsequent to the initial program award, the FAA awarded Boeing two additional projects as options under the CLEEN II program. Both projects related to compact nacelle architectures. The first project focused on demonstrating the aerodynamic viability of a short inlet concept that provides improved fuel efficiency. This project was a collaboration with Rolls-Royce and the final reports were delivered in September 2018.

This report addresses the second option awarded under CLEEN II and focuses on the need for improved acoustics in compact nacelle architectures. Specifically, Boeing designed, fabricated, and integrated acoustically treated bifurcation fairings and blocker doors into the thrust reverser bifurcation regions of a LEAP-1B nacelle. A noise flyover test of the prototype hardware was conducted on the 737 MAX 9 in July 2021, providing data on the benefits from these technologies for future incorporation into next-generation nacelles. This testing demonstrated acoustic attenuation exceeding the pre-test predictions of 1.2 EPNdB cumulative for current aircraft in a retrofit scenario and supported the 1.5 to 2.4 EPNdB cumulative benefit for compact nacelle architectures in future aircraft, depending on the depth of treatment available in any given configuration.

Boeing's approach for CLEEN II built on its extensive experience in environmental technology demonstration programs. The project leveraged the Boeing ecoDemonstrator program which gave Boeing the unique opportunity to demonstrate aft fan duct acoustic technologies on a production aircraft.

As was done during the initial CLEEN program, Boeing employed its Program Management Best Practices (PMBP) to manage cost, schedule, technical performance, and risk. This approach, along with appropriate milestones and reviews, ensured readiness for flight demonstration.

# 2.0 Project Overview

## 2.1 Aft Fan Duct Acoustics Background and Summary

Boeing continues development of an advanced integrated propulsion system for implementation on the next generation of Boeing aircraft. Central to this development is the compact nacelle propulsion architecture, a key enabler of the ultra-high bypass (UHB) ratio engines that will be required.

Compact nacelles provide fuel burn improvement through drag and weight reductions, but experience drawbacks related to acoustics. As nacelle architectures become more compact, treatable acoustic area throughout the propulsion flow path is reduced. The effectiveness of conventional acoustic liners is also diminished because of new fan duct geometries with lower length to height ratios. Additionally, new fans generate source noise spectra with elevated tone levels at lower frequencies that are difficult to attenuate with conventional lining systems. The combined effects of lining area loss, reduced lining effectiveness and lower frequency fan tones result in a noise performance risk exceeding 2-3 EPNdB in some configurations, driving a need for tailored improvements to the lining architecture.

In 2018, Boeing's Quiet Technology Demonstrator 3 (QTD3) program highlighted advanced inlet liners, developed and flight tested in collaboration with NASA (Figure 2-1) [3]. These new inlet liners exceeded expectations and showed improvements over current liner configurations. Improvements to the inlet lining systems addresses the noise experienced by communities in the local vicinity of airports both during takeoffs and landings as the airplane approaches the observer. This is often referred to as forward arc noise with the communities positioned ahead of the airplane. Aft arc noise represents the noise source heard as the airplane has flown over the communities and continues to fly along its path. Whereas previous inlet lining projects focused on forward arc noise, this CLEEN II project focused on the aft arc with the objective of reducing fan noise by applying acoustic lining design improvements, along with increased acoustic lining coverage, to the aft fan duct acoustic lining system (Figure 2-2).

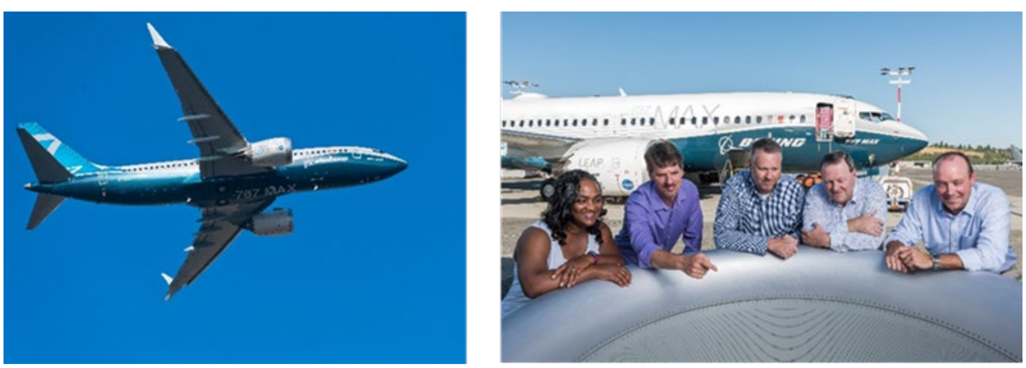


*Figure 2-1 - Photos from QTD3 flight demonstration in 2018 showing 737 MAX 7 aircraft (left) and NASA leaders standing with Advanced Inlet (right).*

Specifically, this project extended application of advanced acoustic liner designs into the bifurcation duct region aft of the fan. Design data, prior experimental results and localized acoustic predictions were applied to an advanced liner concept for the inner flow structure that efficiently attenuates aft-radiating noise. The objective of this prototype hardware demonstration was to obtain flight scale data on the extent of acoustic performance that can be recovered through additional treatment in critical areas of the duct and apply the knowledge gained to next-generation, compact nacelles.

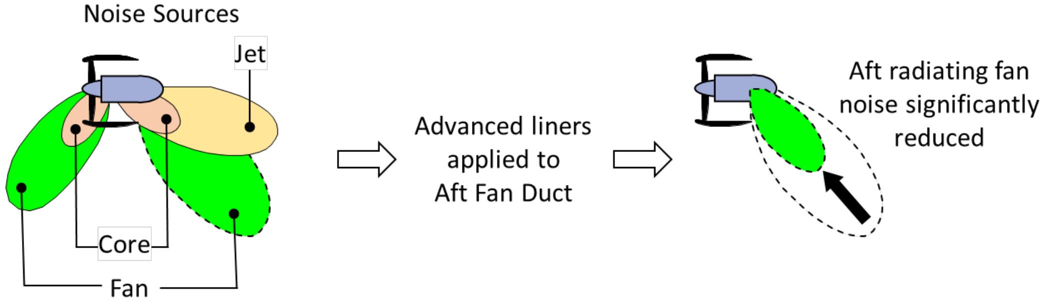



*Figure 2-2 - Advanced liner technology applied to the aft fan duct and blocker doors reduces aft radiating fan noise.*

Boeing designed and fabricated a set of flight-worthy acoustic fairings or “glove” prototypes for the upper and lower bifurcation regions of a production LEAP-1B Thrust Reverser (TR) (Figure 2-3). The gloves are mechanically fastened over the existing Titanium inner wall structure to increase both the effective treated area, and the effective depth of the lining. Additionally, production blocker doors are replaced with treated versions of an advanced acoustic design (Figure 2-4). These changes significantly increase the treated area of the aft fan duct from 50% to 70% of total wetted area (increase of 40%). These fan duct lining prototypes incorporate the following key acoustic features:

- Cores with more focused attenuation performance for low frequency fan tones while maintaining high frequency attenuation capabilities
- Facesheets for improved performance over a wider range of engine power settings
- Expansion of lining area and an increase of lining depth

The prototype hardware was flown in July 2021 on a 737 MAX 9 on loan from Alaska Airlines as part of the Boeing ecoDemonstrator program. For the duration of testing, the test engine was also equipped with the NASA Multi-Degree of Freedom (MDOF) Low Drag Liner inlet developed as part of the QTD3 program and loaned to the Boeing CLEEN II program by NASA, as well as an acoustically smooth forward fan case provided by CFM International. Flight testing took place over twelve days in Glasgow, Montana.

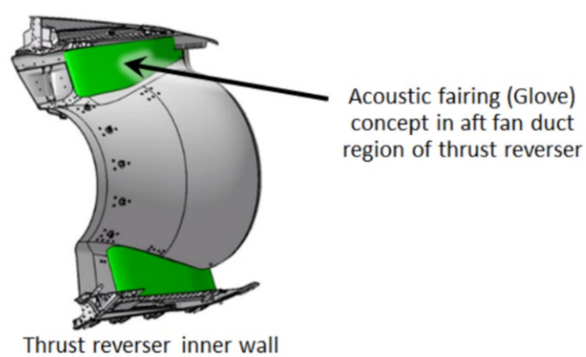



*Figure 2-3 - Thrust reverser inner wall bifurcation with acoustic fairings “gloves”.*

Production blocker doors (untreated) | Treated blocker door concept

*Figure 2-4 - Production (untreated) blocker door shown next to concept for acoustically treated prototype with facesheet removed.*

## 2.2 Technology Benefits

The benefits of the Boeing CLEEN II Aft Fan Acoustic technologies are summarized in Table 2-1. Pre-test benefit predictions were shown to be conservative by the flight test program. The discussion below provides further details on how the pre-test and final projections were developed.

*Table 2-1 - Benefits of the CLEEN II Aft Fan Acoustic technologies*

| Compact Nacelle Technologies | Goal Impact | Benefits (Cumulative EPNdB) | | Application |
|---|---|---|---|---|
| | | Target | Final | |
| Acoustic improvements to Thrust Reverser Aft Fan Duct:<br>• Increased acoustically treated area<br>• Advanced acoustic liner | Community Noise Reduction | 0.4 to 1.2 | 1.5 to 2.4 | new aircraft |
| | | 0.2 to 0.6 | Up to 1.2 | retrofit |

## 2.3 Program Management

The Boeing CLEEN II program was led by Boeing Research and Technology (BR&T), the research and development unit of Boeing. Boeing Commercial Airplanes (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 flight tests. Together the business units performed as an integrated “best of Boeing” team to accomplish CLEEN II 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 several subcontractors and suppliers.

## 2.4 Schedules/Milestones/Deliverables

An overview of the original project schedule, including technical development, major milestones and deliverables is provided below in Figure 2-5. As a result of several factors outside the control of the Boeing CLEEN II team, including the availability of the 737 MAX aircraft for flight testing and the impact of a worldwide pandemic, the project was delayed by approximately 15 months. Figure 2-6 depicts the revised schedule, as executed. Flight testing that had been planned for spring of 2020 occurred in the summer of 2021.

Accompanying these major program-level milestones were lower tier program milestones and technology-level milestones. The flight test program was tied-to and integrated-with Boeing's ecoDemonstrator program and schedule. Upon maturation of preliminary designs, a Preliminary Design Review (PDR) and Detailed Design Review (DDR) were conducted to ensure technology maturation appropriate for readiness for flight test. The Safe to Fly (S2F) milestone represents the full ecoDemonstrator program level approval of the CLEEN II modified TR for operation on the flight test vehicle.

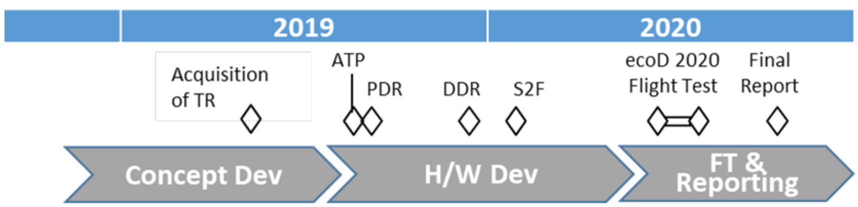



*Figure 2-5 - Overview of the Boeing CLEEN II Aft Fan Duct Acoustics Project (at contract award)*

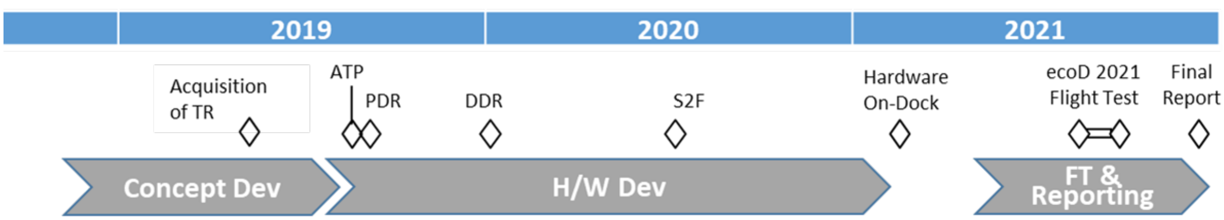



*Figure 2-6 - Overview of the Boeing CLEEN II Aft Fan Duct Acoustics Project (as executed)*

# 3.0 Technology Demonstration

## 3.1 Technology Development

The primary objective of this project was to regain the acoustic performance lost when implementing compact nacelle architectures in the next generation of Boeing aircraft. Compact nacelles enable UHB engine installation and also provide fuel burn improvement through drag and weight reductions, but experience drawbacks related to acoustics. As nacelle architectures become more compact, treatable acoustic area is reduced, and for this reason and others, the net impact on noise performance could exceed 2-3 EPNdB.

One way to regain acoustic performance, is to improve the acoustic attenuation of the aft fan duct in terms of increasing the amount of treated area as well as designing that treatment in a way to optimize the attenuation of aft fan radiating noise sources. Boeing has done extensive research and development of nacelle inlets to address forward radiating fan noise. This project builds on that knowledge and experience with a focused demonstration of thrust reverser acoustic technologies.

The CLEEN II Aft Fan Duct Acoustics project Tier 2 schedule in Figure 3-1 summarizes project tasks, milestones, and associated deliverables as the project was executed and factoring in the 15 month delay primarily caused by the slide to the ecoDemonstrator program and by collateral impacts resulting from the COVID-19 pandemic. We integrated lower tier schedules with proactive earned value management to ensure the project was performed within cost and schedule constraints. In addition, the FAA received technical and programmatic status through monthly reports and at major reviews and CLEEN II consortiums.

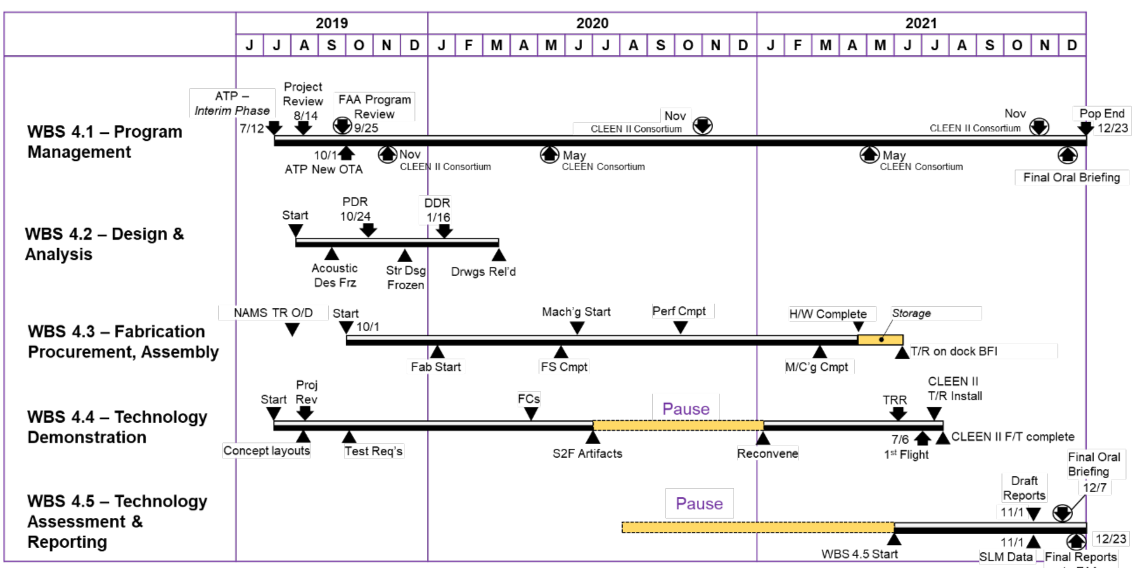
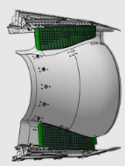
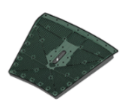



*Figure 3-1 - CLEEN II Aft Fan Duct Flight Demonstration project Tier 2 schedule*

## 3.2 Acoustic design approach

The overall acoustic goals were to end up with a design that resulted in both a clearly measureable noise reduction and a high probability of product insertion. With this in mind, the design concept was to increase acoustic lining area, maximize its efficiency and distribute it for maximum noise reduction. In addition, analytical predictions were used to guide and optimize the hardware design. This led the team to optimize the acoustic treatment in bifurcations and blocker door regions. The motivation behind this approach is founded in developing best practices for compact nacelle acoustic treatment, which inherently contains less duct length and diameter, and therefore less wetted area available to integrate acoustic treatment. Furthermore, next generation engines are expected to have greater available surface area in the bifurcations compared to current configurations due to higher bypass ratios. Table 3-1 shows the objective and executed acoustic lining area in the final design. Figure 3-2 compares the final acoustic area developed for the CLEEN II experimental TR to the production LEAP-1B fan duct lining coverage.

*Table 3-1 - Acoustic lining area in CLEEN II experimental TR*

| Region | | Design Objective | Final Design |
|---|---|---|---|
| Bifurcations |  | 60% acoustic yield per bifurcation | 48% upper<br>59% Lower |
| | | Full-depth area (>27%) | 31% upper<br>37% lower |
| Blocker Doors |  | 70% acoustic yield per blocker door | 65% |

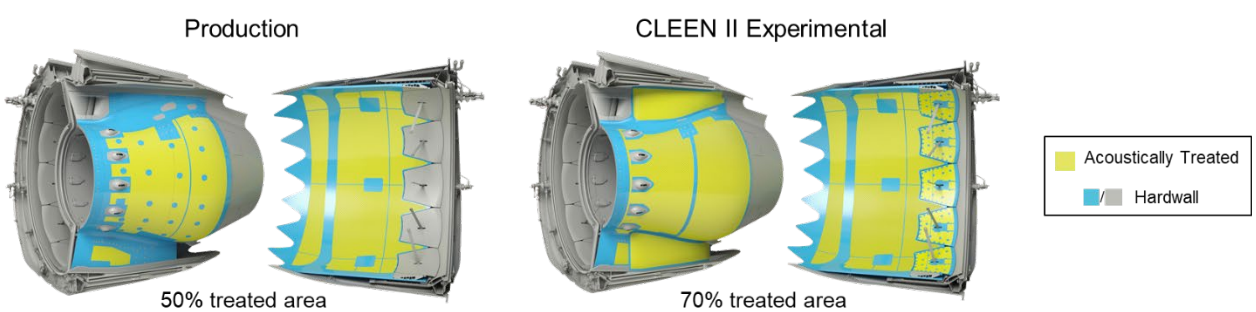



*Figure 3-2 - Total acoustic treatment in the CLEEN II experimental TR compared to the production TR.*

In order to know the design improvement was measurable, a cumulative noise reduction target of 0.2 to 0.6 EPNdB on the 737 MAX was set as being something that experience suggested would be able to be measured in a demonstration flight test. This target, when applied to a future aircraft, would be expected to result in a larger cumulative noise reduction of between 0.4 and 1.2 EPNdB. Also, in order to maximize the probability of measurement, the fan tone noise was specifically targeted for reduction since these tones are seen clearly in measurements.

Two duct attenuation modeling tools were used for the acoustic design and analysis of the bifurcation fairings and blocker doors: CDUCT [2] and COMSOL Multiphysics® [1]. CDUCT is a Boeing developed code which utilizes a parabolic approximation of the convected Helmholtz equation in order to efficiently model acoustic propagation in an acoustically treated, complex-shaped duct with mean flow. The parabolic approximation in CDUCT neglects reflections that couple downstream propagating waves with upstream propagating waves and transforms the problem into solving one-way wave propagation, which can be accomplished with a computationally fast marching method. In addition, the parabolic approximation in CDUCT is a low-angle implementation that is less accurate for high-angle spinning modes, but can quickly produce results on typical engineering workstations. This code generated the Mach number contours and acoustic mode propagation plots shown in Figure 3-3.

COMSOL Multiphysics® is commercially available software used for modeling physics and processes in many different fields of engineering, manufacturing, and science. For CLEEN II, the flow through the aft fan duct was modeled with the compressible potential flow physics module and acoustic propagation was modeled with the linearized potential frequency domain acoustics module. These modules utilize the Finite Element Method (FEM) to solve the appropriate partial differential equations. The software is able to utilize geometry from Computer Aided Design (CAD) models which accurately describe both the flow surfaces as well as the acoustic area boundaries. As a result of this additional complexity, the COMSOL® predictions took much longer and were typically performed on a Boeing High Performance Computing Linux Cluster.

A validation analysis was performed early in the project to establish the appropriate methodology for the 737 MAX fan duct. Using available aft-radiating fan noise test data, the prediction models were compared for application on the CLEEN II project. The CDUCT code was then selected as the primary design and pre-test prediction tool for the CLEEN II experimental TR as it was able to provide accurate trend data with fast turn around time.

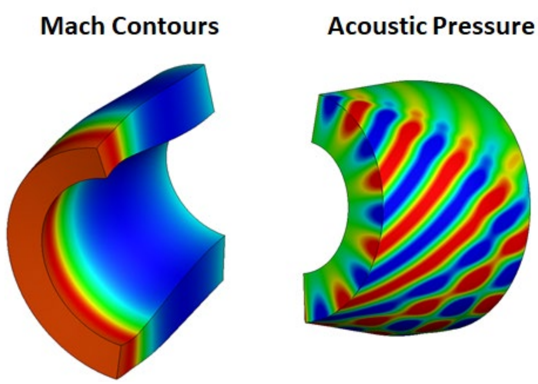



*Figure 3-3 - Example of fan tone spinning mode propagating down the duct, where acoustic pressure encounters the bifurcations*

## 3.3 Aerodynamics design

The bifurcation fairings, or gloves, are installed over the top of the existing structure in the fan duct bifurcation region. This was an efficient and cost-effective way to test prototype bifurcation acoustic lining, but for several reasons would not be the approach taken for implementing bifurcation acoustic treatment in a production nacelle. One reason for this is that the fairings protrude into the fan duct and impact the aerodynamic contours created by the TR inner walls.

In order to minimize this impact on engine performance, which can adversely affect engine operation as well as acoustic performance, an aerodynamic contour for the bifurcation gloves was developed to minimize these impacts while ensuring safety of flight and making sure that quality acoustic data can be collected during the flight test.

Several iterations of the glove contour were attempted prior to finalizing the configuration. The final glove configuration was assessed using 3-D Computational Fluid Dynamics (CFD) analyses for several key operating conditions. The resulting fan duct delta mass flow confirmed minimal duct flow loss at key conditions. Likewise, the exhaust system overall delta thrust impact was well within acceptable limits for safe operation and flight.

In addition to the Boeing assessment, the 3-D CFD results were shared with the LEAP-1B engine manufacturer, CFM International, who provided a “No Technical Objection” memorandum for operation on the ecoDemonstrator aircraft with the acoustic gloves installed.

## 3.4 Mechanical Design of fabrication of the prototype hardware

Using the acoustic requirements along with the validated aerodynamic contours for the bifurcation gloves, design of the prototype hardware was accomplished using standard Boeing practices and design guidelines for flight test hardware. As previously mentioned, the hardware is designed for installation on the LEAP-1B engine for flight testing on the 737 MAX 9 ecoDemonstrator. To develop the experimental hardware as cost efficiently as possible, Boeing modified an existing flight test thrust reverser (TR) that had been built during the original 737 MAX development program. This TR was a spare unit intended for Nautical Air Miles Survey (NAMS) flight testing and had been in storage since the initial NAMS flight testing completed. After a detailed inspection confirming it had retained its flight worthy status, it was shipped to Charleston, South Carolina where the design and fabrication of the hardware modifications were completed by the BR&T team at the Boeing Technology Center in Ladson, SC.

Rather than redesigning the bifurcations in the fan duct, we designed and fabricated a bespoke set of flight-worthy acoustic fairings or “glove” prototypes for installation into the existing thrust reverser. The untreated production blocker doors were replaced with treated versions of an advanced acoustic design. Figure 3-4 provides an overview of the added and modified hardware.

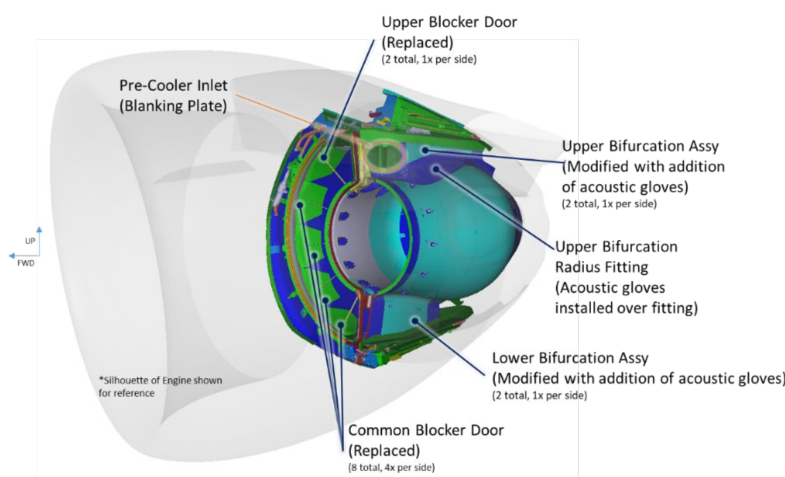



*Figure 3-4 - Thrust reverser walk-around showing each of the features being added and/or modified*

## 3.5 Pretest Acoustic Benefit Predictions

Prior to flight testing, the predicted benefit of the CLEEN II technologies on an airplane level was assessed. This process factored in tonal and broadband noise levels at approach, flyover, and lateral positions to develop a cumulative EPNdB prediction as shown in Figure 3-5.

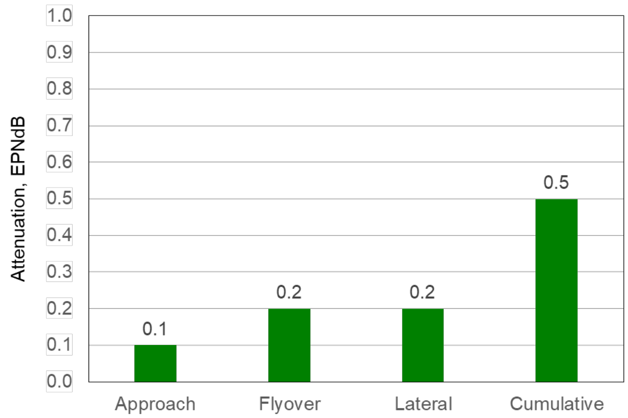



*Figure 3-5 - Pre-test prediction of airplane level attenuation resulting from CLEEN II Experimental TR acoustic technologies*

# 4.0 Test Article Description

## 4.1 Thrust Reverser Articles and Configurations

The thrust reverser test articles consisted of a Production TR and an Experimental TR (Figure 4-1). Each TR was tested in a fully-treated and fully-hardwall configuration, utilizing speed tape to cover all the acoustic perforations to represent hardwall configurations. A fifth configuration, with only the Experimental TR bifurcations exposed, was also part of the test plan.

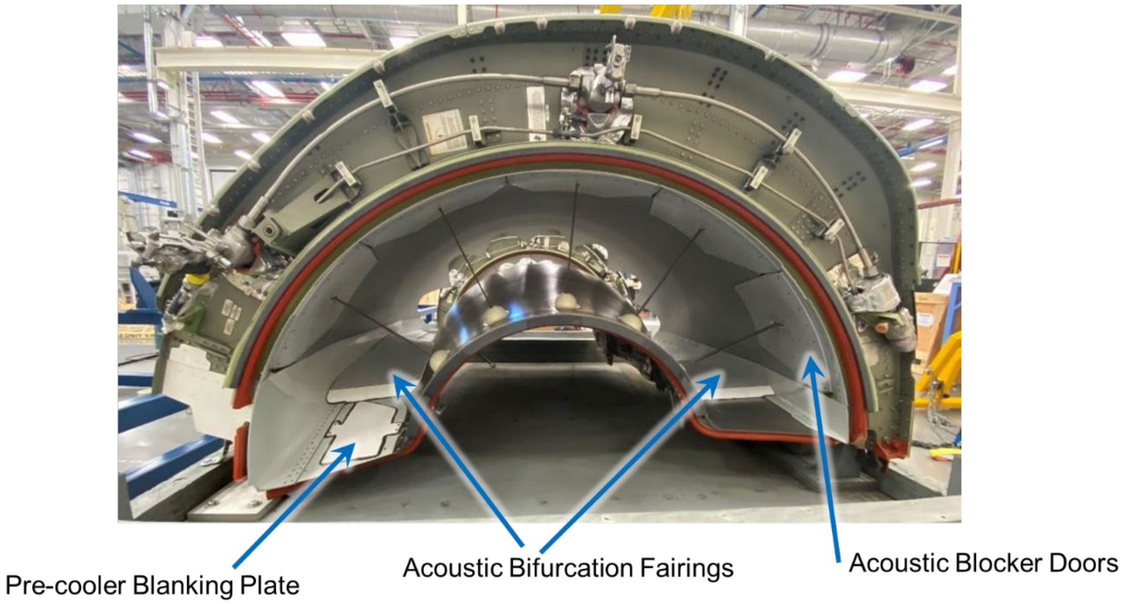



*Figure 4-1 - Photo of one half of CLEEN II Experimental TR.*

# 5.0 Test Site and Ground based instrumentation

## 5.1 Test Site

The CLEEN II acoustic flyover test was held at Glasgow Industrial Airport near Glasgow, Montana (FAA identifier 07MT). It is a deactivated US Air Force SAC Base with elevation 2762 feet.

The acoustic instrumentation was set up north of the approach end of Runway 14L as shown in Figure 5-1. The test conditions simulating takeoff noise were conducted by flying south-to-north over Runway 32R such that the target altitude, airspeed and engine thrust were achieved over the microphone arrays at the correct time. The test conditions simulating approach noise were conducted approaching Runway 14L flying north-to-south (Figure 5-2).


*Figure 5-1 - Glasgow Industrial Airport aerial view*

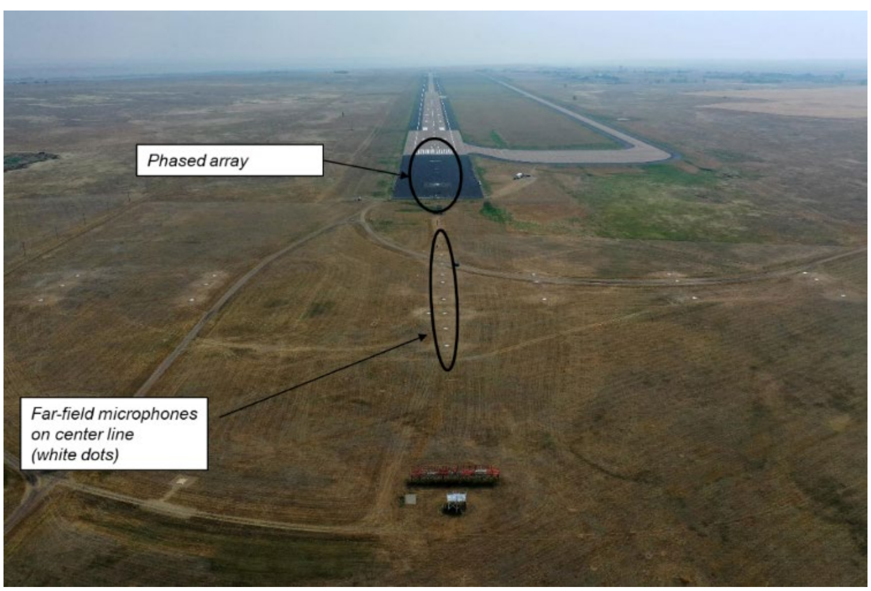



*Figure 5-2 - View of Northwest Runway with phased array and centerline microphones*

Noise testing personnel were stationed at Glasgow, MT for the duration of the test. Two mobile test trailers were brought onto the airport ground by the Boeing Aero Noise and Propulsion (ANP) laboratory to provide workspace for test data recording and on-site data processing. They are referred to as Big MAC (Mobile Acoustic Center) and Phased Array over the radio communications during flight testing. The Noise Lab test director and Acoustic on-site test focal continuously communicated with the flight crew on board the airplane using radios on a private communications channel. Figure 5-3 shows the Glasgow runway end with Phased Array trailer off to the side, and a small metal structure approximately 200 ft away from the overrun. The structure is about 12 feet tall and did not interfere with testing or instrumentation.

*Figure 5-3 - Glasgow runway end with a small structure highlighted by the red circle.*

## 5.2 Weather Instrumentation

At Glasgow airport, weather conditions are monitored at the surface and in atmospheric layers up to 3000 ft. A photo of the surface weather system is shown in Figure 5-4. The ANP laboratory 10−meter surface weather system (SWX) was used to measure weather parameters at a location geographically representative of the test site.

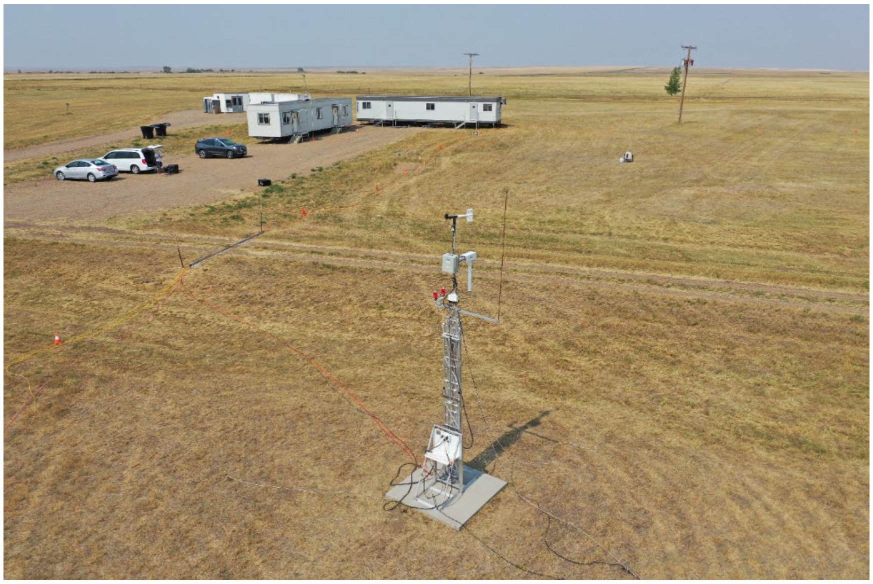


*Figure 5-4 - 10m Surface Weather Station, SWX, with the data acquisition and analysis trailers in the background*

Upper air weather monitoring (UAWX) is a critical component of gathering acoustic data. The upper air weather data is used in two ways. First, the weather conditions were checked against the test requirements criteria. Second, the weather data is used to correct the noise measurements to a standard atmosphere, so acoustic data may be reviewed on a normalized basis. The Metrology (MET) airplane shown in Figure 5-5 is a Cessna 206, and measures the air temperature, wind, and relative humidity in a pod mounted on the wing strut. The MET airplane was launched prior to the pre-test briefs, and then every hour during the test window.

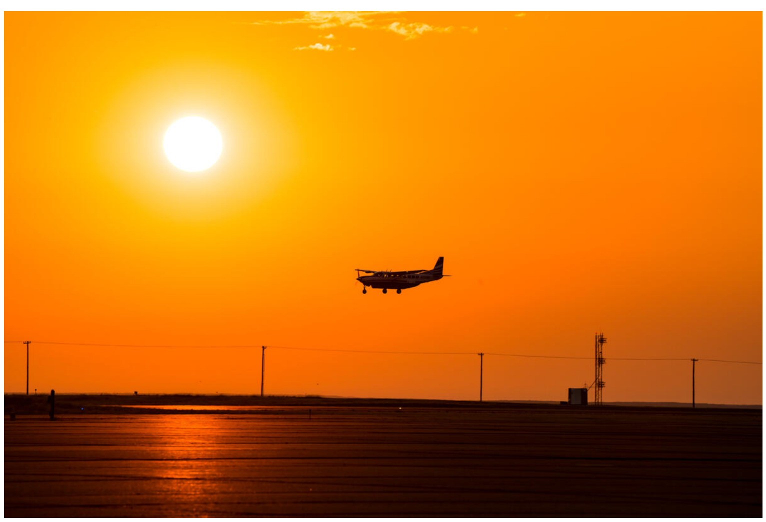


*Figure 5-5 - Upper Air Weather Airplane performing a Metrology run*

## 5.3 Ground Array Noise Instrumentation

Boeing transported all of the equipment and ground personnel necessary to complete the community noise flyover test at Glasgow, MT. This included the following support instrumentation:

- Acoustic data system (including microphones and data processing instrumentation)
- Surface weather system (SWX)
- Upper air weather measurement (UAWX)
- Ground telemetry station
- 840 channel Phased Array microphone noise data recording system
- On-site data reduction system
- GPS landing system ground instrumentation
- Global airplane positioning system (GAPS) ground station
- Weather forecasting

## 5.4 Flyover Array Microphones

The Flyover Array consisted of ground plane microphones on SAE bases and four-foot pole microphones that matched a certification setup. The layout of the ground microphone arrays in relation to the runway threshold are depicted in Figure 5-6. The 840 microphone phased array was the closest to the threshold and the center of the ground microphone array 1850' away at the coordinate system origin (x, y, z = (0, 0, 0)).

An SAE ground microphone base and one of the pole microphones are shown in Figure 5-7. Pole microphones are set at 4 ft height and are the standard microphone configuration for acoustic certification testing. The ground microphone ensemble array data are used exclusively to determine the noise effects of the technology being tested since ground reflection can have a detrimental effect on being able to spectrally see the effects and separate them.

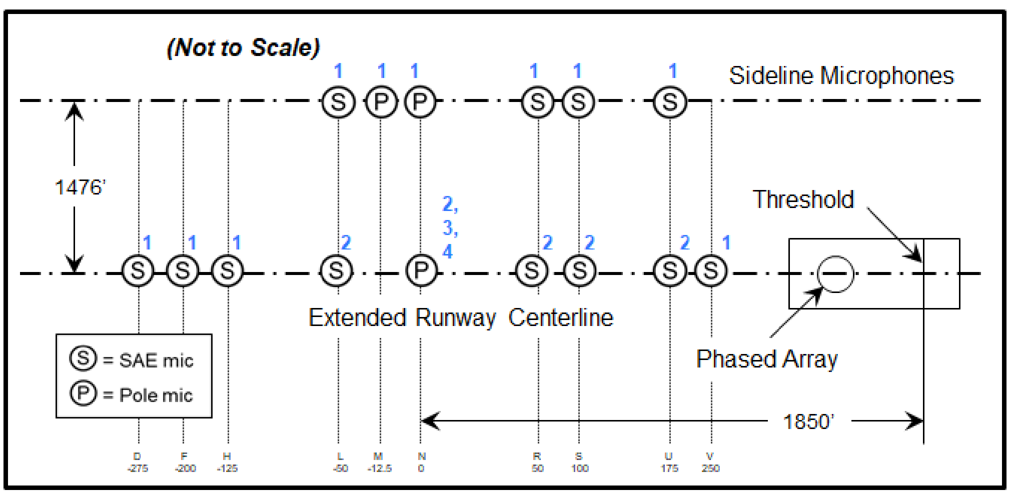



*Figure 5-6 - Layout of the Glasgow, MT Microphone Arrays*


*Figure 5-7 - SAE Ground Plane Microphone Base and Pole Microphone*

## 5.5 Phased Array Microphones

The ground phased array consisted of nested subarrays of various aperture sizes and microphone distributions. The subarrays were designed to provide optimal measurement capabilities over multiple overlapping frequency bands, as well as optimal capabilities as a function of airplane emission angle. Data were processed at emission angles from 60° to 120° in 10° increments (7 angles total). Microphones were shared between subarrays in order to reduce channel count. The phase centers of all subarrays were co-located. Figure 5-8 shows an example of three subarrays within the phased array.

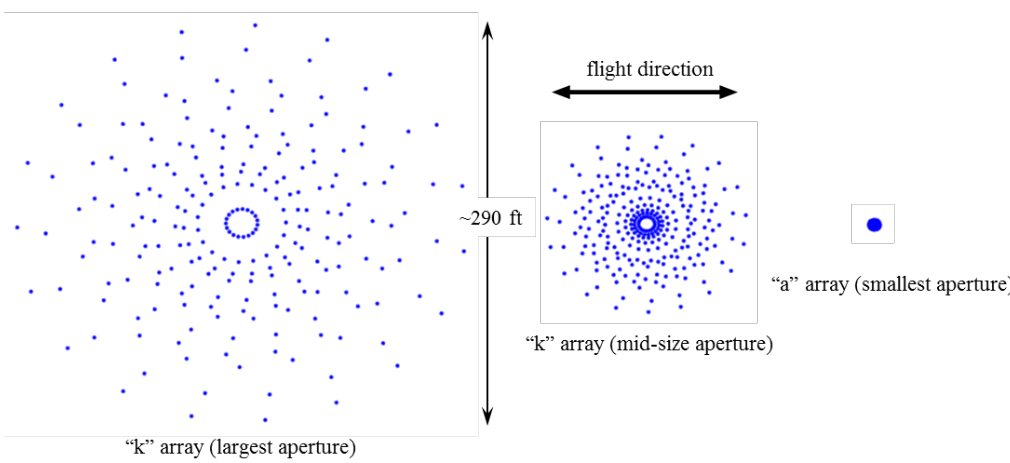



*Figure 5-8 - Sample phased array subarray configurations.*

A highly accurate survey process is used to locate the microphones and generate the defined pattern. The microphones are marked with white notecards. The power supply and pre-amplifiers are covered with foam to minimize interference with the recordings of the phased array microphones. Figure 5-9 contains photos of the phased array setup. Phased array microphones are smaller and of lesser quality than the ground microphones, but function well on a relative basis to generate the beamforming data for noise source determination.

*Figure 5-9 - Phased Array Microphones, power supplies, and locators*

# 6.0 Test Airplane

A 737 MAX 9 was the flying test bed for the CLEEN II Compact Aft Duct project (Figure 6-1). The Boeing 737 MAX is a narrow-body twin-engine aircraft series developed by Boeing Commercial Airplanes as the fourth generation of the B737 aircraft, outfitted with CFM LEAP-1B engines. The aircraft used for the test was tail number 1D204, on loan from Alaska Airlines as as part of the Boeing ecoDemonstrator program and was fully representative of a production aircraft from an acoustics standpoint. Additionally, no external modifications were made that would impact airframe acoustic characteristics.

*Figure 6-1 - Boeing 737 MAX 9 on Glasgow, MT Airport tarmac*

## 6.1 Test Engine

The CFM LEAP-1B engine is a high bypass turbofan engine with a 69.4” fan diameter and 18 fan blades. It is a modernized replacement for the successful CFM56-7B that is featured on the 737NG. The right engine, taken from the pilot’s frame of reference (Aft looking forward), was selected for the test article configurations (Figure 6-2).

*Figure 6-2 - Right Engine outfitted with test hardware*

The acoustic flyover conditions were performed with the right engine at power and the left engine at flight idle. This technique has been utilized on previous technology tests with good acoustic results. A key advantage of testing one engine at power is that only one set of modified engine nacelle hardware item of each design configuration is required, rather than a test outfitting both engines. The acoustic analysis simulates two-engine operation by doubling the engine noise component. A set of airframe noise conditions were also conducted for both takeoff and approach conditions with both engines at idle conditions for the purpose of subtracting out the noise contribution of the airframe. Subtracting out the airframe from the total measurements leaves the noise contribution from the engine. In order to improve the signal to noise of the aft fan component, additional noise improvements to the inlet and engine forward fancase acoustic treatment were incorporated and tested with every tested configuration. These improvements were an acoustically smooth forward fan case provided by CFM International and an inlet equipped with an acoustically smooth triple acoustic liner provided by NASA.

# 7.0 Test Execution

## 7.1 Test Summary

Flight testing started on July 8, 2021 with the fully hardwall Production TR. The tape was removed immediately upon completion of the flyover testing and the fully treated Production TR was tested the next day.

After completion of the first two configurations, the CLEEN II Experimental TR was installed and testing resumed. Four configurations of the CLEEN II Experimental TR were tested with the last day of testing occurring on July 18. All planned conditions were successfully completed.

Figure 7-1 shows a Flight Aware webpage screen capture of the actual flight race track pattern for the aircraft from one day of testing (July 8th). Initial racetracks were generally "looser" at 12-15 minutes per loop. As each day progressed and pilots grew more comfortable, the racetracks tightened up to approximately 7 minutes per loop. When the MET airplane was launched each hour, the airplane left the racetrack pattern and flew away from the airport. MET runs typically lasted about 10 minutes.

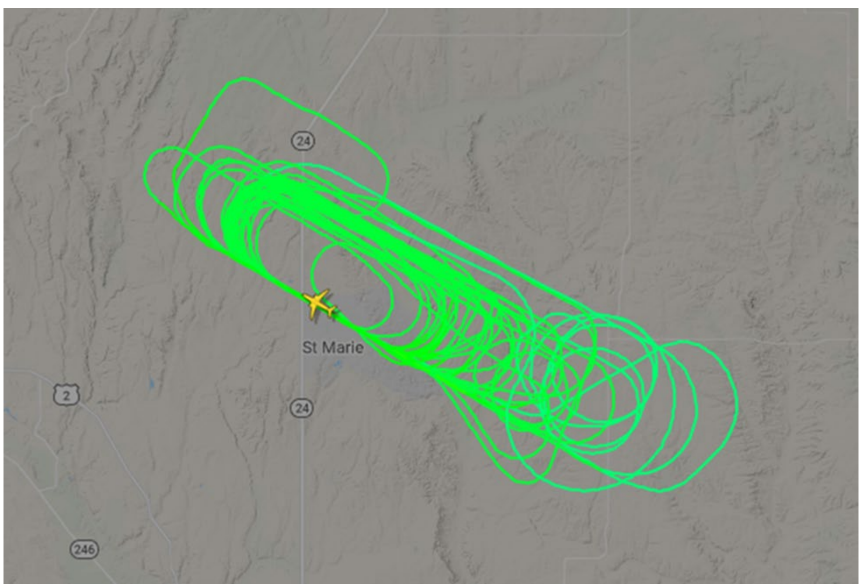



*Figure 7-1* - Flight Tracks for a Typical Test Day

# 8.0 Test Results

## 8.1 Retrofit Scenarios

To assess the CLEEN II aft fan duct acoustic technologies in a retrofit scenario, the airplane level assessment of the 737 MAX 9 aircraft was performed using normalized flight test data. Figure 8-1 shows the total effects of the CLEEN II package where the total airplane level cumulative noise attenuation is on the order of 1.2 EPNdB relative to the 737 MAX 9 airplane with the addition of the acoustically smooth forward fan case and the NASA MDOF inlet. This result is significantly greater than the pre-test predictions particularly at the flyover and lateral points.

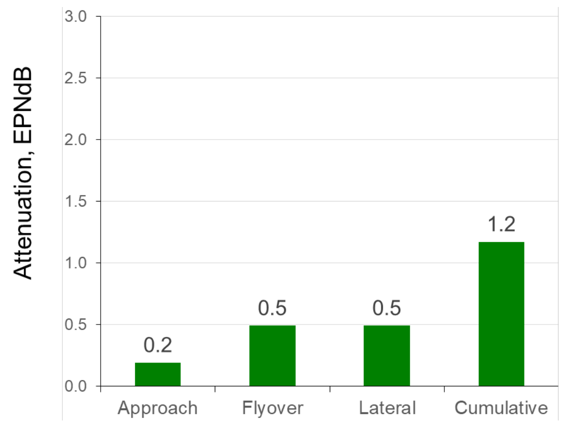



*Figure 8-1 - Total Airplane Benefit of the CLEEN II technologies as applied to a 737 MAX 9 Airplane*

## 8.2 Next Generation Aircraft

The results from the testing were then scaled and applied to an airplane model representative of the next generation of Boeing aircraft. Figure 8-2 shows this result. As expected, due to the larger contribution of aft fan noise, the effect of the advanced acoustic lining on this airplane is significantly greater. Note that this prediction makes assumptions regarding the depth of lining in the ultimate UHB compact nacelle. As a result, a range of potential attenuation values are provided in Table 2-1, representing varying assumptions for available lining depth.

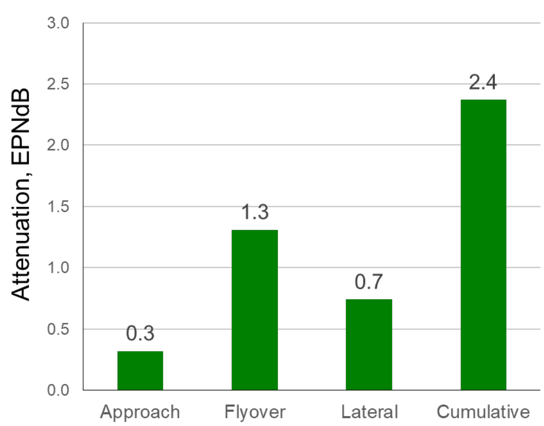



*Figure 8-2 - Total Airplane Benefit of the CLEEN II technologies as applied to a next generation Boeing aircraft*

# 9.0 Summary

This project successfully demonstrated acoustic technologies to be implemented in the compact nacelles that enable the fuel burn and weight efficiency targets for the next generation of Boeing aircraft, taking them to TRL7 through representative flight testing on the 737 MAX 9 ecoDemonstrator. These technologies can also be applied to some current Boeing aircraft in a retrofit scenario. The CLEEN II team set out to improve community noise on the order of 1.2 EPNdB cumulative for new aircraft and 0.6 EPNdB cumulative in a retrofit scenario, but in fact exceeded those goals significantly as presented herein and as summarized in Table 9-1.

Boeing had projected that UHB engines installed with compact nacelles could result in a noise performance risk exceeding 2-3 EPNdB, so achieving this result provides strong incentive to incorporate these CLEEN II aft fan acoustic technologies into the next new aircraft.

*Table 9-1 - Benefits of CLEEN II Aft Fan Acoustics technologies*

| Compact Nacelle Technologies | Goal Impact | Benefits (Cumulative EPNdB) | Application |
|---|---|---|---|
| Acoustic improvements to Thrust Reverser Aft Fan Duct:<br>• Increased acoustically treated area<br>• Advanced acoustic liner | Community Noise Reduction | 1.5 to 2.4 | new aircraft |
| | | Up to 1.2 | retrofit |

This report summarizes the second option awarded to Boeing under the CLEEN II program. Additional data is available in CLEEN II contractual deliverables, including design review packages, consortium briefings, ground and flight test reports, and monthly status reports. Additional documentation is archived at Boeing for use in technology transition efforts.

# Acronym List

| | |
|---|---|
| ASCENT | Aviation Sustainability Center |
| ATP | Authority to Proceed |
| BCA | Boeing Commercial Airplanes |
| BCW | Boeing Canada Winnipeg |
| BR&T | Boeing Research and Technology |
| BT&E | Boeing Test and Evaluation |
| CDTR | Curved Duct Test Rig |
| CFD | Computational Fluid Dynamics |
| CFRP | Composite Fiber Reinforced Plastic |
| CN | Compact Nacelle |
| dB | Decibel |
| DDR | Detailed Design Review |
| ECS | Environmental Control System |
| ecoD | ecoDemonstrator |
| EIS | Entry Into Service |
| EO&T | Engineering, Operations, and Technology |
| EPNdB | Effective Perceived Noise, Decibels |
| EPNL | Effective Perceived Noise Level |
| GAPS | Global airplane positioning system |
| MDOF | Multiple Degree of Freedom |
| MET | Metrology Airplane |
| NAMS | Nautical Air Miles Survey |
| OTA | Other Transaction Agreement |
| PDR | Preliminary Design Review |
| PMBP | Program Management Best Practices |
| PoP | Period of Performance |
| QTD | Quiet Technology Demonstrator |
| SAC | Strategic Air Command |
| SAE | Society of Automotive Engineers |
| S2F | Safe to Fly |
| SDOF | Single Degree of Freedom |
| SWX | Surface Weather Station |
| TR | Thrust Reverser |
| UAWX | Upper air weather monitoring |
| UHB | Ultra High Bypass |

# References

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