NASA/CR–2016-219005

Flight Services and Aircraft Access: Active Flow Control Vertical Tail and Insect Accretion and Mitigation Flight Test

Edward A. Whalen
The Boeing Company, Hazelwood, Missouri

January 2016

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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Nomenclature

β	Sideslip Angle
δ_r	Rudder Deflection
AFC	Active Flow Control
AOA	Angle of Attack
APU	Auxiliary Power Unit
ARC	Ames Research Center
ARFF	Aircraft Rescue and Firefighting
ASRB	Airplane Safety Review Board (NASA)
ATC	Air Traffic Control
BCA	Boeing Commercial Airplanes
BT&E	Boeing Test and Evaluation
CFD	Computational Fluid Dynamics
CSFL	Continued Safe Flight and Landing
EME	Electromagnetic Effects
EMI	Electromagnetic Interference
ENOVIA	Enterprise inNOVation Interactive Application
ERA	Environmentally Responsible Aviation
ES	Engineered Surface
FBO	Fixed Base Operator
FCF	Functional Check Flight
FOD	Foreign Object Damage
FTP	Flight Test Plan
GSE	Ground Support Equipment
GUI	Graphical User Interface
IAM	Insect Accretion and Mitigation
IAW	Initial Air Worthiness (Flight)
KBFI	Boeing Field – King County International Airport
LaRC	Langley Research Center
MAK	Methyl Amyl Ketone
MPK	Methyl Propyl Ketone
NDI	Non-Destructive Inspection
NSRS	NASA Safety Reporting System
OML	Outer Mold Line
PD	Product Development
RTB	Return To Base

SMAAART	Structures, Materials, Aerodynamics, Aerothermodynamics, and Acoustics Research and Technology
SOF	Safety of Flight
SOW	Statement of Work
TAI	Thermal Anti-Ice
TRACON	Terminal Radar Approach Control Facilities
TO	Take Off
TOL	Temporary Operating Limitation
TUI	TUI Group travel and tourism company

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1 Introduction

This document serves as the final report for the Flight Services and Aircraft Access task order NNL14AA57T (Reference (3)) as part of NASA Environmentally Responsible Aviation (ERA) Project ITD12A+. It includes descriptions of flight test preparations and execution for the Active Flow Control (AFC) Vertical Tail and Insect Accretion and Mitigation (IAM) experiments conducted on the 757 ecoDemonstrator. For the AFC Vertical Tail, this is the culmination of efforts under two task orders (Reference (1) and (2)).

The task order was managed by Boeing Research & Technology and executed by an enterprise-wide Boeing team that included Boeing Research & Technology, Boeing Commercial Airplanes, Boeing Defense and Space and Boeing Test and Evaluation.

Figure 1 illustrates the organizations engaged while executing the Flight Services and Aircraft Access task order. Boeing BR&T in St. Louis was responsible for overall Boeing project management and coordination with NASA. The 757 flight test asset was provided and managed by the BCA ecoDemonstrator Program, in partnership with Stifel Aircraft Leasing and the TUI Group.

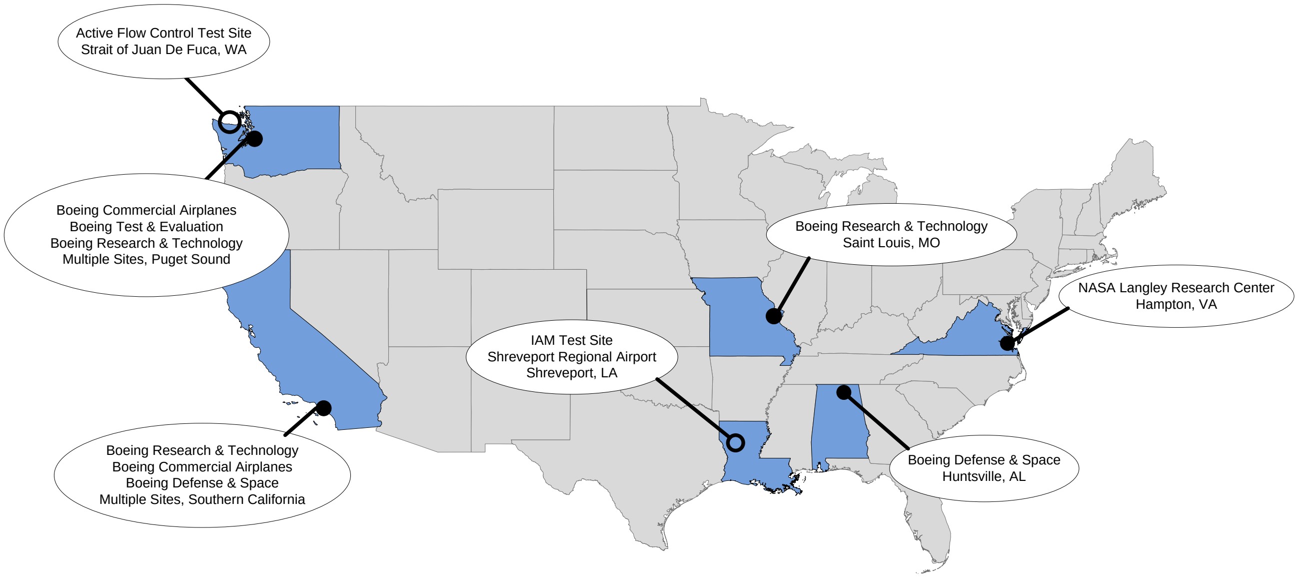


Figure 1: Engagement Map – Flight Services and Aircraft Access Task Order

With this report, all of the required deliverables related to management of this task order have been met and delivered to NASA as summarized in Table 1. In addition, this task order is part of a broader collaboration between NASA and Boeing.

Table 1 Project Management Deliverable Summary

Deliverable Number	Deliverable Description	Delivery Date
4.1	Monthly Technical Letter Progress Reports	Monthly
4.2	Kick-Off Presentation	5/2/14
4.9	Integrated Schedule	4/18/14
4.13	NSRS List	3/17/15
4.15	Crew Currency Report	3/17/15
4.21a	Draft Final Report	7/31/15
4.21b	Final Report	12/23/15

1.1 AFC

The purpose of the Active Flow Control (AFC) Enhanced Vertical Tail Technology Development Project was to determine the applicability of active separation control for commercial aircraft operation. As part of their Environmentally Responsible Aviation (ERA) Project, NASA sought to demonstrate the potential viability of reducing vertical tail size through the use of Active Flow Control in flight.

Under the Flight Services and Aircraft Access task order, Boeing installed and demonstrated the performance of the AFC-enabled vertical tail in flight. Testing on the 757 ecoDemonstrator aircraft validated the integration and function of AFC applied to a vertical tail. This report summarizes the work performed by the Boeing team as defined by contract NNL10AA05B task order NNL14AA57T. With the delivery of this report, all of the required AFC deliverables have been met, as summarized in Table 2.

Table 2 AFC Deliverable Summary

Deliverable Number	Deliverable Description	Delivery Date
4.5	“Quick Look” Flight Test Data Report	Daily during flight test
4.7	Flight rate per AFC Flight Day	4/17/14
4.10	Bill of Materials for AFC mass flow distribution system	7/31/14
4.11	AFC Research Flight Campaign Presentation	3/26/15
4.16	Flight Day Report	Daily during flight test
4.17	Safety of Flight review minutes	4/22/15
4.21a	Draft Final Report	7/31/15
4.21b	Final Report	12/23/15

1.2 IAM

As part of their Environmentally Responsible Aviation (ERA) Project, NASA sought to demonstrate the potential benefits of Insect Accretion and Mitigation (IAM) technologies. One of the challenges of wing laminar flow is early boundary layer transition from laminar to turbulent due to roughness induced by insect contamination. IAM coatings are an attempt to mitigate insect residue adhesion through both chemical composition and coating topography.

Boeing performed engineering development work to design, fabricate, install, and flight test IAM technology on the Boeing 757 ecoDemonstrator. Boeing, in collaboration with NASA, collected flight test data on the IAM coatings during testing in Shreveport, LA. Shreveport was selected based on high insect population densities desired for present IAM testing. These tests encompassed three phases (5a, 5b, and 5c) called out in the proposed SOW (Reference (3)) devoted to the low speed flight testing of the IAM technologies.

This report summarizes the work performed by the Boeing team on the IAM technology as defined by contract NNL10AA05B task order NNL14AA57T. With the delivery of this report, all of the required IAM deliverables have been met as summarized in Table 3.

Table 3: IAM Deliverable Summary

Deliverable Number	Deliverable Description	Delivery Date
4.3a	Engineered Surface Substrate TTR1 Presentation	6/26/14
4.3b	Engineered Surface Substrate TTR1 Closure Report	6/26/14
4.4a	Engineered Surface Substrate TTR2 Presentation	10/30/14
4.4b	Engineered Surface Substrate TTR2 Closure Report	11/6/14
4.6a	4-inch x 6-inch Witness Plates from the Spray out 1	5/16/14
4.6b	4-inch x 6-inch Witness Plates from the Spray out 2	9/29/14
4.6c	4-inch x 6-inch Witness Plates from the Spray out 3	1/9/15
4.8	Flight rate per IAM Flight Day	3/24/15
4.12	IAM Research Flight Campaign Presentation	3/24/15
4.14	Return the Flight Tested Engineered Surfaces	5/12/15
4.16	Flight Day Report	Daily during flight test
4.17	Safety of Flight review minutes	4/22/15
4.18	Engineering surface substrate recommendations	6/26/14
4.19	Engineering surface substrate size and shape recommendations	11/6/14
4.20	Attachment and removal procedures of the Engineering surface substrate	11/6/14
4.21a	Draft Final Report	7/31/15
4.21b	Final Report	8/30/15
4.22	Camera system accelerometer location recommendation	9/12/14
4.23	Camera system accelerometer data	4/10/15

4.24	4-inch x 6-inch Witness Plates from Spray out 2.A	12/5/14
4.25	30-inch x 29-inch Plates from Spray out 2.A	12/5/14

2 Flight Test Airplane

The 757 ecoDemonstrator was a Model 757-222 from Stifel Aircraft Leasing, obtained for this project after retirement from revenue service with United Airlines. The airframe was line number 263, serial number 24627, with effectivity NE016. It was re-registered N757ET after refurbishment for use as the 757 ecoDemonstrator.

The airplane was fitted with Pratt & Whitney PW4037 engines leased from Delta Airlines. The port side (left) engine was a 4037M. This engine was modified via Service Bulletin to increase the available thrust from 37,000 to 40,000 pounds during AFC testing to provide increased thrust asymmetry.

The airplane was also modified both internally and externally to incorporate other technologies being tested by Boeing independent of this contract and to install flight test instrumentation. The airplane entered layup for installation of hardware and instrumentation on 1 Sept 2014. First Flight was on 17 Mar 2015. The airplane as configured for AFC testing is shown in Figure 2.

Figure 2: 757 ecoDemonstrator as configured for AFC Testing

3 AFC Technology Demonstration

3.1 Objectives

The objectives of the AFC flight demonstration were as follows:

- Demonstrate the ability to integrate a prototype AFC system into an airframe, and thereby highlight key integration challenges.
- Demonstrate AFC impact on rudder effectiveness in flight using available APU flow rates.
- Collect in-flight data for comparison to full-scale wind tunnel results and CFD predictions.

It should be noted that it was not possible to test the system at vertical tail design conditions (negative Beta and large rudder deflections) principally due to the airplane’s relatively large vertical fin and low airspeed / low altitude safety limitations. However, meaningful measurements were obtained through standard flight test practices which enabled extrapolation into the design conditions using available full-scale wind tunnel test data on a 757 vertical tail.

3.2 Technology Description

Active Flow Control modifies a flowfield by adding energy to it, in this case in the form of an array of sweeping jets, to enhance desirable flow characteristics or suppress undesirable flow characteristics. For the vertical tail, the active flow control was applied to mitigate the separation that occurs on the rudder at high deflection angles and thereby increase the sideforce generated by the vertical tail.

Testing at the National Full-scale Aerodynamics Complex (NFAC) 40x80 wind tunnel demonstrated AFC control authority enhancement of a full scale Boeing 757 vertical tail. It explored the effects of actuation parameters such as exit jet momentum, actuator spacing, and actuator patterns across a range of test points representative of takeoff and landing conditions. Results showed that AFC provided a significant increase in sideforce. This was accomplished within the flow capability of the 757 airplane Auxiliary Power Unit (APU) compressor.

Ultimately, application of AFC to a vertical tail could enable reduction of the tail wetted area that would translate into a reduction in fuel consumption and greenhouse gas emissions. A 0.5% reduction in fuel use is estimated for a 777-class airplane based on potential vertical tail size reduction with suitably practical AFC integration (Reference (4)).

3.2.1 Sweeping Jet Actuators

The key component of the AFC system used in these demonstrations is the sweeping jet actuator. This device emits a continuous jet of air that oscillates from one side of the outlet nozzle to the other. This jet “oscillation” works like a dynamic effector but without the complications of moving internal parts or pulsed flow from the source. For these demonstrations, the actuator nozzles were placed just forward of the rudder hinge line on the non-moving portion of the tail (vertical stabilizer).

Figure 3 shows the features of a sweeping jet actuator that is representative of the type used for these demonstrations. The device achieves a sweeping motion due to a dynamic instability inherent in the design of the interaction region of the device. The instability is excited via feedback paths resulting in the cyclic attachment of the jet to either wall of the interaction region, which causes the exiting jet to sweep across the nozzle between exit walls “A” and “B”.

Figure 4 presents a Schlieren visualization of the flow field generated by a sweeping jet actuator. In the vertical tail application, the actuators were installed with the long axis perpendicular to the trailing edge of the fixed portion of the tail. This resulted in a spanwise (vertical direction) sweeping motion of the jet.

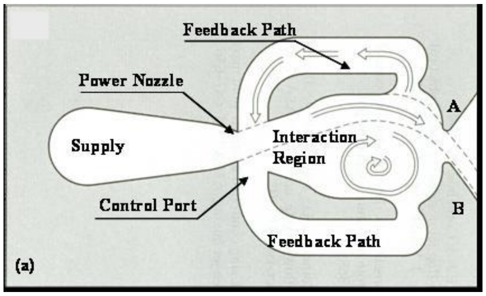


Figure 3: Drawing of the components of a sweeping jet actuator

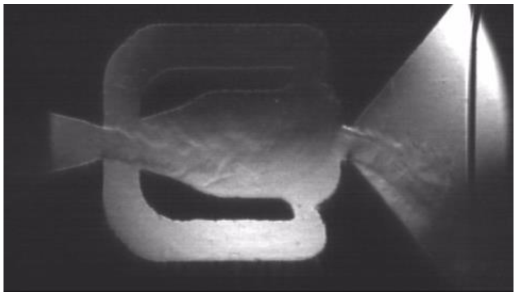


Figure 4: Schlieren image of a sweeping jet actuator flowfield. Note the jet that is toward the bottom of the nozzle at the right side of the image. (Photo credit: Caltech)

3.3 AFC Schedule Highlights

The task order contract (Reference (3)) covered the completion of engineering design work and analysis, parts fabrication, lab testing, system installation, and flight testing. Design work began in mid-2013, concurrent with NFAC wind tunnel testing. The Preliminary Design Review (PDR) was held in November 2013, with the Critical Design Review (CDR) following in January 2014. Both PDR and CDR packages were provided to NASA under the Phase 1 contract (Reference (2)). Drawing releases and parts fabrication began in March 2014 and continued through December 2014. Aircraft modifications started in September 2014 and were completed in February 2015.

Figure 5 is an annotated photograph depicting the external arrangement of the AFC system on the 757 ecoDemonstrator.

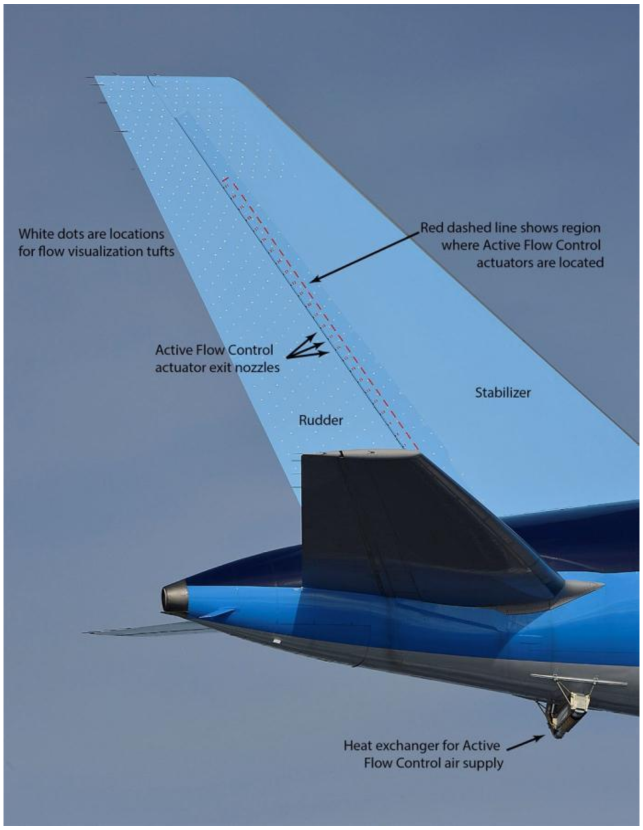
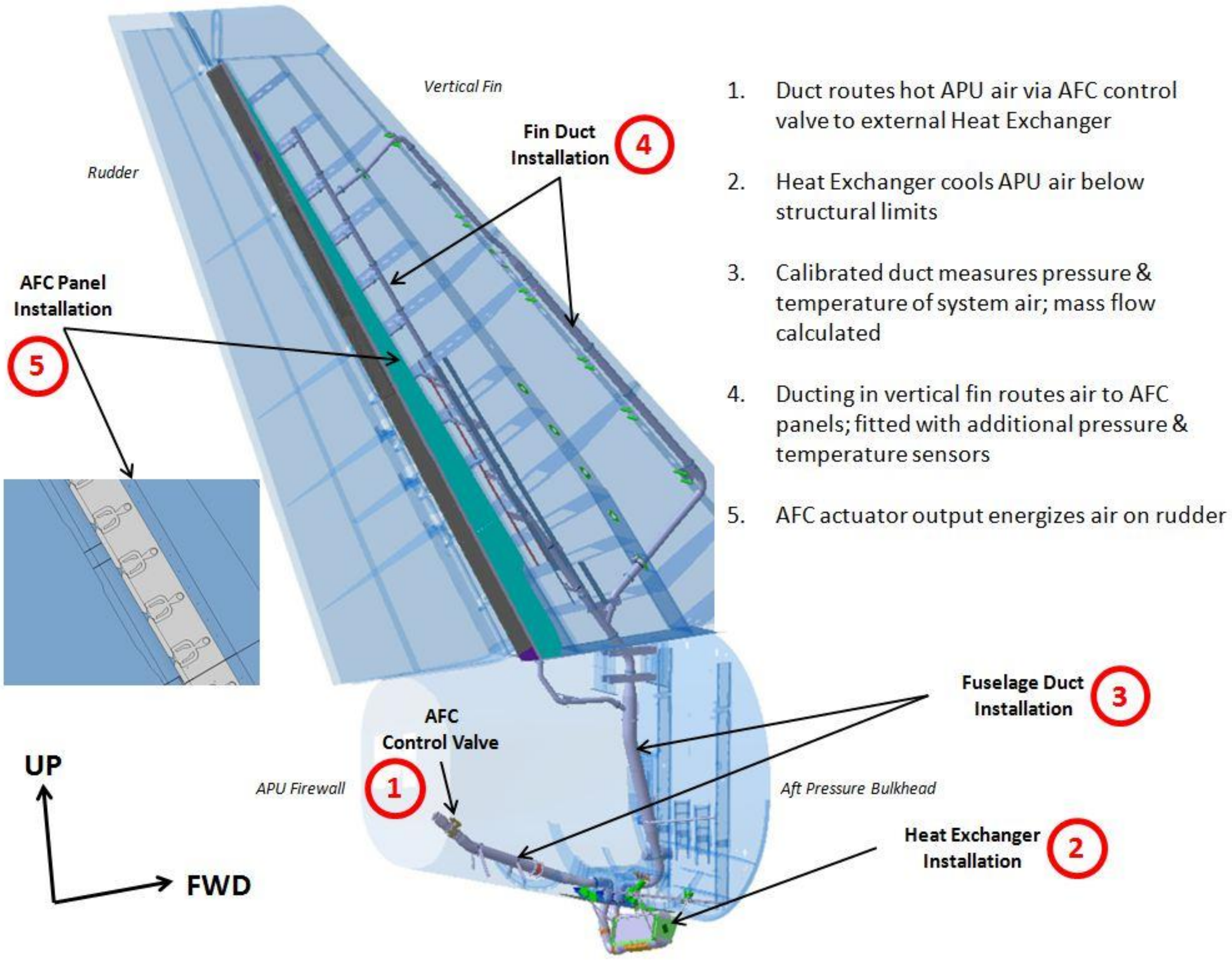


Figure 5: External AFC system arrangement

3.4 AFC Mass Flow Distribution System

Figure 6 illustrates the AFC modifications installed into the vertical fin and aft fuselage. The 757 production bleed air system was modified to enable use of the APU compressor as the AFC air source. A control valve was installed adjacent to the existing APU shutoff valve to enable flow rate variations. An air-to-air heat exchanger was mounted underneath the aft body of the airplane to cool the APU air to comply with fin and rudder structural requirements. A calibrated duct was installed downstream of the heat exchanger to measure flow rates, and ducting was installed in the vertical fin to supply air to each of 31 actuators. To minimize changes to existing hardware, the AFC actuators were mounted on panels external to the outer mold line of the vertical fin.

The sweeping jets added momentum to the mixing of near-wall flow over the rudder. This helps to keep the flow attached over the rudder and can increase rudder effectiveness at higher rudder deflections.



1. Duct routes hot APU air via AFC control valve to external Heat Exchanger
2. Heat Exchanger cools APU air below structural limits
3. Calibrated duct measures pressure & temperature of system air; mass flow calculated
4. Ducting in vertical fin routes air to AFC panels; fitted with additional pressure & temperature sensors
5. AFC actuator output energizes air on rudder

Figure 6: AFC Modifications to 757 EcoDemonstrator Aft Fuselage and Vertical Fin

3.4.1 AFC System Integration

Hardware integration was made more difficult since the airplane had already been built. For example, tubing in the vertical fin was installed in multiple pieces due to limited access. Tubing bends and branches had to be designed to fit within the existing geometry to avoid cutting structure. In a new design, longer tubes and more optimized flow paths could be incorporated reducing both installation time and the number of couplers (saving weight).

Careful design and stress analysis ensured the tubing would be able to withstand maximum loading during flight without leakage, and be able to accommodate thermal expansion due to the heated APU air. Similar analyses ensured the vertical tail would be able to withstand the additional weight of the tubing and side forces generated during test.

The airplane was modified in the Boeing Field Flight Test hangar in Seattle. Figure 7 illustrates the scaffolding used to gain access to the aft fuselage and vertical fin.

Figure 7: Scaffolding surrounding the 757 ecoDemonstrator aft fuselage and vertical fin

Figure 8 shows some of the ducting installed inside the vertical fin and the access challenges. Since many tubing joints were required, periodic leak checks were performed during installation to ensure proper sealing. This disciplined approach saved time overall by not having to “chase leaks” at the end when access to repairs would have been much more difficult.

Figure 8: Duct installation inside the vertical fin

In addition to routing tubing around structure, it was also necessary to mitigate interference with systems. As shown in Figure 9, ducting ran through equipment bays containing rudder control actuators. A slight interference with hydraulic hoses was remedied by installing 45 degree angle fittings at the hose ends and "clocking" the hoses away from the duct. As an additional precaution, the hoses were wrapped with a protective coating to prevent abrasion in case of incidental contact under load. An inspection plan was put in place to look for damage during flight. None was found.

Figure 9: Hydraulic lines and AFC ducting

Since hot APU compressor air was being used as the AFC source, it had to be cooled to meet structural and system temperature limits. For the purposes of flight test, an externally mounted heat exchanger provided the most cost effective solution. An existing qualified unit was used that provided both acceptable back pressure and the necessary thermal performance. Figure 10 shows the heat exchanger mounted underneath the aft fuselage and some of the structural reinforcements at the tubing penetrations and heat exchanger attachment points. This type of installation would obviously not be appropriate for a production design.

Figure 10: Installation of the heat exchanger below the aft fuselage

The AFC panels were installed on the fixed portion of the vertical stabilizer. The actuator nozzle outlets were located immediately upstream of the rudder bullnose and each actuator was numbered to aid in data analysis. Figure 11 shows the installation during the build process. The actuator outlets appear as black triangular shapes between the actuator number and the rudder. The circles on the rudder mark locations for future installation of flow cones. The final configuration is shown in Figure 12 with the flow cones installed. These were used to provide flow visualization during the flight test program.

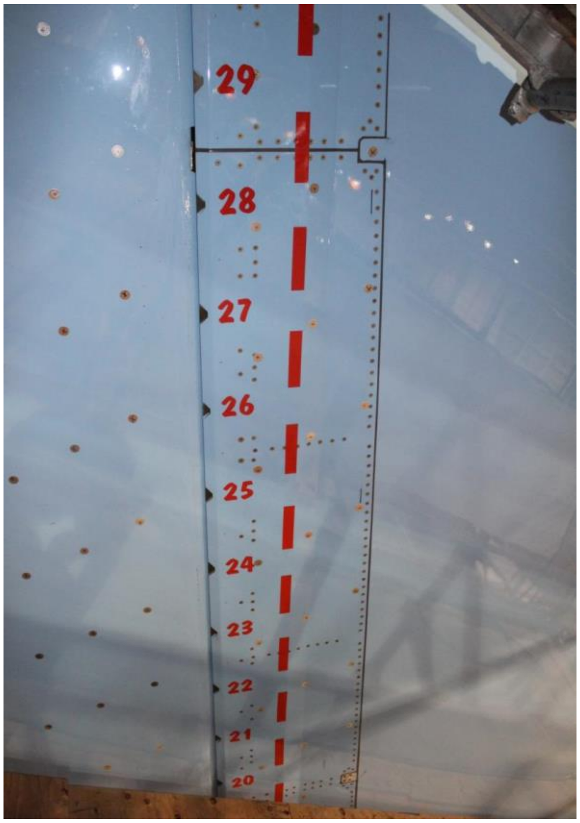


Figure 11: Close-up external view of typical AFC panel installation

Figure 12: Flow cone installation on the vertical fin and rudder

3.4.2 AFC Instrumentation

Three types of instrumentation supporting AFC flight testing were installed on the 757 ecoDemonstrator:

1) The airplane was fitted with standard sensors to provide air data and airplane performance characteristics, including control-surface positioning measurements.
2) The AFC system was fitted with pressure and temperature sensors to monitor and record mass flow and system performance. System mass flow was calculated from calibrated pressure and temperature data.
3) Flow cones were installed on the starboard (right) side of the vertical fin and rudder to allow for external flow visualization.

Only category 2 instrumentation to monitor and record AFC system performance was installed under the NASA task order. Figure 13 and Figure 14 illustrate details of the AFC system instrumentation used in the aft fuselage and the vertical fin, respectively.

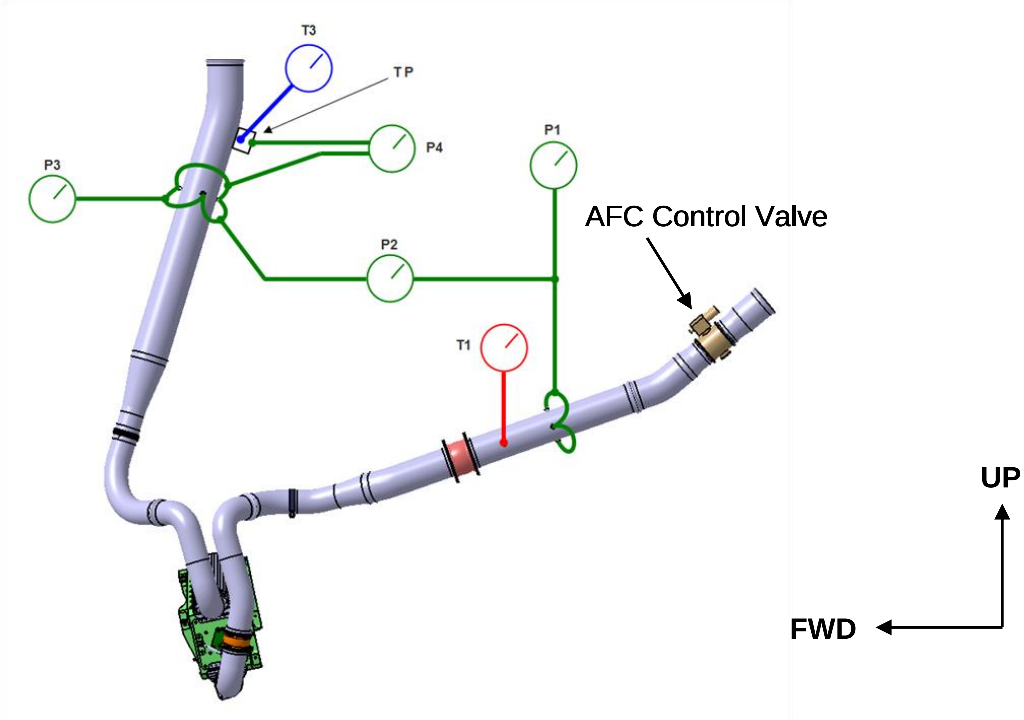


Figure 13: AFC Fuselage Instrumentation

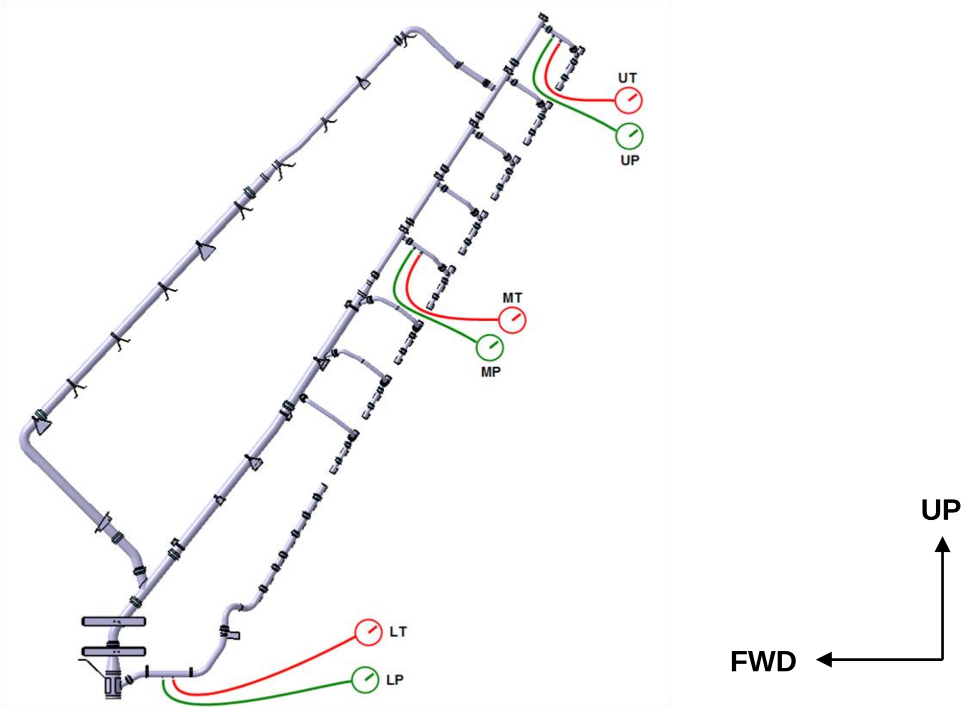


Figure 14: AFC Vertical Fin Instrumentation

3.4.3 Laboratory and Ground Tests

A series of laboratory and ground tests were conducted to ensure the AFC system worked as planned prior to flight. These tests included:

- Heat exchanger vibration testing – conducted to establish the frequency response and vibration level limitations of the heat exchanger.
- AFC flow valve and valve controller integration – conducted to validate proper operation of the system controller architecture and develop the in-cabin software interface (GUI) used to control the AFC system in flight.
- Valve controller EMI testing – conducted to validate the controller would not interfere with airplane systems when in operation.
- Duct calibration – conducted to establish the mass flow calibration necessary to derive AFC system performance from pressure and temperature parameters installed in the duct.
- System leak tests – conducted at key points in the assembly process to ensure acceptable performance.
- AFC system ground test – conducted to validate the system functionality and verify AFC flow valve control before flight. This test also measured AFC actuator output and spanwise homogeneity of flow output from the 31 AFC sweeping jets.

3.5 AFC Enhanced Vertical Tail Research Flight Campaign

The AFC flight campaign was conducted to measure the impact AFC had on rudder effectiveness and aerodynamic loads while demonstrating the viability of the system in a flight environment.

3.5.1 Safe to Fly

A significant amount of time was invested to validate, verify, and ensure the airplane as configured for AFC testing would be safe to fly. Several reviews of the system design and its impact on the airplane were held within each affected engineering organization. Wind tunnel test data and systems analysis were used to appropriately resolve identified risks. Findings and conclusions were documented and approved by the 757 Chief Engineer prior to flight.

The NASA ASRB (Airplane Safety Review Board) process was not used for this project. NASA instead elected to participate in the multiple review board meetings held as part of the overall Boeing process. In addition, on-site NASA QA personnel reviewed every step of the system installation. The Federal Safety Hotline was available to all participants throughout the flight test program to report any safety concerns.

One of the risks addressed during the AFC Safe to Fly process was the threat of a bird strike on the exposed heat exchanger. While it could be shown statistically that this threat wasn't likely, additional steps were taken to provide complete assurance that Continued Safe Flight and Landing (CSFL) would not be compromised even if the heat exchanger was hit.

Structural stiffeners shown in Figure 15 were installed underneath the maintenance platform in the aft fuselage to ensure that if the heat exchanger suffered a bird strike, the damage would not propagate into the fuselage.

Figure 15: Structural stiffeners under the maintenance platform

3.5.2 Site Location

Flight conditions necessary to demonstrate AFC effectiveness required that testing be performed over water with visual flight rules.

The Strait of Juan de Fuca was chosen based on the following criteria:

- Anticipated lost days using meteorological analysis of historical weather patterns
- Cost effectiveness for flight crew and test crew
- Compatibility and availability of chase plane for flow visualization photography.

Figure 16 shows the Strait and its proximity to Boeing Field.

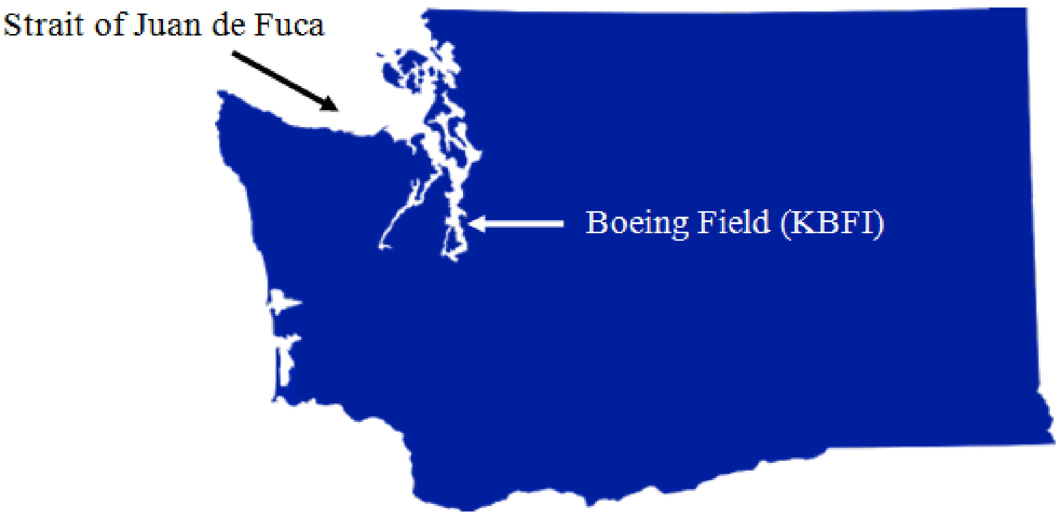


Figure 16: Map of Washington State depicting Boeing Field and the Strait of Juan de Fuca

3.5.3 Flight-Test Planning

Figure 17 shows the AFC flight test sequence. Initial testing included all 31 AFC actuators. After this was completed, the system was modified to disable 15 actuators and test the remaining 16 AFC actuators (every other actuator operational).

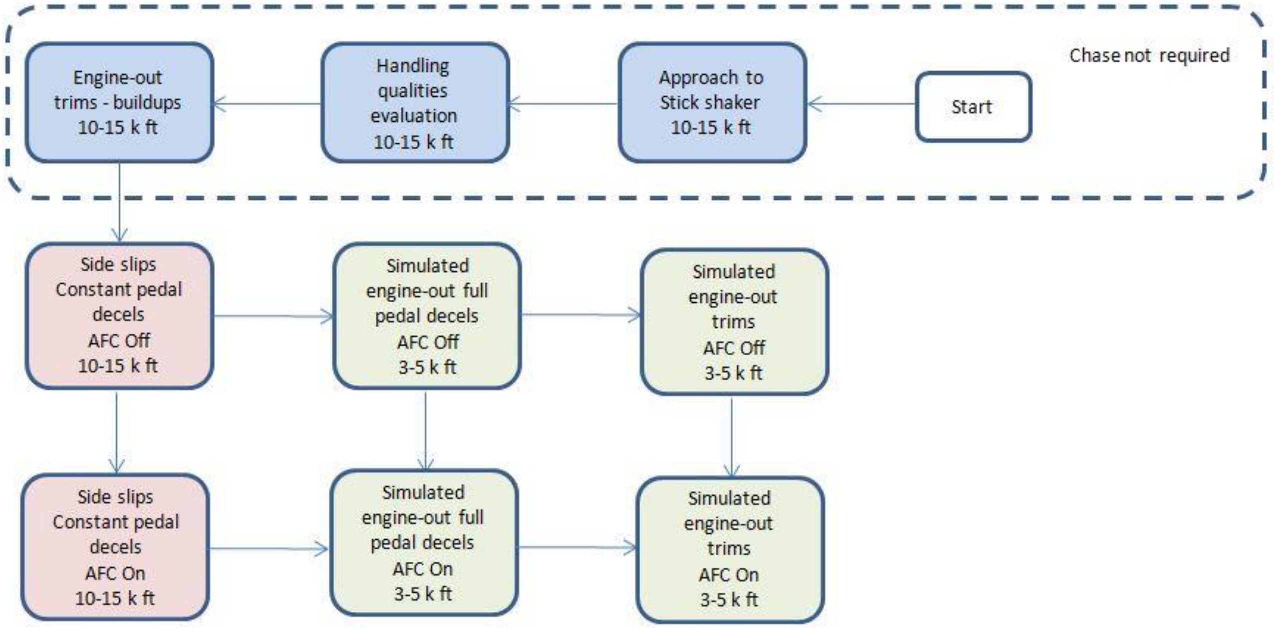


Figure 17: AFC Flight-Test Sequence

3.5.4 AFC Flight Test Summary

Prior to the start of AFC testing, the airplane conducted two flights to perform handling quality and system functional checks after the installation lay-up period.

Four days of AFC flight testing were completed, composed of six flights in total. All flights originated from and returned to KBFI (Boeing Field - King County International). The initial flight assessed airplane handling qualities with the AFC system operating for the first time. All maneuvers were conducted at high altitude (10,000 to 15,000 ft). Minimum acceptable speed and maximum AOA (angle of attack) were determined at this time.

AFC testing on the second day captured decelerations, sideslips, and trims with the AFC system on and off. These conditions were conducted at high altitude and were repeated at low altitude (3,000 to 5,000 ft).

The third day consisted of two sorties as the airplane was configured at a lighter weight. Remaining trims and all AFC on conditions were completed at low altitude. Conditions previously conducted were repeated for data quality.

The AFC system was modified after the third day to disable airflow to every other actuator, leaving 16 of the original 31 operational. This was done to simulate a partially-failed system.

The fourth and final day of testing also consisted of two sorties. The first completed sideslips and decelerations with AFC on and off at high altitude. The second and final sortie completed low altitude trims again with the AFC system on and off.

This flight marked the completion of AFC flight test conditions. The airplane then entered a lay-up period wherein the AFC system ducting and heat exchanger was removed. The APU was reconnected to the rest of the airplane bleed system per the standard 757-200 configuration.

3.5.5 Flight Test Conditions Achieved

Table 5 summarizes the test conditions executed during the course of planned AFC testing. All AFC flight conditions were conducted with wing flaps at Flaps-30, and gear retracted. Rudder deflections of approximately 30 degrees were obtained at lowest speeds and at lowest altitudes tested.

Table 4 Summary of all flight test conditions achieved during AFC testing

Maneuver Type	**AFC Total Flow Rate**					**Speed (KCAS) / Altitude(1,000 ft)**
	31 Actuators				**16 Actuators**	
	Off	**Maximum**	**Intermediate**	**Low**	**Low**	
Approach to Stick shaker	✓	-	-	-	-	162 / 10-15
Handling Qualities Evaluation	✓	-	-	-	-	130 / 10-15
	✓	-	-	-	-	125 / 10-15
	✓	-	-	-	-	120 / 10-15
	✓	-	-	-	-	115 / 10-15
	✓	-	-	-	-	110 / 10-15
Steady-Heading Sideslips – Right Pedal	✓	-	-	-	-	140 / 10-15
	✓	-	-	-	-	125 / 10-15
	✓	-	-	-	-	110 / 10-15
	✓	-	-	-	-	110 / 10-15
Steady-Heading Sideslips –	✓	✓	-	-	✓	140 / 10-15
	✓	✓	-	-	✓	125 / 10-15

Left Pedal	✓	✓	-	-	✓	110 / 10-15
Constant Pedal Decelerations – 10 deg Sideslip	✓	✓	-	-	✓	152 / 10-15
Constant Pedal Decelerations – 5 deg Sideslip	✓	✓	-	-	✓	152 / 10-15
Full Pedal Simulated Engine-out Decelerations	✓	✓	✓	-	✓	152 / 3-5
Simulated Engine-out Trims – TLF / Idle	✓	-	-	-	-	110 / 10-15
	✓	✓	✓	✓	✓	140 / 3-5
	-	-	-	-	✓	130 / 3-5
	✓	✓	✓	✓	✓	125 / 3-5
	-	-	-	-	✓	115 / 3-5
	✓	✓	✓	✓	✓	110 / 3-5
Simulated Engine-out Trims – Max / Idle	✓	-	-	-	-	110 / 10-15
	✓	✓	✓	✓	✓	140 / 3-5
	-	-	-	✓	-	130 / 3-5
	✓	✓	✓	✓	✓	125 / 3-5
	-	-	-	✓	-	115 / 3-5
	✓	✓	✓	✓	✓	110 / 3-5

3.5.6 AFC Aircraft Data Summary

During each test flight, AFC system performance and aircraft information data were recorded from onboard instrumentation and ship system parameters. The data included aircraft altitude, velocity, angles and rates; rudder angles and loads; and AFC temperatures, pressures, and flow rates. These data files were delivered to NASA as documented in Reference (16).

The photos from the chase plane of the vertical fin flow cones were digitally overlaid to provide an enhanced composite snapshot of the air flow during a given test condition. Each composite image represents one second of time during a condition and combines approximately five separate sequential images taken from the chase plane. The attachment points of each cone were aligned in each photo to construct the composite images. Figure 18 illustrates the difference in flow field with AFC off and on. When AFC is off, the tuft orientation at many locations on the vertical fin does not coincide with the cone orientation in previous or subsequent photos taken within a fraction of a second of each other. This spreading or scattering of the cones in the composite photo indicates unsteady separated flow. When the flow is attached and smooth, the cone from one picture to the next nearly coincides. The Figure below shows much less variation in cone orientation when AFC is on, indicating that AFC is positively affecting the air flow over the rudder.

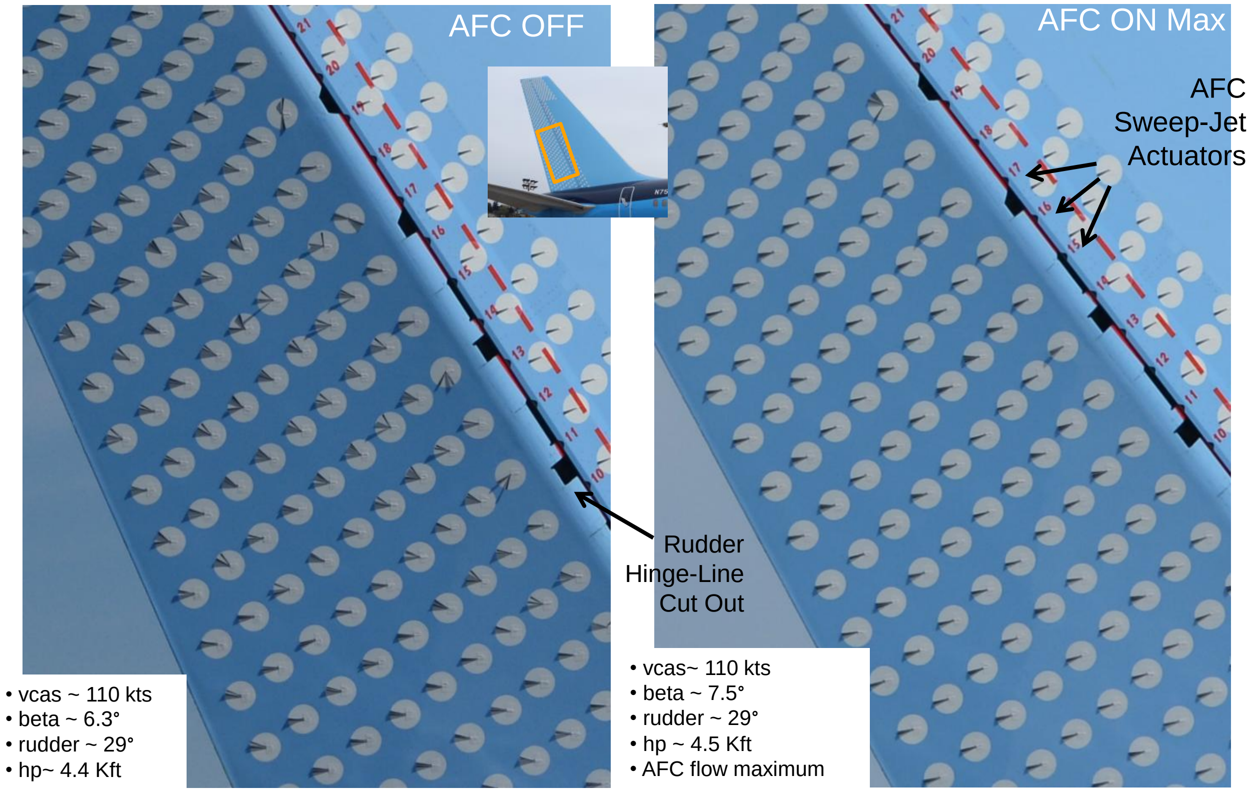


Figure 18: Composite images of vertical fin flow cones with AFC off (left) and AFC on (right)

Preliminary analysis of aircraft parameters indicates that AFC increases rudder effectiveness at the flight conditions tested. These results are consistent with the flow-visualization results obtained from cone images.

4 IAM Technology Demonstration

One of the challenges for the practical implementation of wing laminar flow technology is early transition from laminar to turbulent flow due to roughness induced by insect contamination. Suitable Insect Accretion and Mitigation (IAM) coating technologies may reduce wing and leading edge insect residue adhesion.

4.1 Objectives

The objectives of the IAM flight demonstration were as follows:

- Evaluate the performance of multiple coatings under simulated airline operational conditions,
- Characterize insect accretion distribution on transport airplane wing surfaces, span-wise and chord-wise,
- Collect data to support insect density profile during takeoff and landing operations.

To support these test objectives, the IAM substrate design was required to maximize frontal area on the leading edge, provide side-by-side comparison between coated and uncoated surfaces, not significantly deviate from the baseline aircraft leading-edge profile and support panel removal and installation in one crew shift.

4.2 Technology Description

The Insect Accretion and Mitigation coating technology relies on both chemical composition and topography of the coatings to maximize the ability to reduce insect residue adhesion.

4.3 IAM Design, Fabrication and Installation

The Design, Fabrication and Installation (NNL14AA57T Phase 3) statement of work for IAM included definition of the optical window and camera configuration, recommendations for the substrate, installation and removal procedures, and sprayout applications of the various IAM coatings.

The flight test configuration chosen based on NASA inputs involved installing 4 substrates on slat 8 and 4 substrates on slat 9. Figure 19 shows 757 slat numbering nomenclature. Figure 20 summarizes slat substrate installation configurations on the slats of the right-hand (starboard) side wing. Engineered Surfaces (ES) have the IAM coating applied to the substrate. Uncoated panels were installed on alternating locations as controls. Figure 21 shows substrate numbering on the slats.

To capture insect impact data during flight and facilitate rapid evaluation of the test success criteria during operation, high-resolution cameras were mounted in the forward fuselage. Photographic data was monitored and reviewed real-time during flight testing.

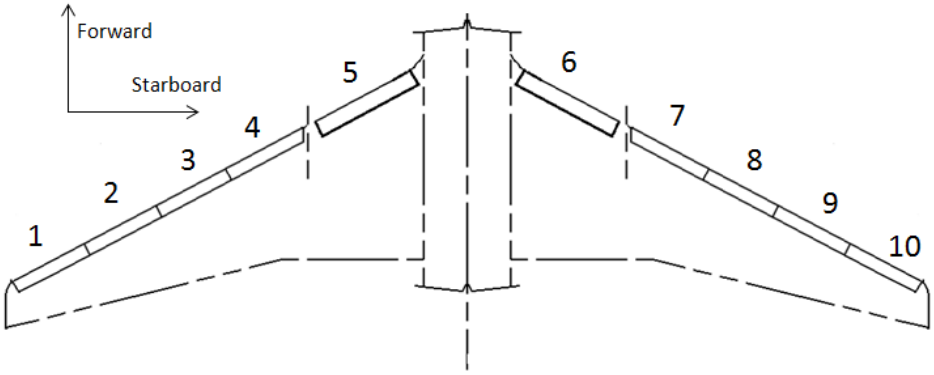


Figure 19: 757 Slat Numbering Nomenclature

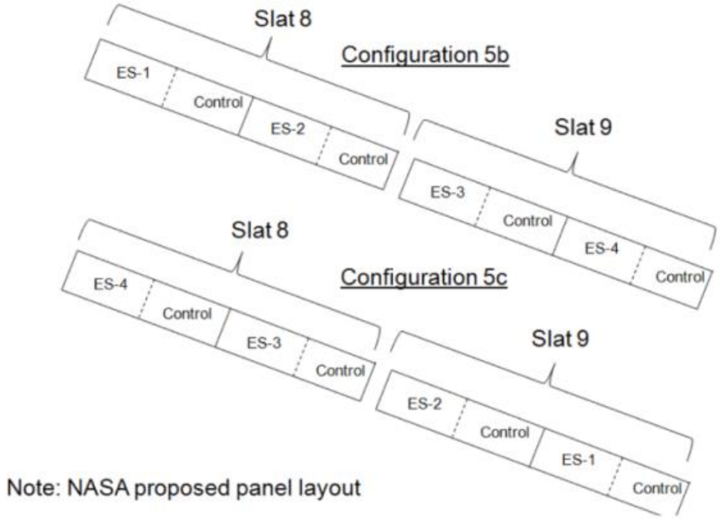


Figure 20: Substrate Installation Locations on Slats 8 and 9 (Top View).

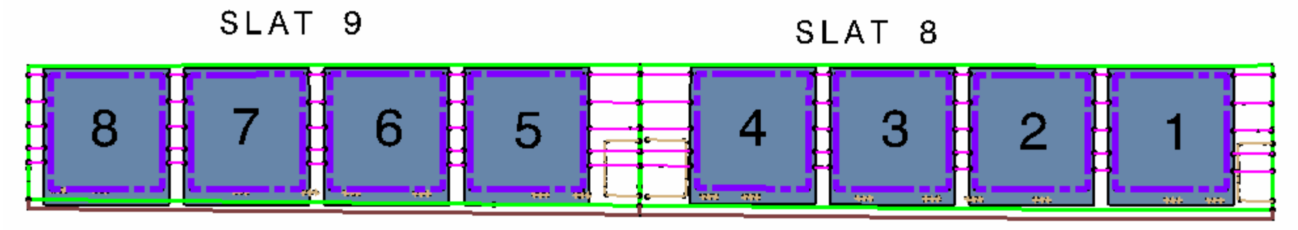


Figure 21: Substrate numbering locations on slats (Front View)

4.3.1 Camera Design

Efficient testing required a real-time assessment of the status of the insect density relative to the minimum requirement (GFI 5.3) between each takeoff and landing. To gather this data, NASA agreed to provide cameras capable of detecting insect strikes in flight. Boeing assisted in the camera selection process as well as designing and integrating the necessary installation hardware to provide highest quality images.

4.3.1.1 Camera Selection/Settings

Lab testing performed by NASA and insect size information led to a 1mm X 1mm minimum insect residue size expected. In order to capture as many strikes as possible, imaging requirements defined by NASA were to resolve a 1mm X 1mm dot with 9 pixels (Reference (9)). To meet this criteria, Nikon D800E cameras with Nikon AFS-NIKKOR 300mm f/2.8G ED VRII telephoto lenses were selected. Based on ground testing performed by NASA (Reference (10)) with a mockup of the physical layout, this hardware was shown to provide adequate resolution to satisfy the criteria if an optically clear window was used. Details of the optical window are in the Optical Window Design section below.

The IAM cameras were positioned in the passenger cabin of the aircraft at windows 2 and 3 on the starboard side as shown in Figure 22. This was done to provide an adequate field of view to capture the test panel locations as shown in Figure 23. The camera at window 2 was focused on Slat 9, and the camera at window 3 was focused on Slat 8. The camera, lens and mounting assemblies (GFP 6.2-6.4) were installed on a camera mount assembly that was attached to the aircraft. Further details of the camera mount design can be found in the Camera Mount Design section below.

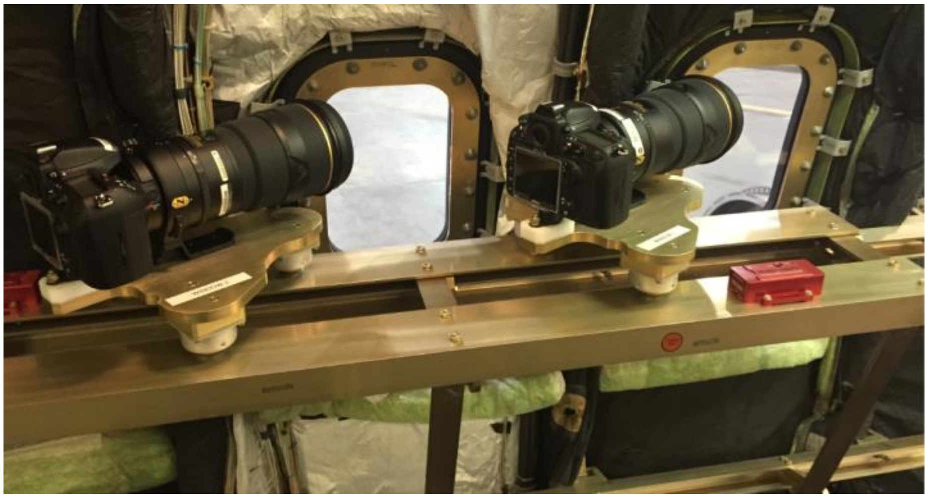


Figure 22: IAM Cameras Mounted in Windows 2 and 3

Figure 23: Example of Photo of Slat 8 from Window 3 IAM Camera

The preferred camera settings to use during IAM test flights were selected during test flights of other technologies on the 757 ecoDemonstrator aircraft during April 2015.

To maximize depth of field across the slat, the camera was manually focused and the aperture was stopped down to the lens limit of f/22. Motion blur of the wing bending was determined not to be an issue for shutter speeds of 1/320 sec or faster. Lighting was a challenge. Depending on the heading of the aircraft, a direct sunlight reflection washed out many sample test photos. To reduce the risk of "washed out" photos, spot metering with a -1 exposure bias was selected. To allow for a small f-stop with a relatively fast shutter speed, an ISO of 2000 or less was deemed to produce sufficiently crisp photos.

4.3.2 Camera Mount Design

Boeing collaborated with NASA to design a mount to position the two cameras used to capture insect hits during the flights. NASA and Boeing engineers visited Boeing's first 757 flight test airplane (NA001) on February 14, 2013 with the goal of identifying the optimum position for placing the cameras. The team installed targets of various sizes representing bug strikes on the four slats outboard of the right engine. From this information and digital models of the geometry, the forward-most windows were identified as the best position to place the cameras to get the appropriate field of view.

NASA designed the mounting hardware connected to the camera that would interface with the mount connected to the aircraft structure. Boeing provided a general vibration environment (Reference (23)) so dampeners could be incorporated to reduce the risk of image blur due to high-frequency vibrations. A tripod base mount was developed for each camera that would connect to the lens and incorporate the dampeners in the feet of the mount. Figure 24 shows the camera mount design model with the camera included.

Figure 24: NASA Mount Design with Camera Attached

Boeing designed a “table-top” rack that would attach to the internal fuselage frame. The table top design allowed both cameras to be attached to the same mount while positioned to view out windows 2 and 3, as shown in Figure 25.

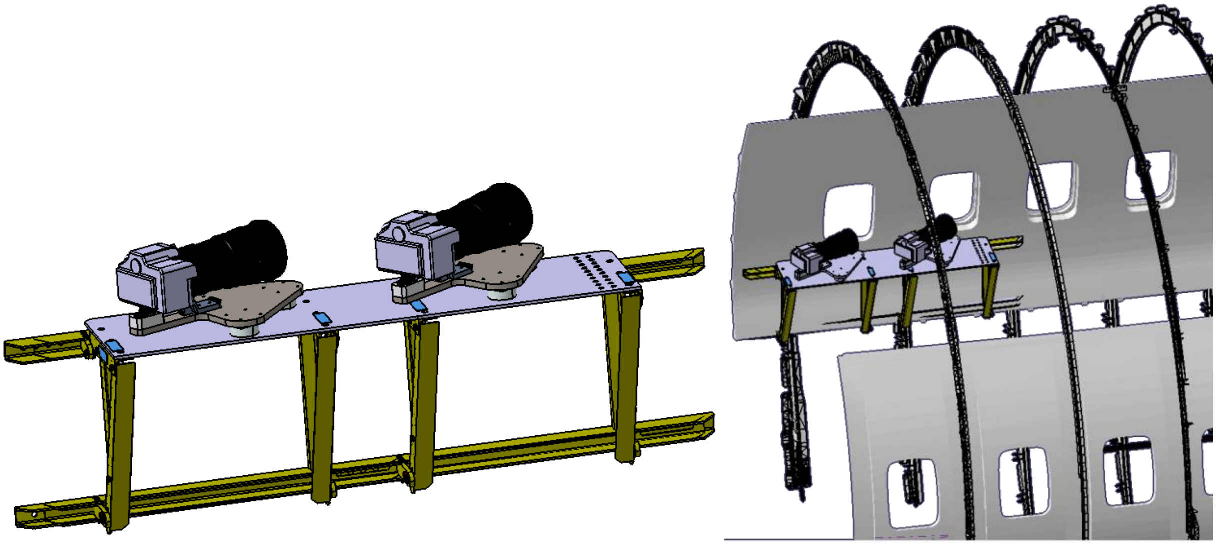


Figure 25: Boeing "Table-Top" Camera Mount Design

4.3.3 Optical Window Design

The camera testing performed by NASA (Reference (10)) assessed the degradation of the image quality through different window options to a baseline with no window at all. The test included optically clear glass and a standard 757 window pane. From these initial results, NASA recommended that optically clear glass be used to meet the resolution requirement for a 1mm sized insect.

Following sections describe the design changes developed at Boeing to modify the existing flight test window installation to meet the optical requirements.

4.3.3.1 Window Material Selection

To maximize resolution, optical glass aligned perpendicular to the camera lens is preferred. Due to physical, cost, and schedule constraints, an acrylic window with an anti-reflective coating was proposed (Reference (24)). It was tested using the same hardware (cameras and acrylic lens) that would be on the aircraft. The angle through the lens, distance to the wing location of the panels, and a spare slat to capture the wing contour were mocked up at several different lighting conditions. Results from these tests showed that image quality and resolution would be acceptable. The design changes were coordinated and accepted by NASA.

4.3.4 IAM Substrate Design

4.3.4.1 Substrate Material

The substrate material recommendation (Deliverable 4.18) was delivered as a part of the Table Top Review 1 (TTR1, Reference (11)) (Deliverables 4.3a & 4.3b). The recommendation was based on the coating application process and requirement to remove without damage to the accrued insects post flight and lay flat for inspection. Additionally, only commercially available alloys with accepted material allowables characteristics would be chosen. The materials were tested on a 757 slat 3 nose, which is the mirror of slat 8. Results are shown in Table 6.

Table 5:Candidate Subtrate Material tested around 757 Slat Nose

Thickness	Alloy	Notes
0.002	foil	wrinkles
0.003	foil	wrinkles
0.005	foil	wrinkles
0.012	7075-T6 Bare	good
0.012	7075-T6 Clad	best
0.016	2024-T3 Bare	creases
0.016	7075-T6 Bare	stiff
0.016	7075-T6 Clad	stiff

Clad 7075-T6 was chosen as the preferred material. Clad is easier than bare metal to surface prep for installation and for application of the IAM engineered surface. The clad surface is 1100 series aluminum which was previously flown on a NASA insect accretion test on a Falcon jet for similarity. The panel thickness of 0.012 in. was chosen as it was bendable enough that it could be applied by hand and remain in place with removable adhesives. The 0.016" thick sheet was too stiff. It was difficult to lay smooth and would quickly disbond. Aluminum foils were not acceptable as the metal would plastically deform upon application and wrinkle on removal.

4.3.4.2 Material Size

An objective of the design was to have all panels the same size and rectangular. This would allow any panel to be located in any position and minimize the cost of substrate manufacturing, installation, tracking, and shipping. The final panel size recommendation (Deliverable 4.19) was 27 inches in width (measured in spanwise direction) by 30 inches in length (measured in chordwise direction). The chord length was determined by the maximum chord length at the outboard end of slat 9. The substrate was installed with a 0.5 inch offset from the slat upper surface trailing edge to provide for surface area to bond speed tape during installation. Similarly, the panel was 0.9 inches away from the seal skirt trailing edge. See Figure 26 for the dimensions along the outboard edge of slat 9 and Figure 27 for the inboard end of slat 8.

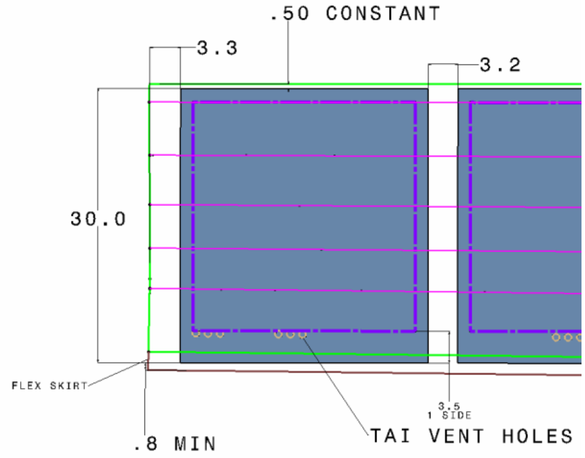


Figure 26: Selected Panel size fitted at the outboard end of slat 9 (Front View)

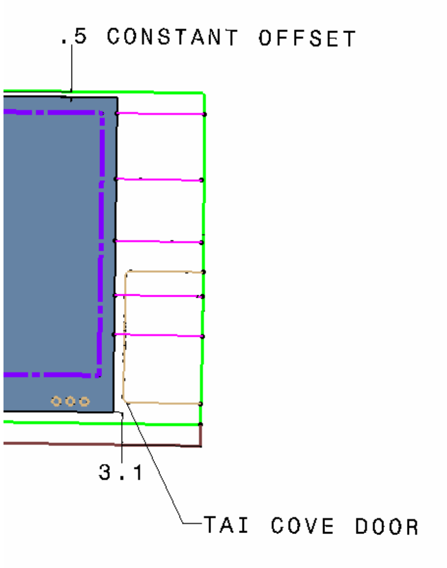


Figure 27: Substrate installation on the inboard end of slat 8 (Front View)

The width was determined to be 27 inches based on slat width, installation and testing. Photo targets were installed between panels requiring 1 inch of spacing. With the speed tape boundary on all panels at 1 inch, 3 inch spacing was required resulting in 27 inch panel spacing. Slat 8 was the panel width driver. See Figure 28 for installation on Slat 8 and Figure 29 for installation on Slat 9.

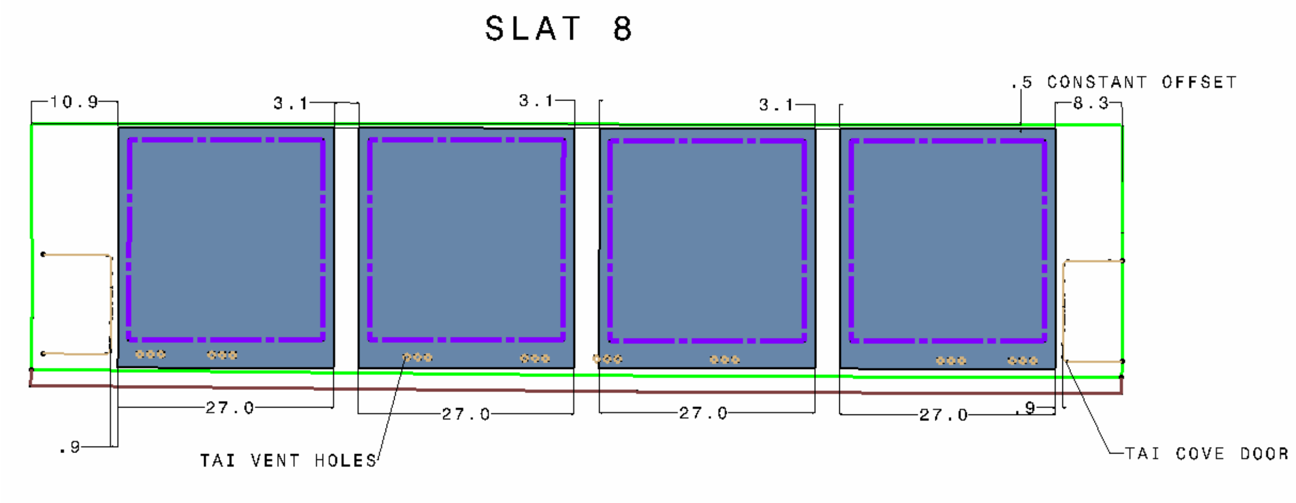


Figure 28: Panel spacing on slat 8 (Front View)

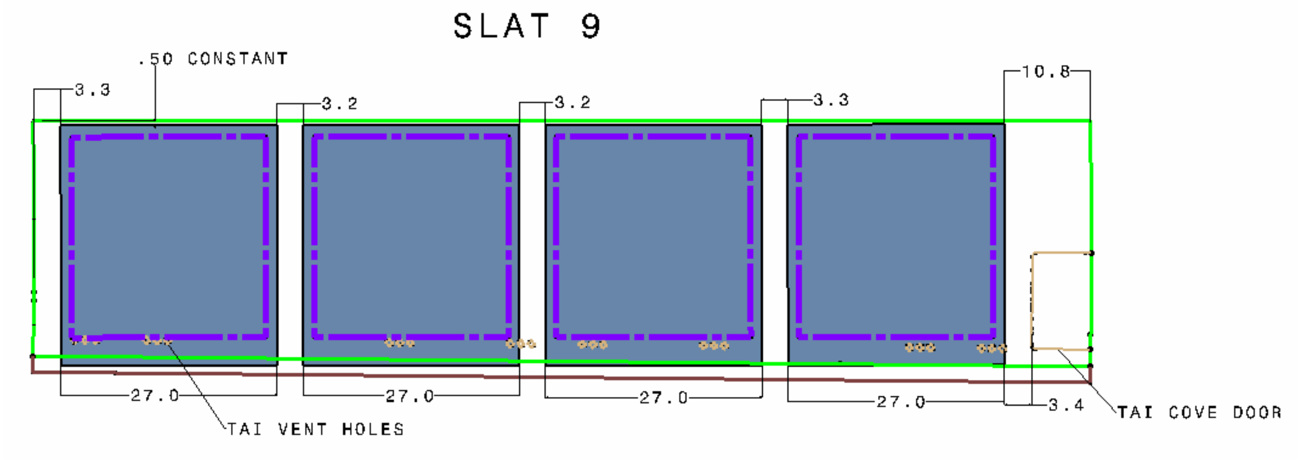


Figure 29: Panel Spacing on Slat 9 (Front View)

4.3.4.3 Slat Gridline Markings

To assist in determining insect accretion along zones of the slat, equal frontal area markings were placed on the slats. The frontal area was split into 4 zones starting at the upper engineering surface starting point and at the lowest highlight on the slat. See Figure 30 for a side view of the area line markings. The lines were projected normal to the frontal plane onto the slat surfaces. An additional line was added at the lower visible location from the camera mounted in the fuselage window since the underside of the slat was not viewable. Due to the varying size profile of the slat chord across the span, the area line markings spacing varied spanwise. See Figure 31 for an isometric view of the slat with area line markings and spacing. Outboard marking of vertical separation is 3.64 inches and inboard is 4.20 inches. The lines were not marked on the Engineered Surface so as to not interfere with the insect accretion. Additional lines were added following the same process on slats 7 and 10 to aid in bug counting on additional slats. One-quarter inch thick lines were painted on the slats with primer. Photo targets were added along the area lines to split between the IAM panels and split the other slats into 4 similar sections. These were added for computer photo processing capability. See Figure 32 for a view of outboard slat 7 and slat 8 with photo targets and painted lines.

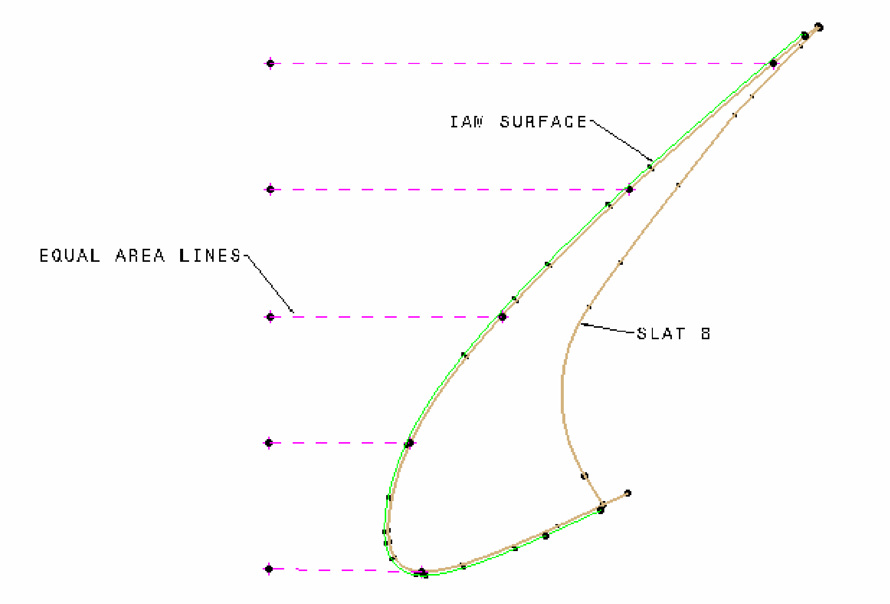


Figure 30: Side view of equal area line markings

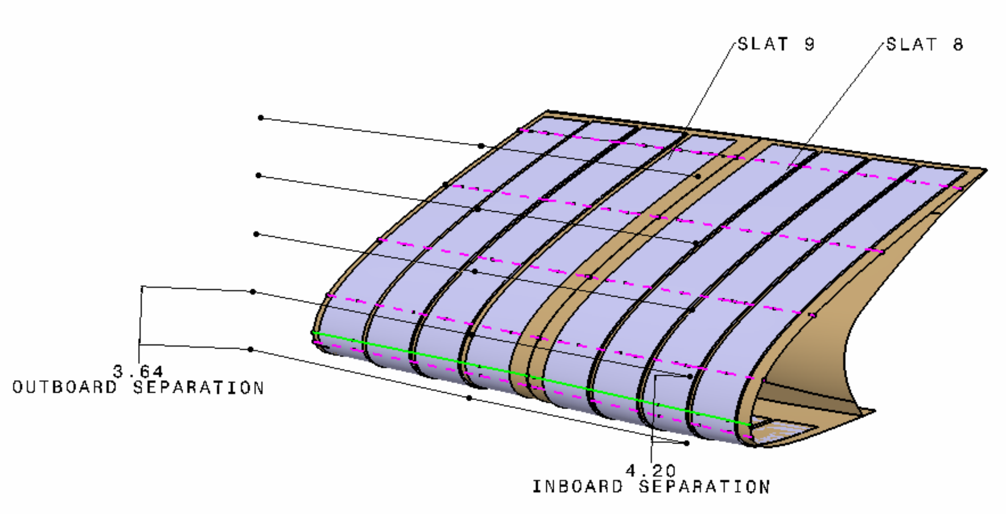


Figure 31: Side View of Equal-Area Line Markings

Figure 32: Painted Lines and Photo Targets on Slats (no IAM panels installed)

4.3.5 IAM Substrate Installation and Removal Design

The substrate installation design was delivered as a part of the TTR-2 on 10/30/2014 (Reference (12)) with an update including some minor changes on 2/6/2015 (Reference (13)) (Deliverables 4.4a and 4.4b). Double-sided adhesive tape was determined to be the best solution for installing the substrate to the slat outer surface. The adhesive tapes chosen would need low enough adhesion strength to allow removal of the substrate without plastic deformation of the substrate but be strong enough to withstand the aero loading. A double-sided tape that would not leave adhesive residue on the slat surface was highly preferable. Additionally, any heat to assist in removal would compromise the insect accretion on the engineered surfaces. Through testing, 3M repositionable tape 9425HT was found to offer the best practical solution. One side of the tape has a high strength adhesive (45oz/in. peel strength) and the other side has a low strength adhesive (12 oz/in. peel strength). The high strength side would be bonded to the substrate so, during removal, the tape would remain attached to the panel, limiting the amount of adhesive residue on the slat surface. This process hastened the surface preparation of the slat surface for the subsequent panels. The high temp (HT) tape was chosen due to the solar radiation and temperatures the panels would be exposed too. The HT material is rated for 250F verses 125F for standard 9425HT tape.

After the panels were bonded to the slats for a test, the lower surface crept and disbonded from the slat due to the stiffness of the panel. To alleviate creep concerns on the lower surface, a 2” strip of high strength (96 oz/inch) double-sided, pressure-sensitive adhesive tape was added. This portion of the substrate would not be subjected to insect accretion so plastic deformation during removal was acceptable.

The tape was laid along the whole inner surface of the substrate in an effort to eliminate air bubbles that may lead to disbonding under aerodynamic load. Due to the stiffness of the aluminum sheet, 2-inch strips of tape with 0.063-inch gaps were laid spanwise along the back surface of the substrate. See Figure 33 for tape configuration on the inner surface of the substrate.

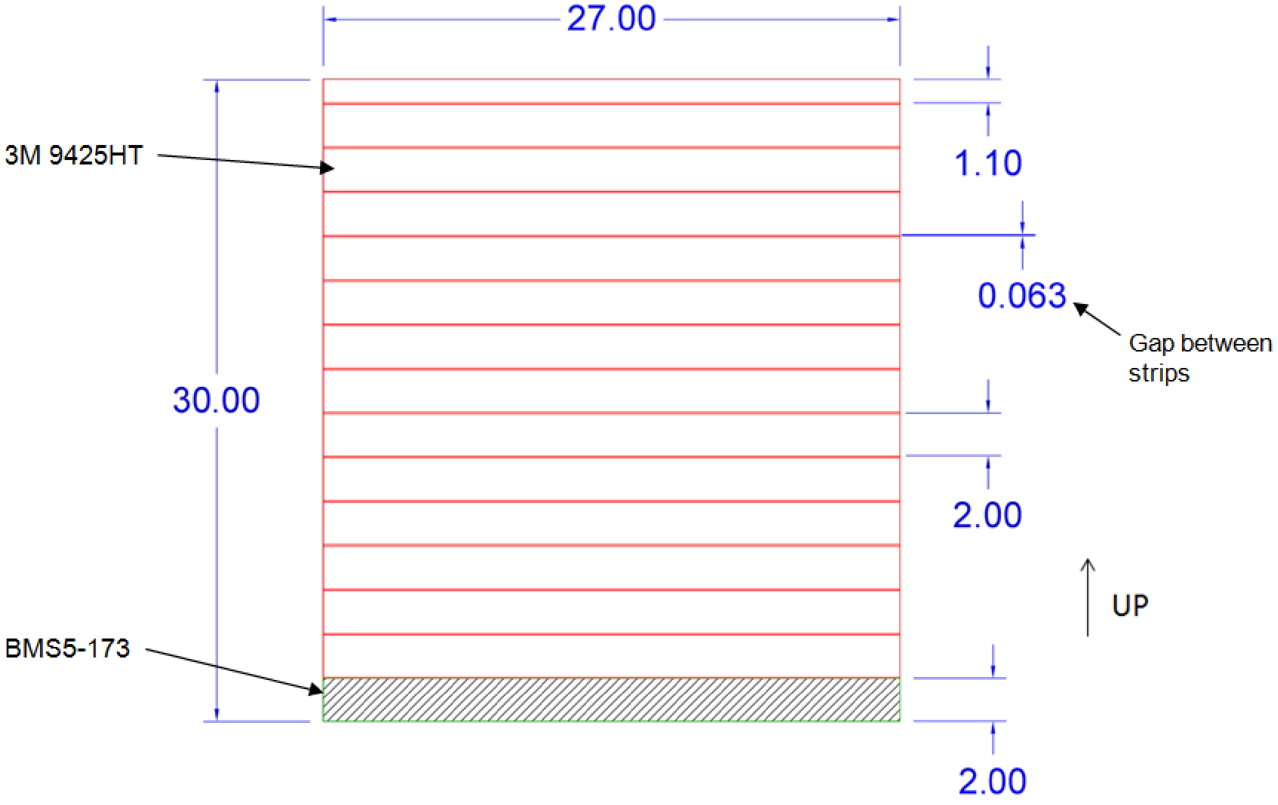


Figure 33: Double-Sided Tape Configuration

To ensure full bonding adhesion from the pressure sensitive tapes and to reduce voids, vacuum pressure was used to for the panel installation. First, the substrate panels were bonded on using the double-sided tape. The panels were then vacuum bagged for a minimum 1 hour at a minimum of 22 inches Hg to ensure full strength. See Figure 34 for view of vacuum bagged substrates. An NDI was performed after bagging to check maximum air void sizes. Prior to installation, Kraft paper was placed over the engineered surface to protect the coating. A tap test was performed on the panel and the voids were drawn on the Kraft paper. The void sizes were checked against the allowable void sizes per the stress analysis prior to removal.

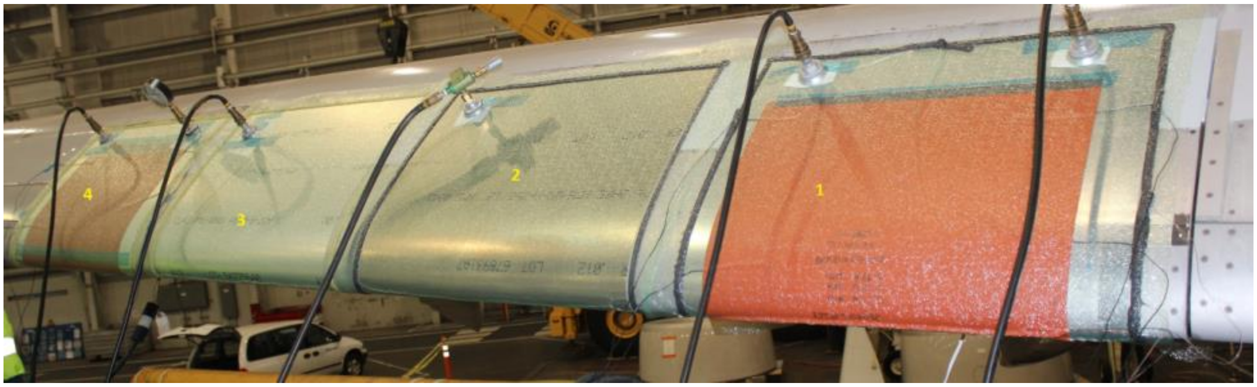


Figure 34: Vacuum Bagging of Substrate on Slats

The substrates are exposed to air flow and are required to be grounded for EME/EMI. A 2.0-inch wide x 1.5-inch long 3M 1181 copper tape is used for grounding from the substrate outer surface to the slat outer surface. See Figure 35 for substrate ground path installation.

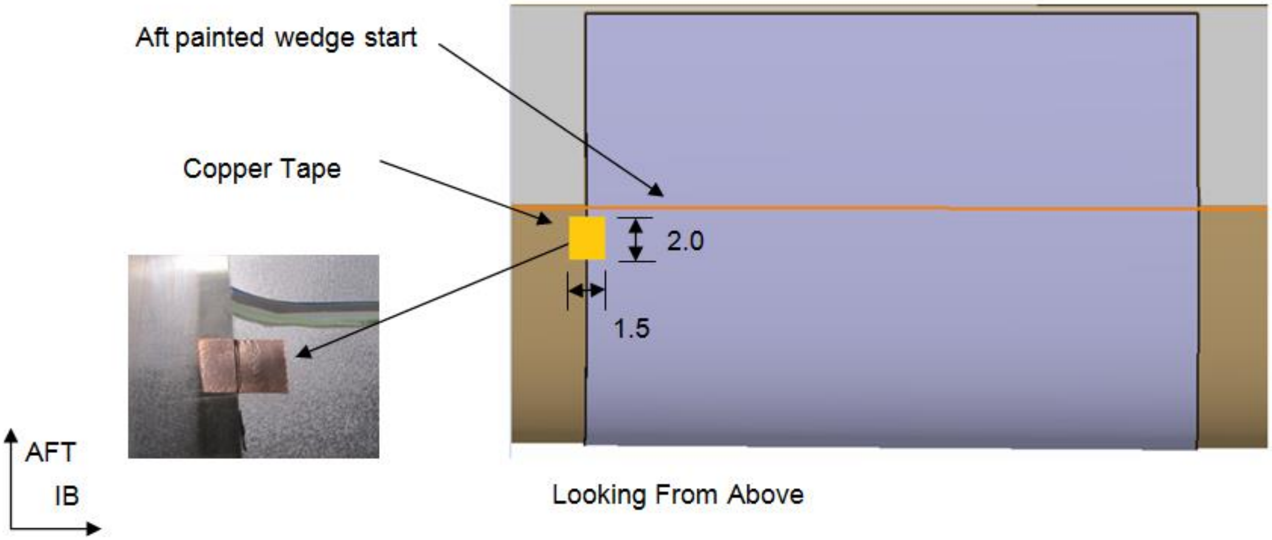


Figure 35: Copper Tape Ground Path Installation (Substrate)

To seal the edges from air ingression and act as a second load path, 2-inch wide 434 aluminized speed tape is applied around the periphery of the panels. The tape is first applied to the upper and lower aft edges and then the inboard and outboard edges. This ensures all the tape joints have aft facing steps. The loss of a single piece of tape will not cause the failure of the adjacent tape. Along the outboard edge, 0.003-0.005 diameter pin holes were added at each tape gap as a vent.

4.3.5.1 IAM Substrate Installation

The installation procedure was provided to the BT&E organization per the Boeing approved process to allow for safe operations. An overview of the steps was provided in Deliverable 4.20 (Reference (14)). Slats 8 and 9 outer surfaces were prepared prior to substrate installation. The surfaces were solvent wiped on the metal leading edge, slat wedge, and lower flex skirt OML with MPK (methyl propyl ketone). The surfaces were then abraded with very fine Scotch-Brite ® pads to promote adhesion. The use of orbital powered sanding tools was permitted. The enamel on the slat wedges was sanded to remove the gloss. After all sanding, the surfaces were solvent cleaned with MPK. To assist in repeatedly locating the IAM panels on the slat surface, 2 inch x 2 inch corner markings were added along the upper trailing edge surface of the slat with fine permanent marker as shown in Figure 36.

To install the panels, the leading edge was first extended to the landing position. The substrates are temporarily located to the locating features without removing the backing tape. The tape at the nose is first removed and bonded. The tape backing strips are then removed one at a time as the panel is rolled/pressed onto the surface working forward to aft to avoid voids. To develop the tape bond strength, a vacuum is then applied. After vacuum bagging, a tap test was performed to confirm acceptable void sizes. The voids are drawn on the Kraft paper protecting the engineer surface as shown in Figure 37. After the voids are deemed acceptable, the Kraft paper is removed and the bonding copper tape is applied and resistance checked. The periphery is wrapped in speed tape and the outboard edge holes are installed. See Figure 38 for a view of the completed installation.

Figure 36: Panel Installed With Upper Trailing Edge Corner Locating Marks

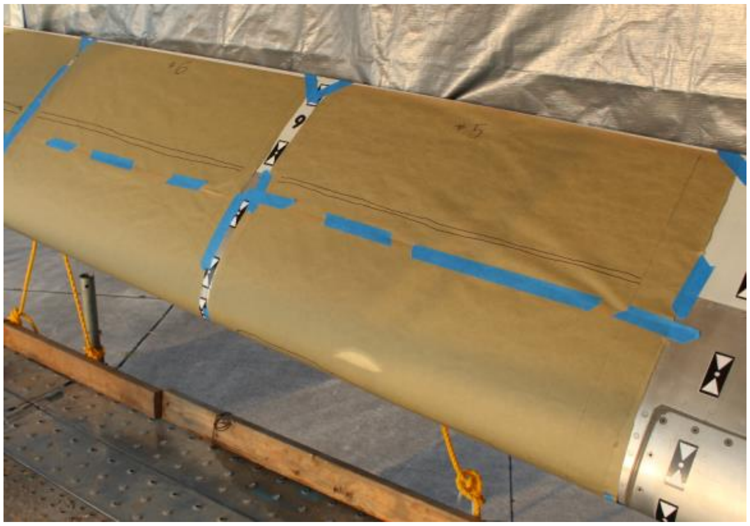


Figure 37: Voids Drawn on Covering Kraft Paper

Figure 38: Complete IAM Panel Installation

4.3.5.2 IAM Substrate Removal

An overview of the steps was provided in Deliverable 4.20 (Reference (14)). To remove the substrate, the speed tape around the periphery and copper grounding tape are removed. After removal of the edge tape, the edges were marked with the location of the photo targets for later location of the equal area lines. The removal of the panel begins at the lower trailing edge on the flex skirt. The panel is peeled away from the slat surface with a plastic or phenolic wedge or scraper to separate the high tack tape from the slat surface. See *Figure 39*, Figure 40, and Figure 41 for removal details. After removal, the substrates were placed in shipping boxes as shown in Figure 42.

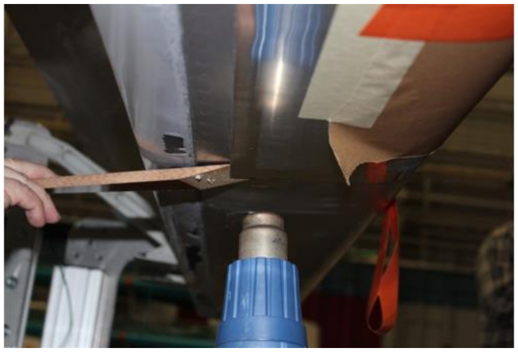


Figure 39: Peel substrate away from slat surface (Lower Surface View)

Figure 40: Peel IAM Panel Away From Slat (Upper Surface View)

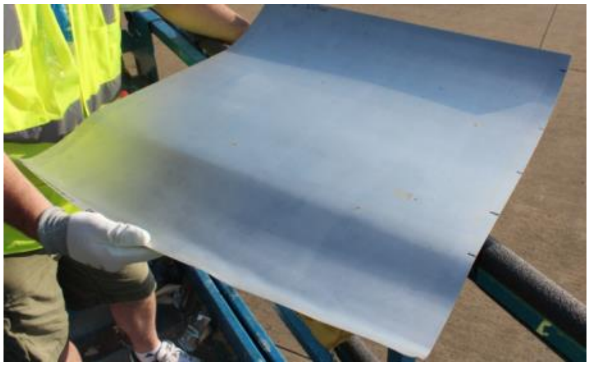


Figure 41: Flat Removed IAM Panel with Edge Marked for Area Lines

Figure 42: Substrate Located in Box with Lid Supports

4.3.6 Structural Analysis IAM Panel Installation

The high level requirement for the IAM panels was to assure continued safe flight and landing (CSFL) in the event a panel came off the airplane. Given that the underlying slat surface is unmodified, a departing panel simply exposes the basic external airfoil, so the airplane meets this requirement. Collateral damage of a departing panel was considered, but since the panels weigh under 2 lbs each they were not deemed a risk to the airplane. Note that the empennage leading edge is certified for an 8-lb bird-strike. The remaining design and analysis effort was focused on minimizing the possibility of a panel coming off the airplane.

The IAM panels are attached with double-sided adhesive tape, and installation trials indicated that voids between the panel and slat surface were probable due to surface waviness and uneven contact. The analysis objective was to show that, given an expected external pressure field, voids would not propagate and cause the panel to depart the airplane. The bond strength of the adhesive tape would be stressed if a net pressure existed across the panel, i.e. pressure within a void higher than on the external surface of the panel. There was concern that trapping a bubble during installation at sea level would create a very high net pressure across the bond at altitude. At the extreme, this could be 14.7 psi x 1.5 safety factor (14.7 psia is sea level standard static pressure). The adhesives being considered for easy panel application and removal were not sufficiently strong enough for this high pressure.

An important feature of the design was to apply the adhesive tape in narrow spanwise strips with a small gap between the strips. This gap would allow any voids to vent to the external pressure field at the tape edge which would significantly reduce the affected area.

4.3.6.1 Summary Void Limitations

The allowable void sizes for the taped panels are shown in Figure 43, with a 2.5” limit for edge flaws and a 3” limit for internal voids.

Strategy

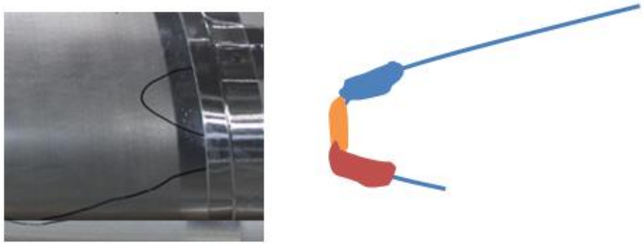
Evaluate external pressures

Test adhesive strength

Develop correlated bond line simulation

Define void limits for installation quality inspection.

Edge Flaws (no overlap) -- 2.5" allowed



Internal Flaws (no overlap) -- 3.0" allowed

Figure 43: Void Limitations

4.3.7 Coatings Application Procedure Development

The primary objectives of the series of sprayouts were to develop and verify the procedures needed to go from the small scale mix quantities (order 100 ml) and small size panels (order 0.2 sq. ft.) sprayed and cured at NASA LaRC to the order-of-magnitude larger mix quantities and panel sizes needed for the 757 ecoDemonstrator flight tests. The ecoDemonstrator panels were sprayed at Boeing to develop a procedure appropriate for the larger panels.

Some particular concerns and questions to be addressed by the preliminary sprayouts were:

1) What formulation quantities would be needed for producing the coated panels for the flight test?
2) What mix protocol is needed to produce the liter-size quantities that would give consistent and uniform mixes to apply?
3) How to mount and orient substrate panels for formulation application?
4) What paint-booth conditions were needed for the final sprayout?
5) What paint gun setting or modifications to the spray gun might be needed to give uniform film build during each coating pass?
6) How many application passes were need to produce the desired cured coating properties?
7) What changes in solvent amount or solvent system are needed to give a formulation that could be applied with ten to 20 minutes between passes (10 minutes being the approximate time it would take to spray eight large panels and observe the sprayout after each pass during final application)?
8) Would the paint gun or formulation composition need to be modified to prevent settling in the filled formulations?
9) How much time to flash off the coated panels prior to cure?
10) How to orient the panels in the cure oven?
11) What is the correct cure protocol for each formulation?
12) Would the performance properties of the cured coatings be adequate for the flight test?

4.3.7.1 Summary

Lessons learned from the series of Sprayouts 1, 2, and 2A led to a successful Sprayout method 3. The final sprayout involved five formulations, each onto eight 27” by 30” by 0.012” 7075-T6 clad panels which were then used in the Flight Test. Results of each sprayout were transmitted to NASA LaRC in after each sprayout test. In addition, "witness" plate examples of the results were also delivered (Deliverables 4.6a, 4.6b, 4.6c, 4.24 and 4.25). Some of the details from the sprayouts are listed below.

4.3.7.2 Mixing, Application and Performance Testing Details

The IAM formulations, resins, and fillers were supplied to Boeing by NASA LaRC. The solvents MEK (methyl ethyl ketone), MAK (methyl amyl ketone), and cyclohexanone were procured by Boeing. The formulations were mixed then sprayed in a humidity and temperature controlled paint booth and oven cured.

Insect adhesion mitigation performance was performed at NASA LaRC after delivery of at least two 4" X 6" panels from each sprayout method. NASA Langley personnel observed Sprayouts 2 and 3.

Other IAM coating performance tests were done at Boeing. Adhesion was measured using a cross hatch adhesion test similar to ASTM D3359.B on dry and 7-day wet soaked samples, Ra and Rq surface roughness was measured with a mechanical profilometer using ISO 97 with cutoff of 0.03 micro inches (x5), and panel flexibility was measured either using ASTM D522.B mandrel bend or by actual bending of the trial panel over a slat taken from the ecoDemonstrator. Final dry film thicknesses were also measured.

4.3.7.3 Sprayout 1

Sprayout 1, performed from May 12 to 17, 2014, consisted of a series of 5 trial formulations (IAMC-1, -2, -3, -4, -5) and a pre-run formulation IAMC-PR that was the same as IAMC-1. The IAMC-PR formulation was used to gain experience prior to the start of the trial. Each formulation was to be sprayed at two different thicknesses. Aluminum substrates used varied in size from 4" by 6" to 12" by 12" and in thickness from 0.016" to 0.040". All substrates were sprayed with an adhesion promoter conversion coat, AC-131, followed by an aerospace, non-chrome containing corrosion inhibiting primer prior to application of the IAMC formulation. The original formulation instructions called for using only MAK as the solvent. Cures were either at 50 °C or were cures that started at 100 °C and then went to 170 °C.

After the initial –PR formulation sprayout, it was apparent that this formulation could only be applied as a thin layer for each application pass and needed approximately 30 minutes between application passes instead of the target of 10 to 15 minutes. Also the –PR cured panels showed de-wetting and shrinkage. Consequently, Sprayout 1 formulations were then modified during the trial to include some MEK in the solvent and some of the formulations (IAMC-2, -4) were sprayed horizontally. An issue found during mixing of some formulations was that the resin was not completely dissolving with some remaining in the mix flask and/or plugging the spray gun.

Testing results showed the expected dry film thicknesses were generally less than expected based on a theoretical calculation, IAMC-4 had large measurable variations in coating thickness across the panel, and IAMC-1 had noticeable shrinkage at the coating edges. Surface roughness was above 100 micro-inches for IAMC-5, and crosshatch adhesion was marginally acceptable for IAMC-3 and this formulation also had peeling and cracking in the mandrel bend test.

4.3.7.4 Sprayout 2

After Sprayout 1, the decision was made to use 0.012 inch thick 7075-T6 aluminum as the substrate for the IAM coatings for the Flight Test. Consequently a pre-trial was held on July 23 and 24, 2014 to determine a suitable method for spraying out and curing 30 inch by 30 inch panels at 170 °C for up to 6 hours. Considerations were given to the lack of rigidity of the large panel making them difficult to keep flat while applying coating, the need for a non-coated area for adhering the panels onto the slat for the flight test, the possibility of warping the panel during a high temperature cure if the panel was not flat, the need for a high cure temperature tape that would not leach silicone into the coating during the cure, and that up to 8 panels of a formulation will need to be cured at one time. Using a commercially available, high temperature cure, polyurethane aerospace coating as the test bed formulation, it was found that the 7075-T6 substrate panels could be sprayed nearly vertically (70 degrees from horizontal) when taped onto a 0.040” 2024-T3 backing panel using Shercon PC-90 tape. The panels could then be cured at 170 °C for up to 6 hours when laid flat in the cure oven without warping or having silicone contamination from the tape, and that the tape could be used to picture-frame the coating so that there would then be areas for adhering the test panels onto the slat without applying the Flight Test tape to the coating and potentially causing tape adhesion issues (Figure 44).

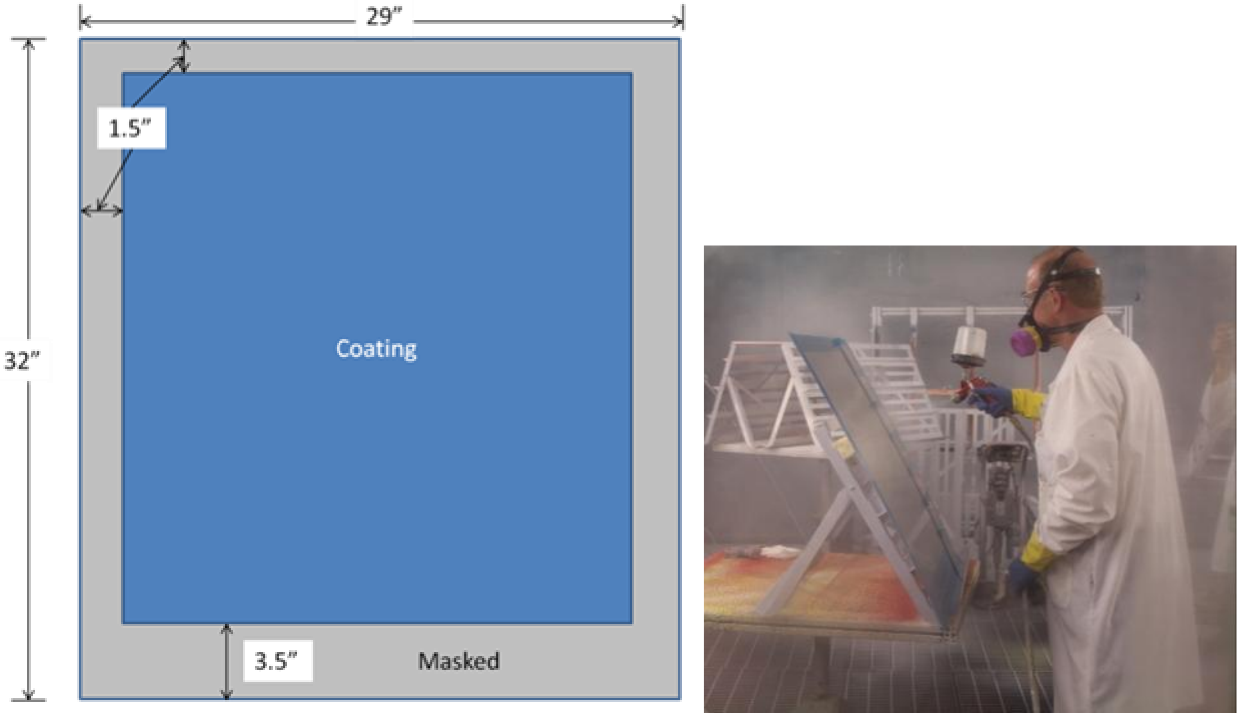


Figure 44: Example of IAM Coated Substrate Appearance

Sprayout 2, performed from September 23 to 25, consisted of a series of 5 trial formulations (IAMC-1, -2, -3, -4, -5) similar to that in Sprayout 1. However, the formulation solids level was lowered by 10 to 20% for IAMC-1, -3, and -4 and more MEK was added to the solvent package for IAMC-2, -3, and -4. Aluminum substrates used varied in size from 4” X 6” to 29” X 32” and in thickness from 0.012” to 0.020”. Substrates used were aluminum 0.012” thick 7075-T6 except when 0.020 inch thick 2024-T3 clad panels were required for a performance test. All substrates were sprayed with an adhesion promoter conversion coat, AC-131. However in this sprayout, only formulations -2, -3, and -5 were followed by an aerospace, non-chrome containing corrosion inhibiting primer prior to application of the IAMC formulation as -1 and -4 formulations are unfilled epoxies. Application times between coating passes were changed based on Sprayout 1 and real time observations made during Sprayout 2. Cure protocols were the same for Sprayout 1, except for IAMC-3 where the 6 hour cure at 50 °C was replaced by a 6 hour cure at 120 °C.

During mixing of IAMC-1 and -5, it was noted that the oxetane component seemed to solvate at a totally different rate than the hardeners component that were supplied in the same container so that NASA recommended that in the future, they be shipped separately. Also in IAMC-5, the solution tended to separate while it rested so a paint shaker was needed for re-dispersion. The amine solution in IAMC-4 did not dissolve readily under sonication at room temperature so as suggested by NASA the solution was heated to 50 °C where it disperse easily under sonication. IAMC-2 appeared to need longer sonication times to disperse the filler than when a smaller amount of the formulation was made at NASA.

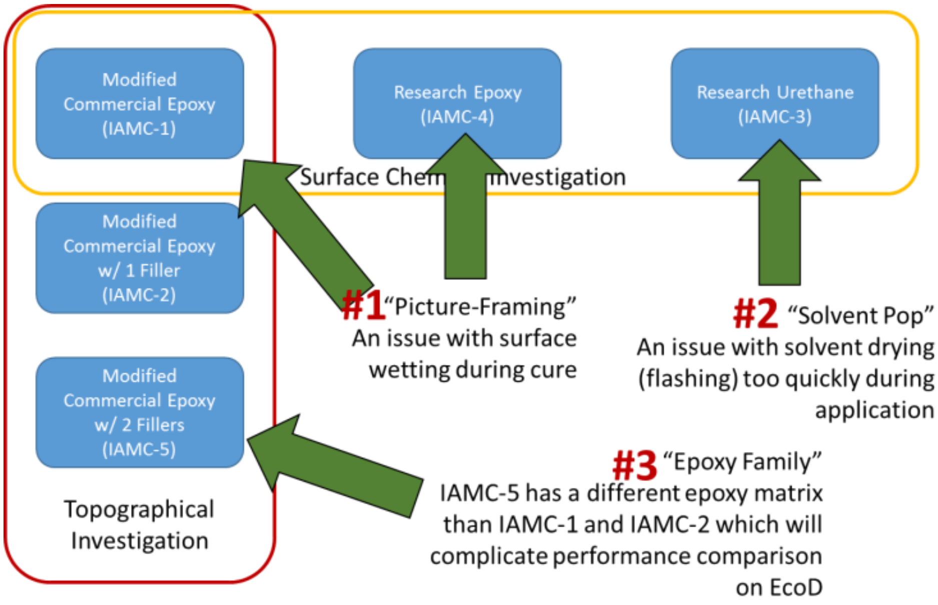
During application of IAMC-1, some de-wetting was still present but less than in Sprayout 1. After cure, there was some “picture framing” (thickening) around the coating edges. IAMC-2 slowly “gummed up” the gun during application so the solution should be filtered prior to filling the spray gun to minimize this effect. IAMC-3 showed solvent pop after cure and was attributed to switching to an all MEK solvent blend. IAMC-5 was filtered with a large mesh filter prior to filling the spray gun and slight manual agitation was applied by the Boeing painter during coating application and between application passes.

Test results showed the expected dry film thickness was less than expected based on a theoretical calculation. The root cause for much of this decrease was identified and arose because not all solution sprayed was applied to the panel as some was lost during spraying between panels and at edges to insure the complete panel had a uniform and consistent coating. Surface roughness R_a was above 500 micro-inches for IAMC-2. All formulations passed the dry/wet scribe adhesion test. Some cracking was observed in all three IAMC-1 test panels, while one IAMC-3 test panel had some cracking.

4.3.7.5 Sprayout 2A

An additional trial sprayout was requested by LaRC prior to the final sprayout for the Flight Test. The purpose of this sprayout as identified by LaRC is summarized in Figure 45. Because of the issue with different epoxies used in the Topographical Investigation portion identified in Figure 45, formulation IAMC-5A of Sprayout 2A used the epoxy resin of formulation IAMC-5 but with no fillers, while formulation -5B used only one of the two fillers found in formulation IAMC-5 (Figure 46). In order to spray out the filled systems without undue particle settling, a spray gun with agitated reservoir was identified by Boeing (

Figure 47). In order to minimize the “picture framing” issue identified in the previous sprayouts, an elevated temperature flashoff at 30 °C and a multiple temperature step cure up to 170 °C was specified for IAMC-1 and -4 by LaRC. Based in part on the solvent packages in commercial high temperature cured urethanes, such as that used in the pre-trial of Sprayout 2, the IAMC-3 solvent package was modified to be a mixture of MAK and cyclohexanone, which are less volatile solvents than the MEK used in Sprayout 2, and the temperature was slowly ramped up to the specified cure temperature of 120 °C.

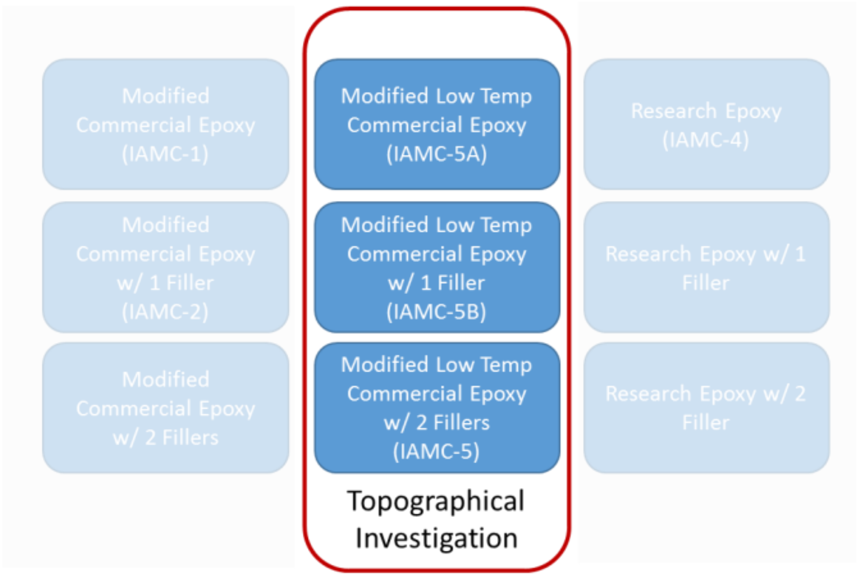


#1 "Picture-Framing"
An issue with surface wetting during cure

#2 "Solvent Pop"
An issue with solvent drying (flashing) too quickly during application

#3 "Epoxy Family"
IAMC-5 has a different epoxy matrix than IAMC-1 and IAMC-2 which will complicate performance comparison on EcoD

. Figure 45: Areas for Improvement Needed Based on Sprayout 2 (From NASA LaRC)



Risk:

- IAMC-1 picture framing issue is not resolved in Spray Out IIa,

Mitigation:

- Generate coatings in Spray Out IIa using epoxy resin from IAMC-5 for both the unfilled and 1 filler cases.

Figure 46: Areas for Improvement Needed –Topographical Investigation Alternative (From NASA LaRC)

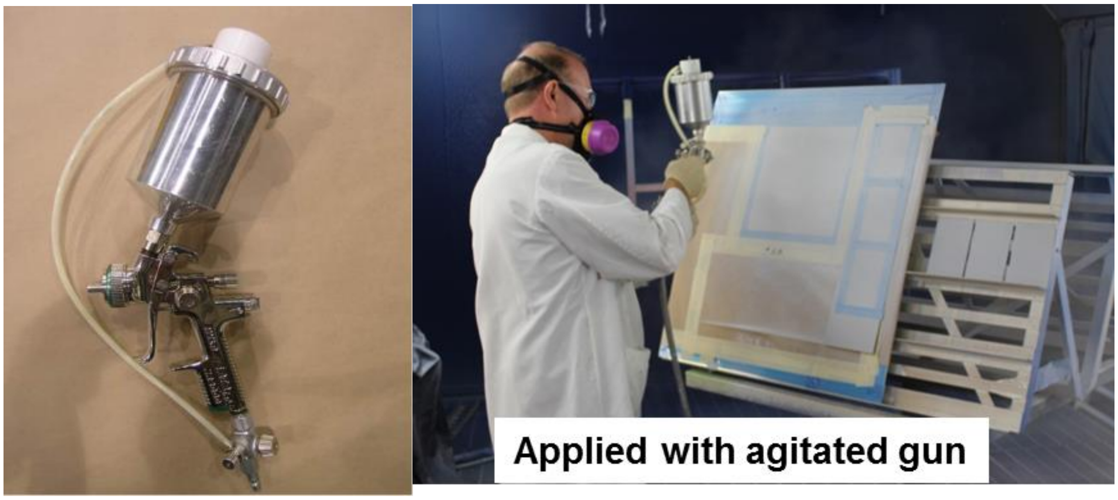


Figure 47: Sata NR2000 D=Gravity Fed Paint Gun with Agitator

Sprayout 2A, performed from December 3 to 5, 2014, consisted of the 5 trial formulations (IAMC-1, -3, -4, -5A, and -5B). Besides the use of formulations, -5A, and -5B, differences from Sprayout 2 included a refinement in the mixing and application procedures as well as in the solvent package and cure protocols. Due to time constraints for making the formulations at LaRC, 12” X 12” test patches were applied to the large 0.012 inch thick 7075-T6 clad aluminum panels as illustrated in Figure 48. These panels were also given to the Structures group for testing on the ecoDemonstrator slat. All substrates were sprayed with an adhesion promoter conversion coat, AC-131. In this sprayout, only formulations -3 (urethane base), -and 5B (filled epoxy) were followed by an aerospace, non-chrome containing corrosion inhibiting primer. The other formulations were unfilled epoxies.

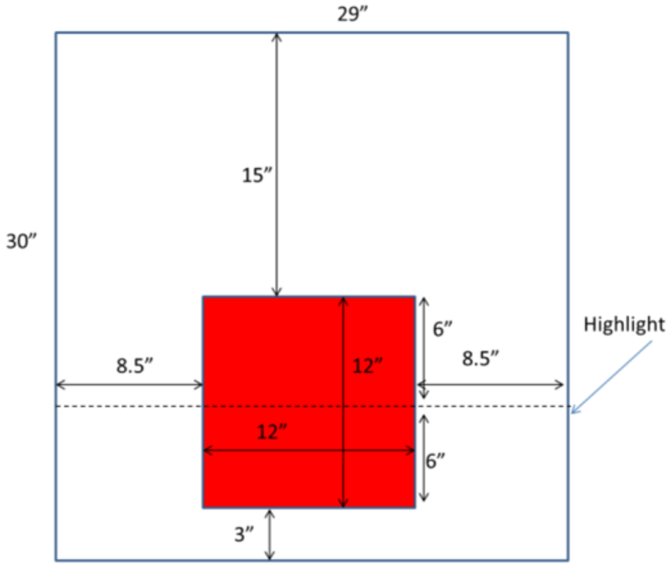


Figure 48: Large Panel Pattern for Sprayout 2A.

No issues were noted during mixing of IAMC-1 or IAMC-5A. IAMC-3 required some additional mixing and sonication for dissolution of materials into the new solvent blend. IAMC-4 required a small amount of additional solvent and sonication for dispersion of the amine in this formulation IAMC-5B required some additional sonication for dispersion of the filler.

During application of IAMC-1, some de-wetting was still present and strong de-wetting and shrinkage occurred during cure. For IAMC-3 which used a less volatile solvent package than in Sprayout 2, some particulates were observed, but wetting between coats was much better and less and smaller size solvent pop was observed after curing. For IAMC-4, there was still some de-wetting and shrinkage after cure, but it was judged to be acceptable when a large size (30” X 29” panel) is completely coated. IAMC-5A had some sagging on the second pass, but it was thought it could be managed by increasing the time between application passes slightly as the coating wet in well to previously applied layers. IAMC-5B sprayed well with the agitated reservoir spray gun with good wet-in into the previous application pass. Filler settling and separation were minimal. Upon curing there were some large grit structure, but they were thought to arise due to a delay between mixing and application involved with getting the agitator gun adjusted.

Dry film thicknesses were typically within 20% of expectation. Surface roughness Ra was above about 200 micro-inches for IAMC-5B, but this was expected since this formulation was being considered for the topological investigation. All formulations passed the dry/wet scribe adhesion test although a test in the thicker coating area of an IAMC-1 test panel indicated a marginal failure.

4.3.7.6 Sprayout 3 (IAM Coated Panels for Flight Test)

Based on the results from three previous sprayout trails performed at Boeing and the plan by NASA LaRC to investigate both chemistry and topological changes in the Fight Test, formulations selected by LaRC for the final sprayout were IAMC-3, -4. -5, -5A, and -5B. Sprayout 3 was performed from March 2 to March 7, 2015 in the presence of NASA personnel. Mixing procedures were only changed slightly from the previous sprayout of the formulations in those cases where it was noted that additional processing was needed to ensure coating uniformity. Two to three batches of each formulation were made in order to provide enough material for the sprayouts. Application and cure procedures were similar to the previous sprayout of these formulations except for minor adjustments to account for the number of large panels being sprayed, eight for each formulation. All substrates were sprayed with an adhesion promoter conversion coat, AC-131. In this sprayout, formulations -3 (urethane base), -5 (filled epoxy with one filler) and -5B (filled epoxy with two fillers) were followed by an aerospace, non-chrome containing corrosion inhibiting primer after the conversion coat and prior to the insect adhesion mitigation formulation application. The other formulations were unfilled epoxies.

Layout for coating application used on the Flight Test Panels and the witness panels that were sent to LaRC are shown in Figure 49. After the sprayouts, a judging board consisting of Boeing and NASA personnel ranked the large 0.012” X 27” X 30” 7075-T6 Al clad panels from 1 to 8 within each formulation for uniformity and consistency. The higher ranked panels from each coating formulation were then to be used in the Test Flights in Shreveport.

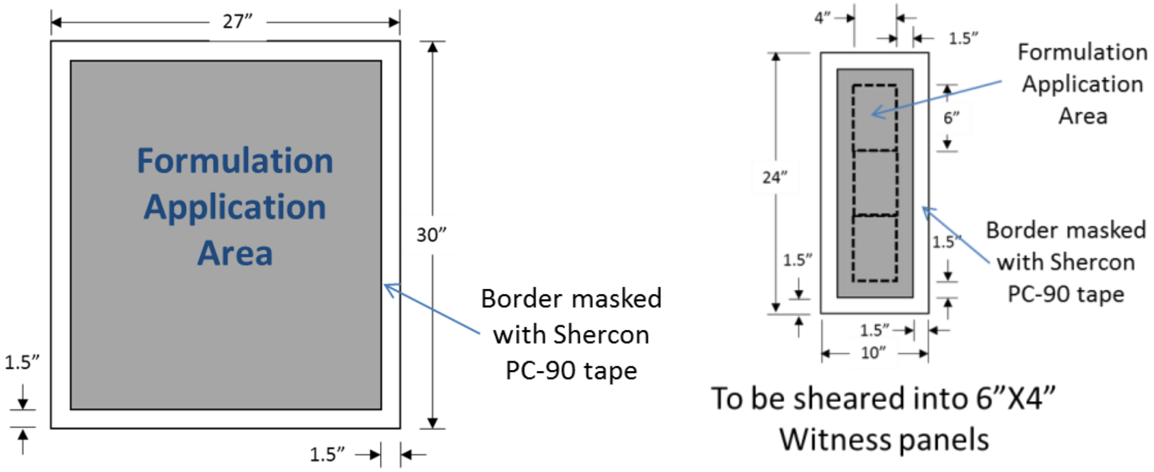


Figure 49: Layout of Large Flight Test and Witness Coated Panels

The mixing and application protocol for Sprayout 3, which was written based on the previous sprayout results, was generally followed. Any changes to the protocol were documented in the redline copy referenced at the end of this section. One change was that in the mixing of IAMC-4 the sonication time was increased from 15 minutes to as long as 40 minutes in one batch to ensure dispersion of the ingredients into solution. Examples of the coatings made during sprayout 3 are given in Figure 50.

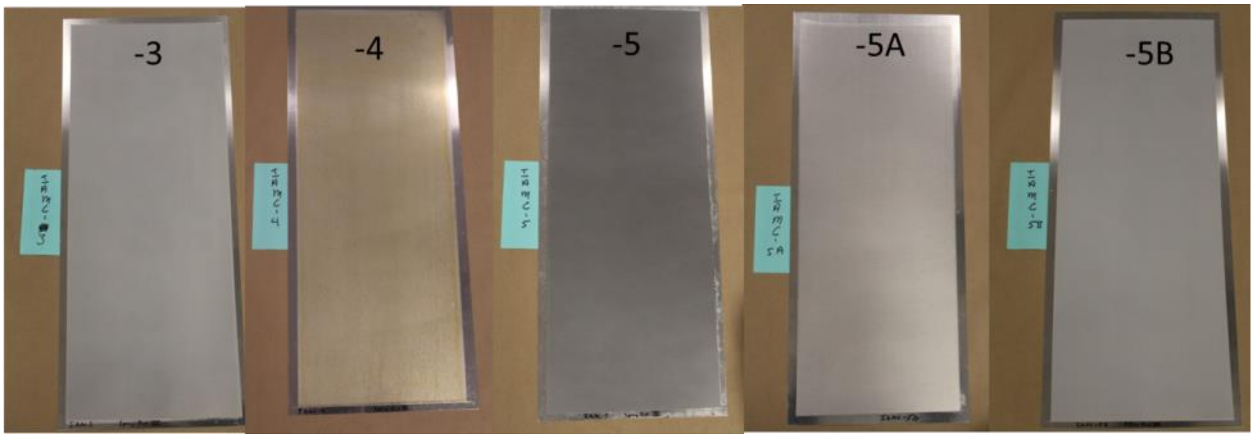


Figure 50: Coated Witness Panel Produced during Sprayout 3

Dry film thickness was in the expected range for each of the formulations. Surface roughness Ra was about 10 µin for IAMC -5A, 60 µin for -5, and 400 µin for -5B, which gave a good range of surface roughness for the topological investigation. The surface roughness for the surface chemical investigation varied only from about 5 to 10 µin so topological effects were minimized in this set. All formulations passed the dry/wet scribe adhesion test.

Results sent to LaRC were:

1) “LaRC_SOIII_RedlineCopy”. April 7, 2015.
2) “Test Property Spreadsheet- SO_III_Combined”. March 30, 2015.
3) “LaRC Sprayout 3 03-27-15 R2”. March 27, 2015.

4.4 IAM 757 ecoDemonstrator Flight Test Program

The primary test objective of the coatings is to keep the wing leading edge clean and free of insect residue. A secondary benefit of the test is categorizing the insect accretion profile on the wing leading edge through a range of altitudes (up to 10,000 ft), during normal takeoff and landing operations. To support these test objectives, the substrate design was required to maximize frontal area on the leading edge, provide side-by-side comparison between coated and uncoated surfaces, not significantly deviate from the aircraft leading edge profile and support panel removal and installation in one crew shift.

4.4.1 Safe to Fly Review

The Safe to Fly review for the IAM technology to fly on the aircraft was held at Boeing on April 3, 2015. The review included the Boeing chief engineer for the 757 ecoDemonstrator and NASA personnel via telephone.

The Boeing chief engineer for the 757 ecoDemonstrator formally approved the operation of the aircraft with IAM installed via signature on the Block 3 Safe to Fly Coordination Sheet, released April 22, 2015 (Reference (15)) which satisfied Deliverable 4.17.

4.4.2 Site Selection

The primary risk factor identified in the project Risk, Issue and Opportunity (RIO) management was the likelihood of encountering enough insects to meet the NASA-defined insect residue density criteria. Without adequate insect activity, the ability to collect a statistically significant dataset to assess the performance of the different IAM coatings could be compromised. Based on previous testing by NASA with a Falcon aircraft, up to 15 flight cycles could be necessary to achieve the density criteria. To improve the likelihood for success, a search for the optimum site to conduct the flight test was performed.

4.4.2.1 Site Selection Team

The site selection team (Table 6) was led by NASA Ames Research Center (ARC) with representatives from NASA Langley Research Center (LaRC), Boeing, Volpe and the University of California, Davis. Volpe was contracted to provide quantitative data from the national airport database, and acted as the primary contact between the team and airports of interest. An entomologist from UC Davis provided expertise on insect activity.

Table 6: Site Selection Team

Name	Organization
Bruce Storms	NASA-Ames
Robert Fong	NASA-Ames
Mike Alexander	NASA-LaRC
Keith Harris	NASA-LaRC
Tom Farrell	Boeing
Jeffrey Crouch	Boeing
Lynn Kimsey	UC Davis
Amir Tabrizi	Volpe
Melanie Soares	Volpe

4.4.2.2 Site Selection Criteria

The team identified several key site selection factors including physical attributes, meteorological attributes, and insect population likelihood. These were used to rank the locations with the highest probability for success. The final criteria list was agreed to on August 20, 2013 (Reference (5)) and is summarized below.

Physical Attributes

- Continental US
- Runway long enough to support the modified B757 (>8,000ft)
- Low traffic counts (<500 aircraft per day), particularly during day-time hours
- Control tower
- Note available airspace (i.e. noting distance to airports or test facilities in the approach vicinity)
- Near wetlands or agricultural areas

Meteorological Attributes – provided by month

- Low weather delay count (i.e., amount of rainy days)
  - Rainy days are defined by rain lasting at least one hour during daylight hours
- Daily temperature range between 65 and 90 Degrees Fahrenheit during daylight hours for a minimum 4 hour window
- Humidity > 30% during daylight hours
- Little or no wind over 10kts for a minimum 4 hour window
- March – May 2015 are target months

Insect Population Likelihood

- Given the physical and weather attributes described above, offer a recommendation by month as to the likelihood of insect strikes
- Species and size by geographical area likely similar except for pollinators introduced by local farmers

Based on the historical data provided by Volpe, the primary criteria used to sort airports were the meteorological attributes that affect insect population; specifically, temperature, wind speed and likelihood of rain. Temperature restrictions allowed the geographical area to be focused to the West-Coast and Southern states.

With these criteria, the initial airport list included a total of 86 airports from 15 states. The team reviewed additional qualitative criteria comparing airport layouts, familiarity of Boeing Test and Evaluation (BT&E) and possibilities for nearby alternate locations.

4.4.2.3 Airport Questionnaire

From the down-selected list of airports, the top 12 sites were interviewed for more details using a common set of questions developed by the team. Volpe handled communications with the representatives from each airport. These questionnaires were intended to assess the airports' interest to support this activity and gather further information on likelihood for obtaining adequate insect density. Of the 12 sites selected to receive the questionnaire, eight of them responded. The final questionnaire and responses were distributed to the team (Reference (6)).

4.4.2.4 Airport Site Visits

After reviewing the airport responses to the questionnaire the plan was to visit the top three, as determined by the team. These site visits were used to inspect the facilities and assess any additional impressions not covered in the formal criteria. The timing of the visit was approximately one year before testing and as close as possible to the same time of year to give the team an idea of representative conditions for that time of year. These visits were to locations in Florida, Louisiana and California. The sites and dates visited are shown in

Table *7*.

Table 7: Site Visits

Airport	Date of Visit
Tallahassee, FL (KTLH)	4/14/2014
Fort Myers, FL (KRSW)	4/16/2014
Stockton, CA (KSCK)	4/22/2014
Fresno, CA (KFAT)	4/23/2014
Shreveport, LA (KSHV)	4/29/2014
Alexandria, LA (KAEX)	4/30/2014

4.4.2.5 Final Site Selection

After the site visits concluded, each organization within the selection team ranked their preferred sites. Shreveport, LA was the unanimous choice.

4.4.3 Flight Test Planning

Boeing collaborated with NASA on the development of the test phases to ensure the objectives of the test were adequately captured. The overall plan was captured in the ConOps discussions (Reference (16)). A successful sortie was defined as one that collects a minimum of 25 insects/square foot on two of the four panels per slat. Phase 5a was used to gather a baseline with uncoated panels and develop the bulk of the insect profile information. Although the panels in 5a were uncoated, the preparation of the external surface was preferred by Boeing to be “de-glossed” to reduce the risk of poor image quality due to lighting issues. NASA’s preference was to keep the shiny finish the panels were delivered with, to limit the variables between their lab testing and the flight test results. A meeting was held on March 26, 2015 where it was agreed (Reference (18)), the panels in 5a would be “de-glossed” using scotch-brite pads that kept the roughness values the same as the baseline finish, and phase 5b and 5c would use the shiny finish for the reference panels.

Using the panel layout definition, specific panel configurations flown during phases 5b and 5c were defined by NASA using the rankings list created after Sprayout 3 (Reference (19)). The spanwise locations of the coating types were changed between 5b and 5c to ensure no bias in the data due to spanwise variation of the insect density.

4.4.4 Flight Profile Development

Particulars of the flight profile were selected to maximize insect accretion while flying a variety of takeoff conditions to simulate actual airline operations and taking into account airplane limitations. The aircraft configuration required specific Temporary Operating Limitations (TOLs) and Aircraft Advisories to be in place for the duration of the flight test. The limitations applied for the IAM installations specifically were to restrict the retraction capability of the leading edges and limit the maximum pressure altitude to 10,600 feet.

To achieve a range of climb rates and speeds, takeoffs were performed at a range of flap detents, F01, F05 and F20. All landings during IAM testing were performed at detent F20. In addition to flap detent, final climb altitude varied between 1,500, 5,000 and 10,000 feet. With one exception during Phase 5C, full stop landings were used during bug collection flights to simulate airline operations.

4.4.5 Weather Contingencies

Due to unavailability of a hangar at Shreveport Regional Airport, Boeing provided a contingency plan to protect the IAM panels from rain. The plan included two parts: 1.) a scaffolding rain cover and 2.)

a tarp. The contingency plans were presented to NASA and accepted on April 1, 2015 (Reference (20)).

A precipitation weather cover was requested to cover the panels in case of inclement weather during testing. Rainfall on the insect accretion post flight would add an unknown variable to the results. It was also desirable to reduce moisture on the panels overnight. The design of the cover required it to be installed within minutes, be offset of the leading edge so as to not touch the surfaces, be water resistant, not allow the wind to blow rain onto the surfaces, and not be a hazard to the airplane.

It was determined a cover for each slat was preferable over one large cover. This would make the cover more manageable to prevent contact of the IAM surface during installation. The covers were successfully tested with a watering can. 0.25 inch diameter holes were punctured at the lowest inboard points adjacent to offsets to provide a water drain path. See Figure 55.

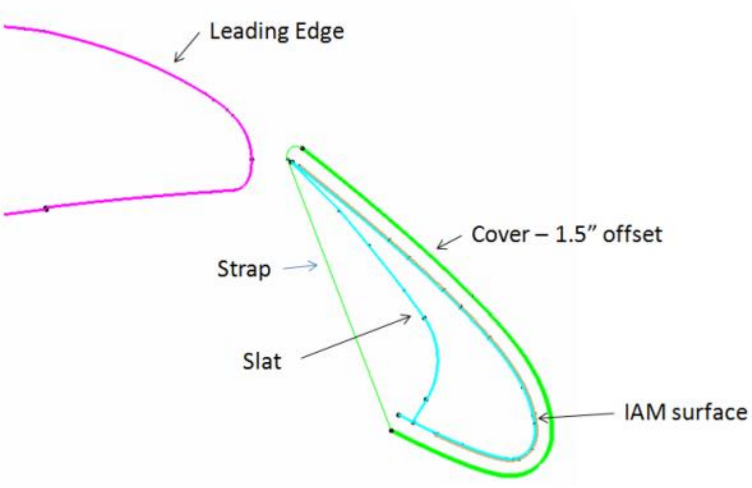


Figure 51: Slat Cover Installation Cross-Section

Figure 52: Slat Covers Installed

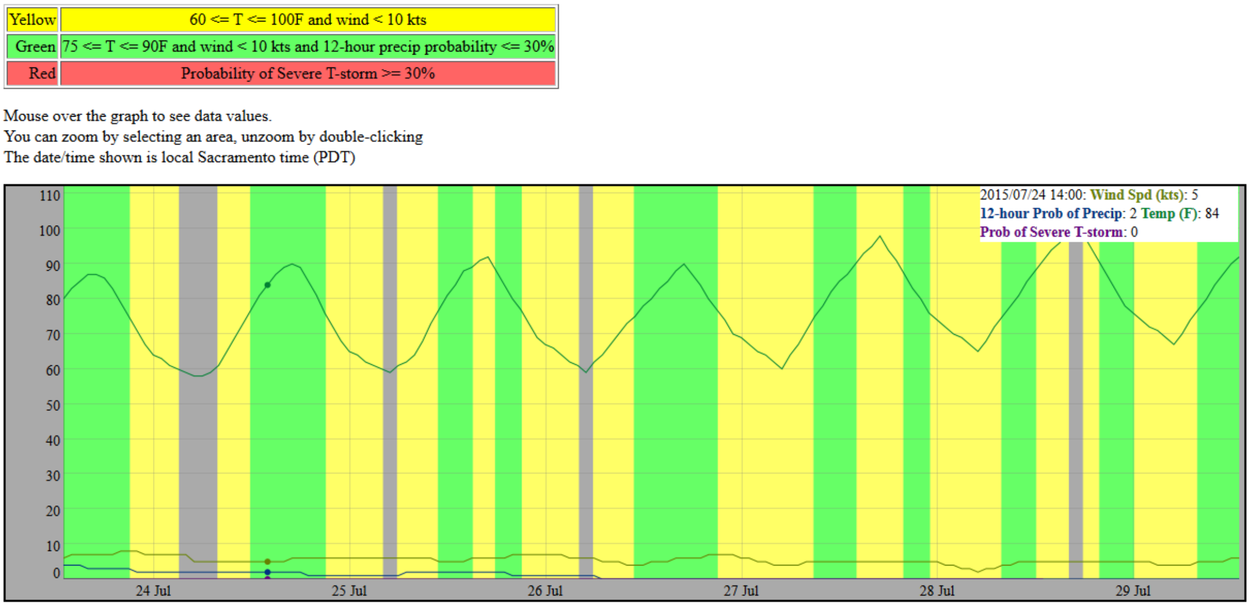
Figure 53: Slat Covers Installed From Lower Surface

Figure 54: Testing for Water Proofing

Figure 55: Drain Path for Water Pooling at Covers Lowest Point

4.4.6 Test Operations Preflight Activities

The testing in Shreveport was expected to be highly weather dependent. Prior to testing, temperature, precipitation, and wind limits were established through consultation with project entomologists. Boeing analyzed historic meteorological and local weather forecast data for the airports in the area to predict testing windows with weather conducive to greatest insect activity. A running forecast was used to manage test operations, see Figure 56. This site was valuable for adapting the plan as the test team learned which weather factors had stronger influence on insect density.



Yellow	60 <= T <= 100F and wind < 10 kts
Green	75 <= T <= 90F and wind < 10 kts and 12-hour precip probability <= 30%
Red	Probability of Severe T-storm >= 30%

Mouse over the graph to see data values.
You can zoom by selecting an area, unzoom by double-clicking
The date/time shown is local Sacramento time (PDT)

Figure 56: Atmospheric Physics Forecast (Ground Temperature) (from BT&E internal website)

4.4.7 Flight Summary

The typical test day plan was presented to NASA at the Flight Campaign Briefing on March 24, 2015 (Reference (21)) which satisfied Deliverables 4.12 and 4.8. This plan included the steps for pre-flight preparation, in-flight execution and decisions, and post-flight activities for the three different phases of testing (5a, 5b, and 5c). The flow times for each task were estimated and incorporated into the test scheduling. A brief summary of the test plan flow times compared to the average test metrics is shown in Table 8.

Table 8: Average Testing Flow Times Compared to Estimates

Metric	Estimate	Actual (Avg.)
Flight Cycle Time (brake release to landing)		
1,500 ft max altitude	10 min	6 min
5,000 ft max altitude	15 min	10 min
10,000 ft max altitude	20 min	17 min
Taxi Time Between Circuits	10 min	12 min
Inspect/Clean/Refuel Turn Time	2.5 hrs	2.0 hrs

Onsite the testing performance was better than expected due to favorable conditions providing better than expected insect accretion. A total of 11 flight days were needed to collect the required data; four days fewer than planned. Only two days were lost due to weather and a total of four multiple-sortie days were achieved. A summary of the flight log is covered in the Flight Log section below.

4.4.8 Inspections

The crew aboard NE016 monitored the on-board camera data during the flight. Once it was ascertained they had enough bug accretion, the plane would return to base. With the crew still on-board, a joint effort was made by NASA and Boeing ground crews to verify that the bug density on the IAM control panels met the density criteria.

To ensure a bug density of 25 hits/square foot, a square foot template was used to conduct the counting initially. Figure 57 outlines the zone numbering used; note Zone 0 is the underside of slat below the first white line in Figure 57. Because of the slat curvature, a trend was noted after the first couple flights where zone 4 consistently received the lowest number of bug hits.

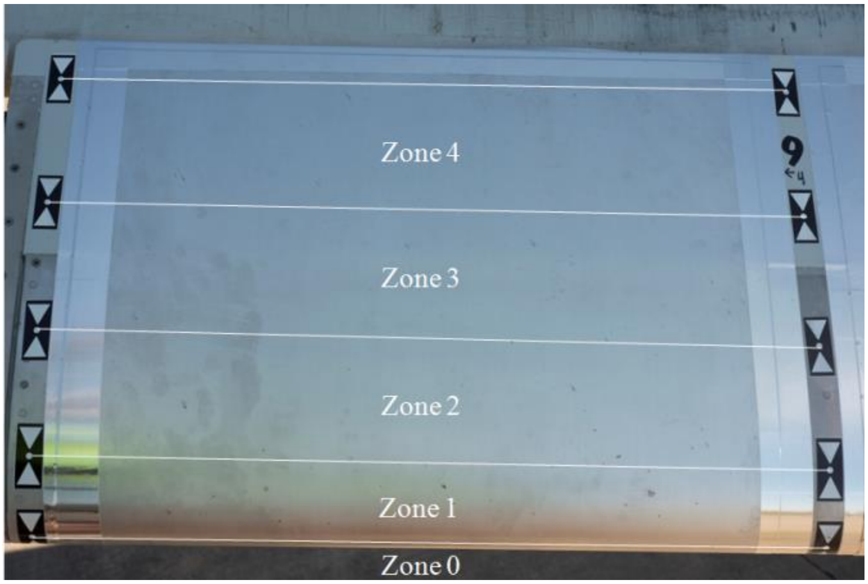


Figure 57: Panel Zone Numbering (View from Above)

As a result, using a simple square foot template proved difficult to show enough bug density. It was determined that counting the number of bug hits in zones 2 and 3 would provide a better density count. The process was then changed to count the number of bug hits in zones 2 and 3 where a total count between 53 to 62 hits in both zones would meet the density criteria. If the criterion was not met, the crew would determine if the weather conditions were conducive to conduct more circuits or if the testing needed to be called off for the day. If the criterion was met, then a detailed bug count was completed on the surrounding slats on the right wing. The slat counts represented control data to identify possible bug density generation factors such as location along the wing. To count the number of bug hits, the count was recorded by zone following the same zone format outlined in Figure 58. For the slats without IAM panels that were counted, green paint was used to isolate the different zones for counting.

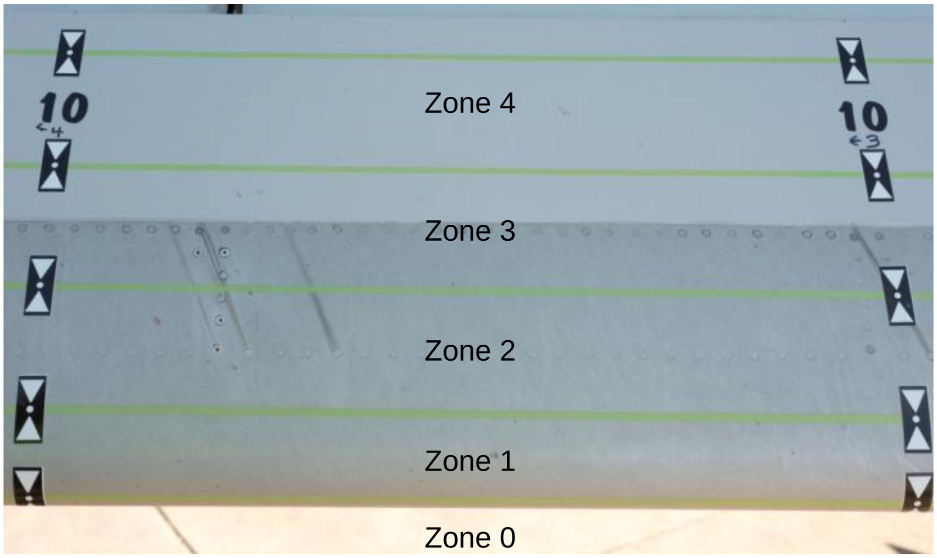


Figure 58: Slat Zone Numbering

After counting a zone, the total number of hits for that zone was recorded according to a table (see in Inspection Data Summary section for an example). The count was purely numerical in nature as no special attention was given to bugs based on size. For any bug hits that spanned more than one zone, only the zone in which the bug hit originated was counted. Streaks or “protein stains” were also considered as hits and were included in the count. In addition, NASA’s entomologist was available to identify the various insects that had hit the panels.

4.4.9 Flight Log

The flight testing in Shreveport was split into three distinct panel configurations: 5a, 5b, and 5c. Phase 5a included 5 sorties, 5b included 4, and 5c included 6 sorties. A summary of sorties flown for each configuration is provided in the tables below.

Table 9: Phase 5a Flights Summary

Phase 5a	**DATE**	**4/29/2015**	**4/30/2015**	**4/30/2015**	**5/1/2015**	**5/1/2015**
	FLIGHT #	**007-002 Flt1**	**007-003 Flt2**	**007-003 Flt3**	**007-04 Flt4**	**007-04 Flt5**
	CONFIG - RIGHT	**RA**	**RA**	**RA**	**RA**	**RA**
	TIME (1st BREAK RELEASE - ENGINE OFF)	**17.43.42 - 19.26.28**	**15.55.50 - 17.50.20**	**20.11.05 -21.22.17, 21.53.39 - 22.46.58**	**15.59.13 - 17.33.20**	**19.44.52 - 22.09.12**
	TOWER WIND DIRECTION/SPEED (KT) at 500ft	**010/11,010/12,350/07**	**330/4 at 800ft, 290/5 at 700ft, 340/7, 340/7at 1K, 340/9**	**290/7 at 700ft, 320/11, 270/8, 290/5, 280/7,330/5,330/4**	**110/3, 100/3, 070/4, 020/6**	**360/6, 290/4, 330/3, 310/6, 350/6, 010/5**
	FLAPS AT T/O	**20,5,20**	**20,1,20,1,20**	**20,20,20,20+20,20,20**	**1,1,1,1**	**5,5,5,5,5,5**
	MAX ALTITUDE	**10,000ft**	**5,000 ft**	**5,000ft**	**5,000ft**	**5,000ft**
	# OF FULL LANDING	**3**	**5**	**4+3**	**4**	**6**
	# OF TOUCH AND GO	**0**	**0**	**0**	**0**	**0**
	# OF RUNWAY FLYBY	**0**	**0**	**0**	**0**	**0**

Table 10: Phase 5b Flights Summary

Phase 5b	DATE	5/2/2015	5/3/2015	5/4/2015	5/4/2015
	FLIGHT #	007-05 Flt6	007-06 Flt7	007-07 Flt8	007-07 Flt9
	CONFIG - RIGHT	RB	RB	RB	RB
	TIME (1st BREAK RELEASE - ENGINE OFF)	15.44.16 - 17.20.20	15.40.31 - 17.47.03	15.40.38 - 17.24.03	19.35.36 - 21.14.49
	TOWER WIND DIRECTION/SPEED (KT) at 500ft	150/5, 160/7 at 800ft, 160/7 at 1000ft, 190/5	220/10, 200/10G14, 200/12, 200/11, 190/11, 200/11	calm, 180/6, 160/5, 150/6, 170/7	100/10,calm,120/10,120/10G15,130/10
	FLAPS AT T/O	20,20,20,20	5,5,5,5,5,5	1,1,1,1,1	20,5,20,5,20
	MAX ALTITUDE	10,000ft	5,000ft	5,000ft	5,000ft
	# OF FULL LANDING	4	6	5	5
	# OF TOUCH AND GO	0	0	0	0
	# OF RUNWAY FLYBY	0	0	0	0

Table 11: Phase 5c Flights Summary

Phase 5c	**DATE**	**5/5/2015**	**5/6/2015**	**5/6/2015**	**5/7/2015**	**5/8/2015**	**5/10/2015**
	FLIGHT #	**007-08 Flt10**	**007-09 Flt11**	**007-09 Flt12**	**007-10 flt 13**	**007-11 Flt14**	**007-12 Flt 15**
	CONFIG - RIGHT	**RC**	**RC**	**RC**	**RC**	**RC, slats retracted**	**RC**
	TIME (1st BREAK RELEASE - ENGINE OFF)	**15.48.50 - 15.21.21**	**13.23.04 - 16.09.15**	**18.34.38 - 20.27.47**	**14.34.37 - 16.01.50, 17.55.34 - 19.20.27****	**18.12.39 - 19.26.18, 20.17.39 - 20.43.13**	**16.23.08 - 16.40.39, 17.59.21 - 19.01.01******
	TOWER WIND DIRECTION/SPEED (KT) at 500ft	**130/16, 160/12 at 800ft, 160/12, 140/13**	**160/10 at 800ft, 150/12, 120/10 at 700 ft, 140/10, 100/11 at 700 ft, 150/13, 140/12, 140/12**	**130/9, 150/10&15, 160/13, 130/10 at 800 ft, 170/08, 140/08, 130/11,**	**150/10, 160/07, 150/11, 140/9, 130/14, 120/11, 150/7**	**180/6, 160/6 at 1000ft, 210/5, 190/7, 200/8, 190/7, 170/10, 180/8, 190/10 170/5, --/-- ,170/5,**	**180/14, 170/16, 180/6, 160/9, 160/8, 170/6 at 800ft, 160/11**
	FLAPS AT T/O	**20,20,20,20**	**20,20,20,20,20, 20,20,20**	**5,5,5,5,5,5,5**	**1,1,1+1,1,1,1**	**1,1**	**5,20 + 5,20,5,20,5**
	MAX ALTITUDE	**5,000ft***	**10,000ft (4 flights) 5,000ft (last 4 flights)**	**5,000ft**	**5,000ft**	**1,500ft*****	**1500ft**
	# OF FULL LANDING	**4**	**8**	**7**	**3+4**	**1+1**	**2+5**
	# OF TOUCH AND GO	**0**	**0**	**0**	**0**	**0**	**0**
	# OF RUNWAY FLYBY	**0**	**0**	**0**	**0**	**9+2 at 500ft (AGL)**	**0**

*Planned for 10,000ft but several layer of clouds up to 10K --> change plan to 5,000ft, unsuccessful in meeting density criteria & wind conditions deteriorated

** Refuel in between flights and waiting for the ceiling to burn off.

***Max Altitude 1500ft instead of 5000ft due to ceiling (2000ft) and preferring to stay VFR (visual flight rule) and out of any potential precipitation.

****Insect Density Inspection between the two flights.

4.4.10 Image Data Summary

For each sortie, the IAM cameras were positioned to each capture slats 8 and 9. Images were captured approximately once every second during test conditions.

Although resolution was designed to be adequate to capture most insect impacts, focus, optical window quality, and lighting conditions adversely impacted what was visible. It is estimated that 15-30% of total insect impacts were discernible in the image data. A large portion of the insect impacts counted on the ground were streaks or small particles which were not visible in the in-flight images. In addition, day to day (and photo to photo) variations in focus, optical window quality, and lighting conditions adversely influenced the ability to observe these impacts during flight. A section from an in-flight photo is shown in Figure 59.

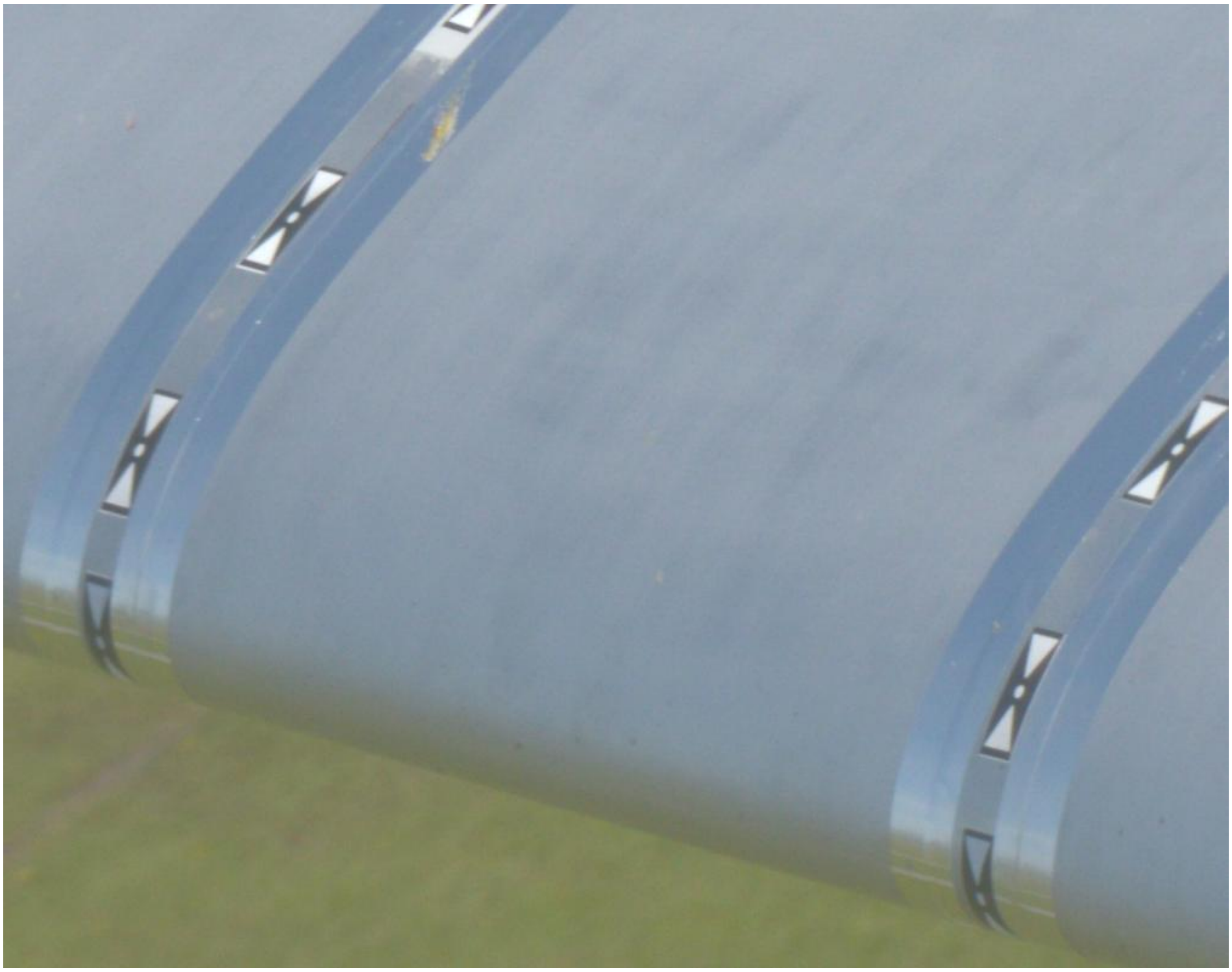


Figure 59: Example In-Flight Photo

In addition to the in-flight images obtained, post flight photographs of the relevant leading edge surfaces were captured as well. These images were taken from outside of the aircraft at a much closer range. As such, much more details were visible in the on-ground images. An example photo from the ground inspection is shown in Figure 60.

Figure 60: Example On-Ground Photo

All images collected in-air and on the ground were delivered to NASA at the conclusion of testing as documented in Reference (22).

4.4.11 Aircraft Data Summary

During each test flight, aircraft data was recorded from onboard instrumentation and ship's systems. The information included aircraft altitude, velocity, configuration, and outside ambient conditions. These data files were delivered at the end of testing to NASA along with comments from flight crew per Reference (22).

4.4.12 Inspection Data Summary

Insects were counted on the IAM panels and reference slats. Counts are recorded by panel and slat zone. On reference slats 7 and 10, spanwise area was discretized into five zones similar to IAM slats 8 and 9. Counts were provided to NASA at the conclusion of testing (Reference (22)).

Typical counts showed a higher accretion rate in the lower zones and a relatively constant accretion rate spanwise. The zones close to the nacelle on Slat 7 tended to collect fewer insects since the nacelle provides some shielding from the ballistic trajectories.

Accretion counts are plotted as a raw count, and as accretion / square foot. Example table and charts from Phase 5C flight 4 are shown below in Table 12, Figure 61 and Figure 62.

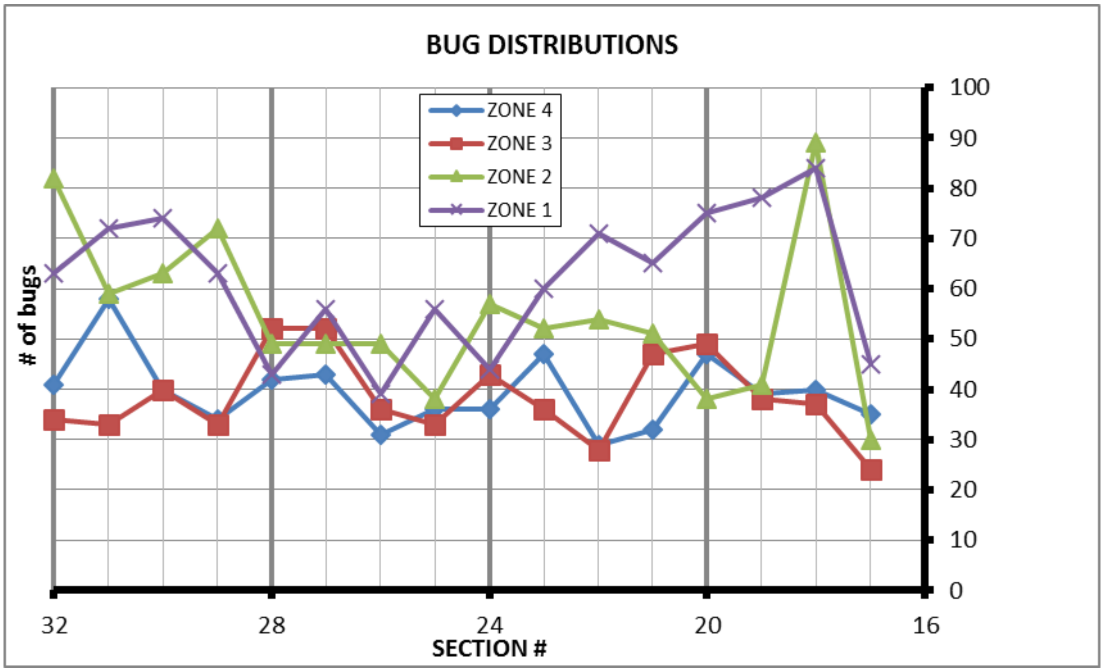


Figure 61: Flight 4 Accretion Distributions

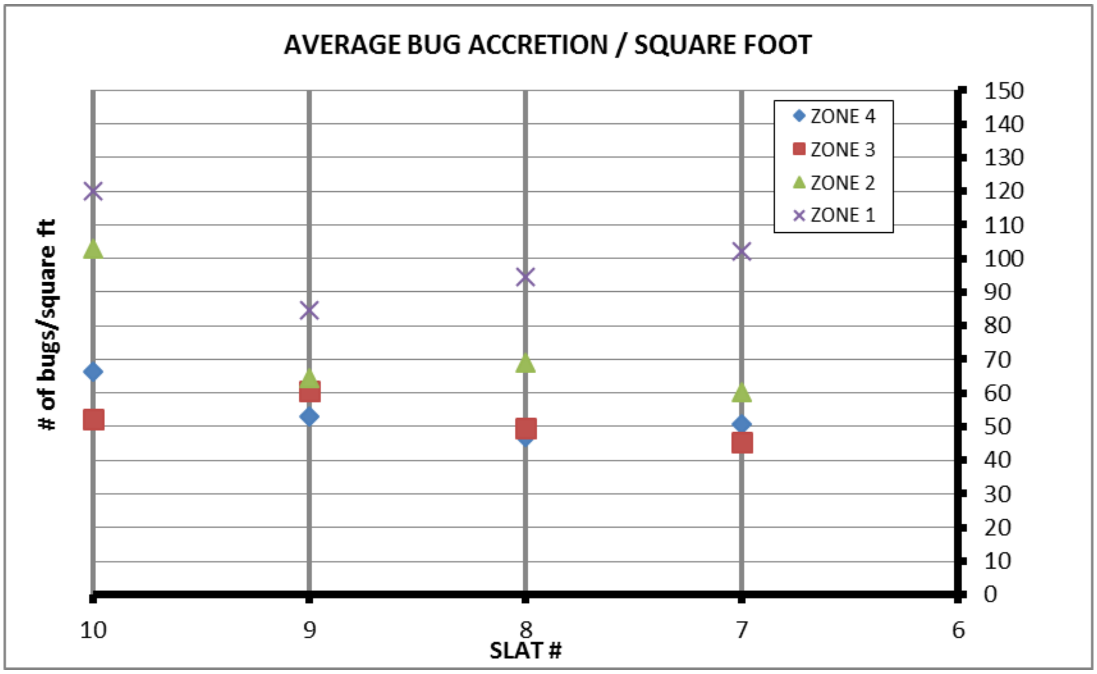


Figure 62: Flight 4 Accretion Per Square Foot

Table 12: Flight 4 Insect Count

ZONE	R10				R9				R8				R7			
	REF	REF	REF	REF	CONTROL	TEST	CONTROL	TEST	CONTROL	TEST	CONTROL	TEST	REF	REF	REF	REF
	32	**31**	**30**	**29**	**28**	**27**	**26**	**25**	**24**	**23**	**22**	**21**	**20**	**19**	**18**	**17**
4	41	58	40	34	42	43	31	36	36	47	29	32	47	39	40	35
3	34	33	40	33	52	52	36	33	43	36	28	47	49	38	37	24
2	82	59	63	72	49	49	49	38	57	52	54	51	38	41	89	30
1	63	72	74	63	43	56	39	56	44	60	71	65	75	78	84	45
0	5	10	9	7	7	7	9	13	12	11	11	9	9	12	14	5
TOTAL	225	232	226	209	193	207	164	176	192	206	193	204	218	208	264	139

5 Summary

This report summarizes the work performed by the Boeing team on AFC and IAM technology as defined by the NASA contract NNL10AA05B task order NNL14AA57T. With the delivery of this report, all of the required AFC and IAM deliverables have been completed.

The AFC Enhanced Vertical Tail demonstration was the culmination of several years of technology maturation, including: sub-scale wind tunnel testing, full-scale wind tunnel testing, CFD simulation studies and a system integration study. The objectives of the AFC demonstration were to: demonstrate the ability to integrate a prototype AFC system into an airframe, demonstrate AFC impacts on rudder effectiveness in flight and collect in-flight data for comparison to full-scale wind tunnel data and CFD simulations. These objectives were achieved by designing, fabricating, installing and flight testing a sweep jet based AFC system on the vertical tail of the 757 ecoDemonstrator. The AFC system functioned as designed and significantly affected the control power of the rudder, as evidenced by flow cone visualization, measured forces and moments, and pilot feedback. As a result of this demonstration, a significant body of knowledge has been created that will influence future applications of active flow control. In addition, the need for maturation of the integration and manufacturing readiness of the technology has been highlighted as the primary challenge for commercial application of AFC.

The Insect Accretion and Mitigation demonstration assessed a subset of the most promising coatings, developed by NASA, for the mitigation of insect accretion in a transport category aircraft flight environment. The objectives of the demonstration were to assist NASA in the application of the coatings onto a full scale test article, collect data to assess the ability of the coatings to reduce the amount of residue accumulated during typical aircraft takeoff and landing operations, as well as gather information to document the altitude profile describing when insect strikes were collected. These objectives were achieved by designing, fabricating, installing and testing panels with IAM coatings on starboard-side wing slats of the 757 ecoDemonstrator. Photographic, physical inspection and aircraft flight profile data were collected and delivered to NASA to assess the IAM performance. Results from the data collected indicate a measurable reduction in insect residue for some of the formulations tested. This unique opportunity produced information that will help inform the development of this technology so that it may one day lead to application on a future commercial aircraft design.

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14. ABSTRACT

This document serves as the final report for the Flight Services and Aircraft Access task order NNL14AA57T (Reference (3)) as part of NASA Environmentally Responsible Aviation (ERA) Project ITD12A+. It includes descriptions of flight test preparations and execution for the Active Flow Control (AFC) Vertical Tail and Insect Accretion and Mitigation (IAM) experiments conducted on the 757 ecoDemonstrator.

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