FAA Continuous Lower Energy, Emissions and Noise (CLEEN) Technologies

Boeing Program Overview

CLEEN Consortium Public Session
November 19, 2014
Atlanta, GA

Boeing CLEEN Program

Boeing CLEEN Technologies

Program Overview & Status

CMC Nozzle Flight Test

Boeing CLEEN Technologies

Technology	Goal Impact
Fuel system material swell & fuel absorption	Alt Fuels
Adaptable Trailing Edges 	Fuel-burn Noise
Ceramic Matrix Composite Acoustic Nozzle 	Fuel-burn Noise

Benefits

Alternative Fuels

- Analysis of impacts on non-metallic fuel system components for Aromatics and Cycloparafins
- Test results and documentation used in support of the ASTM International standard approved in 2012 for synthetic fuel blends up to 50%

Adaptive Trailing Edges

- Fuel Savings: potential of -2% in some single and twin aisle configurations
- Noise reduction: potential of -1.5 dB cum in some single and twin aisle configurations

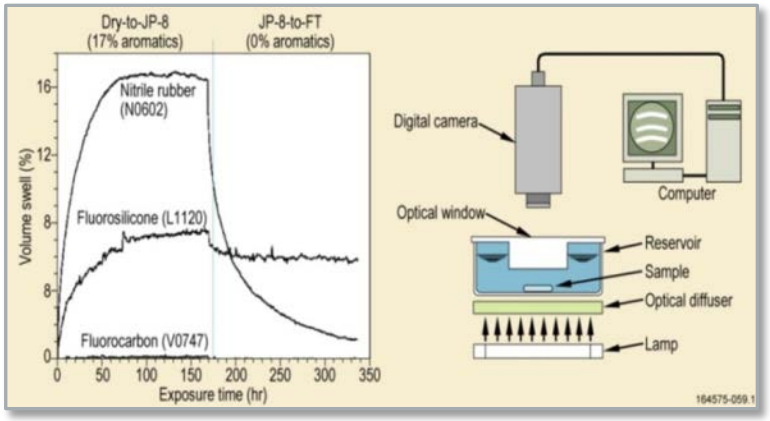
Ceramic Matrix Composite Nozzle

- Fuel Savings: Potential of -1.0%
- Noise reduction: parity or better compared with treated metallic hot structure
- Nozzle Weight Reduction > 20% below Ti
- Enabler for lighter, hotter, more efficient engine and nacelle architectures

Alternative Fuels Testing

Objectives:

- Evaluate the impact of SPK Fuels and Fuel Blends on Non-metallic Materials used in Commercial Aircraft Fuel Systems
- Generate data to help industry determine effects of the type and concentration of Aromatic and Cycloparaffins on material properties (e.g. seal swell)
- Help enable alternative fuel blends greater than 50% content



Work Statement:

- Select sample fuel blends for analysis
- Measure composition of fuel absorbed by materials for variety of fuels/blends. Establish statistical bounds for behaviour of typical fuel system material
- Conduct volume swell test for common components such as O-rings, sealants and coatings
- Produce Public Report

Benefits:

Support to ASTM Specifications and “Drop-In” renewable fuel replacement strategies

Adaptive Trailing Edge

Objective:

- Develop and demonstrate a prototype adaptive trailing edge system capable of tailoring wing performance to reduce noise and fuel burn at different flight regimes

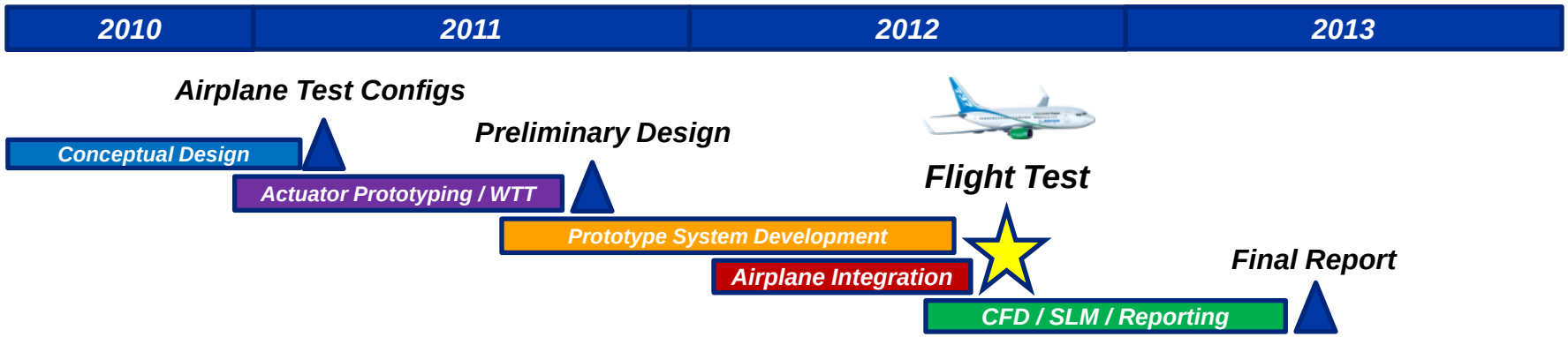
Work Statement:

- Conduct technology survey, CFD analysis and wind tunnel testing to predict performance and define demo system architecture
- Evaluate airplane-level performance impacts of ATE system through CFD models and ground testing
- Develop and integrate prototype ATE system into airplane and demonstrate actuation and control system in flight (TRL 7)

Benefits:

Reduced Fuel Consumption, community noise

Enable more efficient wing architectures



ATE Flight Test completed Sept ’12 Glasgow, MT

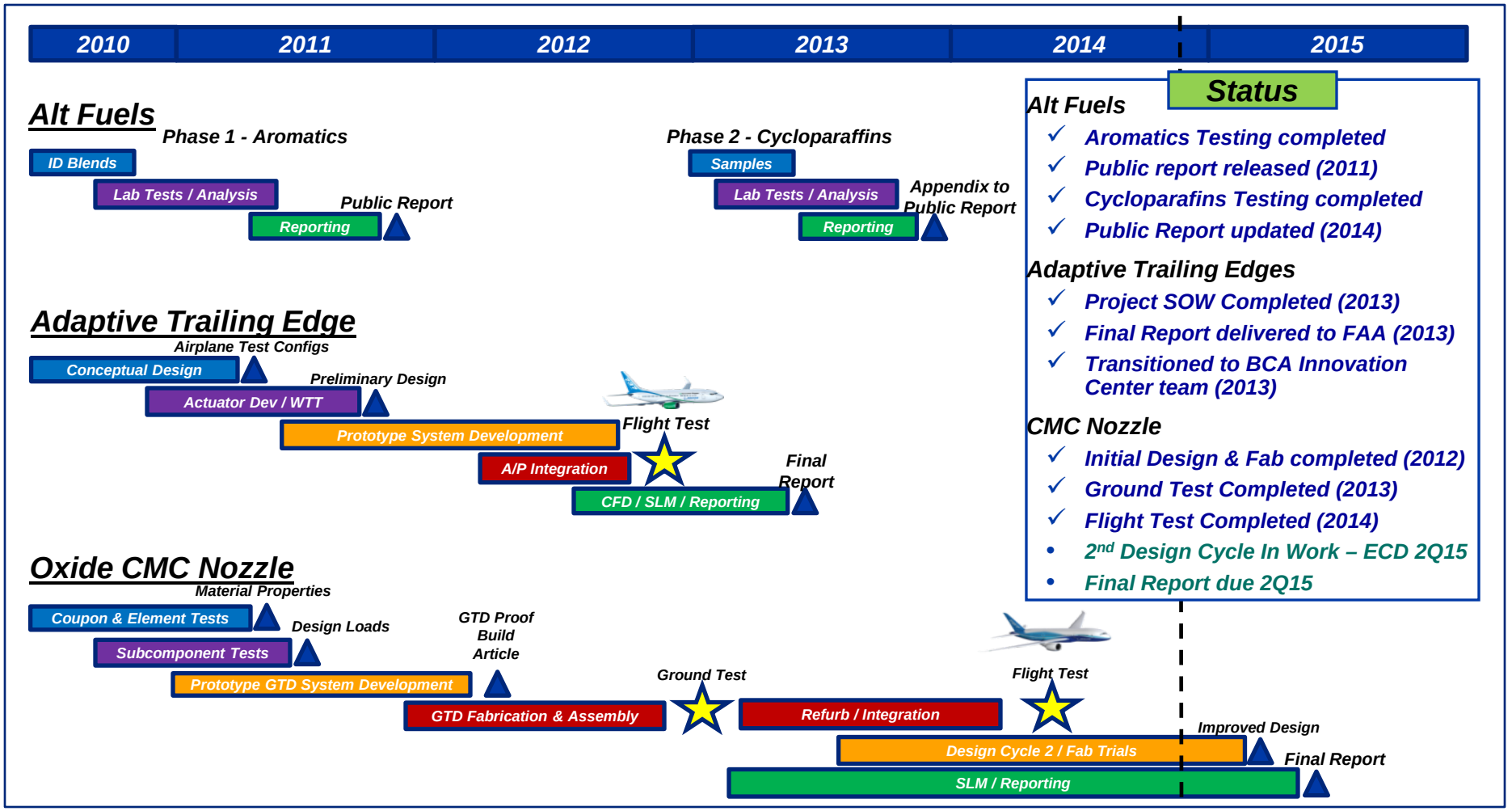
Flight Test Summary

- 10 Flight Test days
- 28 Aug – 6 Sept 2012
- 51.5 Hours of flight test time
- 6 airplane configurations

ATE Flight test achieved TRL 7

- Demonstrated Mini-Flap driven by **SMA Actuators**
- Demonstrated **closed loop feedback control** of mini-flap **during flight**
- Tested single slotted flap and simulated mini-split-flap at low speed
- Generated aerodynamics and loads data on **high and low speed** flight conditions
- **Verified predictions of community noise take off and approach** data using certification microphones and phased array
- **Failure modes** validated

Boeing Program Status



Status

Alt Fuels

- ✓ Aromatics Testing completed
- ✓ Public report released (2011)
- ✓ Cycloparafins Testing completed
- ✓ Public Report updated (2014)

Adaptive Trailing Edges

- ✓ Project SOW Completed (2013)
- ✓ Final Report delivered to FAA (2013)
- ✓ Transitioned to BCA Innovation Center team (2013)

CMC Nozzle

- ✓ Initial Design & Fab completed (2012)
- ✓ Ground Test Completed (2013)
- ✓ Flight Test Completed (2014)
- • 2nd Design Cycle In Work – ECD 2Q15
- • Final Report due 2Q15

Program on track to complete successfully in 2015

CMC Acoustic Nozzle

Objective:

- Demonstrate material system that can enable lighter, quieter, more efficient engines
- Design, fabricate and demonstrate an acoustic ceramic matrix composite (CMC) primary exhaust system

Work Statement:

- Conduct Coupon, element & subcomponent testing, establish design loads, validate design tools / methods
- Conduct Proof of Concept Build at full scale
- Test Prototype system in ground demonstration (TRL 6)
- Demonstrate prototype system in flight (TRL 7)

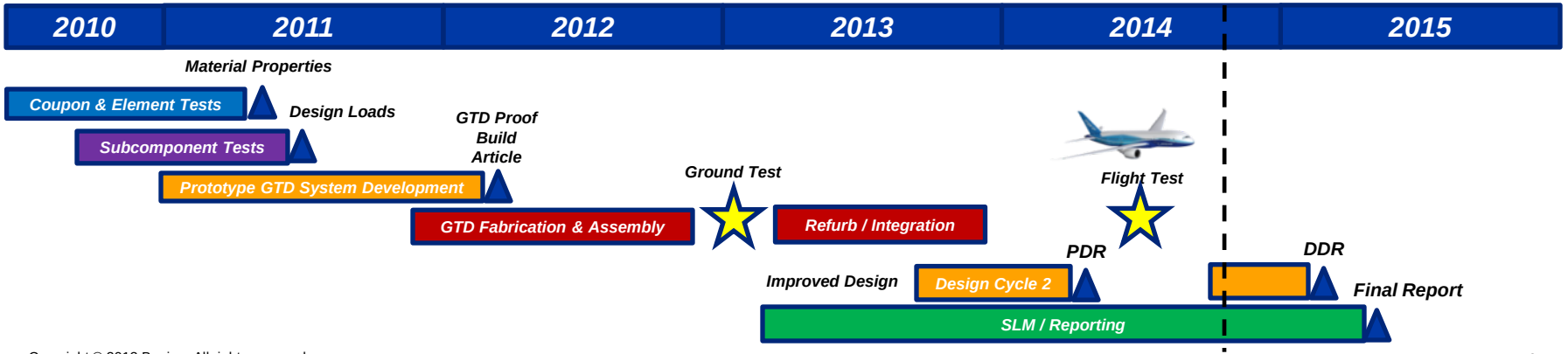
Benefit:

Reduce weight by up to 20% relative to Titanium

Acoustic treatment that operates above 1500°F

Baseline Material: 2D N610/AS Oxide CMC

Baseline Demonstration Engine: Rolls Royce Trent 1000



Building Block Approach

TRL

7

Flight Test
- Flight loads
- Installed acoustic performance
- In-field repair demo

6

Ground Test
- Actual environment
- Demo performance

- Technology Improvements

Full Scale Producibility
- Repair demo
- Instrumentation
- Assembly & installation

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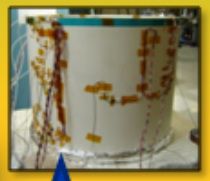
Subcomponent Test
- Producibility at scale
- Attachment integration
- Durability in simulated environment



Element Testing
- Validation of designs
- Producibility at increasing scale/features

4

Coupon Testing
- Concept feasibility
- Material properties

PDR Oct '10 | CDR June '11 | Fab Dec '11 | GTD Feb '13 | FTD July '14

CMC Nozzle Ground Test completed Feb ‘13

RR Test Facility Stennis, MS

- 4.5 weeks of powered testing
- 38 runs, 75 hrs on condition
- All objectives met or exceeded

Data Acquired (125+ channels)

- Thermal (on and off body)
- Loads, Stress
- Dynamics (on and off body)
- Repair techniques

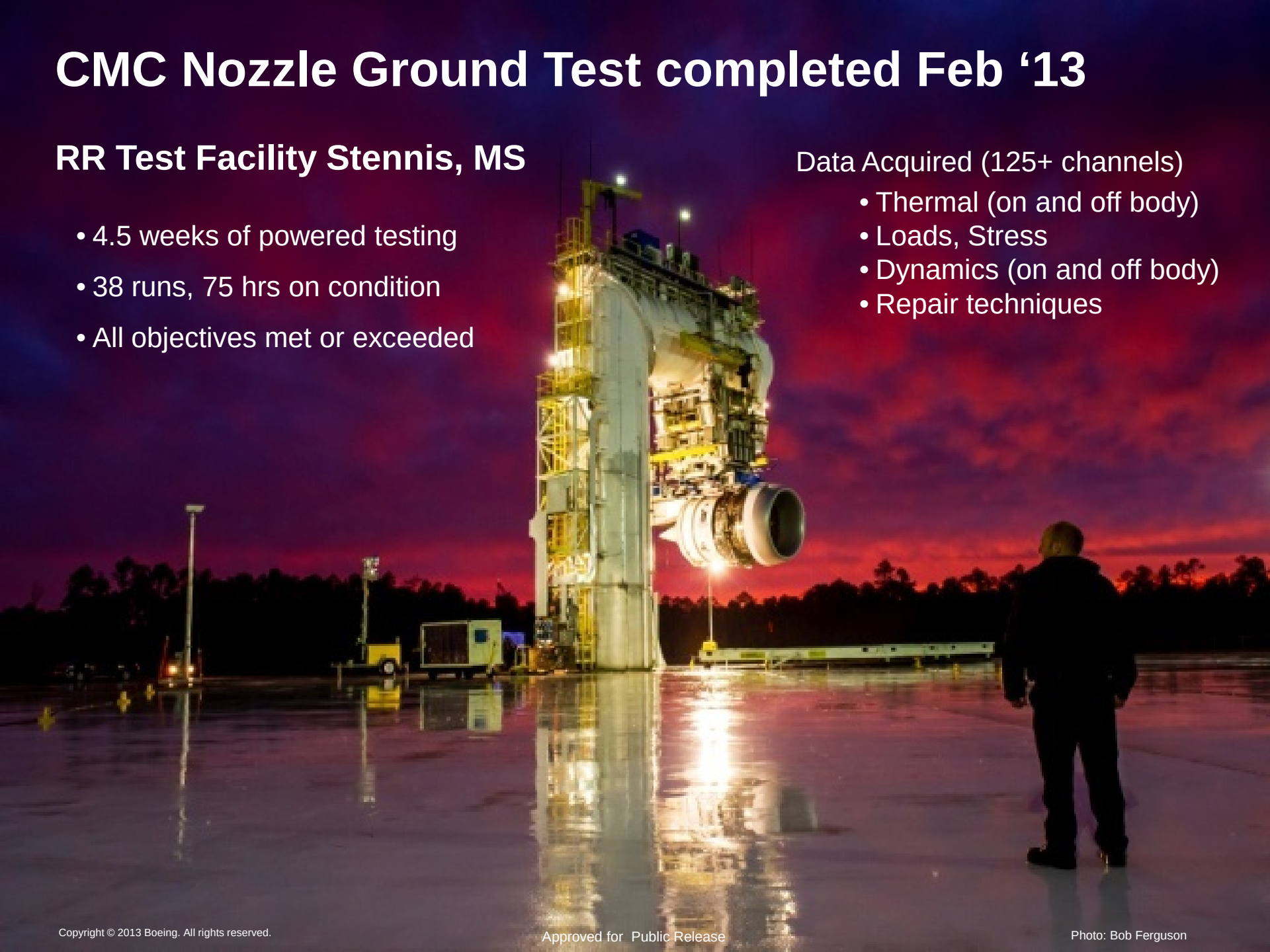
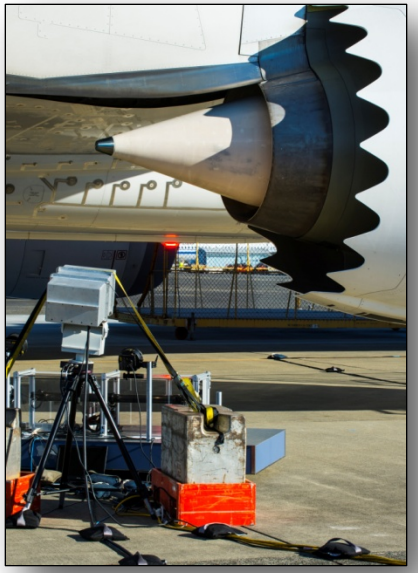


Photo: Bob Ferguson

Flight Test Objectives

- **Conduct in-depth thermal assessment**
- **Verify structural performance in flight**
- **Verify installed acoustic performance**
- **Verify Repair and Patch techniques**
- **Accumulate as much flight-time on CMC exhaust as possible**



CMC Exhaust Flight Test Instrumentation

Fairing (4 instruments)
- 3 thermal couples
- 1 strain gages
- 0 accelerometers

Nozzle (31 instruments)
- 25 thermal couples
- 2 strain gages
- 4 accelerometers

Centerbody (6 instruments)
- 4 thermal couples
- 2 strain gages
- 0 accelerometers

CMC Nozzle Assembly w/ Fairing

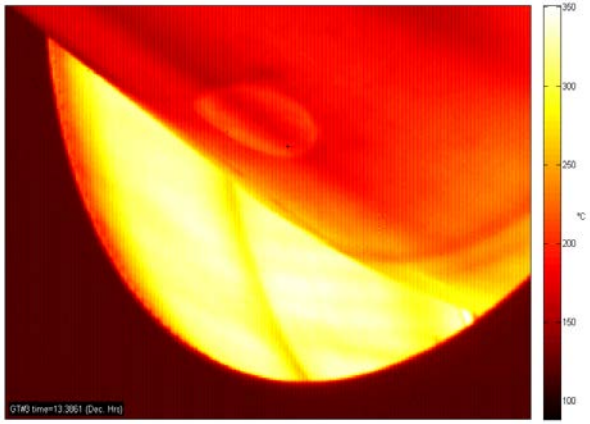
CMC Centerbody (plug)

Installation at Boeing Field

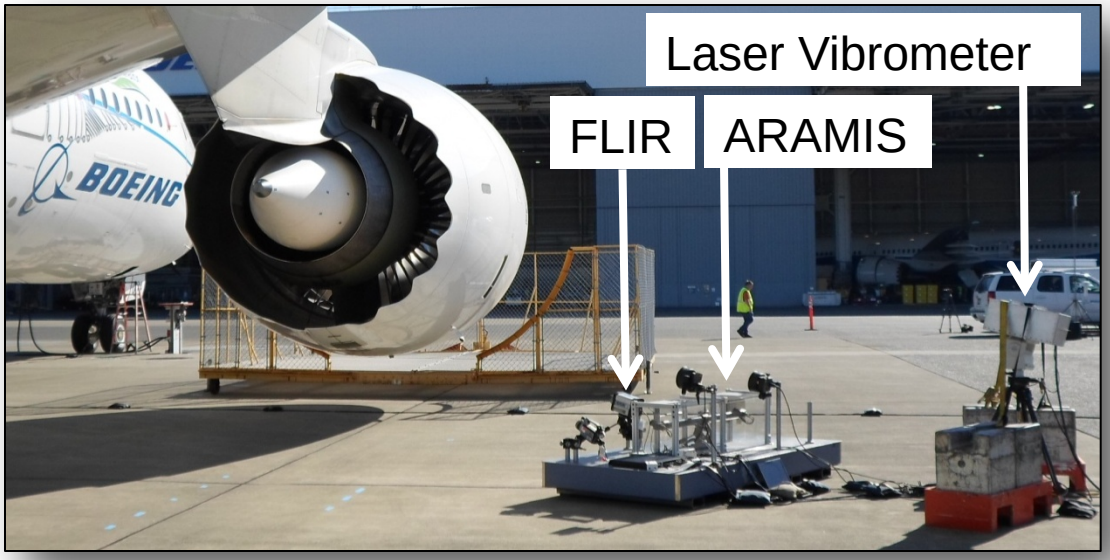
Ground Test Systems

Three external measurement systems used for "off body" measurements during pre & post-flight ground runs:

- **ARAMIS Digital Image Correlation**
  - 2 video cameras track the displacement of a dot pattern on the test article
  - Dot displacement is then used to calculate surface strain
- **Forward Looking Infrared (FLIR)**
  - FLIR imaging was used to map temperatures
- **Laser Vibrometer**
  - Used to measure dynamic displacements & natural frequency of the exhaust



Ground test 3 start FLIR fringe plot

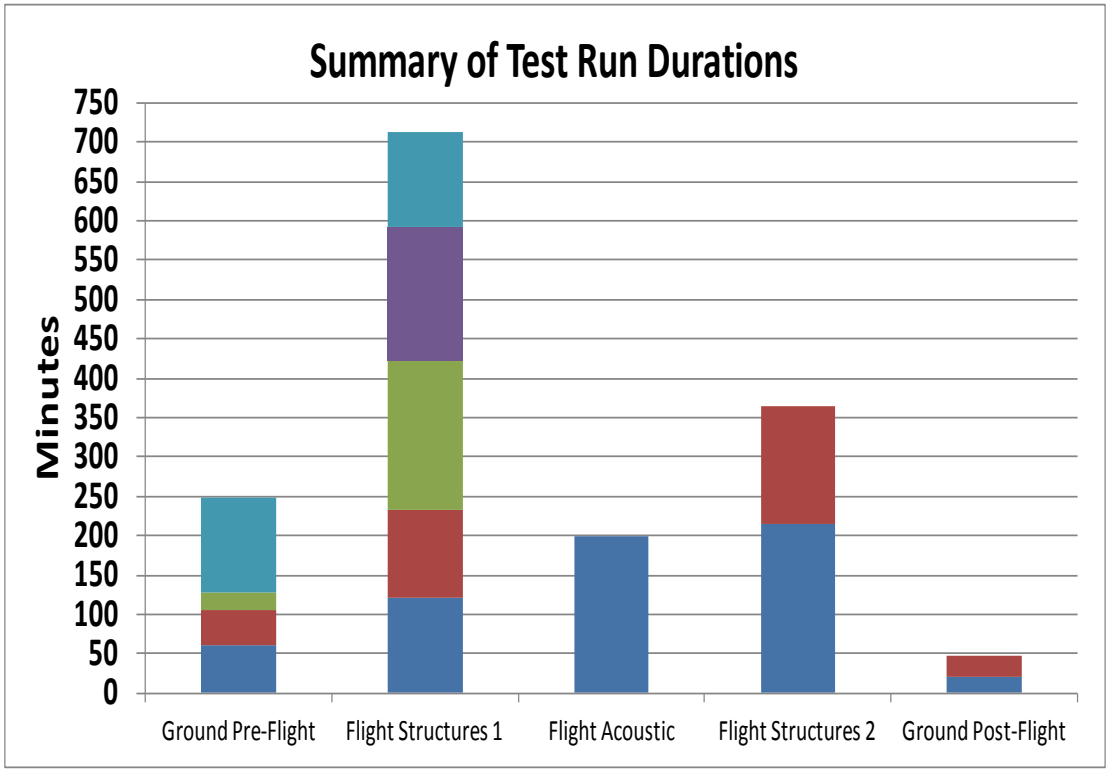


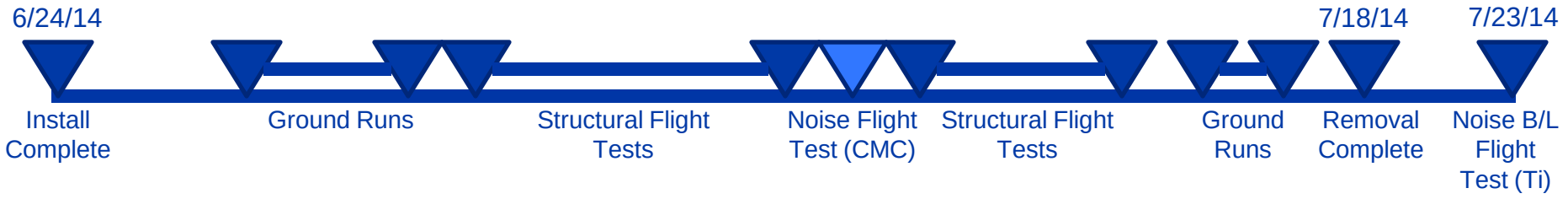
Flight Test Aircraft: 787 ecoDemonstrator (ZA004) w/ RR Trent 1000 Engines

Flight Test Overview

10 Days of Testing

- 28.5 test hours
- 15 ground starts
- 2 flight starts
- 7 ground engine runs
- 8 test flights





Structural Flight Testing

Steady State Test Points:

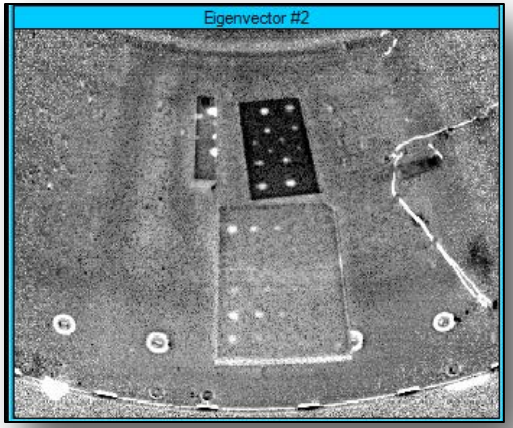
- Typical flight profiles, speed and altitude
- Cruise conditions
- Max continuous power

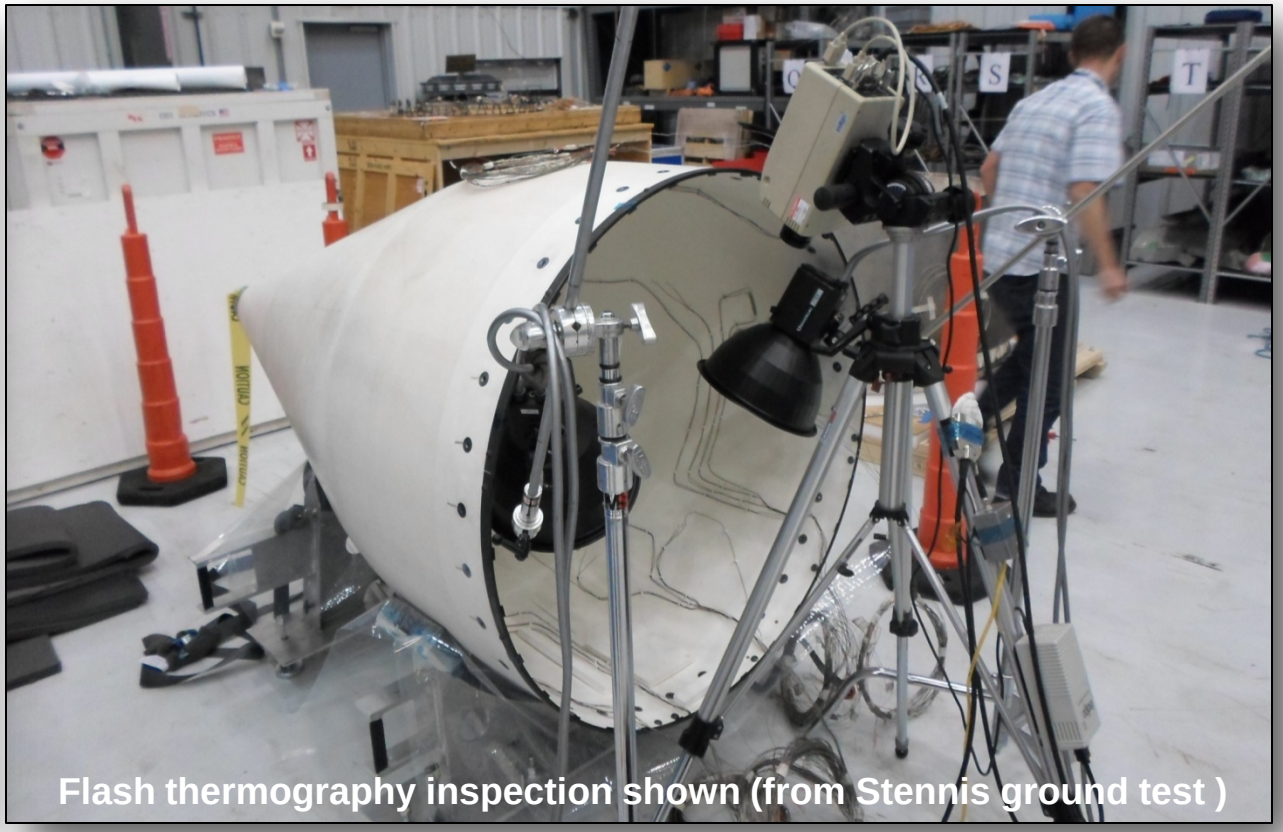
Maneuver Test Points:

- Start transients
- Throttle transients
- Snap throttles
- Wind-up turns up to 2.3g, left and right
- Pitchovers to 0.3g
- In-flight shutdowns and relights
- Landing thrust reverser deployment

No Structural Degradation Observed

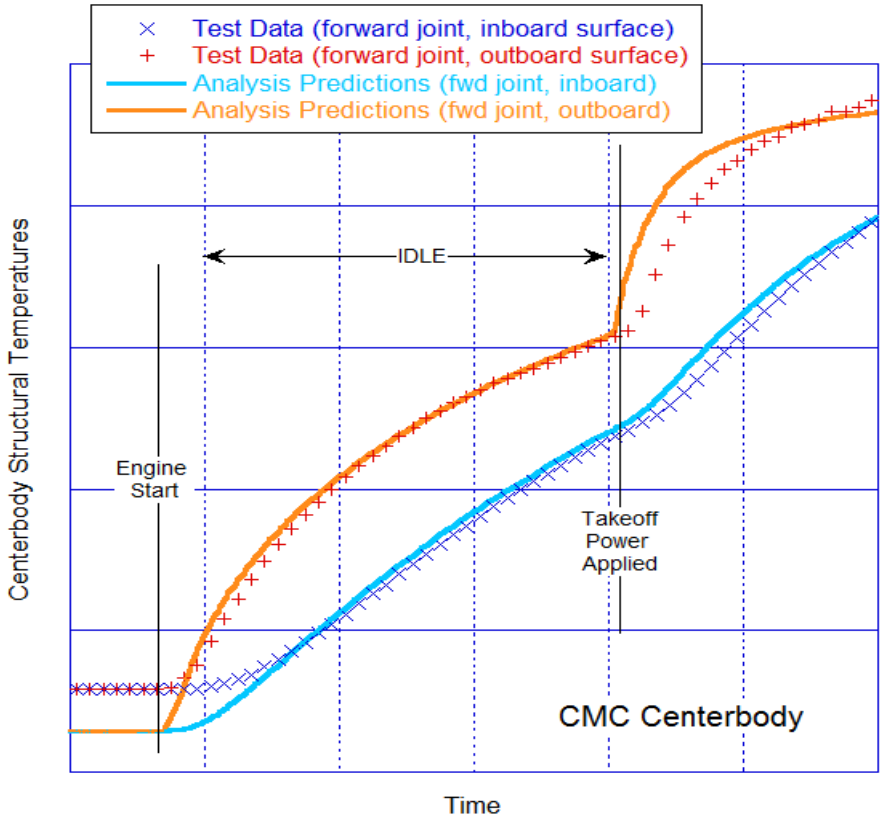
- Post flight non-destructive evaluation included visual, tap test, & thermography
- Dynamic data supports validation of structural integrity of CMC articles
  - Structural fundamental frequencies unchanged over flight testing





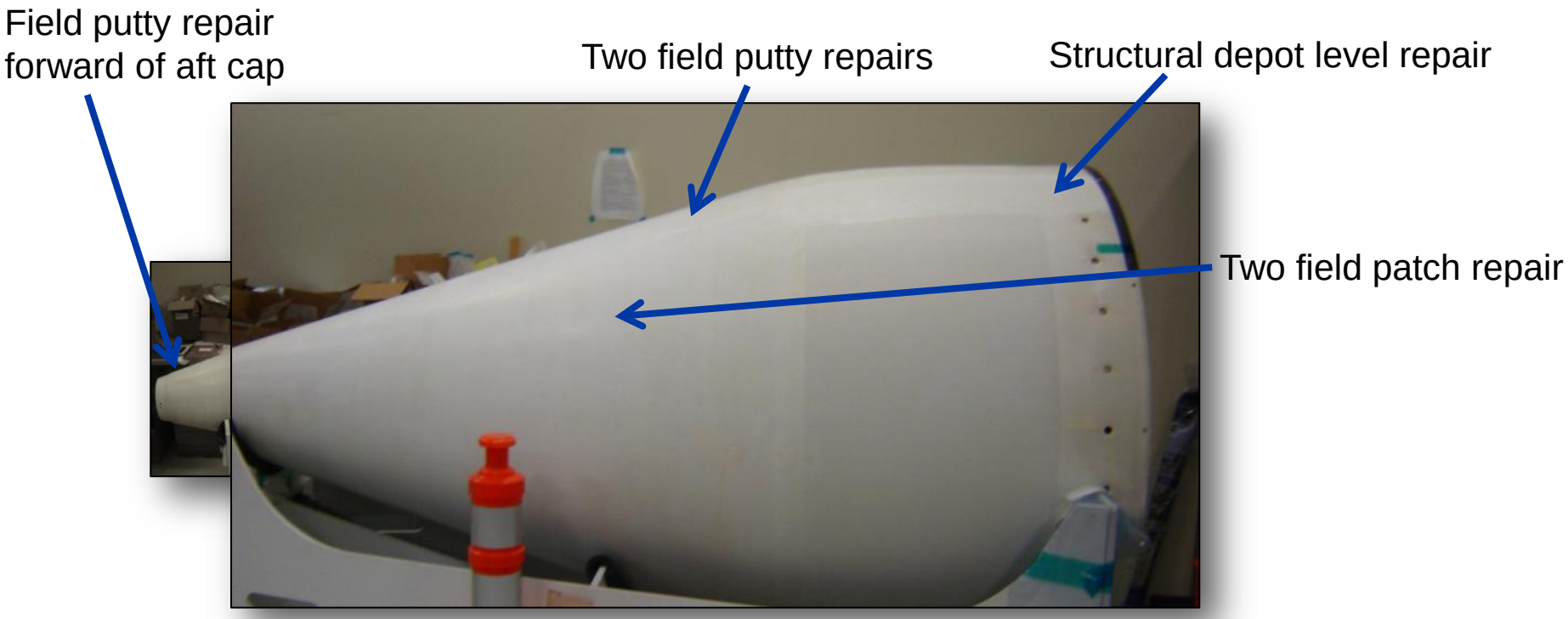
Thermo-structural Response

- **Measurements matched well with predictions informed by Stennis ground tests (from 2013)**
- **Flight test series expanded tested thermal-structural envelope**



Repair Demonstrations

- **Structural pre-flight depot level centerbody repair**
- **Simulated in-field repairs**
  - No induced/simulated damage under in-field repair patches
  - Portable equipment used for all repairs

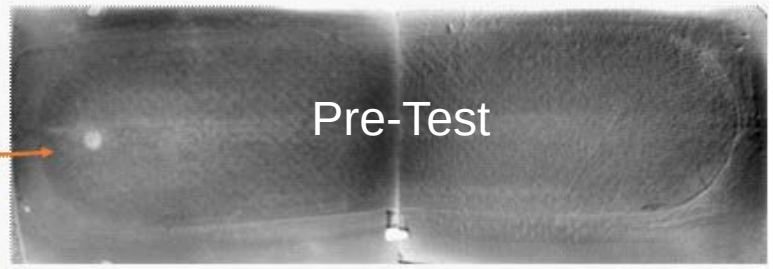


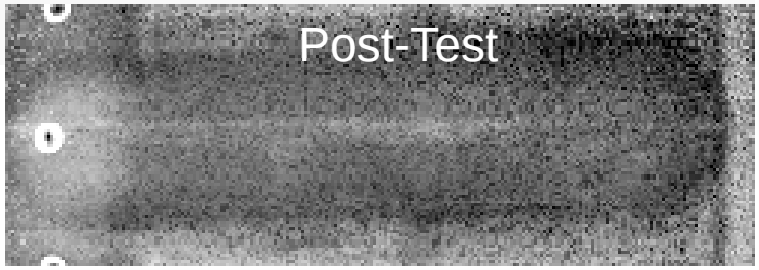
Internally funded repair technology leveraged flight test opportunity

Performance of Repairs

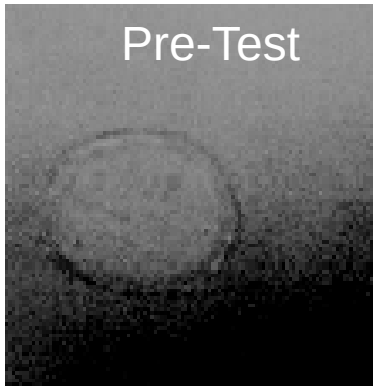
- **No change between pre and post-test conditions for all repair demonstrations**
- **Determined via visual, coin tap, and NDE thermographic inspection**

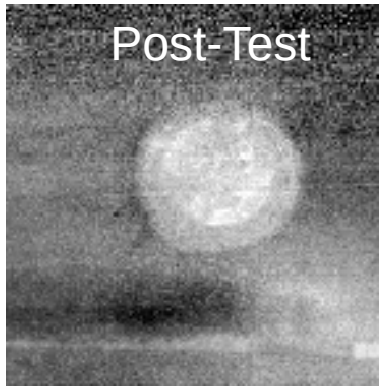
CMC Structural Repair





CMC In-Field Patch Repair



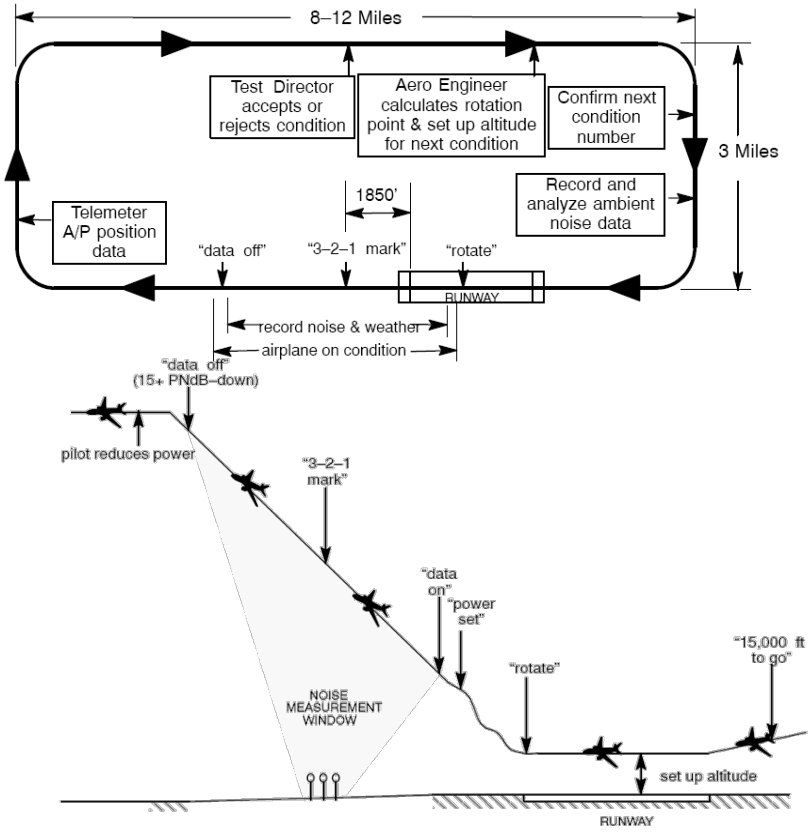


Repair technologies demonstrated to TRL 7 supporting technology transition

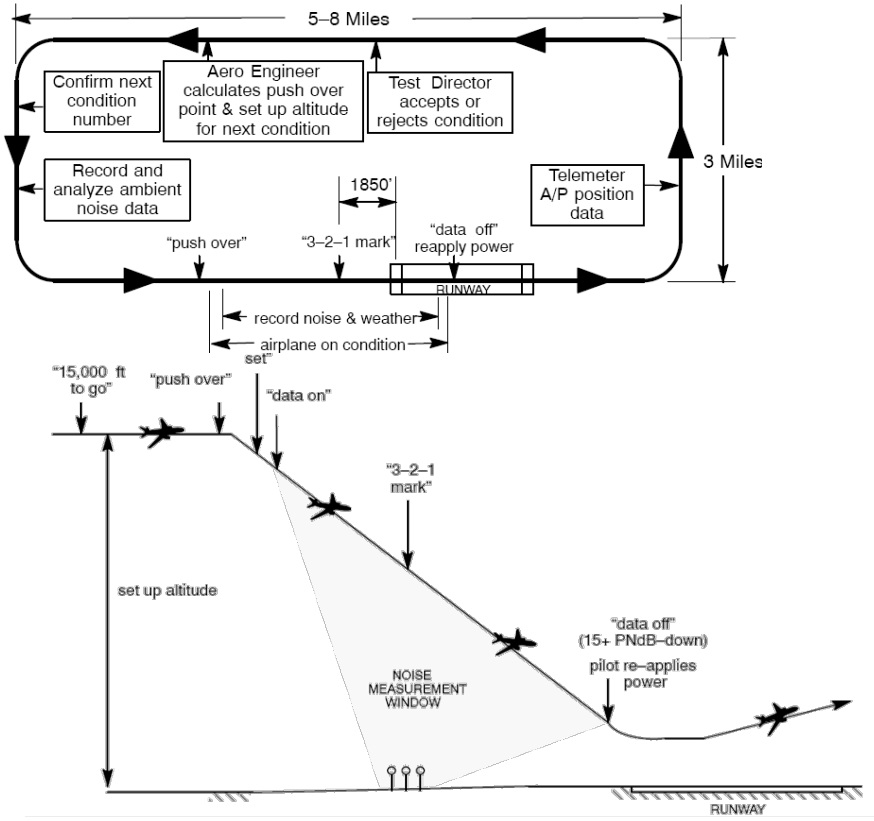
Noise Flight Testing

- Racetrack flight pattern typical of community noise certification testing
- Compare CMC exhaust to production exhaust
- Free field and phased array ground microphones (no sideline microphones)

Takeoff:



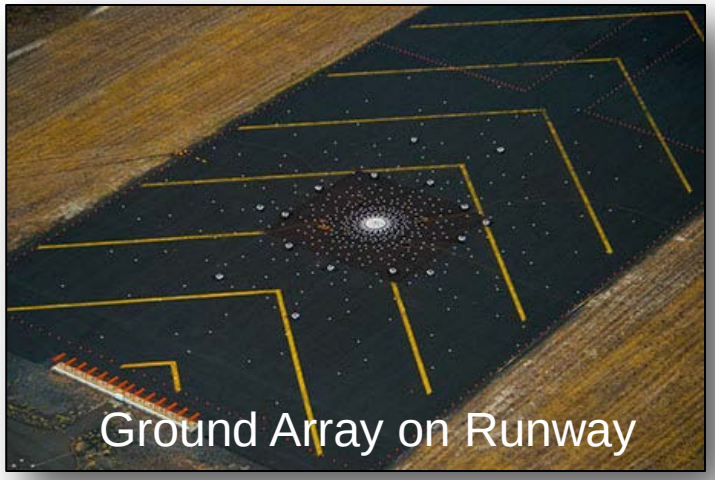
Approach:



Farfield Array and Phased Array at Moses Lake, WA

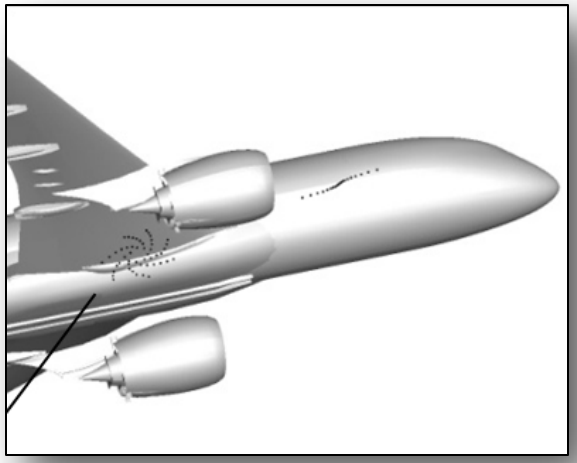

Farfield Pedal Microphone Array

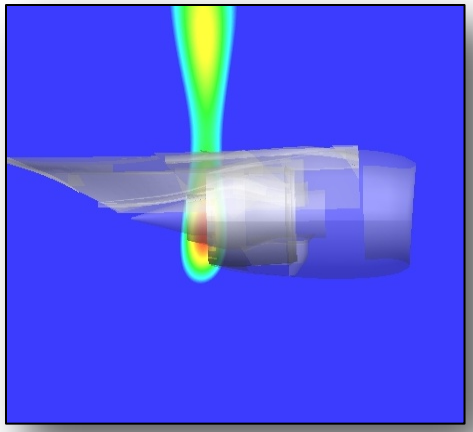

Farfield Pedal Microphone

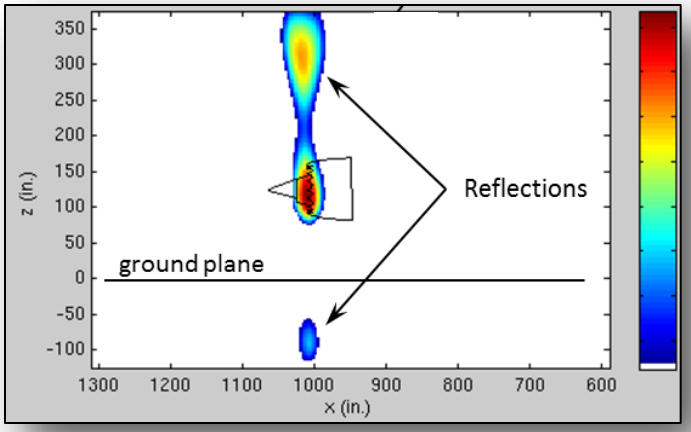

Ground Array on Runway


Center of Ground Array

Side of body array data

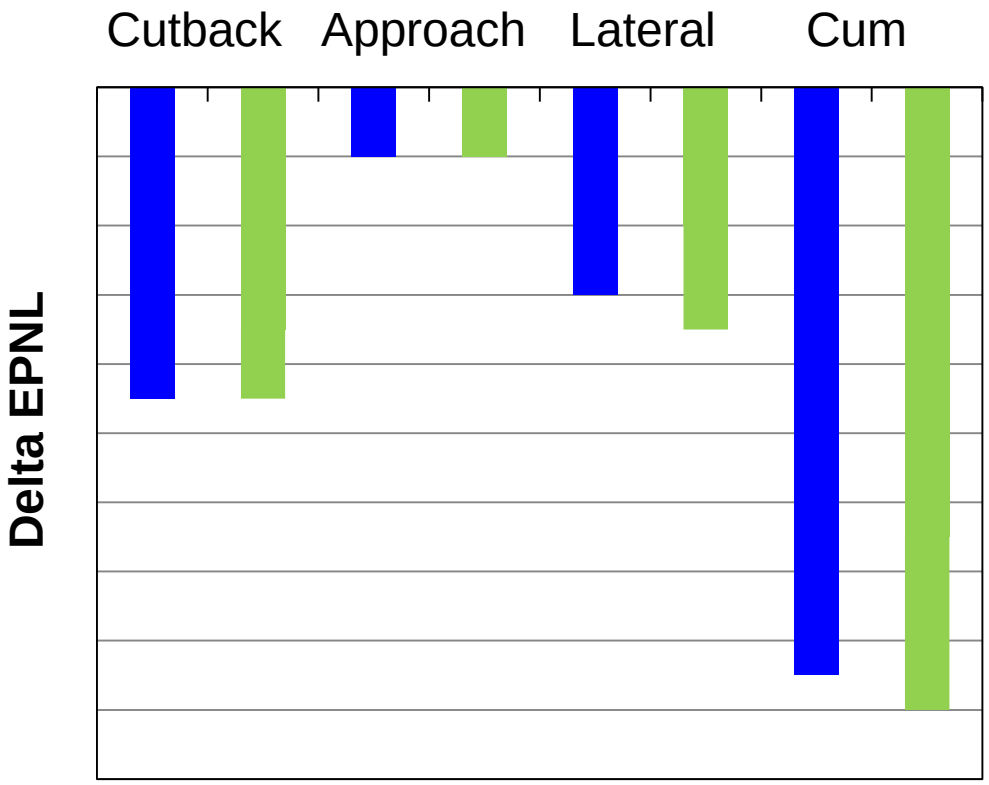






Side of Body Array provides improved insight on Nozzle

Community Noise



Hard Wall
Primary Nozzle
(No Treatment)

Metallic Acoustic Baseline

CMC Acoustic Liner*

* Test Data Corrected to equivalent L/H of metallic baseline

Quieter

Performance of CMC exhaust was equivalent or better than Titanium baseline

Acoustic Analysis Summary

- **First successful validation of CMC acoustic performance at airplane level**
- **Test data and predictions show good agreement**
- **A CMC acoustic nozzle has been demonstrated to be effective**
- **Tools and SLM can now be updated**

CMC Flight Test - July 2014
Moses Lake, WA

Test Summary

- 7 July – 23 July 2014
- 3 Ground Test days
- 12 Flight Test days
- 2 airplane configurations
- 28.5 Hours of engine run time
- 17 Engine Cycles

Data Acquired

- Thermal (on and off body)
- Loads, Stress/Strain (off body)
- Dynamics (on and off body)
- Ground microphone Array
- Ground community noise mics
- Side of body acoustic array
- Laser Vibrometry, FLIR, ARAMIS

CMC Flight test achieved TRL 7

- Acquired flight loads data for maneuvers up to 2.3g
- Evaluated structural depot level and in-field repair technologies
- Generated community noise takeoff and approach data using microphones and phased array
- Generated thermal performance data during engine start transients
  - In flight shut down, cold soak, restart
  - Ground runs successfully push exhaust beyond design envelope with no damage

Photo Credit: Leon Brusniak

CMC Nozzle Accomplishments

- ✓ Coupon, Joint & Acoustic Element Tests
- ✓ Subcomponent Test (TRL 5)
- ✓ Successful Proof of Concept Build
- ✓ Repair Demonstration
- ✓ Ground Test (TRL 6)
- ✓ Flight Test Planning
- ✓ Hardware Refurbishment
- ✓ Flight Test 3Q14 (TRL 7)
- Design Cycle 2 Improved Design
- Final Report

Summary

Boeing Program is Nearing Completion

- *Alt Fuels and ATE Technology Projects complete*
- *Major CMC Ground and Flight Demonstrations Complete*
- *CMC Design Cycle 2 and Reporting in 2015*
- *SLM and benefits being updated*

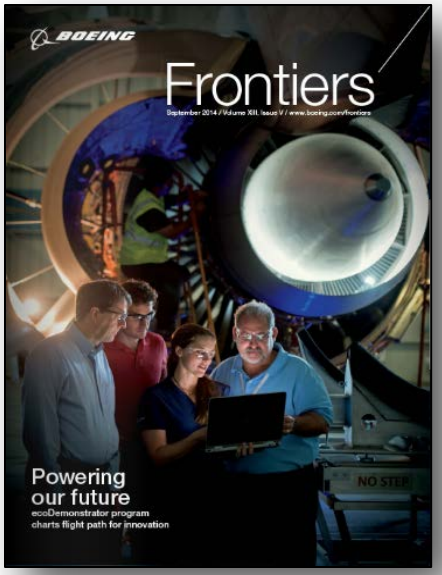
The Oxide CMC Exhaust Tests demonstrated:

- *Thermal performance in excess of Inconel at a weight 20% below Titanium*
- *Noise performance equivalent or better than metallic designs*
- *Capability of operation at 1500^{o}F continuously*

Seeing positive impacts

- *Support to ASTM spec (2012)*
- *Making contributions to FAA CLEEN program goals*
- *Improved understanding of integration issues of technologies*
- *Incorporating learning into future designs*
- *Maturation & risk reduction from CLEEN helping to accelerate transition*

Thank you



Rolls-Royce

ALBANY Engineered Composites

ATK

AA

eco demonstrator

UDRI University of Dayton Research Institute

Photos: Bob Ferguson

Approved for Public Release