CLEEN II

Structurally Efficient Wing (SEW) Compact Nacelle (CN) Short Inlet Ground Test

CLEEN II Consortium Public Plenary Session
Terry Richardson – Boeing CLEEN II PM (Tim Tyahla-SEW, Jennifer Kolden-CN)
May 2, 2018

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Boeing CLEEN II Projects

Structurally Efficient Wing:
- Develop, build, and test a next-generation wing structure that demonstrates significant improvements in structural efficiency
- Show a continued weight reduction as compared to the 777-200 baseline
- Contribute to the FAA CLEEN II goal of reducing fuel burn, potentially reducing fuel consumption up to 3.5% through weight reduction of the wing.

Compact Nacelle:
- Demonstrate aerodynamic performance of a short inlet by testing on the ground in crosswind, using existing hardware and a Rolls-Royce Trent 1000 engine.
- Validate propulsion-aero design tools and transition to development program.
- Contribute to the FAA CLEEN II goal of reducing fuel burn 1.0% through weight and drag reduction of the nacelle
# CLEEN II SEW & CN Technologies

## SEW CLEEN II Technology

<table>
<thead>
<tr>
<th>Technology</th>
<th>Goal Impact</th>
<th>Benefits and Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advancing manufacturing technologies</td>
<td>Fuel burn reduction</td>
<td>Lower weight, higher performance wing</td>
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<tr>
<td>Advanced prepreg composites</td>
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<tr>
<td>Resin-infused stitched blade stringers</td>
<td>CO₂ Production Avoidance</td>
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<tr>
<td>Resin-infused hat stringers</td>
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<tr>
<td>Advanced alloy metallic ribs</td>
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<tr>
<td>Resin-infused sine wave rib</td>
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<tr>
<td>Stamped thermoplastic ribs</td>
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## CN CLEEN II Technology

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<thead>
<tr>
<th>Technology</th>
<th>Goal Impact</th>
<th>Benefits and Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced length and diameter nacelle as compared to in-service engine</td>
<td>Fuel burn reduction</td>
<td>CN technologies provide 14%-16% reduction in fuel</td>
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<tr>
<td>installations</td>
<td>CO₂ Production Avoidance</td>
<td>consumption on 125-seat and larger aircraft yielding</td>
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<td>over 400 million tons of fuel saved</td>
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All technologies contribute to the fuel consumption reduction goal by reducing structural weight and/or Drag.
Boeing Structurally Efficient Wing (SEW)

Anticipated Benefits: Cumulative predicted impact over twenty years:
- Jet A fuel consumption savings of approximately 200 million tons
- CO2 production avoidance of approximately 660 million tons

Risks/Mitigation Plans:
- Risks Identified, mitigation plans in place

Objectives: Demonstrate a suite of material and structural technologies that will contribute to the FAA’s CLEEN II goal of achieving fuel burn reductions by 2026.

Work Statement: Boeing’s disciplined development and building-block test approach will mature structural wing technologies and will demonstrate via the Wing Component Test Article (WCTA).

Accomplishments/ Milestones since Boeing initiated this technology/project:
- OTA Signed Oct 2015
- CoDR completed Mar 2016
- PDR completed Jan 2017
- DDR completed Jul 2017

Schedule:
- Oct 2015 ATP (completed)
- Mar 2016 CoDR (completed)
- Jan 2017 PDR (completed)
- Jul 2017 DDR (completed)
- Jun 2018 TRR
- Jun 2019 Program End
SEW Year 1-3 Major Achievements

- Concept of Design Review (CoDR) completed early
- Preliminary Design Review (PDR) & Coupon Tests completed (TRL4)
- Building Block Tests Completed (TRL5)
- Detail Design Review (DDR) completed early
- Tooling, Part & Test Fixture Fab Completed
CLEEN II Structurally Efficient Wing (SEW) Technology Demonstrations

- **Upper Skin**
  - BMS8-276
  - Non-traditional laminates
  - Co-bonded Stringers

- **Vent Stringers**
  - Braided carbon fiber
  - Resin infused
  - Co-bonded to upper skin

- **Blade Stringers**
  - Stitched
  - Resin infused
  - Co-bonded to upper skin

- **Spars**
  - Advanced IM+

- **Lower Skin**
  - Advanced IM+
  - Non-traditional laminates
  - Integral Stringers

- **Ribs (fuel and dry bay)**
  - Al-Cu-Li

- **Ribs (dry bay)**
  - Stamped thermoplastic CFRP

- **Rib (dry bay)**
  - Sine-wave
  - Braided
  - Resin infused

Reduce Weight up to 28% as Compared to the 777-200
CLEEN II Boeing SEW – Accelerated Schedule

Technology Risk Reduction

Multi-Year Project Schedule

Program Milestones

<table>
<thead>
<tr>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
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Program Management

- Seattle WA
- Everett WA
- Seattle WA
- Wichita KS

Design

- 1/4
- 5/9
- 7/21
- 6/30
- 6/5
- 3/12
- 6/28

Coupon & Element Fab & Static Test Complete

- 5/10
- 6/5
- 3/12
- 6/28

Sub Component Fab & Test Complete

- 7/4
- 9/25
- 5/30
- 9/28
- 3/12

WCTA Tooling Design & Fab

- 4/1
- 11/15
- 3/20
- 3/28

WCTA Fab & Assembly

- 11/16
- 6/6
- 3/19
- 6/28

WCTA Tech Demonstrate

- 7/4
- 9/28
- 6/28

Tech Assessment

= original baseline date
= current accelerated date

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### SEW Critical Path to Test Readiness Review (TRR)

#### Project: CLEEN II Critical Path Network Gantt Chart

**Project:** CLEEN II  
**A2.5 (Test Readiness Review) Needed:** 07/26/2018  
**Projected:** 07/26/2018

**Based on:** Early Dates  
**Date:** 04/19/2018  
**Time Now:** 04/12/2018

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<table>
<thead>
<tr>
<th></th>
<th>2017</th>
<th>2018</th>
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<tbody>
<tr>
<td></td>
<td>Nov’17</td>
<td>Dec’17</td>
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<tr>
<td><strong>WCTA Fabrication &amp; Assembly &amp; Instrumentation (at ADC)</strong></td>
<td></td>
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<tr>
<td>Skins Trimmed</td>
<td></td>
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<tr>
<td>Path 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. TF = 0d</td>
<td></td>
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<tr>
<td><strong>Ribs Prepped For Assembly</strong></td>
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<tr>
<td><strong>Spars Prepped For Assembly</strong></td>
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<tr>
<td><strong>Substructure Assembled</strong></td>
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<tr>
<td><strong>Paths</strong></td>
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<tr>
<td>Path 1</td>
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<tr>
<td>Path 2</td>
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<tr>
<td>Min. TF = 12d</td>
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<tr>
<td><strong>WCTA Shipping To NIAR</strong></td>
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<tr>
<td><strong>WCTA Preparation (at NIAR)</strong></td>
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<tr>
<td><strong>Test Readiness Review</strong></td>
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<tr>
<td><strong>6/6</strong></td>
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<td><strong>6/11</strong></td>
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<tr>
<td><strong>7/26</strong></td>
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**WCTA Assembly and Test Fixture Integration Receive “Critical Path” Attention**
SEW WCTA Assembly Plan Overview

- **Assembly Stanchions**
  - Z-Stands
  - ME Fixtures
  - Hamar Laser Reflectors

- **Robotic Drill**
  - Drilling Application
  - Fastener Installation

- **Lower Skin Cart**
  - Location and Positioning Features
  - Vacuum Provisions

- **Handling Equipment**
  - Existing OHME/Spreader Bar
SEW WCTA Assembly Preparation

SEW Assembly Cell With Transport Cart

Upper Skin

Resin Infused Sine-wave Rib

Thermoplastic Rib
SEW Wing Component Test Article Test

Test Structure

SEW full scale test article

Test Instrumentation
- Fully Instrumented with 90 Gages
  - 30 Axial Strain Gages
  - 60 Rosetted Strain Gages

Test Sequence
- DLL Checkout
- 1 DSO .52 DLL, R=-.4
- 1.0 DLL Up & Down Bending
- 1.5 DLL (DUL) Up & Down Bending
- Up Bending to Failure or 2.25DLL
## SEW - TRR Exit Criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>ECD</th>
</tr>
</thead>
<tbody>
<tr>
<td>WCTA Assembly Complete (test fixture, instrumentation assembled and delivered)</td>
<td>6/11/2018</td>
</tr>
<tr>
<td>WCTA Test Plan Complete (objectives, configuration, loads, test sequencing, inspections, instrumentation, and schedule all defined)</td>
<td>7/10/2018</td>
</tr>
<tr>
<td>WCTA Test Integration • Test Setup Complete • <strong>Test Safety Reviewed, Agreed Upon and Complete</strong> • FAA/Boeing/NIAR Agree Test is Ready to Go</td>
<td>7/26/2018</td>
</tr>
<tr>
<td>Test Readiness Review (TRR) Complete</td>
<td>7/26/2018</td>
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</tbody>
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Compact Nacelle – Overview

**General Engine Characteristics**
- 2025 EIS
- Geared Low Pressure Ratio Fan
- Bypass Ratio of 12 to 14
- Large Fan, Small Core
- Core Mounted Accessories

**Nacelle Technologies Required**
- PAI Optimization
- Short Inlet (0.4 L/D or less)
- Advanced T/R Configuration
- Improved Acoustic Solutions
- Advanced Manufacturing
- New High-temp materials
- Advanced Bleed Systems
Compact Nacelle (CN) - Short Inlet

Anticipated Benefits: Cumulative predicted impact over twenty years:
- Compact Nacelle architecture is enabler of advanced UHB engines with 2025 EIS
- 14%-16% reduction in fuel consumption on 125-seat and larger aircraft yielding over 400 million tons of fuel saved.
- CO2 production avoidance of ~1200 M tons
- Achieve 1% Block Fuel savings through weight and drag reductions

Objectives:
- Measure effects of inlet flow distortion at the fan face in cross wind.
- Validate Short Inlet design tools for transition to Boeing’s next development program.

Accomplishments since project launch:
- Project Launched – Apr ‘17
- Short Inlet delivered to Stennis – Apr ‘17
- Kickoff Meeting / Test Plan review – Jul ‘17
- Block 1 testing completed – Aug ‘17
- Baseline Inlet delivered to Stennis – Dec ‘17
- Block 2 TRR completed – Dec ‘17
- Block 2 testing completed – May ‘18

Work Statement:
Conduct ground crosswind test of a Boeing Short inlet installed on a Trent 1000 engine at the Rolls-Royce Stennis, Mississippi test facility.

Schedule:
- Limited Rights Report – Aug ‘18
- Public Report – Nov ‘18
- Final Briefing – Nov ‘18
- Program End – Dec ‘18

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Short Inlet Technology Risk Reduction

<table>
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<tr>
<th>Technical Risk</th>
<th>Mitigation</th>
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</table>
| Inlet lip separation at off-design conditions | • Completed Phase 1 study on aerodynamic design and prediction tool verification prior to design of hardware  
• Developed plan using aggressive short inlet to exercise tools  
• Using experimental results to validate tools  
• Calibrating tools using 787 Certification Data |
| Inlet - fan face distortion, impacting fan efficiency, weight and flutter/resonance (Rolls-Royce focus) | • RR performed separate fan flutter and resonance test (outside CLEEN)  
• Served as risk reduction to proceed with crosswind testing |
| Nacelle integration and build impacts | • Close coordination with program nacelle design team  
• Integration addressed during requirements and design phases  
• Consistent bulkheads, engine interfaces, loads cases, equipment integration requirements |
| Aerodynamic integration with production BPR/FPR (2025 EIS) | • Leverage existing capabilities and extensive certification database  
• Models calibrated and verified by ground test with baseline inlet previously tested on 787 ecoDemonstrator (2014)  
• Short Inlet Aerodynamics & prediction tools (separation & prediction)  
• Fan Aerodynamics (stall, efficiency in distorted flow)  
• Fan Aeromechanics (flutter and resonant responses) (RR only test) |

Modeling is key to Successful short inlet integration with low FPR Fan
Short Inlet Development

Multi-Year Project Schedule

<table>
<thead>
<tr>
<th>Project Launch</th>
<th>SRR</th>
<th>DDR</th>
<th>RR Short Inlet H/W Complete</th>
<th>CLEEN ATP</th>
<th>K/O Mtg</th>
<th>Ground Test Block 1</th>
<th>Ground Test Blocks 2/3/4</th>
<th>Final Report</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>2016</td>
<td>2017</td>
<td>2018</td>
<td></td>
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Tool Calibrations
Puget Sound

 Reqts & HW Dev
Charleston, SC

Ground Testing
Stennis, MS

Reporting

TRL 4

TRL 5

TRL 6

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Short Inlet Ground Test (TRL6) – March 2018

- 6.5 weeks of powered testing
- 3 ground plane heights
- 2 crosswind directions
- Crosswinds up to 40kts
- Short and Baseline Inlets tested
- All objectives met or exceeded

Data Acquired (425+ channels)
- 75 - Inlet static pressure taps
- 25 - Inlet lip Kulites
- 6 – Fan entry Kulites
- 12x12 – fan inlet rakes
- 18 OGV – strain gauges
- 9 OGV x12 - Pressure rakes
- 7 OGV x 12 – Temp rakes
- 46 Fan strain gauges

Approved for Public Release

Photo: Bob Ferguson
Short Inlet - Initial Ground Test Results

- Fan Flutter testing cleared engine/inlet for test [RR test only]

- Short inlet performed as predicted by developmental tools, in-line with baseline inlet performance
  - Attached up to 35 kts
  - Separation at 40 kts

- Inlet rakes did not affect inlet lip isentropic Mach number distribution

- Gained confidence in tools during worst case crosswind test that supported rationale for not pursuing flight test option
Short Inlet Accomplishments & Next Steps

- Project Launched – Apr ‘17
- Short Inlet delivered to Stennis – Apr ‘17
- Kickoff Meeting / Test Plan review – Jul ‘17
- Block 1 testing completed – Aug ‘17
- Baseline Inlet delivered to Stennis – Dec ‘17
- Block 2 TRR completed – Dec ‘17
- Block 2 testing starting – Jan ’18
- Block 2 testing completed – May ‘18 Mar ’18
  - Data analysis complete – Jul ‘18 Jun ‘18
  - SLM complete – Aug ‘18 Jul ‘18
  - Limited Rights Report delivered – Aug ‘18 Jul ‘18
  - Public Report delivered – Nov ‘18 Sep ‘18
  - Final Briefing – Nov ‘18 Sep ‘18
  - Project Completes – Dec ‘18 Oct ‘18

Program Completion is accelerated by two months
CLEEN II Program Participation Advantages

Benefits to Boeing for participation in CLEEN II

▪ Collaboration with FAA and visibility of Industry’s collective progress toward shared goals
▪ Accelerates technology risk reduction and transition into the fleet.

Potential impact if projects were not funded by the FAA

▪ Reduced FAA visibility of industry tech development
▪ Reduced fidelity of System Level Models and Fleet benefits projections
▪ Overall influence on fleet would be under/overstated
▪ Reduced Visibility into Potential constraints on sustained aviation growth
Collateral Benefits

- **Structurally Efficient Wing (SEW)**
  - Broad applications across current/future Commercial & Defense programs
  - Accelerates Development & Validates Simulations
    - Thermoplastics
    - Resin Infusion
    - IM+ Material System
    - Advanced Fabrication and Assembly Techniques

- **Short Inlet for Compact Nacelle (CN)**
  - Baseline for new development program
  - Baseline for follow on development programs
Summary

Boeings CLEEN II technologies represent some of our highest impact concepts with a clear path to certification and implementation.

- The building-block test approach on SEW will develop the selected technologies along the TRL scale, resulting in a TRL 6 demonstration when the Wing Component Test Article (WCTA) test is complete.

- Short Inlet testing, successfully completed in March (TRL 6), will validate the Short Inlet design tools & methods.

- Compact Nacelle will complete in October – two months early.

- SEW & CN contribute to the FAA’s CLEEN II goal of reducing fuel burn.

- FAA & Industry benefit from continued CLEEN program investment and collaboration.
Thank you

Rolls-Royce

Georgian Aerospace Systems Design Laboratory
Acronyms

ATP  Authority to Proceed
CoDR Concept Design Review
DDR  Detailed Design Review
DLL  Design Limit Load
DUL  Design Ultimate Load
DSO  Design Service Objective
ECD  Estimated Completion Date
EIS  Entry Into Service
H/W  Hardware
K/O  Kick Off
Kts  Knots
OGV  Outlet Guide Vane
PDR  Preliminary Design Review
RR  Rolls Royce
SEW  Structurally Efficient Wing
T/R  Thrust Reverser
TRL  Technology Readiness Level
TRR  Test Readiness Review
WCTA Wing Component Test Article