CLEEN II Consortium Program Update – Public Plenary GE Aviation

May 08, 2019

Approved for Public Use

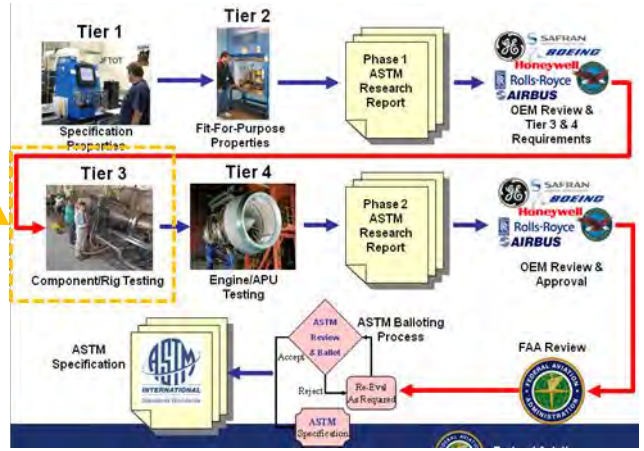
GE CLEEN Technologies Summary

CLEEN Technology Name	Goal Impact	Benefits and Application
Sustainable Alternative Fuels	Alternative Fuels	Advance approvals of multiple synthetic fuels on ASTM roadmap
MESTANG	Fuel burn	Up to 3% benefit for single-aisle aircraft
FMS	Fuel burn	Up to 5% benefit, 0.9% fleetwide average
Advanced Acoustics	Noise	Up to 3 EPNdB cum with neutral fuel burn impact

Sustainable Alternative Fuels

CLEEN II Sustainable Alternative Fuels

Rig test evaluations



ASTM D4054

Benefits:

- Advance to fully synthetic fuels.
- Advance approvals of multiple synthetic fuels on ASTM roadmap.
- Extend further to lean combustion systems evaluations.
- Determine if sensitivities of combustion parameters observed at component level could be duplicated at system level, or are they washed out?

Objectives:

- Advance approval and intro of "drop in" fuels:
  - Support ASTM D4054 – testing/demo phase
  - Conduct work complimentary to other FAA programs

Work Scope:

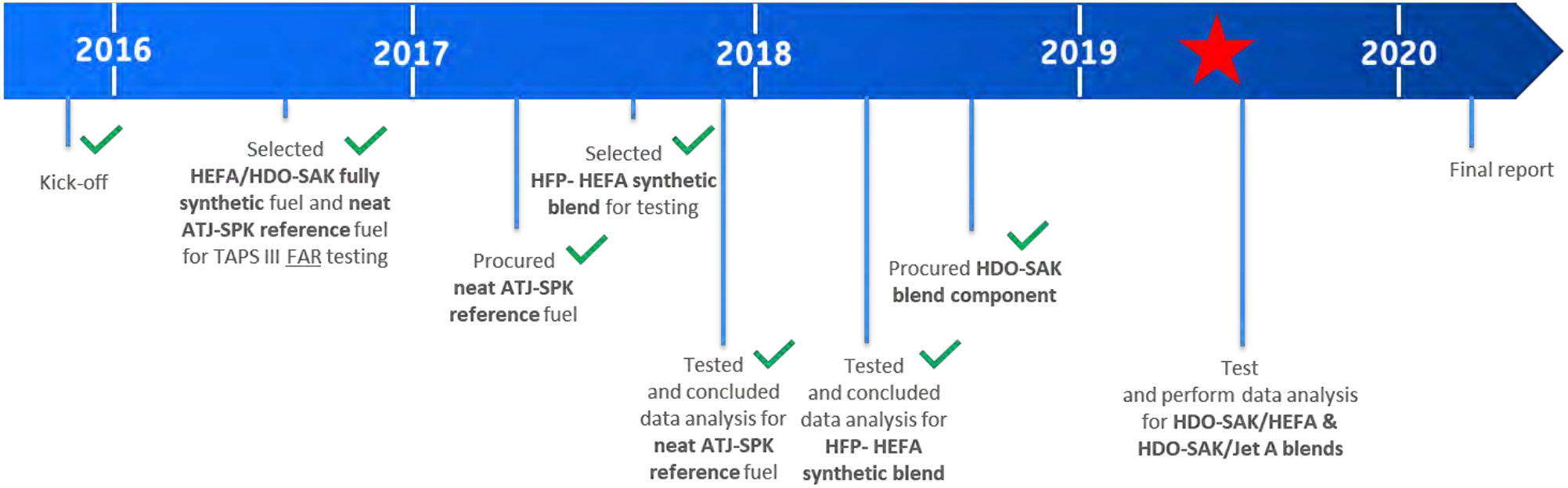
- Test two fuels, one fully synthetic and two blends, in ASTM roadmap – (FAR* test).
- Test one fuel defined by FAA's National Jet Fuel Combustion Program (NJFCP) – (FAR test).

*FAR: Full Annular Combustor Rig

Since November 2018 Consortium:

- Have been waiting for the test cell to be available for HDO-SAK (Virent) testing. FTF is late May.
- Compositional characterization of neat HDO-SAK completed.
- Investigating thermal stability characteristics.

Schedule



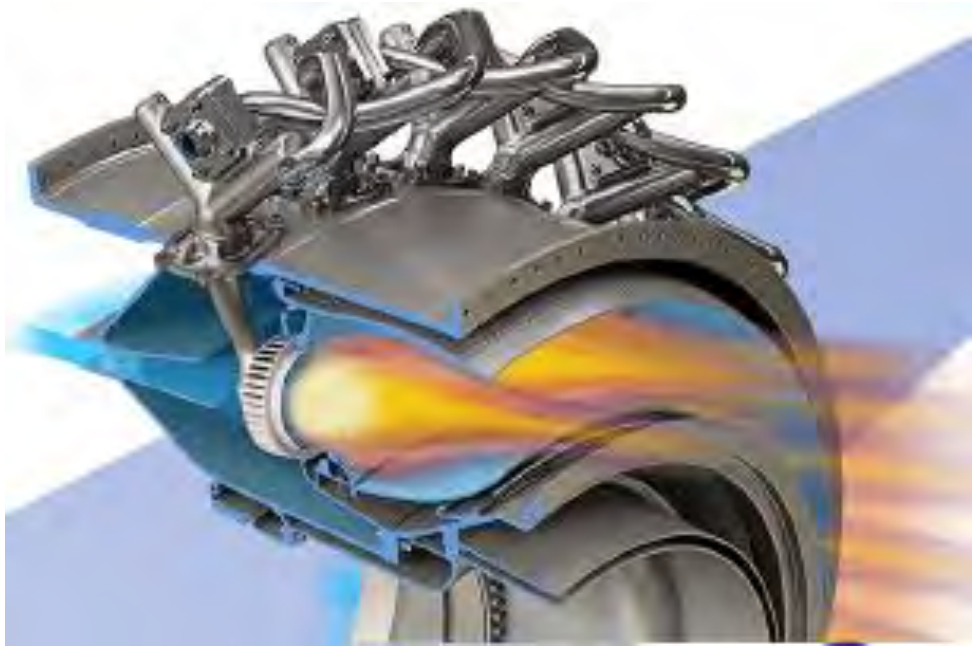
Operability focused evaluation: ignition, blow-out, sub-idle efficiency (HFP-HEFA only), high-power fuel cut (HFP-HEFA only)

Program Objectives Status

Objective	Status
Supplement other FAA programs	Adequacy of NJFCP tools validated via ATJ-SPK tests
Advance practical fuel approval #1	HFP-HEFA selected, testing and data analysis completed
Advance practical fuel approval #2	HDO-SAK/Jet A blend, testing late Q2
Advance fully synthetic fuels approvals	HDO-SAK/HEFA blend, testing late Q2

HDO-SAK Blends Test Campaign

- Hydro-deoxygenated Synthetic Aromatic Kerosene from Virent
- Going through ASTM approval – OEMs felt the need to conduct more testing with HDO-SAK/conventional fuel blends out of ASTM D4054 Phase I review
- Results to support the approval of HDO-SAK
- 25% aromatic blends with HEFA-SPK & Jet A provided by USAF
- Testing late Q2 2019



Neat (100%) HDO-SAK - GCxGC Analyses

POSF No.	13349	
Hydrogen content (weight %)	10.2	
Average Molecular Wt (g/mole)	124	
	Weight %	Volume %
Alkylbenzenes	95.46	95.56
Diaromatics	<0.01	<0.01
Cycloaromatics	2.31	2.06
Total Aromatics	**97.78**	**97.62**
Total iso-Paraffins	**0.22**	**0.27**
Total n-Paraffins	**0.11**	**0.14**
Monocycloparaffins	1.28	1.37
Dicycloparaffins	0.61	0.60
Tricycloparaffins	<0.01	<0.01
Total Cycloparaffins	**1.89**	**1.97**
Average Molecular Formula - C	9.2	
Average Molecular Formula - H	12.5	

CLEEN Sample #1 (2019)

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	Weight %	Volume %
Alkylbenzenes	95.57	95.68
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Total Cycloaromatics	2.19	1.95
Total Aromatics	**97.76**	**97.63**
iso-Paraffins	**0.24**	**0.28**
n-Paraffins	**0.03**	**0.04**
Monocycloparaffins	1.27	1.36
Dicycloparaffins	0.70	0.69
Tricycloparaffins	<0.01	<0.01
Total Cycloparaffins	**1.98**	**2.05**
Average Molecular Formula - C	9.2	
Average Molecular Formula - H	12.6	

CLEEN Sample #2 (2019)

POSF No.	12918	
Hydrogen content (weight %)	10.3	
Average Molecular Wt (g/mole)	125	
	Weight %	Volume %
Alkylbenzenes	92.63	92.84
Diaromatics	0.03	0.02
Cycloaromatics	4.69	4.21
Total Aromatics	**97.35**	**97.07**
Total iso-Paraffins	**0.75**	**0.90**
Total n-Paraffins	**0.26**	**0.32**
Total Monocycloparaffins	1.09	1.16
Total Dicycloparaffins	0.56	0.56
Total Tricycloparaffins	<0.01	<0.01
Total Cycloparaffins	**1.65**	**1.72**
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Past Sample (2016)

Almost exclusively alkylated aromatics; matches independent sample from 3yrs ago.

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Neat (100%) HDO-SAK - Thermal Stability Tests

Method	Test	Min	Max	Result	Fail
ASTM D 3241 - 18	Thermal Stability @ 310°C				
	Tube Deposit Rating, Visual			>4AP	X
	Change in Pressure (mmHg)			0	
ASTM D 3241 - 18	Thermal Stability @ 260°C				
	Change in Pressure (mmHg)		25	0	
	Tube Deposit Rating, Visual	<3 (Max)		1	
	Tube Deposit Rating, Ellipsometric (nm)		85	8	

CLEEN Sample #1 (2019)
POSF 13349

Method	Test	Min	Max	Result	Fail
ASTM D 3241 - 18	Thermal Stability @ 310°C				
	Tube Deposit Rating, Visual			>4AP	X
	Change in Pressure (mmHg)			0	
ASTM D 3241 - 18	Thermal Stability @ 260°C				
	Change in Pressure (mmHg)		25	0	
	Tube Deposit Rating, Visual	<3 (Max)		1	
	Tube Deposit Rating, Ellipsometric (nm)		85	8	

CLEEN Sample #2 (2019)
POSF 13350

Comfortably passes at Jet Fuel requirement temperature of 260°C
Currently investigating breakpoint temperature – fails at 310°C
Paraffinic fuels (SPKs) have 325°C requirement; it is expected that SAKs would have lower breakpoint temperature than SPKs

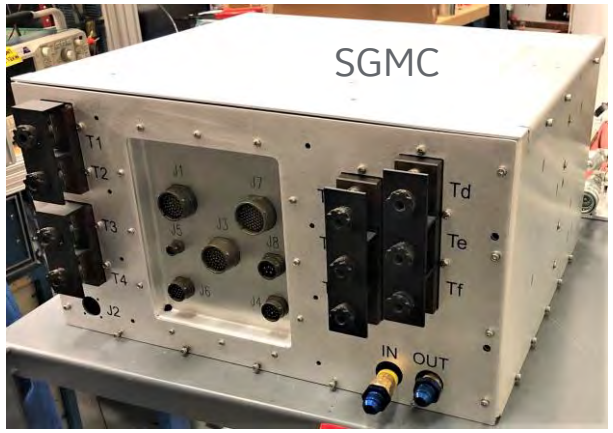
More Electric Systems and Technologies for Aircraft in the Next Generation (MESTANG)

MESTANG Technology Overview

Next-gen Commercial Aircraft will need a more power system to realize practical fuel savings and/or mission capability

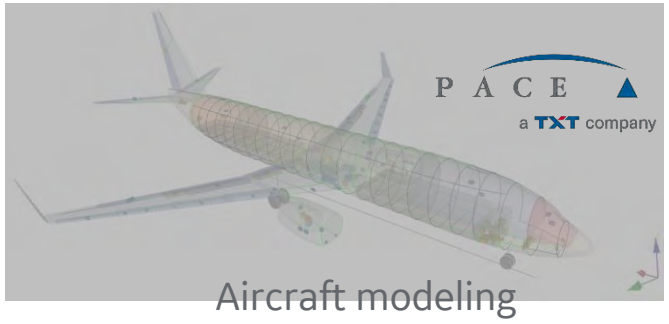
Project objectives:

- Prove ±270 VDC primary power system feasibility through lab demonstration and modeling
- 150kW ±270 VDC High Pressure Spool Starter / Generator (HPSG)
- Demonstrate all-SiC based Starter / Generator / Motor Controller (SGMC)
- Demonstrate dual spool equivalent power extraction
- Prove up to 3% fuel savings by performing aircraft + engine + power system aircraft modeling
- Limited TRL 6 rating by 2020 at EPISCENTER



Customer objectives:

More Electric Systems and Technologies for Aircraft in the Next Generation (MESTANG), is an integrated aircraft power system designed to support future "more-electric" aircraft architectures that reduce fuel burn by up to 3 percent for single-aisle aircraft while improving performance at equivalent cost

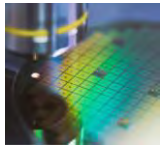


Project Schedule

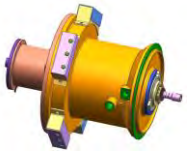
FY/CY 2019 Accomplishments / Milestones:

- ✓ **Completed** System Test Spiral V – December 14, 2018
- FAA Consortium – May 7-9, 2019
- SGMC v1.0 – May 31, 2019
- HPSG v1.0 and PCU – May 31, 2019
- FAA Consortium – November 5-7, 2019
- System Test Spiral VI & Demo – December 16, 2019

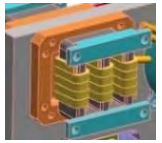
Fabricated GE Gen3 SiC



✓ Generator Preliminary Design



Design for EMI



TRL 4 Prototype **SGMC** v1.0

Prototype **SGMC** v2.0

✓Consortium ✓Consortium Consortium Consortium Consortium

Q1 - Q4'17 | Q1 - Q4'18 | Q1'19 | Q2'19 | Q3'19 | Q4'19 | Q1'20 | Q2'20 | System Demonstration 2020

HW Component Tests

System/ HW-SW Integration Tests

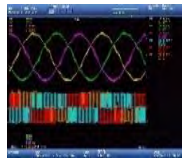
✓PDR ✓DDR ✓**System Test Spiral V**

System Test Spiral VI **TRL 5 ***

System Test Spiral VII-VIII

System Test Spiral IX **TRL 6 ****

Manufactured ±270 VDC Silicon Carbide Modules



Powered Converter Tests

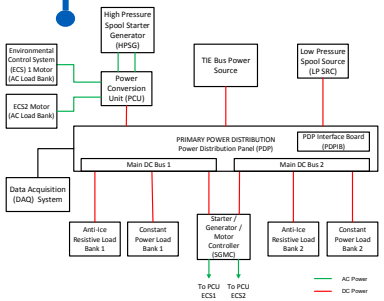
TRL 4 Prototype **HPSG** v1.0

Prototype PCU v1.0

Prototype **HPSG** v2.0

* HPSG & SGMC HW SW Lab Integration

** HPSG & SGMC Limited Environmental Testing along with Final HW SW Lab Integration



MEA Fuel Savings – 500 NM Mission

Aircraft/Mission (Pacelab SysArc):

Aircraft:	Narrow Body (Boeing 737-NG)
Baseline:	Pneumatic Wing Anti-Ice/ECS 115VAC Electrical System
MEA:	Electric Wing Anti-Ice/ECS +/-270VDC Electrical System, Dual-spool
Mission:	500 NM + Taxi In/Out
Anti-Ice:	Systems on, except during cruise

Final Updates made in CY 2018:

- Dedicated flight profiles for Baseline and MEA
- Full flight profile (gate-to-gate)
- Calculated wholly within Pacelab environment
- MEA weight increase modeled
- Electric ECS air-inlet drag modeled
- Optimized HP / LP split

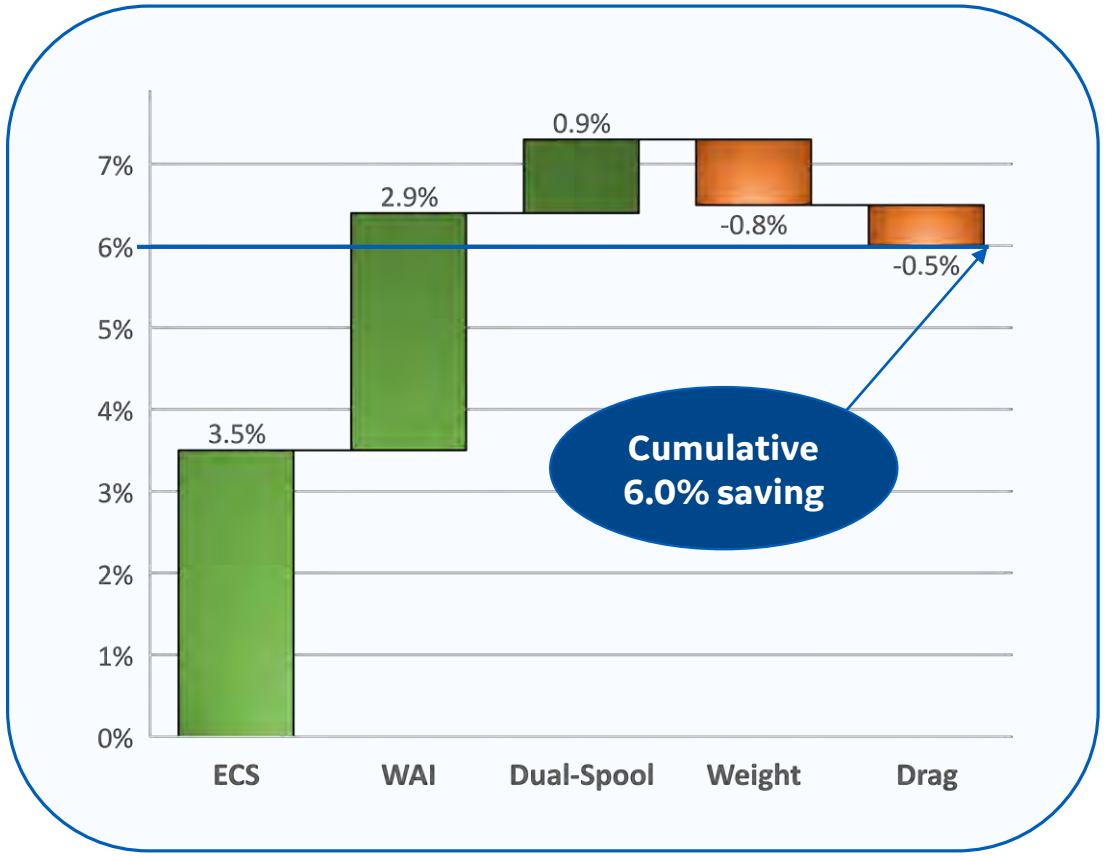
MEA Fuel Savings per Flight Phase (500 NM Mission)

Fuel Consumed (height = lb) and Savings (%) per phase of flight

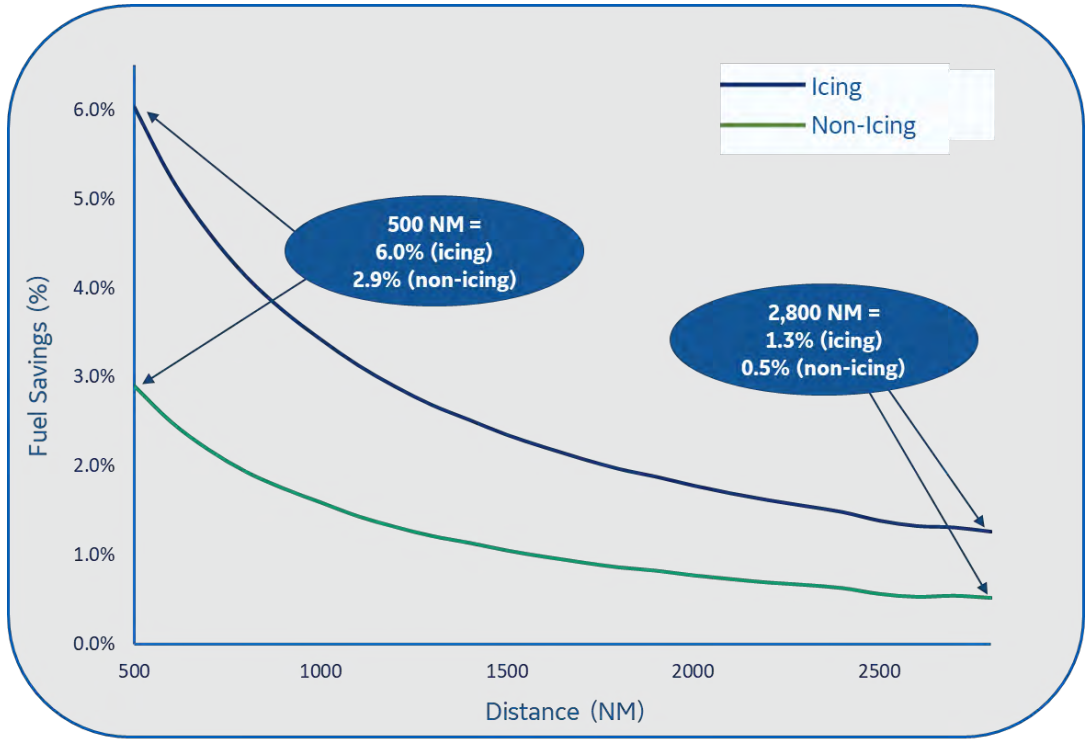
Up to 6.0 % overall fuel savings for a 500 NM mission

MEA Fuel Savings - Breakdown

Fuel Savings Breakdown – 500 NM Mission

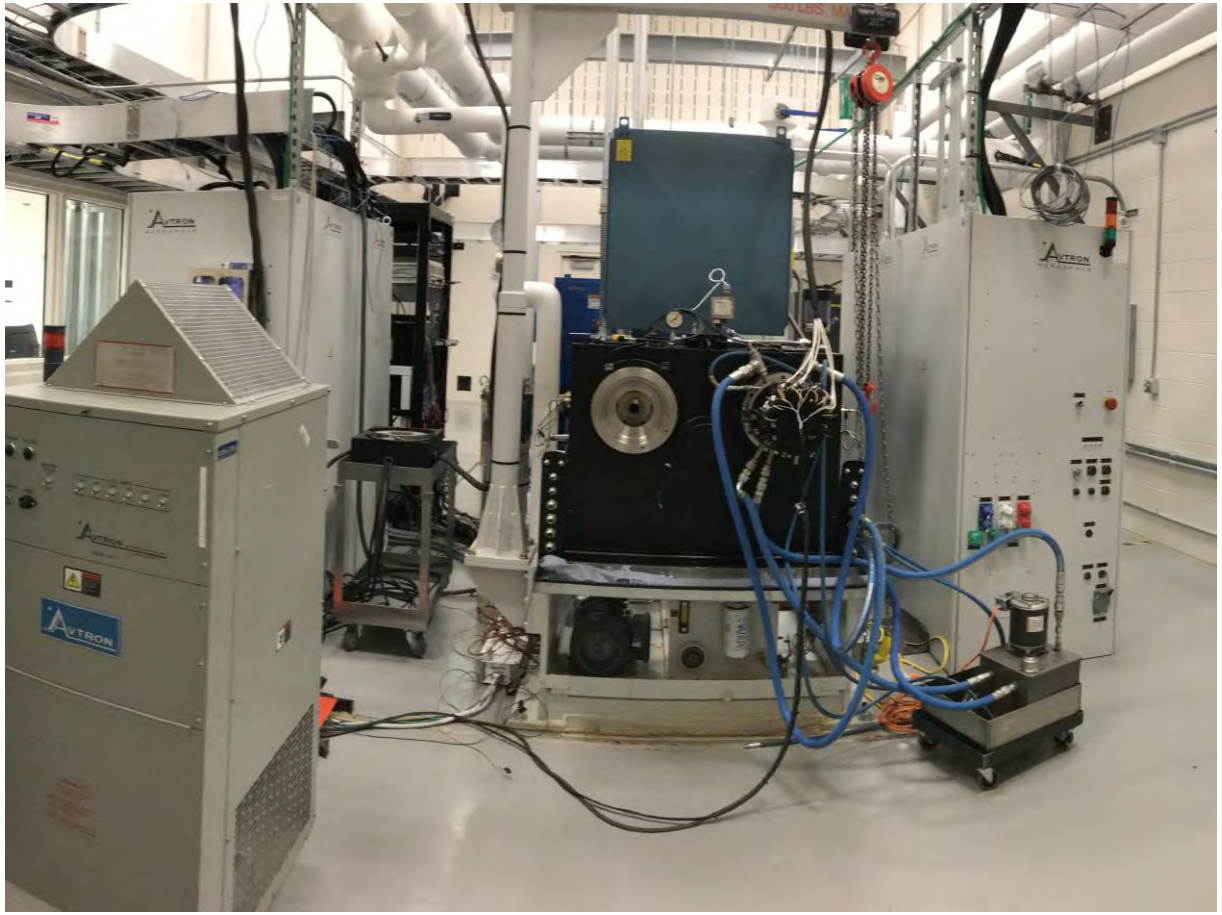


Savings by Mission Distance – Icing & Non-Icing



Lab Setup Status

Front view of drive stand

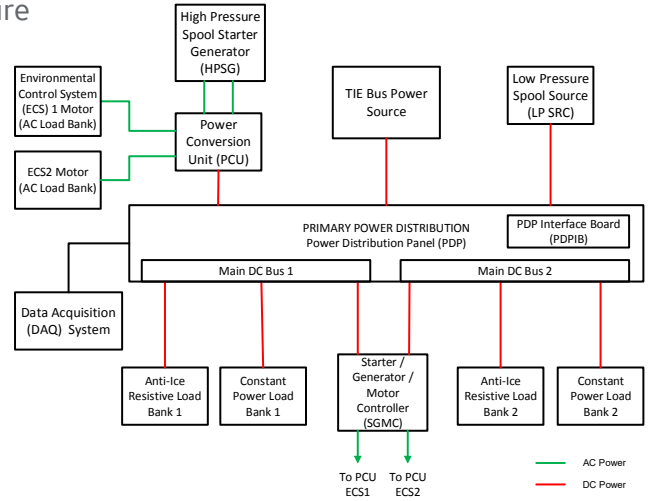


Drive stand control, oil cart, test rack

SGMC Development

Project Technology – HPSG, SGMC

Demonstration Architecture



Benefits:

- More efficient +/- 270VDC power system to realize practical fuel savings and/or mission capability
- 600kW aircraft power system
- Demonstrate electric engine start capability
- Demonstrate all-SiC power system
- Limited TRL 6 by 2020 at EPISCENTER

Objectives:

Mature an integrated aircraft power system consisting of a bleedless, dual-spool engine, and +/- 270VDC more-electric primary power system

Work Statement:

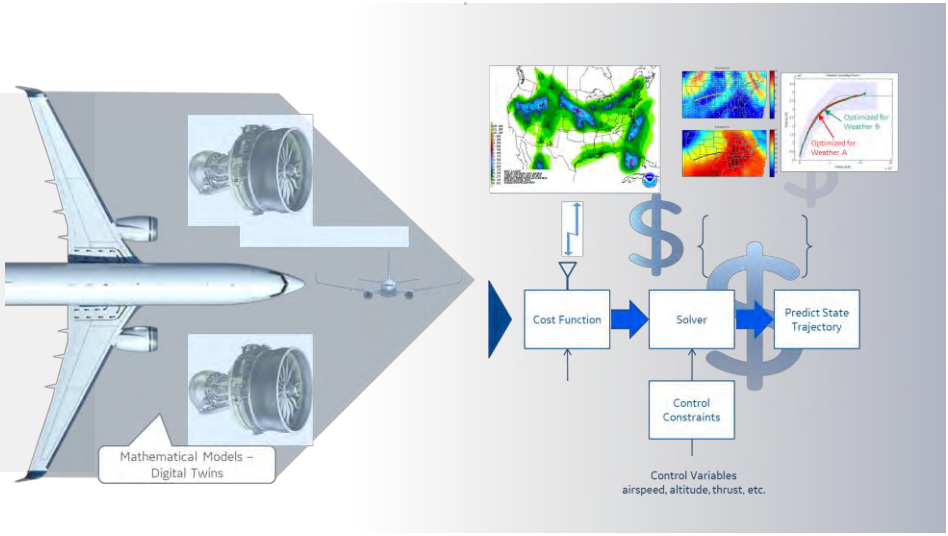
- Gain up to 3% Fuel Savings in Single-Aisle A/C Family using the proposed power system model
- Full power system solution with improved performance at equivalent cost

Key CLEEN II Accomplishments:

• Program Kick Off	4/1/2016
• Architecture Trade Study and initial 300 kW Architecture	10/19/2016
• Enhanced 300 kW Architecture for PDR	3/21/2017
• Preliminary Design Review (FAA)	5/1/2017
• Finalized 300 kW Architecture	9/14/2017
• Completed initial Systems Requirement Document (SRD)	12/8/2017
• Completed initial Interface Control Document (ICD)	4/6/2018
• Detailed Design Review (FAA)	4/25/2018
• System Test Spiral I - III	8/1/2018
• System Test Spiral IV	10/3/2018
• Completed PACE Baseline and MEA Model SFC calculation	10/12/2018
• System Test Spiral V	12/14/2018

Flight Management System (FMS)

Executive Summary



Objective

- Develop algorithms to optimize performance to minimize cost of flying city pairs, complying with IFR
- High accuracy/ resolution model of the atmosphere; wind-optimized cruise; unified climb, cruise, descent; optimal required times of arrival
- Reduction in community noise & emissions

Results To Date:

- Up to 4% fuel savings relative to legacy (constant alt)
- Up to 2.5% fuel savings relative to legacy w/ AOC-assisted step climb

2018 Accomplishments

- **Gen B** – Wind optimal cruise altitude
- **Gen C** - Unified Climb, Cruise, and Descent with steps in cruise

2019 Milestones

- Detailed Design Review (completed Feb/2019)
- Complete demonstration and final report
- Complete benefit assessments

Past 6 Months

- Achieved TRL 6 for GEN D
- TRL 5 benefit assessment complete

Benefits enabled by Connected FMS

Utilizes a set of algorithms that create a cost function / prediction sequence to help determine the optimal flight path

GEN A Best cruise altitude

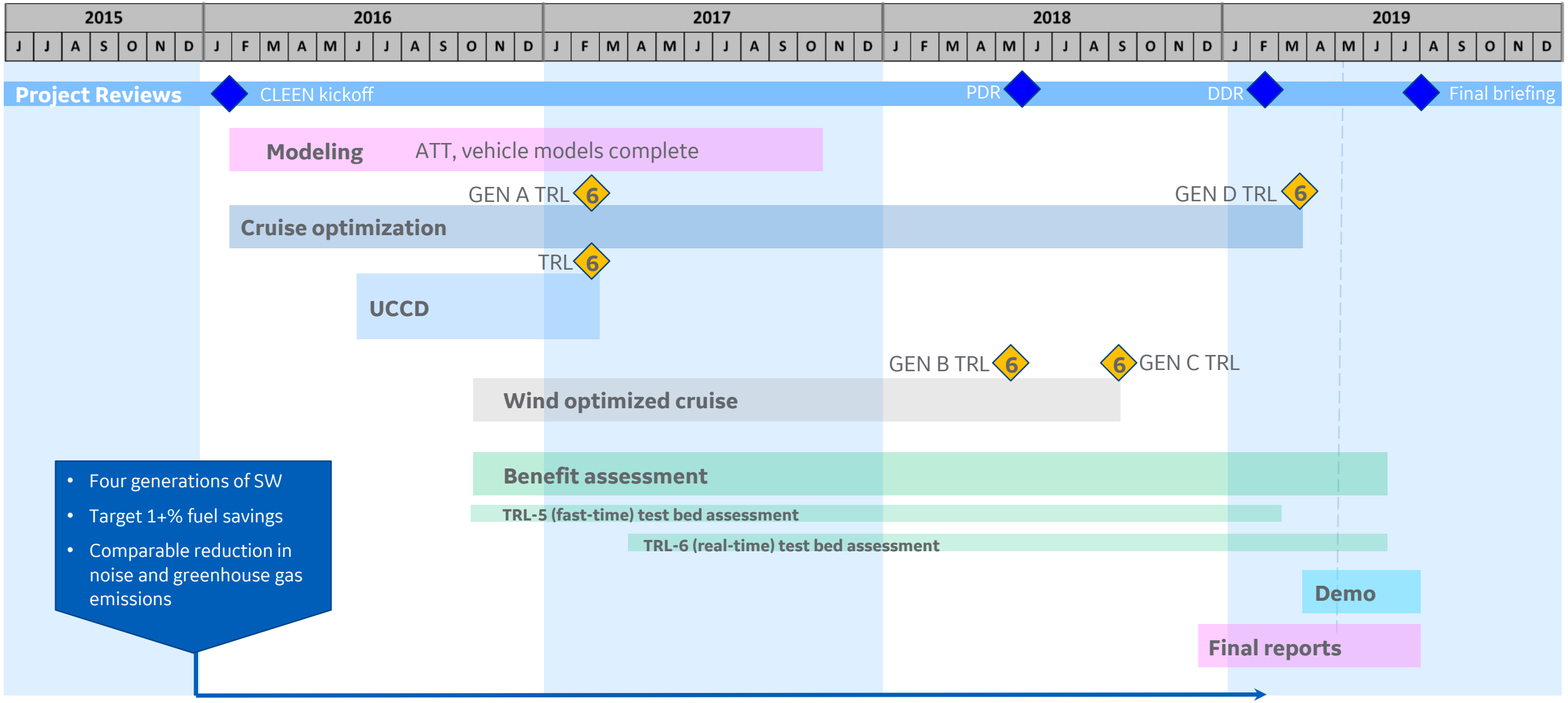
UCCD Best full flight + variable climb

GEN B Constant alt weather opt

GEN C Optimal cruise steps

GEN D Req Time Arrival (RTA)

Project Schedule

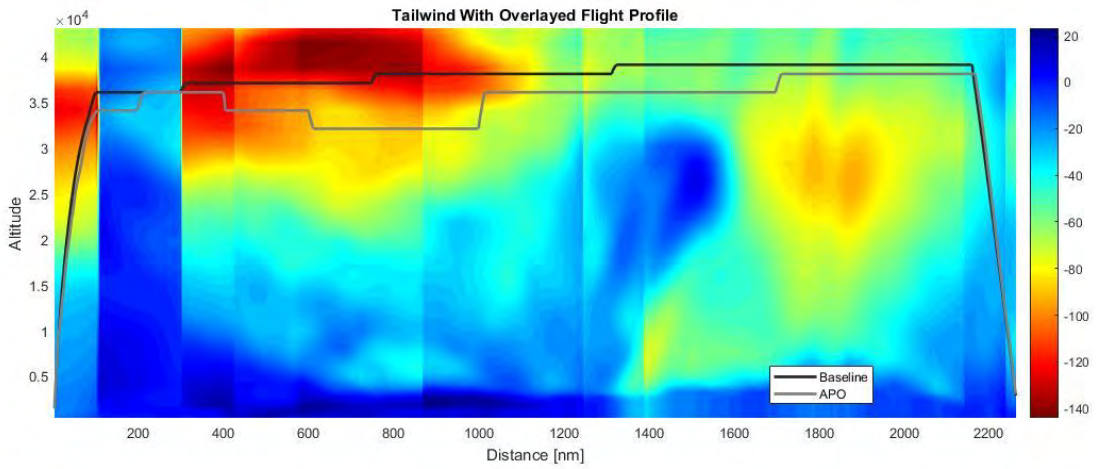


- Four generations of SW
- Target 1+% fuel savings
- Comparable reduction in noise and greenhouse gas emissions

Unified Climb-Cruise-Descent Optimization with High Fidelity Weather and Cruise Steps

GEN C

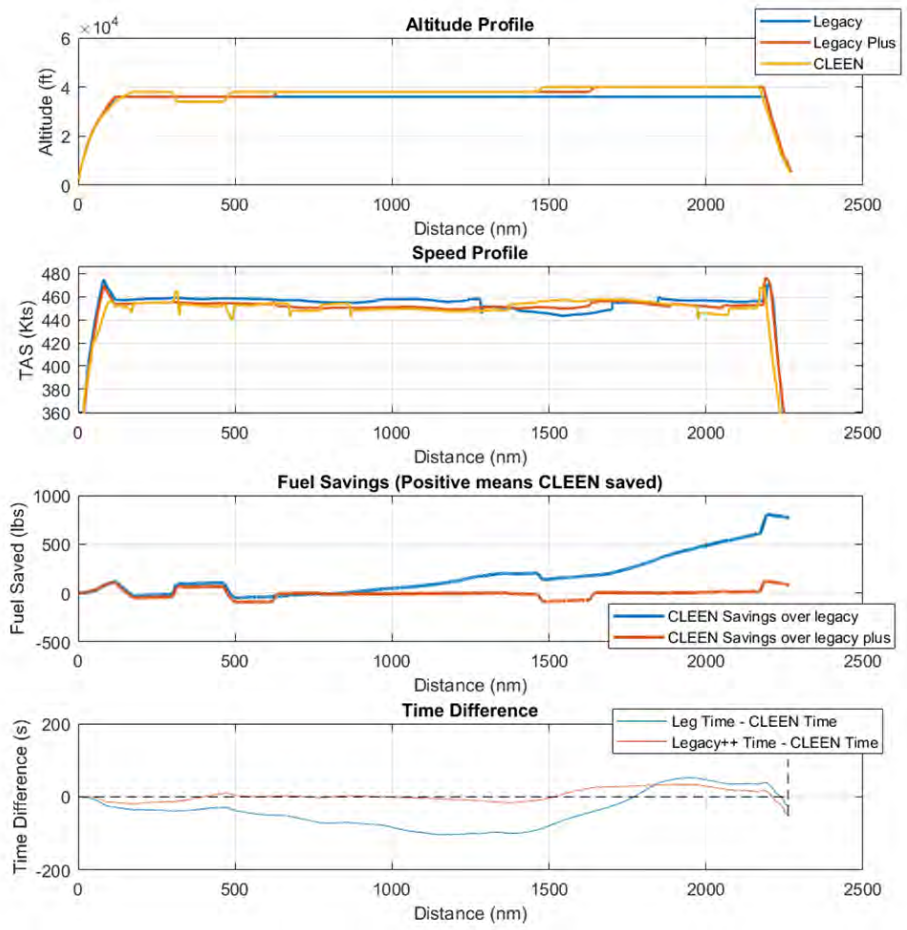
Up to 4.0%	Max fuel savings against Legacy FMS
Up to 2.5%	Max fuel savings against existing AOC tools
130x	More Weather Data



Unified Climb-Cruise-Descent Optimization with Required Time of Arrival (RTA)

GEN D

Up to 5.0%	Max fuel savings against Legacy FMS
Up to 3.0%	Max fuel savings against existing AOC ground tools
2x	Fewer repredicts – decreased trajectory negotiation
52%	Wider achievable RTA window



Fleet-Wide Mean Benefit Assessment

Legacy

Constant cruise altitude

Legacy++

AOC ground tool altitude steps

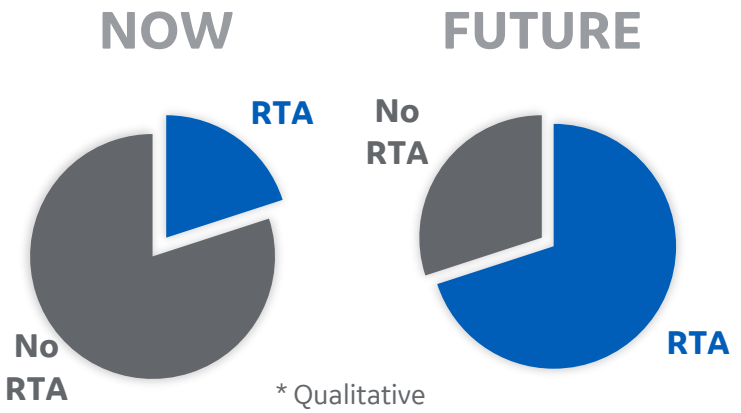
Generation C

Variable thrust / variable speed climb + cruise altitude steps with weather

Generation D

Generation C optimization w/ RTA constraint

Fuel Savings (Cost Index 0)	No RTA (GEN C)	With RTA (GEN D)
Legacy	0.9%	0.7%
Legacy++	0.3%	0.4%

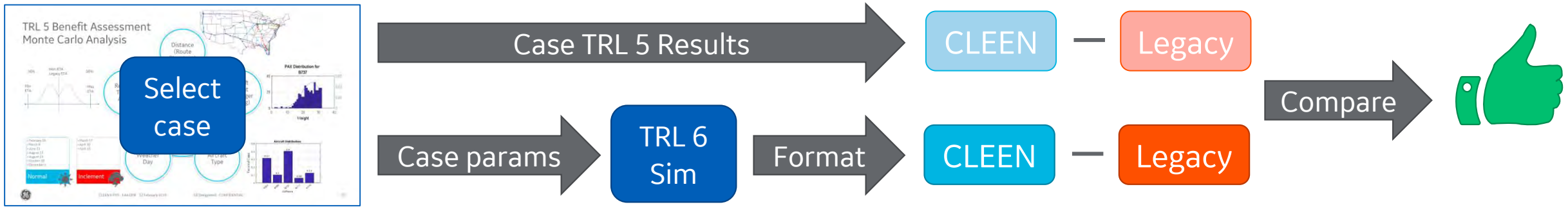


* Qualitative

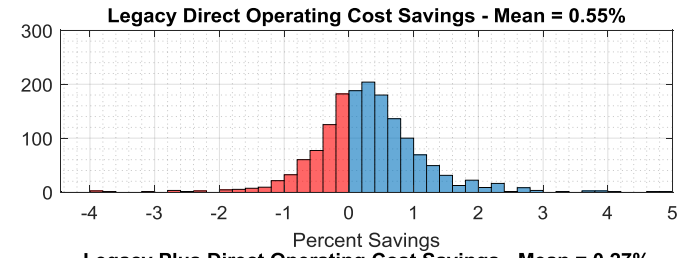
Test Plan: Benefit Assessment Confirmation

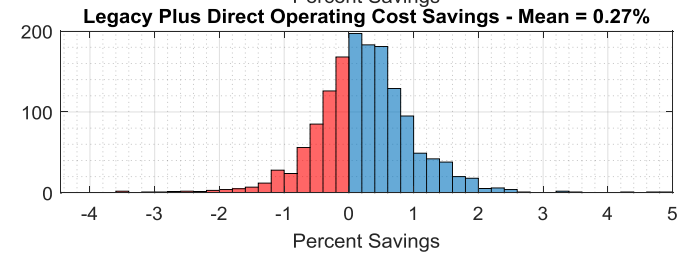
Problem: Infeasible to simulate all flights in real-time TRL 6 system.

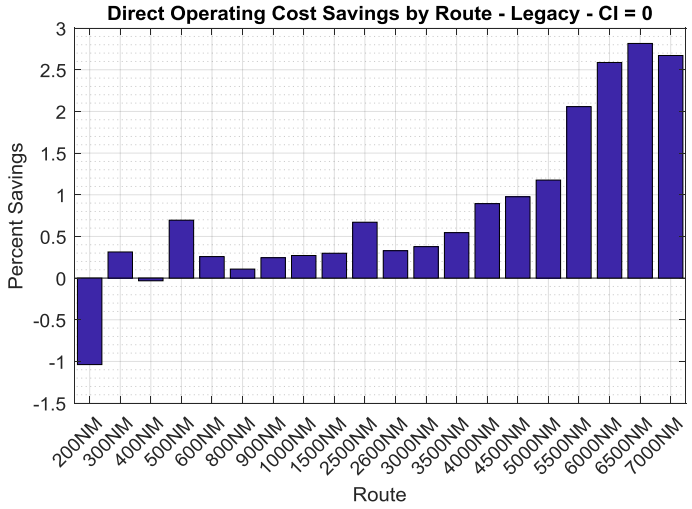
Solution: Confirm fast-time TRL 5 results against TRL 6 system for limited sample size.

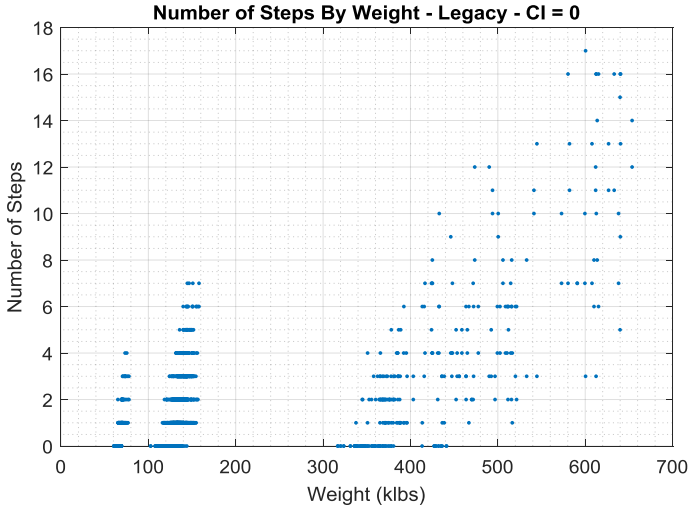


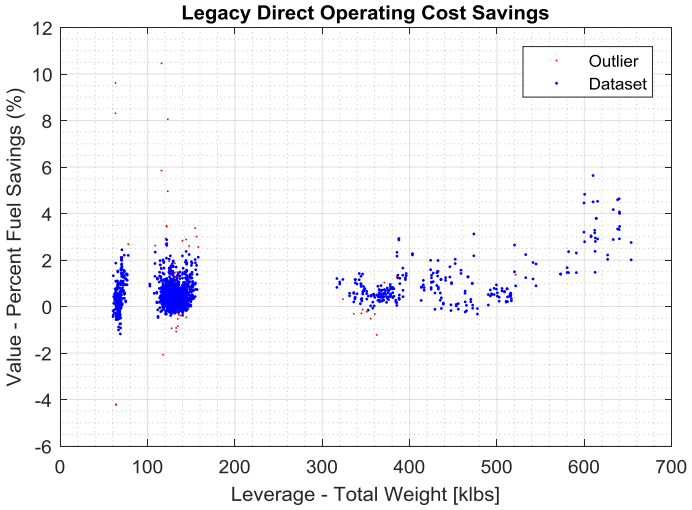
Georgia Tech Data for CLEEN Rollup Assessment

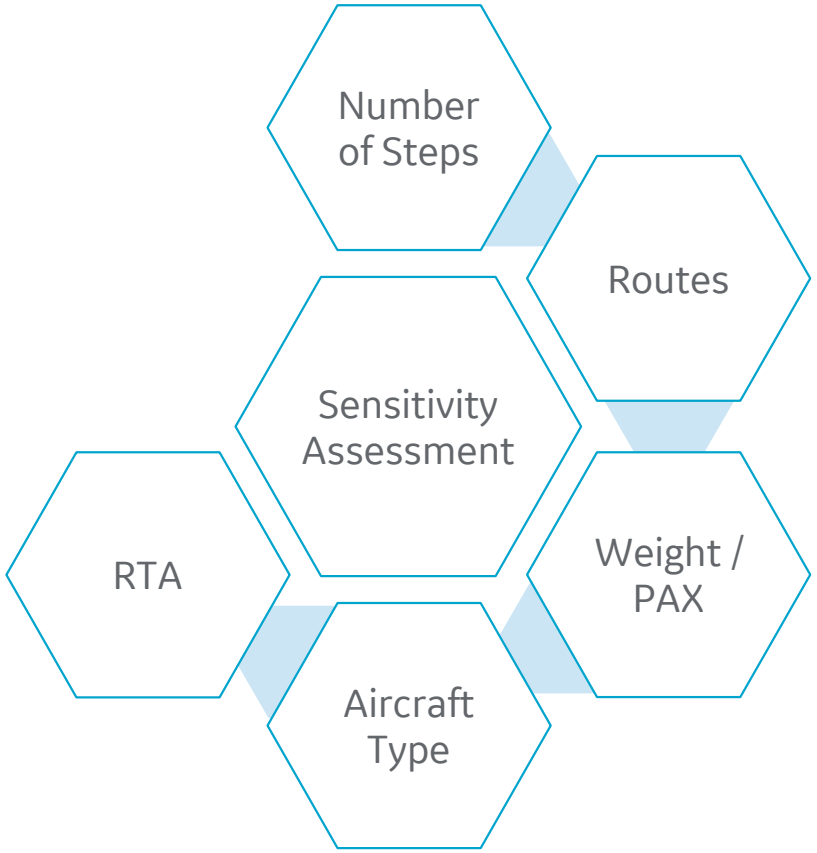






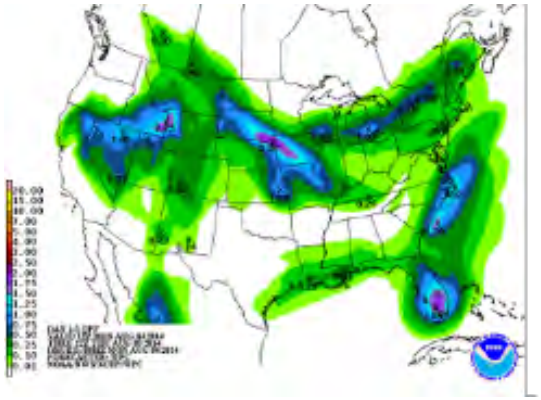






Will engage in 2019Q2

Project Technology



Anticipated Benefits:

- 0 – **5%** fuel savings relative to legacy FMS
- 0 – **3%** fuel savings relative to legacy FMS assisted by AOC-defined step climbs
- Comparable reduction in community noise and greenhouse gas emissions

Risks/Mitigation Plans:

- Low cost, rapid introduction into service ⇨ EFB application integrated with FMS
- Community acceptance ⇨ Consulting with OEMs, Airlines, NASA, and NextGEN Program Office

Objective: Develop algorithms that find the set of optimum controls to minimize the cost of flying a city pair while constrained to comply with IFR.

Work Statement:

- GEN A ⇨ Reformulate cruise, integrate with climb and descent (UCCD)
- GEN B ⇨ Add high-resolution weather
- GEN C ⇨ Add variable cruise altitude
- GEN D ⇨ Constrain to arrive at required times (RTA)

Accomplishments/Milestones:

- GEN A UCCD (TRL 6) ⇨ Completed Nov 2016
- GEN B Hi Fidelity Weather (TRL 6) ⇨ Completed Jun 2017
- GEN C Optimal Step (TRL 6) ⇨ Completed Sept 2018
- GEN D RTA Constrained (TRL 6) ⇨ Completed Feb 2019

Schedule:

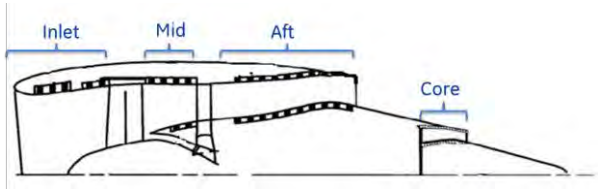
- PDR ⇨ Completed Jun 2018
- DDR ⇨ Completed Feb 2019
- TRL 6 FMS & EFB prototype ⇨ Completed Mar 2019
- Final Report and Demonstration ⇨ 20193Q

ADJUST FLIGHT PATH 45° NW

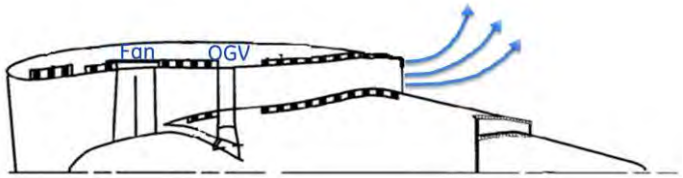
Low Pressure Ratio (LPR) Advanced Acoustics

Project Technology:

Novel Liners



Fan Source Strength Reduction



Anticipated Benefits:

- *Improved Acoustic Liner Benefit re: Single Degree Freedom Liners,*
  Target ~ 2EPNdB Cum, Neutral Performance.
- *Improved Fan Noise Source Strength Reduction re: LEAP.*
  Target ~ 1 EPNdB Cum, Neutral Performance.

Objectives:

- *To Develop Novel Acoustic Liners.*
- *To Develop Fan Source Strength Reduction Concepts.*

Work Statement:

- *Design, Develop, Fabricate and Test Novel Acoustic Liner.*
- *Aeroacoustic Design and Testing of Fan noise source strength reduction concepts.*

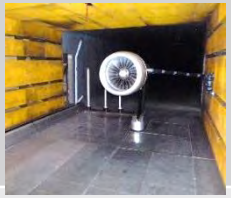
Accomplishments/ Milestones:

- *Tested several Novel Liner Concepts in a Normal Impedance tube.*
- *Built and started testing a 2nd round of Novel Designs at NASA Langley GFIT- Q3 2019.*
- *Completed Detailed Aeroacoustic Design Review- Q1 2019.*

Schedule:

	FY 2018	FY 2019	FY 2020
Novel Acoustic Liner	TRL/MRL- 3/3	TRL/MRL- 4/4	TRL/MRL- 6/5
Fan Noise Source Strength Reduction	TRL-3		TRL- 4

Project Schedule

Technology	Earlier	FY 2018	FY 2019	FY 2020 (Planned)
1. Novel Acoustic Liner Technology Test part geometry	Concepts Developed and Tested in Normal Impedance Tube <5" X 5" 	Grazing Flow Test Rig Round 1 2.5" X 21"	Grazing Flow Test Rig Round 2 2.5 X 21" 	Engine Test Full scale 360°
TRL/MRL		3/3	4/4	6/5
2. Fan Noise Source Strength Reduction	Down Select and Identify Source Strength Reduction Concepts	Preliminary Design of one Aeroacoustic fan Source Strength Reduction Design	Pre test Prediction & Fabrication	Wind Tunnel UPS test 
TRL		3		4

Engine Test FY 2021

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Summary and Next Steps

Novel Liners

- Several liner core designs were tested in Normal Impedance Tube and Grazing Flow and a Validated Analytical Tool was developed
- Started Fabrication and Testing of Novel Liners for Phase 2 Grazing Flow Tests – Q3 2019
- Static Engine Test with Novel Liner in Inlet Planned in FY 2020

Fan Source Strength Reduction

- Low order validated Screening tool and 3D CFD/CAA tool and prior test data were used to guide Aeroacoustics Design
- Detailed Aeroacoustic Design Review completed Q1 2019
- Test in a UPS rig planned for FY 2020