CLEEN II Consortium– Public Plenary
GE Aviation

May 2, 2018

Approved for Public Use

GE CLEEN Technologies Summary

CLEEN Technology Name	Goal Impact	Benefits and Application
MESTANG	Fuel burn	Up to 3% benefit for single-aisle aircraft
Advanced Acoustics	Noise	Up to 3 EPNdB cum with neutral fuel burn impact
FMS	Fuel burn	1% benefit
Alternative Fuels	Alternative Fuels	Full Annular Rig test to support approval & insertion of alternative fuels; focus on operability impacts NJFCP fuel (100% Gevo ATJ-SPK); 100% synthetic (HEFA SPK + Virent HDO-SAK)); 25% aromatic Virent HDO-SAK/Jet A; HFP-HEFA blend
TAPS III – Technology Program	Emissions	35% reduction relative to CAEP/8 (55 OPR) Technology applicable to GE9X engine / 777X aircraft

CLEEN II Consortium– Public Plenary

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

Presenter: Venkatesh Saligrama
Date: May 2, 2018

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MESTANG Technology Overview

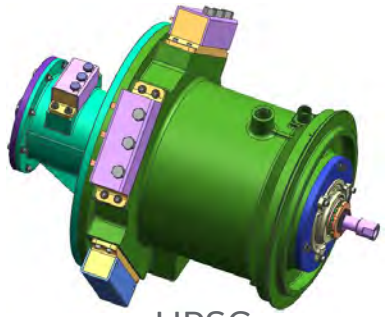
Next-gen Commercial Aircraft will need a more power system to realize practical fuel savings and/or mission capability

Project objectives:

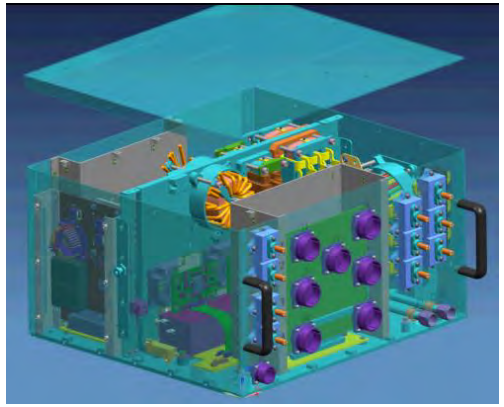
- **Prove ±270 VDC primary power system feasibility through lab demonstration and modeling**
- **150kW ±270 VDC High Pressure Spool Starter / Generator (HPSG)**
- **Demonstrate all-SiC based Starter / Generator / Motor Controller (SGMC)**
- **Demonstrate dual spool equivalent power extraction**
- **Prove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

Customer Outcomes:

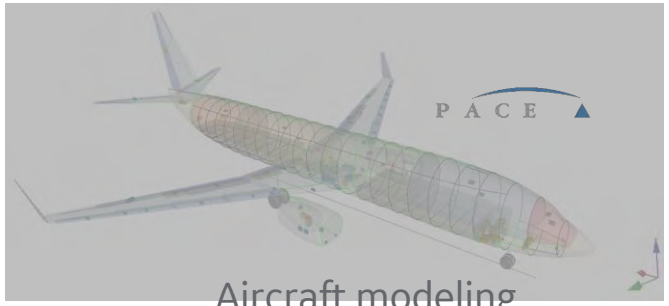
More Electric Systems and Technologies for Aircraft in the Next Generation (MESTANG), is an integrated aircraft power system designed to support future "more-electric" aircraft architectures that reduce fuel burn by up to 3 percent for single-aisle aircraft while improving performance at equivalent cost



HPSG



SGMC



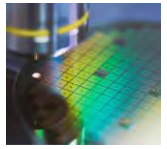
Aircraft modeling

Project Schedule

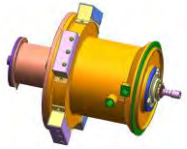
FY2018 Accomplishments:

- **Completed** internal DDR (iDDR): Systems, HPSG , SGMC – April, 2018
- **Started** building SGMC & HPSG Prototypes
- **Started** Test Setup at EPISCenter
- **Completed** FAA DDR – April 25, 2018
- FAA Consortium – May 01 – 03, 2018

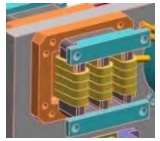
Fabricated GE Gen3 SiC



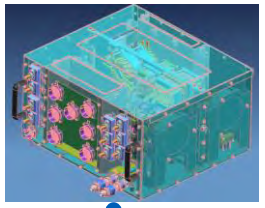
Completed Generator Prelim Design



Design for EMI



Prototype SGMC Build



Consortium

Q1'17 Q2'17 Q3'17 Q4'17 Q1'18 Q2'18 Q3'18 Q4'18

Component Tests 2018-19

System Demonstration 2020

Passed PDR

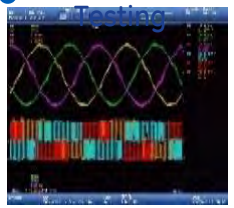
iDDR

DDR

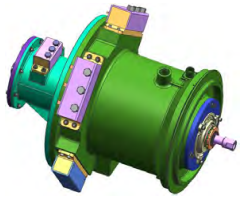
Consortium

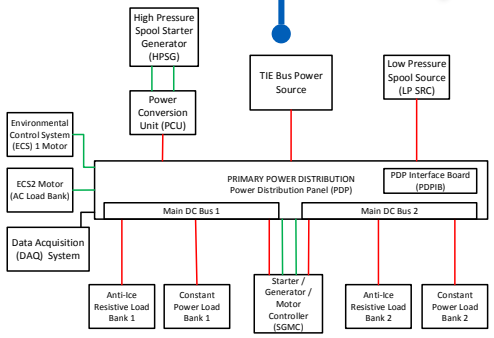
Manufactured ±270 VDC Silicon Carbide Modules

Powered Converter Tests



Prototype HPSG Build



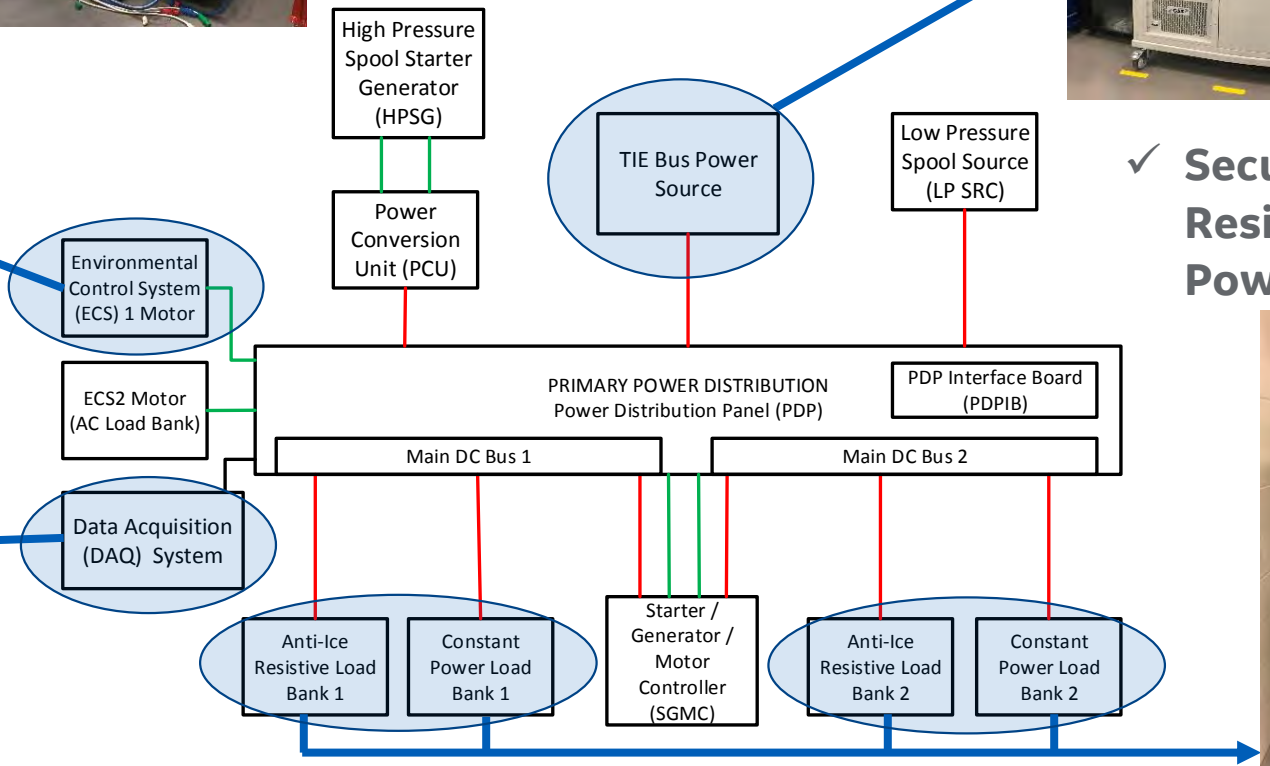


Accomplishments: Lab Setup and Planning

CLEEN II MESTANG Lab

- ✓ **HPSG Avtron Drive Stand, Oil Cart, and Control Panel installed**

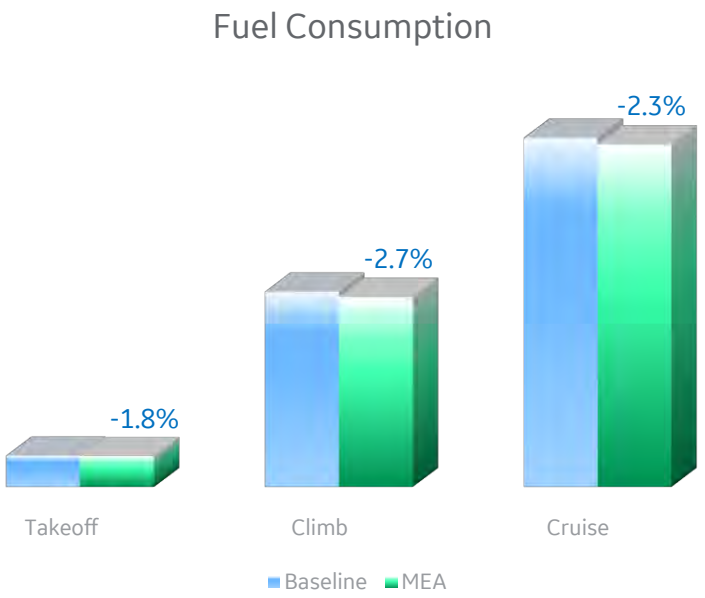
- ✓ **Secured Regatron Power Supply**

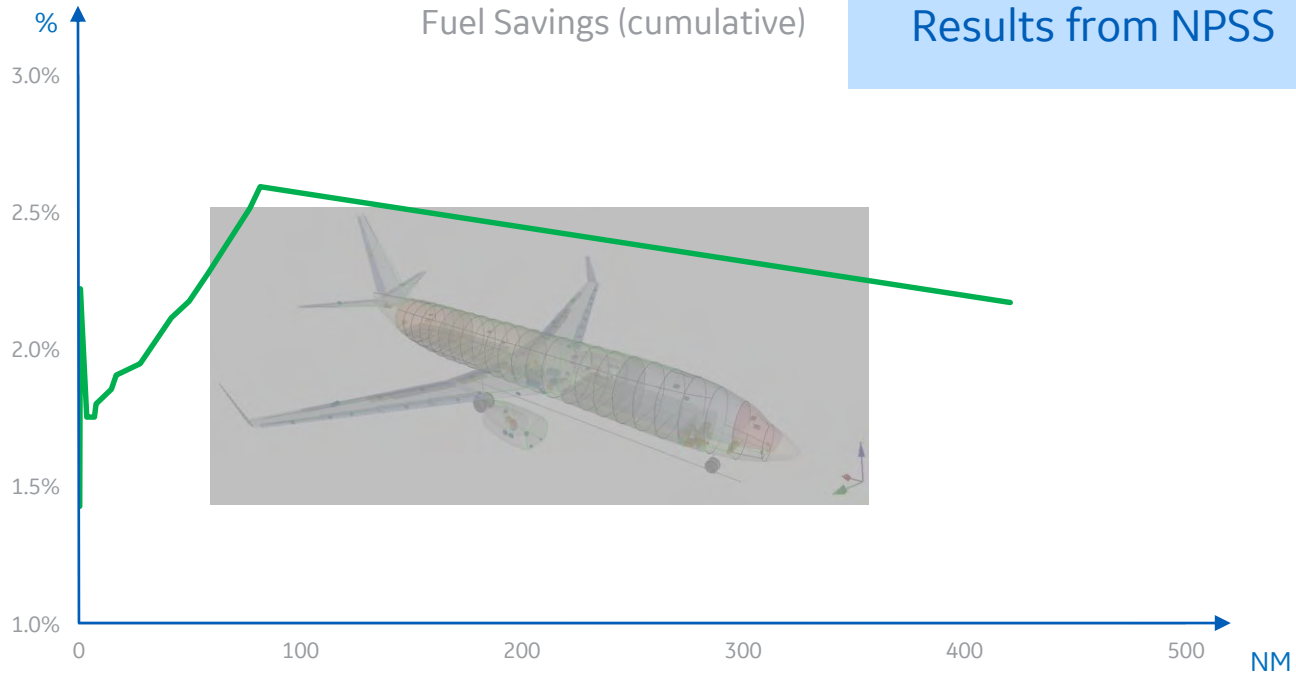


- ✓ **Secured NHR Resistive / Constant Power Load Bank**

- ✓ **Secured DAQ System**
- ✓ **Test Equipment Rack**

Preliminary Fuel Consumption Benefits



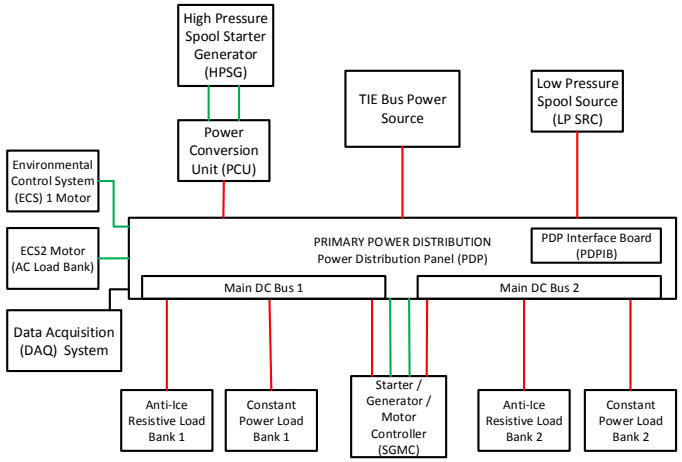


Results from NPSS

MEA consumes less fuel → 2.2% reduction

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
• Completed internal Preliminary Design for Systems, HPSG and SGMC	3/30/2017
• 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) with Electrical Interface	4/6/2018
• Completed internal Detailed Design Review for Systems, HPSG and SGMC	4/6/2018
• Detailed Design Review (FAA)	4/25/2018

CLEEN II Consortium– Public Plenary Advanced Acoustics

Presenter: Mugam Murugappan
May 2nd , 2018

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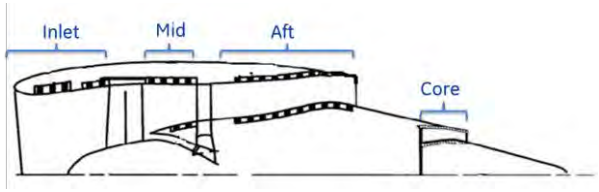
Elevator Speech

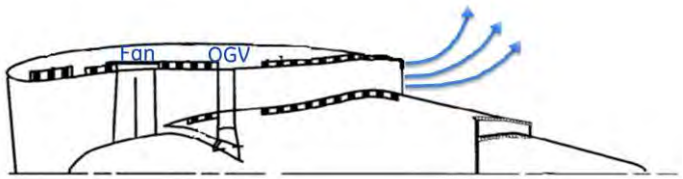
As turbofan engine bypass ratios and fan diameters increase for improved fuel burn efficiency, conventional engine nacelles become too large and heavy thereby limiting the performance benefits of the increased engine bypass ratio. Engine and airframe designers are developing new technologies to enable compact inlets and exhaust nozzles, and ways to minimize overall engine length. Next generation high bypass ratio engines will have reduced acoustic liner duct lengths, reduced overall treatment area, and compact Fan-OGV spacing. New, more effective acoustic suppression liner technologies and reduced Fan-OGV wake interaction technologies are essential to ensuring compliance with ever more stringent future noise goals. The current project proposes to Design, Optimize and Mature novel acoustic liner and fan source strength technology. We also expect these proposed concepts to provide superior noise benefit without compromising on fuel burn and performance of aircraft.

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.

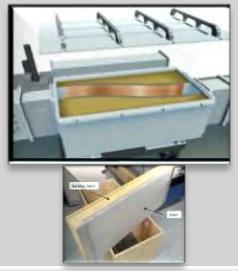
Accomplishments/ Milestones:

- *Fabricated Novel Liner Panels*
- *Initiated Aeroacoustic Design- Q1 2018*

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
1. Novel Acoustic Liner Technology Test part geometry	Concepts Developed and Tested in Normal Impedance Tube <5” X 5” 	Grazing Flow Test Rig 2.5” X 21” 	Curved Duct Test Rig 15” X 32” 	Engine Test Full scale 360°
TRL/MRL		3/3	4/4	6/5
2. Fan Noise Source Strength Reduction		Aeroacoustic Design	Pre test Prediction & Fabrication	Wind Tunnel test and Analysis
TRL		3		4

Engine Test FY 2021

6

Summary and Next Steps

Novel Liners

- Design and Fabrication of 5”x5” Novel Liner Coupons for Normal Impedance Test Completed
- Fabrication of Novel Liners for Grazing Flow Test Rig Completed
- Phase 1 Grazing Flow Tests Planned – Q2 2018; Phase 2 Grazing Flow tests Planned for Q3 2018

Fan Source Strength Reduction

- Design Consensus Review of Aeroacoustics Design Completed- Q1 2018
- CFD/CAA tools to Guide Aeroacoustics Design
- Conceptual and Preliminary Design Review planned for Q2 and Q3 2018

CLEEN II Consortium– Public Plenary– Flight Management System

Presenter: Dave Lax
Date: May 2, 2018

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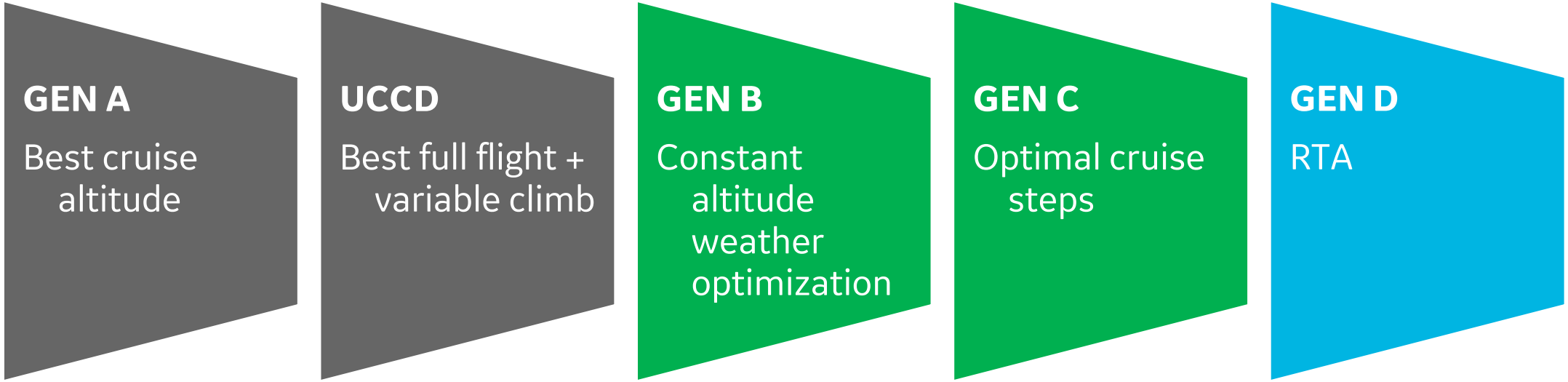
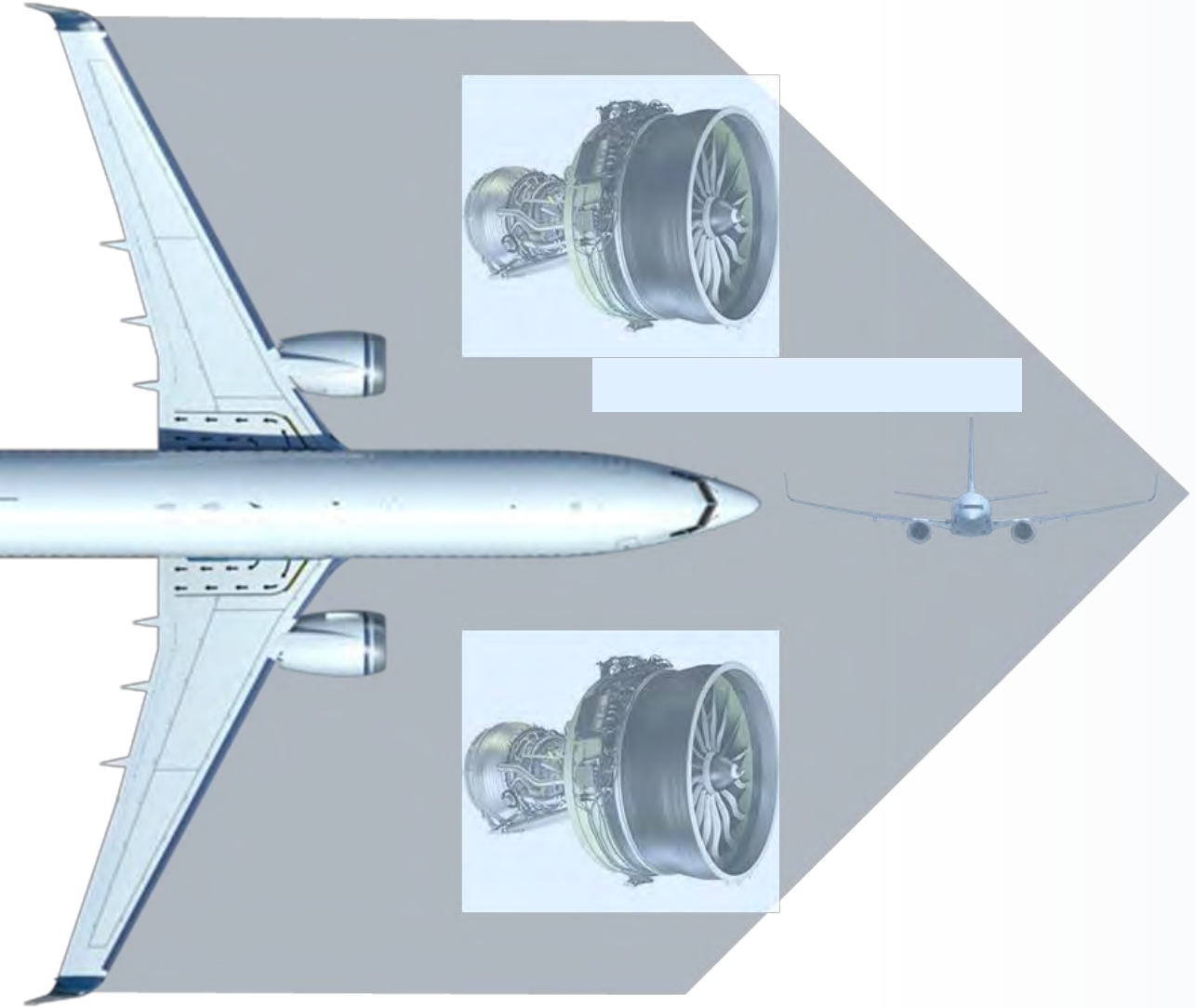
Technology Description

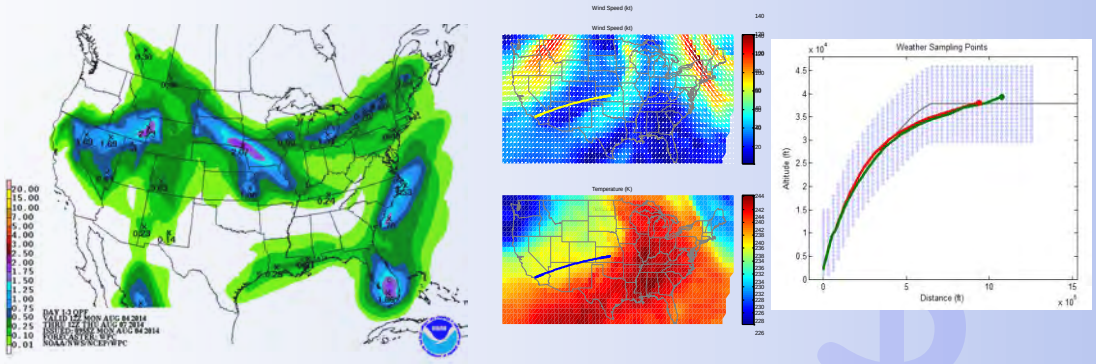
Development of algorithms that find the set of optimum controls to minimize the cost of flying a city pair while constrained to comply with IFR.

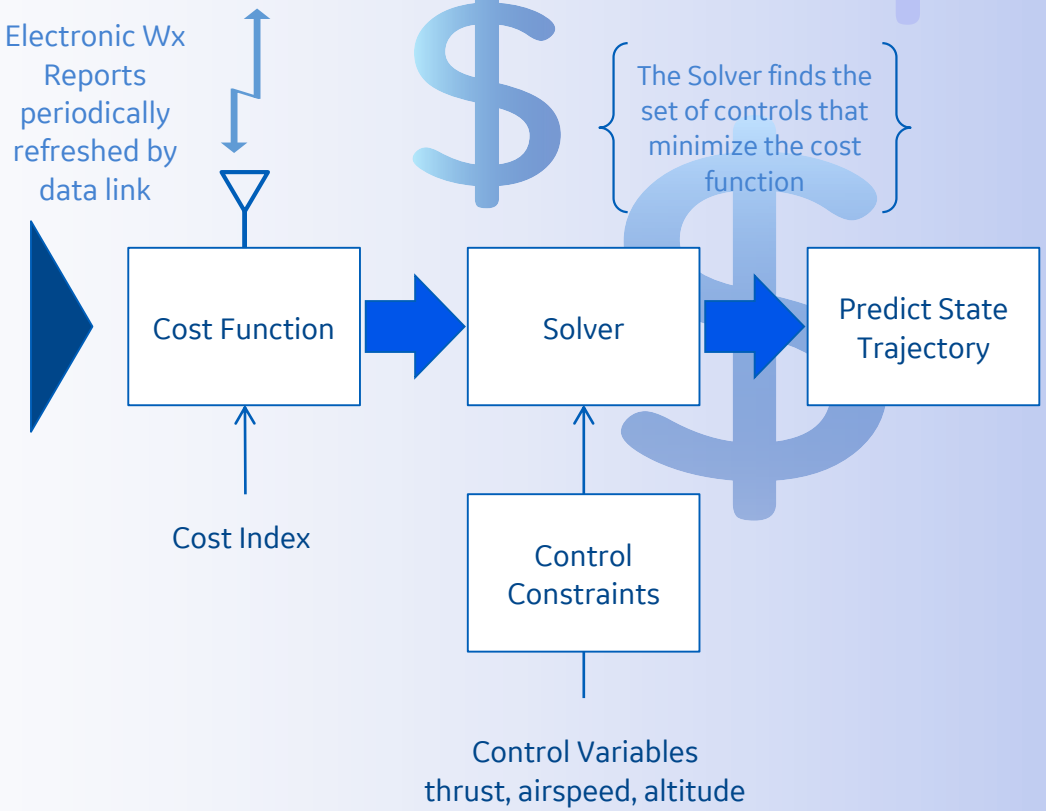
Utilizes a set of algorithms that create a cost function / prediction sequence to help determine the optimal flight path.



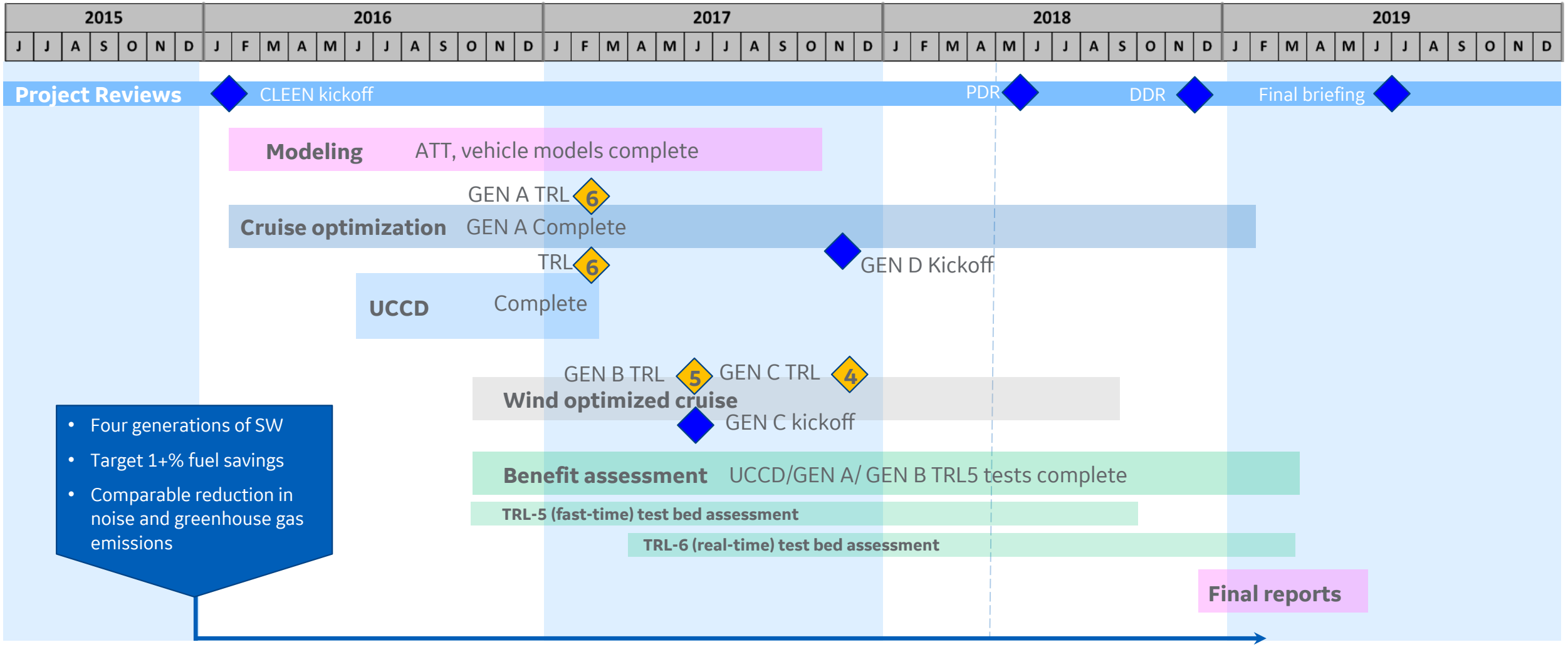
Cost-Optimal Flight Management







Project Schedule

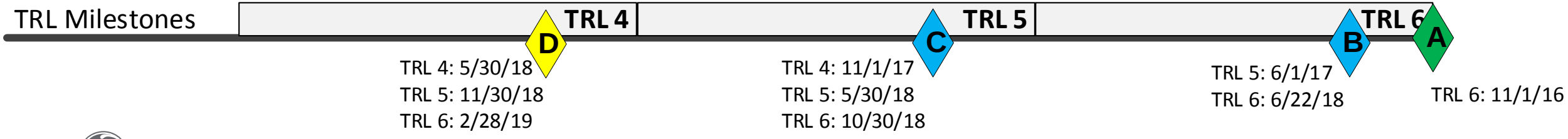


Past Achievements

Technology development activities continues to yield significant savings

Savings vs. Legacy	Gen B	Gen C	Gen D
Fleet-wide Mean	0.5%	0.7%	**1.4%**

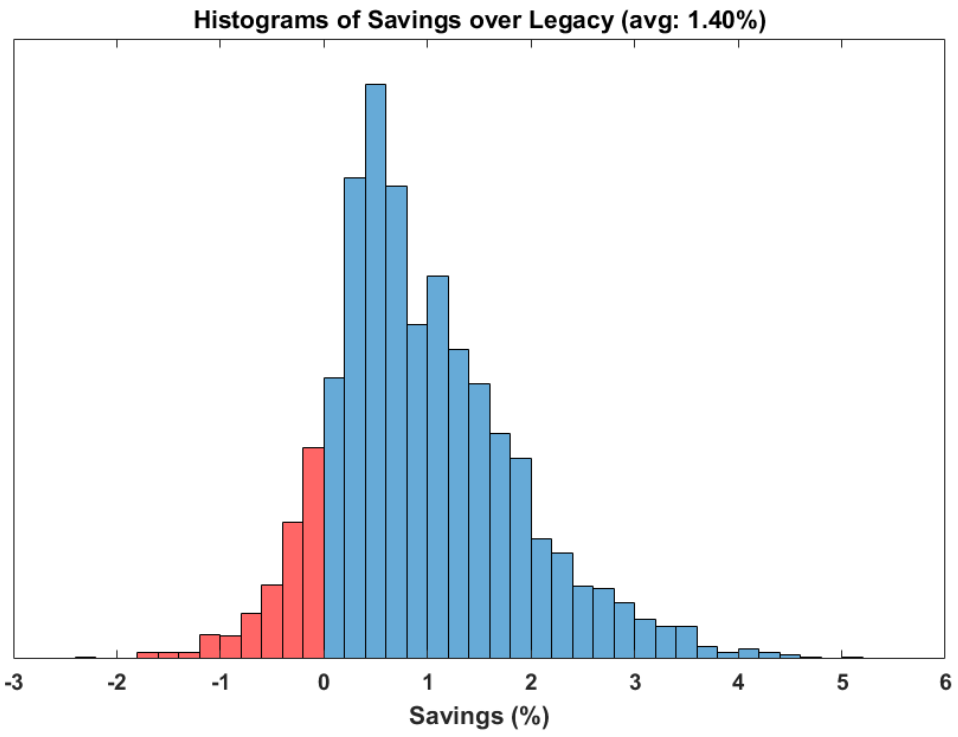
Technology maturation on track towards wide-scale EIS.



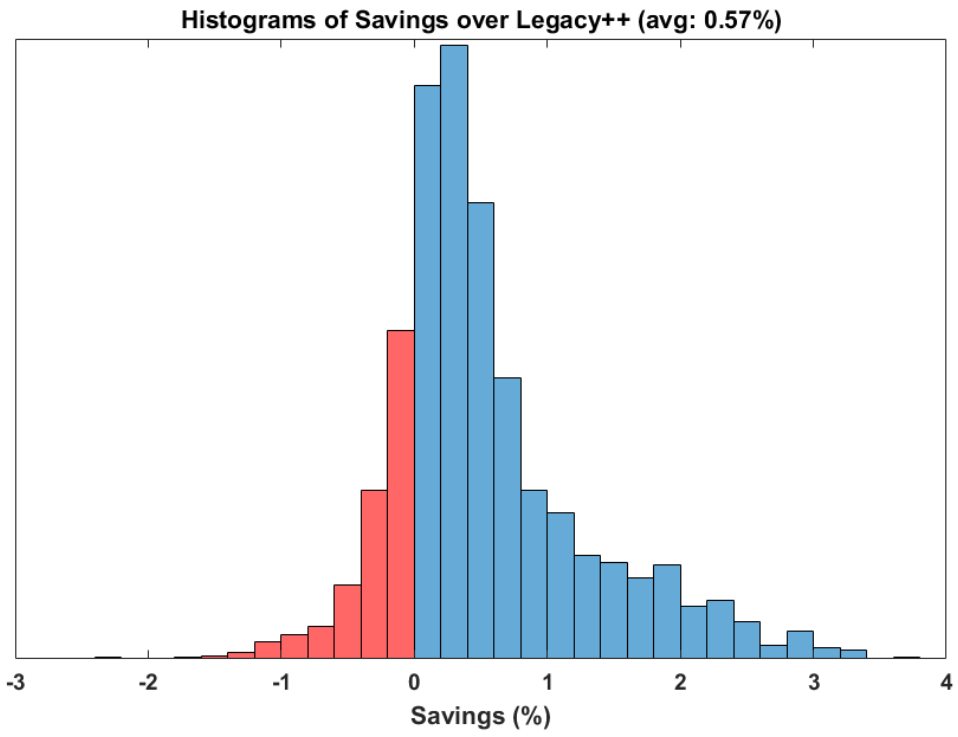
GEN D TRL 4 ⇨ $\Delta h_{Cruise} = f(weather, performance, RTA)$

Single-Aisle Transport

Up to 5% savings relative to Legacy (Constant Cruise Altitude)



Up to 3.5% savings relative to Legacy w/ AOC-Assisted Step Climb



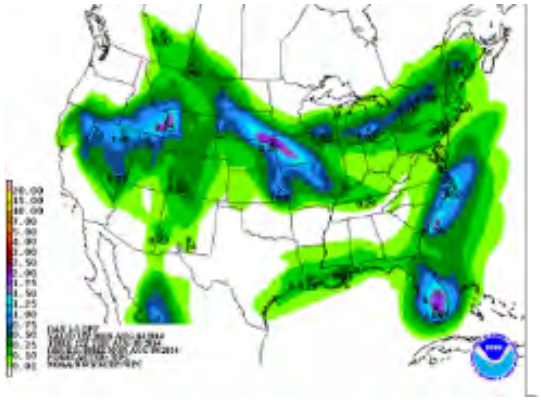
Most cases show benefit – negative cases will be mitigated through TRL 6+ implementation

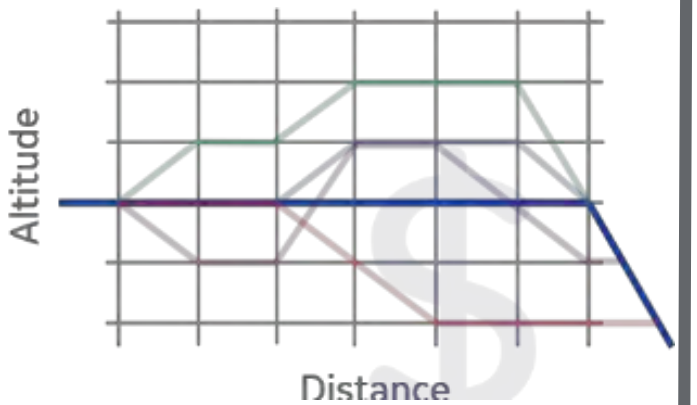
Future Plans

For the remainder of the project…

- **Confirm TRL4 results** at larger (fleet-wide) scale in GEN C and GEN D TRL5 benefit assessments
- Enable technology introduction through **TRL6 development** of GEN C and GEN D
- **Validate** that real-time TRL6 FMS and EFB software provides the anticipated benefits
- **Document** results and **demonstrate** the system

Project Technology





Anticipated Benefits:

- 0 – **5%** fuel savings relative to legacy FMS
- 0 – **3.5%** 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)	Nov 2016
• GEN B Hi Fidelity Weather (TRL 5)	Jun 2017
• GEN C Optimal Step (TRL 5)	May 2018*
• GEN D RTA Constrained (TRL 5)	Nov 2018*

*TRL 4 Benefit Assessments Complete

Schedule:

- PDR ⇨ 2nd Quarter 2018
- DDR ⇨ 4th Quarter 2018
- TRL 6 FMS & EFB prototype ⇨ 1st Quarter 2019
- Final Report ⇨ 2nd Quarter 2019

ADJUST FLIGHT PATH 45° NW

CLEEN II Consortium - Public Plenary Sustainable Alternative Fuels

Presenter: Gurhan Andac
Date: May 2, 2018

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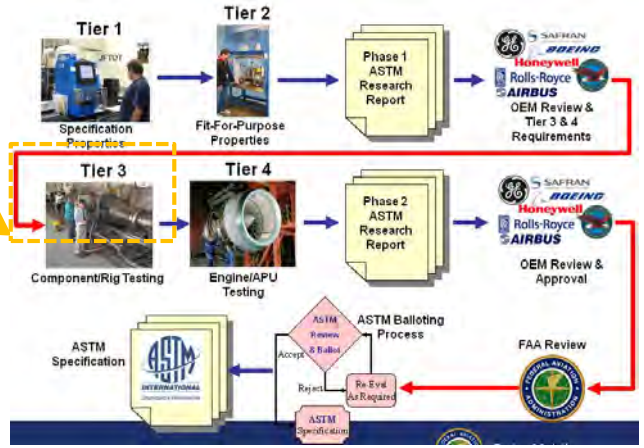
CLEEN II Sustainable Alternative Fuels:

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 evals
- 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:

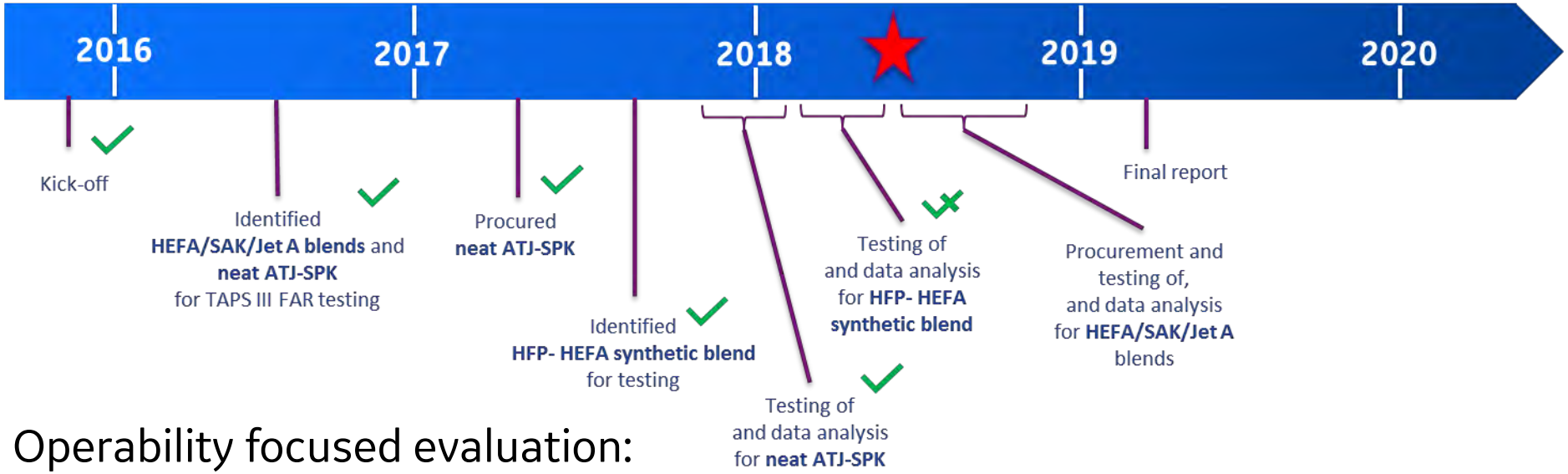
- Test two fuels, one fully synthetic and two blends, in ASTM roadmap – (FAR* test)
- Test one fuel defined by FAA's National Jet Fuel Combustion Program (NJFCP) – (FAR test)

*FAR: Full Annular Combustor Rig

Since November 2017 Consortium:

- NJFCP fuel (100% Gevo ATJ-SPK) testing completed. Results reported to NJFCP program. Effort publicly announced via press release.
- HFP-HEFA blend acquired from Neste Oil. Testing completed except sub-idle efficiency Jet A baseline tests.
- Virent HDO-SAK purchase completed - testing of SPK/SAK/Jet A blends TBD; pivoting test scope per ASTM report review

Schedule



Operability focused evaluation:

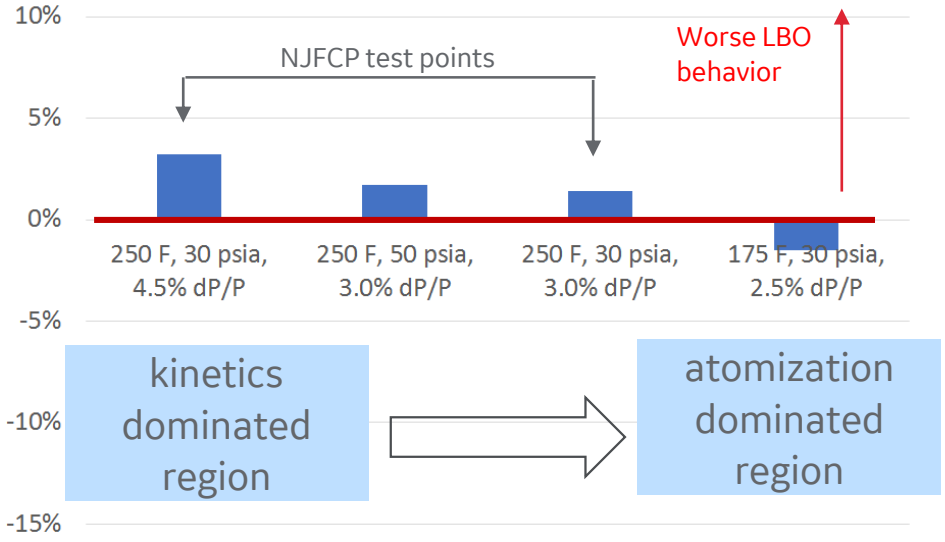
- ignition, blow-out, sub-idle efficiency

Program Objectives Status

Objective	Status
Supplement other FAA programs	Adequacy of NJFCP tools validated
Advance practical fuel approval #1	HFP-HEFA selected, testing almost complete
Advance practical fuel approval #2	HDO-SAK/Jet A blend selected, procurement in place
Advance fully synthetic fuels approvals	HDO-SAK/HEFA blend selected, procurement in place

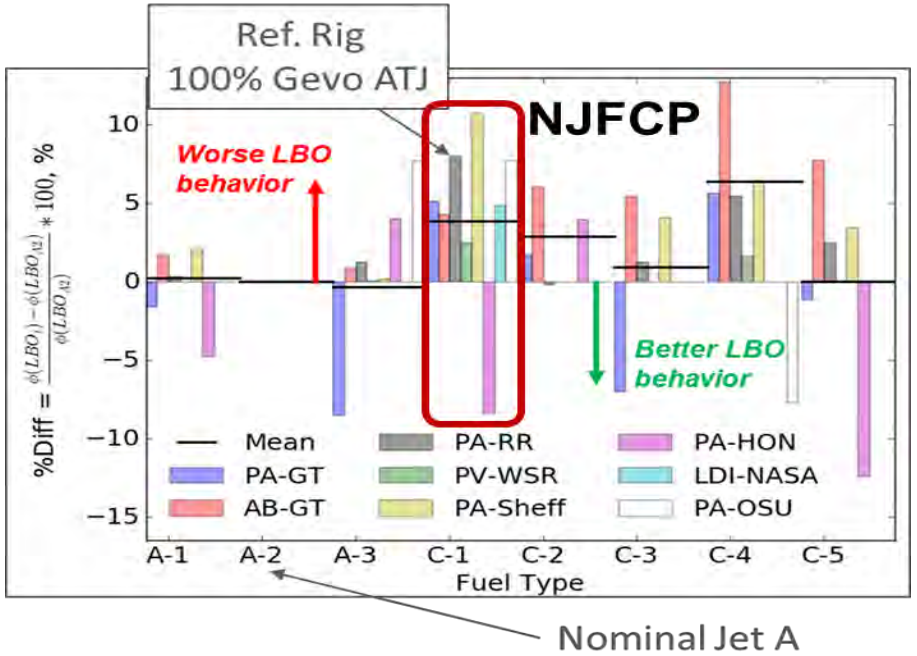
Neat (100%) ATJ-SPK Test Campaign
- Fuel *composition* and *property* impact on LBO

Neat ATJ-SPK is referred to as C1 in NJFCP



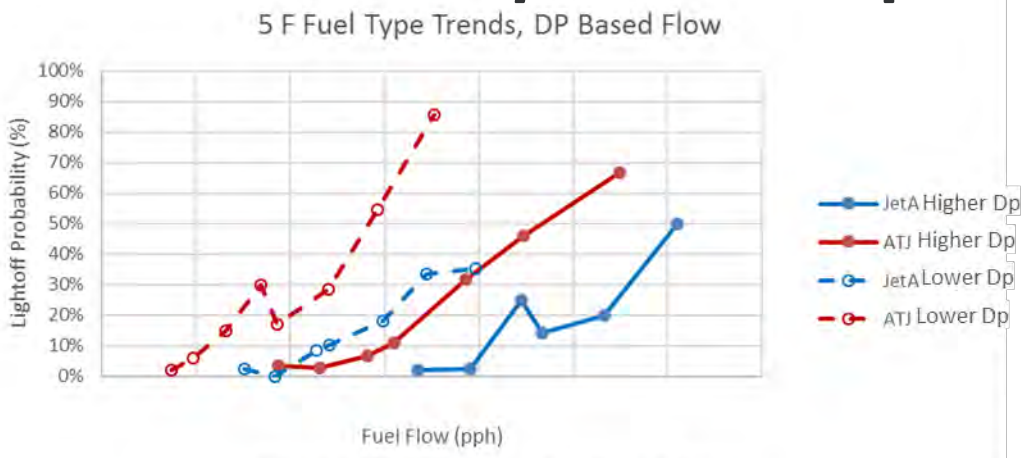
C1 fuel has negative impact on LBO performance in kinetics dominated region

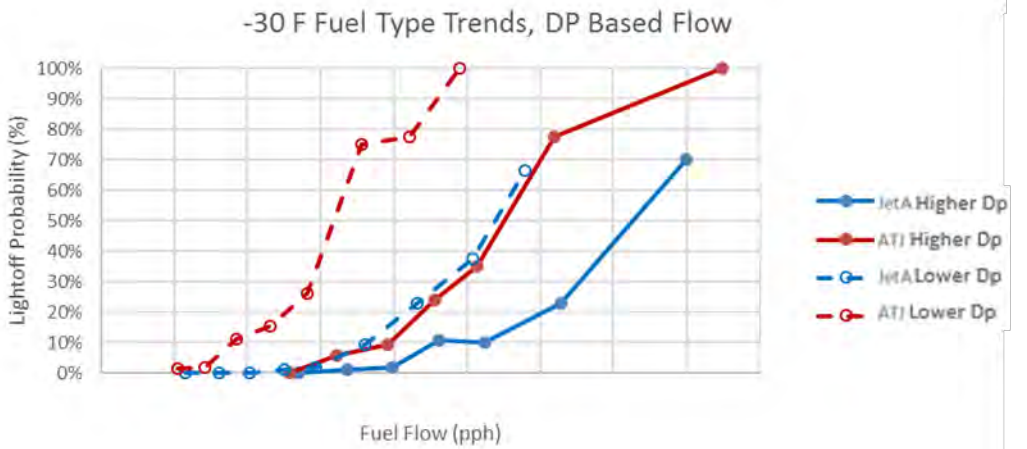
C1 fuel has positive impact on LBO performance in atomization dominated region – perhaps due to difference in distillation/volatility



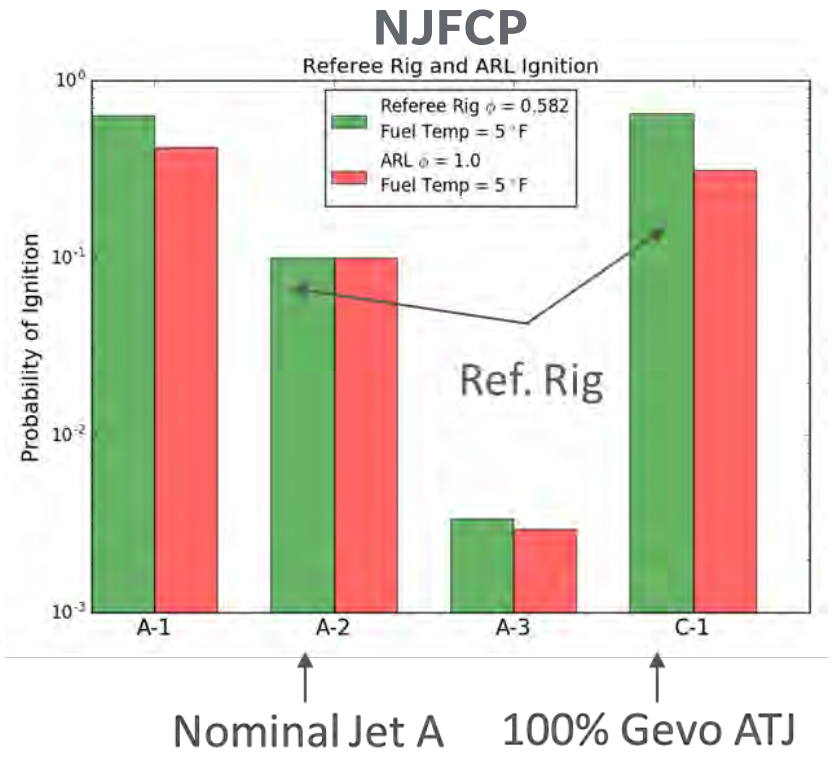
Consistent trend w/ NJFCP referee rig
<u>Lessons learned</u>: Fundamental and generic tests can duplicate full combustor LBO behavior. Such tools could be used for screening & evaluation. Kinetics and physical property sensitive regimes might yield to opposite behaviors/impacts.

Neat ATJ-SPK Test Campaign
- Fuel *composition* impact on ignition



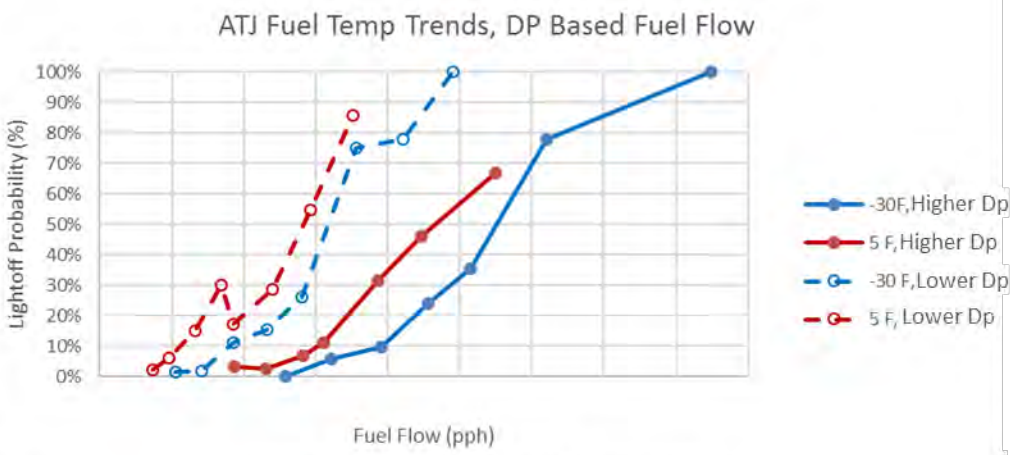


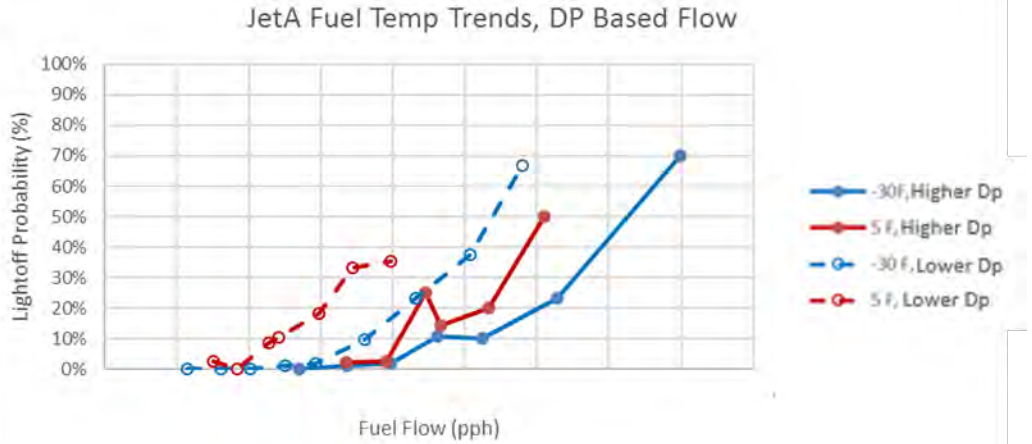
At similar flow rates, C1 fuel has a higher ignition probability than A2 fuel at all tested conditions



Consistent trend w/ NJFCP referee rig & past independent experience
<u>Lesson learned</u>: Fundamental and generic tests can duplicate full combustor ignition behavior. Such tools could be used for screening & evaluation.

Neat (100%) ATJ-SPK Test Campaign - Fuel *temperature* impact on ignition





At 5 °F, less flow is needed to achieve ignition than is required at -30 °F

- Jet A temperature sensitivity ~2x that of C1, ~17% vs ~9%

<u>Lesson learned</u>: Colder fuel temperatures are harder to ignite (expected). Ignition with C1 fuel is less sensitive to fuel temperature chilling than Jet A – distinct kerosene compositions might impact cold flow behavior

HFP-HEFA Blend Test Campaign

- High Freeze Point Hydroprocessed Esters and Fatty Acids (a.k.a. Green Diesel) blend from Neste Oil of Finland
- 16% HFP-HEFA/84% Jet A-1
- Going through ASTM approval – OEMs felt the need to conduct additional rig testing out of ASTM D4054 Phase I review – *results to support the approval*
- Testing almost complete – data processing in progress

Test Description	
Operability	
Start Testing, Cold Fuel	✓
Start Testing, Nominal Fuel	✓
LBO Testing, Nominal and Heated Fuel	✓
Start Testing, Nominal Fuel, Above Ambient/HPFC*	✓
Sub-Idle Efficiency, Nom Fuel, Repeat with Jet A	✗

***HPFC: High Power Fuel Cut**

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*
- HDO-SAK purchase complete; fuel production close to completion
- 25% aromatic blends with HEFA-SPK & Jet A provided by USAF
- Testing time TBD; targeting this year
- Test matrix is to be a sub-set of previous ones

Opportunity Cost

Very competitive market with demanding, educated customer base

- Fuel burn –---> business case
- Emissions and Noise ---> regulatory requirements

Without FAA support….tenuous technology business case
Delay/suppress technology advancement and competitiveness
Alternate resources….international funding (Europe, China) that exposes IP and impacts job opportunities