CLEEN II Consortium Program Update – Public Plenary GE Aviation

November 15, 2017

Approved for Public Use

MESTANG Dayton, Ohio

Flight Management Systems Grand Rapids, Michigan

TAPS Combustor / Alternative Fuels Cincinnati, Ohio

CLEEN II Technologies Summary

CLEEN Technology Name	Goal Impact	Benefits and Application
Alternative Fuels	Alternative Fuels	Full Annular Rig (FAR) test to support approval & insertion of alternative fuels; focus on operability (Lightoff, LBO) impacts • NJFCP fuel (100% Gevo ATJ-SPK); 100% synthetic (HEFA SPK + Virent SAK)); HFP-HEFA blend
MESTANG	Fuel burn	3% benefit for single-aisle aircraft [aircraft or engine size class] with expected entry into service by [year].
FMS	Fuel burn	1% benefit
TAPS III – Technology Program	Emissions	35% reduction relative to CAEP/8 (55 OPR) Technology applicable to GE9X engine / 777X aircraft

CLEEN II Technologies Summary

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

Satish Prabhakaran

MESTANG Overview

Silicon Carbide Secondary Power

DC Generator

DC Breaker

Next Gen DC Power System

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

Project objectives:

- Retire risk for ±270 VDC solid state power system
- Technologies for 600 kW power system
- Demonstrate all-SiC power system
- TRL 6 power system by 2019-20 at EPISCENTER

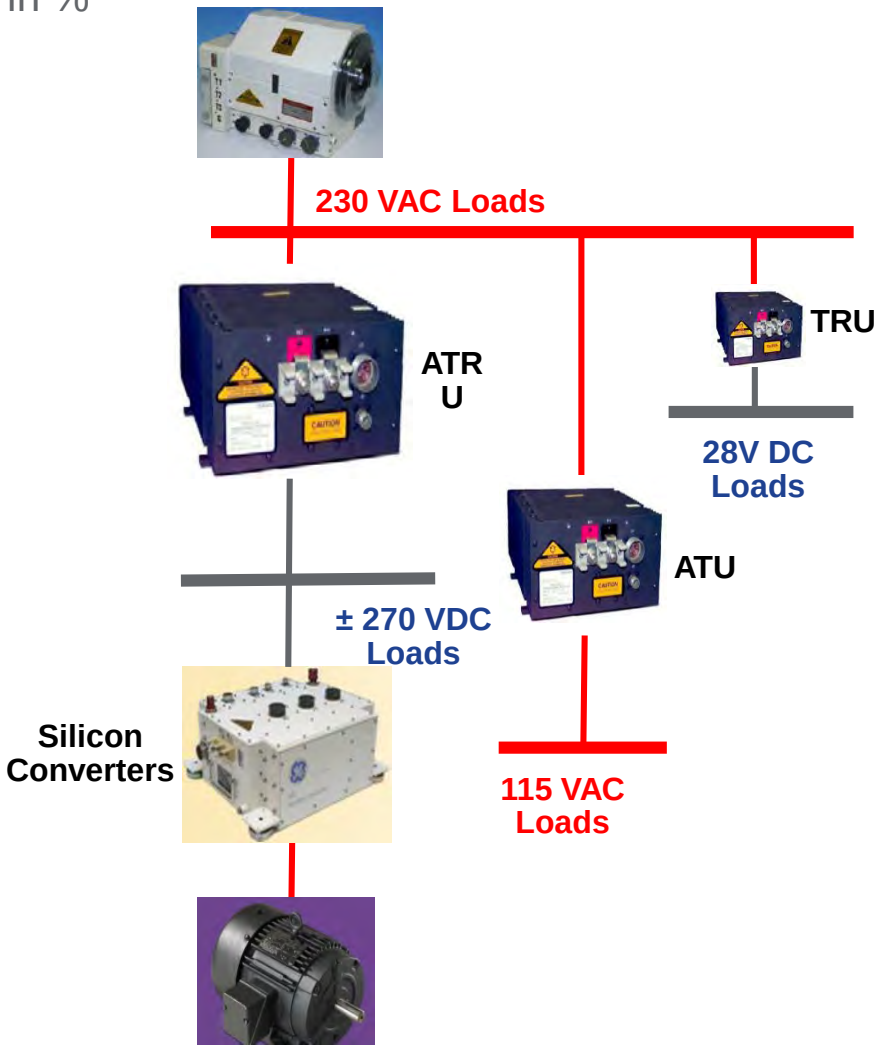
Customer Outcomes:

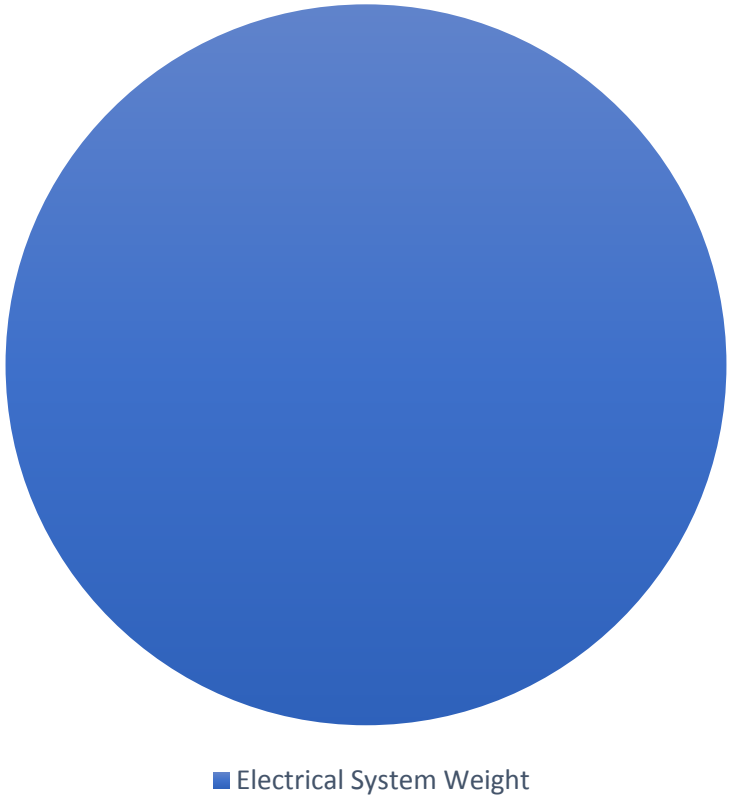
More Electric Systems and Technologies for Aircraft in the Next Generation (MESTANG), is an integrated aircraft power system designed to support future "more-electric" aircraft architectures that reduce fuel burn by up to 3 percent for single-aisle aircraft while improving performance at equivalent cost

Aircraft level trade studies defined technical approach

Conventional MEA - AC Distribution System with Silicon

Weight in %

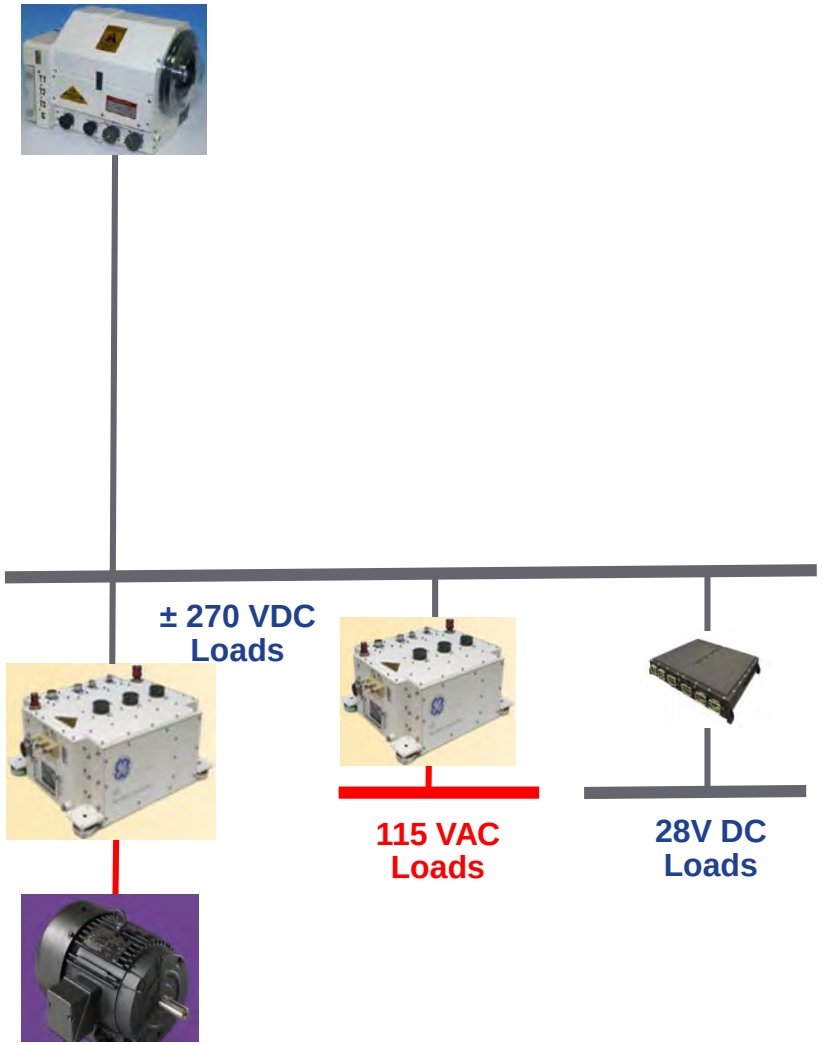




High Power AC Generators
High Power Silicon Converters
Passive Transformer Rectifier Units

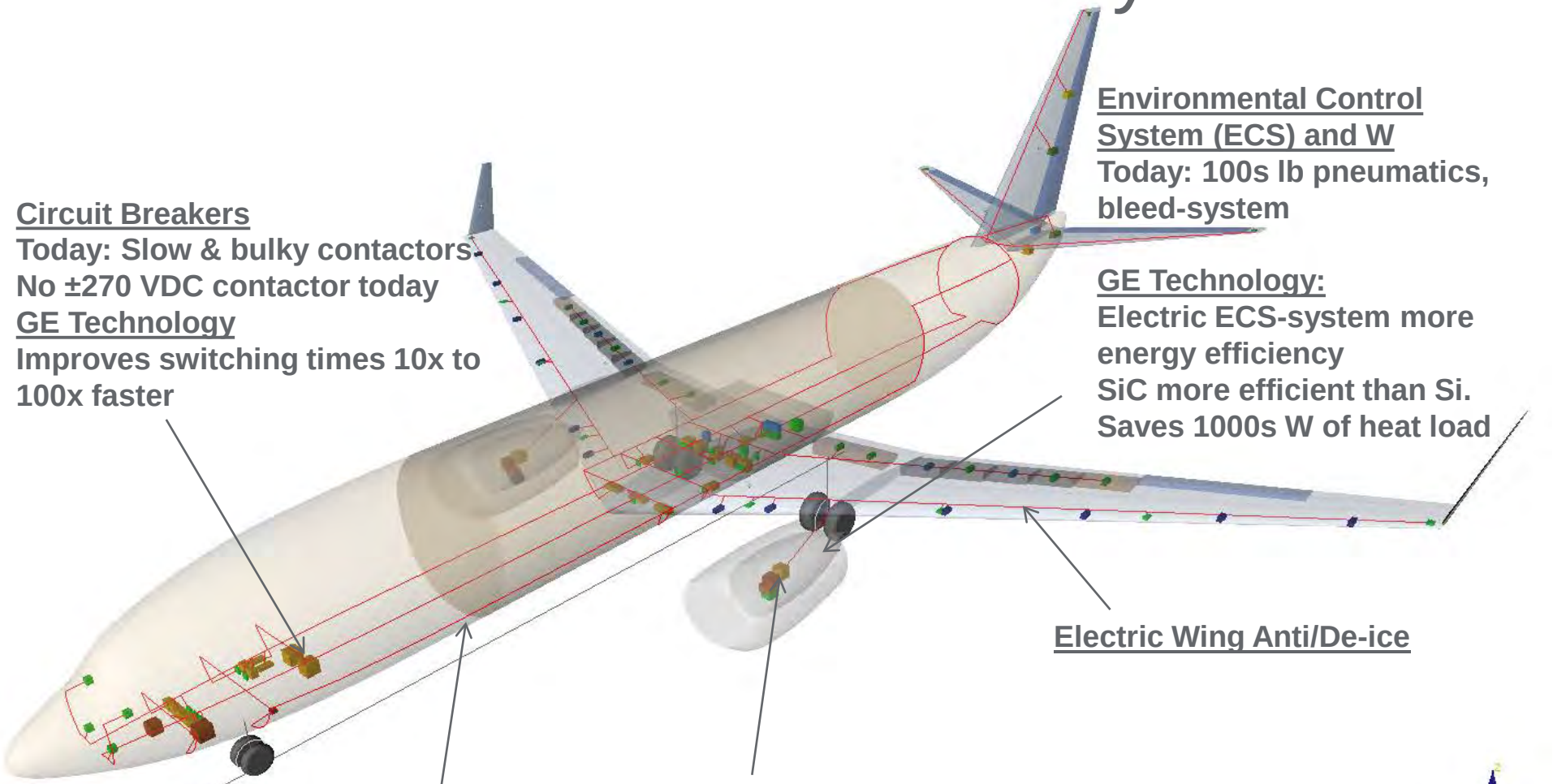
GE - DC Distribution System using Silicon Carbide

Weights in %



Advanced High Power AC Generators
Lighter, More Efficient Silicon Carbide Converters
All Active Power Conversion
DC Distribution

GE Silicon-carbide based MEA System



Environmental Control System (ECS) and W
Today: 100s lb pneumatics, bleed-system

GE Technology:
Electric ECS-system more energy efficiency
SiC more efficient than Si.
Saves 1000s W of heat load

Circuit Breakers
Today: Slow & bulky contactors
No ±270 VDC contactor today
GE Technology
Improves switching times 10x to 100x faster

Electric Wing Anti/De-ice

Direct +/-270VDC distribution
Today: Heavy TRU/28V cable
GE Technology
±270 VDC to 28 V Power Electronics
Saves 100s lbs

DC generator
Today: 100s lbs of AC-DC ATRU
GE Technology
Advanced generator rectifier system
Saves 1000s W heat load
Saves 100s lbs

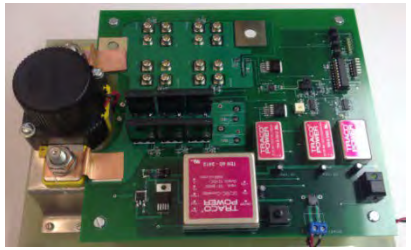
Key Technologies for Future MEA Application

DC Generation

±270 VDC Starter generators with Integrated Electronics

2x Lighter

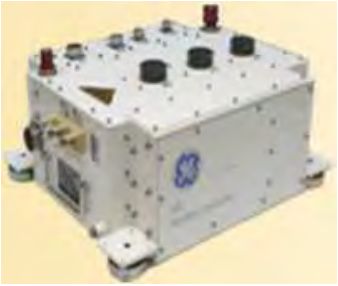
DC Distribution



±270 VDC Circuit Breakers with Arc-free Galvanic Isolation

10x Faster

DC-DC/ DC-AC Conversion



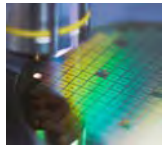
Silicon Carbide Converters ±270 VDC to 28 VDC ±270 VDC to 115/230 VAC

2x Lighter
2x Lower Loss

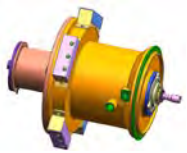
Accomplishments

- Performing Aircraft + Engine + Power System Assessments
- GE Maturing TRL6, ±270VDC System in CLEEN2
- Designed for Off-ramp Derivatives of Components/Architectures
- Systems integration at EPISCenter, Dayton, Ohio, 2019-2020

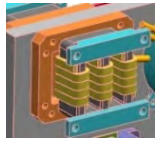
Fabricated GE Gen3 SiC



Completed Generator Prelim



Design for EMI



Brass-board Converter

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

Component Tests 2018-19

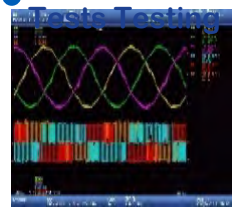
System Demonstration 2020

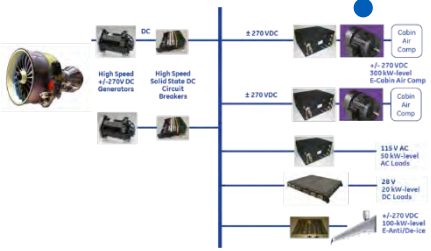
Passed PDR

DDR

Manufactured ±270 VDC Silicon Carbide Modules

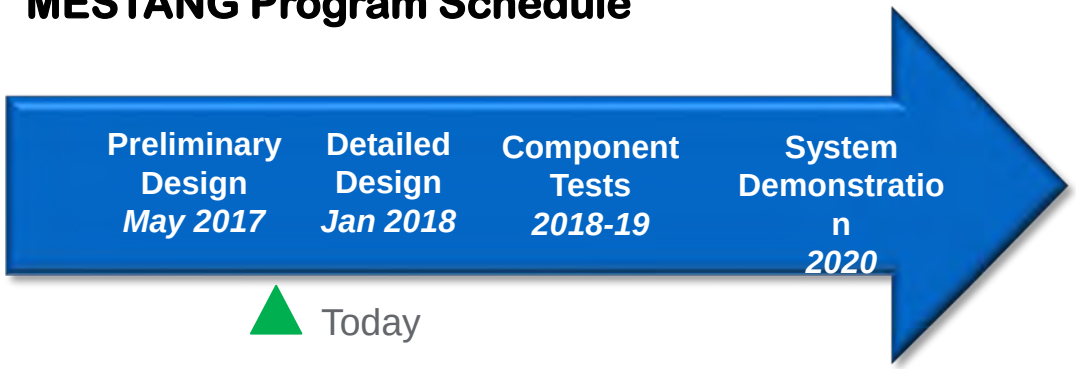
Powered Converter Tests Testing





Summary

MESTANG Program Schedule



Benefits:

- Light-weight +/- 270VDC power system to realize practical fuel savings and/or mission capability
- 600kW – 1MW power system
- Demonstration all-SiC power system
- TRL6 Level System by 2019-2020 at EPISCENTER
- Subsystems certifiable for retrofits before 2026

Objectives:

Mature an integrated aircraft power system consisting of a bleedless, dual-spool engine, and a second-generation more-electric primary power system

Customer Outcome:

- Up to 3% Fuel Savings in Single-Aisle A/C Family
- GE Power System with improved performance at equivalent cost

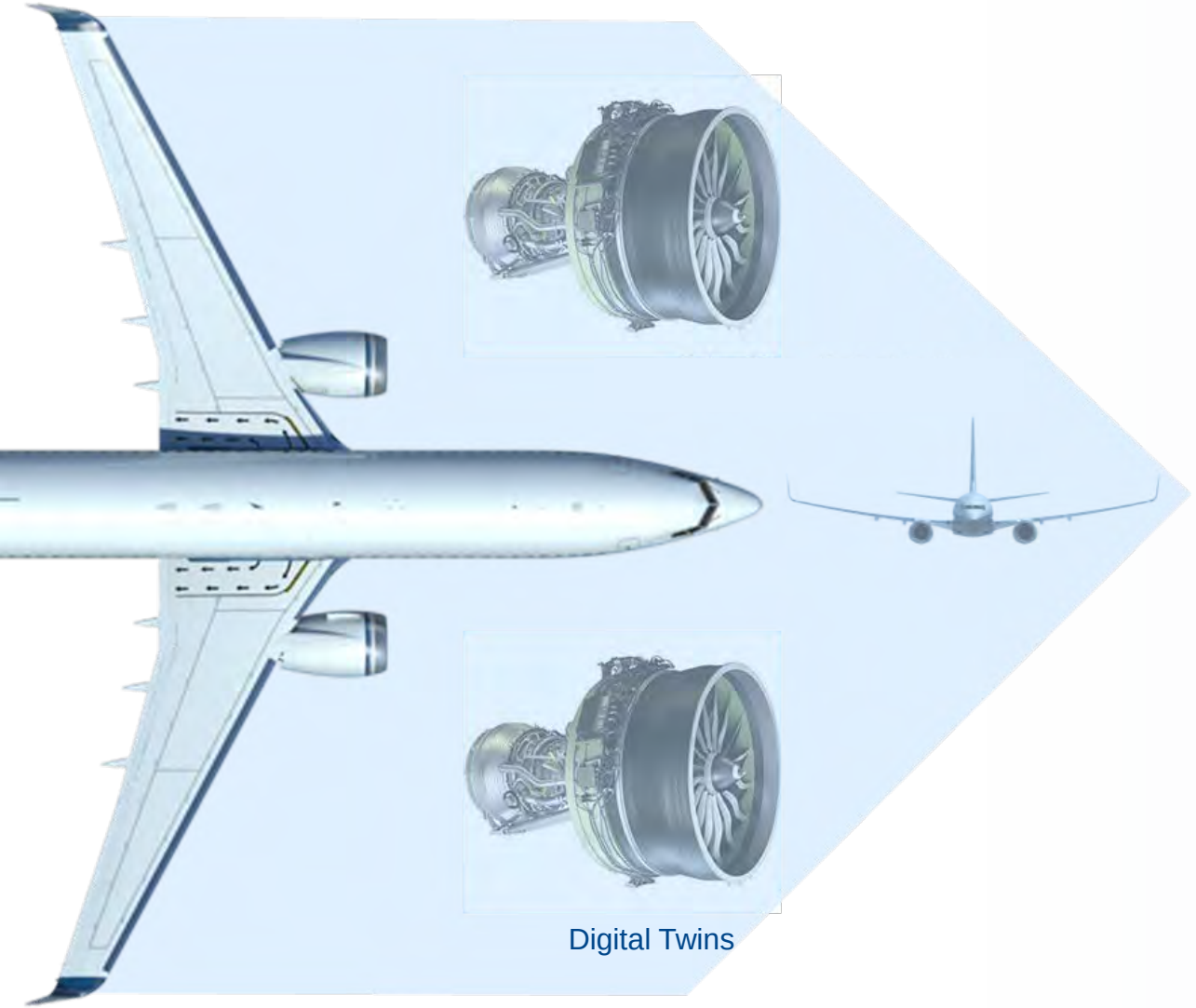
Key CLEEN II Accomplishments:

- Completed Preliminary Designs:
  - Generators
  - Motor Controllers
  - DC Circuit Breaker
- Performed Concept demos
- Completed PDR on May 01, 2017 – detailed design underway

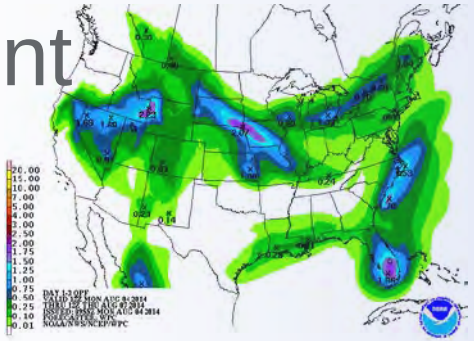
Flight Management Systems

Mark Darnell

Cost-Optimal Flight Management



Digital Twins



Electronic Wx Reports periodically refreshed by data link

The Solver finds the set of controls that minimize the cost function

Cost Function → Solver → Predict State Trajectory

Cost Index

Control Constraints

Control Variables
thrust, airspeed, altitude

Flight Management System Technology Areas

GEN A
- Optimum cruise altitude

UCCD
- Optimum climb, cruise, descent

GEN B
- UCCD with high-resolution weather

GEN C
- GEN C with variable cruise altitude

GEN D
- GEN D constrained by RTA

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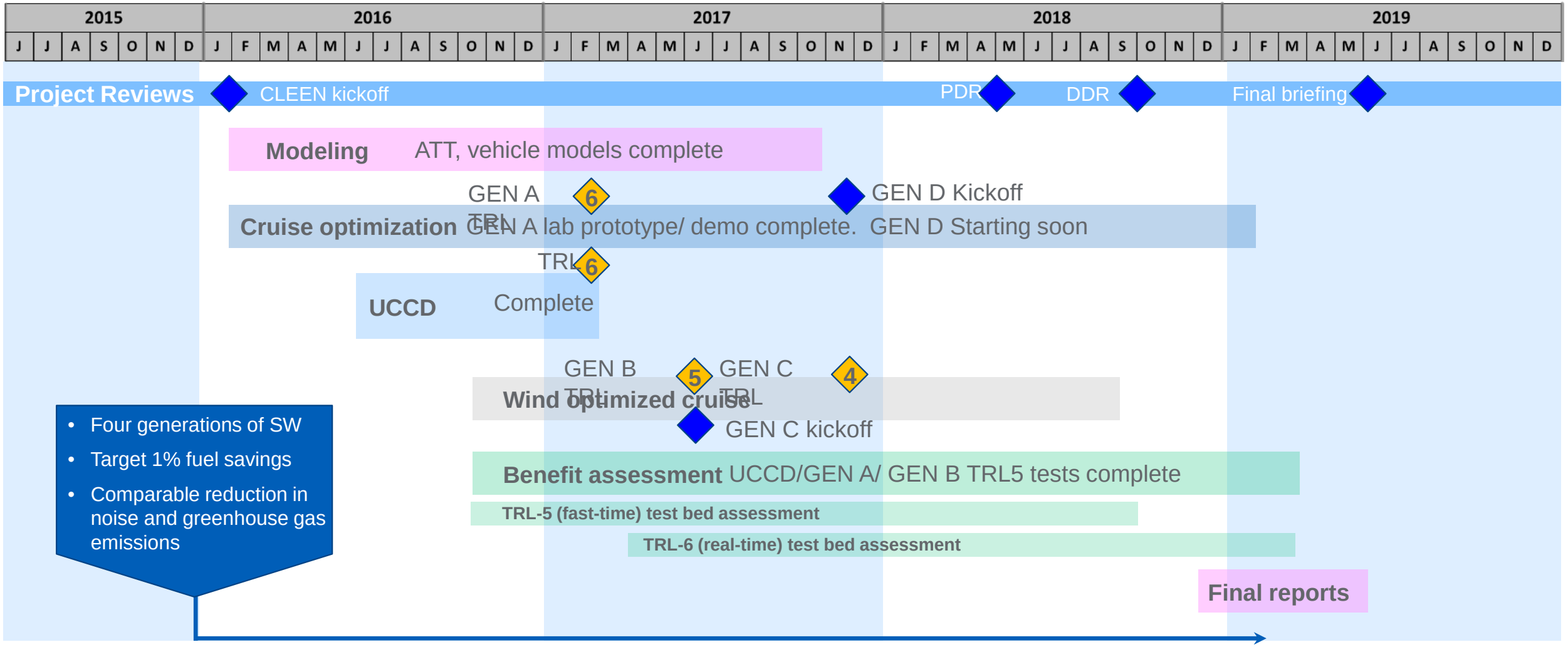
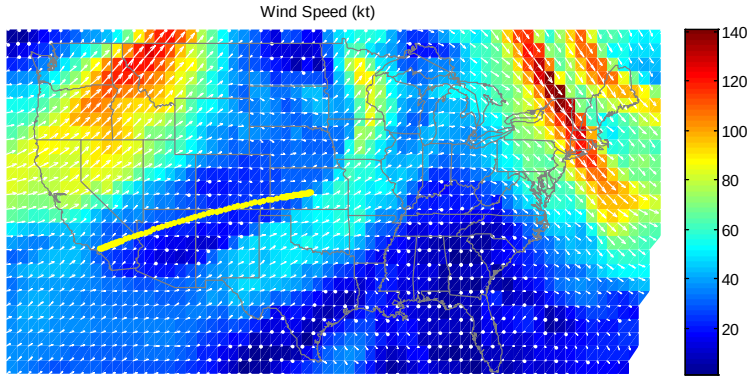
CLEEN II Project Plan

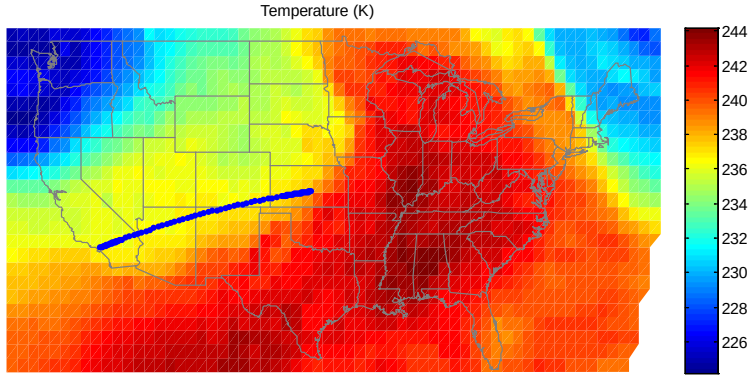


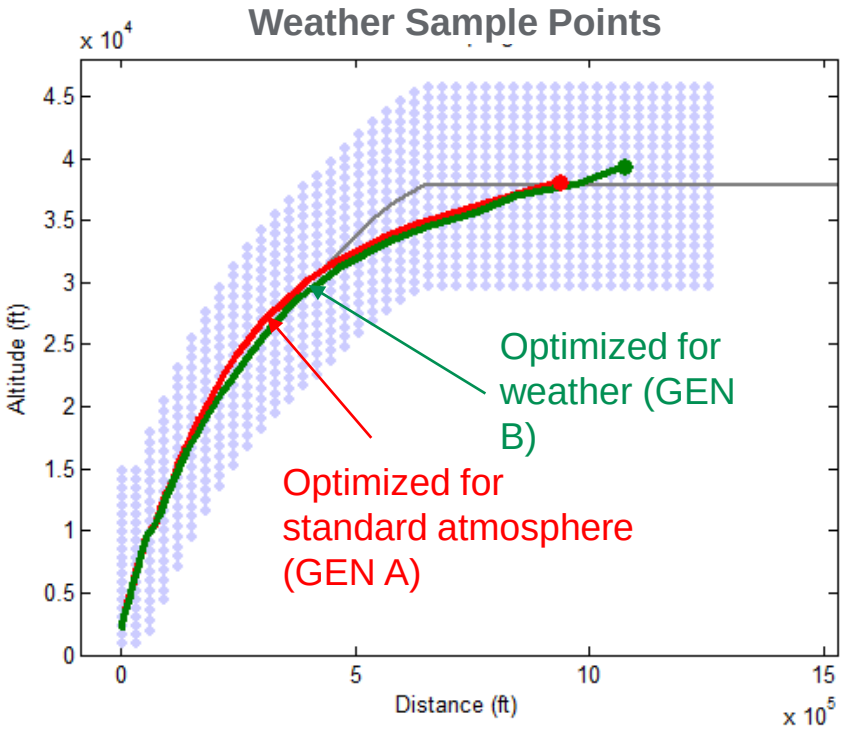
Accomplishments – Generation B

High-Resolution Weather Model

Project 4-D weather along a corridor that bounds the route of light, and thereby extend the range of the admissible control







Combined cost-optimal UCCD with high-resolution weather model

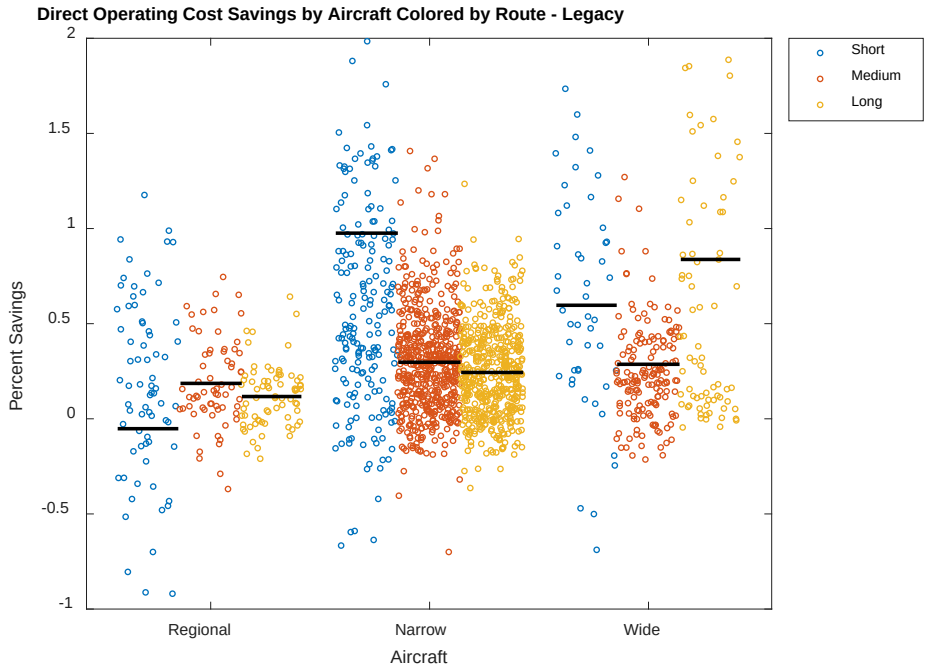
Modified solver accounts for non-convex cost function

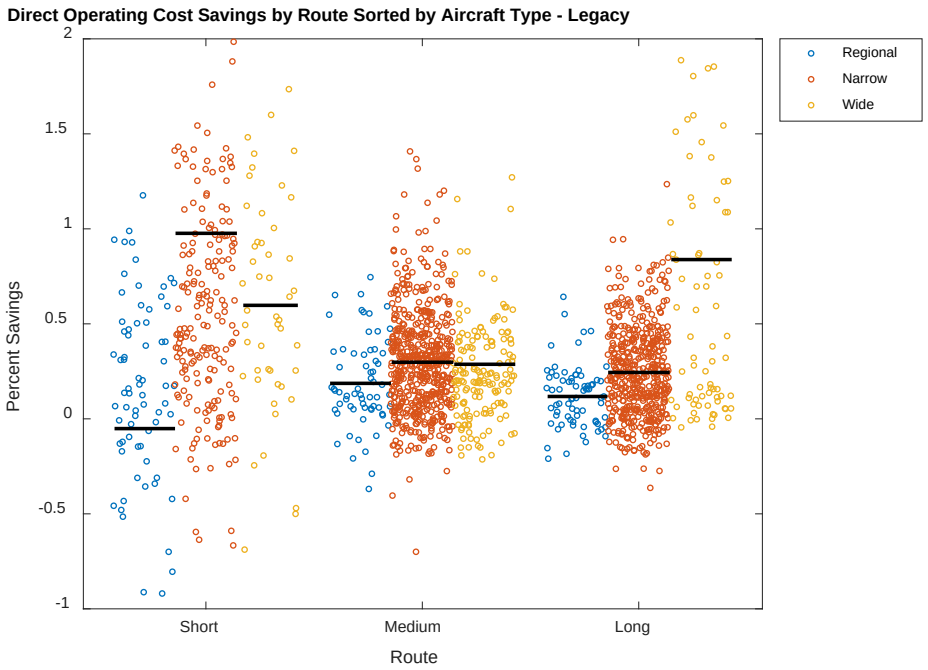
Modified solver includes operational constraints, which precludes inadmissible controls

GEN B TRL 5 – Breakout by AC Type and Route

Narrow Body and Wide Body transports realize greater savings than Regional Jet

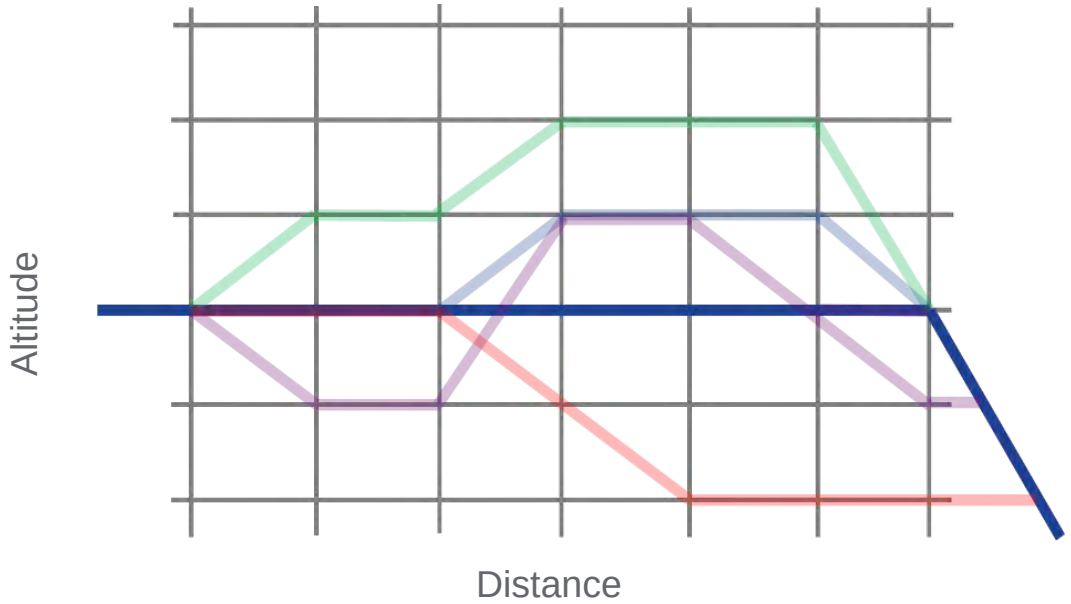
Short and Long routes yield greater benefit due to optimal climb and cruise altitude





Achievements – Generation C Software

- Step-change in cruise altitude as a function of weather and vehicle performance
- Combined with cost-optimal climb, cruise, descent (UCCD)

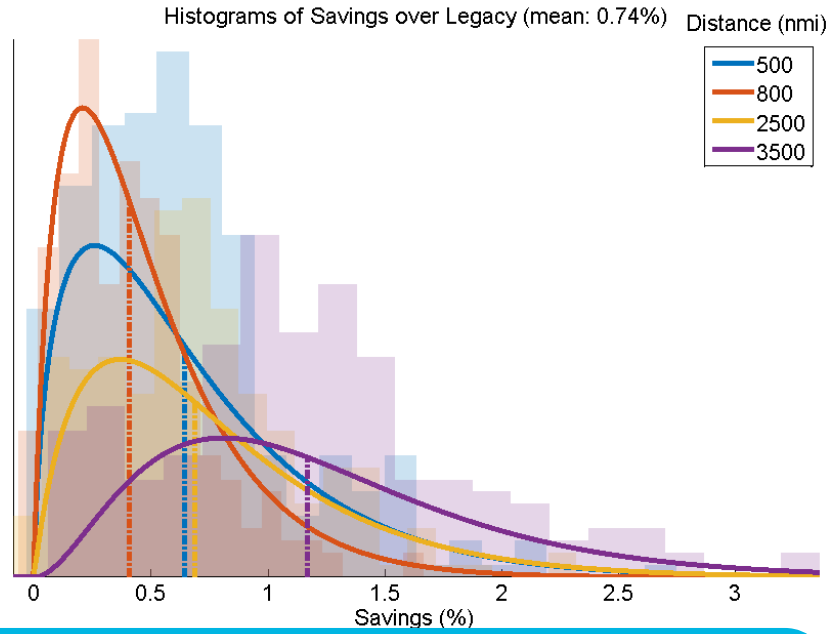


GEN C TRL 4 ⇨ $\Delta h_{Cruise} = f(weather, performance)$

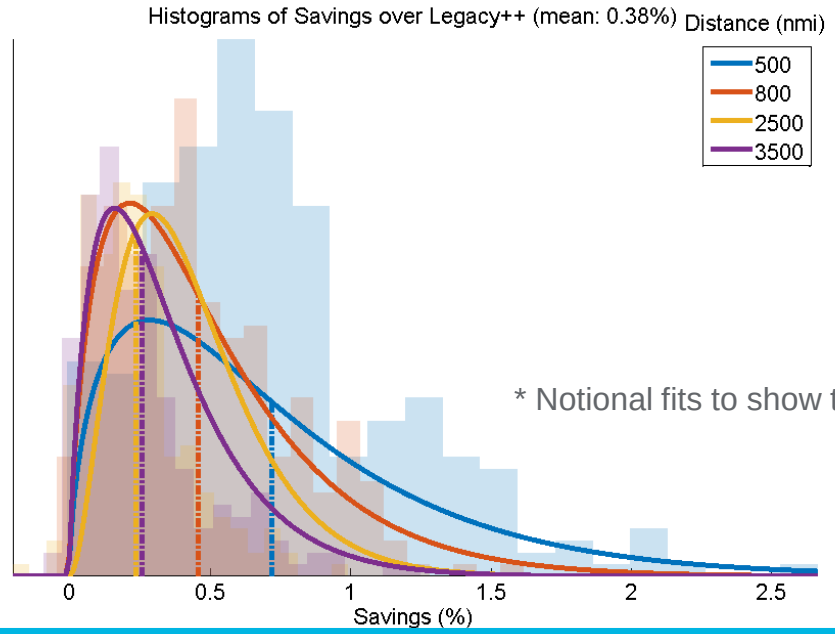
Single-Aisle Transport

0 – 3.5% savings relative to Legacy (Constant Cruise Altitude)

0 – 2% savings relative to Legacy w/ AOC-Assisted Step Climb



Savings increase with distance ⇨ cruise steps dominate



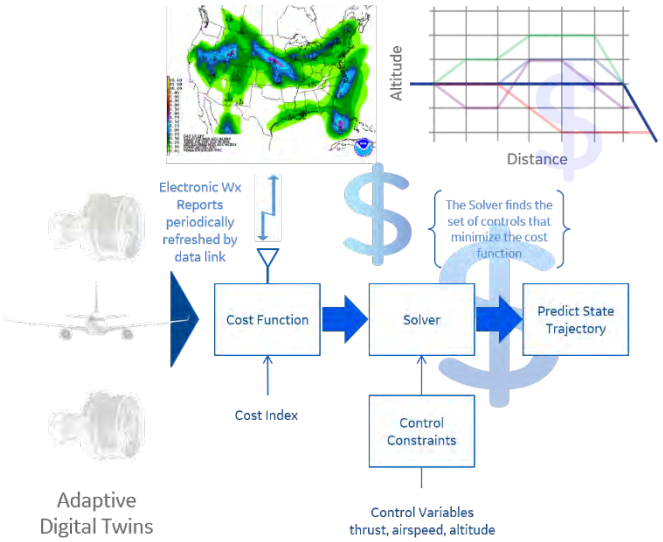
* Notional fits to show trends

Savings decrease with distance ⇨ climb phase dominates

Future Plans

- Assess benefit of TRL 5 GEN C prototype ⇨ Underway
- Design of GEN D software ⇨ Underway
  Admissible control constrained to arrive at user-specified times assigned to waypoints
- Testing TRL 6 GEN C FMS and EFB prototypes ⇨ Underway

Project Technology



Anticipated Benefits:

- 0 – **3.5**% fuel savings relative to legacy FMS
- 0 – **2**% 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:

- Fast-time Advanced Technology Testbed
- Assessed benefit of TRL 5 UCCD, GEN A, GEN B
- Assessed benefit of TRL 4 GEN C
- Assessment of TRL 5 GEN C underway
- Development of GEN D underway
- Development of TRL 6 EFB and FMS underway

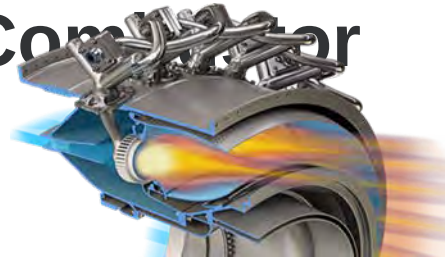
Schedule:

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

TAPS III Combustor Sustainable Alternative Fuels

John Herbon
Gurhan Andac

TAPS III – Tech Program Combustor



- Higher pressure
- Reduced cooling flow
- Advanced materials

CLEEN II:

- Improved premixer for <CAEP/12 NOx target
- Advanced modeling/design tools
- TRL6 Core Demo of emissions/performance

Benefits:

- GE9X projected SFC ~10% below GE90-115B
- LTO NOx >35% margin to CAEP/8 @ 55 OPR
- Mission cruise NOx reduction below SOA
- Low-NOx technology for application in highest OPR/largest engines; design tools/methods for scaling to future applications and engine cycles

Risks / Mitigation Plans:

- Combustor operability and/or durability issues can prevent optimal emissions
  - Develop multiple concepts & test/down-select; Develop advanced modeling capabilities for accurate, early insight

Objectives:

Advance the development of next-generation low-NOx TAPS III combustor to TRL6

Work Statement:

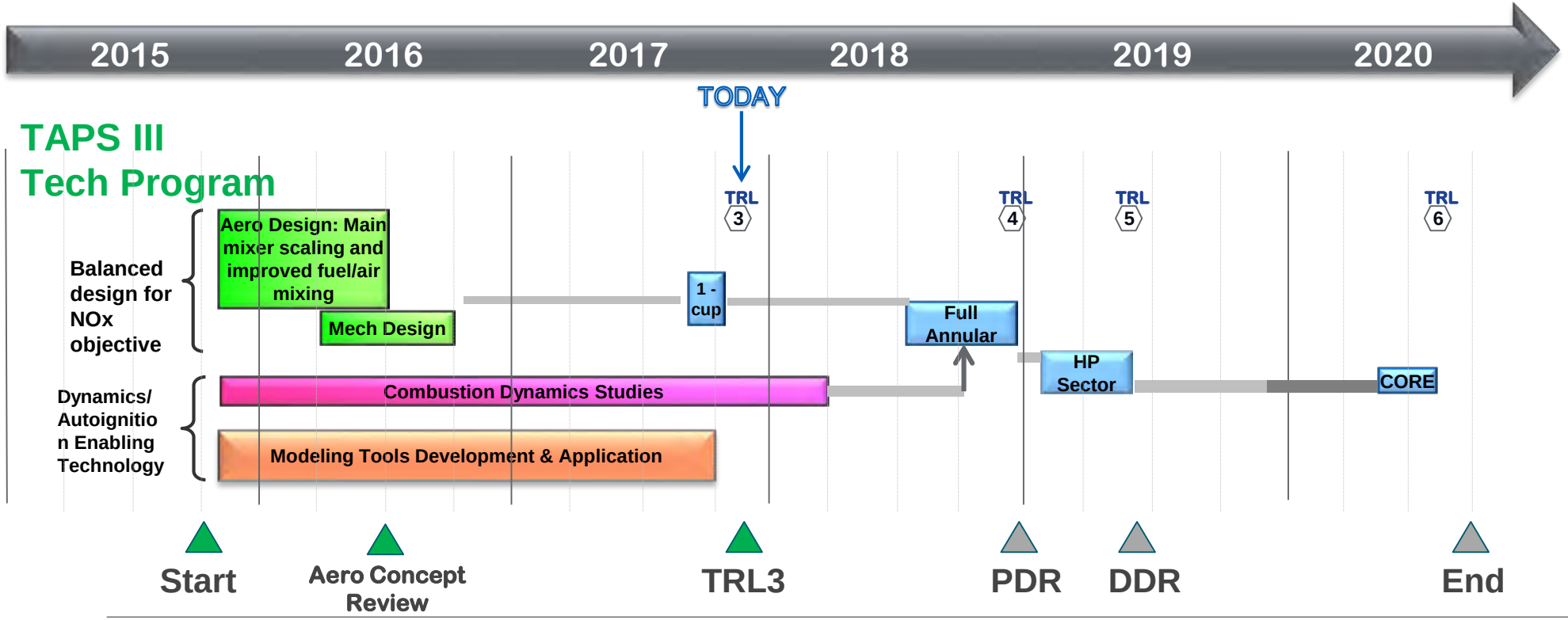
- Establish baseline NOx / performance
- Develop technologies: Fuel injection, aerodynamic mixing, modeling tools
- Staged advancement to TRL6 via rigs & core engine demonstration

CLEEN II Accomplishments (* since May 2017):

- 3 adv. premixer architectures conceived & modeled
  - 2 architectures released for mfg (8/2016)
- Initial configuration completed testing in single cup, HP sector, FAR1C and FAR2A: P4' mapping, emissions, L/O & LBO, cruise efficiency (6/2017)
- Combustion dynamics models developed & validated against rig data (4/2017)
- *Analytical screening (pre-test predictions) of alternate concepts completed (8/2017)
- *Screening tests for P4', emissions; TRL review (11/2017)

CLEEN II / TAPS III – Technology Program Goals & Schedule

- LTO NOx emissions (FAA Goal) 35% margin to CAEP/8 @ 55 OPR
- Cruise NOx emissions (GE Goal) < SOA
- Solid Particulate Matter (GE Goal) 60% margin to CAEP/6 (based on Smoke no.)
- Combustor Durability (GE Goal) Increased TOW



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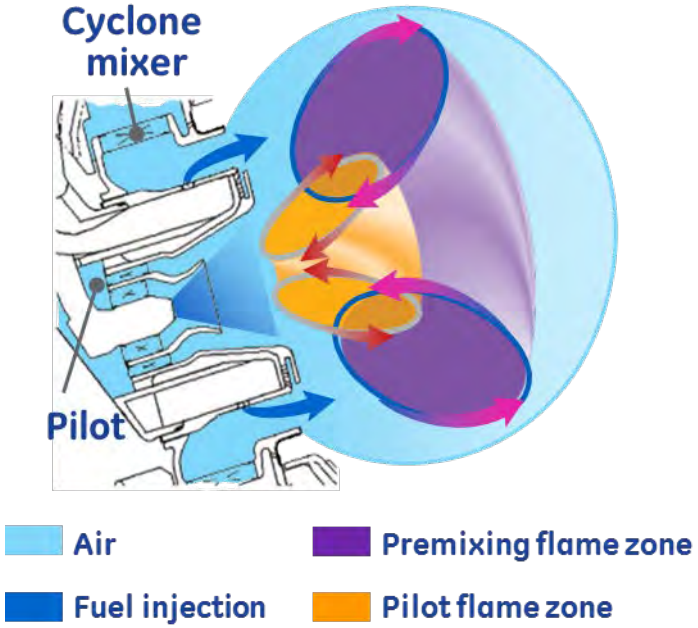
TAPS (Twin Annular Premixing Swirler) Architecture

- Twin annular flames
  - Staged combustion within mixer
  - Lean-premixed fuel/air mixture in main swirler for reduced NOx at high power
  - Central pilot for good operability and low CO/HC at low power
  - Greater NOx Reduction at Cruise



- CLEEN II / TAPS III – Technology Program
  - Advances mixer aero and fuel injection designs to achieve CLEEN low emissions targets in highest OPR / large engine cycle

Pilot Only

Pilot + Main

Nozzle sprays shown without air flow
(or cyclone mixer)

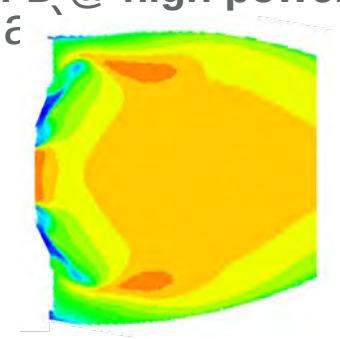
TAPS III – Technology Program: Concept screening to TRL3

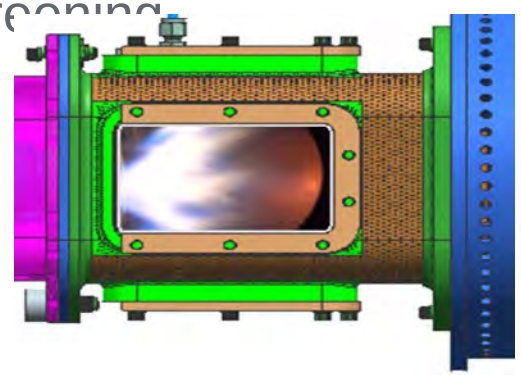
Over the last 18 months:

- Tested initial concept in high TRL rigs (Single Cup, High Pressure Sector, and Full Annula
- Designed & analyzed multiple alternate concepts to meet CLEEN II NOx targets
- Down-selected to a few configurations and released for trial manufacturing
- Fuel nozzles and mixers for Concepts B and D screened in single-cup rig @ GRC (sub-cruise)
- Concept C configuration fuel nozzle and mixer hardware built for high power screening
- Single cup tests executed, and TRL review completed

Next step: down-select and HW release for Full Annular Rig test

CFD @ high power

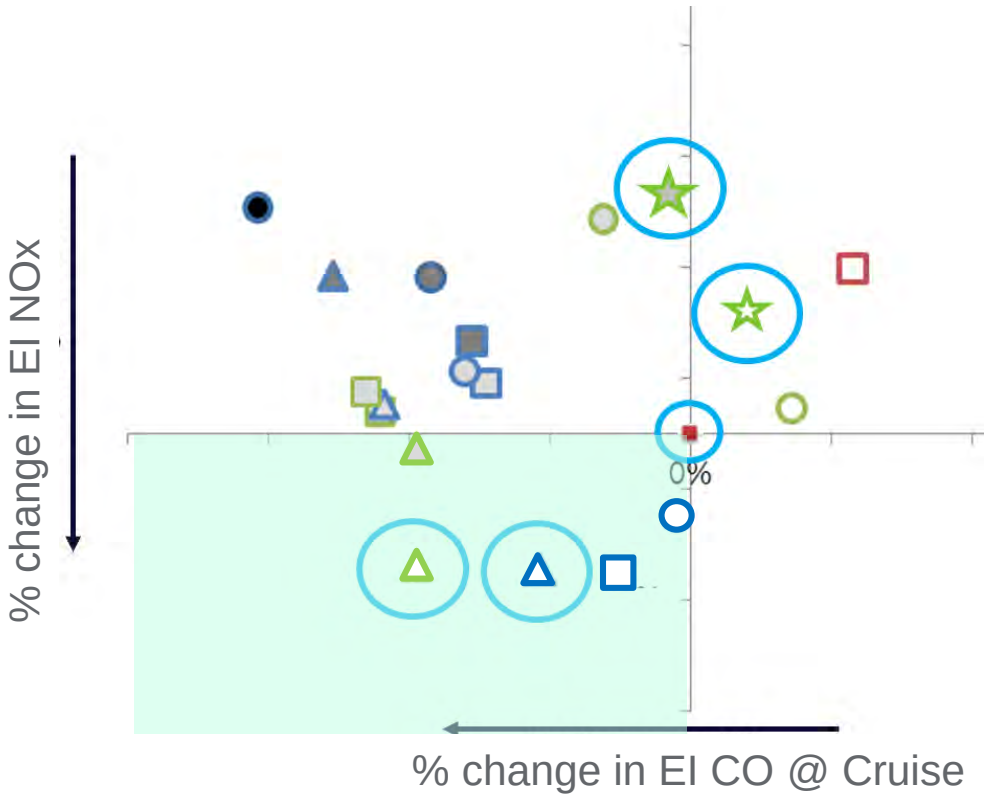




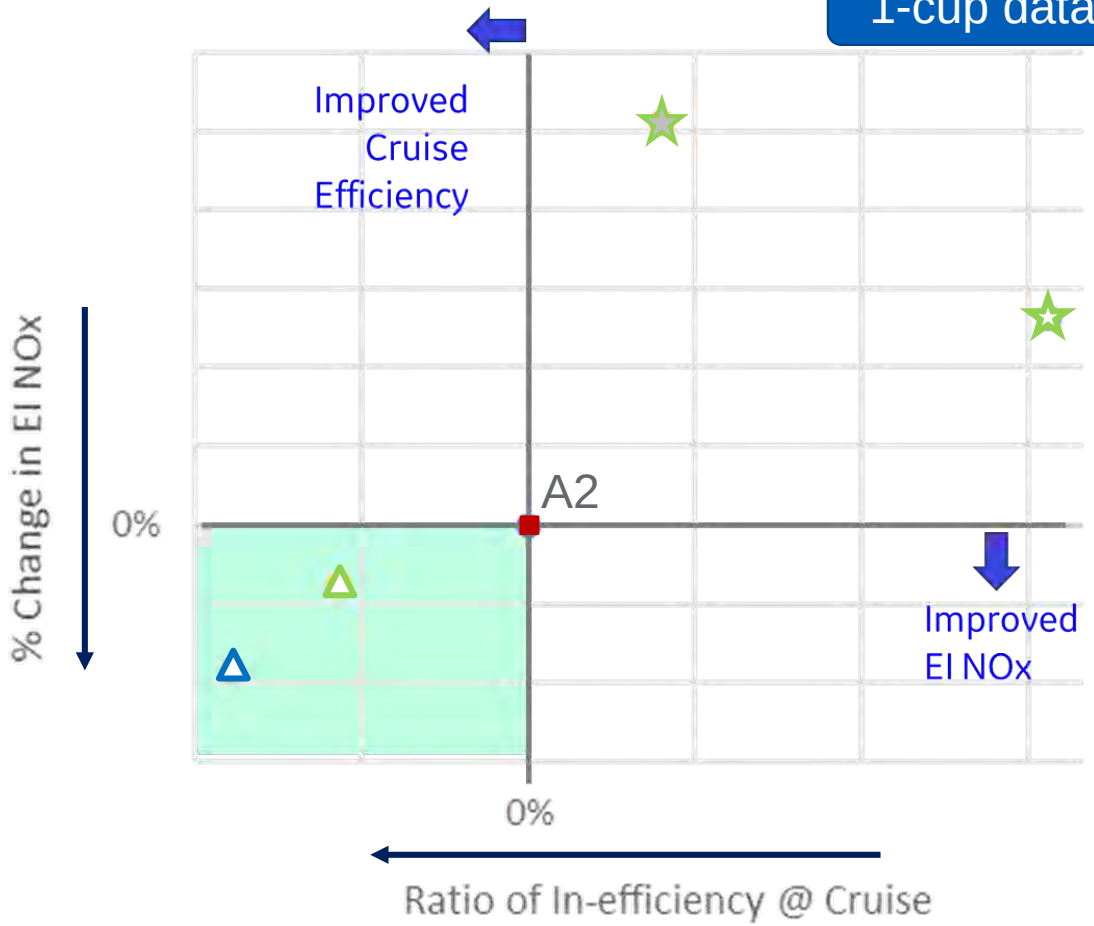
CLEEN II Test Rig @ GRC

Emissions Screening Data – Cruise Eff. & High Power NOx

CFD – Pre/test



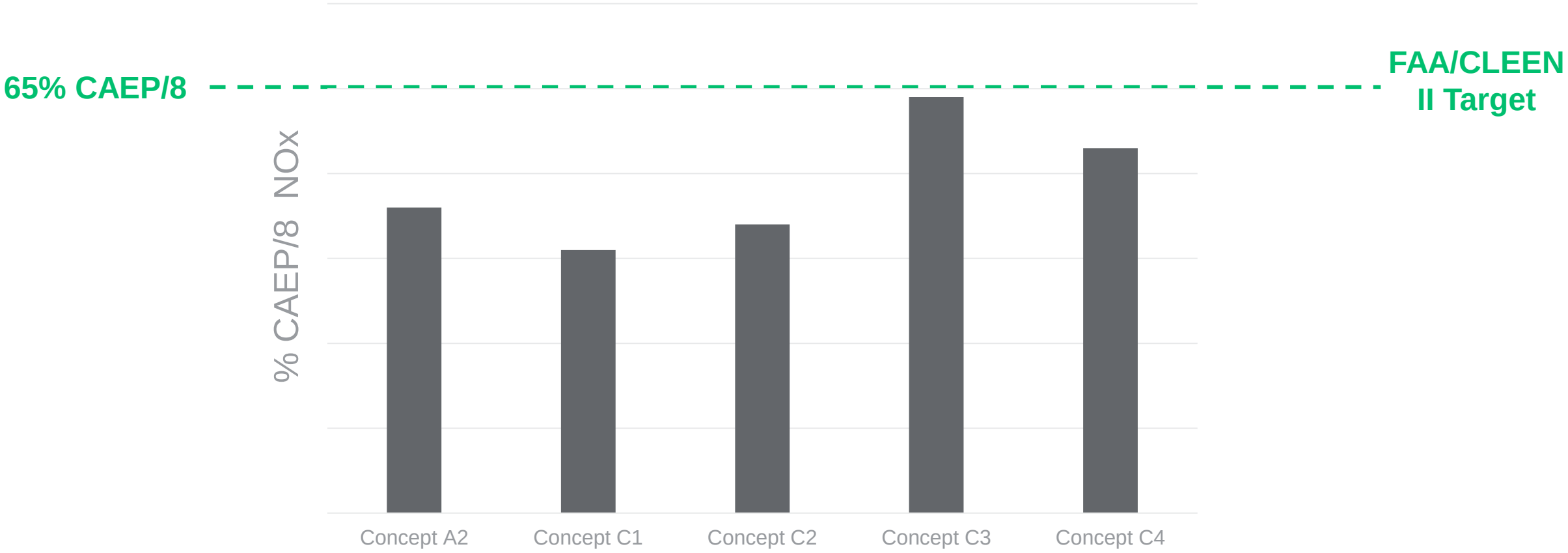
1-cup data



- **Data plotted relative to initial Concept A2 (which is projected to meet CLEEN II objectives)**
- **Indicates generally similar trends to CFD pre-test predictions**
- **2 concepts further improve high power NOx while maintaining / improving cruise efficiency**

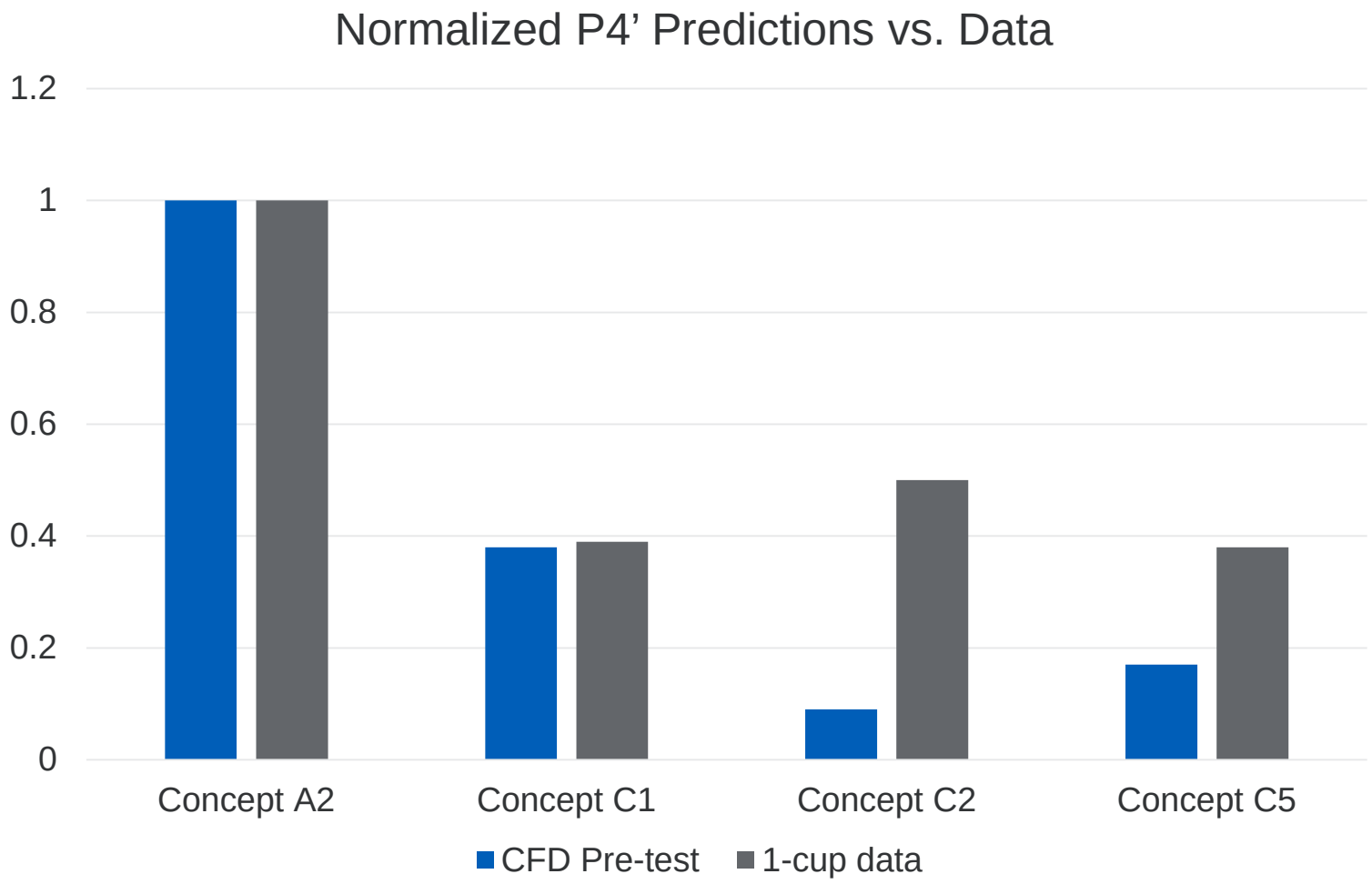
Projection to CAEP/8 NOx

**Based on EI NOx taken from single cup rig data



- **All 5 tested concepts are projected to meet CLEEN II target for LTO NOx**

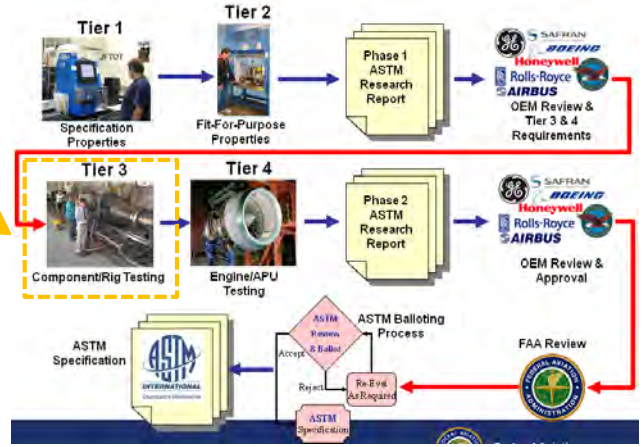
Dynamics data summary



- **Data plotted relative to initial Concept A2 (which is projected to meet CLEEN II objectives)**
- **Indicates generally similar trends to CFD pre-test predictions**
- **All 3 tested concepts anticipated to have acceptable P4' at the modeled/tested condition**

CLEEN II Sustainable Alternative Fuels:

Rig test evaluations



ASTM D4054

Benefits:

- Advance from blends to fully synthetic fuels
- Extend database further to lean combustion system evaluations – synergize with TAPS III
- Direct impact on approval of practical new fuels
- Determine: Do sensitivities of combustion parameters, observed at component level, have a significant impact at system level?

Objectives:

Advance approval and intro of "drop in" fuels

- Support ASTM D4054 – testing/demo phase
- Conduct work complimentary to other FAA programs

Work Scope:

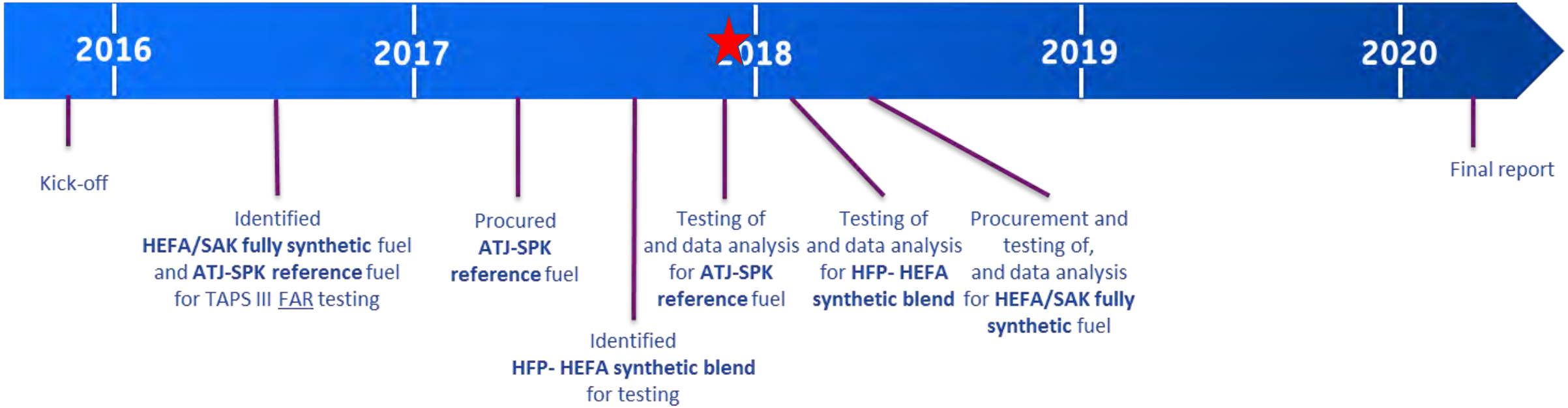
- Test two fuels, one neat and one blend, in ASTM roadmap – (FAR* test)
- Test one fuel defined by FAA's National Jet Fuel Combustion Program (NJFCP) – (FAR test)

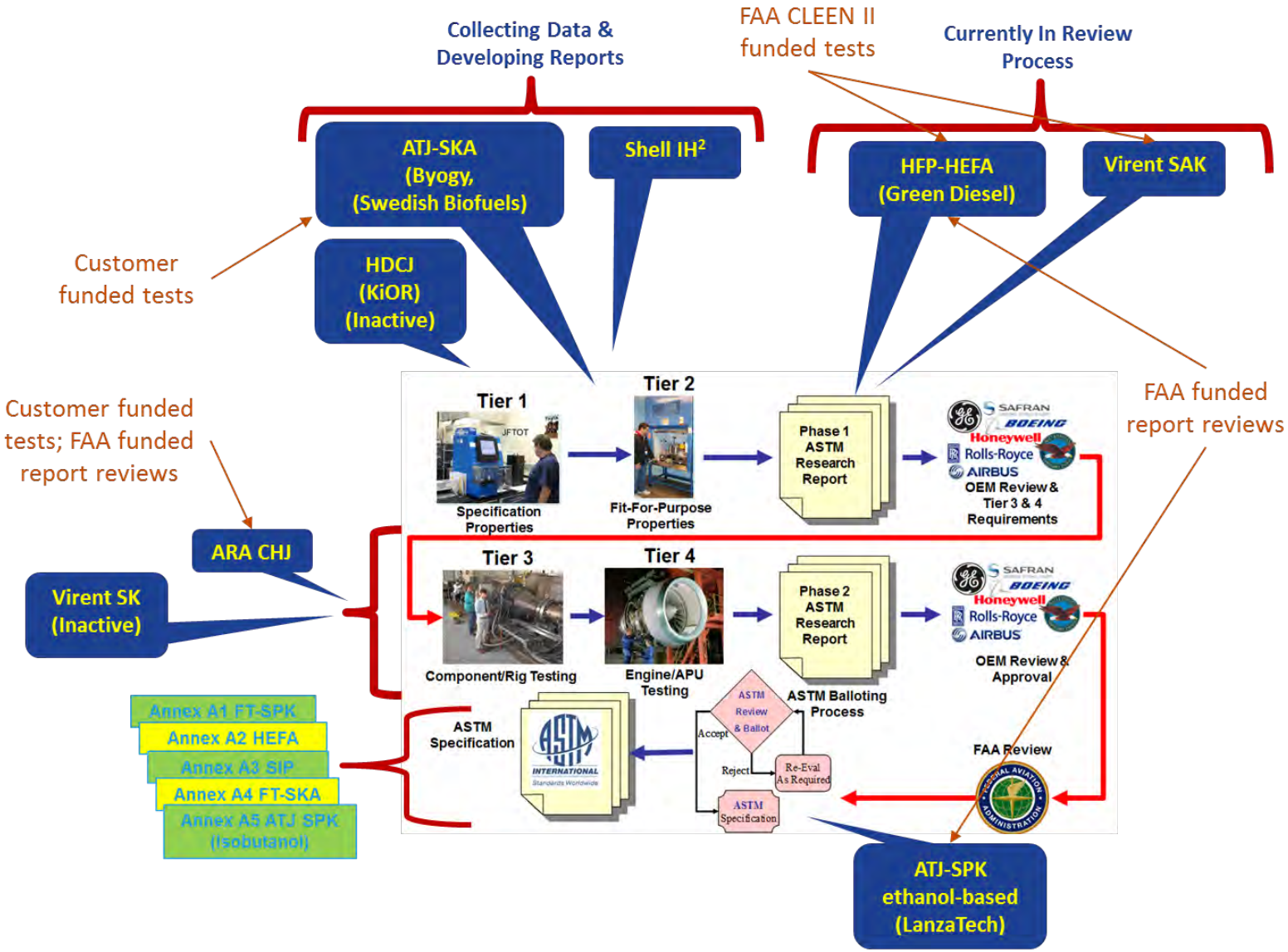
*FAR: Full Annular Combustor Rig

Progress since May 2017 Consortium:

- NJFCP fuel (100% Gevo ATJ-SPK) brought to Evendale - testing imminent
- 100% synthetic fuel (HEFA SPK + Virent SAK) RFQ out to producer - testing Q2 '18
- *Core engine testing of a 100% synthetic fuel in '20 was replaced by FAR testing of High Freeze Point HEFA blend - testing Jan '18*

Schedule



- Key figures of merit to be evaluated: ignition, blow-out (i.e., Operability).
- Later FAR tests will rely on baseline data collected in first campaign (no re-baselining planned)

Current GE activities