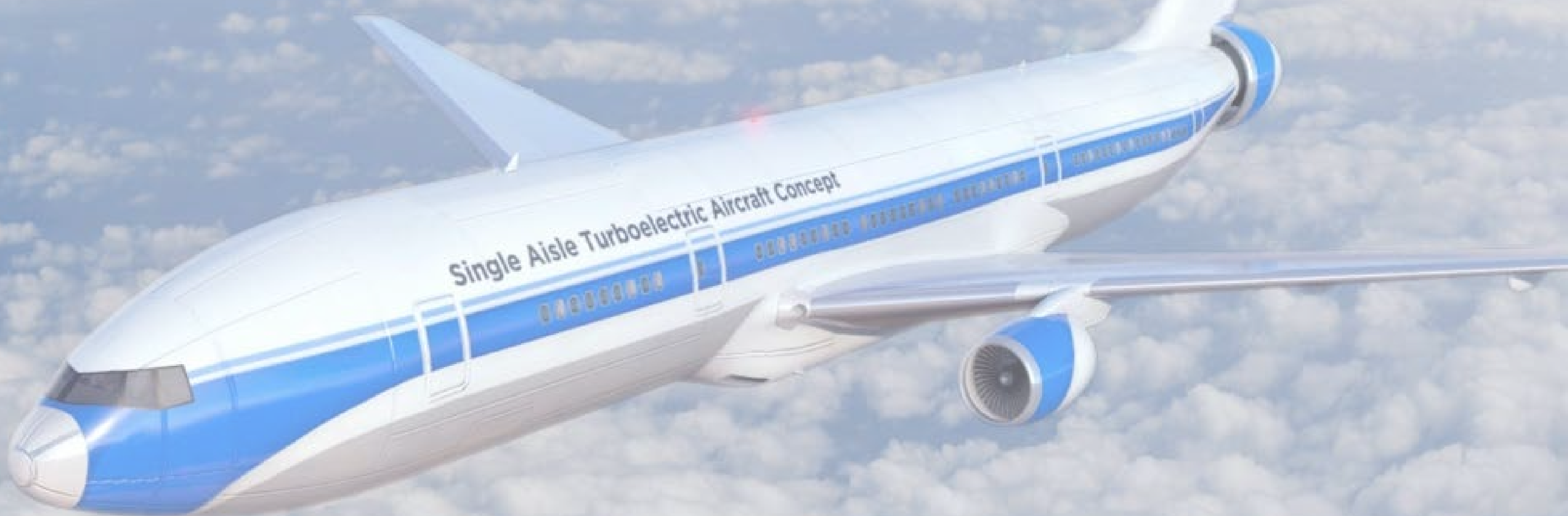
Conceptual Design of a Single-Aisle Turboelectric Commercial Transport with Fuselage Boundary Layer Ingestion



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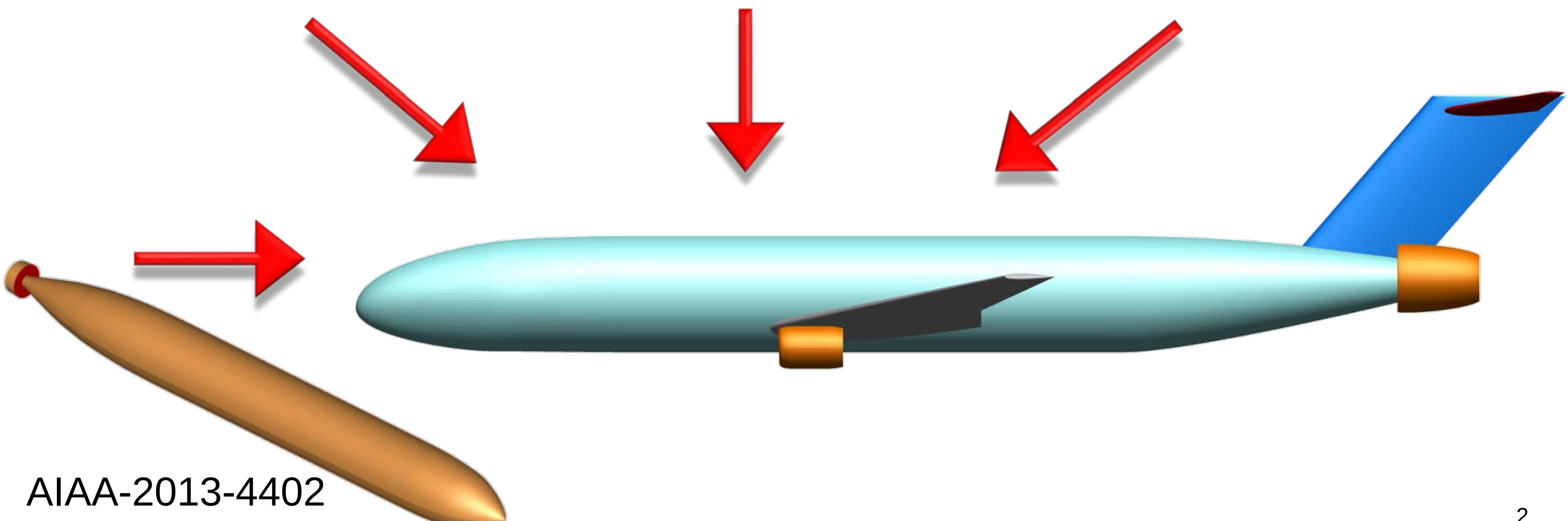
Concept Germination

SUGAR VOLT

SUGAR Freeze

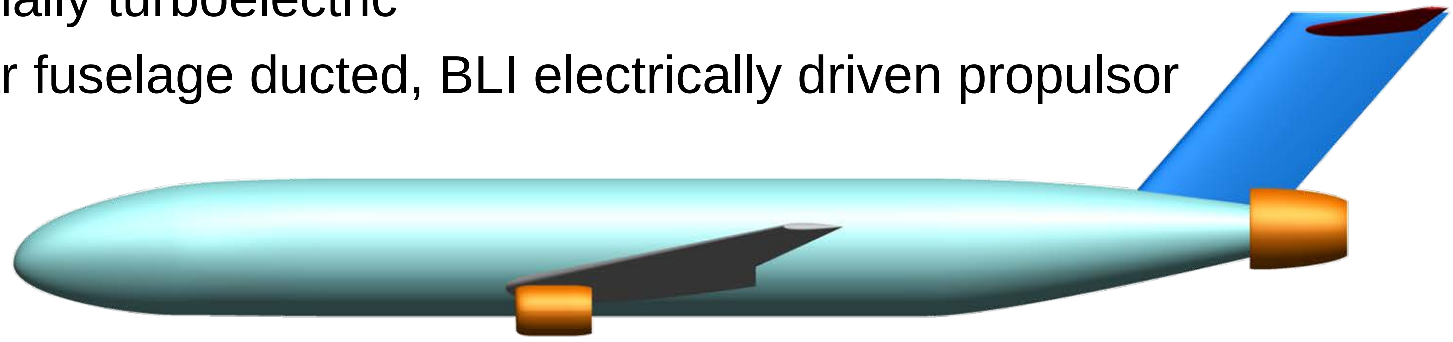
N3X



AIAA-2013-4402

Concept Description

- STARC-ABL: **S**ingle-aisle **T**urboelectric **A**i**RC**raft with **A**ft **B**oundary **L**ayer propulsion
- Conventional single aisle tube-and-wing configuration
  - Includes N+3 technologies for 2035 timeframe
  - Mach 0.7, 3500 nm design range, 900 nm economic mission
  - Used Refined SUGAR mission as reference
  - 154 passengers (dual class)
- Twin underwing mounted N+3 turbofan engines with attached generators
- Partially turboelectric
- Rear fuselage ducted, BLI electrically driven propulsor



Simplifying Assumptions

- Detailed aerodynamic shaping of rear fuselage and BLI propulsor nacelle ignored
- Thermal management system losses not included, although ROM weight estimate included in system weights
- BLI propulsor operating at constant HP for higher power settings, operational limits on turbofan LPC sets BLI HP at low throttle settings
- Assuming conventional electrical system and motors, 90% total electrical system efficiency
- Using boundary layer from Boeing SUGAR High CFD solution, cruise and low speed
  - *Fixed CFD solution that does not capture aero-propulsive coupling*

Propulsion System Design Assumptions

- Two turbofan wing engines and the tailcone thruster sized at the top of climb (TOC) or the rolling takeoff (RTO) condition, which ever is the more limiting
- Turbofan engines are based on the Georgia Tech public domain version of the GE hFan with the motor replaced by a generator and total engine resized to balance power and meet thrust requirements
- 750V normal c

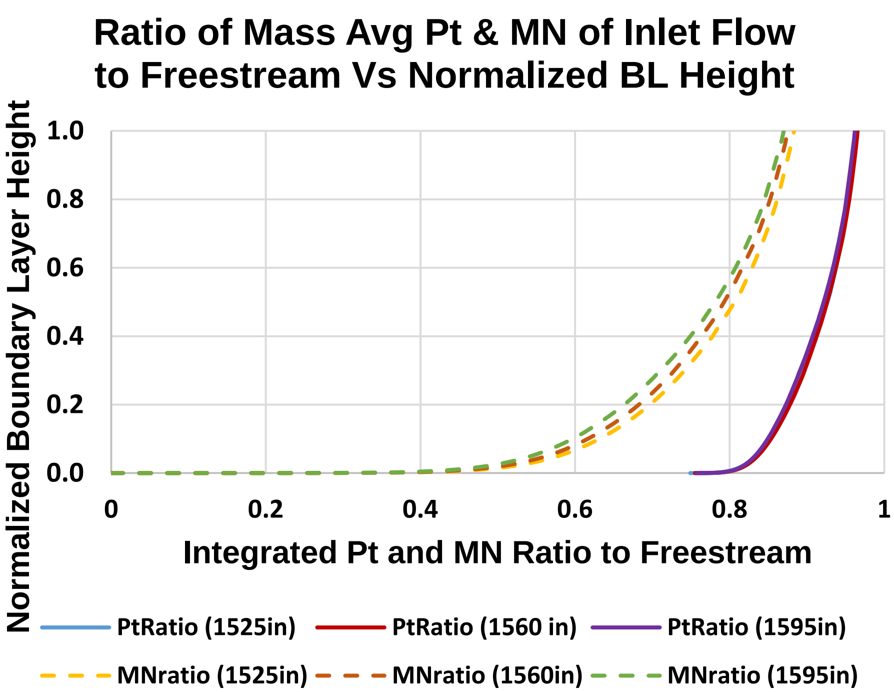
Specific power targets for currently funded 3 year research efforts

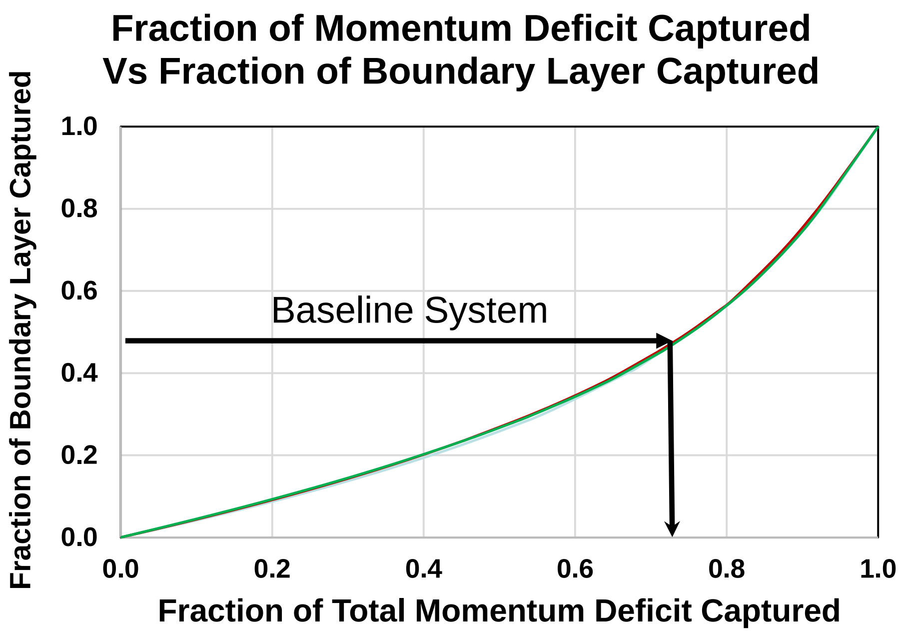
GT Turbofan		
Fan	1.45	93.9%
LPC	1.45	92.0%
HPC	27.9	90.6%
HPT	2800 R	92.5%
LPT	1690 R	94.1%
Tailcone		
Fan	1.25	95.7%

TMS Comp.	**Pwr / Spec Wt**	**Efficiency**
Generator	8 hp/lb	96%
Motor	8 hp/lb	96%
Inverter	10 hp/lb	98%
Cable	3.9 kg/m	99.6%
Circuit Protection	33 kg/MW	
TMS	0.68 kW(th)/kg	

Boundary Layer Modeling

- For each height in the boundary layer the mass-averaged MN and Pt were calculated
- Increasing the amount of ingested boundary layer increases the captured momentum deficit in the wake
  - The power required to capture the entire boundary layer was excessive
  - 3500 hp at TOC captures 46% of the boundary layer which captures 72% of the momentum deficit





Propulsion System Performance

	N3CC Baseline Turbofans*		STARC-ABL Generator Turbofans*		+ BLI Tailcone Propulsor		= Total Propulsion System	
	TOC	RTO	TOC	RTO	TOC	RTO	TOC	RTO
Thrust**	6800	34 920	4060	22 780	3210	5560	7260	28 350
TSFC	0.441	0.2922					0.3875	0.3032
Thrust/hp	0.64	0.99	0.60	0.86	0.92	1.6	0.72	0.96
OPR	58	51	58	49.6	1.25	1.08		
BPR	11.3	11.9	6.4	6.9			14.4	13.3
Fan PR/%Nc	1.45/ 100%	1.39/ 93.2%	1.45/ 100%	1.49/ 100%	1.25/ 100%	1.08/ 62.1%		
LPT Power (hp)	5960	19 490	4940	14 840				
Fan Power (hp)	5320	17 705	3005	12 900	3500	3500		
Gen/Motor (hp)			3870	3870	3500	3500		

* The thrust and horsepower values for the baseline and generator turbofans are the total of both turbofans.

** The aircraft thrust requirements are TOC Fn = 6800 lb, RTO Fn = 28,340 lb

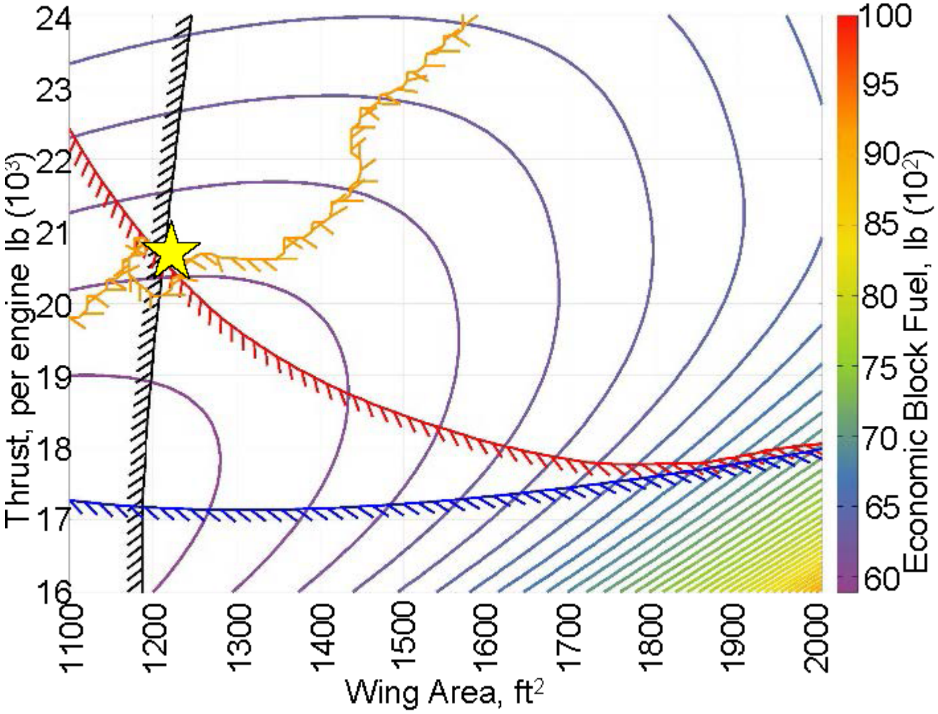
Total Propulsion System Weight

Subsystem	Units	Baseline Turbofan	STARC-ABL Propulsion System
Non-electrical	lb	16 750	10 370
Electrical	lb	-	1990
TMS	lb	-	910
Total	lb	16 750	13 270

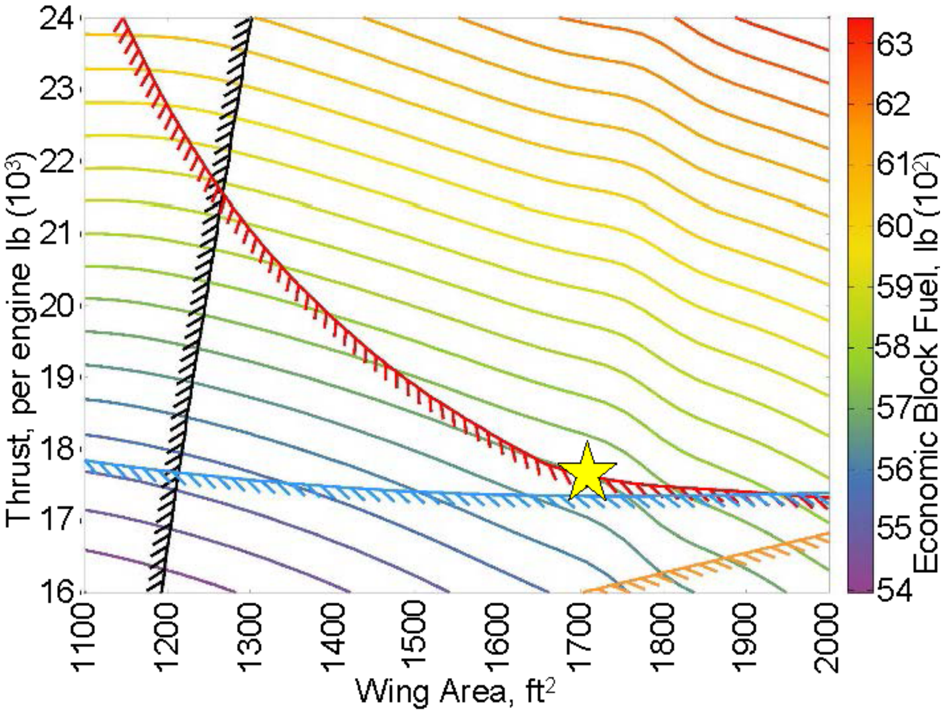
- STARC-ABL propulsion system adds 2900 lb of additional electrical and TMS equipment
- Additional non-electrical weight of the BLI fan and nacelle
- Weight reduction (mainly in the fan and nacelle) of the underwing generator turbofans off-sets the weight of STARC-ABL additional equipment
- Baseline and generator turbofan weights calculated using Georgia Tech methodology that relies mainly on:
  - Regression fits based on corrected flow rates and number of stages
  - Fixed dry engine to nacelle weight ratio

Design Space Comparison

N3CC



STARC-ABL



Constraint Lines Legend:

Red: Takeoff Field Length

Blue: SS Excess Thrust

Orange: ICAC

Black: Approach Velocity

Note: Contours and constraint lines are curve fits of discrete data points

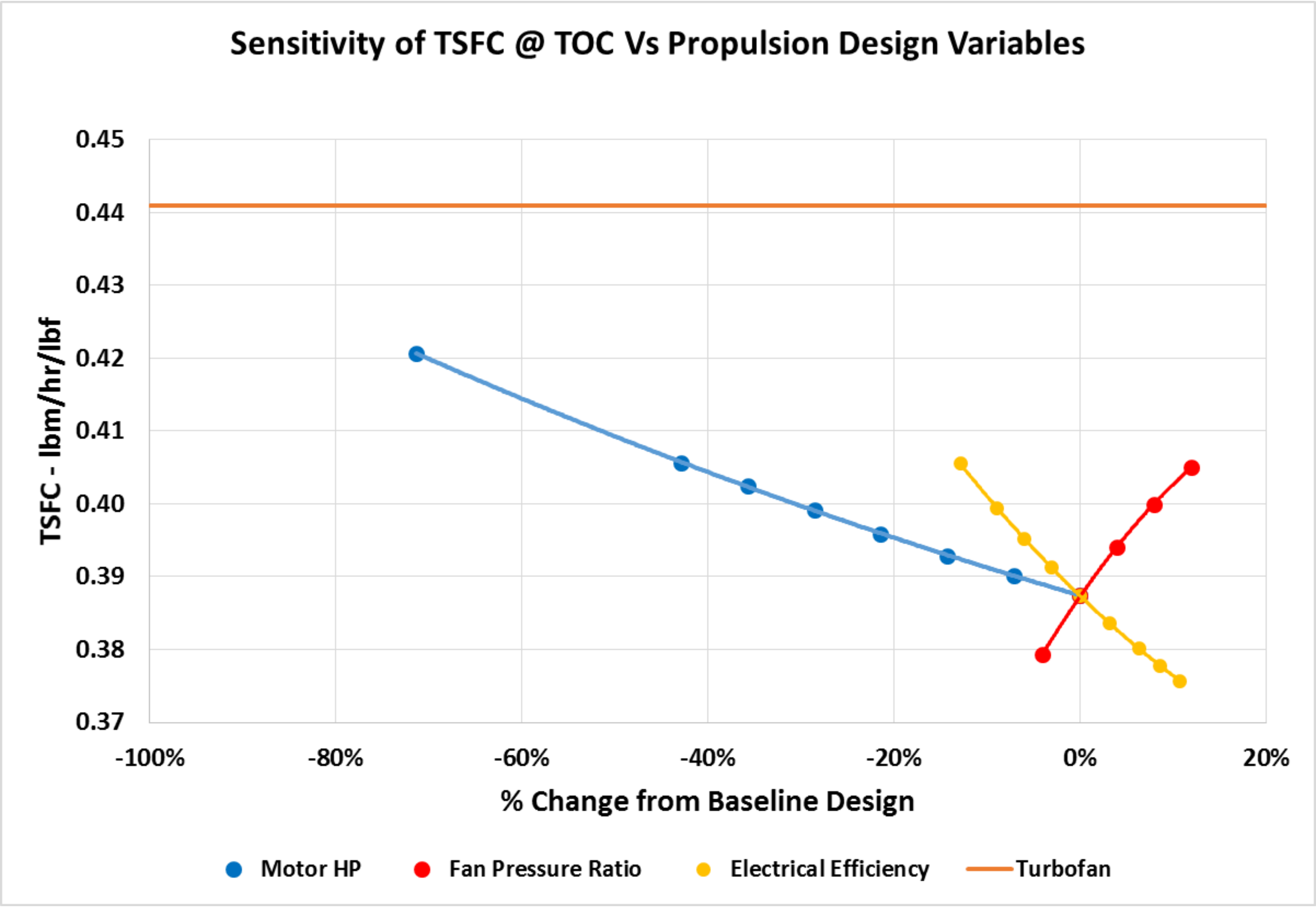
Quick Summary of Results

- Significant reductions in system fuel burn
  - **15%** reduction in start of cruise (SOC) TSFC
  - **7%** reduction in economic mission block fuel
  - **12%** reduction in design mission block fuel
- Fuselage propulsor details
  - Only bottom 46% of boundary layer ingested
  - BLI propulsor placed at most aft fuselage position
  - Driven by an all-electric motor, nominally operating at 3500 HP
  - Electrical system modeled assuming ~10% total system losses
- System details
  - Reduction in turbofan weight offsets additional weight of motors, electrical system, and additional propulsor
  - STARC-ABL architecture fundamentally changes the design space shape

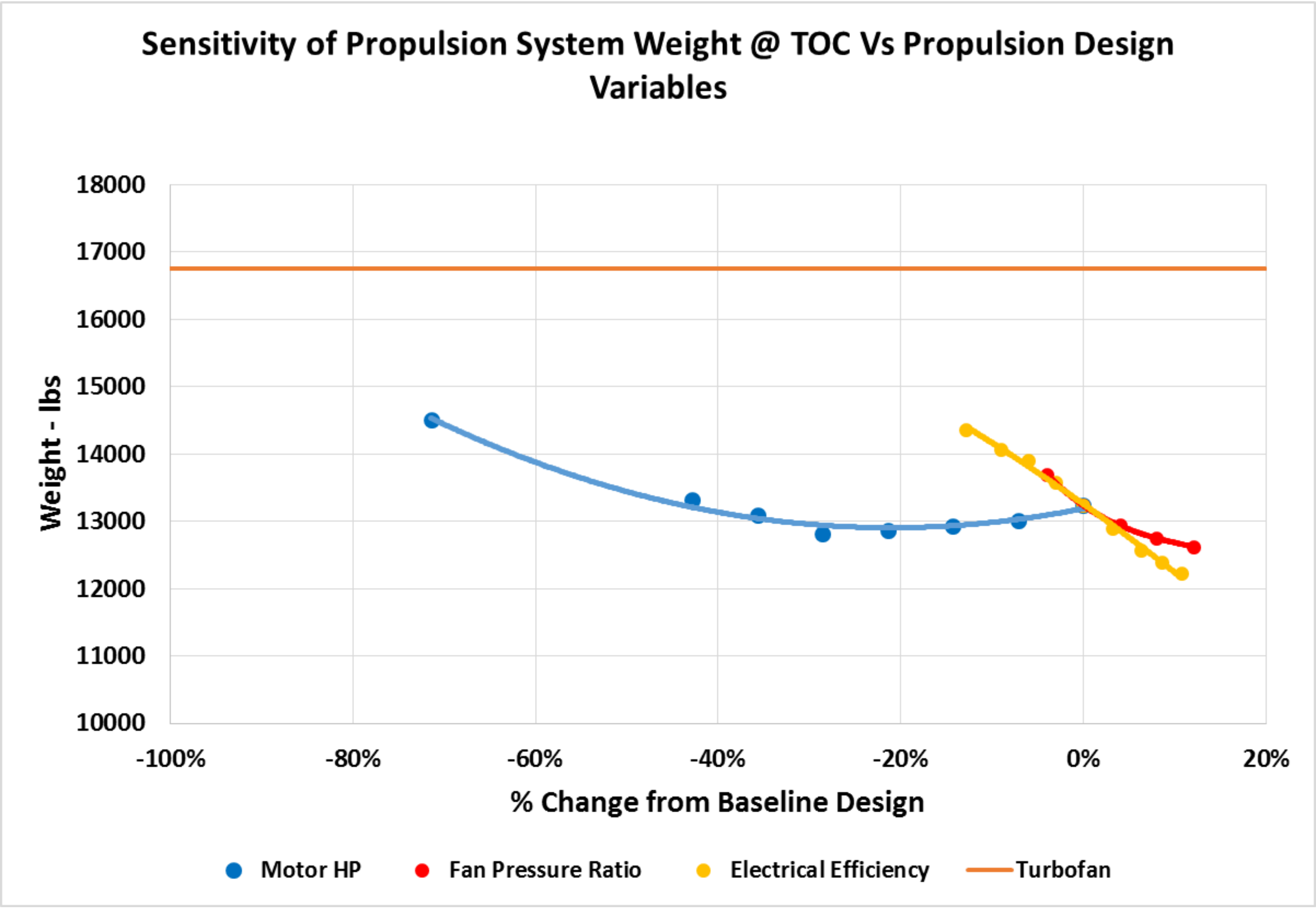
Source of System Level Benefits

- Modeled benefits
  - Reduced turbofan size and weight
  - Decreased turbofan nacelle wetted area
  - Increased propulsive efficiency in rear fuselage propulsor from ingested low-momentum flow
  - Initial estimate shows a reduction in the total propulsion system weight
- Not modeled benefits
  - Reduction in wake dissipation, only secondary effect (MIT D8 experimental results)
  - Aerodynamic shaping of rear fuselage and nacelle producing forward axial force (thrust) due to static pressure field
  - Ability of motor and generators to vary load and speed on turbomachinery for enhanced efficiency and operability across flight regime

System Sensitivities



System Sensitivities



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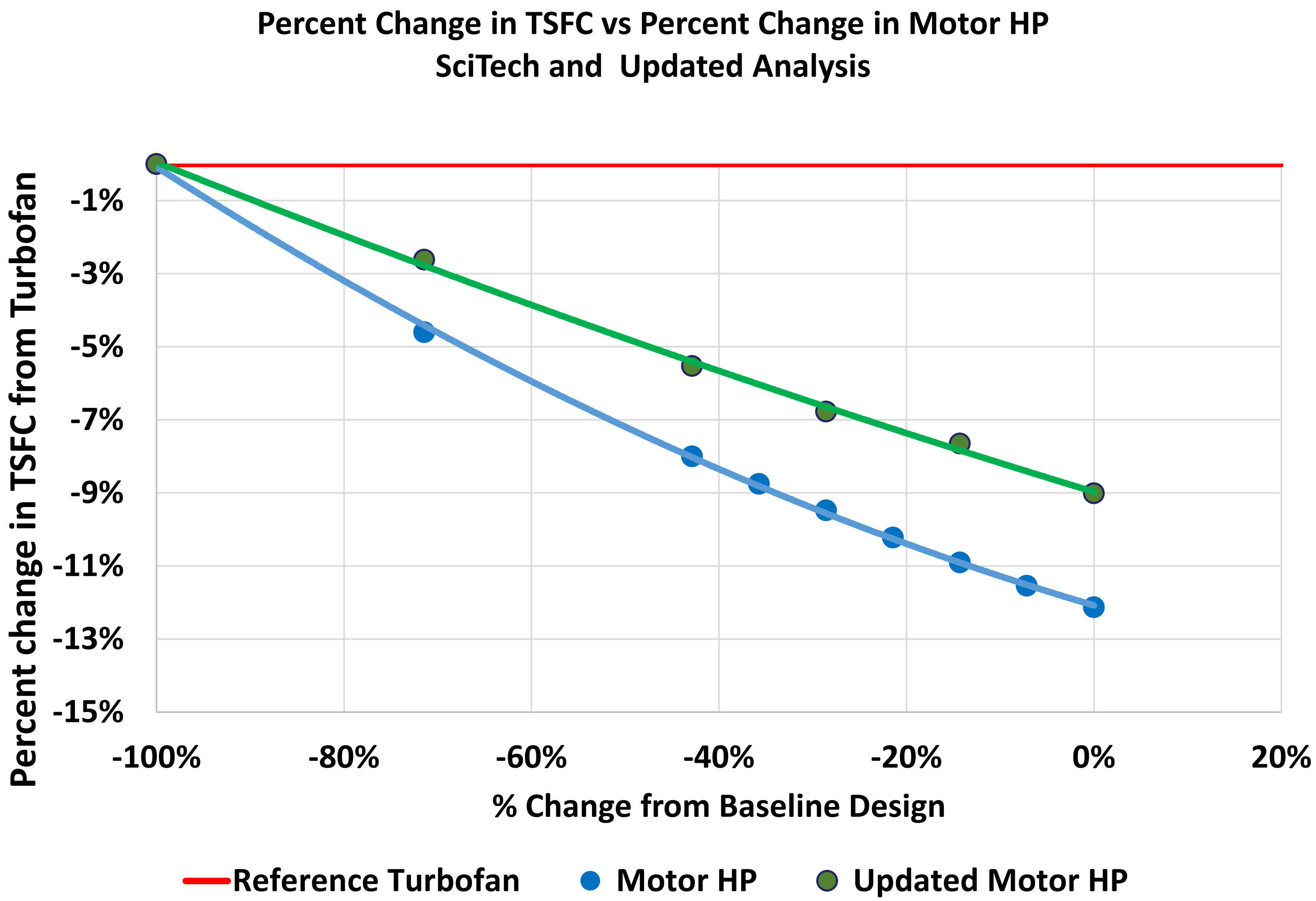

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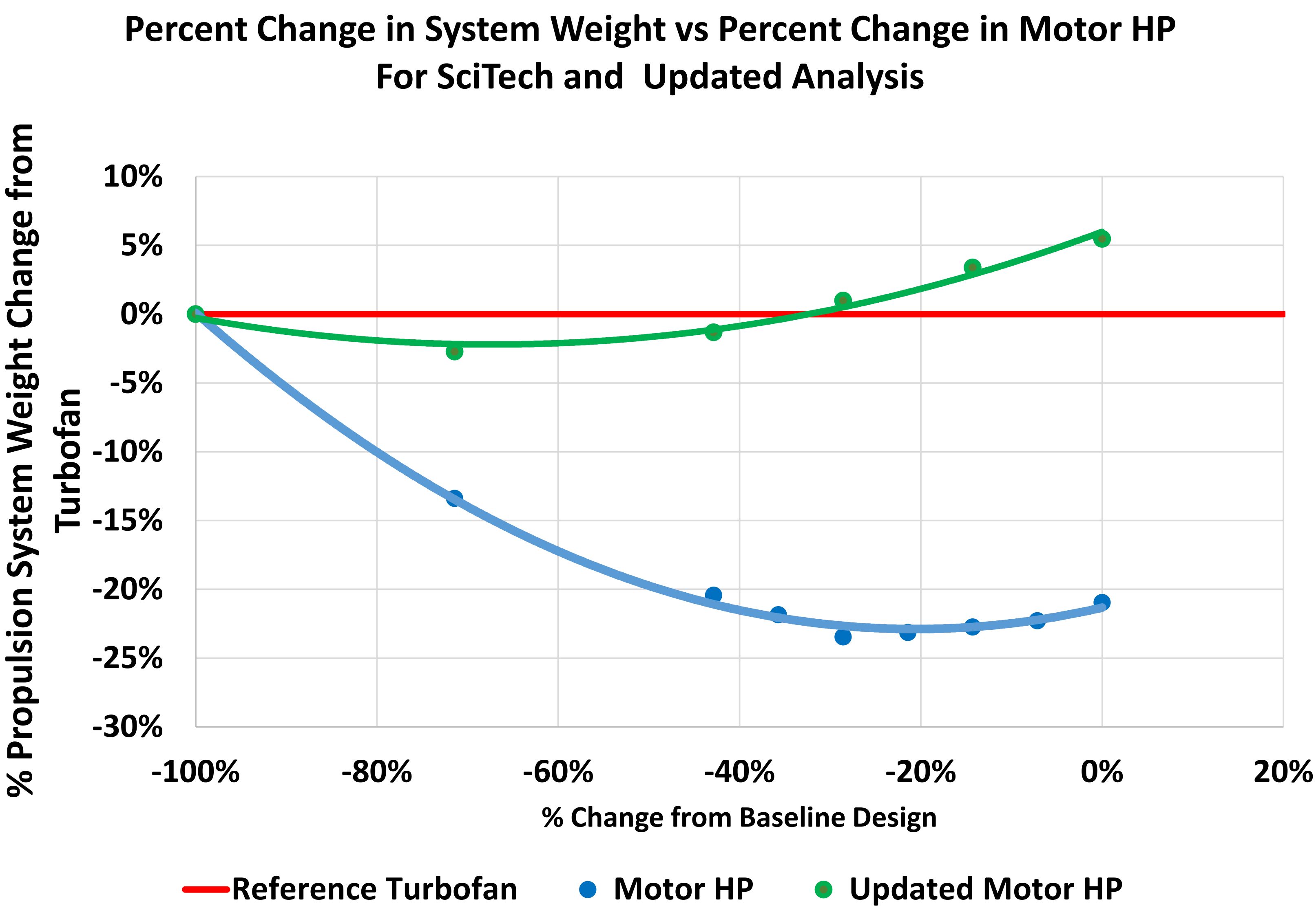


Conclusions

- STARC-ABL concept provides a significant fuel burn reduction even with conservative technology and electrical efficiency assumptions
- Ingesting the entire boundary layer requires an excessive amount of horsepower while offering little additional benefit, ingesting only the lowest momentum portion of the boundary layer provides the greatest benefit
- The rear fuselage BLI propulsor fundamentally changes the shape of the design space compared to a similar technology conventional tube-and-wing configuration, especially by removing the initial cruise altitude capability (ICAC) constraint
- Drastic reduction in underwing turbofan size and weight, while meeting TOC and RTO thrust constraints, offsets the additional weight of the rear fuselage propulsor architecture

Future Work

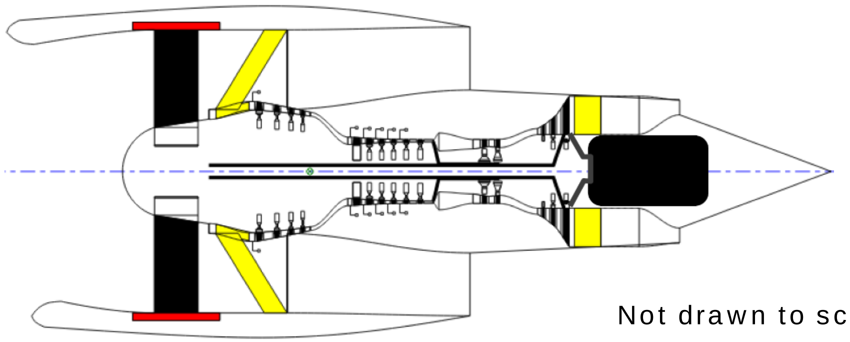
- Aerodynamic shaping of the rear fuselage and nacelle to optimize flow and capture any synergistic aerodynamic effects (thrust)
- Design the thermal management system and include better estimates of weight and efficiency losses
- Optimization of configuration, propulsion system, and throttle schedule simultaneously for increased performance benefits
  - Increased degrees of freedom allow for decoupling of core components allowing each to perform in their optimal region
  - Will provide better guidance on throttle scheduling through the different regions of the flight envelope
  - Propulsion system can be designed in conjunction with entire configuration

Questions?

NASA

Propulsion System Concept Description

- Normal conduction (non-superconducting) electrical system
- Constant 3500 HP to BLI propulsor except at low system throttle settings
- Moderate BLI propulsor fan pressure ratio of 1.25
- Conservative N+3 technology assumptions on propulsion architecture
- BLI propulsor ingests lower portion of boundary layer



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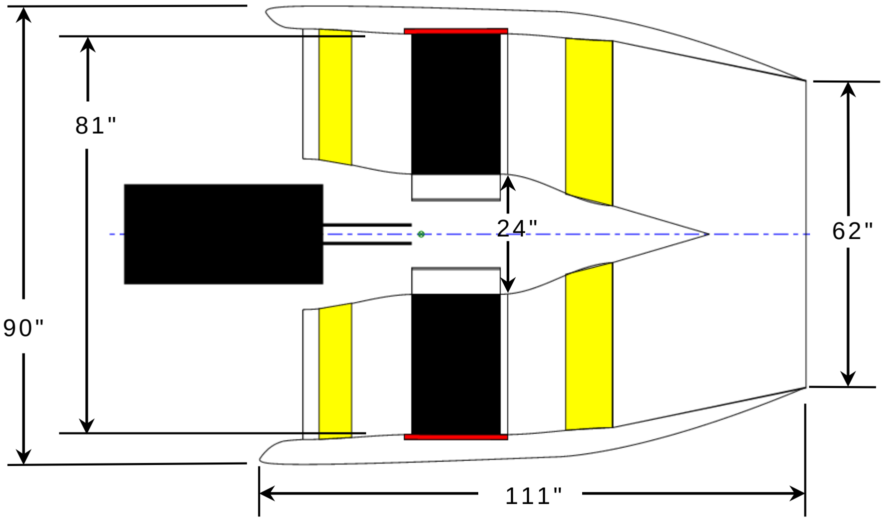

System Sensitivities

- Three system sensitivities performed
  - BLI propulsor design horse power
  - Total system electrical transmission efficiency
  - BLI propulsor fan pressure ratio
- Top of climb (TOC) condition shown
- Original baseline turbofan design shown as a single orange line

Design Space Exploration

- Explored design space shape through contour plot
  - Created matrix of ~1500 data points by varying wing area and thrust
  - Contour plots generated to visually understand how the design space changes due to STARC-ABL architecture
  - Contours colored by 900 nm mission block fuel
  - Constraint lines indicating infeasible designs
    - **Red**: Balanced takeoff field length, must be less than 8190 feet
    - **Black**: Approach velocity, must be less than 140 knots
    - **Orange**: Initial cruise altitude capability (ICAC), must be greater than 5 feet above top of climb (TOC) altitude
    - **Blue**: Second segment climb thrust requirement, must be greater than 0 pounds of excess thrust

Design Assumptions

- Two turbofan wing engines and the tailcone thruster sized at top of climb (TOC/37,574 ft, Mach 0.7) to yield a thrust of **6797** lbf or **28,342** lbf at rolling takeoff (RTO/sea level, Mach 0.2153, ISA+27R), which ever is the more limiting.
- Turbofan engines are based on the Georgia Tech public domain version of the GE hFan with t... ine resized to balance power ... ain the same.
- **750 V** normal c...

Specific power targets for currently funded 3 year research efforts

GT Turbofan		
Fan	1.45	93.9%
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HPC	27.9	90.6%
HPT	2800 R	92.5%
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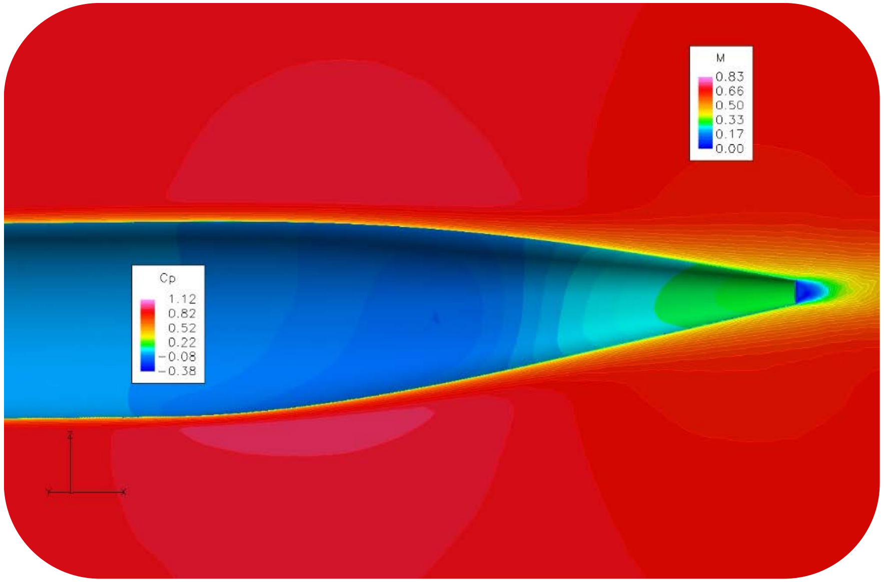
Tailcone		
Fan	1.25	95.7%

TMS Comp.	... Pwr / Spec Wt	Efficiency
Generator	8 hp/lb	96%
Motor	8 hp/lb	96%
Inverter	10 hp/lb	98%
Cable	3.9 kg/m	99.6%
Circuit Protection	33 kg/MW	
TMS	0.68 kW(th)/kg	

Boundary Layer Modeling

- Velocity and total pressure profiles obtained from Boeing for SUGAR High
- Diffusion into the base region of the aircraft means the profiles represent more than just the viscous boundary layer of the fuselage



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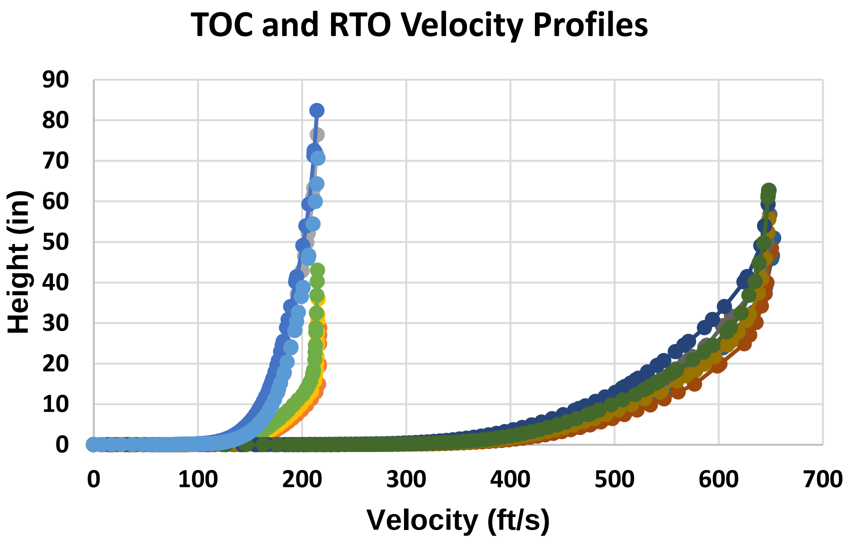

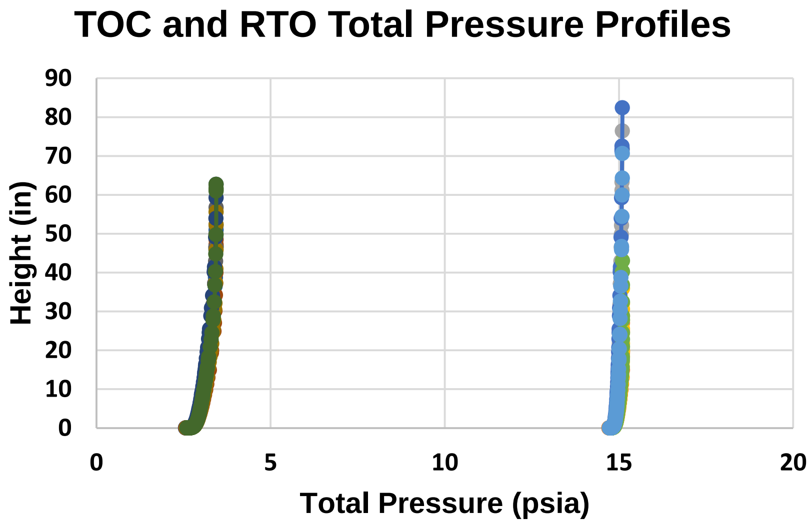

Boundary Layer Modeling

- For each height in the boundary layer the mass-averaged MN and Pt were calculated:

$$\overline{MN} = \frac{\sum_{i=0}^{x} MN_i * W_i}{\sum_{i=0}^{x} W_i} \qquad \overline{P_t} = \frac{\sum_{i=0}^{x} P_{t_i} * W_i}{\sum_{i=0}^{x} W_i}$$

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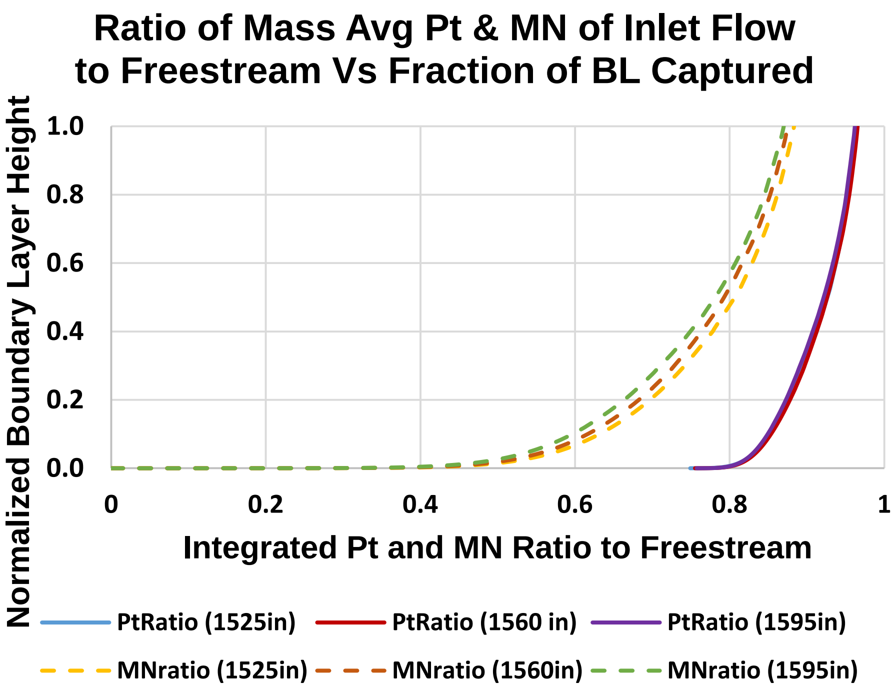
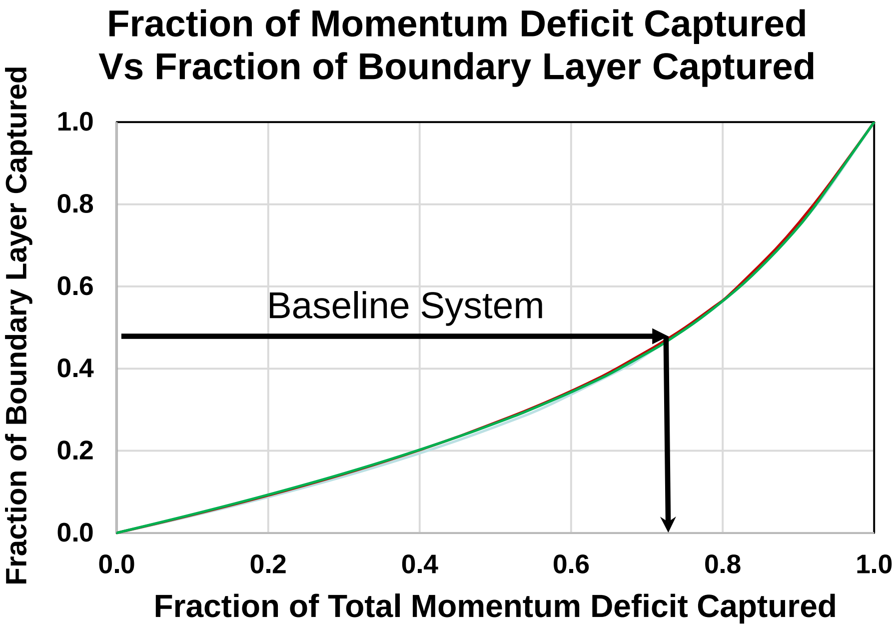




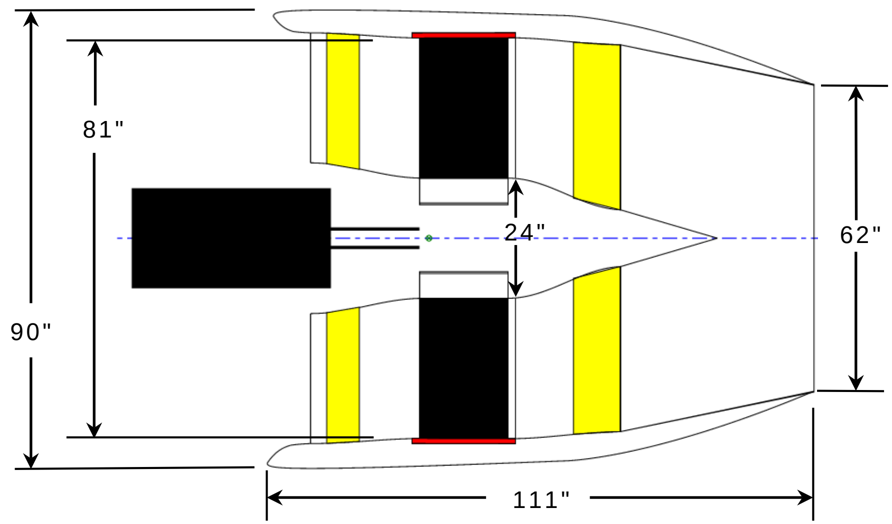
System Analysis Results

- Comparison of N3CC and the STARC-ABL Concepts

Parameter	Units	N3CC	STARC-ABL	% Change
MTOW	lb	129 260	133 370	3.2%
OEW	lb	73 690	80 480	9.2%
Wing Area	sq. ft	1220	1680	37.7%
Thrust (total, SLS)	lb	41 020	35 280	-14.0%
AR	-	11.02	8.29	-24.8%
SOC CL	-	0.59	0.45	-23.7%
L/D @ SOC CL	-	21.4	22.3	4.2%
SOC TSFC	lb/hr/lb	0.437	0.373	**-14.6%**
900 nm Block Fuel/seat	lb/seat	39.53	36.86	**-6.8%**
3500 nm Block Fuel	lb	22 050	19 350	**-12.2%**

Propulsion System Non-electric Size and Weight

BLI Propulsor	
Fan Diameter	81 in
Nacelle Max Diameter	90 in
Nacelle Length	111 in
Bare Weight	1370 lb
Nacelle Weight	700 lb
Total Pod Weight	2070 lb



Generator Turbofan	
Fan Diameter	52 in
Nacelle Max Diameter	58 in
Nacelle Length	115 in
Bare Engine Weight	2510 lb
Nacelle Weight	1630 lb
Total Pod Weight	4140 lb

Baseline Turbofan	
Fan Diameter	70 in
Nacelle Max Diameter	78 in
Nacelle Length	156 in
Bare Engine Weight	4460 lb
Nacelle Weight	3910 lb
Total Pod Weight	8370 lb

Propulsion System Electrical System Properties

Component	Assumption	Efficiency	Size	Weight
Electric Motor	8 hp/lb	96%	3500 hp	440 lb
Inverter	10 hp/lb	98%	3500 hp	350 lb
Generator (2)	8 hp/lb	96%	2@1937 hp	480 lb
Cable 2 x 93' @ 750 V / 1926 amps	3.85 kg/m	99.6%	1.44 MW	480 lb
Circuit Protection	0.5 * Cable Wt			240 lb
Thermal Management System (ROM)	0.68 kW(th)/kg	279 kw(th)		910 lb
Total Electrical + TMS				2930 lb

N+3 Conventional Configuration (N3CC) Baseline

- Overview
  - Originally based upon Boeing's Refined SUGAR concept
  - Conventional tube-and-wing configuration
  - Incorporates N+3 advanced technologies
    - Fuselage riblets
    - High BPR turbofan engines
    - Moderate aspect ratio wing (span constrained)
    - Advanced composite structures
    - NextGen ATM
    - Laminar flow
- Modeling
  - Used numerous sources of information for Refined SUGAR due to incomplete data packages
  - gFan+ turbofan replaced by NASA GRC turbofan with N+3 assumptions
    - Used internal advanced turbofan to ensure apples to apples comparison
    - N+3 Conventional Configuration (N3CC) with no proprietary data

N+3 Conventional Configuration Comparison

- Difference between Refined SUGAR-like and N3CC is the N+3 turbofan engine model created by NASA and sized to meet mission requirements

	Units	Refined SUGAR Phase II	Refined SUGAR-like	N3CC
MTOW	lb	132 100	132 630	129 260
OEW	lb	75 300	76 000	73 690
Wing Area	sq. ft	1420	1390	1220
Thrust (per engine, SLS)	lb	19 300	18 840	20 510
Optimum CL	-	0.595	0.66	0.59
L/D @ Opt CL	-	22.3	22.1	21.3
Mid Cruise TSFC	lb/hr/lb	0.451	0.452	0.438
900 nm Block Fuel/seat	lb/seat	42.34	41.72	39.53

Refined SUGAR Data Sources

- Boeing SUGAR Phase I Final Review Presentation (April 20, 2010)
- Boeing SUGAR Phase I Final Report (NASA CR2011-216847)
- Boeing SUGAR Phase II Final Report (NASA CR2012-217556)
- Boeing SUGAR Phase II Final Update Presentation (Sept. 24, 2014)
- gFan+ like engine deck from Georgia Tech (via Doug Wells)

Conclusions

- Top of Climb TSFC was sensitive to all three rear fuselage propulsor design variables, motor horsepower, fan pressure ratio, and electrical efficiency, but slopes of FPR and electrical efficiency were greater
- Total propulsion system weight is highly sensitive to electrical efficiency and rear fuselage propulsor fan pressure ratio
- Reducing the motor HP by up to 40% has little effect on propulsion system weight, but the TSFC increases

Acknowledgments

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Overview

- Concept description
- Quick summary of results
- N+3 Conventional Configuration
  - Description of baseline
  - Comparison of baseline to Refined SUGAR concept
- Simplifying assumptions
- Propulsion system modeling
  - Boundary layer modeling
  - System performance
  - Weight estimates
- System design space exploration
- Results
  - Turboelectric concept benefits
  - System sensitivities
- Future work
- Conclusions