System Level Studies for NASA

Model Development toward Zero Emissions

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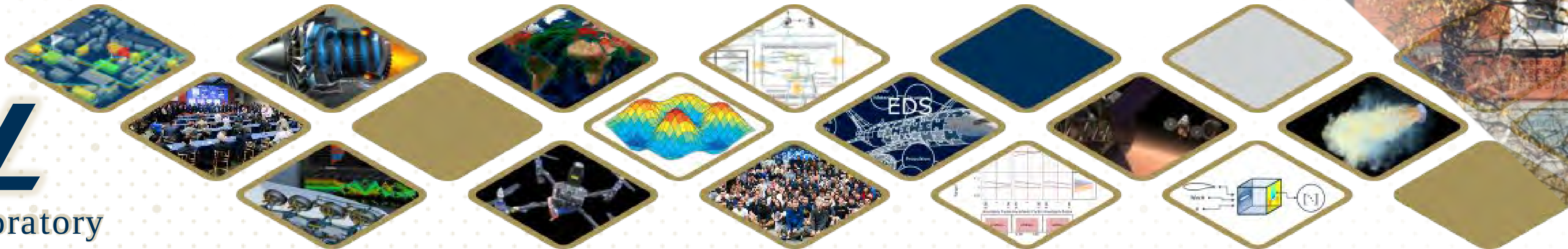


Aerospace Systems Design Laboratory

Zero Emissions Initiative

Explore possible ways one could achieve zero emissions aviation by considering both in-flight emissions (not limited to CO2) relating to the aircraft vehicle system as well as identifying important emissions from the broader aviation system.

https://en.wikipedia.org/wiki/Tupolev_Tu-155

https://en.wikipedia.org/wiki/NASA_X-57_Maxwell

Electrified Propulsion

Sustainable Aviation Fuels

Efficient Jet Engines

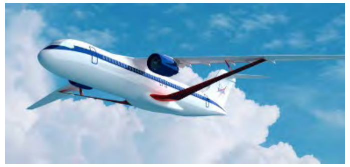
Net Zero Emissions : Key Enablers

Airframe Design

Flight Operations

Software

https://blog.geaviation.com/product/ge9x-engine-achieves-faa-certification/



https://www.nasa.gov

https://www.ana.co.jp/group/en/csr/environment/operating/

Conceptual Designs toward Zero Emissions



	Tube & Wing (T&W)	Blended Wing Body (BWB)	Strut Braced Wing (SBW)
Jet-A/SAF Turbofan	✓ (Current Workplan)	✓ (Current Workplan)	✓ (Current Workplan)
Jet-A/SAF Turbofan + Mild Electrification	✓ (Current Workplan)	✓ (Current Workplan)	✓ (Current Workplan)
Hydrogen (LH2) Turbofan	✓ (Current Workplan)	✓ (Current Workplan)	✓ (Near Term Workplan)
LH2 Turbofan + Mild Electrification	✓ (Current Workplan)	✓ (Current Workplan)	✓ (Near Term Workplan)
Jet-A/SAF Single Rotor Open Rotor (SROR)	✓ (Current Workplan)	✓ (Far Term Workplan)	✓ (Far Term Workplan)
SROR + Mild Electrification	✓ (Current Workplan)	✓ (Far Term Workplan)	✓ (Far Term Workplan)
LH2 SROR	✓ (Far Term Workplan)	✓ (Far Term Workplan)	✓ (Far Term Workplan)
LH2 SROR + Mild Electrification	✓ (Far Term Workplan)	✓ (Far Term Workplan)	✓ (Far Term Workplan)

Current Workplan ✓ | Near Term Workplan ✓ | Far Term Workplan ✓

Benefits of Hydrogen

- Hydrogen fueled aircraft may offer tangible benefits over kerosene, synfuel, and other sustainable alternatives:
  - Increase in range compared to batteries and fuel cells [12]
  - Lower lifecycle and operational emissions than kerosene and synfuel aircraft [12][13][14]
  - Lower production energy requirement than sustainable synfuel [12]
  - Fuel production can be less expensive and easier to scale than sustainable synfuel and biofuel [12]
  - Clear industry support: Airbus [15], ZeroAvia [16], H2FLY [17], Universal Hydrogen [18]

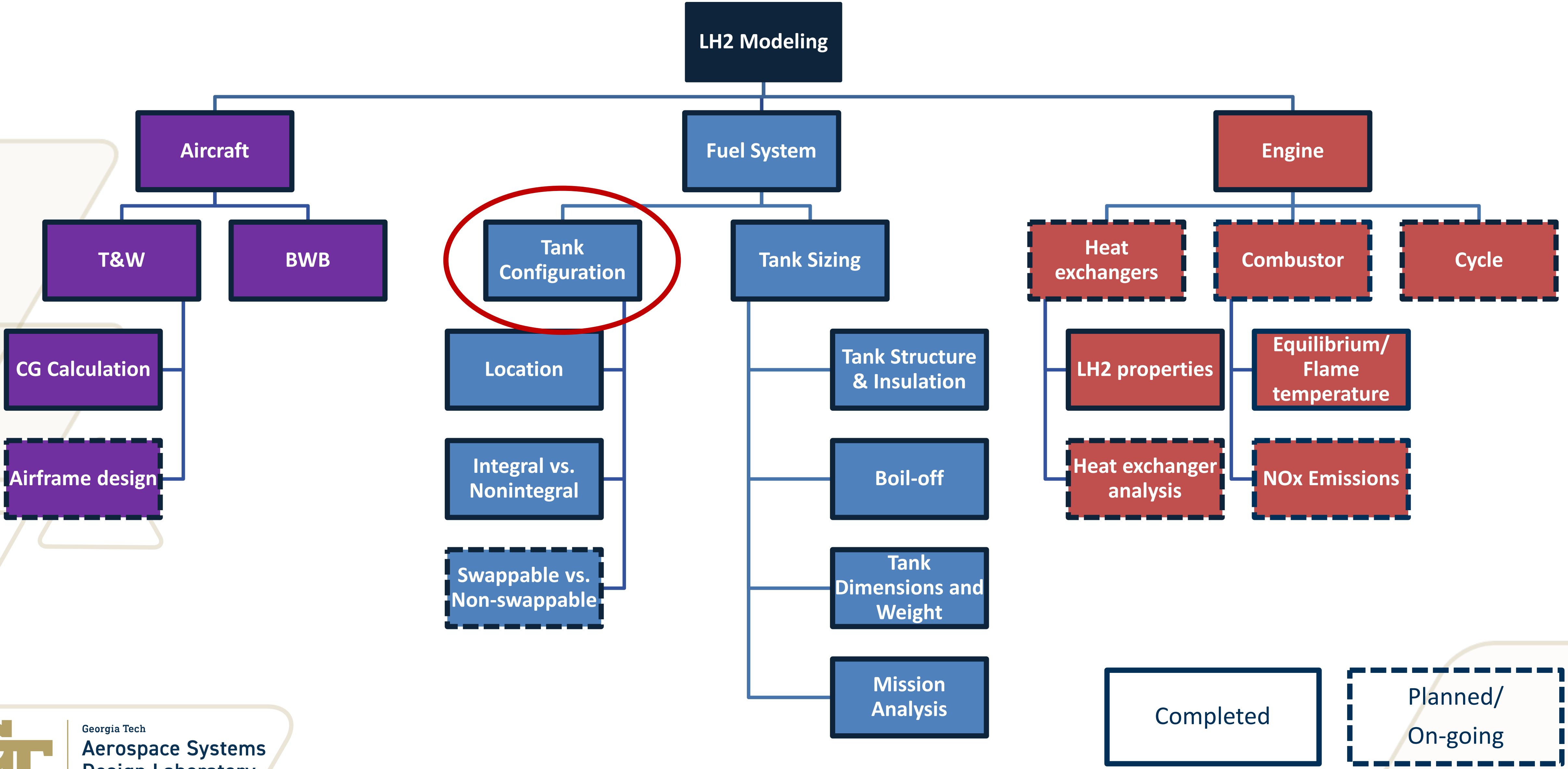
[5]

Change of in-flight emissions and emission related effects[1]

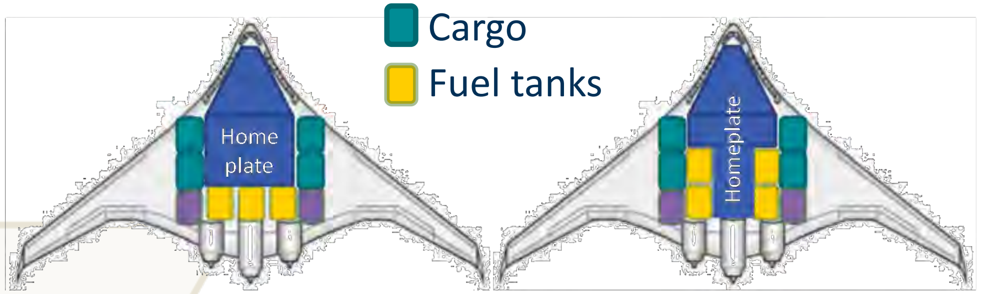
	Direct CO_2	NO_x	Water vapor[2]	Contrails, cirrus
Synfuel	-0% / -100% (Net)[3]	-0%	-0%	-10-40%
Hydrogen turbine	-100%	-50-80%	+150%	-30-50%
Hydrogen fuel cell	-100%	-100%	+150%	-60-80%

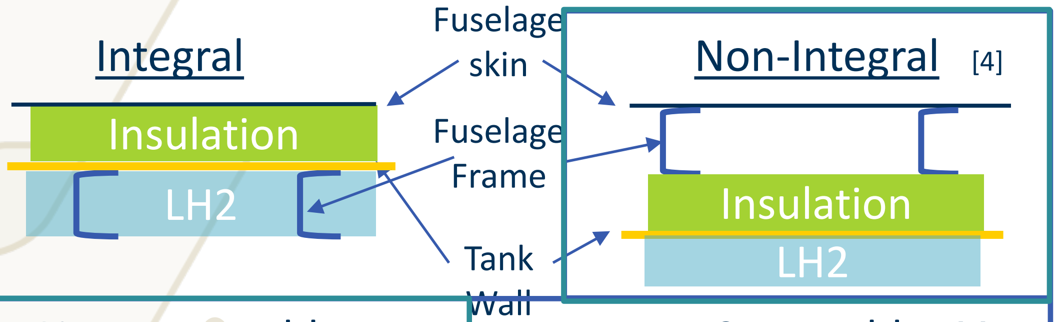
[2]

Overview of LH2 Modeling Developments



Tank Configuration





Non-swappable

Swappable [5]

Tank Location: T&W: Aft Fuselage

- Least modification to existing T&W
- Doesn't block access to cockpit
- Airbus looking at this configuration

BWB: Lateral/Aft of Homeplate

- Works well with wide geometry of BWB
- Lateral keeps CG central

Airframe OML:

T&W [6]

- Fuselage extension as required for fuel
- Wing moves aft to account for CG change
- Current, no other changes to airframe OML

BWB (2 configurations)

- Passenger cabin and tank size are part of aero/structural optimization
- Fixed OML – trade passengers vs range based on LH2 that can fit in OML

Integral vs Non-integral:

T&W and BWB: Non-integral

- Non-integral is easier to integrate and maintain with existing fuselage structure
- Integral has better gravimetric index (GI)

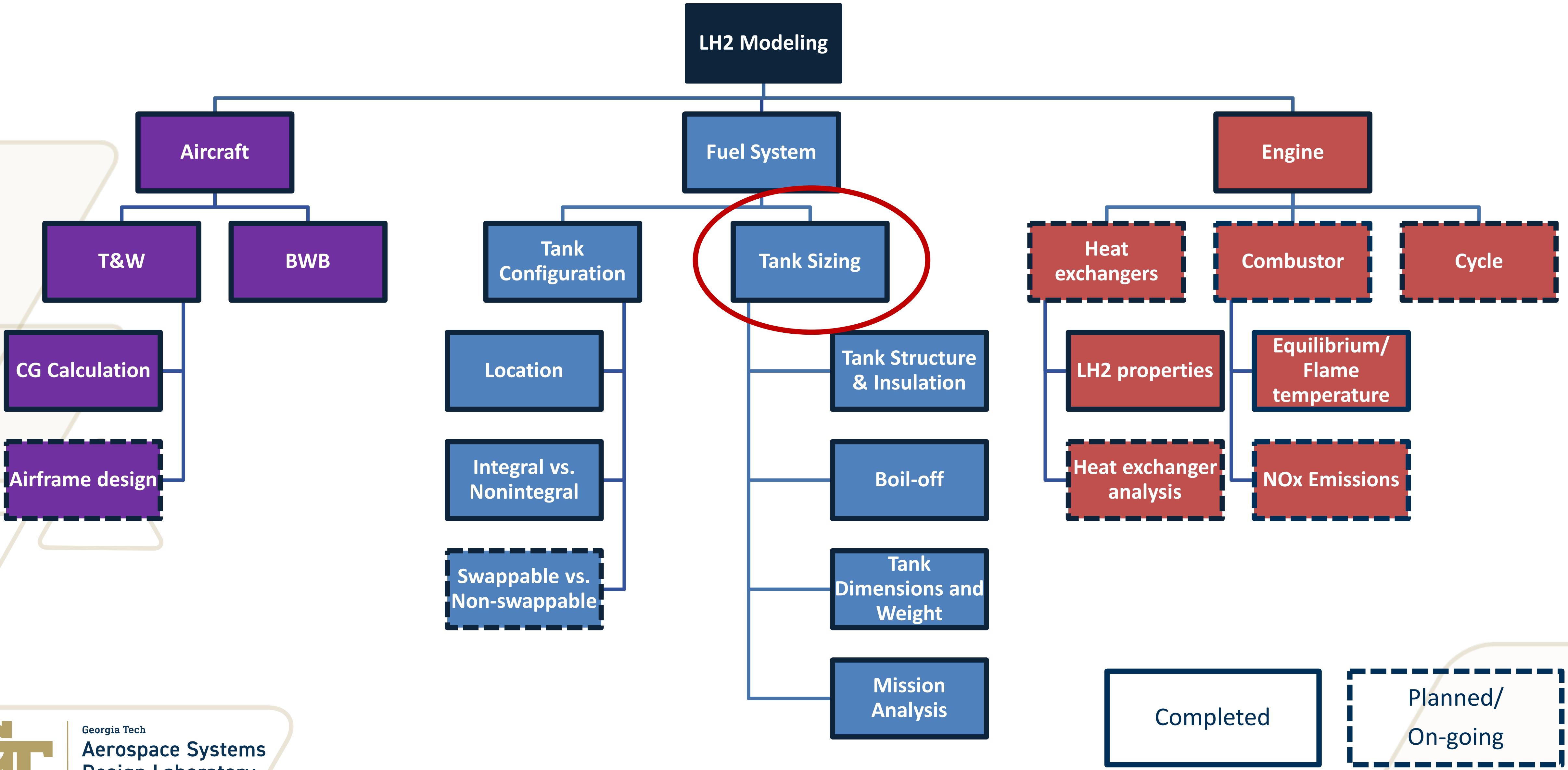
Swappable vs Non-swappable:

T&W: Non-swappable

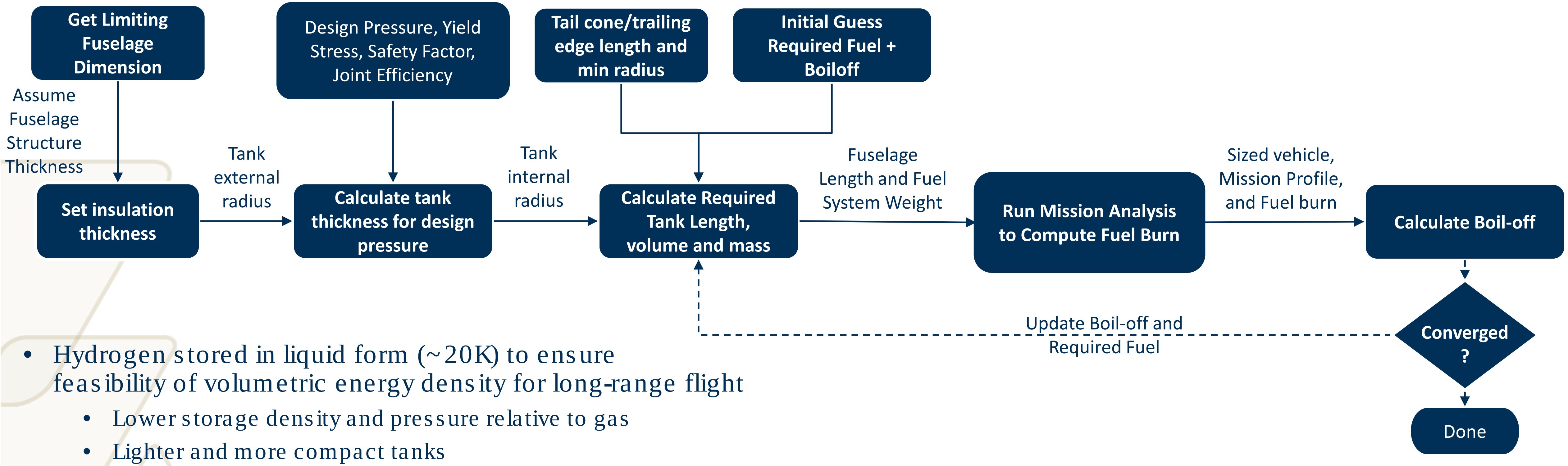
BWB: Non-swappable for aero/structural optimization; Swappable for fixed OML

- Non-swappable has better GI
- Swappable allows filling before airplane arrives and easy swapping of tanks for quicker turnaround times

Overview of LH2 Modeling Developments

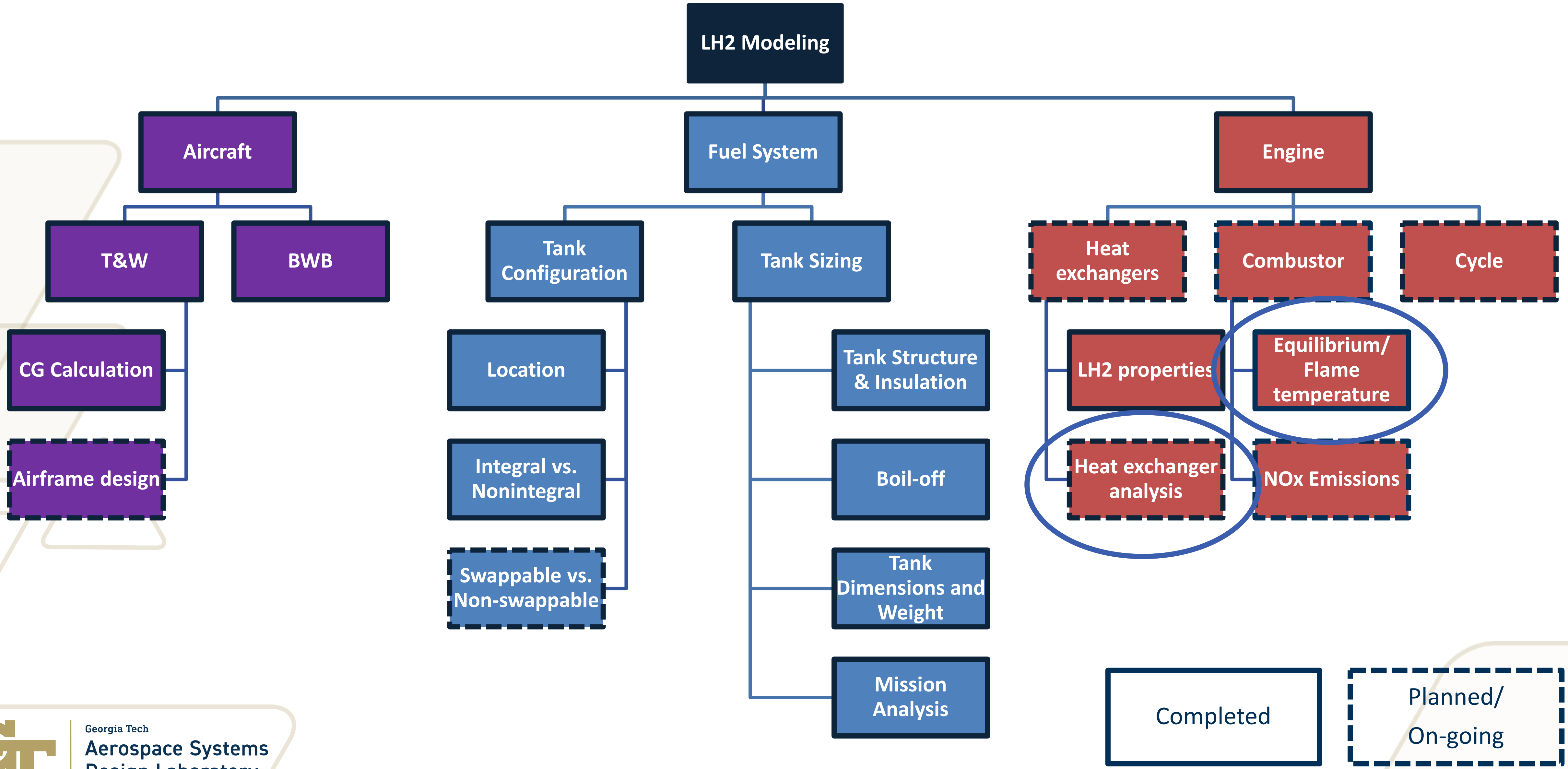


Tank Sizing: Overview



- Hydrogen stored in liquid form (~20K) to ensure feasibility of volumetric energy density for long-range flight
  - Lower storage density and pressure relative to gas
  - Lighter and more compact tanks
  - Tanks must be insulated
- Requires 4x the volume of kerosene tanks for same range
  - Preferred (not required) shape is spherical/cylindrical to minimize surface area and therefore heat transfer to fuel
  - No longer viable to store fuel in wings → smaller wings
  - Downstream impacts on landing gear, wing placement, empennage sizing, and more
- Boil off, or vaporization, occurs through the mission
  - If boiloff is greater than engine fuel flow then need to vent
  - If engine fuel flow is greater than boiloff then need to artificially boil

Overview of LH2 Modeling Developments



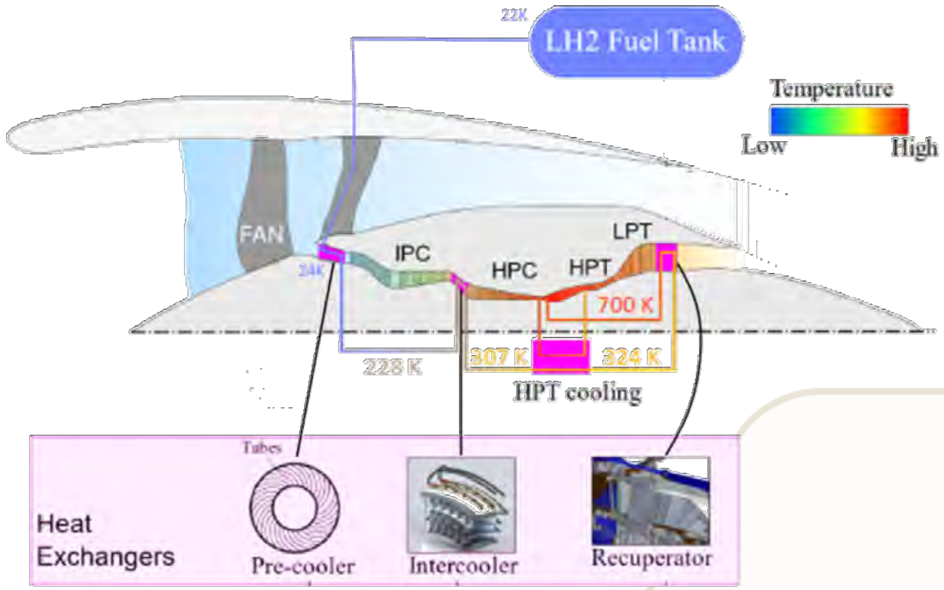
Modeling H2 Turbofan Using NPSS

- Hydrogen Engine Cycle Modeling
  - Typically use GasTbl ThermoPacakage but this is only applicable to Jet-A type fuel
  - AllFuel, Janaf and CEA can model H2
    - AllFuel matches fairly well to CEA at standard temperature but can't model different amounts of fuel heating
    - Janaf matches CEA very well and is much faster to run relative to CEA
- Selected Janaf for use but needs to use different station properties to properly model fuel temps properly

Sample results for equivalence ratio of 0.6
(Fuel and air are at the same temperature and pressure)

Fuel temp (K)	Fuel pressure (atm)	JANAF - Product temperature (K)	CEA – Product temperature (K)	Percent difference
200	17	1761.32	1760.46	0.049%
400	17	1920.76	1920.42	0.018%
600	17	2080.02	2078.66	0.065%
800	17	2246.13	2235.91	0.455%
1000	17	2394.56	2390.67	0.162%

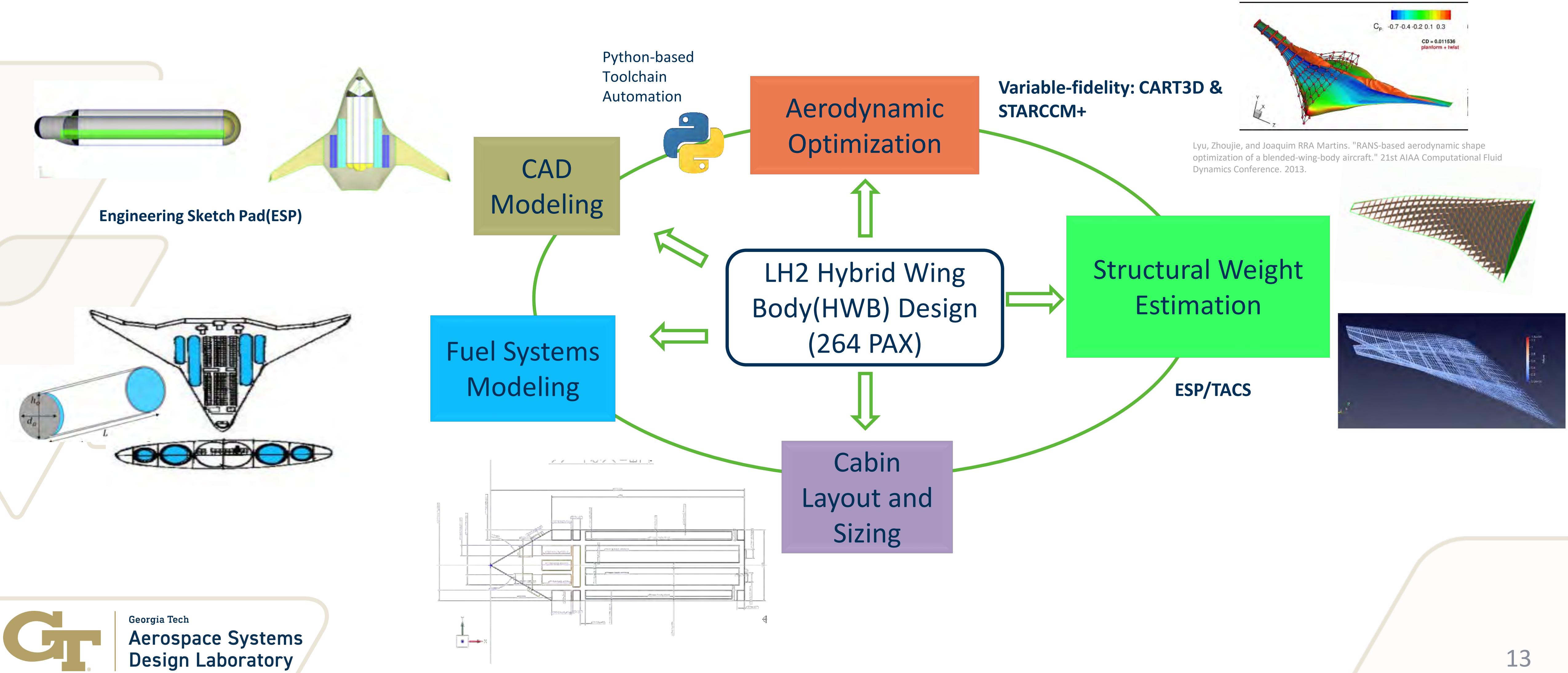
- Hydrogen needs to be heated to ~150 – 250K before combustion
- Current heat exchanger model assumes a cross-flow tube-fin heat exchanger
- Initial work is focused on sizing only a recuperator to heat the H2 to 200K



Blended Wing Body Aero-Structural Optimization

Aerospace Systems Design Laboratory

BWB Airframe Design Process

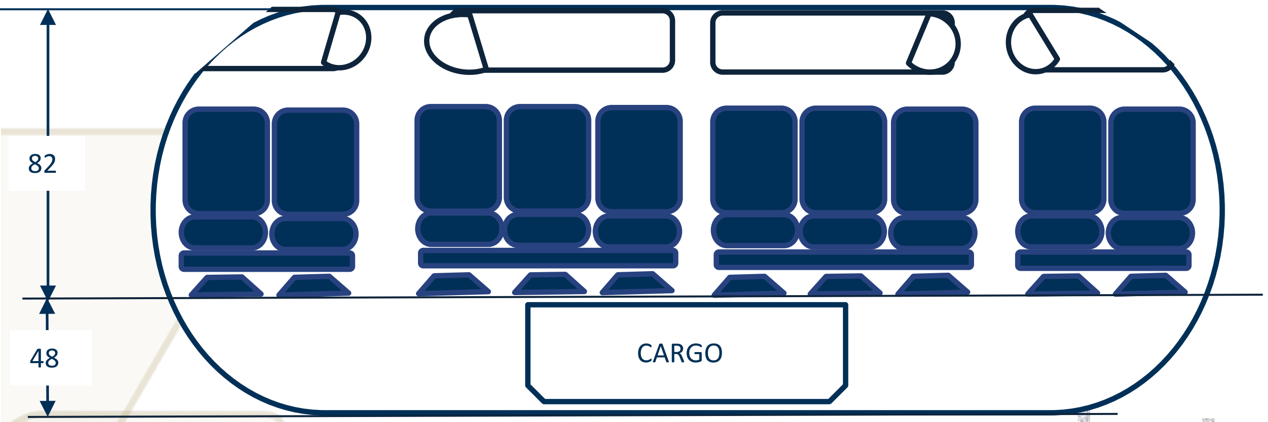


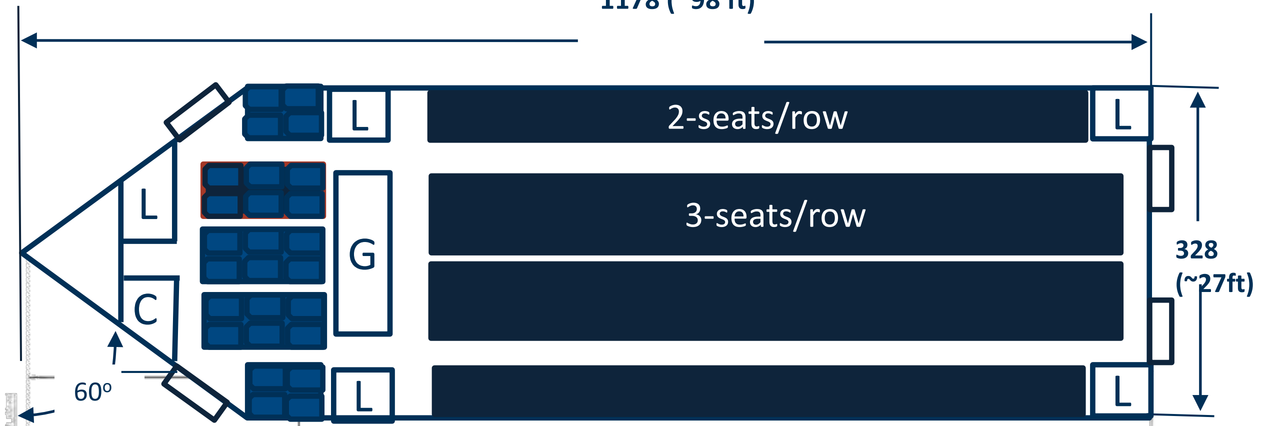
Lyu, Zhoujie, and Joaquim RRA Martins. "RANS-based aerodynamic shape optimization of a blended-wing-body aircraft." 21st AIAA Computational Fluid Dynamics Conference. 2013.

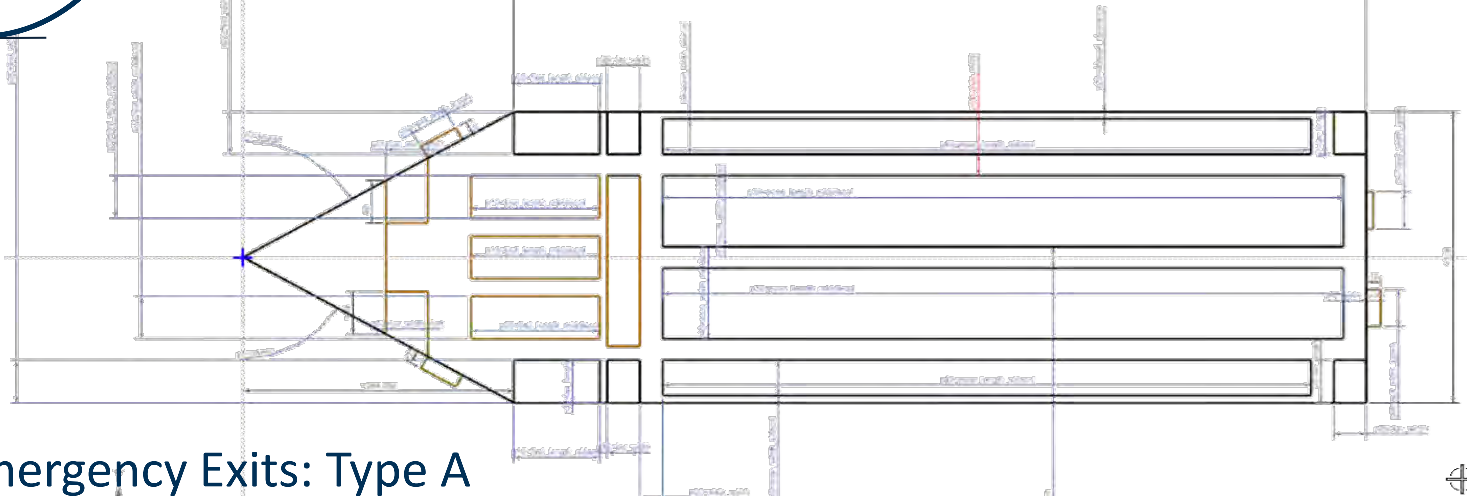
Cabin Design as an Aero-Structural Optimization Constraint

Cabin Layout: BWB – 264 PAX

All dimensions in inches





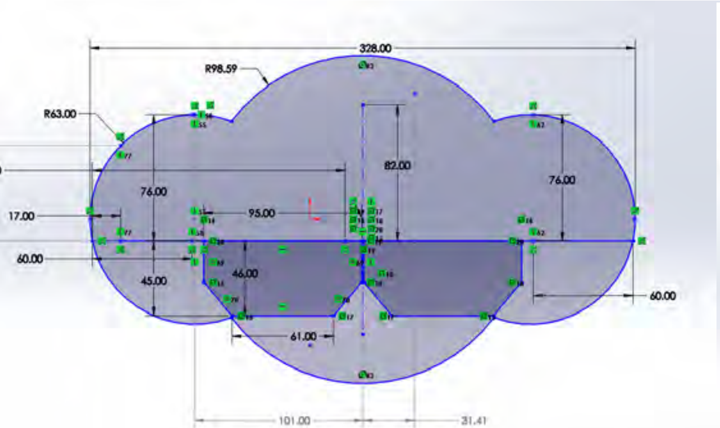


Assumptions:

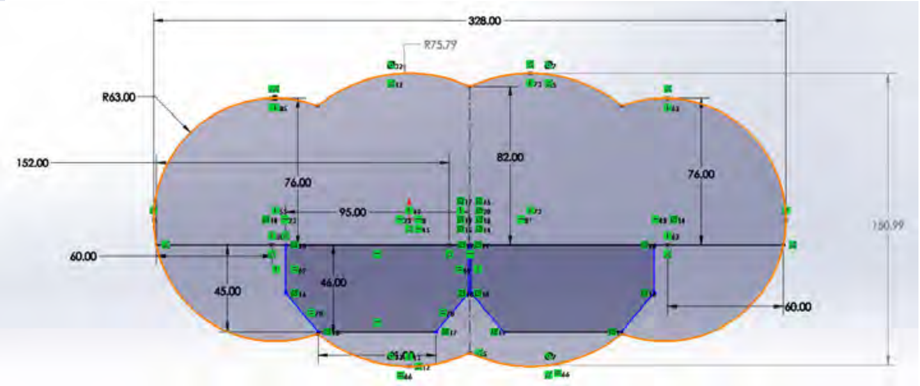
- For Business class used the Delta one seats
  - 45 in pitch, 24 in width
- For Economy class used the Comfort+ seats
  - 34 in pitch
  - 18 in width

- Emergency Exits: Type A
  - 42 in wide by 72 in high, with corner radii not greater than seven inches
- Cargo
  - 2 bays of LD3-45 containers

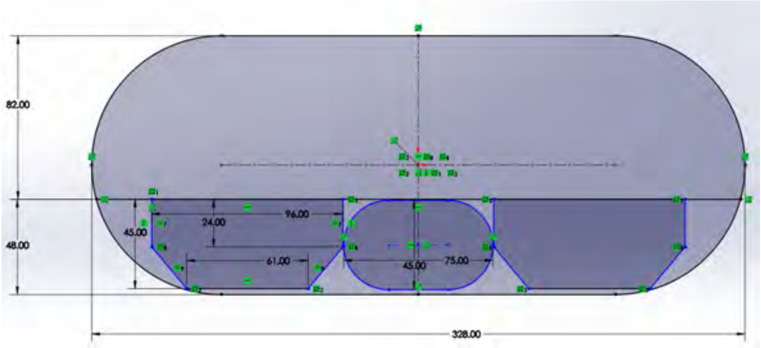
Pressurized Cabin Design : Structural Considerations



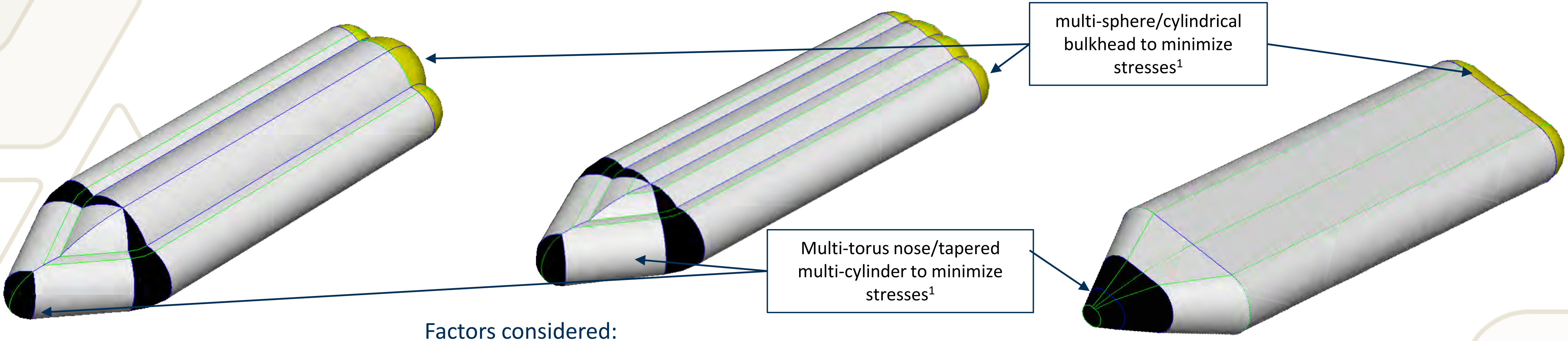
Multi-bubble (3-bubble section)



Multi-bubble (4-bubble section)



Elongated Oval (Racetrack section)

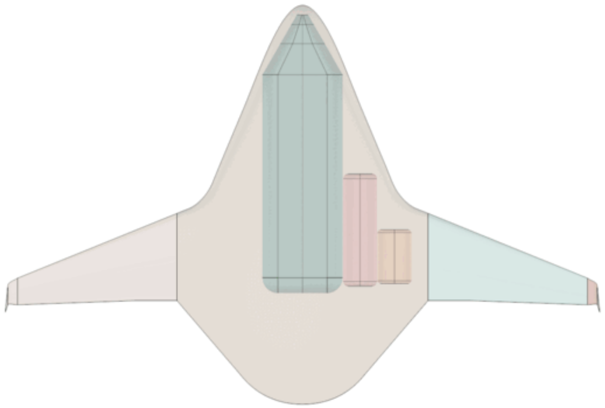


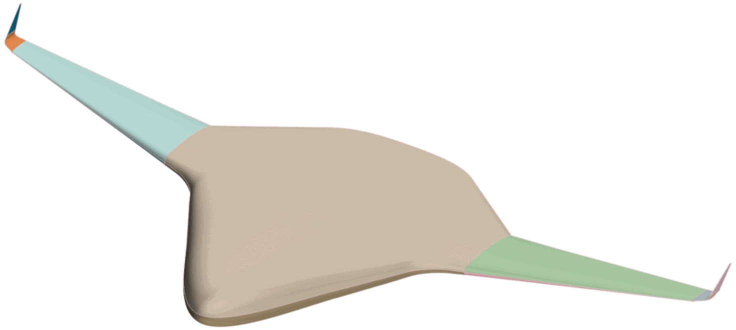
Factors considered:

- Overall cabin height
- Passenger comfort
- Cabin interior design flexibility
- Cabin area to weight ratio (determined using FEA[2])

Optimal Design Space Exploration Informed by Design Constraints

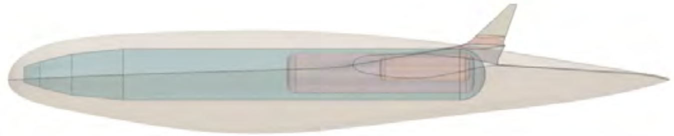
Span, Sweep & Chord Variations





Wing Dihedral, Twist Variations

Airfoil Shape/Thickness Variation



- High fidelity CFD simulations are expensive (HPC time and cost)
- DoE samples are filtered based on the design volume and thickness constraints
- Optimal exploration of the variation domain helps avoid using non-informative simulation points and build surrogates with more relevant training data

Variable Fidelity Surrogate-based Aerodynamic Optimization

X^i = Design Variable i

Inputs: (X^m)

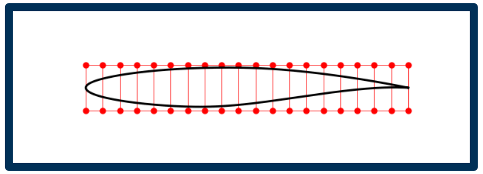
1.1 Euler-based CFD

Outputs: $f(X^m)$

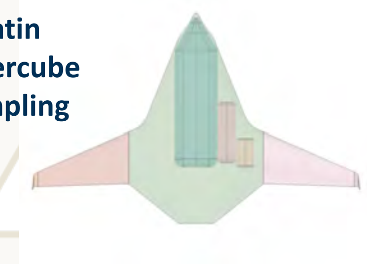
Inputs: $f(X^m)$,

1.2 Reduce Dimension
Method: Active Subspace

Multi-criteria Objective function
g($f(X)$)



Latin Hypercube Sampling



Outputs: $(X^m \rightarrow X^n)$

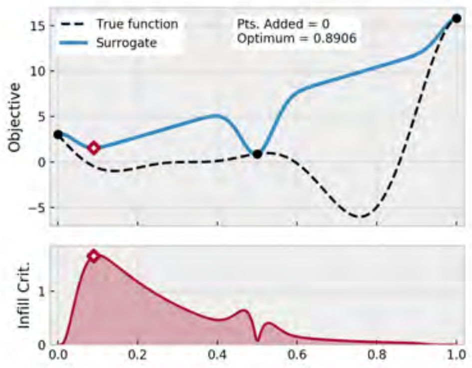
Inputs: $\widehat{X}^n$

2. Construct NS-based Surrogate
Method: Krigging and Adaptive Sampling

Outputs: $\hat{f}\ (\widehat{X}^n)$

3. Evaluate Objective Function

Outputs: $g\ (\hat{f}\ (\widehat{X}^n))$



CONVERGED ?

No

Infill 5 design points

Yes

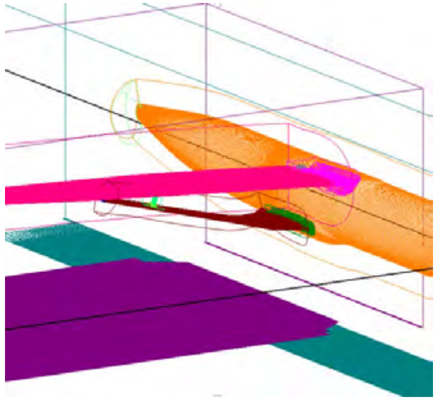
DONE

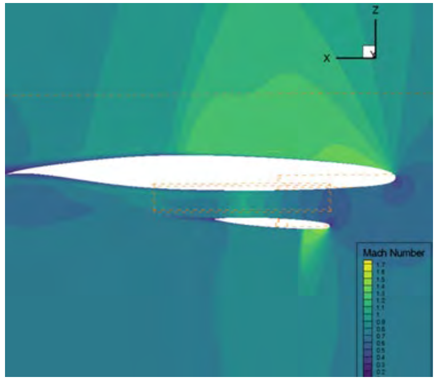
TTBW Aerodynamic Design Optimization Capability

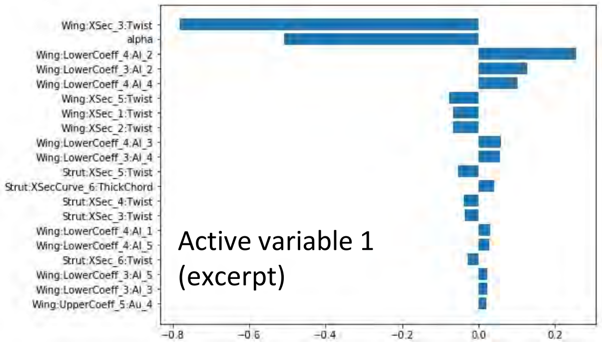
- A two step multi-fidelity approach for efficiently optimizing the aerodynamic performance of the TTBW

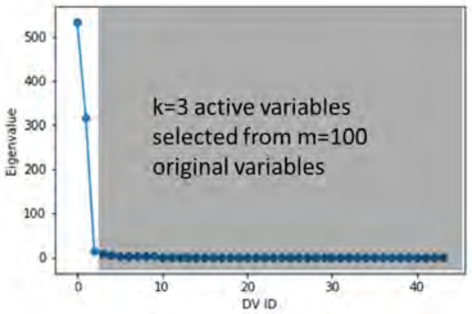
- Step 1: Dimensionality reduction using the active subspace method (gradient based or gradient free)
  - Using an inviscid CFD solver like Cart3D
  - Cheap and relatively quick to run compared to RANS

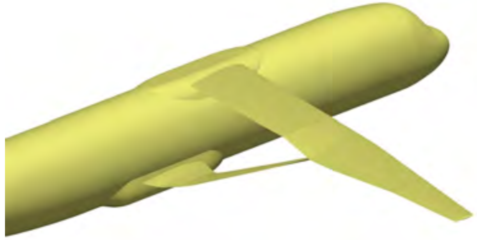
- Step 2: Bayesian adaptive sampling to efficiently march towards an improved design
  - Using RANS CFD
  - Gradient free approach
  - Balances exploration of the design space while exploiting potential regions of good performance



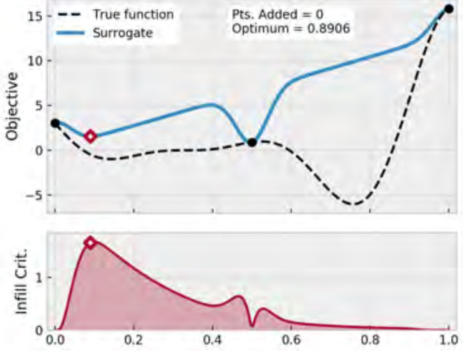






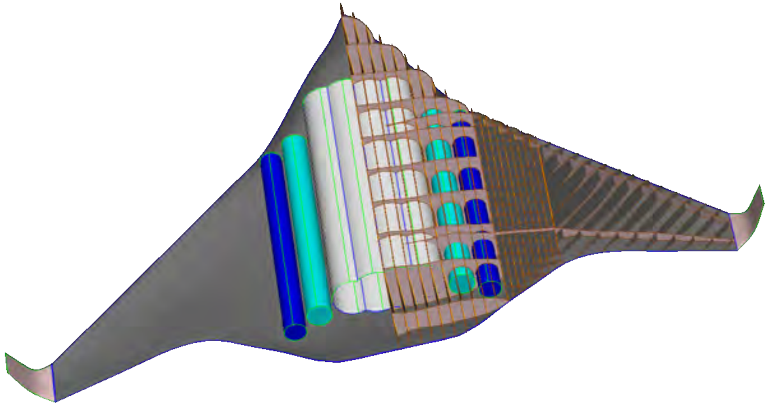


"How much do we expect L/D to improve if we run the next design point?"



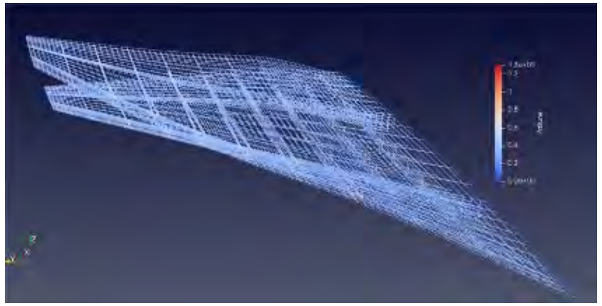
BWB Structural Optimization

ESP Geometry → 1. Internal Structure Generation in ESP



↓ CAPS2FUN

2. FUN3D and TACS[7] aeroelastic analysis → 3. Adjoint-based gradient evaluation for properties optimization (pyOPT)



↓

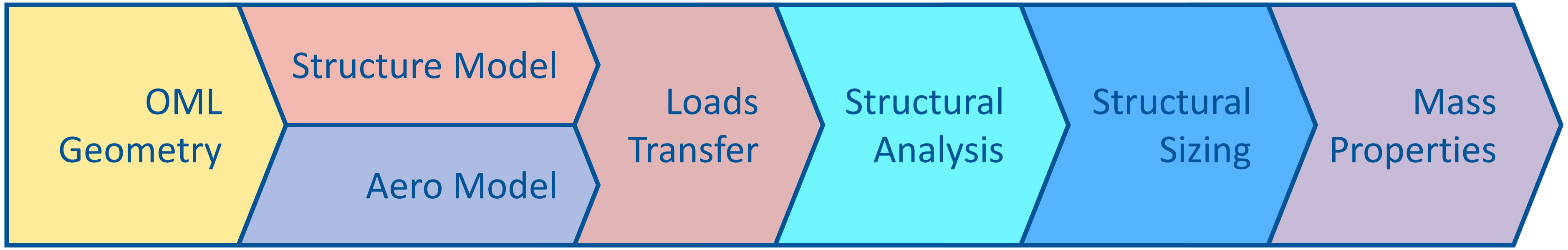
4. Update Geometry with optimized structure → (CAPS2FUN) → 2. FUN3D and TACS[7] aeroelastic analysis

4. Update Geometry with optimized structure → Extract Optimized Structure Properties

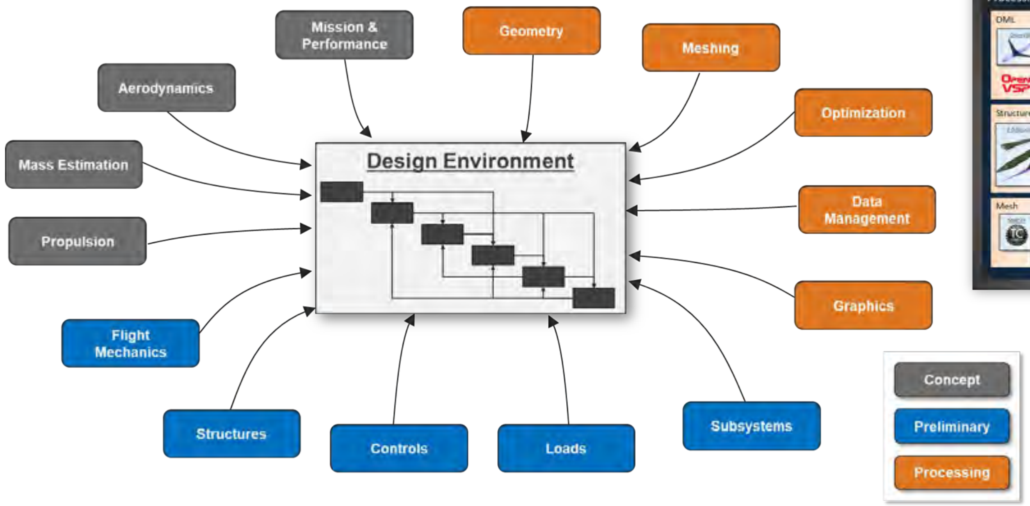
Component	Weight	Dimensions
Frame group	xx.xx	xx.xx
Stringer group	xx.xx	xx.xx
Skin group	xx.xx	xx.xx
Support group	xx.xx	xx.xx

Overview of Structural Sizing Approach

Workflow for Structural Weight Estimation



Enabled by Rapid Airframe Design Environment (RADE)



1. Jason Corman

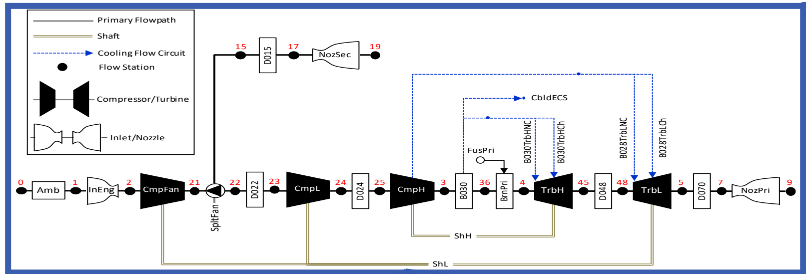
Propulsion System Modeling

GT Representation of RISE

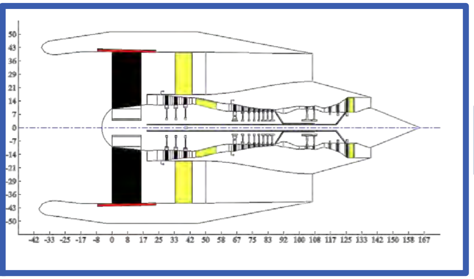
GT Representation of Geared Turbofan

GT Representation of Direct Drive Turbofan

Parametric Numerical Propulsion System Simulation (NPSS) Model



Flowpath (WATE++) Model



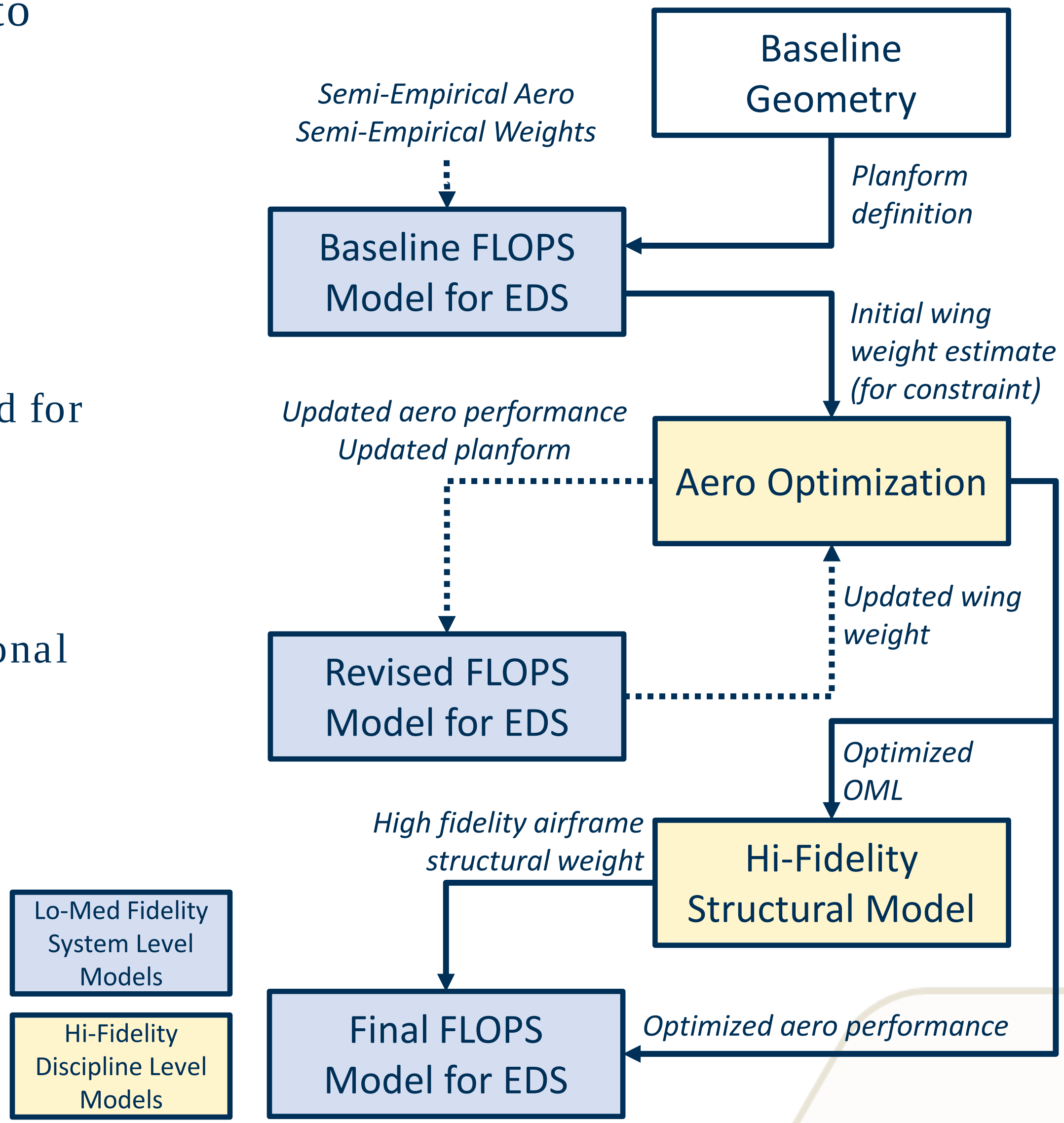
- Multi-Design Point Sizing
- Size Effects
- Parametric component maps
- Cooling flow sizing
- Operability Management
- Cycle Optimization
- Power Management

Engine Performance Deck for Mission Analysis

Mach	Altitude	Power Code	Gross Thrust	Ram Drag	Fuel Flow	TSFC
0.00	0.0	0	97300.0	0.0	28176.2	0.28958
0.00	0.0	0	90813.3	0.0	25699.3	0.28299
0.00	0.0	0	84326.7	0.0	23509.5	0.27879
0.00	0.0	0	71353.3	0.0	19480.7	0.27302
0.00	0.0	0	58380.0	0.0	15795.0	0.27055
0.00	0.0	0	45406.7	0.0	12147.5	0.26753
0.00	0.0	0	32433.3	0.0	8530.6	0.26302
0.00	0.0	0	19460.0	0.0	5249.2	0.26974
0.00	0.0	0	13622.0	0.0	3921.1	0.28785
0.00	0.0	0	7784.0	0.0	2681.9	0.34454
0.00	0.0	0	4865.0	0.0	2129.4	0.43770
0.10	0.0	0	101255.2	11079.0	29339.2	0.32535
0.10	0.0	0	94913.4	10748.9	26685.0	0.31706
0.10	0.0	0	88536.4	10383.7	24465.8	0.31305
0.10	0.0	0	75727.2	9598.0	20359.3	0.30787
0.10	0.0	0	62836.6	8730.8	16634.9	0.30745
0.10	0.0	0	49855.6	7773.4	12959.5	0.30796
0.10	0.0	0	36736.6	6677.8	9290.7	0.30908
0.10	0.0	0	23367.1	5331.8	5836.3	0.32361
0.10	0.0	0	17202.1	4577.4	4412.0	0.34948
0.10	0.0	0	10850.9	3636.8	3048.0	0.42251
0.10	0.0	0	7539.2	2759.0	2137.6	0.53181
0.20	0.0	0	104420.3	22526.7	29592.0	0.36135
0.20	0.0	0	98343.2	21909.1	27076.0	0.35424
0.20	0.0	0	92196.9	21222.4	24876.5	0.35050
0.20	0.0	0	79795.9	19740.6	20806.4	0.34645
0.20	0.0	0	67239.4	18103.2	17093.1	0.34787
0.20	0.0	0	54510.2	16293.1	13458.7	0.35217
0.20	0.0	0	41530.8	14232.9	9819.4	0.35971
0.20	0.0	0	28096.5	11717.7	6282.9	0.38360
0.20	0.0	0	21790.8	10325.7	4752.7	0.41453
0.20	0.0	0	15178.0	8626.5	3294.7	0.50290
0.20	0.0	0	11655.0	6750.5	2139.2	0.63580
0.25	0.0	0	106920.5	28520.5	29786.4	0.37993

Development of a System Level Model

- Need to tie high-fidelity aero and structural optimization efforts to fuel burn and emissions estimates
- An EDS model provides the required mapping
  - Changes to the OML can be captured through modifications of a FLOPS model
  - FLOPS + NPSS + WATE++ along with other codes in EDS together provide a system level performance estimate
  - Aerodynamic performance and structural weight estimates required for mission analysis is replaced with higher fidelity estimates
- EDS model also allows for leveraging existing capabilities to:
  - Investigate multiple engine architectures for a given airframe (notional GEnx, notional PW1133, SROR, etc.)
  - Swap out conventional Jet-A powered engines with LH2 powered engines
  - Consider hybrid-electric propulsion architectures
  - Optimize the cycle for any engine to best match the given airframe



System Level Results to Come

	Fuel Burn Improvement**	Noise Improvement***
T&W Baseline (Jet-A)	--	--
T&W 2030 Technology Reference Aircraft (Jet-A)*		
2030 T&W Turbofan (Jet-A) + Mild Electrification		
2030 T&W Turbofan (LH2)		
2030 T&W Turbofan (LH2) + Mild Electrification		
2030 T&W SROR (Jet-A)		
2030 T&W SROR (Jet-A) + Mild Electrification		
2030 BWB Turbofan (Jet-A)		
2030 BWB Turbofan (LH2)		
2030 BWB Turbofan (LH2) + Mild Electrification		
2030 SBW Turbofan (Jet-A)		
2030 SBW Turbofan (Jet-A) + Mild Electrification		

*Relative to T&W Baseline

**Relative to 2030 TRA

***EPNdB Margin Relative to Chapter 14

Summary Remarks

- Presented parametric modeling capabilities for future concepts aimed at zero carbon emissions
  - Parametric geometry generation for both aero and structural optimization
    - Accounting for cabin and tank constraints
  - Multifidelity aerodynamic modeling
    - Adaptive sampling
    - Active subspace optimization
  - Hydrogen tank model
  - Structural weight prediction
  - Parametric NPSS/WATE++ engine modeling
- These modeling elements are needed for capturing system level impacts of potential future sustainable concepts