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Subsonic Ultra Green Aircraft Research Phase II: N+4 Advanced Concept Development

Marty K. Bradley and Christopher K. Droney
Boeing Research and Technology, Huntington Beach, California

May 2012

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Space Administration

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Abstract

This final report documents the work of the Boeing Subsonic Ultra Green Aircraft Research (SUGAR) team on Task 1 of the Phase II effort. The team consisted of Boeing Research and Technology, Boeing Commercial Airplanes, General Electric, and Georgia Tech.

Using a quantitative workshop process, the following technologies, appropriate to aircraft operational in the N+4 2040 timeframe, were identified: Liquefied Natural Gas (LNG), Hydrogen, fuel cell hybrids, battery electric hybrids, Low Energy Nuclear (LENR), boundary layer ingestion propulsion (BLI), unducted fans and advanced propellers, and combinations. Technology development plans were developed.

The team generated a series of configurations with different combinations of some of these technologies. The higher heating value of LNG reduces the weight of fuel burned, but because of heavier aircraft systems, more energy is used for a given flight. LNG fueled aircraft have the potential for significant emissions advantages and LNG enhances the integration of fuel cells into the aircraft propulsion and power system.

An unducted fan increases propulsive efficiency and reduces fuel burn. Adding a fuel cell and electric motor into the propulsion system also leads to improvements in emissions and fuel burn. An aft fuselage boundary layer propulsor also resulted in a fuel burn benefit.

Foreword

Part of the mission of Boeing Research & Technology, as the company's advanced, central research and technology organization, is to help create the long-term future of aerospace by identifying and maturing new technologies.

However, while Boeing is interested in developing environmentally progressive vehicles, it would be premature to conclude that any of the concepts studied under this contract will replace any of Boeing's commercial products.

This is an advanced concept and technology study that examines a wide variety of alternative fuel and energy technologies and is not an offer, commitment or promise on the performance or capabilities of any future Boeing product.

Acknowledgments

This project and report reflect the combined efforts of the SUGAR Task 1 team. The team members for this task are Boeing Research and Technology, Boeing Commercial Airplanes, GE Aviation, and the Georgia Institute of Technology. The coordinated effort of this team has produced this report.

The team would like to thank Erik Olson and Mark Guynn of the NASA Langley Research Center for their guidance as the NASA Contracting Officer Technical Representative (COTR), and task technical advisor (TA), respectively. The team would also like to thank Gerry Brown, a NASA subject matter expert, for his contribution.

Additionally, other experts from NASA, the Department of Energy, the Air Force Research Lab, the Federal Aviation Administration, and Virginia Tech contributed during the N+4 technology workshop or made suggestions for the Energy Study Outline.

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Nomenclature

APU	Auxiliary Power Unit
ASDL	Georgia Tech Aerospace Systems Design Laboratory
BET	Boeing Equivalent Thrust foe engine sizing
BLI	Boundary Layer Ingestion
BOP	Balance of Plant for fuel cell systems
CASES	Boeing Computer Aided Sizing and Evaluation System
C_D	Drag Coefficient
CFD	Computational Fluid Dynamics
CH4	Methane
C_L	Lift Coefficient
COTR	NASA Contracting Officer Technical Representative
DF	Ducted Fan
DOC	Direct Operating Cost
DoE	Department of Energy
DP	Distributed Propulsion
DTE	Divergent Trailing Edge airfoil
EIS	Entry Into Service date
ERA	Environmentally Responsible Aviation
ERA	Environmentally Responsible Aviation
FAA	Federal Aviation Administration
FC	Fuel Cell
FEM	Finite Element Model
GE	General Electric
GT	Georgia Tech or Gas Turbine
H2	Hydrogen
HE	Hybrid Electric propulsion
ICAC	Initial Cruise Altitude Capability
ISA	International Standard Atmosphere
JP	Conventional Jet fuel (Jet-A, JP8, etc.)
L/D	Lift to Drag ratio
LENR	Low Energy Nuclear Reactor (or Reaction)
LNG	Liquefied Natural Gas
LP	Low Pressure spool of the engine
LRC	Long Range Cruise Mach
LTO	Landing and Takeoff
M	Mach number
MADM	Multi-Attributes Decision Making
MEW	Manufacturer’s Empty Weight
MIT	Massachusetts Institute of Technology
MTOW	Maximum Takeoff Weight
NFPA	National Fire Protection Association
NLF	Natural Laminar Flow
NOx	Molecules such as NO, NO2, NO3, etc.
OEW	Operational Empty Weight
OML	Outer Mold Line

RE	Reynolds Number
SC	Superconducting
SOFC	Solid Oxide Fuel Cell
SUGAR	Subsonic Ultra Green Aircraft Research
TA	NASA Task Technical Advisor
TOFL	Takeoff Field Length
TOGW	Takeoff Gross Weight
TOPSIS	Technique for Ordered Preference by Similarity to Ideal Solutions
TP	Turboprop
TRL	Technology Readiness Level
UDF	Unducted Fan (also open fan or open rotor)
VT	Virginia Tech

1.0 Introduction

In the SUGAR Phase I study(1), Boeing identified and analyzed advanced concepts and technologies for aircraft that would fly in the 2030-2035 timeframe. One of the recommendations from that study was to conduct a follow-on study to consider the synergistic benefits of methane and/or hydrogen fuel.

Considering the Boeing results and recommendations, those of the other contractor teams, as well as other NASA experts, NASA developed Research Objectives for Phase II which included:

- N+4 Advanced Vehicle Concept Study to leverage the substantial investment of Phase I and study the effect of additional technology development time beyond that assumed in Phase I

Boeing structured an N+4 task in the SUGAR Phase II program to address the recommendations from Phase I as well as the research objective provided by NASA. A summary of the N+4 task statement of work is included here:

1. Define advanced turbofan, hybrid electric, and open rotor engines with an Entry into Service (EIS) date of 2040-50
2. Study propulsion systems based on cryogenic fuels that are used to cryogenically cool components
    - Assess how the use of cryogenic fuel enables fuel cells
    - Qualitatively assess how the cryogenic technologies affect the operations, safety and economics of engine and aircraft designs
3. Develop a reference conventional aircraft configuration and determine its fuel burn, emissions, noise and takeoff performance
4. Develop an advanced unconventional aircraft configuration with an EIS date of 2040-50 and determine its fuel burn, emissions, and noise and takeoff performance.
5. Identify advanced technologies that are most applicable to the 2040-50 timeframe and compatible with the reference and unconventional aircraft configurations.
6. Using an approach similar to that in Phase I, the contractor shall evaluate and rank the chosen technologies and generate technology development roadmaps.

The work in this task was structured into the subtasks shown in Figure 1.1, and the approach and results are discussed in the sections that follow. The results in this task are assessed against the updated set of NASA N+3 goals shown in Figure 1.2.

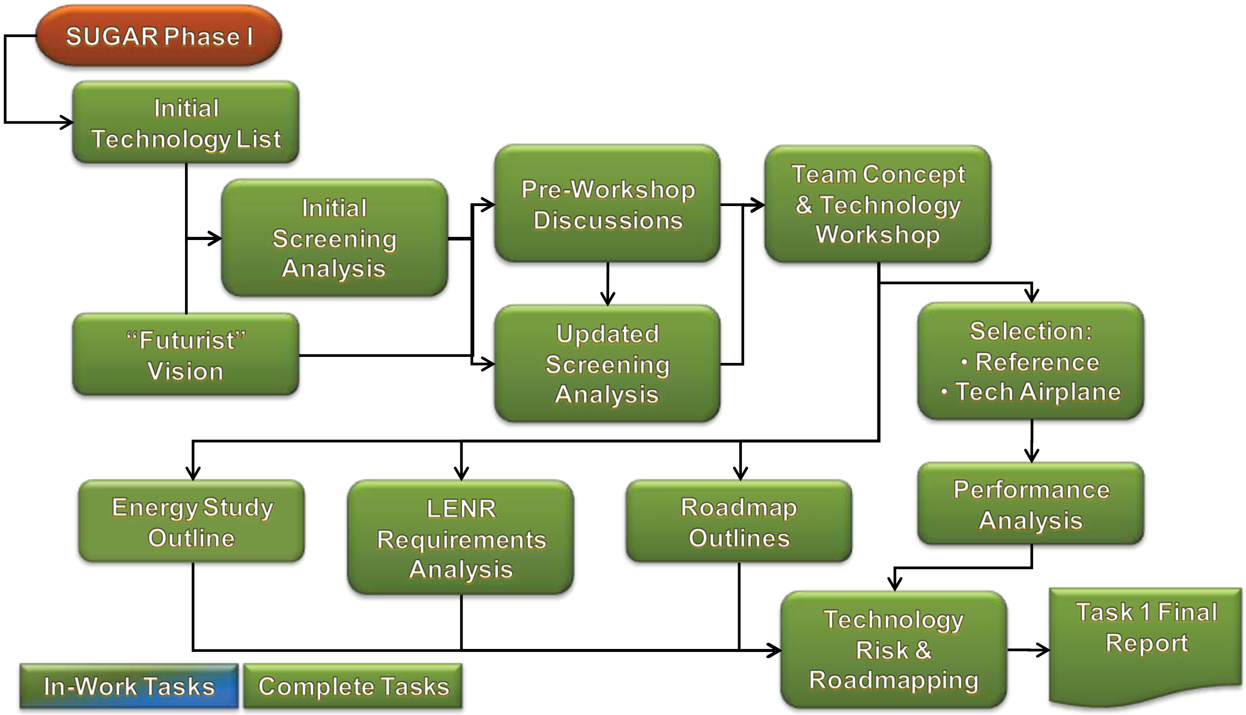
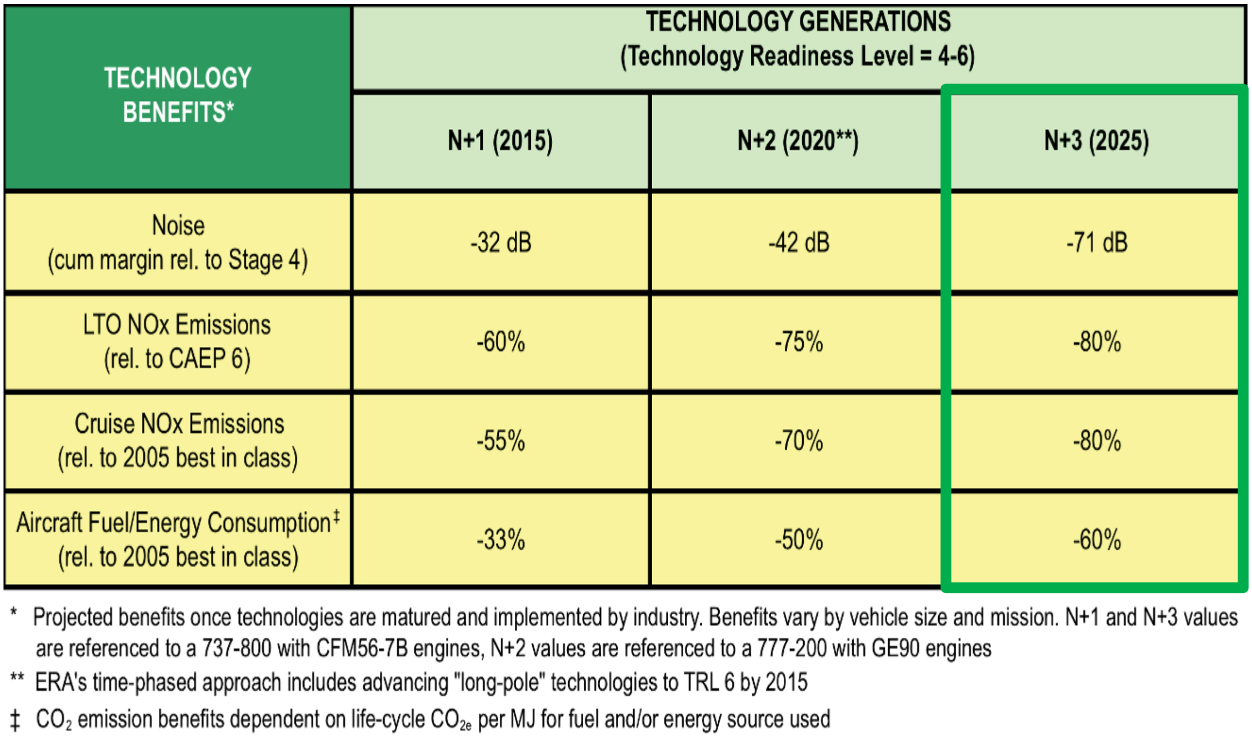


Figure 1.1 – SUGAR N+4 Task Flow



TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-71 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)	-33%	-50%	-60%

* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines

** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

‡ CO_2 emission benefits dependent on life-cycle CO_{2e} per MJ for fuel and/or energy source used

Figure 1.2 – NASA Noise, Emissions, Fuel, and Energy Goals

2.0 Technology Selection

Based on the Phase I recommendations and the requirements of the statement of work, the task was begun with the following list of technologies to consider:

- Hybrid battery-gas turbine propulsion with ducted fan & open rotor
- Fuel cells
- Fuel cell-gas turbine hybrid propulsion systems
- Cryogenic fuels including methane & hydrogen
- Cryogenically cool generators, motors, converters and transmission lines
- Cryogenic fuel allowing supplemental power to be supplied by fuel cells
- Advanced batteries
- Other technologies also can get better

The Boeing Company solicited input from the Georgia Tech Aerospace Systems Design Laboratory (ASDL) to apply their expertise in the areas of technology planning. Working closely with Boeing and General Electric, ASDL modified the process utilized in Phase I to select advanced technologies and enhance the Phase I technology roadmaps to the extended N+4 timeframe.

2.1 Process Overview and Background

In SUGAR Phase I, the development of the technology roadmaps was based on a clean sheet design. The process developed for Phase I focused on utilizing qualitative and consensus building techniques to identify the concepts and technologies that would be quantitatively analyzed. However, for SUGAR Phase II, The Boeing Company utilized a simplified spreadsheet based method to enable quantitative analysis of a multitude of configurations and technologies to help inform the N+4 workshop decisions. Based on having quantitative data on various concepts and technologies, a process to down select to the most promising N+4 technologies and concepts was developed.

The process utilized Systems Engineering techniques such as Matrix of Alternatives, Multi-Attributes Decision Making (MADM) and Technique for Ordered Preference by Similarity to Ideal Solutions (TOPSIS) to assist in identifying promising technologies to meet the NASA goals. The direction provided to the team as an outcome of Phase I was to consider alternative energy sources and refine the N+4 configuration and technology set. The flow of the evolution of the SUGAR Free to the N+4 Super Refined SUGAR is depicted in Figure 2.1.

The same Phase I Baseline SUGAR Free and Refined SUGAR configurations were used, but an N+4 Reference needed to be developed. This N+4 Reference configuration is an improved version of the conventional tube and wing Super Refined SUGAR which utilizes the gFan+

engine, all applicable previous aerodynamics, subsystems, and structures N+3 technologies. It has a 118 foot constrained wingspan and a weight reduction relative to N+3 technologies.

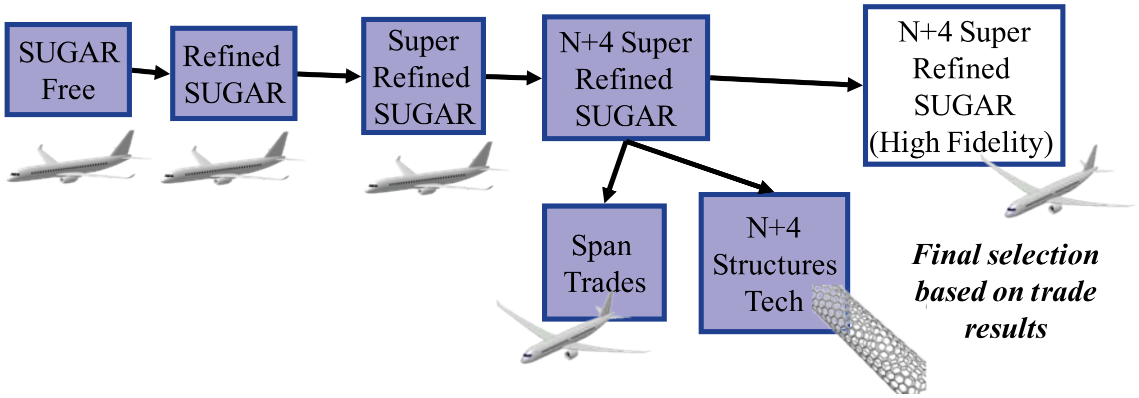


Figure 2.1 – Evolution of the N+4 Reference Concept

Once the N+4 Super Refined SUGAR was established, a process was developed, Figure 2.2, to evaluate possible N+4 technologies which initially included:

- Hybrid battery-gas turbine propulsion (HE)
- Fuel cells (FC)
- Fuel cell-gas turbine hybrid propulsion systems
- Cryogenic fuels (e.g. methane & hydrogen)
- Cryogenically cool engines, generators, motors, converters and transmission lines (SC)
- Cryogenic fuel allowing supplemental power to be supplied by fuel cells
- Advanced batteries
- Open rotor/turboprop
- Other technologies that could get better beyond the N+3 assumed level

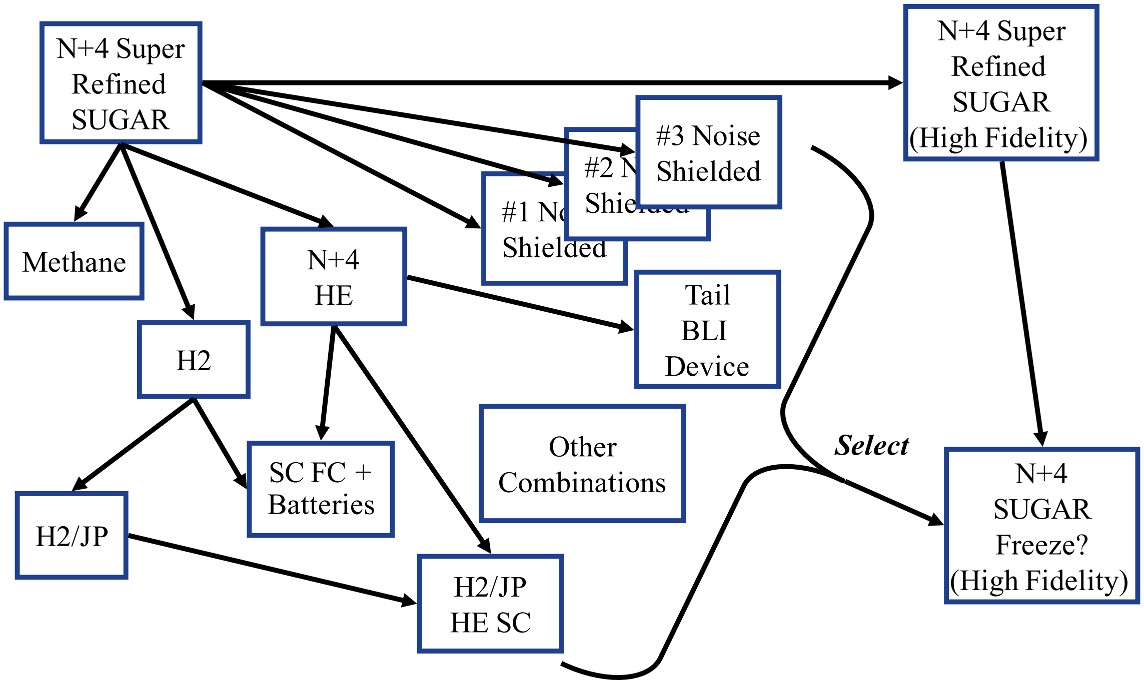


Figure 2.2 – N+4 Configuration Analysis Flow

A number of technology combinations were developed, a subset of which is depicted in Figure 2.3. The spreadsheet analysis described previously was used to quantitatively assess these various technology and vehicle options with respect to the NASA goals. This acted as a screening exercise which filtered the concepts and technologies to be scored during the workshop. A set of metrics was established to quantitatively compare different concepts which included block energy, global emissions, landing and takeoff (LTO) emissions, noise, cost, and technology maturation risk. As a result of the pre-screening, 4 major configurations were identified and included a reference N+4 system, a conventional fuel system, a hydrogen fueled system, and a methane-natural gas system. Consideration was also given to how to incorporate more noise shielding as the configuration was refined.

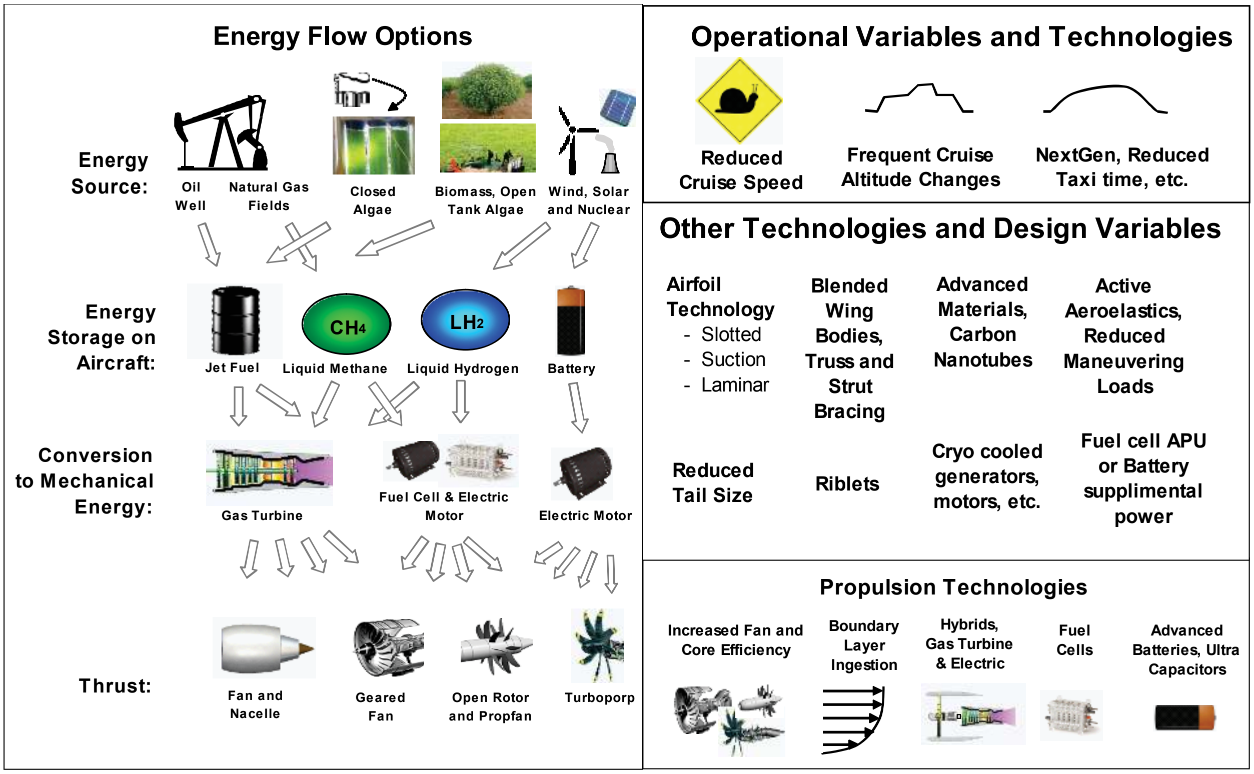


Figure 2.3 – N+4 Configuration Initial Screening – Technologies and Options

2.2 Pre-workshop activities

The team developed a number of pre-workshop activities that were conducted over a series of Webex teleconferences. An initial pre-workshop kickoff Webex was held on May 18, 2011 to frame the workshop context and introduce NASA personnel and the team to prior analysis and the game plan moving forward. The agenda of the kickoff included:

- Futurist vision presentation on different energy scenarios
- Review of initial concepts and technology screening work and technology performance assumptions for propulsion core and fan efficiencies, laminar flow, and structural weight, cryo tanks, fuel cells. Metrics for concept evaluation were also discussed.
- Overview of the process approach during the workshop
- Identify pre-workshop assignments/actions for the participants
- Recommended adjustments to technology assumptions
- Information on alternate configurations to share

As a follow up to the kickoff Webex, two subsequent Webex meetings were held on June 1 and June 15, 2011. The primary focus of these telecons was to:

- Review of any pre-work from the participants

  - Recommended adjustments to technology assumptions including propulsion system performance (GE)
  - Technology discussions– Presentations were made that covered hydrogen technology (NASA, GT, and Boeing), distributed propulsion (Boeing and GE), and Low Energy Nuclear Reactors (Boeing)
  - New configurations to consider – Configuration with noise shielding (Boeing) and previous work on configurations with hydrogen tank integration (Boeing).
- Updated detailed plan for the workshop, including definitions of metrics and scales for scoring during the workshop
- Updated technologies and configurations assumptions and results including more information of battery, fuel cell, boundary layer ingestion propulsion, and cruise Mach sensitivity

2.3 N+4 Workshop Process

The general process for the two day workshop is depicted in Figure 2.4. To accomplish the desired goal of the workshop an agenda was developed to facilitate group discussions and the breakouts for three sub-teams: Onsite, Virtual East, and Virtual West. The agenda for the workshop was:

- Workshop logistics
- Workshop process overview and objectives
- Pre-workshop activities update
- Debrief of Purdue/FAA meeting (a separate advanced aviation technology meeting)
- Group breaks into sub-teams to score and refine each concept
  - Review initial concepts
  - Review technology assumptions
  - Individuals score each concept with respect to the metrics
  - Email file to facilitator
  - Facilitator will compile all scores
  - Group discussion on results (play with weightings on metrics)
  - Identify what technology gaps may exist
  - Identify how the noise can be improved
  - Refine the prioritized concept
  - Create out-brief
- Onsite team discusses concepts and scoring
- Virtual East discusses concepts and scoring
- Virtual West discusses concepts and scoring
- Identification of common elements between concepts

- All concepts discussion and ranking
- Identification of most promising concept/technology to take forward in the analysis
- Workshop wrap up and next steps

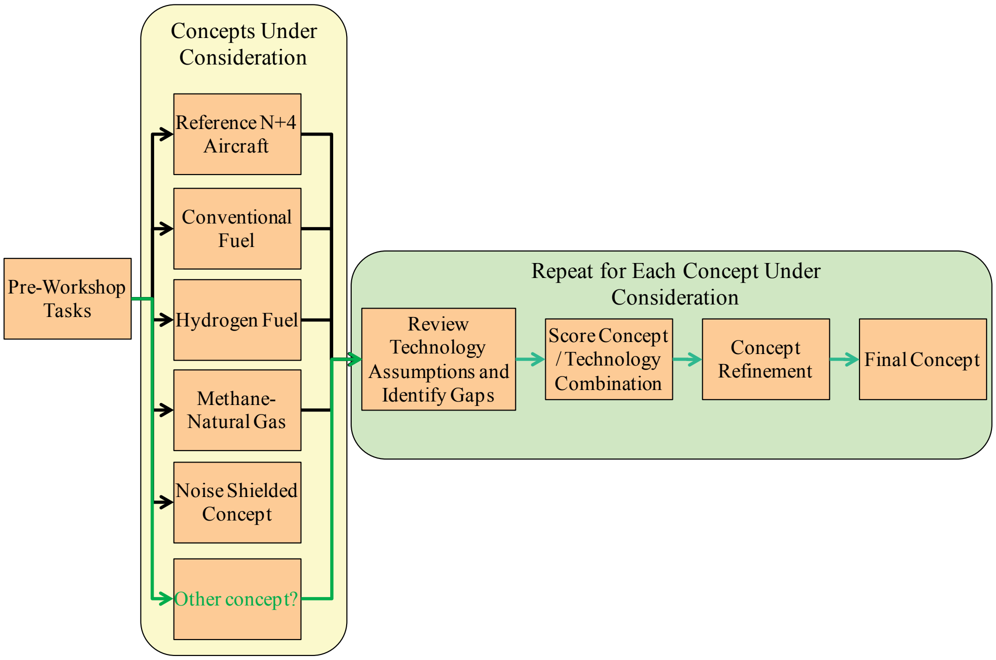


Figure 2.4 – N+4 Workshop Process Diagram

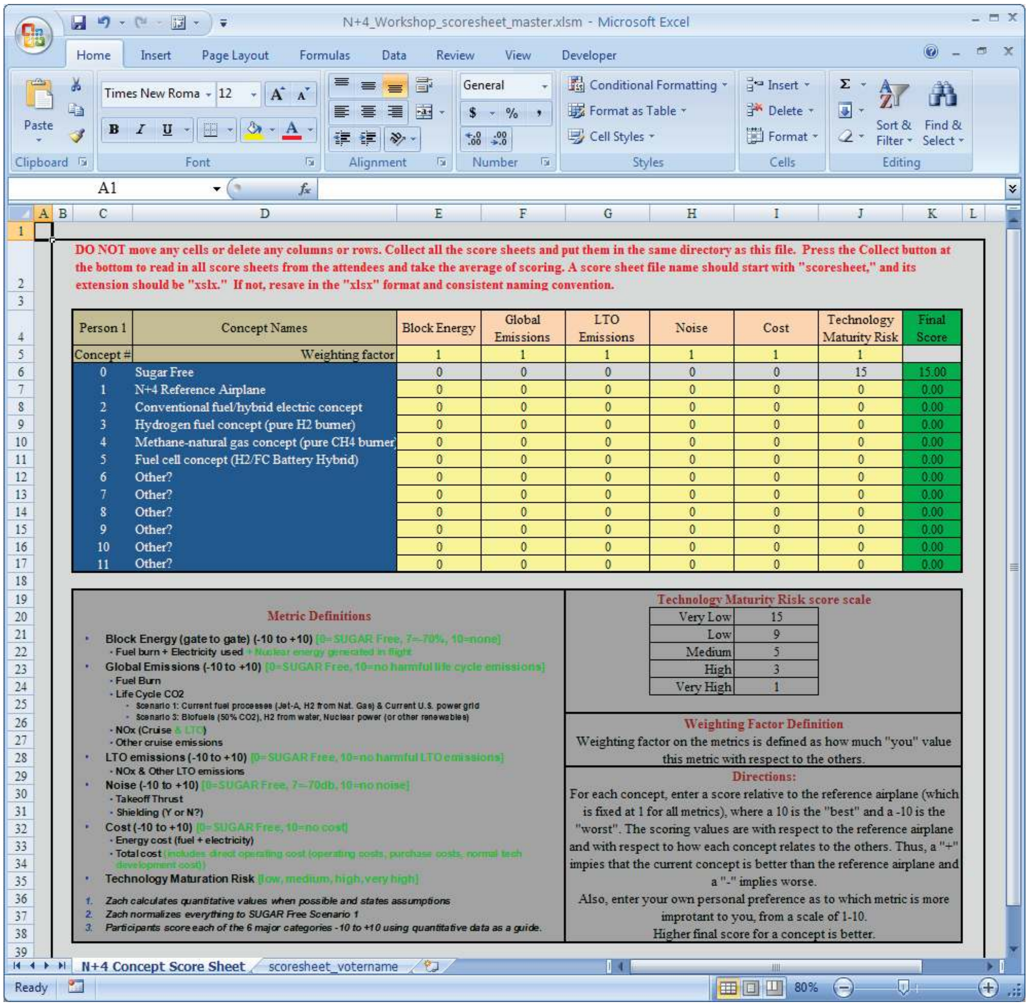
To facilitate the sub-team scoring, a spreadsheet template was developed and included a qualitative scale for the metrics under consideration and each team would independently score each concept. A snapshot of the template is depicted in Figure 2.5. Each team was instructed to score each concept against the metrics. The scales utilized for the metrics were developed by the whole team prior to the workshop and are defined in Table 2.1. The concepts to be scored included:

0. Scoring is relative to SUGAR Free Baseline (737NG Equivalent)
1. Reference airplane
2. Conventional fuel/hybrid electric concept
3. Hydrogen fuel concept (H_2 Burning)
4. Methane-natural gas concept (CH_4 Burning)
5. Fuel cell concept (H_2/FC Battery Hybrid)
6. Team selected alternate concepts, including:
    a. Distributed Propulsion
    b. Low Energy Nuclear Reactor (LENR)
    c. H2/FC Gas Turbine Hybrid
    d. Dual fuel H2/Jet-A burner

e. Other combinations
f. Other ideas

Table 2.1 – N+4 Workshop Scoring Metrics

	Min	Max
Block Energy	-10	10
Fuel Burn		
Electricity Used		
Nuclear Power		
Global Emissions	-10	10
Fuel Burn		
Life Cycle CO2		
Scenario 1: Current Fuel Process & Power Grid		
Scenario 2: Biofuels, H2 from Water, Nuclear Power		
NOx		
Other Cruise Emissions		
Emissions	-10	10
LTO Emissions		
NOx & Other Emissions		
Noise	-10	10
Takeoff Thrust		
Shielding		
Cost	-10	10
Energy Cost (Fuel + Electricity)		
Total Cost (includes DOC)		
Technology Maturation Risk	Low	Very High



DO NOT move any cells or delete any columns or rows. Collect all the score sheets and put them in the same directory as this file. Press the Collect button at the bottom to read in all score sheets from the attendees and take the average of scoring. A score sheet file name should start with "scoresheet," and its extension should be "xslx." If not, resave in the "xlsx" format and consistent naming convention.

Person 1	Concept Names	Block Energy	Global Emissions	LTO Emissions	Noise	Cost	Technology Maturity Risk	Final Score
Concept #	Weighting factor	1	1	1	1	1	1	
0	Sugar Free	0	0	0	0	0	15	15.00
1	N+4 Reference Airplane	0	0	0	0	0	0	0.00
2	Conventional fuel/hybrid electric concept	0	0	0	0	0	0	0.00
3	Hydrogen fuel concept (pure H2 burner)	0	0	0	0	0	0	0.00
4	Methane-natural gas concept (pure CH4 burner	0	0	0	0	0	0	0.00
5	Fuel cell concept (H2/FC Battery Hybrid)	0	0	0	0	0	0	0.00
6	Other?	0	0	0	0	0	0	0.00
7	Other?	0	0	0	0	0	0	0.00
8	Other?	0	0	0	0	0	0	0.00
9	Other?	0	0	0	0	0	0	0.00
10	Other?	0	0	0	0	0	0	0.00
11	Other?	0	0	0	0	0	0	0.00

Metric Definitions

- Block Energy (gate to gate) (-10 to +10) [0=SUGAR Free, 7=-70%, 10=none]
  - Fuel burn + Electricity used + Nuclear energy generated in flight
- Global Emissions (-10 to +10) [0=SUGAR Free, 10=no harmful life cycle emissions]
  - Fuel Burn
  - Life Cycle CO2
    - Scenario 1: Current fuel processes (Jet-A, H2 from Nat. Gas) & Current U.S. power grid
    - Scenario 3: Biofuels (50% CO2), H2 from water, Nuclear power (or other renewables)
  - NOx (Cruise & LTO)
  - Other cruise emissions
- LTO emissions (-10 to +10) [0=SUGAR Free, 10=no harmful LTO emissions]
  - NOx & Other LTO emissions
- Noise (-10 to +10) [0=SUGAR Free, 7=-70db, 10=no noise]
  - Takeoff Thrust
  - Shielding (Y or N?)
- Cost (-10 to +10) [0=SUGAR Free, 10=no cost]
  - Energy cost (fuel + electricity)
  - Total cost (includes direct operating cost (operating costs, purchase costs, normal tech development cost))
- Technology Maturation Risk [low, medium, high, very high]

1. *Zach calculates quantitative values when possible and states assumptions*
2. *Zach normalizes everything to SUGAR Free Scenario 1*
3. *Participants score each of the 6 major categories -10 to +10 using quantitative data as a guide.*

Technology Maturity Risk score scale

Very Low	15
Low	9
Medium	5
High	3
Very High	1

Weighting Factor Definition

Weighting factor on the metrics is defined as how much "you" value this metric with respect to the others.

Directions:

For each concept, enter a score relative to the reference airplane (which is fixed at 1 for all metrics), where a 10 is the "best" and a -10 is the "worst". The scoring values are with respect to the reference airplane and with respect to how each concept relates to the others. Thus, a "+" impies that the current concept is better than the reference airplane and a "-" implies worse.

Also, enter your own personal preference as to which metric is more improtant to you, from a scale of 1-10.

Higher final score for a concept is better.

Figure 2.5 – N+4 Workshop Score sheet Template

As part of the sub-team activities each team would need to: sketch each of the concepts, develop scoring rationale and any potential issues, identify any problems with determining individual scores and any wide differences of opinion, identify any key technologies needed to enable and enhance concept, and recommend an approach for the integration of noise shielding. To communicate the results to the entire team, each of the 3 teams would prepare and brief one or more slides for each concept considered. Finally, the teams would identify commonality amongst views and downselect to a handful of concepts and technologies to carry forward for the higher fidelity analysis after the workshop.

2.4 N+4 Workshop Outcomes

The work prepared prior to the workshop created tools and resources to facilitate a more streamlined execution of the workshop. Participation in the workshop was both in person and virtual; it was conducted on June 22 and 23, 2011 and consisted of personnel from Boeing, FAA, GE, GT, NASA, and VT. The participants were divided into three teams: Onsite, Virtual East, and

Virtual West, the members of each are listed in Table 2.2. The Onsite team was facilitated by Jimmy Tai (GT), the Virtual East by Marty Bradley (Boeing) and Michelle Kirby (GT), and the Virtual West by Blaine Rawdon (Boeing).

Table 2.2 – N+4 Workshop Teams

On Site Team	Virtual West Team	Virtual East Team
Bradley, Marty (Boeing)	Allen, Timothy (Boeing)	White, Edward (Boeing)
Daggett, David (Boeing)	Cotes, Dwaine (Boeing)	Gowda, Srini (GE)
Droney, Christopher(Boeing)	Guo, Yueping (Boeing)	Brown, Gerald (NASA)
Hoisington, Zachary (Boeing)	Foist, Brian (Boeing)	Wahls, Richard (NASA)
Kirby, Michelle (GT)	Rawdon, Blaine (Boeing)	Wells, Doug (NASA)
Murrow, Kurt (GE)	Wakayama, Sean (Boeing)	Jeffries, Rhett (FAA)
Ran, Hongjun (GT)	Dallara, Emily (Boeing)	Felder, James (NASA)
Nam, Teawoo (GT)	Kowalski, Ed (Boeing)	Schetz, Joe (VT)
Tai, Jimmy (GT)	Wat, Joe (Boeing)	Burley, Casey (NASA)
Hammel, Jeff (GE)	Robbana, Ismail (Boeing)	Sequiera, Christopher (FAA)
Perullo, Chris (GT)	Barmichev, Sergey (Boeing)	Martin, John (NASA)
Guynn, Mark (NASA)	Fink, Larry (Boeing)	Kapania, Rakesh (VT)
Olson, Erik (NASA)	Sankrithi, Mithra (Boeing)	
Leavitt, Larry (NASA)		

The workshop began with an overview of the process that would be used for its duration and to put everyone on the same page as to what their roles and expectations for participation were. A review of the definitions of the metrics to score was discussed and clarification questions were asked by a few participants to gain a clear understanding of what each metric implied. Subsequently, to facilitate an understanding of the concepts to score in the workshop, Boeing reviewed the general assumptions of the N+4 reference concept (Figure 2.6) and then each of the advanced concepts to be scored within the workshop. This information provided a common understanding for each team and an opportunity to ask any clarification questions before the larger group broke into sub-team activities.

- **N+3 Technology suite (NLF, Riblets, Adv Composites, N+3 mission)**
- **N+4 structural weight factors are a minor improvement over N+3 assumptions:**
  - **7.6% improvement in wing bending material strength/weight**
  - **2.3% Fuselage, Landing gear and Tail weight improvements**
  - **No change to propulsion weights**
  - **5.0% Reduction in all other miscellaneous items**
- **gFan+ turbine engine technology**
- **Natural laminar flow on wing upper surface, vertical and horizontal tails with limits for sweep, RE and shocks**
- **1000 Wh/kg batteries (N+3 assumption was 750)**
- **Jet-A: $4.00/Gallon**
- **No cost complexity factors used**
- **Hybrid and LH2 Production electricity cost: $.12/kWh**
- **Cost Outputs done for scenario 2.**
- **Cruise Mach: .70**

Aerodynamic Assumptions

Korn K (.95 adv supercrit)	0.93
Laminar Flow Level (0-4)	2
Wetted Area Roughness Factor	1.03
Upsweep Drag, ft^2	0.5
Flap Tracks, ft^5	0.5
Gear Pods, ft^2	0.5
Misc Base Drag, ft^2	1

Propulsion Assumptions

Electric Power Source	Battery
Battery Wh/KG	1000
Elec Motor Peak Efficiency	0.95
Wire Loss	0.99
Motor Contoller Loss	0.98
Gear Reduction Loss	0.985
Generator Efficiency	0.985

Configuration

Fuselage Vertical Diameter, feet	12.74
Fuselage Width, feet	12.74

Structural Assumptions (Wing)

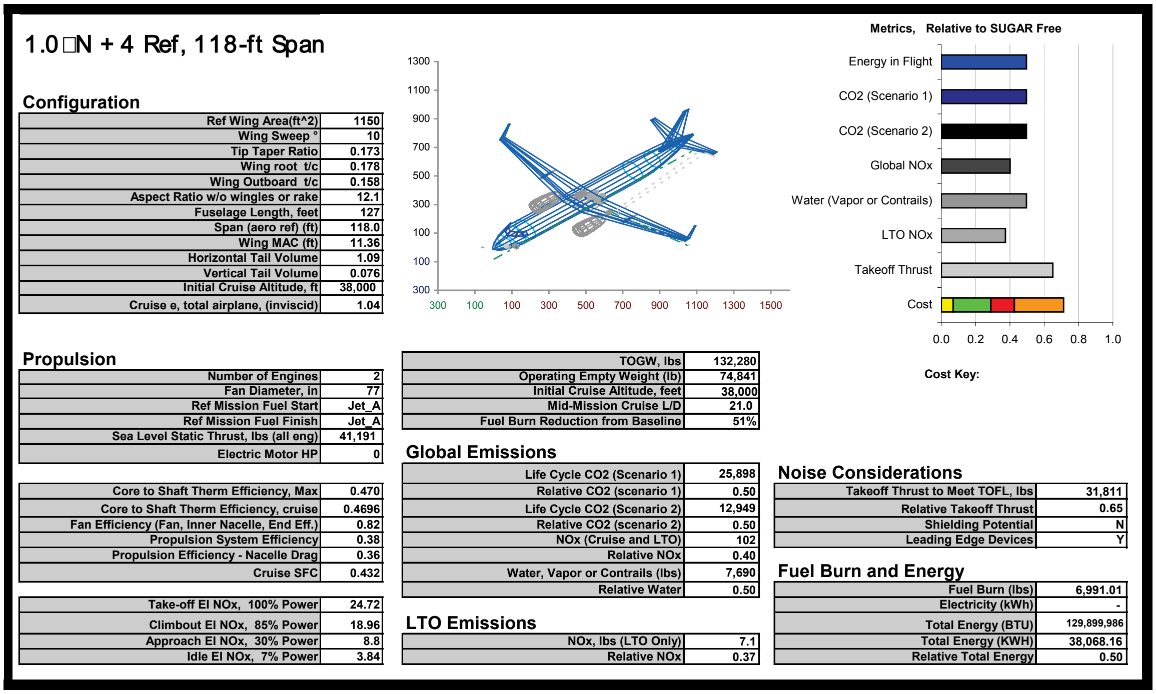
Stress at Limit Load, psi (upper)	70,000
density (lb/in^3, upper)	0.07
Stress at Limit Load (lower)	64,000
density (lb/in^3, lower)	0.07
Wing E	14,000,000
Strut E	20,000,000
Min Gauge Inboard (in)	0.20
Min Gauge Outboard (in)	0.10
Aerial Weight C1 (flat area)	3.45
Aerial Weight C2 (thickness)	2.6

Weight Assumptions

Fuse Weight Factor	0.82
Horizontal Tail Overall Wt Factor	0.825
Vertical Tail Overall Wt Factor	0.825
Landing Gear Overall Wt Factor	0.825
Fixed Equip, operation, misc	0.95

Figure 2.6 – N+4 General Assumptions

Next, the larger group was provided an overview of each of the main concepts brought to the workshop based on the spreadsheet analysis tool. A sample of the template used for each concept is provided in Figure 2.7. The modeling and technology assumptions were then discussed for each concept and the larger group then broke into the sub-teams to conduct the scoring.



1.0□N + 4 Ref, 118-ft Span

Configuration

Ref Wing Area(ft^2)	1150
Wing Sweep °	10
Tip Taper Ratio	0.173
Wing root t/c	0.178
Wing Outboard t/c	0.158
Aspect Ratio w/o wingles or rake	12.1
Fuselage Length, feet	127
Span (aero ref) (ft)	118.0
Wing MAC (ft)	11.36
Horizontal Tail Volume	1.09
Vertical Tail Volume	0.076
Initial Cruise Altitude, ft	38,000
Cruise e, total airplane, (inviscid)	1.04

Propulsion

Number of Engines	2
Fan Diameter, in	77
Ref Mission Fuel Start	Jet_A
Ref Mission Fuel Finish	Jet_A
Sea Level Static Thrust, lbs (all eng)	41,191
Electric Motor HP	0

Core to Shaft Therm Efficiency, Max	0.470
Core to Shaft Therm Efficiency, cruise	0.4696
Fan Efficiency (Fan, Inner Nacelle, End Eff.)	0.82
Propulsion System Efficiency	0.38
Propulsion Efficiency - Nacelle Drag	0.36
Cruise SFC	0.432

Take-off EI NOx, 100% Power	24.72
Climbout EI NOx, 85% Power	18.96
Approach EI NOx, 30% Power	8.8
Idle EI NOx, 7% Power	3.84

TOGW, lbs	132,280
Operating Empty Weight (lb)	74,841
Initial Cruise Altitude, feet	38,000
Mid-Mission Cruise L/D	21.0
Fuel Burn Reduction from Baseline	51%

Global Emissions

Life Cycle CO2 (Scenario 1)	25,898
Relative CO2 (scenario 1)	0.50
Life Cycle CO2 (Scenario 2)	12,949
Relative CO2 (scenario 2)	0.50
NOx (Cruise and LTO)	102
Relative NOx	0.40
Water, Vapor or Contrails (lbs)	7,690
Relative Water	0.50

LTO Emissions

NOx, lbs (LTO Only)	7.1
Relative NOx	0.37

Noise Considerations

Takeoff Thrust to Meet TOFL, lbs	31,811
Relative Takeoff Thrust	0.65
Shielding Potential	N
Leading Edge Devices	Y

Fuel Burn and Energy

Fuel Burn (lbs)	6,991.01
Electricity (kWh)	-
Total Energy (BTU)	129,899,986
Total Energy (KWH)	38,068.16
Relative Total Energy	0.50

Figure 2.7 – N+4 Workshop Concept Overview Template

2.4.1 Virtual East Team Summary

The participants of the Virtual East Team conducted individual scoring of each of the concepts, added other concepts as they saw fit, and compiled an average score for each concept against the metrics. Subsequently, the participants discussed the ranking results for each concept.

The members generally agreed on the scoring for the N+4 reference concept. The primary technology assumptions were accepted however, additional structural efficiency was assumed for the N+4 timeframe. With Concept 2 (hybrid electric) the group had some problems determining scores based on variations of where the control volume could be drawn for the block energy metric. This implied that a life cycle energy study might be needed. Consensus was drawn on the key technologies to enable and/or enhance the concept which included:

- Enhancing – tail cone BLI thruster
- Battery technology – some discussion that the development of high performance batteries would also have wide and earlier application to ground transportation
- Recommended integration of noise shielding
- Candidate for distributed propulsion (DP)

Concept 3 (hydrogen powered) also had some issues on scoring due to where the boundary of energy was drawn. A great deal of discussion also surrounded the costs associated with the infrastructure for delivering hydrogen to aircraft. The key technologies discussed included controlling the droplet size of water emissions and locations of the hydrogen tanks for safety/certification issues.

Concept 4 (methane powered) also had some issues on scoring due to where the boundary of energy was drawn; this aspect emerged as a consistent theme. Again, a great deal of discussion also surrounded the costs associated with the infrastructure for delivering methane as compared to hydrogen to the aircraft and also of the risk between the two concepts. Methane was deemed to carry less risk. No key technologies were identified.

Concept 5 (hydrogen/fuel cell hybrid) also had some issues on scoring due to where the boundary of energy was drawn. Again, a great deal of discussion also surrounded the costs associated with the infrastructure for delivering hydrogen to the aircraft. Consensus was drawn on the key technologies to enable and/or enhance the concept and included:

- Fuel cell efficiency = 50% Water produced can be stored and dumped rather than put into contrails
- Enhancing – tail cone BLI thruster

Of the first 5 concepts, 2, 3, and 5 all scored about the same with the assumption that the delivery of the energy from the source was “green”. However, the “green” assumption also suggested the need for an energy life cycle study that extends the control volume for energy beyond the vehicle. The methane concept (#4) was the best cost solution but had an overall lower score.

As a result, the team went through a discriminator discussion to identify the real differences between each of the concepts in terms of advantages and concerns, which included aspects listed below. General consensus could not be reached amongst the group and a straw poll vote was conducted; the hybrid electric concept was the winner of the first five concepts.

- Conventional fuel/hybrid electric concept
    - Concerns:
        - How to recharge the batteries at gate
        - Battery lifetime
        - Battery performance (can it be achieved?)
    - Advantages
        - Energy conversion better over hydrogen from the gate
        - Asks least from grid? Depends on flight patterns and hybrid usage?
        - Better global efficiency over others in terms of fleet wide load over time
- Hydrogen fuel concept (pure H2 burner)
    - Concerns:

    - Conversion of electricity to shaft power (50% at gate then 50% on shaft)
  - Advantages
    - Pumping system in place at gate
    - Easier averaging of the power load on grid: off peak storage – cheaper
    - Less technology risk once we know how to store safely on airplane
    - If electricity were green and free, this might be the best?
- Fuel cell concept (H2/FC Battery Hybrid)
  - Concerns:
    - Battery life time
    - Battery performance (can it be achieved)
    - Weight
    - Requires development of two different energy source technologies
  - Advantages
    - Easier averaging of the power load on grid (using H2): off peak storage – cheaper
    - Easier to capture water at altitude

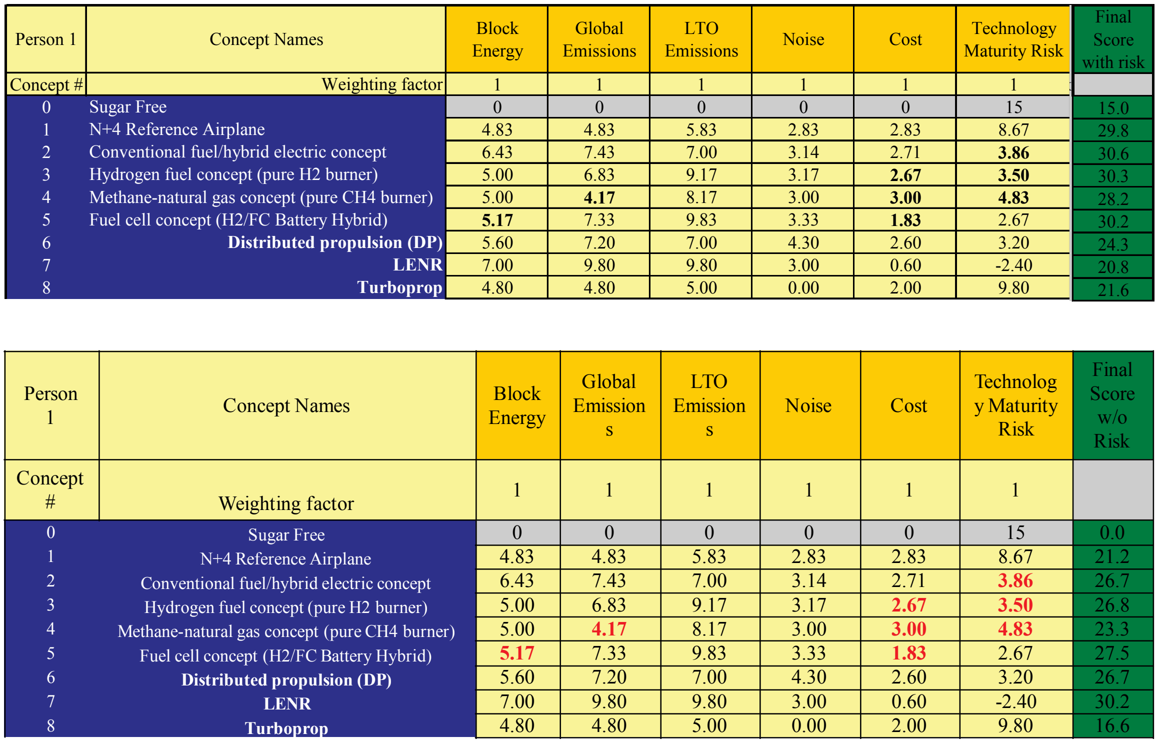
The group continued the discussion of the individual scoring for additional concepts added by group members: Concepts 7, 8, and 9, which were the distributed propulsion (DP), low energy nuclear reactor (LENR), and the turboprop concepts respectively. For Concept 7, the group assumed incremental improvements over the N+4 reference concept and identified that there may exist some technical risks associated with the DP implementation. Consensus was drawn on the key technologies to enable and/or enhance the concept and included:

- BLI – Some concern over technology risk (how well will it really work?)
- Wing tip propulsor integration to reduce induced drag
- Low loss mechanical or electrical power distribution

Concept 8 (LENR) had the same issue with being able to draw the boundary on energy. The group identified that the LENR concept could have tremendous benefits, but the technical risks are extremely high. Lastly, Concept 9 (turboprop) also showed some benefit over the N+4 reference concept, but the group identified that a low noise propeller design was needed. The team then compared the three concepts side by side and concluded:

- LENR nuclear has important advantages, but extremely high risk – if it works, revolutionary to World energy
- DP distributed propulsion is enhancing to multiple concepts if it works as advertised
- TP turboprop scorers were worried about noise

As a result of the Virtual East breakout team, the group provided the scores and rankings (with and without risk included) of each concept to the larger group as depicted in Figure 2.8.



Person 1	Concept Names	Block Energy	Global Emissions	LTO Emissions	Noise	Cost	Technology Maturity Risk	Final Score with risk
Concept #	Weighting factor	1	1	1	1	1	1	
0	Sugar Free	0	0	0	0	0	15	15.0
1	N+4 Reference Airplane	4.83	4.83	5.83	2.83	2.83	8.67	29.8
2	Conventional fuel/hybrid electric concept	6.43	7.43	7.00	3.14	2.71	**3.86**	30.6
3	Hydrogen fuel concept (pure H2 burner)	5.00	6.83	9.17	3.17	**2.67**	**3.50**	30.3
4	Methane-natural gas concept (pure CH4 burner)	5.00	**4.17**	8.17	3.00	**3.00**	**4.83**	28.2
5	Fuel cell concept (H2/FC Battery Hybrid)	**5.17**	7.33	9.83	3.33	**1.83**	2.67	30.2
6	**Distributed propulsion (DP)**	5.60	7.20	7.00	4.30	2.60	3.20	24.3
7	**LENR**	7.00	9.80	9.80	3.00	0.60	-2.40	20.8
8	**Turboprop**	4.80	4.80	5.00	0.00	2.00	9.80	21.6

Person 1	Concept Names	Block Energy	Global Emissions	LTO Emissions	Noise	Cost	Technology Maturity Risk	Final Score w/o Risk
Concept #	Weighting factor	1	1	1	1	1	1	
0	Sugar Free	0	0	0	0	0	15	0.0
1	N+4 Reference Airplane	4.83	4.83	5.83	2.83	2.83	8.67	21.2
2	Conventional fuel/hybrid electric concept	6.43	7.43	7.00	3.14	2.71	**3.86**	26.7
3	Hydrogen fuel concept (pure H2 burner)	5.00	6.83	9.17	3.17	**2.67**	**3.50**	26.8
4	Methane-natural gas concept (pure CH4 burner)	5.00	**4.17**	8.17	3.00	**3.00**	**4.83**	23.3
5	Fuel cell concept (H2/FC Battery Hybrid)	**5.17**	7.33	9.83	3.33	**1.83**	2.67	27.5
6	**Distributed propulsion (DP)**	5.60	7.20	7.00	4.30	2.60	3.20	26.7
7	**LENR**	7.00	9.80	9.80	3.00	0.60	-2.40	30.2
8	**Turboprop**	4.80	4.80	5.00	0.00	2.00	9.80	16.6

Figure 2.8 – Virtual East Team Scoring

2.4.2 Virtual West Team Summary

The participants of the Virtual West Team also conducted individual scoring of each of the concepts and then added other concepts as they saw fit. They compiled the results as an average score for each concept against the metrics. Subsequently, the participants discussed the ranking results for each concept. Virtual West scored the required 5 concepts and then added additional ideas from the group. The list of concepts scored included:

- N+4 Reference Airplane
- Conventional fuel/hybrid electric concept
- Hydrogen fuel concept (pure H2 burner)
- Methane-natural gas concept (pure CH4 burner)
- Fuel cell concept (H2/FC Battery Hybrid)
- SUGAR High TurboProps:
    - Jet A
    - Pure H2 burner
    - H2/FC Battery Hybrid
    - Pure battery-electric

- LENR-powered via heat turbines
- Distributed Propulsion Hybrid-Electric
- Dual Fuel H2/Jet-A

For the Virtual West team there was a slight deviation in how the scoring was conducted, which was later streamlined with the approach taken by the Onsite and Virtual East teams. However, the team members generally agreed on the combined scores.

The Virtual West team identified a number of additional enhancing technologies for each of the concepts they scored that could be considered going forward. The list of potential enhancing/required technologies for each concept is listed in Table 2.3.

Table 2.3 – Virtual West Team Technologies per Concept

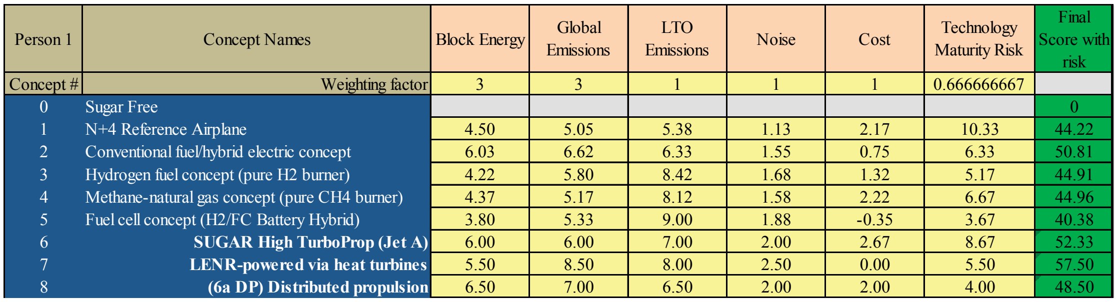
Concept	Technologies
N+4 Reference Airplane	Composite structure Laminar flow Riblets Efficient engines Quiet landing gear and high lift system
Conventional fuel/hybrid electric concept	N+4 Reference technologies Strut braced wing Batteries Hybrid-electric-gas-turbine engines Use more battery power for takeoff noise & LTO emissions
Hydrogen fuel concept (pure H2 burner)	N+4 Reference technologies Hydrogen propulsion system Clean, large-scale hydrogen production Could be strut-braced high wing
Methane-natural gas concept (pure CH4 burner)	N+4 Reference technologies Methane-natural gas propulsion system Methane storage infrastructure Could be strut-braced high wing
Fuel cell concept (H2/FC Battery Hybrid)	N+4 Reference technologies Hydrogen propulsion system Fuel cells Electric motors Batteries Clean, large-scale hydrogen production Could be strut-braced high wing
SUGAR High TurboProps with Jet A	N+4 Reference technologies High-speed propellers Quiet propellers Efficient turboshaft engine Strut-braced wing
SUGAR High TurboProps with Pure H2 burner	SUGAR High Turboprop technologies Hydrogen Fuel Concept technologies
SUGAR High TurboProps with H2/FC Battery Hybrid	Hydrogen Fuel Cell Concept technologies SUGAR High Turboprop technologies Variable speed propellers because of electric motor drive*
SUGAR High TurboProps with Pure battery-electric	SUGAR High Turboprop technologies Electric motors Batteries (especially important for this concept) Variable speed propellers because of electric motor drive*
LENR-powered via heat turbines	LENR Flight weight Conversion of heat to mechanical power Electric generation via gas or steam turbine? Hot fluid transfer to heat exchanger in core? Possible need for radioactive shielding

Concept	Technologies
Distributed Propulsion Hybrid-Electric	Hybrid Electric Concept Propulsion integration Efficient flight weight electric generator Explore more battery power to reduce LTO emissions and noise Explore reduced fan pressure ratio Explore reduced mixing length from small diameter nacelles
Dual Fuel H2/Jet-A	N+4 Reference technologies Hydrogen / Jet-A propulsion system Clean, large-scale hydrogen production

* propulsive efficiency and acoustic benefit

The Virtual West team also identified the same general issues as the Virtual East team in the understanding of the control volume for the block energy scoring. The West team also identified that a life cycle energy study should be conducted for the various energy sources.

As a result of the Virtual West breakout team, the group provided the scores and rankings (with risk included) of each concept to the larger group as depicted in Figure 2.9. Concepts that had only 1 scorer were eliminated since there was insufficient input. As with the Virtual East team, the West team identified that the LENR concept provided the highest payoff.



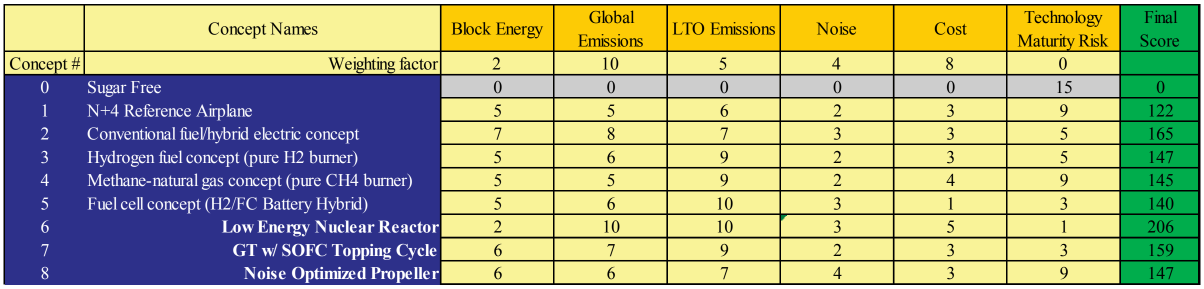
Person 1	Concept Names	Block Energy	Global Emissions	LTO Emissions	Noise	Cost	Technology Maturity Risk	Final Score with risk
Concept #	Weighting factor	3	3	1	1	1	0.666666667	
0	Sugar Free							0
1	N+4 Reference Airplane	4.50	5.05	5.38	1.13	2.17	10.33	44.22
2	Conventional fuel/hybrid electric concept	6.03	6.62	6.33	1.55	0.75	6.33	50.81
3	Hydrogen fuel concept (pure H2 burner)	4.22	5.80	8.42	1.68	1.32	5.17	44.91
4	Methane-natural gas concept (pure CH4 burner)	4.37	5.17	8.12	1.58	2.22	6.67	44.96
5	Fuel cell concept (H2/FC Battery Hybrid)	3.80	5.33	9.00	1.88	-0.35	3.67	40.38
6	**SUGAR High TurboProp (Jet A)**	6.00	6.00	7.00	2.00	2.67	8.67	52.33
7	**LENR-powered via heat turbines**	5.50	8.50	8.00	2.50	0.00	5.50	57.50
8	**(6a DP) Distributed propulsion**	6.50	7.00	6.50	2.00	2.00	4.00	48.50

Figure 2.9 – Virtual West Team Scoring

2.4.3 Onsite Team Summary

The participants of the Onsite Team conducted a group scoring of each of the concepts and then added other concepts as they saw fit and then compiled as an average score for each concept against the metrics. Subsequently, the participants discussed the ranking results for each concept.

As a result of the Onsite breakout team, the group provided the scores and rankings (with risk included) of each concept to the larger group as depicted in Figure 2.10. During the outbrief, the Onsite team suggested the possibility of a hybrid between concepts 4, 7, and 8 might be a viable option. The Onsite team also identified the LENR concept as the highest payoff, but with an associate high risk.



	Concept Names	Block Energy	Global Emissions	LTO Emissions	Noise	Cost	Technology Maturity Risk	Final Score
Concept #	Weighting factor	2	10	5	4	8	0	
0	Sugar Free	0	0	0	0	0	15	0
1	N+4 Reference Airplane	5	5	6	2	3	9	122
2	Conventional fuel/hybrid electric concept	7	8	7	3	3	5	165
3	Hydrogen fuel concept (pure H2 burner)	5	6	9	2	3	5	147
4	Methane-natural gas concept (pure CH4 burner)	5	5	9	2	4	9	145
5	Fuel cell concept (H2/FC Battery Hybrid)	5	6	10	3	1	3	140
6	**Low Energy Nuclear Reactor**	2	10	10	3	5	1	206
7	**GT w/ SOFC Topping Cycle**	6	7	9	2	3	3	159
8	**Noise Optimized Propeller**	6	6	7	4	3	9	147

Figure 2.10 – Onsite Team Scoring

2.5 N+4 Workshop General Observations, Recommendations, and Inspirations

After each sub-team conducted the breakout sessions and then presented the outbriefs to the whole group, the group identified some common themes amongst the sub-team observations that evolved into general observations of the entire concept scoring activity, specifically:

- Hybrid electric scored high from each team, which confirmed the selection of the concept for the current work scope in Phase II, Task 2.2
- General concern over the definition of control volume with block energy
- LENR high payoff, but high risk
- Methane concept identified as a low risk by all groups
- Participants identified that a struggle of the scoring of the concepts really revolved around:
    - Source of power
    - How it is converted
    - How to use that power

As a result of the group discussion, the workshop focus shifted the expected outcome to picking a concept and then subsequently identifying what power application should be used; a summary of the result and recommendations from the group is outlined below:

1) LENR – Very high payoff/very high risk. Recommend small study to set goals and watch tech feasibility and development
2) Positive consensus on Hybrid Electric – validation of Phase I selection. Already covered in SUGAR Tasks 2.2 and 3.3 (except see energy study)
3) Energy study – Life Cycle source to use (H2 or electricity). Estimate electricity use at typical airport. Supports both electric battery charging and H2 production.
4) Hydrogen – Significant benefits and challenges
    - Because H2 aircraft have been studied extensively in the past, we recommend expanding other areas of the technology space
    - H2 infrastructure and some technologies should be worked outside of this study

  - Many H2 cryo aspects will be covered in recommended LNG/methane work below
  - See also energy study above
5) Methane – Low cost and possible early deployment of cryo techs
  - Methane GT SOFC driving a generator with variable speed pitch low noise props … or … Methane GT SOFC Hybrid with low noise turboprop
  - Methane as first step on a roadmap for a cryo fuel / superconducting
  - GE to check on providing Methane GT and Methane GT SOFC cycle for N+4 task
6) Combined Approach to N+4 technology/config assessment:
  - Adv. Tech Configuration with integrated synergistic technologies
    - Aft fuselage BLI integration – synergy with methane GT SOFC to drive aft electric fan (Goldschmied-like device)
  - Technologies that are evaluated separately and could be combined into the Adv. Tech Configuration (or others)
    - Low noise props – investigate variable RPM and shape memory alloys, plasma actuators?

As a result of the workshop recommendations, a number of side studies were identified to help the group conclude on a possible N+4 concept to pass to the higher fidelity analysis. The group called these inspiration ideas that composed a wish list of research that could possibly be conducted within the scope of the current SOW:

1) LENR
  - Study to set goals
  - Watch tech feasibility and development
  - Investigate system architecture options
  - Develop baseline system design and system performance targets
2) Hybrid Electric
  - Life cycle energy study
  - Follow and encourage battery tech and system community
  - Multiple parallel battery technology developments
3) Methane – Low cost and possible early deployment of cryo techs
  - Gas turbine design issues
  - Aircraft system issues & techs
  - Infrastructure issues & techs
  - Synergistic technologies
    - Methane GT SOFC driving a generator
    - Methane GT SOFC Hybrid
    - Cryo fuel / superconducting

4) Hydrogen
    - Leverage multiple previous studies
    - Life cycle energy study
    - Build on methane work (GT, system, infrastructure, cryo, FC's)
    - Gas turbine design issues & techs
    - Aircraft system issues & techs
    - Infrastructure issues & techs
    - Synergistic technologies
        - GT FC Hybrid
        - Cryo fuel / superconducting
5) Other Techs
    - BLI integration
        - Current BLI investigation/validation
        - Aft fuselage BLI – Goldschmied-like device
        - CFD, wind tunnel, and flight validation
    - Low noise high cruise speed (Mach 0.65-0.7) props
        - Leverage existing design tools
        - Investigate variable RPM, shape memory alloys, plasma actuator technologies, techs from rotorcraft

From the results of the N+4 workshop, the team defined specific products to create and subtasks to conduct as part of the N+4 study task.

- Figure 2.11 was developed to show how the technologies from the workshop are related and to illustrate the breakthrough technologies that can reduce emissions and environmental impacts.
- A subtask was defined to do a requirements analysis for Low Energy Nuclear Reactor technology (see Section 3.0)
- A subtask was defined to develop a outline for an energy study to investigate life cycle energy usage for alternative fuel and energy sources for aviation (see Section 4.0)
- An advanced technology airplane concept was selected to be used in evaluating key N+4 technologies including methane, boundary layer ingestion, and a fuel cell hybrid propulsion system (see Section 5.6). Other variations were considered including the use of an unducted fan/propeller (see Section 5.7).
- The list of technologies for roadmapping were selected (see Section 6.0)

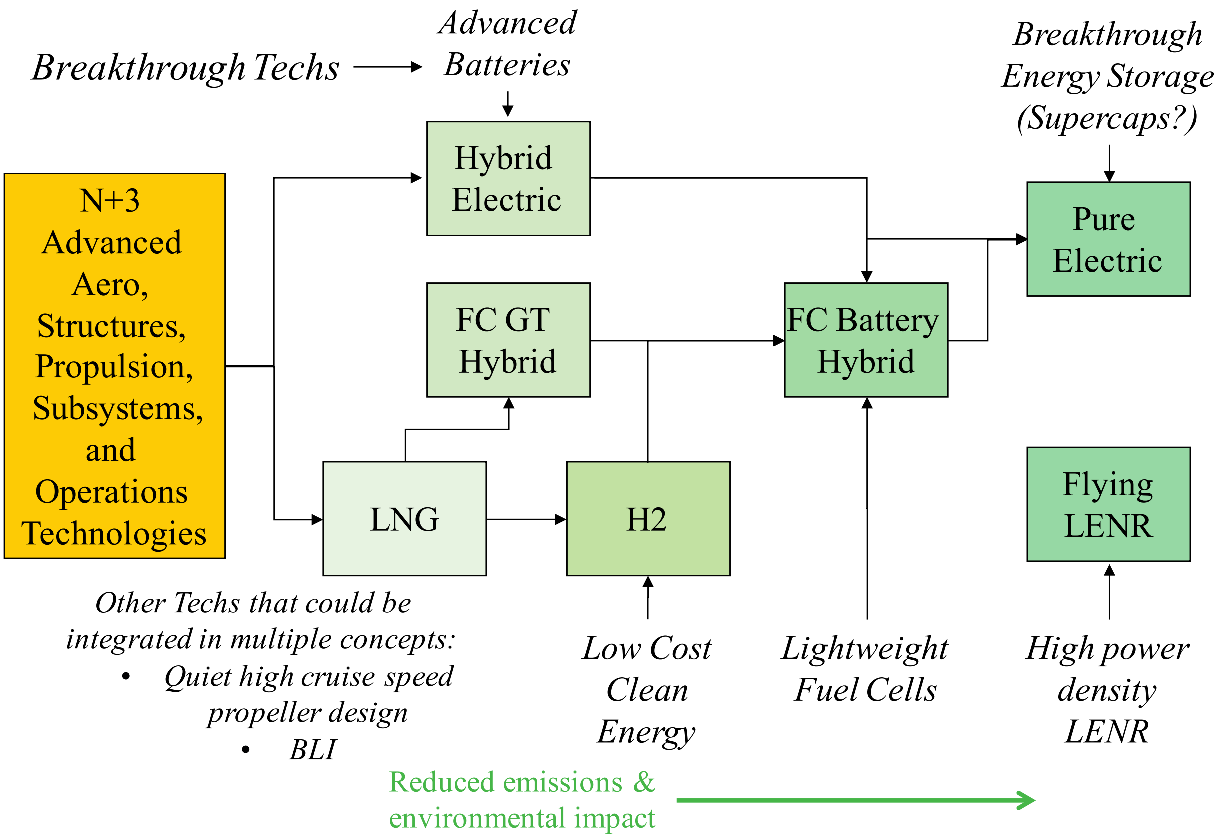


Figure 2.11 – Relationship of N+4 Workshop Technologies

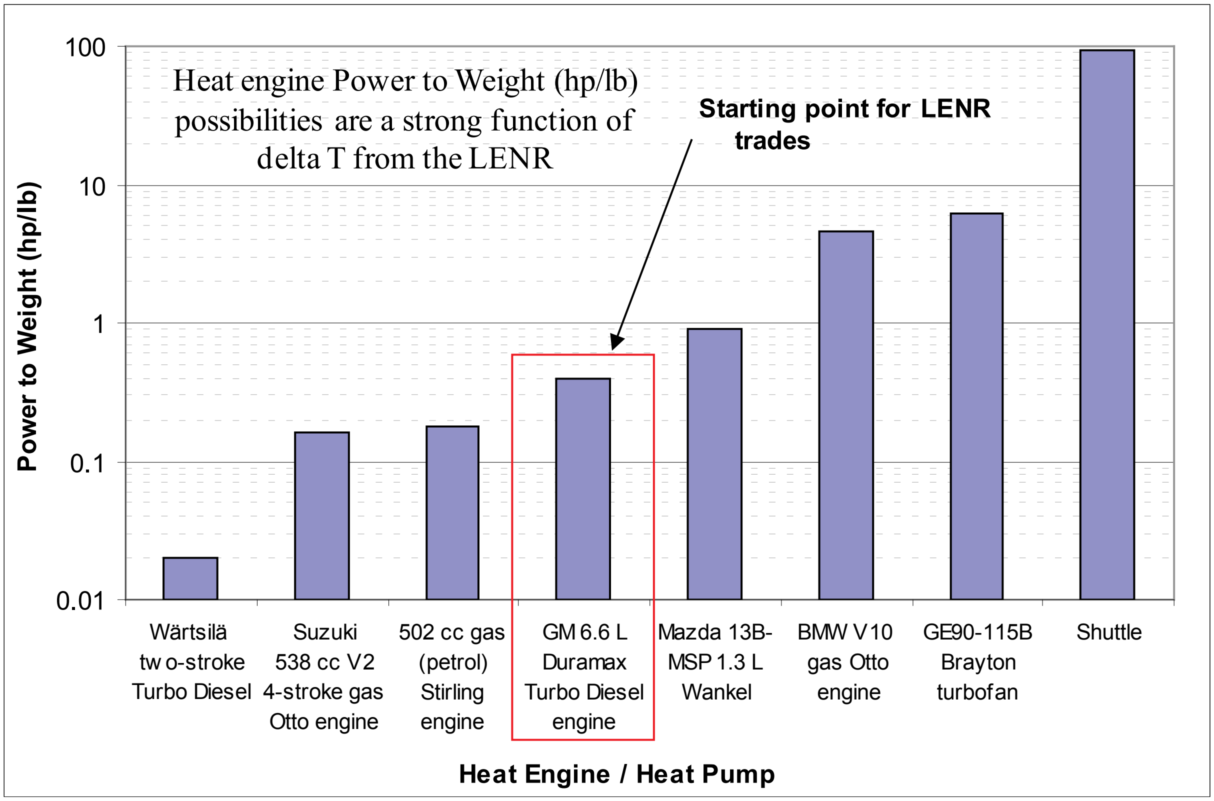
3.0 LENR Requirements Analysis

The idea of using a Low Energy Nuclear Reactor (LENR) was discussed at the N+4 Workshop, both as a ground-based source of energy to create electricity or hydrogen, and an aircraft-carried power source for primary propulsion. Given the potential of clean zero-emissions energy, further work was identified for both applications. Nuclear energy is a potential source of clean low cost energy that should be considered in a detailed energy study (see Section 4.0). In this section we will discuss the potential and requirements for a flying LENR application for aviation.

Since a LENR is essentially a source of heat, a heat engine of some kind is needed to produce useful work that can create an integrated propulsion system for an aircraft. It was decided to do a relatively simple study to determine the range of LENR and heat engine performance that would produce an aircraft competitive to a conventional fueled aircraft.

Some potential heat engine cycles with representative engine power to weight ratios are shown in Figure 3.1. Heat engine power to weight is a strong function of delta temperature from the LENR. Achievable LENR delta temperature is not known at this time and is beyond the scope of this current investigation. Nevertheless, we decided to parametrically vary the LENR and heat engine power per weight and apply a top level operating cost model. Even though we do not know the specific cost of the LENR itself, we assumed a cost of jet fuel at $4/gallon and weight based aircraft cost. We were able to calculate cost per mile for the LENR equipped aircraft compared to a conventional aircraft (Figure 3.2). Looking at the plots, one could select a point where the projected cost per mile is 33% less than a conventionally powered aircraft (Heat engine > 1 HP/lb & LENR > 3.5 HP/lb). Since the power requirements are significantly different at cruise compared to takeoff and climb, we also investigated a hybrid case where batteries and an electric motor are used to supplement the heat engine + LENR at takeoff. This yielded significantly improved results (Figure 3.3) which required lower LENR and heat engine performance levels (Heat engine > 0.4 HP/lb, LENR > 1 HP/lb, & Batteries > 225 Wh/kg).

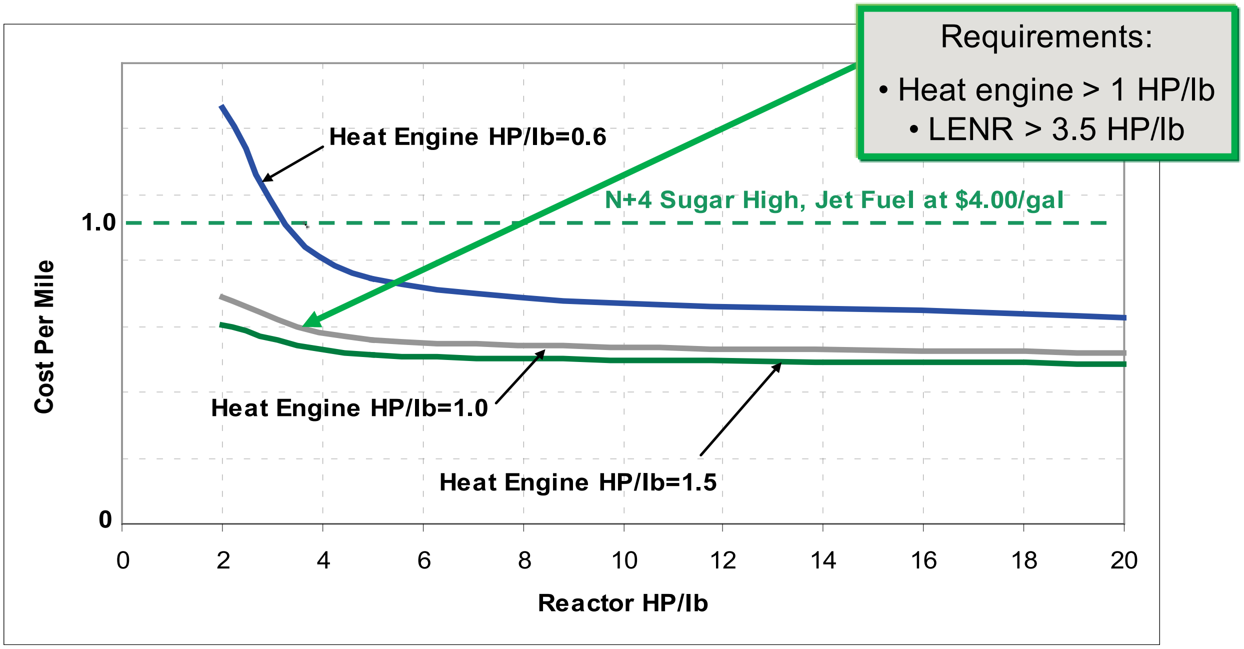
These numbers are illustrative only, as other combinations could yield useful propulsion and power systems, and the results are dependent on cost and performance assumptions. However, the numbers should be useful in establishing initial system goals for LENR concepts.



Heat engine Power to Weight (hp/lb) possibilities are a strong function of delta T from the LENR

Starting point for LENR trades

Figure 3.1 – Potential Heat Engines for LENR Systems



Requirements:

- Heat engine > 1 HP/lb
- LENR > 3.5 HP/lb

Figure 3.2 – Parametric LENR and Heat Engine Performance Parameters

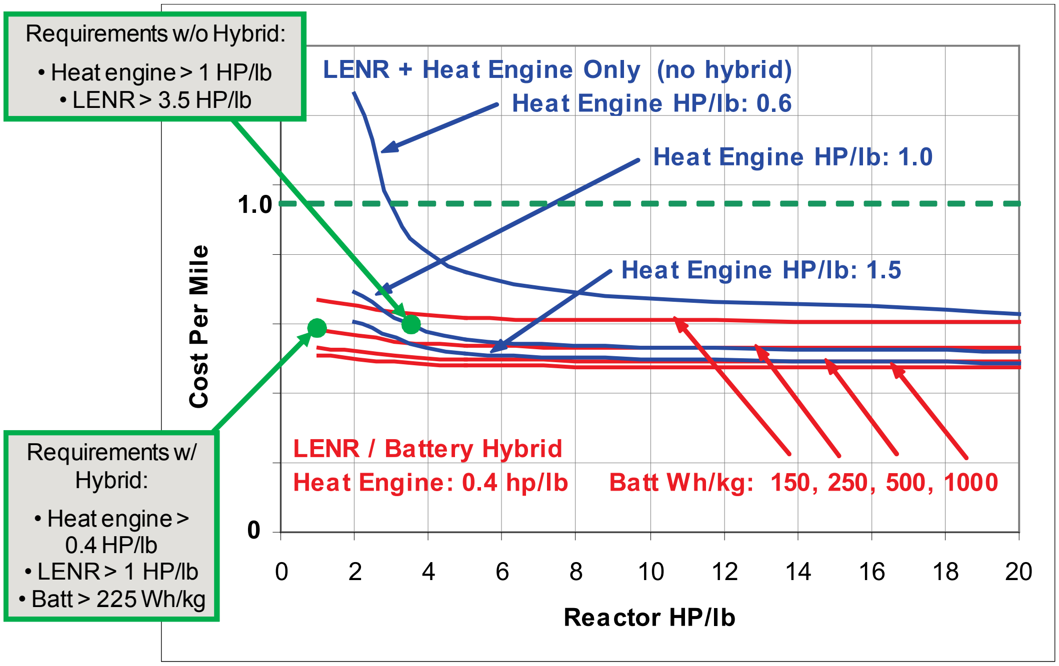


Figure 3.3 – Hybrid LENR + Battery Performance Parameters

4.0 Energy Study Outline Development

The idea of needing to do a life cycle energy study to answer questions and help make decisions about alternative aviation fuels and energy sources came out of the N+4 Workshop. Making some gross assumptions, we were able to determine the potential performance of aircraft powered by various methane, hydrogen, and electricity energy architectures. However, we had no way to determine if any of these approaches were beneficial when the entire aircraft and energy production lifecycles were considered. To answer these kinds of questions, it was decided that a life cycle energy study, focused on aviation specific questions, was needed. Doing such a study is beyond the scope of the current effort, but it was decided that it was worthwhile to develop an outline of what should be contained in such a comprehensive study, with the hope that the study will be conducted sometime in the near future.

After discussion among the team members, we are recommending a study that includes various world energy scenarios to cover the likely range of possible futures and the sensitivity of the results to input assumptions. This study should answer questions about the life cycle usage of natural gas, the production of electricity and hydrogen for aviation, the best use of biofuels, and the impact of a breakthrough in low cost energy generation. We drew upon the results of a student study at Georgia Tech, unpublished work conducted at Boeing, and information from many public sources.(2)(3)(4)(5)(6)

We developed an initial outline and shared it outside the SUGAR team with contacts at NASA, the FAA (Federal Aviation Administration), MIT (Massachusetts Institute of Technology), and the DoE (Department of Energy). We incorporated comments and the final version of the Energy Study Outline is as follows:

1. Background and Motivation
    a. SUGAR N+4 Results
        i. Candidate alternative energy concepts
        ii. Questions about supply, cost, and environmental benefits/impacts
        iii. Questions about uncertainty in assumptions
2. World Energy Assumptions
    a. Energy scenarios and sources
        i. Scenarios should capture – High & low oil price, high and low carbon taxes, cheap electricity, etc.
    b. Approach to handling uncertainties in world energy supply, make-up, and cost
    c. Approach to handling interactions between energy streams and impact of diverting energy streams to aviation
3. Metrics

    a. Cost
        i. Methods used for aircraft, ground infrastructure, and energy costs
    b. Resource availability
        i. % of existing resource supply needed to supply aviation
        ii. Feasibility to expand supply to meet aviation demand
    c. Carbon Dioxide
        i. Complete life cycle
        ii. Operational use
        iii. Energy production
    d. NOx
        i. Methods used for local and global emissions
    e. Other Emissions
        i. List of other emissions (including methane released)
        ii. Methods for calculating
    f. Noise
        i. Method for assessing and data sources
    g. Health Impacts
        i. Types of health impacts
        ii. Methods for calculating and sources
    h. Climate impacts
        i. Methods for calculating

4. Case Studies
    a. Natural gas/methane for ground transportation, electricity, or aviation
        i. Approach with flow chart
        ii. Input data and sources
        iii. Quantification of methane leakage into the atmosphere
        iv. Results with uncertainties and sensitivities to assumptions
    b. Liquid Hydrogen, Electric battery/Jet Hybrids, at airports
        i. Approach with flow chart
        ii. Input data and sources
        iii. Results with uncertainties and sensitivities to assumptions
    c. Biomass for electricity, ground transportation, or aviation
        i. Approach with flow chart
        ii. Input data and sources
        iii. Results with uncertainties and sensitivities to assumptions
    d. Sustainable, low-cost electricity
        i. Approach with flow chart
        ii. Input data and sources

      iii. Results with uncertainties and sensitivities to assumptions
5. Conclusions
    a. Discussion of case study results
    b. Recommendations for aviation
6. Recommendations for future work
    a. Gaps and Unknowns
    b. Next steps

The SUGAR team recommends that such a study be considered for future joint funding by NASA and the Department of Energy or other interested parties.

5.0 N+4 Concept Development and Analysis

The same approach used in Phase I was used to define, analyze, and compare SUGAR N+4 concepts. The same reference mission for a medium-sized (737 class) aircraft was used (Table 5.1). A detailed discussion of the future scenario is contained within Section 2.0 of the Phase I report(1).

Table 5.1 – Phase I Future Scenario Used to Set Payload-Range Requirements

	Regional	Medium	Large
Number of Aircraft	2,675	22,150	7,225
Family Midpoint # of Seats	70	154	300
Avg Distance	575	900	3,300
Max Distance	2,000	3,500	8,500
Avg Trips/day	6.00	5.00	2.00
Avg MPH	475	500	525
Fleet Daily Air Miles (K)	8,500	100,000	55,000
Daily Miles	3,200	4,500	7,600
Daily Hours	6.92	9.23	13.96

SUGAR Phase I and Phase II Focus ⬆

A progression of concepts were selected that will allow the quantitative evaluation of methane/LNG fuel, unducted fans, an LNG hybrid fuel cell, and fuselage boundary layer ingestion. Specific performance cases are listed in Table 5.2 and described in Sections 5.1 to 5.7. Results are compared and summarized in Section 5.8.

Table 5.2 – N+4 Performance and Sizing Runs

Case	Config. Number	Name	Start Config.	Fuel	Engine	Propulsor
1	765-093	SUGAR Free (Baseline)	765-093	JP	CFM-56	Ducted Fan
2	765-094-TS1	N+4 Reference	765-094	JP	JP+2045GT+DF	Ducted Fan
3	765-095-TS1	N+4 High Wing Reference	765-095-RC (Task 2.1)	JP	JP+2045GT+DF	Ducted Fan
4	765-095-TS2	SUGAR Freeze (LNG)	765-095-TS1	LNG	LNG+2045GT+DF	Ducted Fan
5	765-095-TS3	SUGAR Freeze (LNG UDF)	765-095-TS2	LNG	LNG+2045GT+UDF	Unducted Fan
6	765-095-TS4	SUGAR Freeze (LNG FC Hybrid BLI)	765-095-TS2	LNG	LNG+2045GT+ SOFC+BLI	DF + BLI
7	765-095-TS5	SUGAR Freeze (LNG FC Hybrid UDF)	765-095-TS3	LNG	LNG+2045GT+ SOFC+UDF	Unducted Fan

JP – Conventional Jet Fuel (Jet-A)
2045GT – N+4 Gas Turbine technology
DF – Ducted Fan
LNG – Liquified Natural Gas (Mostly Methane)
SOFC or FC – Solid Oxide Fuel Cell
UDF – Unducted Fan
BLI – Boundary Layer Ingestion

5.1 765-093 SUGAR Free (Baseline Aircraft)

A conventional tube and wing aircraft with CFM-56 engines representative of the “N” timeframe of approximately 2008. See the Phase I final report(1) configuration 765-093 (Section 5.3.1) for detailed information. This aircraft is used as the baseline for the fuel burn, energy, and cruise emissions goals. A minor adjustment to correct a Phase I payload sizing inconsistency was made to the group weight statement. The result was a 0.9% reduction in fuel burn for the sized configuration as compared to Phase I. Table 5.3 contains the modified group weights statement. All other vehicle data is the same as it was in Phase I.

Table 5.3 – 765-093 Group Weight Statement

GROUP	WEIGHT (LB)	% TOGW
WING	**18,728**	**10.7%**
BENDING MATERIAL	9,621	5.5%
SPAR WEBS	1,290	0.7%
RIBS AND BULKHEADS	1,226	0.7%
AERODYNAMIC SURFACES	3,351	1.9%
SECONDARY STRUCTURE	3,240	1.8%
TAIL	**3,779**	**2.2%**
FUSELAGE	**17,597**	**10.0%**
LANDING GEAR	**6,712**	**3.8%**
NACELLE & PYLON	**5,548**	**3.2%**
PROPULSION	**11,181**	**6.4%**
ENGINES	10,664	6.1%
FUEL SYSTEM	518	0.3%
FLIGHT CONTROLS	**3,084**	**1.8%**
COCKPIT CONTROLS	252	0.1%
SYSTEM CONTROLS	2,832	1.6%
POWER SYSTEMS	**4,483**	**2.6%**
AUXILIARY POWER UNIT	1,032	0.6%
HYDRAULICS	894	0.5%
ELECTRICAL	2,557	1.5%
INSTRUMENTS	**686**	**0.4%**
AVIONICS & AUTOPILOT	**1,533**	**0.9%**
FURNISHINGS & EQUIPMENT	**10,866**	**6.2%**
AIR CONDITIONING	**1,678**	**1.0%**
ANTI-ICING	**118**	**0.1%**
MANUFACTURER'S EMPTY WEIGHT (MEW)	**85,993**	**49.0%**
OPERATIONAL ITEMS	7,342	4.2%
OPERATIONAL EMPTY WEIGHT (OEW)	**93,335**	**53.1%**
USABLE FUEL	51,500	29.3%
DESIGN PAYLOAD	30,800	17.5%
TAKEOFF GROSS WEIGHT (TOGW)	**175,635**	**100.0%**

5.2 765-094-TS1 N+4 Reference Aircraft

The 765-094 is a span constrained conventional tube and wing configuration. A three view drawing for this configuration is included in the Phase I Final Report (1). For this study, the configuration was modified with a new N+4 gFan++ engine. The configuration also utilizes the same N+3 advanced technologies used in Phase I. The gFan++ Advanced Turbofan (JP+2045GT+DF) engine is summarized in Appendix A. The new engine requires a new drag buildup and mass properties buildup for the configuration. Other changes were also rolled into this phase of the study including new laminar flow accounting to become consistent with the latest results from the recently completed Environmentally Responsible Aviation (ERA) study contract(7). ERA took credit for 70% (30% operational knockdown) of the calculated *passive* laminar flow reduction and included drag increases for the passive system. For SUGAR, N+3 aircraft are taking 85% credit and N+4 aircraft are taking 92.5% credit which represents a progression in the technology. The SUGAR aircraft are also focusing on *natural* laminar flow and do not take any additional penalty for a passive system. Additionally, laminar flow credit is carried on the horizontal, vertical, and nacelles for Phase II.

The high-speed aerodynamic buildup for the Refined SUGAR configuration is summarized in Table 5.4 and Figure 5.1. It should be noted that all the drag buildups in this study are calculated at drag divergence, not at maximum long range cruise Mach number.

Table 5.4 – 765-094-TS1 High Speed Build-up

CONFIGURATION	765-094-TS1
AIRFOIL TYPE	SUPERCRIT. DTE

F BUILD-UP (FT^2)	
FUSELAGE	9.2153
WING	8.1036
WINGLET	0.2173
HORIZONTAL	1.4215
VERTICAL	1.2158
N&P	1.8980
CANOPY	0.0405
GEAR PODS	0.0000
ETC BEFORE SUB	-4.8831
EXCRESCENCE	1.6376
UPSWEEP	0.6012
WING TWIST	0.3948
ETC AFTER SUB	-0.3986
FUSELAGE BUMP	0.5430
F-TOTAL (FT^2)	**20.0070**

E-VISC	**1.00952**

CRUISE C_D BUILD-UP	
M-CRUISE	0.74
CRUISE ALTITUDE	38408
C_L-CRUISE	0.675
C_{D0}	0.01556
C_{DI}	0.01235
C_{DC}	0.001245
C_{DTRIM}	0.000595
C_{DTOT}	0.02975
L/D	22.68952
ML/D	16.790

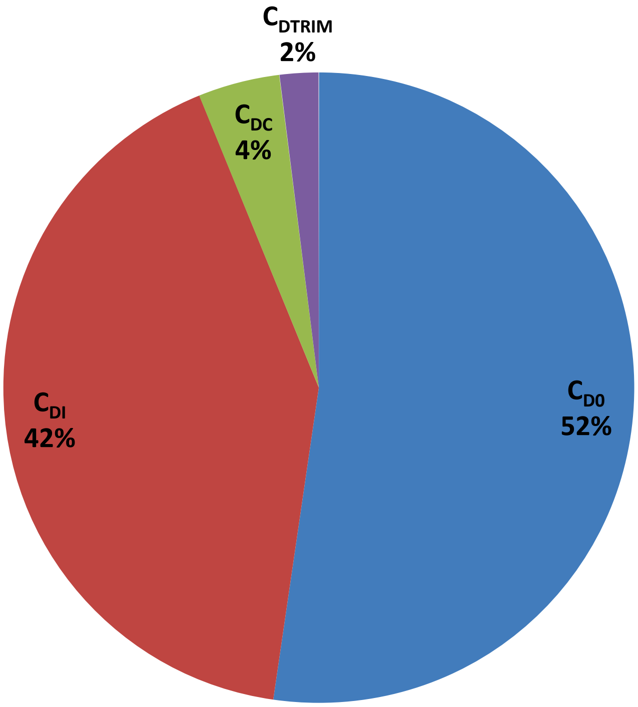


Figure 5.1 – 765-094-TS1 High Speed Build-up

The resulting high speed data is shown in Figure 5.2. The figure illustrates the maximum aerodynamic efficiency (M*L/D) occurring at a cruise Mach of 0.74 and a C_L of 0.700. This is slightly higher than the efficiency at the Mach 0.7 cruise condition.

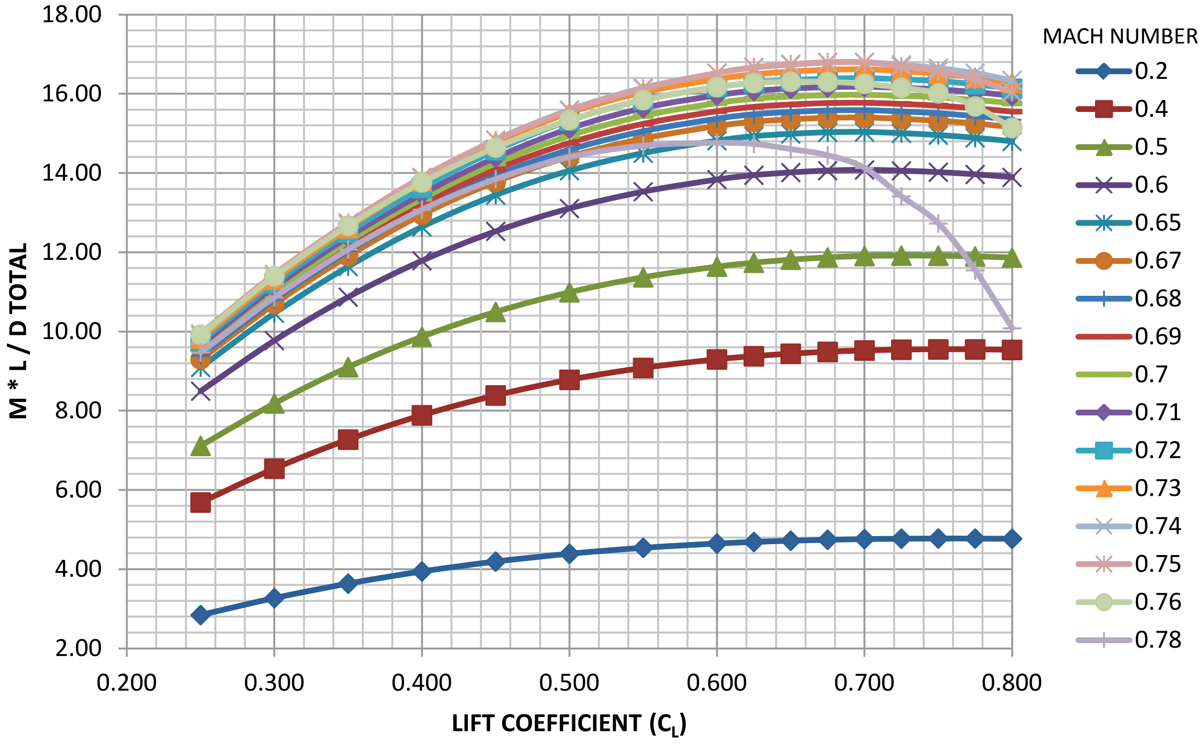


Figure 5.2 – 765-094-TS1 - M * L / D Total

Figure 5.3 through Figure 5.5 show the low speed aerodynamic characteristics for the N+4 Reference aircraft with advanced 2045 technology engines. Low speed data are trimmed as a function of angle of attack, lift coefficient, and drag coefficient at each flap detent. Low speed high lift devices on wing leading and trailing edges are deployed. As with other low speed buildups in this study, these polars are based on an empirical database.

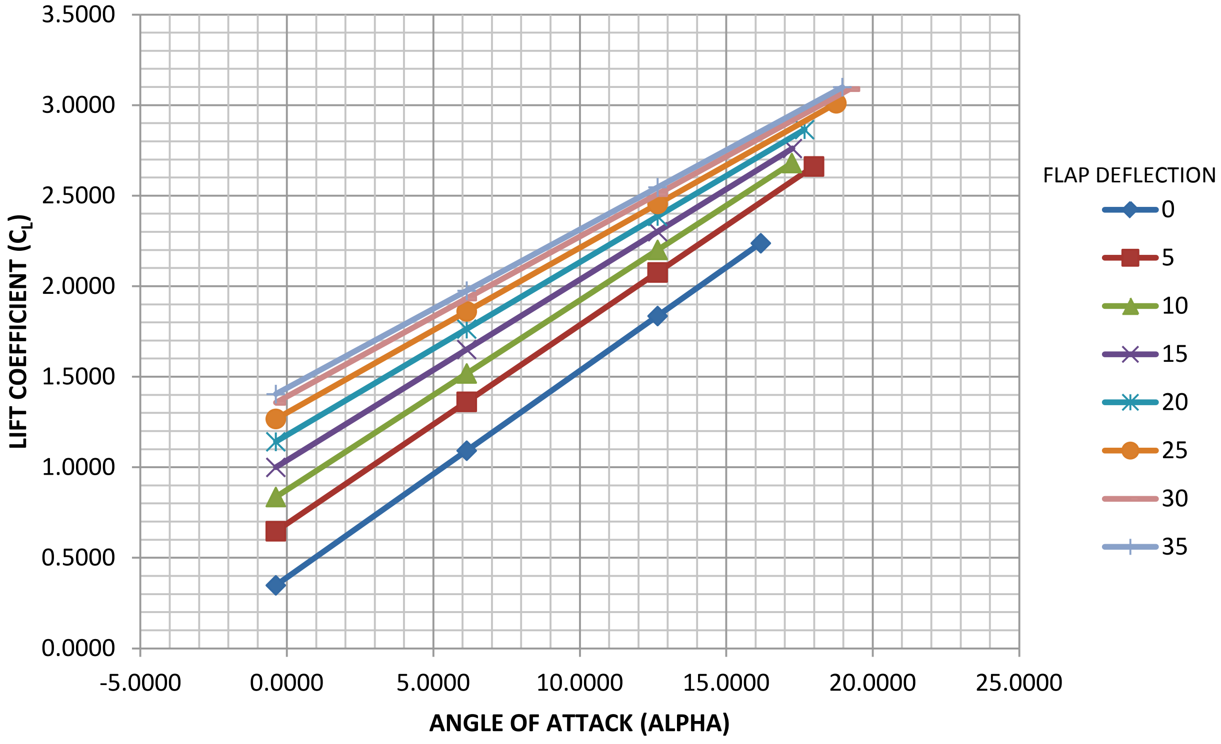


Figure 5.3 – 765-094-TS1 - Low Speed Lift Curve; Free Air

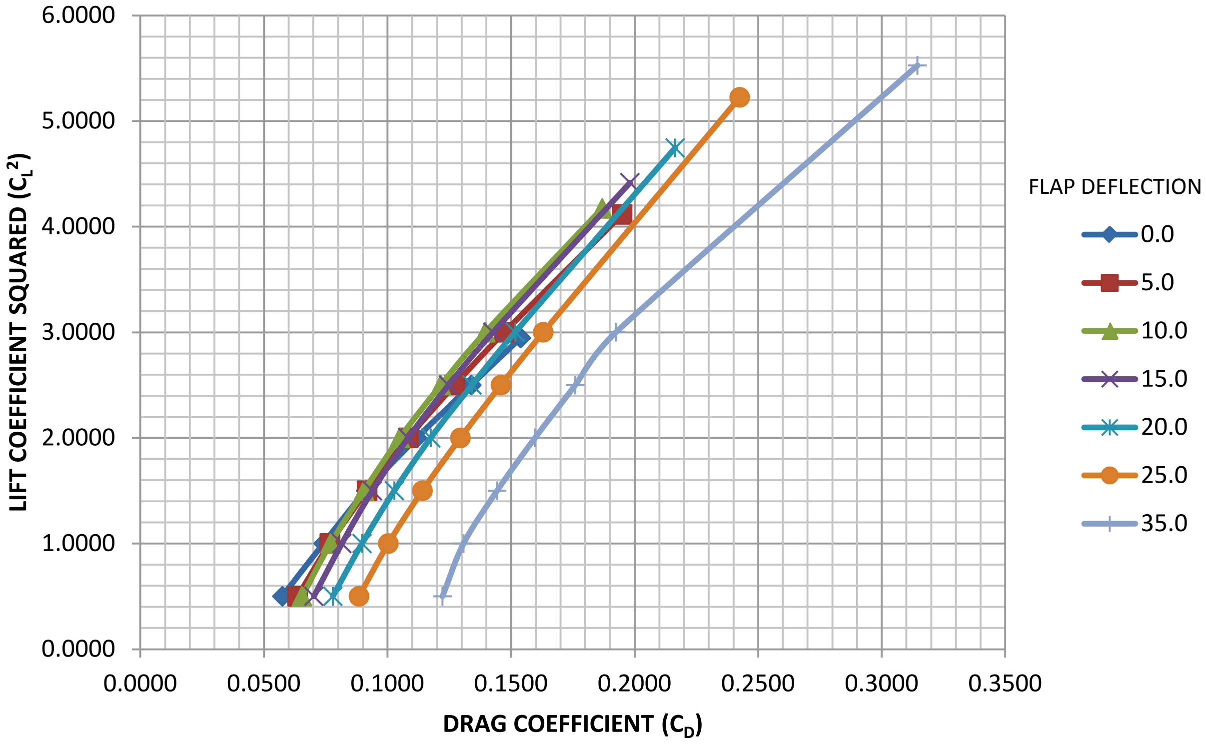


Figure 5.4 – 765-094-TS1 - Low Speed Polar; Free Air

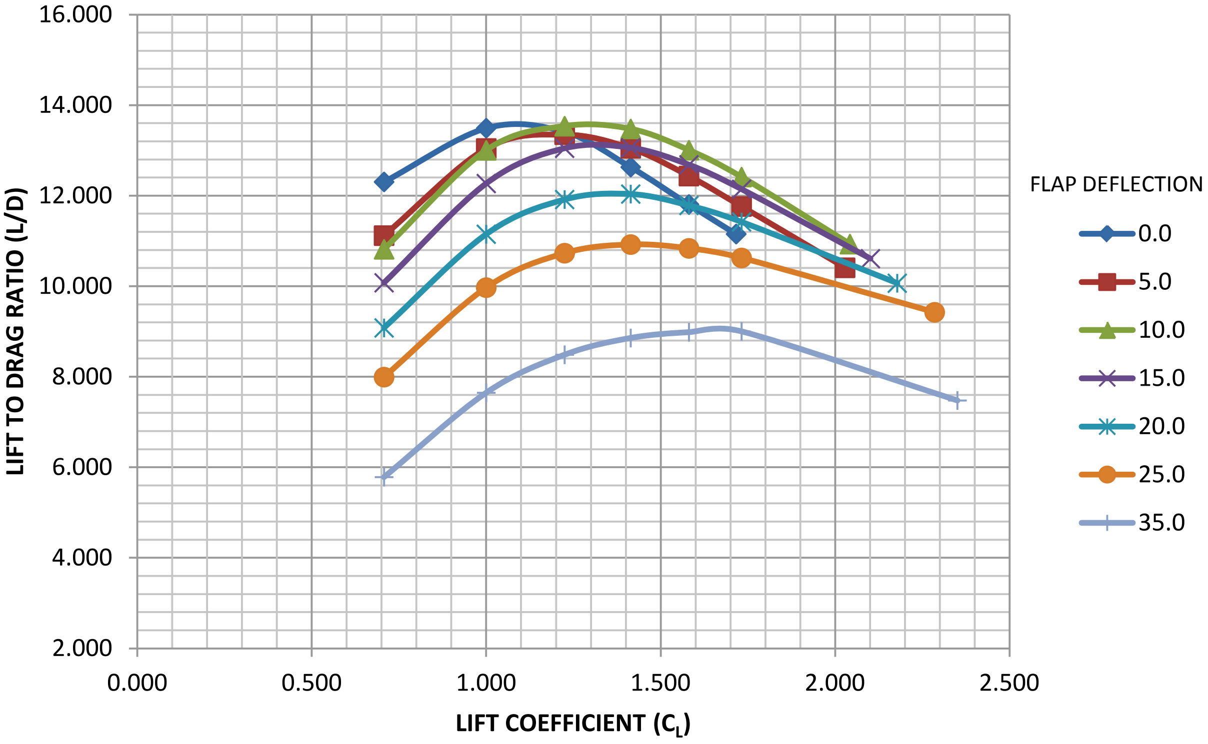


Figure 5.5 – 765-094-TS1 - Low Speed Lift / Drag; Free Air

The N+4 Reference configuration weight was estimated by applying N+3 weight reduction factors to SUGAR Free and updating the engine component weights to be consistent with the 2045 gFan++ engine. Table 5.5 shows the resulting group weight statement which includes each group's percentage of TOGW. This weights breakdown is for an unsized configuration and is used to feed the sizing process.

Table 5.5 – 765-094-TS1 Group Weight Statement

GROUP	WEIGHT (LB)	% TOGW
WING	**13,780**	**10.1%**
BENDING MATERIAL	5,754	4.2%
SPAR WEBS	994	0.7%
RIBS AND BULKHEADS	1,091	0.8%
AERODYNAMIC SURFACES	3,151	2.3%
SECONDARY STRUCTURE	2,791	2.0%
TAIL	**2,676**	**2.0%**
FUSELAGE	**14,946**	**11.0%**
LANDING GEAR	**5,052**	**3.7%**
NACELLE & PYLON	**5,392**	**4.0%**
PROPULSION	**9,898**	**7.3%**
ENGINES	9,280	6.8%
FUEL SYSTEM	618	0.5%
FLIGHT CONTROLS	**3,106**	**2.3%**
COCKPIT CONTROLS	252	0.2%
SYSTEM CONTROLS	2,853	2.1%
POWER SYSTEMS	**4,211**	**3.1%**
AUXILIARY POWER UNIT	1,014	0.7%
HYDRAULICS	901	0.7%
ELECTRICAL	2,297	1.7%
INSTRUMENTS	**773**	**0.6%**
AVIONICS & AUTOPILOT	**1,504**	**1.1%**
FURNISHINGS & EQUIPMENT	**9,115**	**6.7%**
AIR CONDITIONING	**1,441**	**1.1%**
ANTI-ICING	**112**	**0.1%**
MANUFACTURER'S EMPTY WEIGHT (MEW)	**72,006**	**52.8%**
OPERATIONAL ITEMS	7,207	5.3%
OPERATIONAL EMPTY WEIGHT (OEW)	**79,213**	**58.1%**
USABLE FUEL	26,399	19.4%
DESIGN PAYLOAD	30,800	22.6%
TAKEOFF GROSS WEIGHT (TOGW)	**136,412**	**100.0%**

5.3 765-095-TS1 N+4 Truss Braced Wing

This configuration, illustrated in Figure 5.6, is a high-span truss-braced wing configuration with the N+4 gFan++ engine and other advanced N+3 technologies. The configuration draws from the truss braced wing knowledge generated under the SUGAR Phase II contract Task 2.1. The aerodynamic, structural, and weight attributes of the configuration are currently being explored and the results shown in this document reflect Boeing’s current understanding of the aircraft. An aeroelastic FEM and high fidelity CFD are currently being run on a similar configuration under Task 2.1. The gFan++ Advanced Turbofan (JP+2045GT+DF) engine is summarized in Appendix A.

PROJECTED CHARACTERISTICS			
	WING TOTAL	V-TAIL TRAP	H-TAIL TRAP
AREA (SQ. FT)	1477.11	297.68	296.23
ASPECT RATIO	19.55	1.00	5.00
SPAN (INCHES)	2039.30	207.04	461.83
TAPER RATIO	0.35	1.00	0.35
MAC (INCHES)	110.29	207.04	99.50
DIHEDRAL (DEG.)	-1.50	--	-3.00
¼ CHORD SWEEP (DEG.)	12.52	41.00	25.30
ROOT CHORD (INCHES)	130.31	207.04	136.84
TIP CHORD (INCHES)	45.13	207.04	47.89
TAIL VOLUME COEFFICIENT	--	0.07	1.57

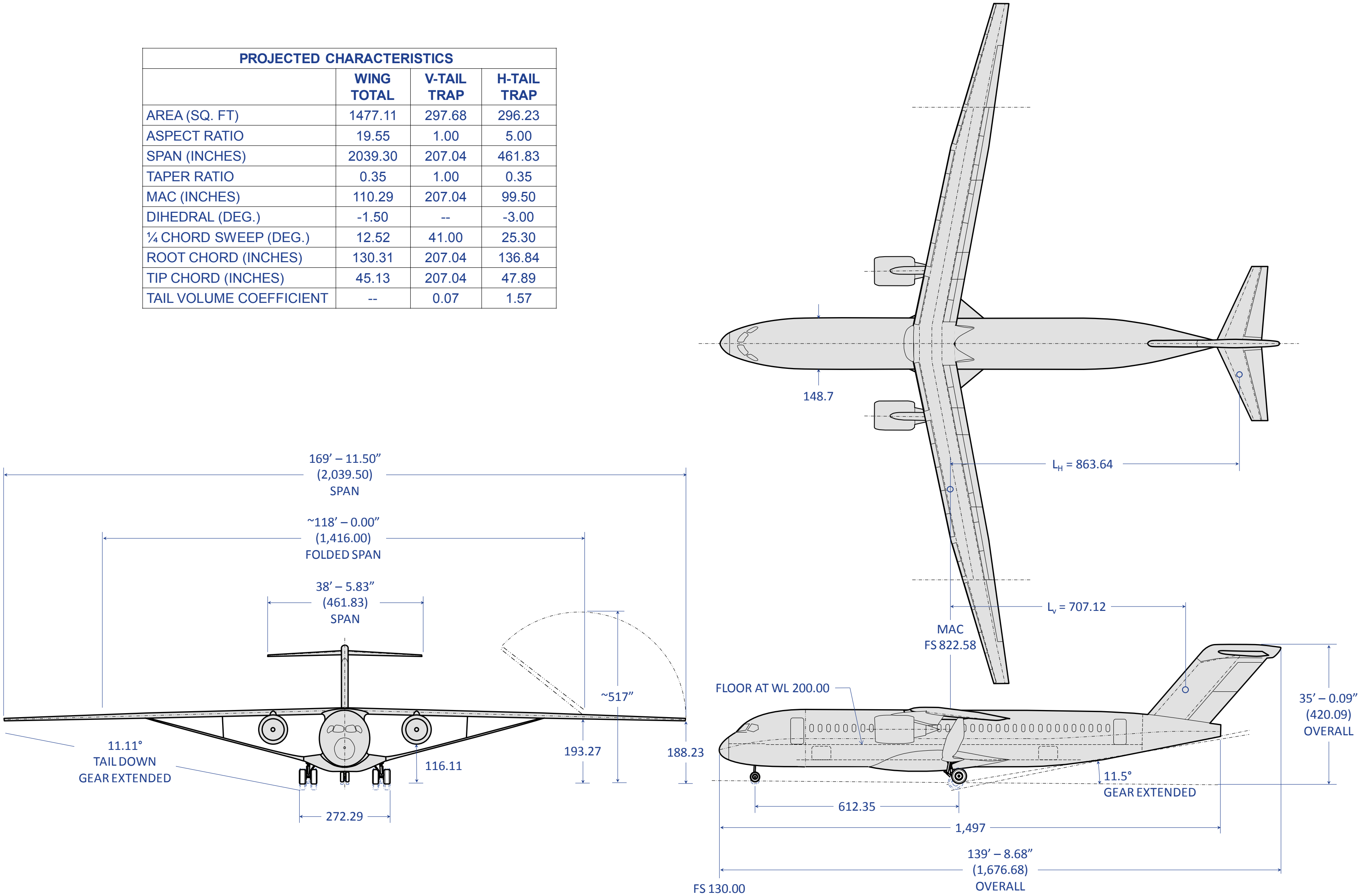


Figure 5.6 – 765-095-TS1 – Truss Braced Wing with gFan++

The high-speed drag buildup for SUGAR N+4 TBW configuration is shown in Table 5.6 and Figure 5.7. This buildup is assisted by the work completed under Task 2.1, however, the CASES empirical database being used to generate the data is still being extrapolated.

Table 5.6 – 765-095-TS1 High Speed Build-up

CONFIGURATION	765-095-TS1
AIRFOIL TYPE	SUPERCRIT. DTE

F BUILD-UP (FT^2)	
FUSELAGE	8.8378
WING	10.3240
STRUT	2.7291
JURY STRUT	0.2519
HORIZONTAL	1.9266
VERTICAL	1.7487
N&P	1.9020
CANOPY	0.0405
GEAR PODS	3.1393
ETC BEFORE SUB	-7.9462
EXCRESCENCE	1.9947
UPSWEEP	0.3414
WING TWIST	0.1640
ETC AFTER SUB	-1.4622
FUSELAGE BUMP	0.3675
F-TOTAL (FT^2)	**24.3590**

E-VISC	**0.93071**

CRUISE C_D BUILD-UP	
M-CRUISE	0.73
CRUISE ALTITUDE	44000
C_L-CRUISE	0.775
C_{D0}	0.01649
C_{DI}	0.01048
C_{DC}	0.002058
C_{DTRIM}	0.000592
C_{DTOT}	0.02962
L/D	26.16257
ML/D	19.099

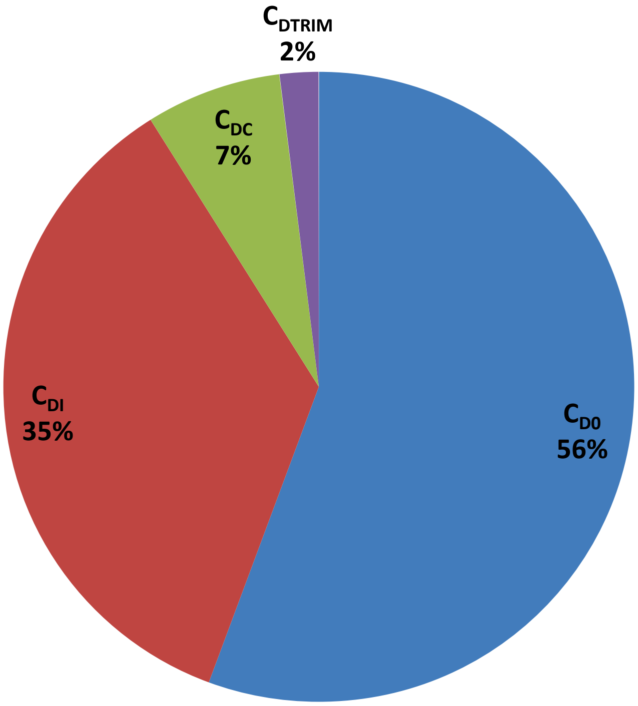


Figure 5.7 – 765-095-TS1 High Speed Build-up

The ETC BEFORE SUB category includes technology projections for natural laminar flow over a portion of the wing, strut, and vertical tail, horizontal tail, nacelles as well as riblets applied to the turbulent portion of the wing and the fuselage. ETC AFTER SUB includes a technology projection for advanced supercritical airfoils with divergent trailing edge. In addition, technologies for low interference nacelles and strut/brace were included in the parasite buildup.

The resulting high speed data is shown in Figure 5.8. The figure illustrates the maximum aerodynamic efficiency (M*L/D) occurring at a cruise Mach of 0.73 and a C_L of 0.775.

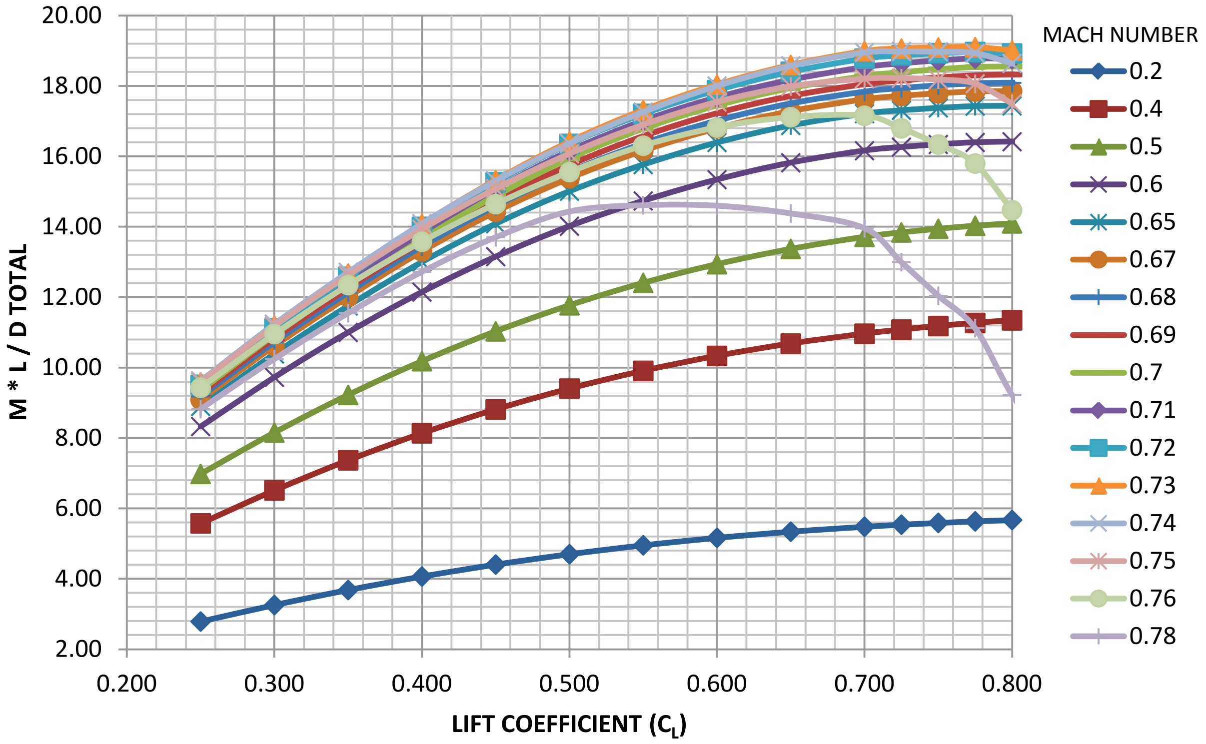


Figure 5.8 – 765-095-TS1 - M * L / D Total

Figure 5.9 through Figure 5.11 show the low speed characteristics for the 765-095-TS1. Low speed data are trimmed as a function of angle of attack, lift coefficient, and drag coefficient at each flap detent. Low speed high lift devices on wing leading and trailing edges are deployed.

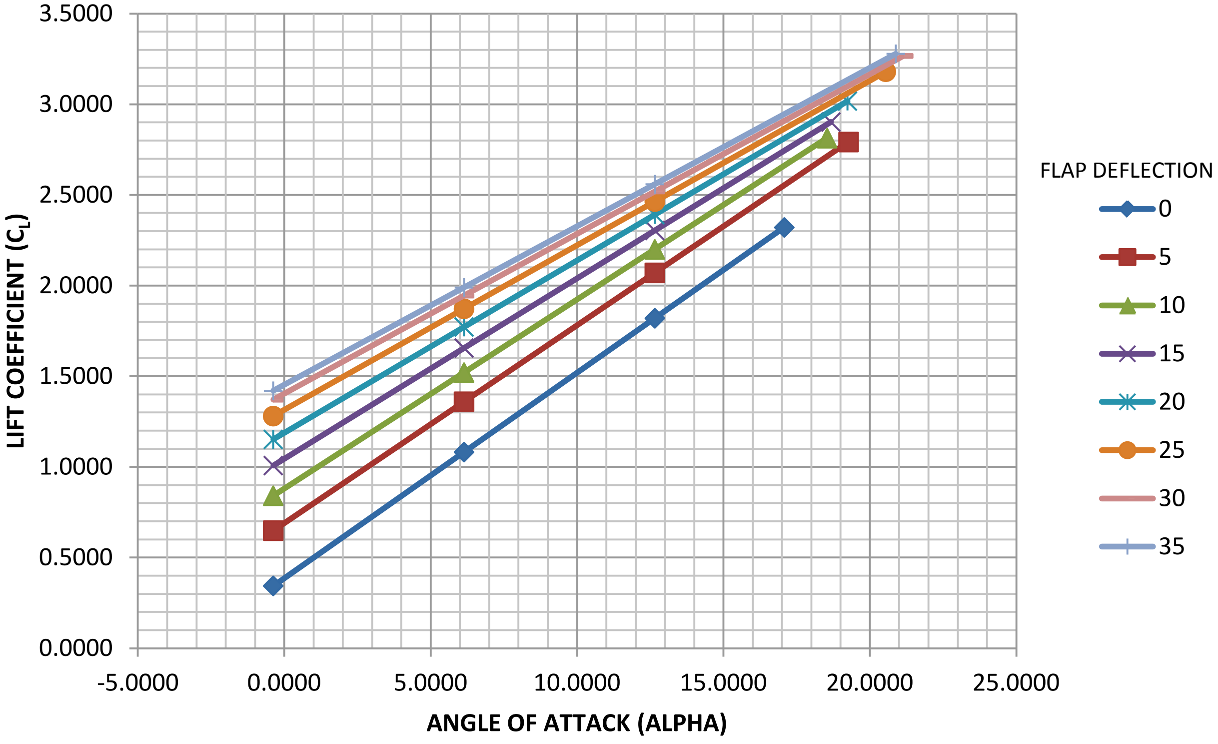


Figure 5.9 – 765-095-TS1 - Low Speed Lift Curve; Free Air

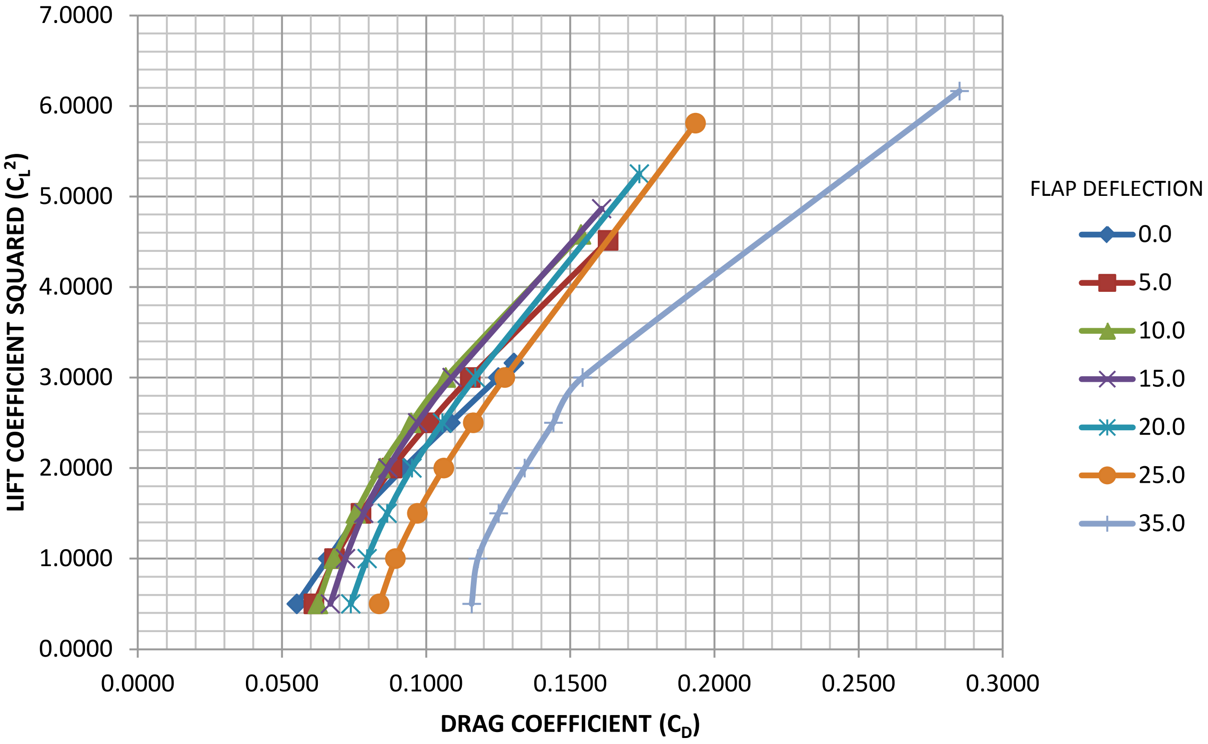


Figure 5.10 – 765-095-TS1 - Low Speed Polar; Free Air

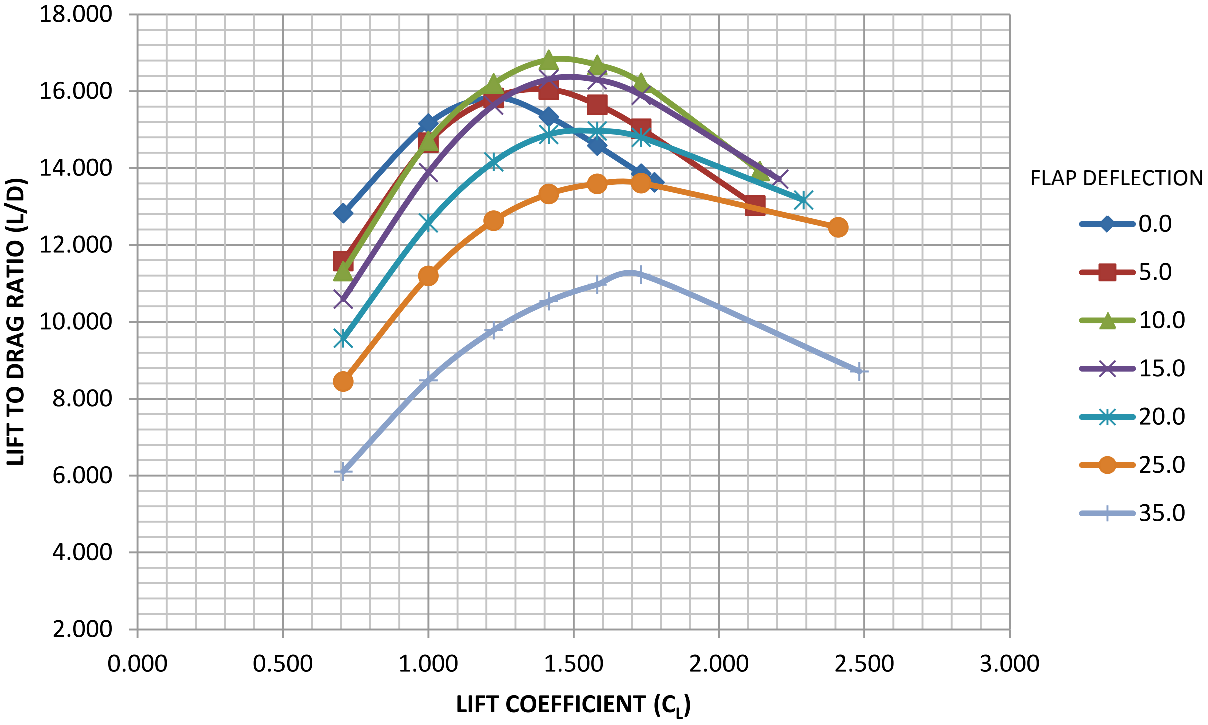


Figure 5.11 – 765-095-TS1 - Low Speed Lift / Drag; Free Air

The weight for the SUGAR N+4 TBW configuration was estimated by applying N+3 weight reduction factors to a calibrated model. The wing was weighed using a station based analysis with Task 2.1 MDO generated loads and empirical allowables adjusted for technology. No penalty was applied for flutter. Table 5.7 shows the subsystem weights and their percentages of TOGW for the as-drawn analyzed weight.

Table 5.7 – 765-095-TS1 Group Weight Statement

GROUP	WEIGHT (LB)	% TOGW
WING	**19,940**	**14.2%**
BENDING MATERIAL	7,399	5.3%
SPAR WEBS	1,850	1.3%
RIBS AND BULKHEADS	1,850	1.3%
AERODYNAMIC SURFACES	4,993	3.6%
SECONDARY STRUCTURE	3,849	2.7%
TAIL	**3,157**	**2.3%**
FUSELAGE	**16,554**	**11.8%**
LANDING GEAR	**4,706**	**3.4%**
STRUT, JURY STRUT, AND INSTALLATION	**5,392**	**3.9%**
NACELLE & PYLON	**2,399**	**1.7%**
PROPULSION	**10,008**	**7.1%**
ENGINES	9,280	6.6%
FUEL SYSTEM	728	0.5%
FLIGHT CONTROLS	**2,683**	**1.9%**
COCKPIT CONTROLS	252	0.2%
SYSTEM CONTROLS	2,431	1.7%
POWER SYSTEMS	**4,078**	**2.9%**
AUXILIARY POWER UNIT	1,014	0.7%
HYDRAULICS	767	0.5%
ELECTRICAL	2,297	1.6%
INSTRUMENTS	**773**	**0.6%**
AVIONICS & AUTOPILOT	**1,504**	**1.1%**
FURNISHINGS & EQUIPMENT	**9,115**	**6.5%**
AIR CONDITIONING	**1,441**	**1.0%**
ANTI-ICING	**123**	**0.1%**
MANUFACTURER'S EMPTY WEIGHT (MEW)	**81,873**	**58.5%**
OPERATIONAL ITEMS	7,207	5.1%
OPERATIONAL EMPTY WEIGHT (OEW)	**89,080**	**63.6%**
USABLE FUEL	20,120	14.4%
DESIGN PAYLOAD	30,800	22.0%
TAKEOFF GROSS WEIGHT (TOGW)	**140,000**	**100.0%**

5.4 765-095-TS2 N+4 Truss Braced Wing with LNG Gas Turbine

This configuration is the same as the 765-095-TS1 but includes a fuselage stretch (Figure 5.12) to accommodate LNG tanks in front of and behind the passenger section. The forward LNG tank is cylindrical to allow passage with minimum clearances to the flight deck. Safety and certification of the installation may be a challenge and could drive significant configuration changes. At a minimum, a vapor barrier would be required to prevent methane leakage into the passenger cabin. A second pressure bulkhead may be required between the methane tank and the passenger cabin. The configuration is currently assumed to take minimal penalty for the integration of the forward tank. Further research is required to understand the tank integration penalties.

The forward tank integration requires a forward constant section extension. The aft tank requires lengthening and reshaping of the upsweep region. The aft constant section cannot be stretched because the airplane would no longer conform to the tail strike requirement carried by the other concepts. The overall stretch required is illustrated in Figure 5.12.

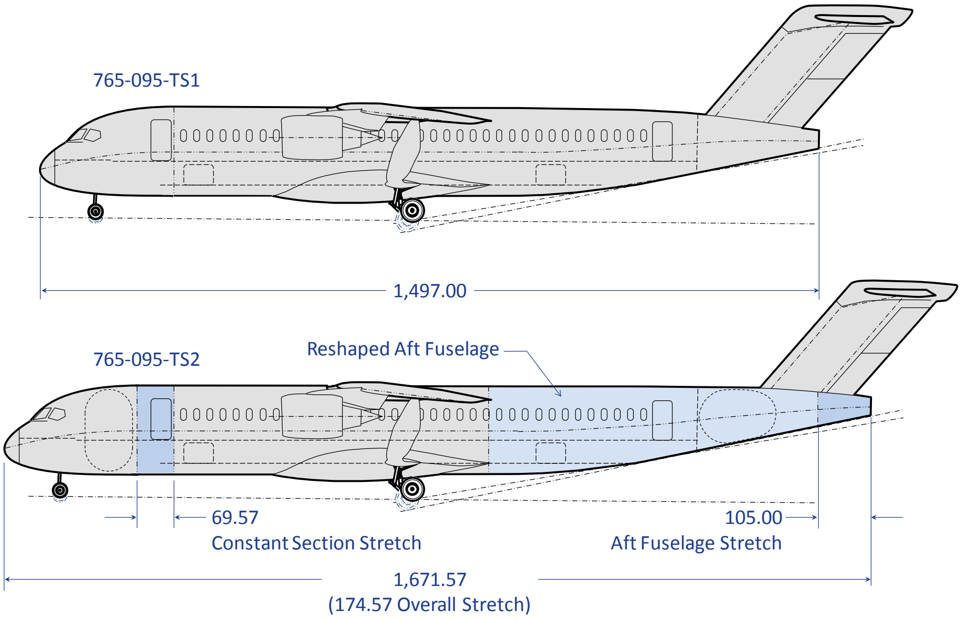


Figure 5.12 – Fuselage Stretched to Accommodate LNG Tankage

The increased fuselage length penalty is partially offset by a reduction in tail area for a given tail volume coefficient. The final N+4 integrated solution is shown in Figure 5.13.

For a description of the LNG propellant system, see Section 6.2.8, LNG and Hydrogen Aircraft Systems.

An overview of the LNG fueled gFan++ advanced turbofan (LNG+2045GT+DF) is provided in Appendix A.

PROJECTED CHARACTERISTICS			
	WING TOTAL	V-TAIL TRAP	H-TAIL TRAP
AREA (SQ. FT)	1477.11	257.76	265.89
ASPECT RATIO	19.55	1.00	5.00
SPAN (INCHES)	2039.30	192.66	437.54
TAPER RATIO	0.35	1.00	0.35
MAC (INCHES)	110.29	192.66	94.27
DIHEDRAL (DEG.)	-1.50	--	-3.00
¼ CHORD SWEEP (DEG.)	12.52	41.00	25.30
ROOT CHORD (INCHES)	130.31	192.66	129.64
TIP CHORD (INCHES)	45.13	192.66	45.37
TAIL VOLUME COEFFICIENT	--	0.07	1.57

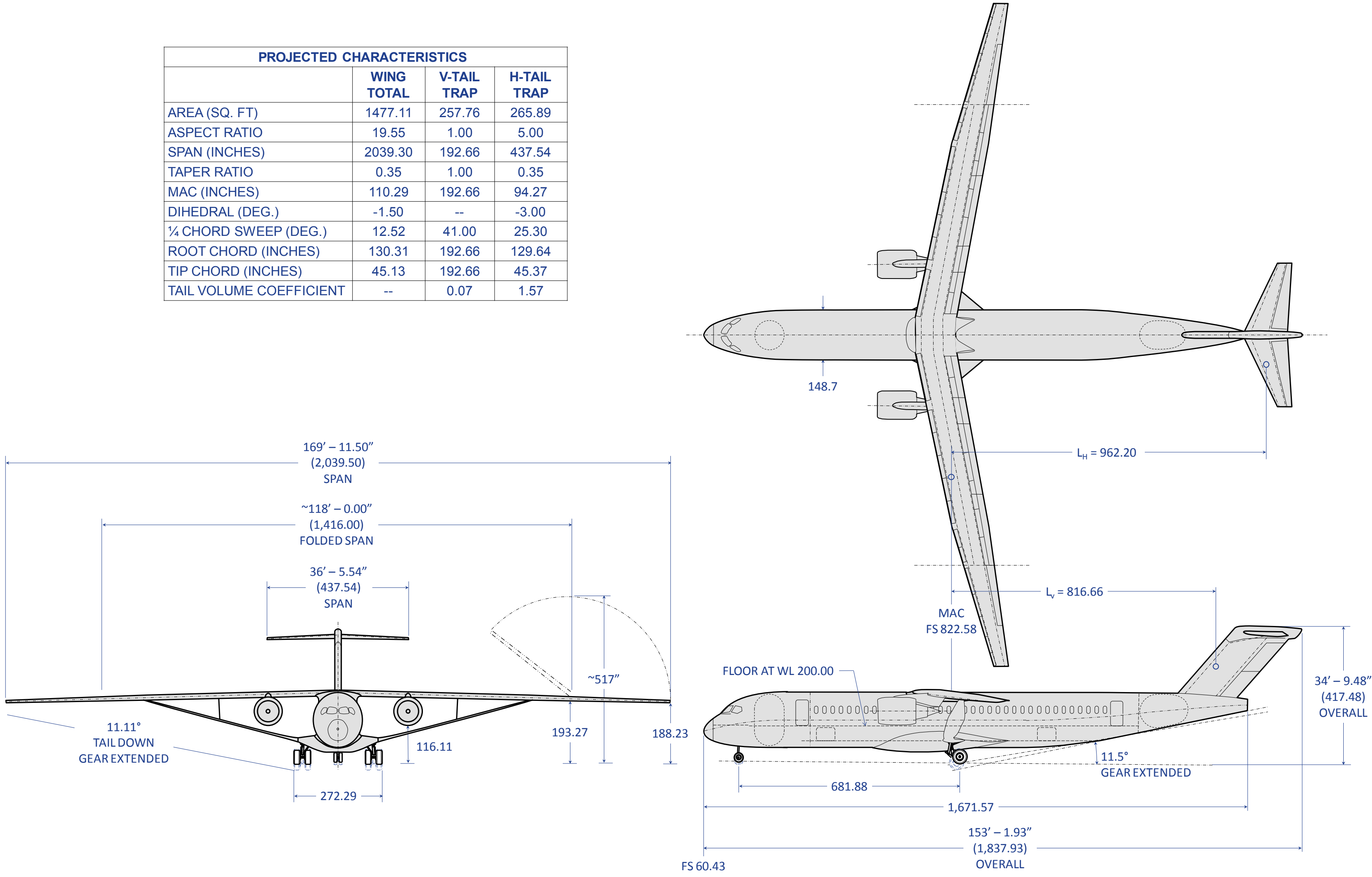


Figure 5.13 – 765-095-TS2 – Truss Braced Wing With LNG gFan++

The high-speed drag buildup, a small change from the 765-095-TS1, is shown in Table 5.8 and Figure 5.14.

Table 5.8 – 765-095-TS2 High Speed Build-up

CONFIGURATION	765-095-TS2
AIRFOIL TYPE	SUPERCRIT. DTE

F BUILD-UP (FT^2)	
FUSELAGE	9.4840
WING	10.3240
STRUT	2.7291
JURY STRUT	0.2519
HORIZONTAL	1.7482
VERTICAL	1.5327
N&P	1.9020
CANOPY	0.0405
GEAR PODS	3.1393
ETC BEFORE SUB	-7.9839
EXCRESCENCE	1.9809
UPSWEEP	0.4870
WING TWIST	0.1640
ETC AFTER SUB	-1.4622
FUSELAGE BUMP	0.3675
F-TOTAL (FT^2)	**24.7049**

E-VISC	**0.95206**

CRUISE C_D BUILD-UP	
M-CRUISE	0.73
CRUISE ALTITUDE	44000
C_L-CRUISE	0.775
C_{D0}	0.01673
C_{DI}	0.01025
C_{DC}	0.002018
C_{DTRIM}	0.000592
C_{DTOT}	0.02958
L/D	26.19685
ML/D	19.124

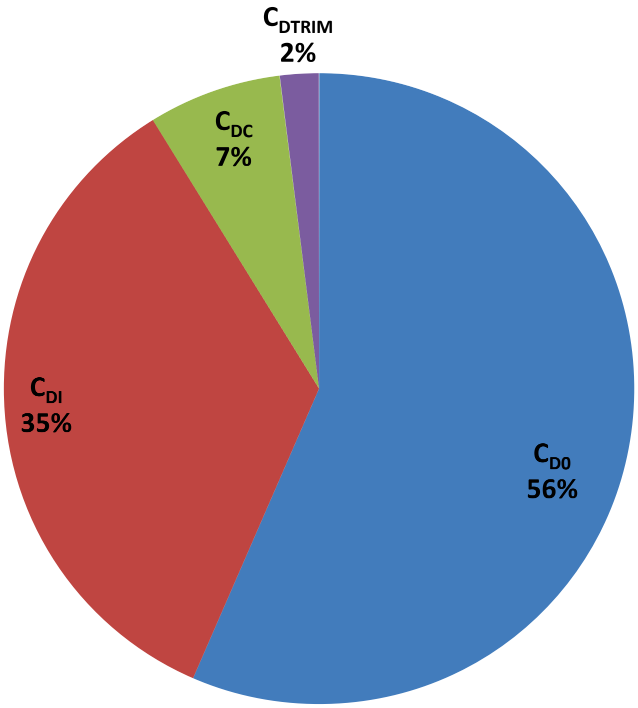


Figure 5.14 – 765-095-TS2 High Speed Build-up

The resulting high speed data is shown in Figure 5.8. The figure illustrates the maximum aerodynamic efficiency (M*L/D) occurring at a cruise Mach of 0.73 and a C_L of 0.775.

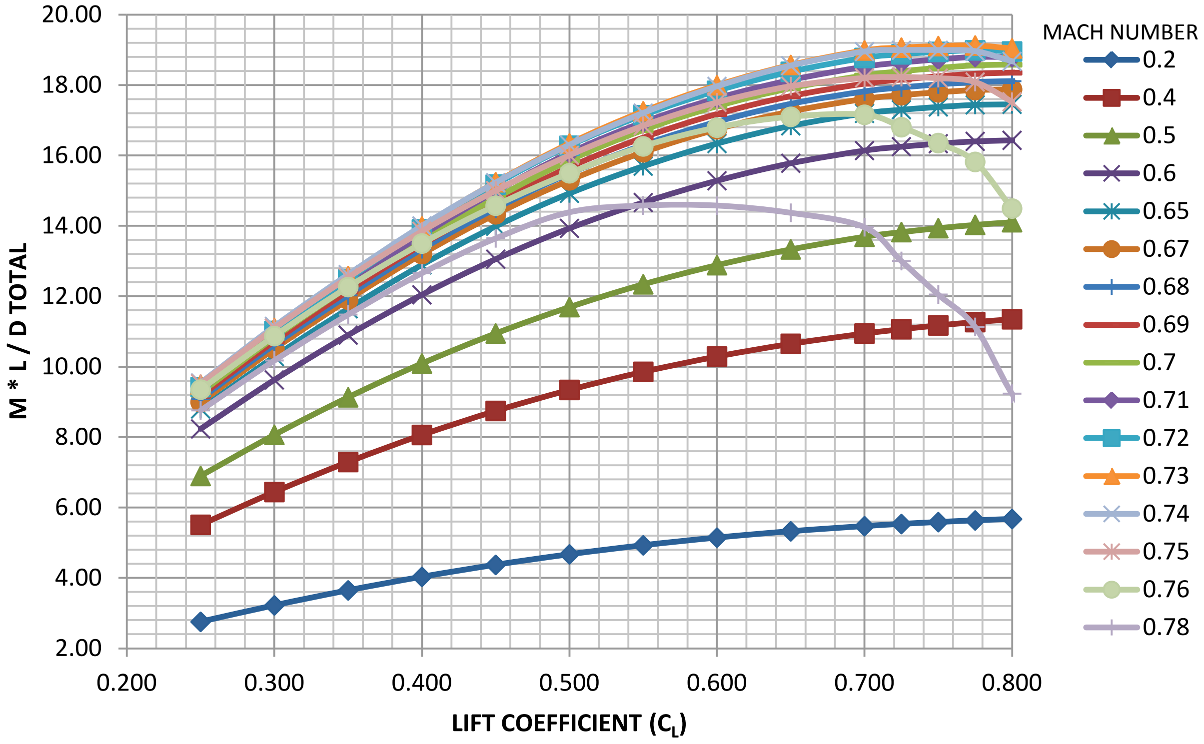


Figure 5.15 – 765-095-TS2 - M * L / D Total

Figure 5.16 through Figure 5.18 show the low speed characteristics for the 765-095-TS2. Low speed data are trimmed as a function of angle of attack, lift coefficient, and drag coefficient at each flap detent. Low speed high lift devices on wing leading and trailing edges are deployed.

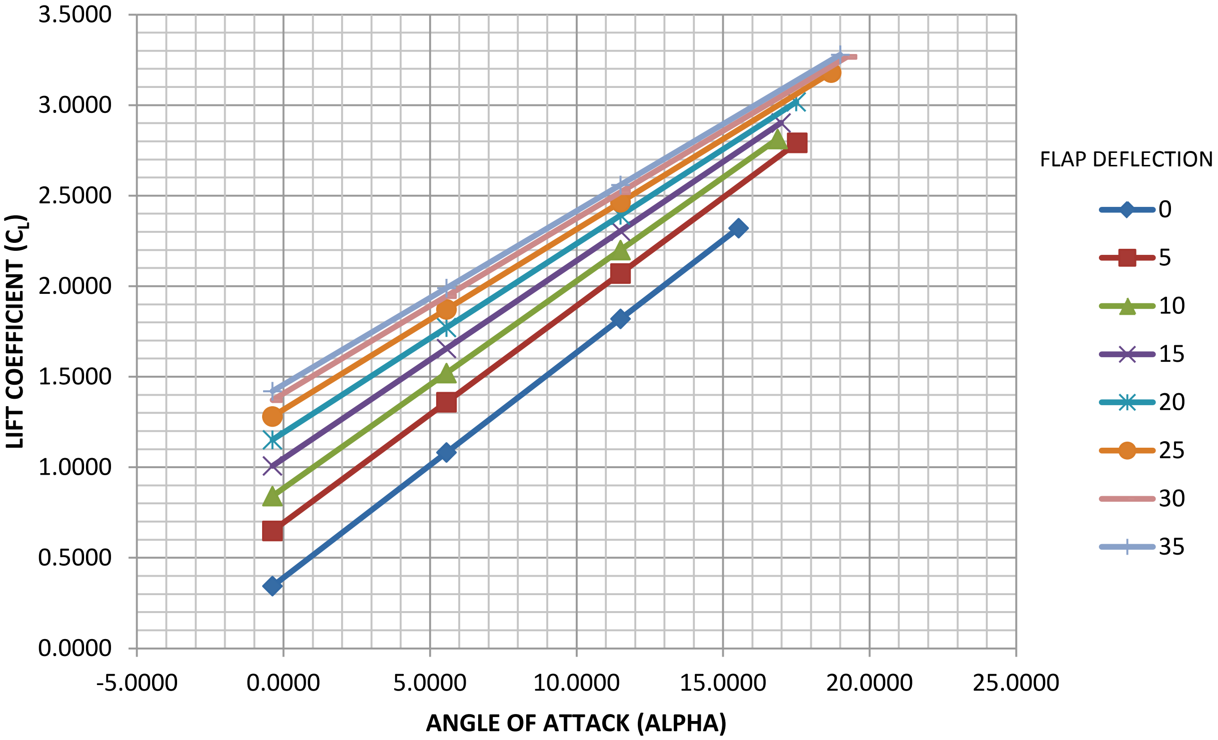


Figure 5.16 – 765-095-TS2 - Low Speed Lift Curve; Free Air

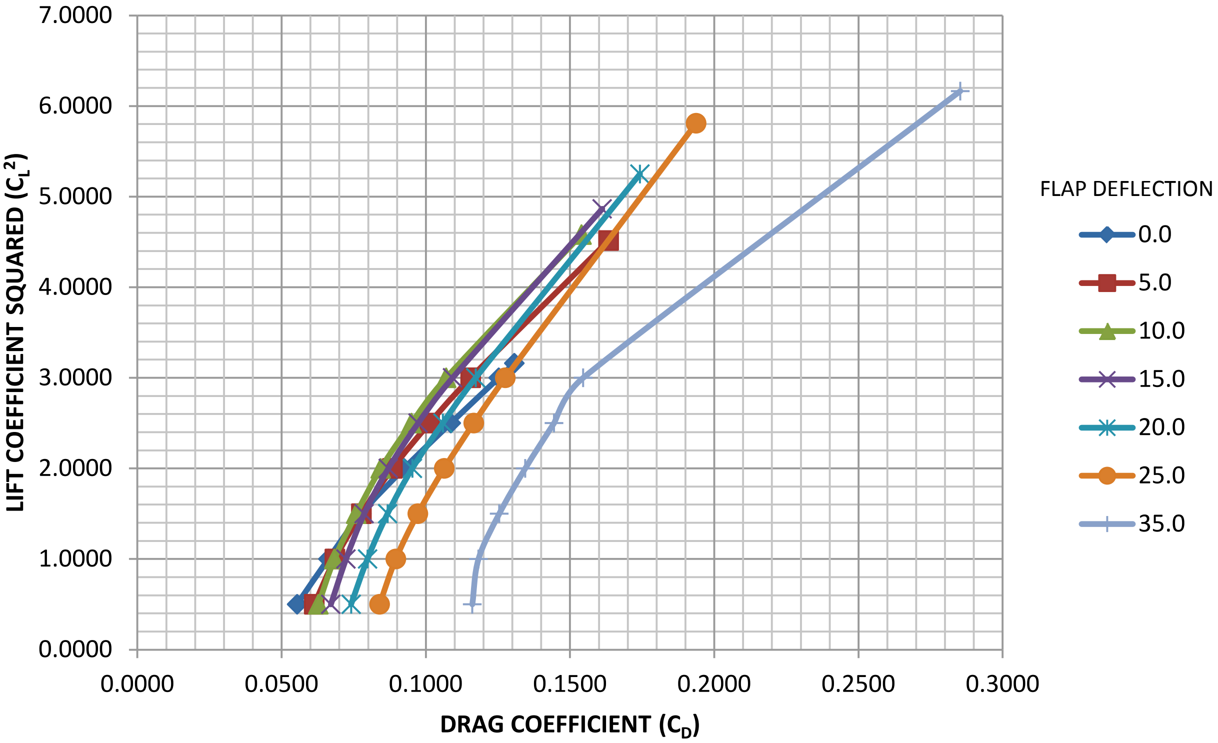


Figure 5.17 – 765-095-TS2 - Low Speed Polar; Free Air

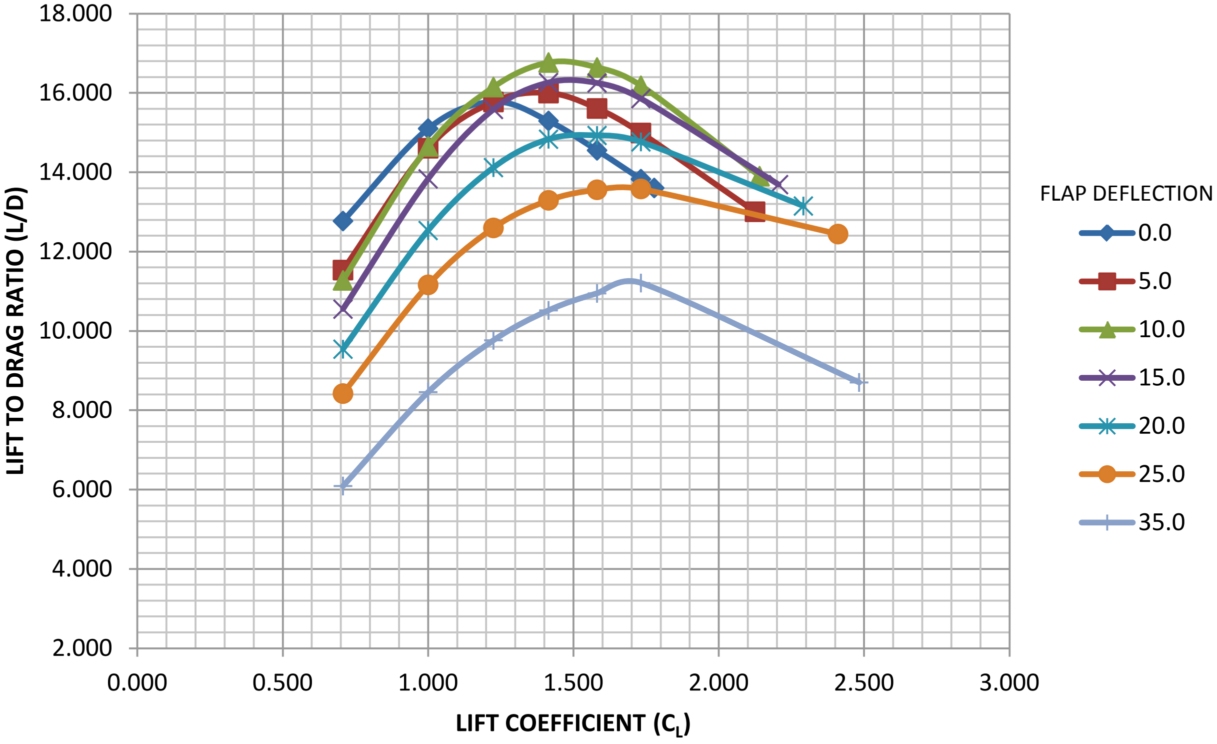


Figure 5.18 – 765-095-TS2 - Low Speed Lift / Drag; Free Air

The weight (Table 5.9) for this configuration was generated starting from the 765-095-TS1 and adding a fuselage stretch and the cryogenic fuel system.

Table 5.9 – 765-095-TS2 Group Weight Statement

GROUP	WEIGHT (LB)	% TOGW
WING	**21,330**	**13.7%**
BENDING MATERIAL	8,197	5.3%
SPAR WEBS	2,049	1.3%
RIBS AND BULKHEADS	2,049	1.3%
AERODYNAMIC SURFACES	5,113	3.3%
SECONDARY STRUCTURE	3,921	2.5%
TAIL	**2,852**	**1.8%**
FUSELAGE	**19,304**	**12.4%**
LANDING GEAR	**5,300**	**3.4%**
NACELLE & PYLON	**5,392**	**3.5%**
STRUT, JURY STRUT, AND INSTALLATION	**2,399**	**1.5%**
PROPULSION	**15,753**	**10.1%**
ENGINES	9,280	5.9%
FUEL SYSTEM	6,473	4.1%
FLIGHT CONTROLS	**2,753**	**1.8%**
COCKPIT CONTROLS	254	0.2%
SYSTEM CONTROLS	2,500	1.6%
POWER SYSTEMS	**4,276**	**2.7%**
AUXILIARY POWER UNIT	1,039	0.7%
HYDRAULICS	789	0.5%
ELECTRICAL	2,447	1.6%
INSTRUMENTS	**818**	**0.5%**
AVIONICS & AUTOPILOT	**1,603**	**1.0%**
FURNISHINGS & EQUIPMENT	**10,300**	**6.6%**
AIR CONDITIONING	**1,564**	**1.0%**
ANTI-ICING	**123**	**0.1%**
MANUFACTURER'S EMPTY WEIGHT (MEW)	**93,765**	**60.1%**
OPERATIONAL ITEMS	7,803	5.0%
OPERATIONAL EMPTY WEIGHT (OEW)	**101,569**	**65.1%**
USABLE FUEL	23,631	15.1%
DESIGN PAYLOAD	30,800	19.7%
TAKEOFF GROSS WEIGHT (TOGW)	**156,000**	**100.0%**

5.5 765-095-TS3 N+4 Truss Braced Wing with LNG Unducted Fan

This configuration (Figure 5.19) is the same as the 765-095-TS2, but with an unducted fan. The LNG fueled gFan++ powerplant with an unducted fan propulsor (LNG+2045GT+UDF) is discussed in Appendix A.

PROJECTED CHARACTERISTICS			
	WING TOTAL	V-TAIL TRAP	H-TAIL TRAP
AREA (SQ. FT)	1477.11	257.76	265.89
ASPECT RATIO	19.55	1.00	5.00
SPAN (INCHES)	2039.30	192.66	437.54
TAPER RATIO	0.35	1.00	0.35
MAC (INCHES)	110.29	192.66	94.27
DIHEDRAL (DEG.)	-1.50	--	-3.00
¼ CHORD SWEEP (DEG.)	12.52	41.00	25.30
ROOT CHORD (INCHES)	130.31	192.66	129.64
TIP CHORD (INCHES)	45.13	192.66	45.37
TAIL VOLUME COEFFICIENT	--	0.07	1.57

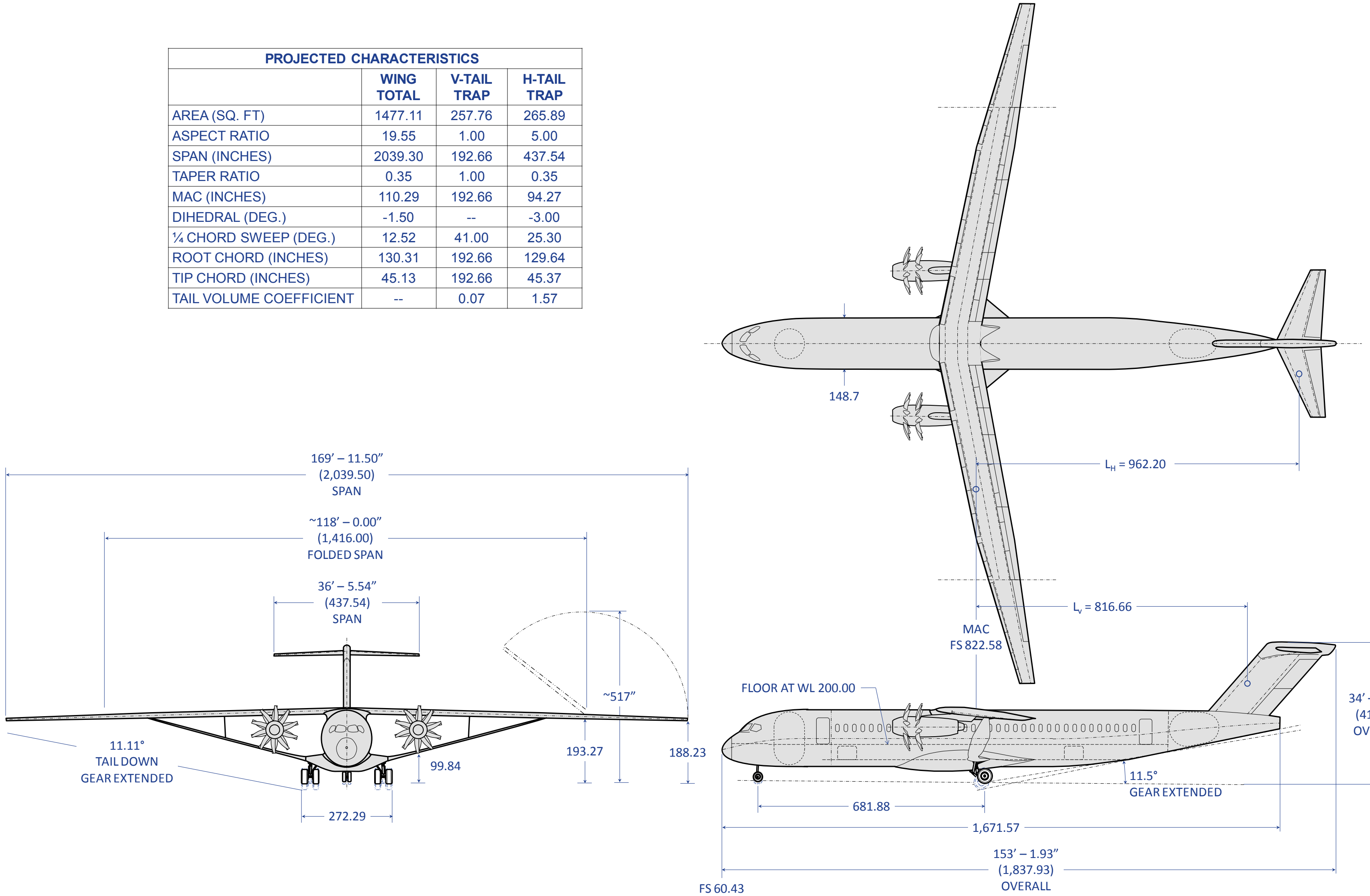


Figure 5.19 – 765-095-TS3 - Truss Braced Wing With LNG UDF

The aerodynamic buildup (Figure 5.20 and Table 5.10) accounts for a decreased portion of wing laminar flow due to the propulsion system wake.

Table 5.10 – 765-095-TS3 High Speed Build-up

CONFIGURATION	765-095-TS3
AIRFOIL TYPE	SUPERCRIT. DTE

F BUILD-UP (FT^2)	
FUSELAGE	9.4840
WING	10.3240
STRUT	2.7291
JURY STRUT	0.2519
HORIZONTAL	1.7482
VERTICAL	1.5327
N&P	1.9520
CANOPY	0.0405
GEAR PODS	3.1393
ETC BEFORE SUB	-6.6657
EXCRESCENCE	2.0978
UPSWEEP	0.4870
WING TWIST	0.1640
ETC AFTER SUB	-1.4622
FUSELAGE BUMP	0.3675
F-TOTAL (FT^2)	**26.1901**

E-VISC	**0.95206**

CRUISE C_D BUILD-UP	
M-CRUISE	0.73
CRUISE ALTITUDE	44000
C_L-CRUISE	0.775
C_{D0}	0.01773
C_{DI}	0.01025
C_{DC}	0.002018
C_{DTRIM}	0.000612
C_{DTOT}	0.03061
L/D	25.31906
ML/D	18.483

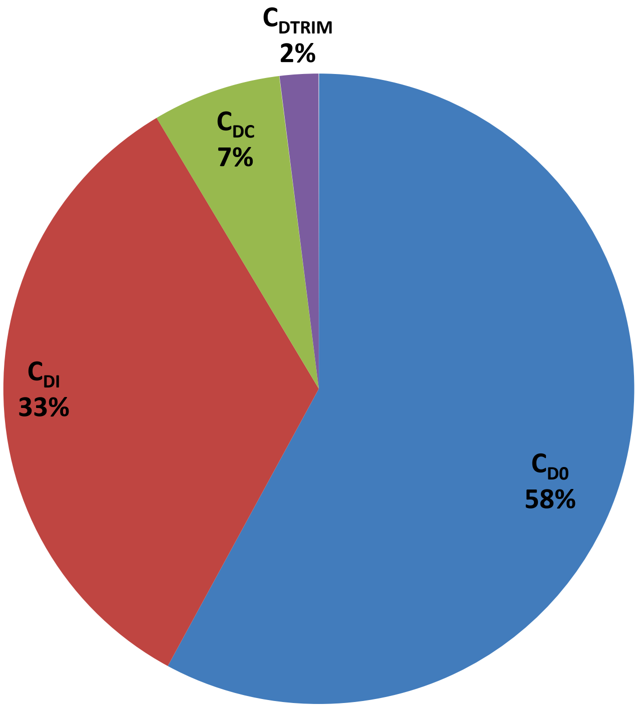


Figure 5.20 – 765-095-TS3 High Speed Build-up

The resulting high speed data is shown in Figure 5.21. The figure illustrates the maximum aerodynamic efficiency (M*L/D) occurring at a cruise Mach of 0.73 and a C_L of 0.775.

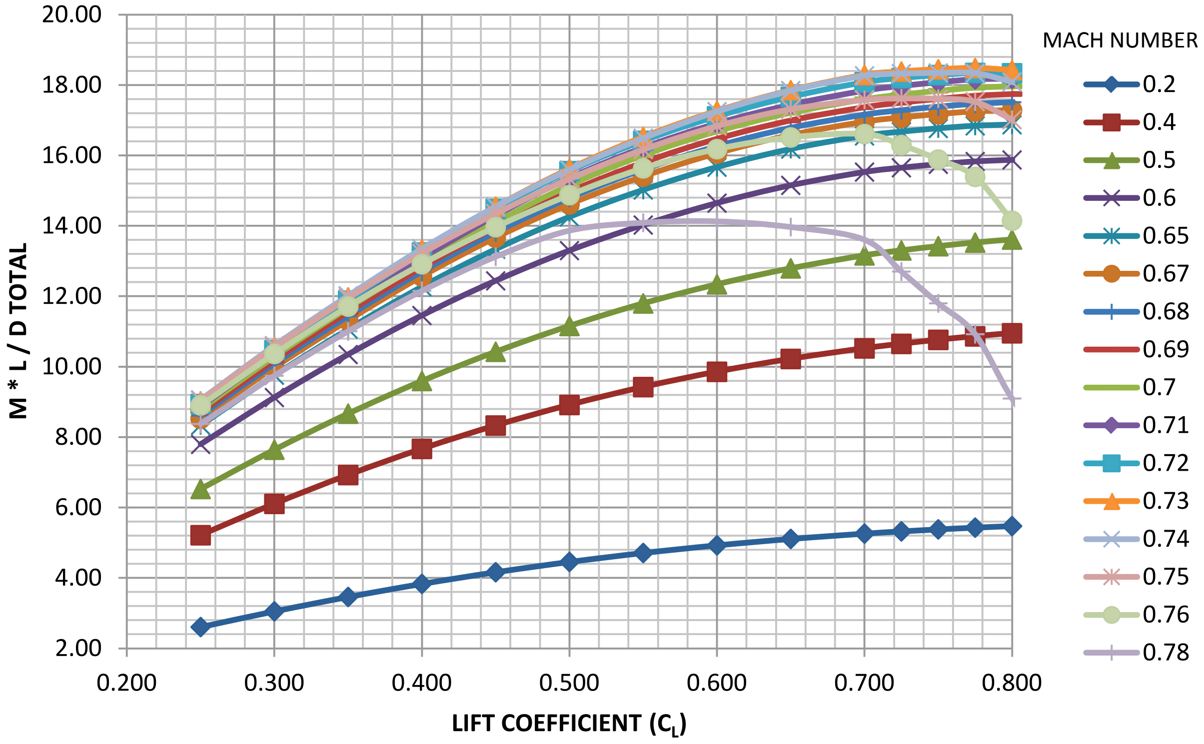


Figure 5.21 – 765-095-TS3 - M * L / D Total

Figure 5.22 through Figure 5.24 show the low speed characteristics for the 765-095-TS3. Low speed data are trimmed as a function of angle of attack, lift coefficient, and drag coefficient at each flap detent. Low speed high lift devices on wing leading and trailing edges are deployed.

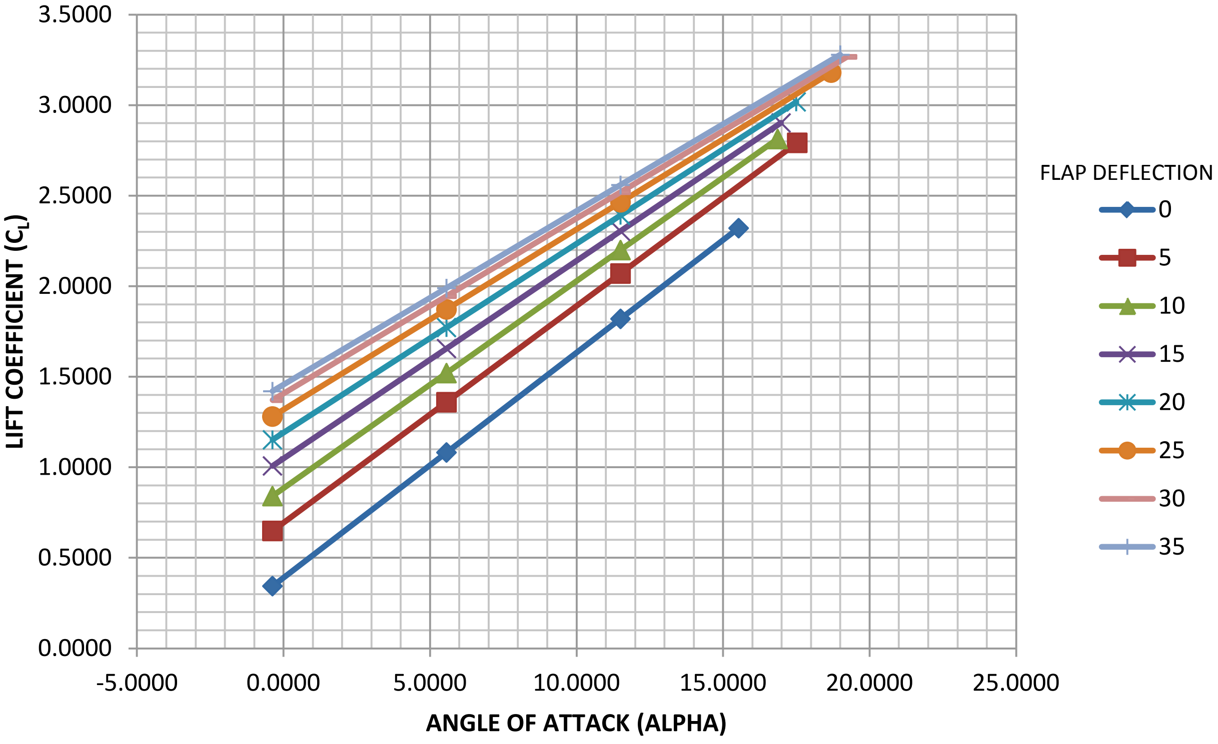


Figure 5.22 – 765-095-TS3 - Low Speed Lift Curve; Free Air

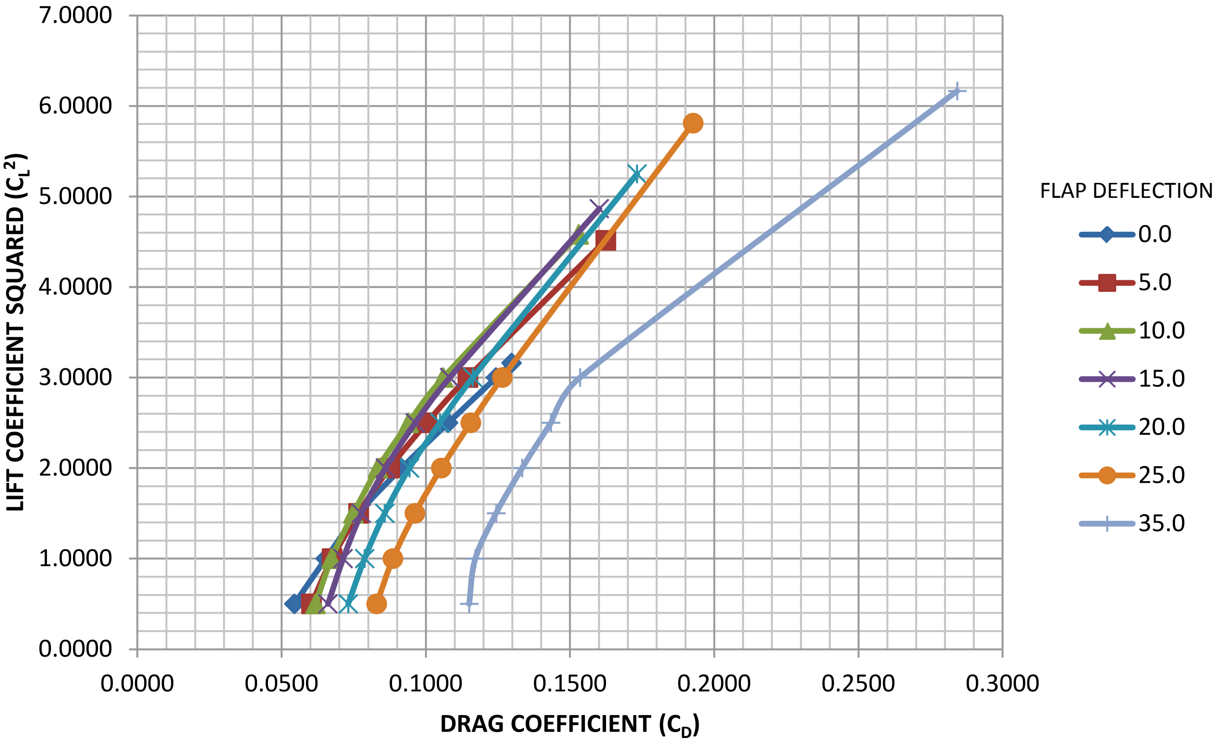


Figure 5.23 – 765-095-TS3 - Low Speed Polar; Free Air

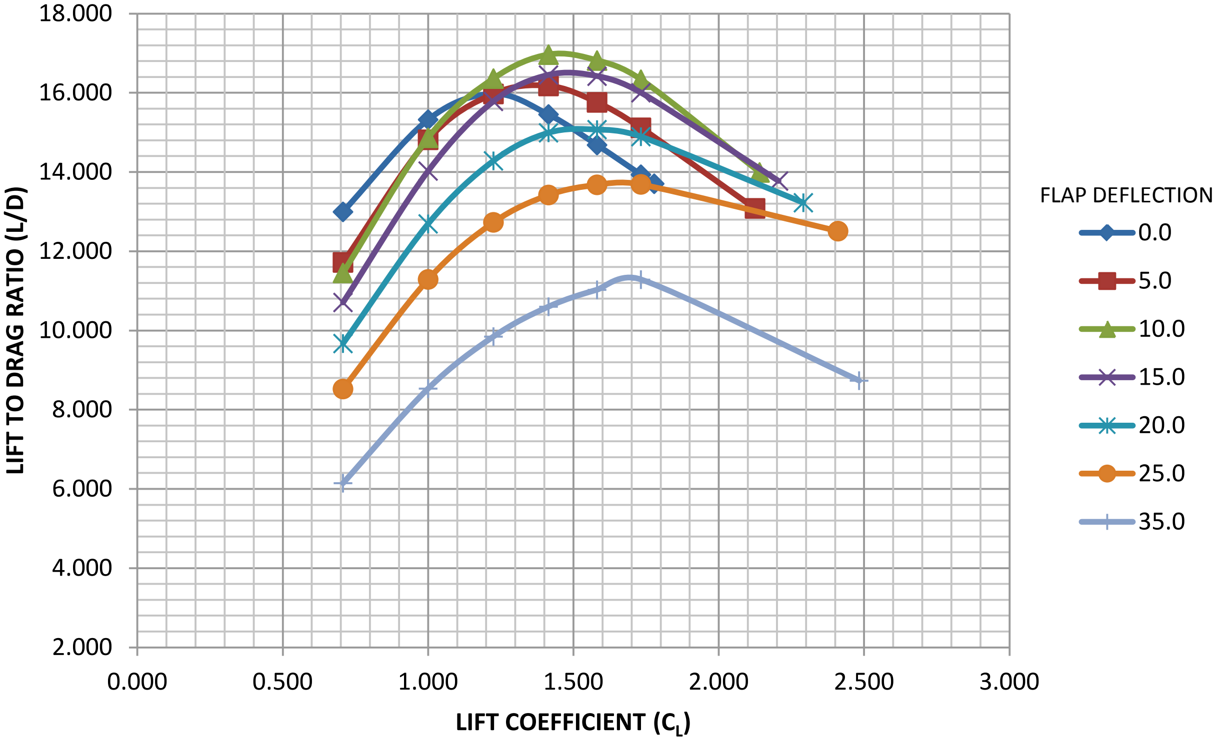


Figure 5.24 – 765-095-TS3 - Low Speed Lift / Drag; Free Air

The weight (Table 5.11) for this configuration was generated starting from the 765-095-TS2 and adjusting propulsion system weight.

Table 5.11 – 765-095-TS3 Group Weight Statement

GROUP	WEIGHT (LB)	% TOGW
WING	**21,330**	**13.7%**
BENDING MATERIAL	8,197	5.3%
SPAR WEBS	2,049	1.3%
RIBS AND BULKHEADS	2,049	1.3%
AERODYNAMIC SURFACES	5,113	3.3%
SECONDARY STRUCTURE	3,921	2.5%
TAIL	**2,852**	**1.8%**
FUSELAGE	**19,304**	**12.4%**
LANDING GEAR	**5,300**	**3.4%**
NACELLE & PYLON	**5,012**	**3.2%**
STRUT, JURY STRUT, AND INSTALLATION	**2,399**	**1.5%**
PROPULSION	**19,083**	**12.2%**
ENGINES	12,610	8.1%
FUEL SYSTEM	6,473	4.1%
FLIGHT CONTROLS	**2,753**	**1.8%**
COCKPIT CONTROLS	254	0.2%
SYSTEM CONTROLS	2,500	1.6%
POWER SYSTEMS	**4,276**	**2.7%**
AUXILIARY POWER UNIT	1,039	0.7%
HYDRAULICS	789	0.5%
ELECTRICAL	2,447	1.6%
INSTRUMENTS	**818**	**0.5%**
AVIONICS & AUTOPILOT	**1,603**	**1.0%**
FURNISHINGS & EQUIPMENT	**10,300**	**6.6%**
AIR CONDITIONING	**1,564**	**1.0%**
ANTI-ICING	**123**	**0.1%**
MANUFACTURER'S EMPTY WEIGHT (MEW)	**96,719**	**62.0%**
OPERATIONAL ITEMS	7,803	5.0%
OPERATIONAL EMPTY WEIGHT (OEW)	**104,519**	**67.0%**
USABLE FUEL	20,681	13.3%
DESIGN PAYLOAD	30,800	19.7%
TAKEOFF GROSS WEIGHT (TOGW)	**156,000**	**100.0%**

5.6 765-095-TS4 N+4 Truss Braced Wing with LNG Fuel Cell Hybrid Gas Turbine and BLI

This configuration, also derived from 765-095-RC (the Task 2.1 aeroelastic FEM configuration), is an N+4 Truss Braced Wing configuration but with a LNG fuel cell hybrid propulsion system and electric aft fuselage boundary layer ingestion propulsor. This configuration uses the fuel cell in a topping cycle configuration as illustrated in Figure 5.25. Details about this propulsion system are discussed in Appendix A. This configuration has been denoted 765-095-TS4. The configuration, shown in Figure 5.26, required additional aft fuselage refinement to accommodate the BLI propulsor without incurring a ground angle limit reduction.

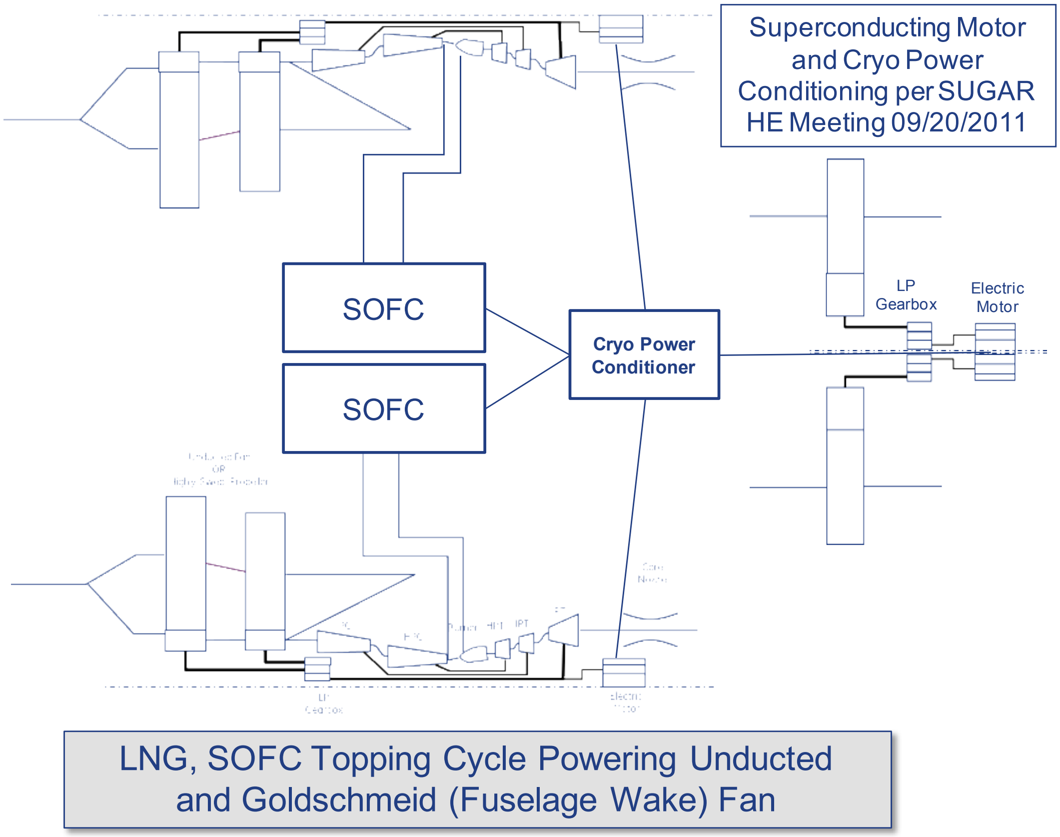


Figure 5.25 – Advanced LNG Fuel Cell Hybrid Configuration with BLI Propulsor

PROJECTED CHARACTERISTICS	WING TOTAL	V-TAIL TRAP	H-TAIL TRAP
AREA (SQ. FT)	1477.11	257.76	265.89
ASPECT RATIO	19.55	1.00	5.00
SPAN (INCHES)	2039.30	192.66	437.54
TAPER RATIO	0.35	1.00	0.35
MAC (INCHES)	110.29	192.66	94.27
DIHEDRAL (DEG.)	-1.50	--	-3.00
¼ CHORD SWEEP (DEG.)	12.52	41.00	25.30
ROOT CHORD (INCHES)	130.31	192.66	129.64
TIP CHORD (INCHES)	45.13	192.66	45.37
TAIL VOLUME COEFFICIENT	--	0.07	1.57

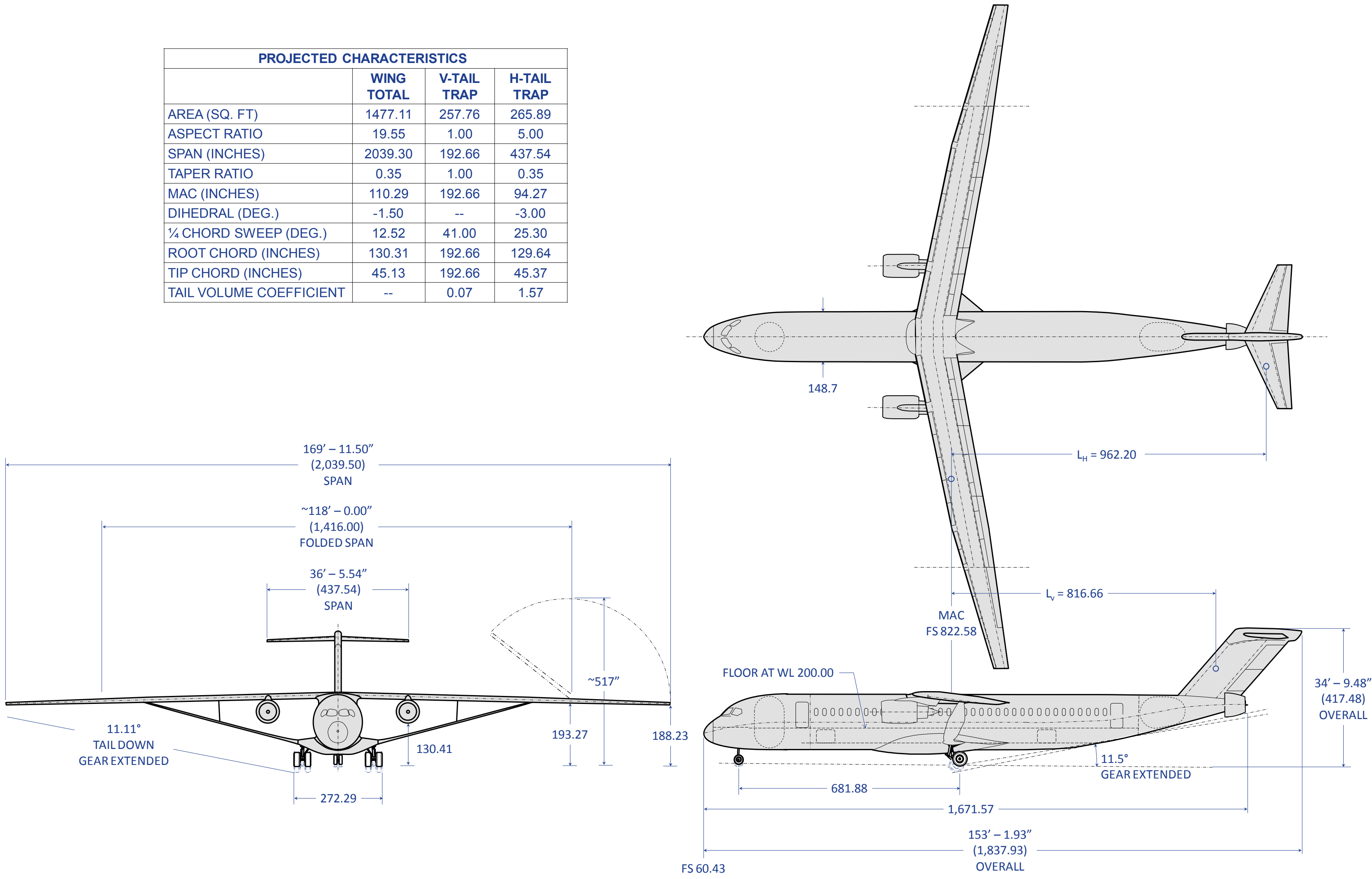


Figure 5.26 – 765-095-TS4 - Truss Braced Wing with LNG Fuel Cell BLI

The aerodynamic buildup of the 765-095-TS4 is similar to other LNG truss braced configurations. The portions of the fuselage that are internal to the aft BLI propulsor flowpath are book kept in thrust. The OML of the aft BLI nacelle is also booked in the fuselage drag. Despite the increased aft fuselage upsweep, the BLI system is assumed to aid in keeping the flow attached and the upsweep drag increment is held constant as compared to other LNG powered configurations in this study. Additional more detailed analysis would be needed to assess the accuracy of this assumption.

Table 5.12 – 765-095-TS4 High Speed Build-up

CONFIGURATION	765-095-TS4
AIRFOIL TYPE	SUPERCRIT. DTE

F BUILD-UP (FT^2)	
FUSELAGE	9.6005
WING	10.3240
STRUT	2.7291
JURY STRUT	0.2519
HORIZONTAL	1.7482
VERTICAL	1.5327
N&P	1.4270
CANOPY	0.0405
GEAR PODS	3.1393
ETC BEFORE SUB	-7.9093
EXCRESCENCE	1.9856
UPSWEEP	0.4870
WING TWIST	0.1640
ETC AFTER SUB	-1.4622
FUSELAGE BUMP	0.3675
F-TOTAL (FT^2)	**24.4036**

E-VISC	**0.95206**

CRUISE C_D BUILD-UP	
M-CRUISE	0.73
CRUISE ALTITUDE	44000
C_L-CRUISE	0.775
C_{D0}	0.01652
C_{DI}	0.01025
C_{DC}	0.002022
C_{DTRIM}	0.0005876
C_{DTOT}	0.02938
L/D	26.38216
ML/D	19.259

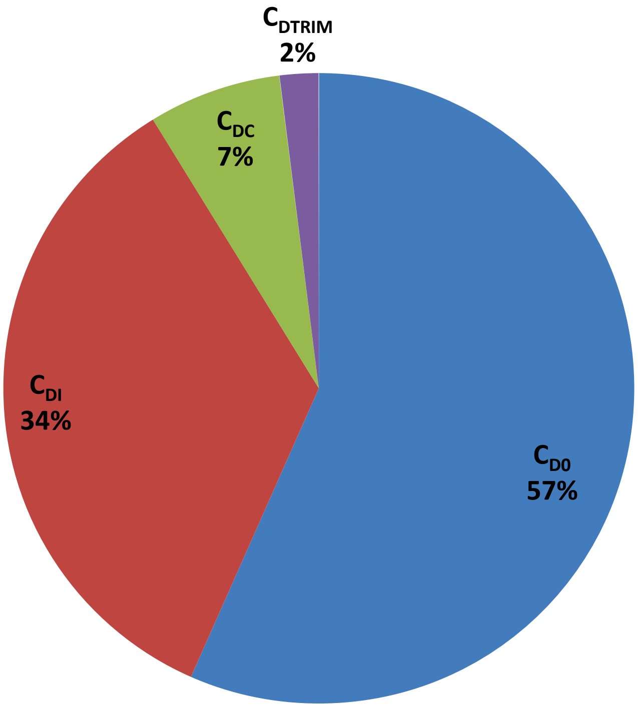


Figure 5.27 – 765-095-TS4 High Speed Build-up

The resulting high speed data is shown in Figure 5.8. The figure illustrates the maximum aerodynamic efficiency (M*L/D) occurring at a cruise Mach of 0.73 and a C_L of 0.775.

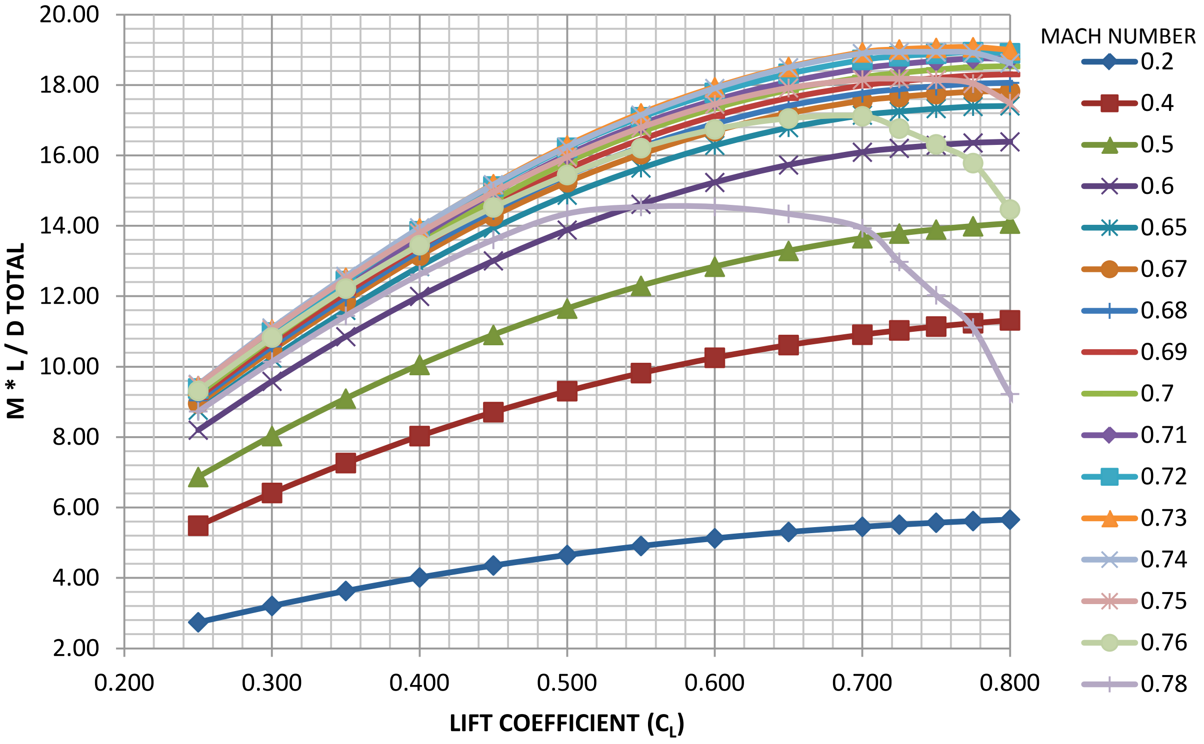


Figure 5.28 – 765-095-TS4 - M * L / D Total

Figure 5.29 through Figure 5.31 show the low speed characteristics for the 765-095-TS4. Low speed data are trimmed as a function of angle of attack, lift coefficient, and drag coefficient at each flap detent. Low speed high lift devices on wing leading and trailing edges are deployed.

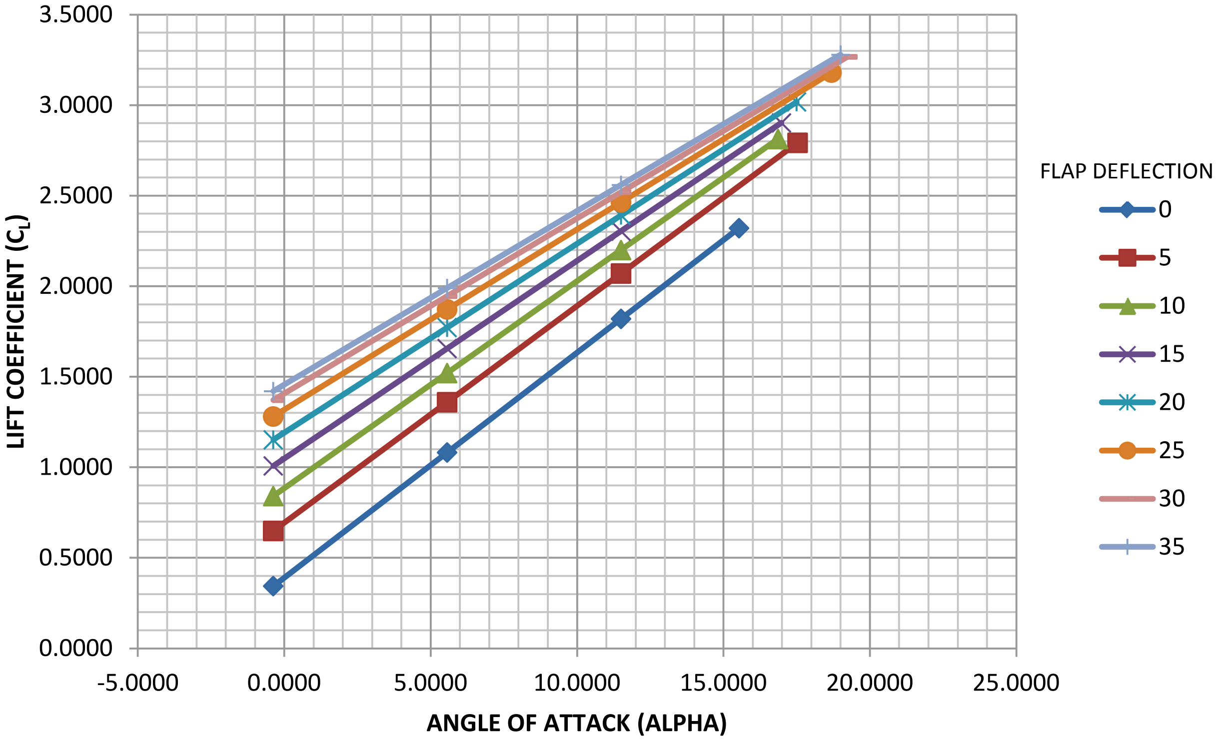


Figure 5.29 – 765-095-TS4 - Low Speed Lift Curve; Free Air

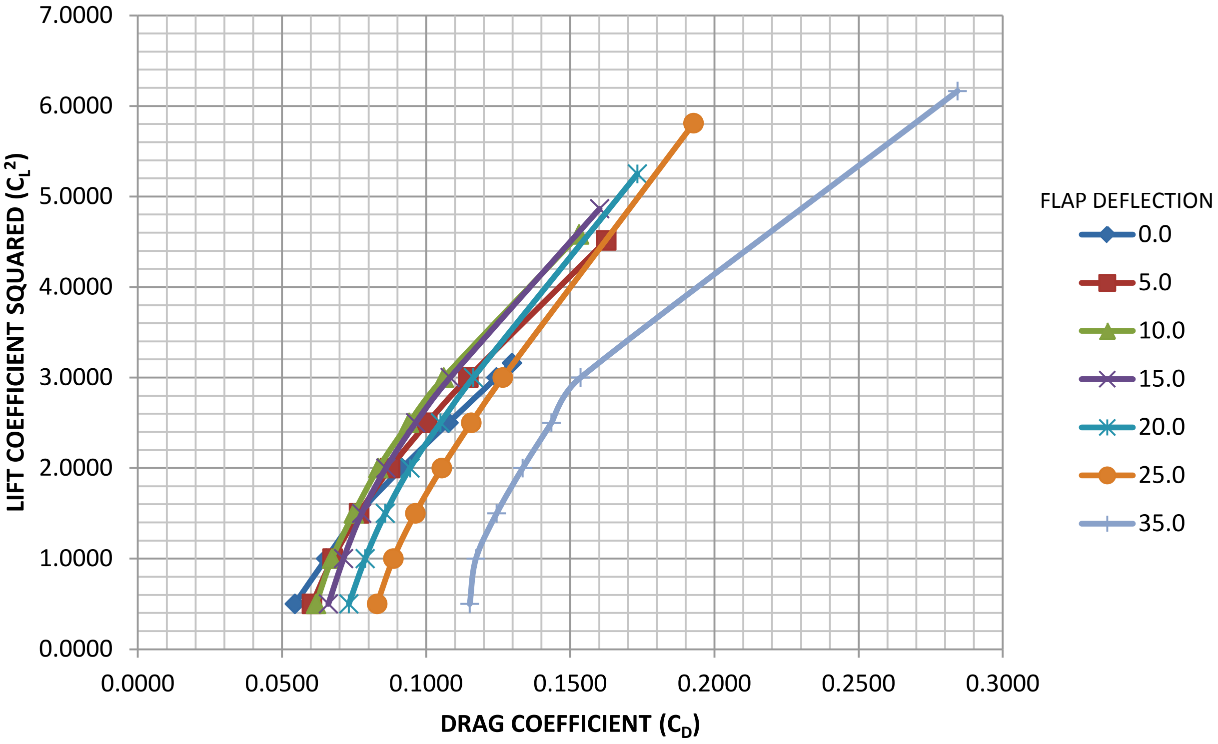


Figure 5.30 – 765-095-TS4 - Low Speed Polar; Free Air

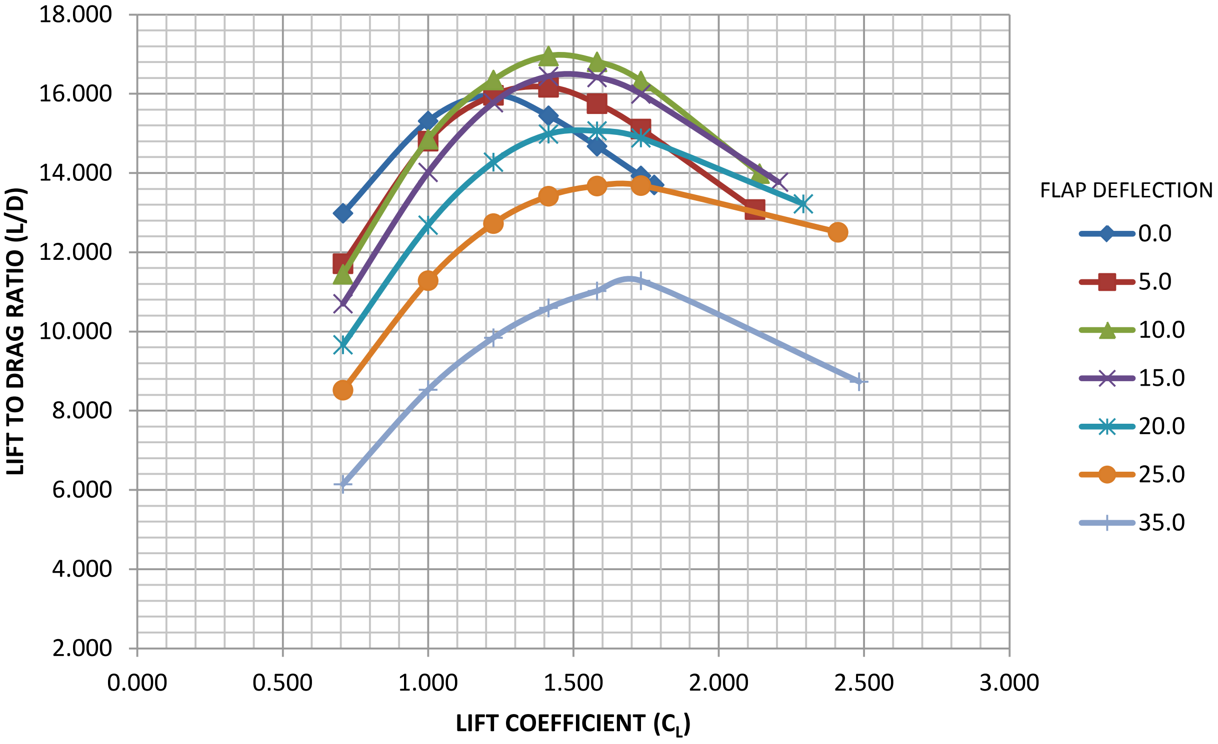


Figure 5.31 – 765-095-TS4 - Low Speed Lift / Drag; Free Air

The weight (Table 5.11) for the configuration was generated starting from the 765-095-TS2 and adjusting propulsion system weight and accounting for the additional fuselage structure to support the BLI device.

Table 5.13 – 765-095-TS4 Group Weight Statement

GROUP	WEIGHT (LB)	% TOGW
WING	**21,330**	**13.7%**
BENDING MATERIAL	8,197	5.3%
SPAR WEBS	2,049	1.3%
RIBS AND BULKHEADS	2,049	1.3%
AERODYNAMIC SURFACES	5,113	3.3%
SECONDARY STRUCTURE	3,921	2.5%
TAIL	**2,852**	**1.8%**
FUSELAGE	**19,433**	**12.5%**
LANDING GEAR	**5,300**	**3.4%**
NACELLE & PYLON	**6,813**	**4.4%**
STRUT, JURY STRUT, AND INSTALLATION	**2,399**	**1.5%**
PROPULSION	**18,746**	**12.0%**
ENGINES	12,271	7.9%
FUEL SYSTEM	6,475	4.2%
FLIGHT CONTROLS	**2,753**	**1.8%**
COCKPIT CONTROLS	254	0.2%
SYSTEM CONTROLS	2,500	1.6%
POWER SYSTEMS	**4,276**	**2.7%**
AUXILIARY POWER UNIT	1,039	0.7%
HYDRAULICS	789	0.5%
ELECTRICAL	2,447	1.6%
INSTRUMENTS	**818**	**0.5%**
AVIONICS & AUTOPILOT	**1,603**	**1.0%**
FURNISHINGS & EQUIPMENT	**10,300**	**6.6%**
AIR CONDITIONING	**1,564**	**1.0%**
ANTI-ICING	**123**	**0.1%**
MANUFACTURER'S EMPTY WEIGHT (MEW)	**98,309**	**63.0%**
OPERATIONAL ITEMS	7,803	5.0%
OPERATIONAL EMPTY WEIGHT (OEW)	**106,112**	**68.0%**
USABLE FUEL	19,088	12.2%
DESIGN PAYLOAD	30,800	19.7%
TAKEOFF GROSS WEIGHT (TOGW)	**156,000**	**100.0%**

5.7 765-095-TS5 N+4 TBW with LNG Fuel Cell Hybrid Gas Turbine Unducted Fan

The 765-095-TS5 configuration was intended to be a derivative version of the 765-095-TS4 with unducted fan propulsion. Early prolusion system trades suggested that the unducted fan was more efficient than the BLI device, so the BLI device was eliminated from the configuration. The solid oxide fuel cell topping cycle was retained but the extracted electrical energy is redirected to an electric motor on the low pressure spool of the engine. The propulsion system is documented in Appendix A.

The OML aerodynamic data for this configuration is identical to the 765-095-TS3 with exception of the reference thrust. Please refer to Section 5.5 for a 3-View drawing and aerodynamic data.

The change in propulsion system weight relative to the 765-095-TS3 requires a new weight estimate which is shown in Table 5.14.

Table 5.14 – 765-095-TS5 Group Weight Statement

GROUP	WEIGHT (LB)	% TOGW
WING	**21,330**	**13.7%**
BENDING MATERIAL	8,197	5.3%
SPAR WEBS	2,049	1.3%
RIBS AND BULKHEADS	2,049	1.3%
AERODYNAMIC SURFACES	5,113	3.3%
SECONDARY STRUCTURE	3,921	2.5%
TAIL	**2,852**	**1.8%**
FUSELAGE	**19,304**	**12.4%**
LANDING GEAR	**5,300**	**3.4%**
NACELLE & PYLON	**5,742**	**3.7%**
STRUT, JURY STRUT, AND INSTALLATION	**2,399**	**1.5%**
PROPULSION	**23,945**	**15.3%**
ENGINES	17,472	11.2%
FUEL SYSTEM	6,473	4.1%
FLIGHT CONTROLS	**2,753**	**1.8%**
COCKPIT CONTROLS	254	0.2%
SYSTEM CONTROLS	2,500	1.6%
POWER SYSTEMS	**4,276**	**2.7%**
AUXILIARY POWER UNIT	1,039	0.7%
HYDRAULICS	789	0.5%
ELECTRICAL	2,447	1.6%
INSTRUMENTS	**818**	**0.5%**
AVIONICS & AUTOPILOT	**1,603**	**1.0%**
FURNISHINGS & EQUIPMENT	**10,300**	**6.6%**
AIR CONDITIONING	**1,564**	**1.0%**
ANTI-ICING	**123**	**0.1%**
MANUFACTURER'S EMPTY WEIGHT (MEW)	**102,307**	**65.6%**
OPERATIONAL ITEMS	7,803	5.0%
OPERATIONAL EMPTY WEIGHT (OEW)	**110,110**	**70.6%**
USABLE FUEL	15,090	9.7%
DESIGN PAYLOAD	30,800	19.7%
TAKEOFF GROSS WEIGHT (TOGW)	**156,000**	**100.0%**

5.8 Concept Comparisons and Summary

The missions used for sizing and performance calculations are the same as in Phase I and are documented in Section 5.1 and 6.1.2 of the SUGAR Phase I Final Report(1).

Sized vehicle performance results for all the configurations are listed in Table 5.15. The benefit of going to an advanced air traffic management system (see Phase I report for details, equates to approximately 17% fuel burn reduction) and the advanced technologies is shown by the difference in performance between the 765-093 and the 765-094-TS1, approximately 50,000 pounds of TOGW. The high span truss braced wing adds 10,000 pounds to TOGW but still shows a reduction in fuel burn. The extra weight of the cryogenic systems causes the sized TOGW to increase 10,000 to 20,000 pounds for all LNG configurations. All of the truss braced wing aircraft are flying at higher cruise lift coefficients than the wing design point. As mentioned previously, the aerodynamic buildups are still relying on extrapolated empirical databases; CFD efforts will clarify the wings actual design characteristics in later contract deliverables for Task 2.1.

Unducted aircraft show smaller wings relative to their ducted fan counterparts. This is partially due to their decreased TOGW but mostly due to a mismatch in thrust at takeoff and top of climb (TOGW / Wing Area Increases ~20 lb / sq. ft. for both cases). The high lapse characteristics of the unducted fan system are causing the takeoff constraints to be easily met with lower wing areas. This causes the aircraft to fly at lower altitudes for a given optimum lift coefficient. These unducted configurations also show significantly lower L/D due to their loss of laminar flow over a portion of the wing and their smaller wingspans.

Mission segment fuel burn for all configurations is shown in Table 5.16.

Fuel, energy, noise, and emissions results are summarized in Table 5.17. For easy comparison, the fuel burn and energy results are repeated from Table 5.15. Noise and emissions were assessed qualitatively by subject matter experts at General Electric. A color coding was used to indicate status toward the NASA defined goals. Several of the LNG configurations come close to meeting, meet, or exceed the NASA N+3 goals for fuel burn, energy, and emissions. No configuration meets the noise goals.

Compared to a conventionally fueled aircraft, using LNG reduces the weight of fuel burned. However, because of the integration of the cryogenic tanks and systems, the total energy used is increased. Use of LNG enables the design of low emission combustors as well as the potential use of fuel cells.

Even though it increases engine weight and adds to the noise challenge, use of an unducted fan propulsor reduces fuel burn and energy use. Integrating a fuel cell into the propulsion cycle is also shown to produce significant benefits. An aft BLI propulsor improves fuel burn and energy use and has some potential for reduced noise.

Table 5.15 – Configuration Performance Summary

Model Sizing Level		765-093 SUGAR FREE	765-094-TS1 N+4 REFINED SUGAR	765-095-TS1 N+4 SUGAR HIGH	765-095-TS2 SUGAR FREEZE	765-095-TS3 SUGAR FREEZE UDF	765-095-TS4 SUGAR FREEZE HYBRID BLI	765-095-TS5 SUGAR FREEZE HYBRID UDF
PASSENGERS / CLASS		154 / DUAL	154 / DUAL	154 / DUAL	154 / DUAL	154 / DUAL	154 / DUAL	154 / DUAL
MAX TAKEOFF WEIGHT	LB	182,600	131,500	140,200	153,300	148,500	158,800	154,200
MAX LANDING WEIGHT	LB	149,400	128,500	138,600	153,200	150,700	161,300	158,000
MAX ZERO FUEL WEIGHT	LB	140,400	120,500	130,600	145,200	142,700	153,300	150,000
OPERATING EMPTY WEIGHT	LB	94,400	74,500	84,600	99,200	96,700	107,300	104,000
FUEL CAPACITY REQ	USG	9,633	4,748	4,526	7,359	6,749	6,697	6,348
ENGINE MODEL		Scaled CFM56-7B27	gFan++	gFan++	LNG gFan++	LNG UDF	LNG Hybrid DF + BLI	LNG Hybrid UDF
FAN DIAMETER	IN	62	62	65	68	128	59	132
BOEING EQUIVALENT THRUST (BET)	LB	27,900	17,200	19,200	20,600	21,700	20,800	22,000
WING AREA / SPAN	FT^2 / FT	1,406 / 121	1,347 / 125	1,306 / 160	1,462 / 169	1,203 / 153	1,624 / 178	1,309 / 160
ASPECT RATIO (EFFECTIVE)		10.41	11.63	19.56	19.56	19.56	19.56	19.56
OPTIMUM C_L		0.584	0.604	0.773	0.763	0.780	0.771	0.776
CRUISE L/D @ OPT C_L		17.997	21.632	25.556	26.505	24.33	27.399	24.977
DESIGN MISSION RANGE	NMI	3,680	3,500	3,500	3,500	3,500	3,500	3,500
PERFORMANCE CRUISE MACH		0.79	0.70	0.70	0.70	0.70	0.70	0.70
LONG RANGE CRUISE MACH (LRC)		0.79	0.70	0.70	0.70	0.70	0.70	0.70
THRUST ICAC (MTOW, ISA)	FT	36,200	36,800	40,600	40,800	37,200	42,600	38,300
TIME / DIST (MTOW, 35k FT, ISA)	MIN / NMI	23 / 148	28 / 181	28 / 180	28 / 180	28 / 180	28 / 180	28 / 180
OPTIMUM ALTITUDE (MTOW, ISA)	FT	34,900	36,700	39,700	39,900	36,900	41,500	37,700
BUFFET ICAC (MTOW, ISA)	FT	36,200	46,700	44,600	45,000	41,600	46,400	42,500
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	8,190	8,190	8,190	8,190	8,190	8,190	8,190
APPROACH SPEED (MLW)	KT	126	117	120	120	131	116	128
BLOCK FUEL / SEAT (900 NMI)	LB	91.51 (Base)	42.53 (-53.5%)	41.62 (-54.5%)	39.21 (-57.2%)	34.66 (-62.1%)	35.88 (-60.8%)	33.26 (-64.1%)
BTU / SEAT (900 NMI)	1,000 BTU	1,700 (Base)	790 (-53.5%)	773 (-54.5%)	816 (-52.0%)	721 (-57.6%)	746 (-56.1%)	683 (-59.8%)

Table 5.16 – Segment Fuel Burn

Fuel Burn (lb)	765-093 SUGAR FREE	765-094-TS1 N+4 REFINED SUGAR	765-095-TS1 N+4 SUGAR HIGH	765-095-TS2 SUGAR FREEZE	765-095-TS3 SUGAR FREEZE UDF	765-095-TS4 SUGAR FREEZE HYBRID BLI	765-095-TS5 SUGAR FREEZE HYBRID UDF
Taxi-Out	525	62	62	56	56	56	56
Takeoff / Climbout	490	286	311	311	303	329	320
Climb	3,719	1,970	1,984	1,881	1,633	1,913	1,494
Cruise	7,463	3,478	3,090	2,857	2,632	2,283	2,455
Descent	466	540	740	720	524	724	516
Loiter	1,081	0	0	0	0	0	0
Approach / Landing	224	152	161	157	133	164	160
Taxi-In	125	62	62	56	56	56	56
Total	**14,093**	**6,550**	**6,410**	**6,038**	**5,337**	**5,525**	**5,057**

Table 5.17 – N+4 Fuel, Energy, Noise, and Emissions Summary

Case	**1**	**2**	**3**	**4**	**5**	**6**	**7**	
Config. Number	765-093	765-094-TS1	765-095-TS1	765-095-TS2	765-095-TS3	765-095-TS4	765-095-TS5	
Name	SUGAR Free	N+4 Reference	N+4 High Wing Reference	SUGAR Freeze	SUGAR Freeze	SUGAR Freeze	SUGAR Freeze	
Fuel	JP	JP	JP	LNG	LNG	LNG	LNG	
Engine	CFM-56	JP+ 2045GT+ DF	JP+ 2045GT+ DF	LNG+ 2045GT+ DF	LNG+ 2045GT+ UDF	LNG+ 2045GT+ SOFC+ BLI	LNG+ 2045GT+ SOFC+ UDF	
Propulsor	Ducted Fan	Ducted Fan	Ducted Fan	Ducted Fan	Unducted Fan	DF + BLI	Unducted Fan	
				Quantitative Scoring				**Goal**
Block Fuel / Seat (900 NMI)	🟥 (Base)	🟨 -53.5%	🟨 -54.5%	🟩 -57.2%	🟦 -62.1%	🟩 -60.8%	🟦 -64.1%	**-60%[*]**
BTU / Seat (900 NMI)	🟥 (Base)	🟨 -53.5%	🟨 -54.5%	🟨 -52.0%	🟩 -57.6%	🟩 -56.1%	🟩 -59.8%	**-60%[*]**
				Qualitative Scoring				**Goal**
Noise	🟥 +3	🟥 0	🟥 0	🟥 0	🟥 +1	🟥 -2	🟥 +1	**-71 dB[†]**
LTO NOx Emissions	🟥 +3	🟨 0	🟨 0	🟩 -1	🟦 -3	🟩 -2	🟦 -4	**-80%[‡]**
Cruise NOx Emissions	🟥 +3	🟨 0	🟨 0	🟩 -1	🟩 -2	🟦 -3	🟦 -4	**-80%[*]**

[*] Relative to Baseline SUGAR Free

[†] Cum Margin Relative to Stage 4

[‡] Relative to CAEP/6

Color Legend to NASA's Goal

🟥 Far From Goal
🟨 Does Not Meet Goal
🟩 Nearly or Meets Goal
🟦 Exceeds Goal

Qualitative Ranking System

Acoustics		Emissions
Quietest	-4	Least
765-094-TS1	0	765-094-TS1
Loudest	4	Most

6.0 Technology Development Plans

Based on team discussions at and after the N+4 Workshop, the team identified a list of technology roadmaps that would be developed. Technology plans have been developed for the following N+4 technologies:

- Hybrid Electric
- High Performance Batteries
- Low Energy Nuclear Reactor
- Fuel Cells
- Boundary Layer Ingestion
- Low-Noise High Cruise Speed Unducted Fans and Propellers
- LNG & Hydrogen Engines
- LNG & Hydrogen Aircraft Systems
- LNG & Hydrogen Infrastructure

Each plan follows a template described in Section 6.1. The template includes an assessment of technical risk, a listing of tasks to improve technical maturity, and estimates for when tasks leading to jumps in technology readiness level (TRL) could be completed. The progression of risk with technical maturity is also outlined in the template.

Specific technology plans are presented in Section 6.2.

6.1 Technology Plan Template

The technology plans in this document are presented in a standardized template. A series of sections provide information on the technologies as described below.

Goals and Objectives – A short description is given on what the technology plan is trying to do.

Performance Area and Impact – Short descriptions are given on the benefits of the technology. The descriptions indicate what the technology does to realize the benefits.

Technical Description – A longer description is given on what needs to be developed, with some indication of why it is needed. This section introduces the major components of the technology. This section may elaborate on how the technology works.

Risk Assessment – A risk grid is presented along with a statement of the risk that was assessed. The current assessment of risk is indicated along with the progression of risk as major Technology Readiness Level (TRL) milestones are achieved. Labels on the risk progression correspond to labels on the major milestones presented in the next section.

Major Milestones – A chart is shown that indicates the dates when TRL jump milestones are expected to be reached. When multiple tasks are planned as part of achieving a particular TRL, the TRL jump occurs on completion of the last task. Synergistic technologies may be presented in the chart.

Maturation Plan – The tasks involved in reaching each major milestone are listed. Each TRL heading has the corresponding milestone label in parentheses.

Dependency – Short descriptions are given for any dependencies associated with the technology or the maturation plan.

Success Criteria – A table is presented to describe the success criteria for each TRL milestone and alternate steps if the criteria are not met.

Notes – This section provides information that is not otherwise captured in the preceding sections.

Roadmap – A chart showing the technology development tasks verses time.

6.2 Technology Plans

6.2.1 Hybrid Engine Technologies

Goals and Objectives:

Develop high performance, flight weight, and prime-reliable electric power components suitable for flight propulsion applications.

Performance Area and Impact:

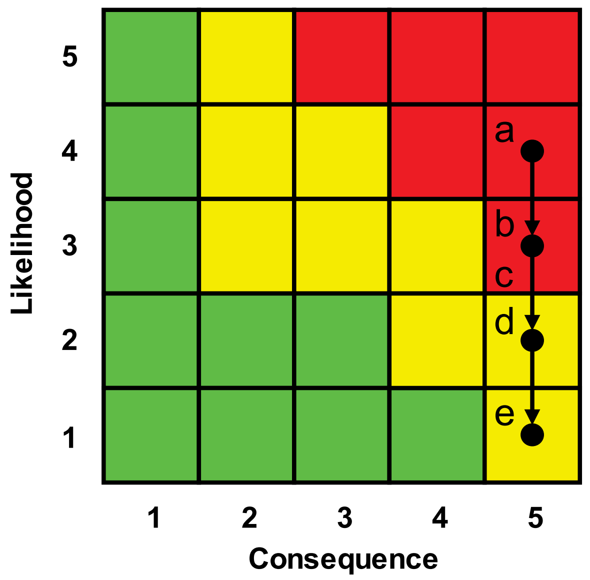
Life-cycle fuel burn and emissions could be reduced by using energy stored in batteries that is generated from alternative energy sources, such as solar, wind, or nuclear.

Noise will be reduced by using stored battery energy to replace some of the energy generated by gas engines, thereby reducing the production of noise from the core of the engines. Hybrid electric systems also could enable distributed propulsion architectures which could enable BLI technology.

Technical Description:

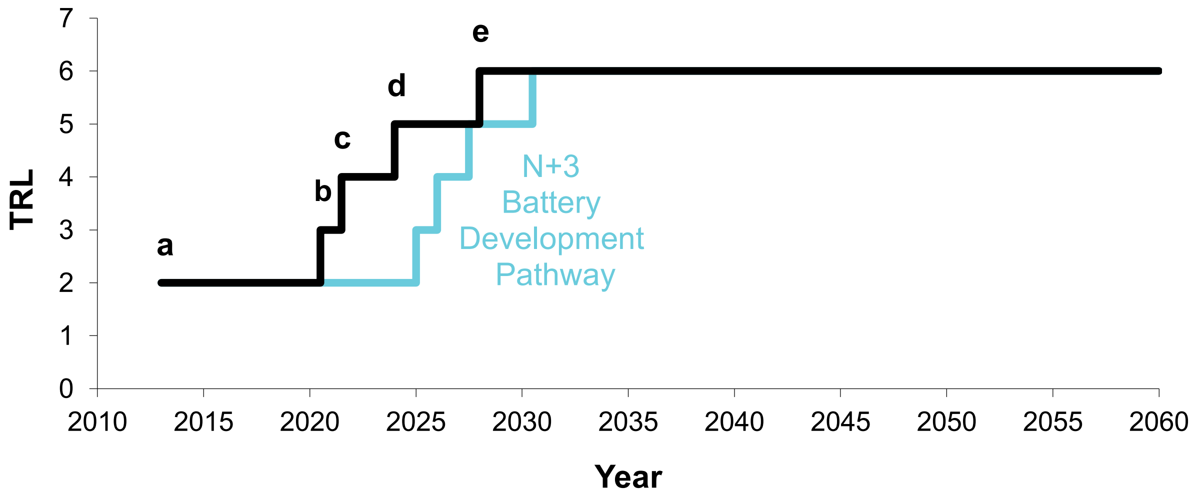
Using energy stored on batteries has the potential to reduce fuel burn, emissions, and noise. Savings are dependent on battery energy density as well as the performance, efficiency, and weight of the electric power components. Efficient, high power, and light weight motors and motor controllers need to be developed. Light weight radiators and surface coolers are also needed to maintain the electric power components at temperatures conducive to high efficiency. A sustained program to develop high voltage conductors and insulators is also needed to support development of the necessary electric power components. A variable core nozzle needs to be developed to allow the engine to operate with more widely varying levels of load introduced by the option to switch to electric power. These components need to be integrated in a hybrid engine system that can be demonstrated in flight. Superconducting components should be considered as possible system enhancing technologies and this would require additional development, design, and testing of cryocooler systems for aircraft.

Risk Assessment:



If hybrid engine performance and weight do not reach the levels assumed in the vehicle analysis, this technology will not contribute the projected benefits in fuel burn, emissions, and noise.

Major Milestones:



Maturation Plan:

TRL 2 (a) Current

Some analysis of the engine system has been performed.
Some mission and sizing analysis has been conducted to assess fuel burn, energy, and global life cycle emissions benefit.

TRL 3 (b)

A life-cycle energy study will examine net benefit to fuel burn and emissions including generation of energy on the ground
A study will assess the potential reductions in airport noise and emissions
3 motor design cycles
3 surface cooler/radiator design cycles
3 motor controller/power electronics design cycles
Sustained program for lightweight high voltage conductors and insulators, with off-ramps every ~18 months
Lightweight variable core exhaust nozzle design
A design developed for a small-scale hybrid electric propulsion system (optional)

TRL 4 (c)

3 motor build, test, report-out cycles
3 surface cooler/radiator build, test, report out cycles
3 motor controller/power electronics build, test, report out cycles
Sustained program for lightweight high voltage conductors and insulators, with off ramps every ~18 months
Lightweight variable core exhaust nozzle build, test
An integrated ground test of a small scale hybrid engine (optional)

TRL 5 (d)

Integration of components into 1st full-scale demonstration engine
1st demonstration engine test
Flight test of a small scale hybrid engine integrated into a small aircraft (optional)

TRL 6 (e)

Integration of components into 2nd full-scale demonstration engine
2nd demonstration engine test

Dependency:

High energy density battery technology is required to harness the benefit of hybrid engine technology.

A suitable off-the-shelf engine asset is needed to support testing.

Success Criteria:

Table 6.1 – Hybrid Engine Technologies Success Criteria

TRL	Success Criteria	Alternate Steps if Unsuccessful
3	Analysis shows hybrid engine system will have performance (fuel burn, emissions, noise) and weight consistent with meeting goals	Continue design of system and components Switch to alternative technology option Consider application to smaller, shorter range aircraft
4	Tests of hybrid engine system components show performance (fuel burn, emissions, noise) and weight consistent with goals	Redesign components with shortfalls Switch to alternative technology option
5	Hybrid engine system components integrated and successfully tested Initial system performance (fuel burn, emissions, noise) and weight indicates goals can be met with some redesign	Redesign system to meet goals Accept meeting reduced goals Switch to alternative technology option
6	Hybrid engine system demonstrates performance (fuel burn, emissions, noise) and weight consistent with goals	Accept meeting reduced goals Switch to alternative technology option

Notes:

Sustained base technology program for flight-worthy motors, conductors and insulators

2 builds for demo engine
Base engine is off-the-shelf
Yields TRL6 by 2027

3.5 design/build/test cycles for motor, motor controller, and associated cooling system hardware yields TRL3+ by 2020

Base engine is off-the-shelf
Yields TRL6 by 2027

Assumes battery technology development program separate from this plan
Ongoing engine design refinement studies

If mission performance (fuel, emissions, noise, cost) improvements are not sufficient for a medium sized aircraft, consider application to smaller shorter range aircraft. This decision is based on assumptions for future energy cost, regulatory environment (noise, emissions), as well as judgment as to achievable battery technology and timeframe.

Superconducting components are a potentially enhancing technology which should be considered. They allow for an improvement in the efficiency of the electric machines; however, current superconductors must be cryocooled to less than 100 deg K while operating. Significant development would be needed in this area. Use of cryogenic fuels (LNG or Hydrogen) is synergistic with superconducting technologies.

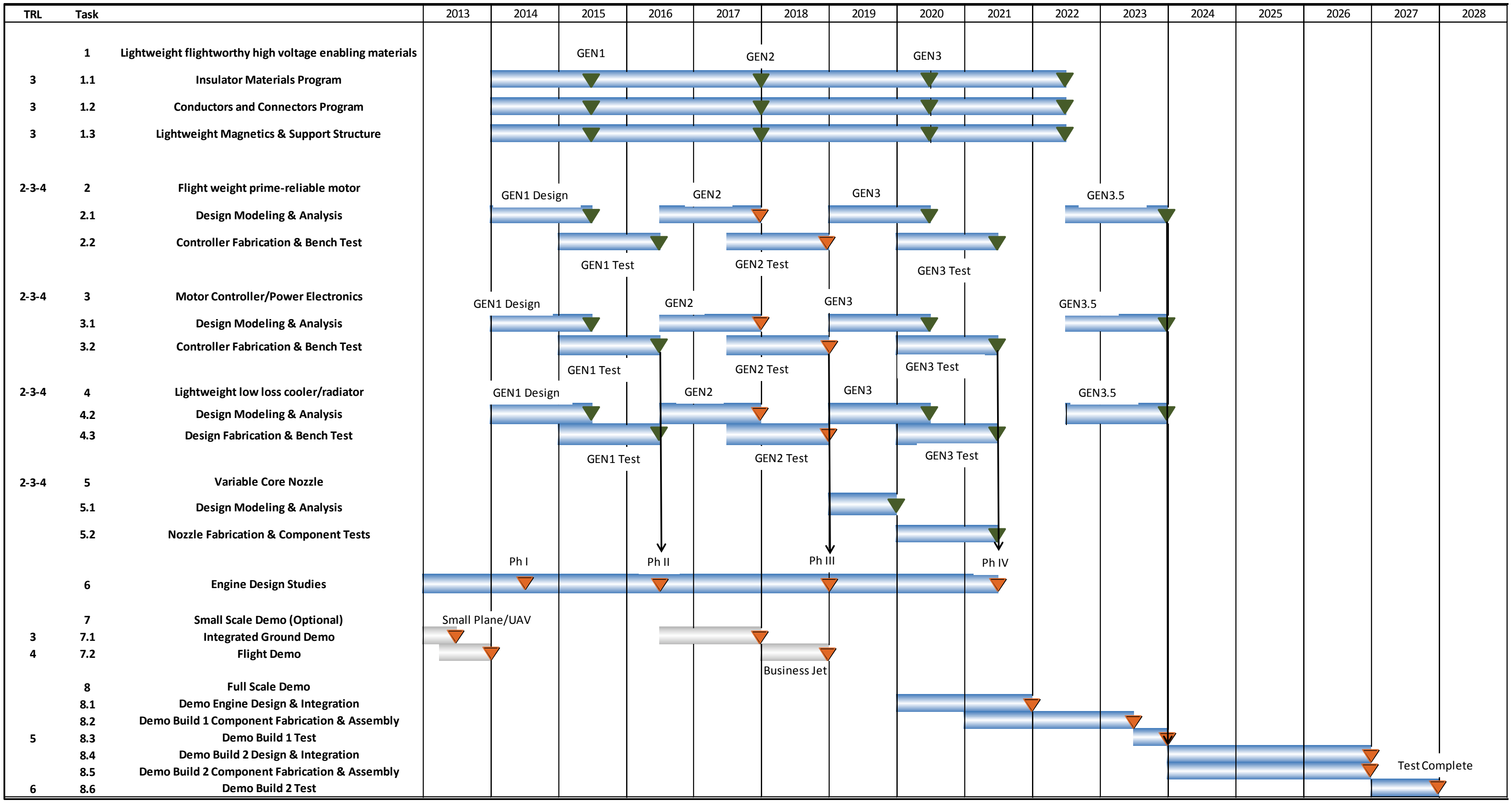


Figure 6.1 – Hybrid Engine Technologies Roadmap*

* The roadmap schedule shown is notional, suitable for overall program planning purposes only, with no implied guarantee or commitment on the part of GE Aviation

6.2.2 Battery Technology

Goals and Objectives:

Foster development of high energy density modular batteries. Work with one or more battery manufacturers to produce batteries that achieve aviation safety requirements and are tailored for aviation performance requirements and usage patterns. Integrate batteries in flight propulsion applications when the batteries are at an appropriate level of development.

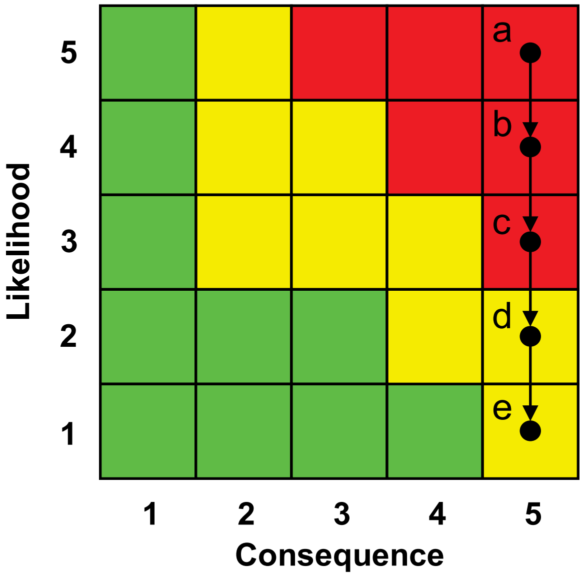
Performance Area and Impact:

Life-cycle fuel burn and emissions could be reduced by using energy stored in batteries that is generated from alternative energy sources, such as solar, wind, or nuclear. High efficiency of electrical components may reduce total energy usage relative to conventional liquid fuels. Life cycle studies will be needed to confirm these savings.

Technical Description:

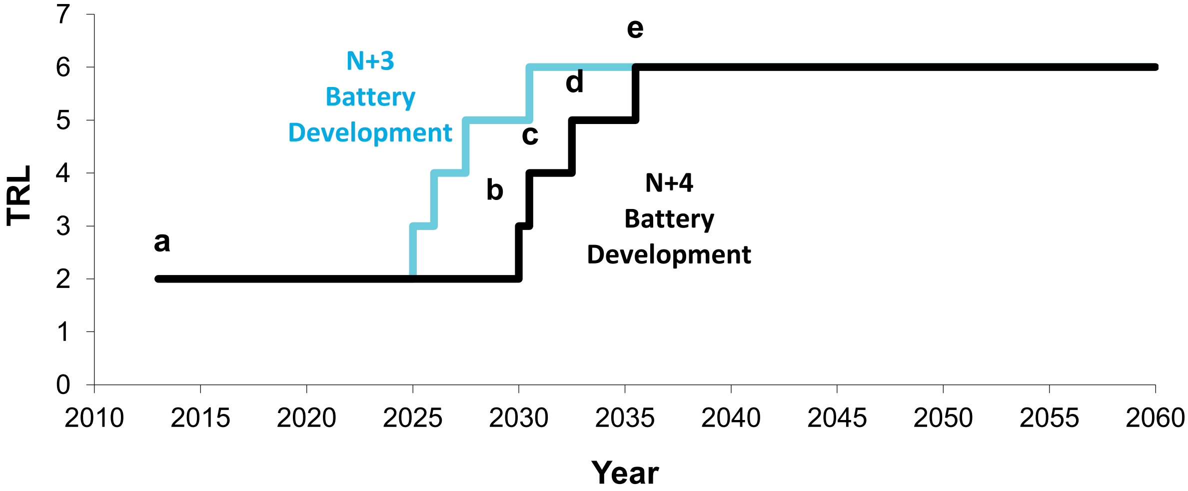
Multiple battery technologies have potential to produce the energy densities needed to reduce fuel burn and emissions in an aircraft application. Low-level studies are needed to produce requirements and data that can be provided to battery manufacturers to encourage the development of battery technology that can support such application. Once suitable batteries are available, a substantial development program will be required to integrate and test these batteries in combination with hybrid-electric engine technology and aviation specific requirements.

Risk Assessment:



If battery energy densities do not reach the levels assumed in the vehicle analysis, this technology will not contribute the projected benefits in fuel burn, emissions, and noise.

Major Milestones:



Maturation Plan:

TRL 2 (a) Current

Theoretical estimates and some small-scale experiments indicate feasibility of reaching the needed energy density

TRL 3 (b)

A life-cycle energy study will examine net benefit to fuel burn and emissions including generation of energy on the ground

Aircraft system studies will define requirements for battery technology (including safety and charge/discharge rate)

Battery manufacturers will develop the basic technology to achieve the required energy density. Develop approach to achieve aviation specific battery life, charge/discharge rate, and safety.

TRL 4 (c)

Battery components will be tested for meeting aircraft power, life, charge/discharge rates, and safety requirements including operation in a relevant environment

TRL 5 (d)

Battery components will be integrated and packaged for testing in flight

A battery package of representative size will be tested in flight or simulated flight conditions

TRL 6 (e)

A battery power system suitable for a demonstrator aircraft will be assembled

The battery power system will be integrated with a hybrid-electric engine

The combined hybrid-electric engine and battery power system will be tested in flight

Dependency:

Aviation batteries are dependent on dramatic improvements in battery technology for other applications such as ground transportation. Hybrid-electric or all-electric propulsion is required to harness the benefit of aviation battery technology.

Success Criteria:

Table 6.2 – Battery Technology Success Criteria

TRL	Success Criteria	Alternate Steps if Unsuccessful
3	Analysis shows battery technology will result in fuel burn and emissions reductions through a complete energy life-cycle Battery energy density reaches required levels	Continue basic battery development Switch to alternative battery option* Switch to alternative technology option* Accept meeting reduced goals**
4	Component testing of batteries show suitability for aircraft application (including life, charge/discharge rate, and safety)	Resume basic battery development Switch to alternative battery option* Switch to alternative technology option*
5	Batteries successfully packaged for use in flight Battery package successfully tested in flight or simulated flight conditions	Redesign battery packaging Switch to alternative technology option*
6	Battery power system successfully tested with hybrid-electric engine in flight	Accept meeting reduced goals** Switch to alternative technology option*

* Baseline battery technology is assumed to be Lithium-Ion, but this chemistry may reach a plateau in performance before needed levels are reached. Alternative battery options include Lithium-Air and liquid electrolyte slurries which would require additional systems. Alternative technology options include hybrid batteries (multiple chemistries), capacitors, hybrid battery capacitor, and flywheels. Lithium-air batteries require design of air induction and exhaust system which would require updated roadmap tasks to be added. Quick modular battery swap out or mechanically rechargeable components could be used if charge rates are not fast enough for quick gate turn requirements.

** Lower performance batteries could be suitable for smaller and especially shorter range aircraft

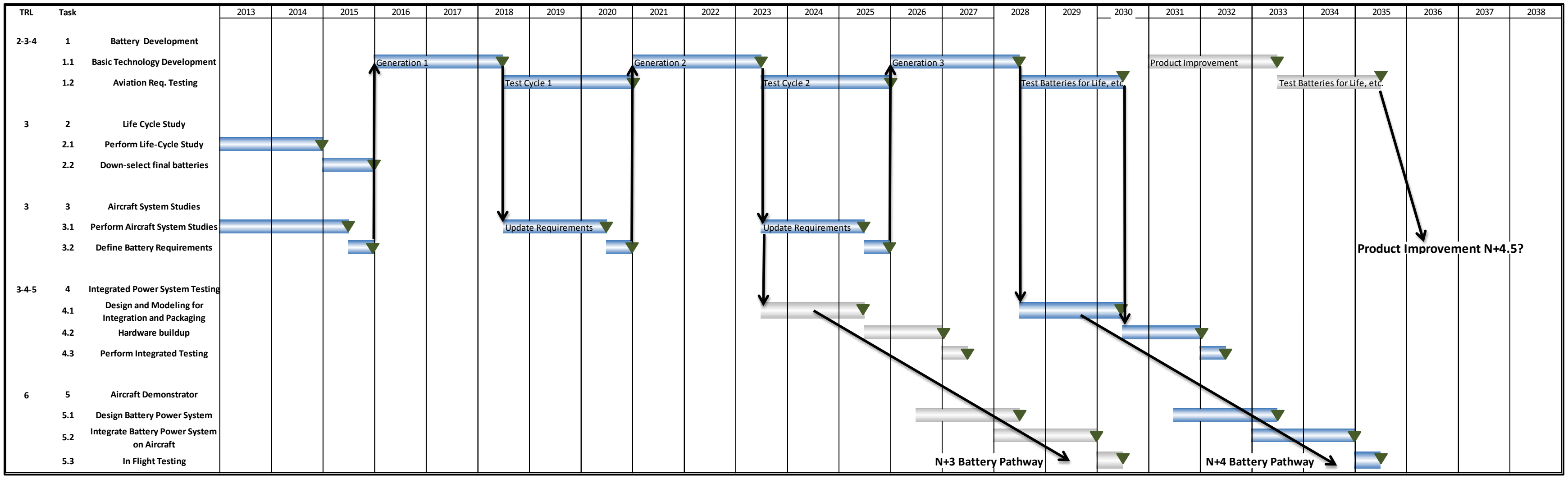


Figure 6.2 – Battery Technology Roadmap

6.2.3 Low Energy Nuclear Reactor Technologies

Goals and Objectives:

Develop technologies for Low Energy Nuclear Reaction (LENR) propulsion systems.

Performance Area and Impact:

Traditional fuel burn and emissions will be reduced or eliminated by using LENR energy.

Noise may be reduced by using LENR heat instead of combustion in the engines.

Technical Description:

LENR energy has the potential to eliminate traditional fuel burn and associated emissions. In the current concept, a LENR reactor generates heat that is distributed to heat engines that use the LENR heat instead of combustion. This concept is dependent on successful development of LENR technology, which has reportedly had some success in generating heat in a catalytic process that combines nickel (Ni) with hydrogen (H) gas(8). This process is reported to produce safe byproducts, such as copper, with no radioactive materials used and no long-lasting radioactive byproducts generated. Upon further investigation, it is thought that low level radiation may be generated during active energy cycles, but that it could be easily shielded and would stop quickly after reactor shutdown. Further development of LENR would be required to produce heat at a high enough temperature to support heat engines in a flight-weight installation. LENR physics analysis and evidence of high temperature pitting in LENR metal substrates indicate that temperatures appropriate for heat engines may have been achieved. It is thought that LENR would use very small amounts of fuel.

Initial LENR testing and theory have suggested that any radiation or radio-isotopes produced in the LENR reactions are very short lived and can be easily shielded. In addition, some prototypes(9) that may be harnessing the LENR process can be controlled safely within designed operating parameters and the reaction can be shut down in acceptable time frames. This heat generating process should reduce radiological, shielding and hazardous materials barriers to entry of aviation LENR systems.

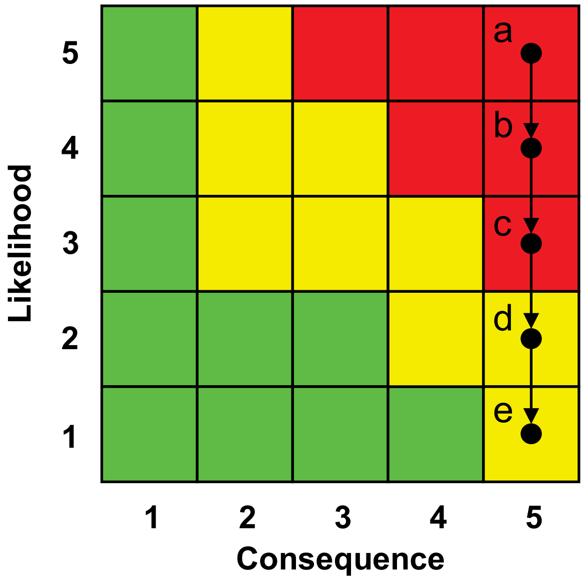
Should LENR development prove successful, a few technology components will need to be developed for LENR-based aircraft propulsion. Heat engines, which run a thermodynamic cycle by adding heat via heat transfer instead of combustion, need to be developed. A system for distributing heat from the LENR core to the heat engines also needs to be developed. Additional systems may need to be developed for supporting the LENR core, including systems to deliver reactants and remove byproducts. The Ni-H LENR system would use pure hydrogen and a proprietary nickel and catalyst substrate. Hydrogen usage would be small compared to systems that combust hydrogen. Initially, hydrogen storage might involve cryogenics. The cold liquid hydrogen (LH_2) fluid might be used in a regenerative system whereby cooling is supplied to super-conducting generators, electric feeders, and motors while the gas would be used as a fuel in the LENR reactor. The primary LENR byproducts that would require periodic removal from the aircraft are the catalyst and nickel that are contained within the reactor core. Through thoughtful design of the reactor core, preliminary information suggests that these can be easily removed and replaced. The reactor core might then be recycled at low cost, due to the absence of toxic products in the core.

Technology Status:

Multiple coherent theories that explain LENR exist which use the standard Quantum Electrodynamics & Quantum Chromodynamics model. The Widom-Larson(10) theory appears to have the best current understanding, but it is far from being fully validated and applied to current prototype testing. Limited testing is ongoing by NASA and private contractors of nickel-hydrogen LENR systems. Two commercial companies (Leonardo Corp. & Defkalion) are reported to be offering commercial LENR systems. Those systems are advertised to run for 6 months with a single fueling cycle. Although data exists on all of these systems, the current data in each case is lacking in either definition or 3rd party verification. Thus, the current TRL assessment is low.

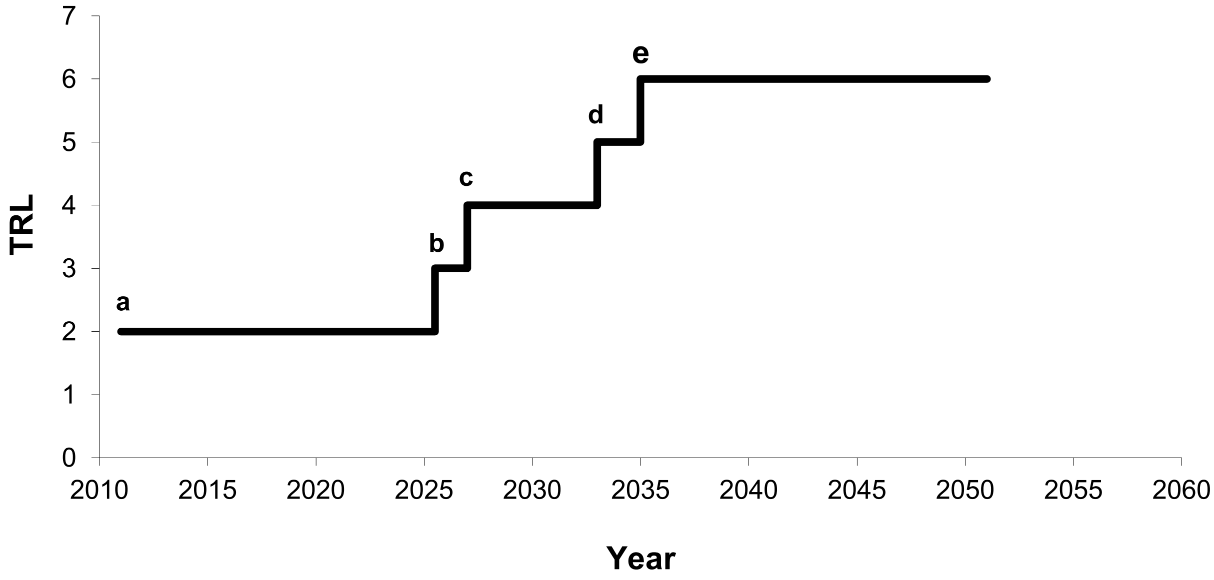
In this study the SUGAR Team has assumed, for the purposes of technology planning and establishing system requirements that the LENR technology will work. We have not conducted an independent technology feasibility assessment. The technology plan contained in this section merely identifies the steps that would need to take place to develop a propulsion system for aviation that utilizes LENR technology.

Risk Assessment:



If development of LENR, heat engines, or heat distribution systems is not successful, this technology will not contribute the projected benefits in fuel burn or emissions.

Major Milestones:



Maturation Plan:

TRL 2 (a) Current

A concept for a LENR propulsion system has been generated
Basic principles of LENR are reported to have been demonstrated

TRL 3 (b)

Definitive laboratory test data released and validated showing that the concept works
System level goals (power/weight, etc.) for LENR and heat engine established using a sensitivity study
A conceptual design of a LENR propulsion aircraft and its systems will be performed
Heat engine will be designed and analyzed, based on expected LENR temperature differential achievable
Heat distribution system will be designed and analyzed
Design and analysis will be performed on other systems to support LENR

TRL 4 (c)

A basic heat engine will be built and tested
A basic heat distribution system will be built and tested
Supporting LENR system components will be built and tested
LENR core reactor technology is demonstrated (external development)

TRL 5 (d)

LENR propulsion components will be integrated in a working system
LENR propulsion system will be demonstrated in ground test
Critical LENR propulsion system components will be tested in flight

TRL 6 (e)

LENR propulsion system will be demonstrated in flight

Dependency:

Development of LENR reactor technology is assumed to be developed successfully in an external program. An initial requirements assessment indicates that it is beneficial to develop a hybrid system to augment thrust at takeoff, so as not to oversize the LENR system for cruise conditions

Success Criteria:

Table 6.3 – LENR Technologies Success Criteria

TRL	Success Criteria	Alternate Steps if Unsuccessful
3	Analysis shows LENR propulsion system can meet aircraft propulsion requirements (including safety)	Switch to alternative technology option or abandon concept if feasibility cannot be clearly established.
4	Tests of LENR propulsion system components show performance and weight consistent with successful system operation and safety	Redesign components with shortfalls Switch to alternative technology option
5	LENR propulsion system components integrated and successfully tested	Redesign system for successful operation Switch to alternative technology option
6	LENR propulsion system demonstrates successful in-flight operation	Switch to alternative technology option

Notes:

Alternate technologies include other types of self contained nuclear reactors such as thorium, cold fusion, traveling wave, etc.

Alternate heat engines include Sterling, Diesel, Wankel, Otto, and Brayton cycles.

If a safe flight-weight system is not judged to be achievable, the alternative approach is to keep the reactor on the ground and use it to produce electricity or hydrogen for use in aircraft (see other roadmaps).

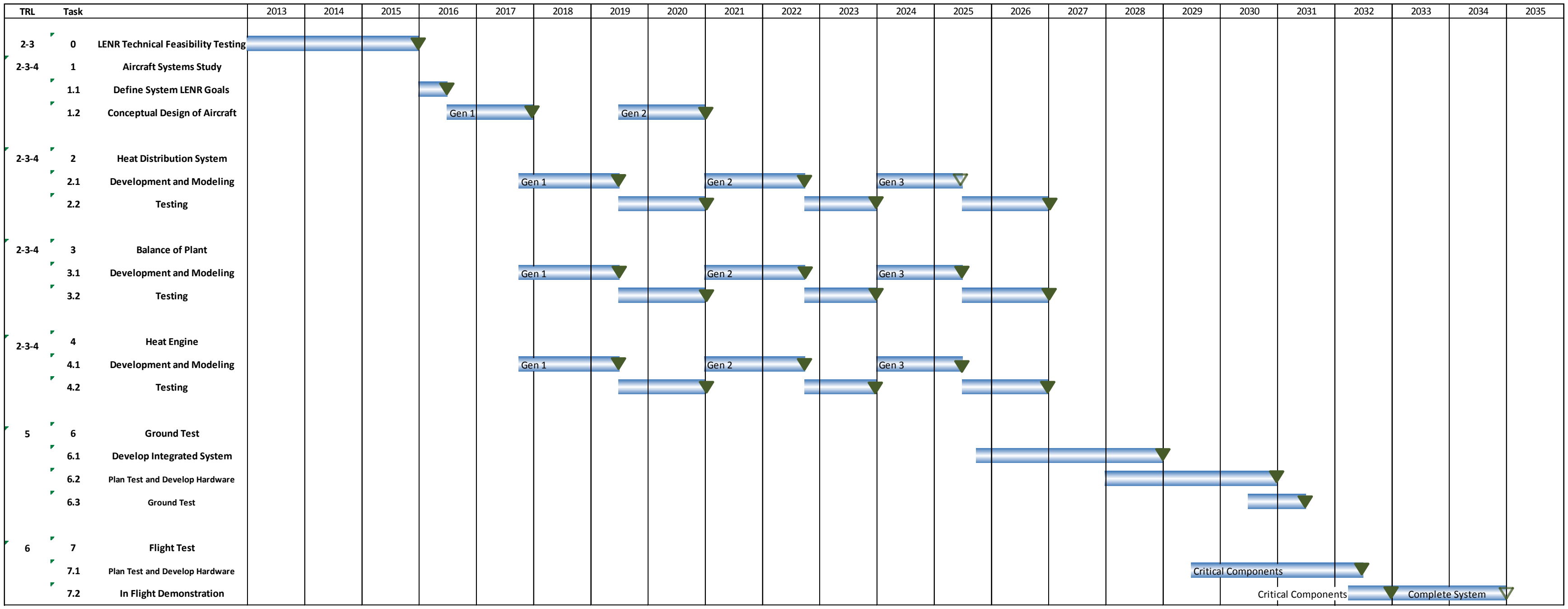


Figure 6.3 – LENR Technologies Roadmap

6.2.4 Fuel Cell Technologies

Goals and Objectives:

Develop technologies for LNG and hydrogen fuel cells.

Performance Area and Impact:

Fuel burn and emissions will be reduced by using fuel cells in a hybrid system with either a gas turbine or batteries.

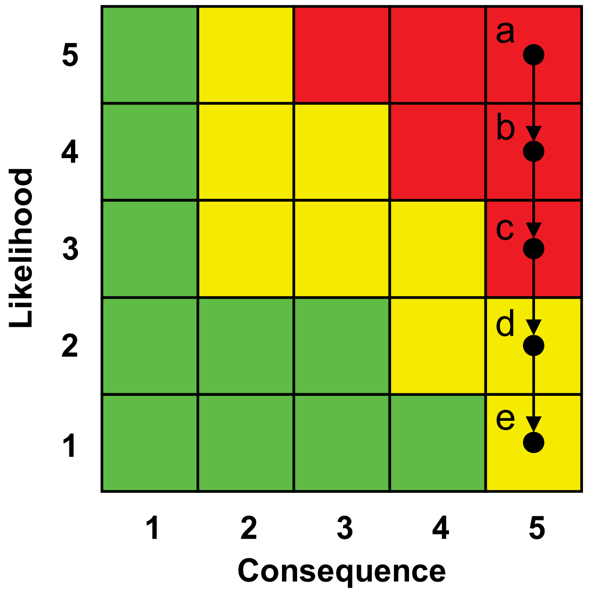
Noise may be reduced by using electric motors and fuel cell waste heat instead of combustion in the engines.

Technical Description:

Fuel cells have the potential to drastically increase the thermodynamic efficiency of the aircraft propulsion system. Fuel cells are capable of using both pure hydrogen and hydrocarbon fuels. Hydrocarbon fuels, such as liquid natural gas (LNG), offer the advantage of high energy density. Pure hydrogen has associated issues with fuel storage in terms of volume limitations due to its low energy density, but advanced hydrogen storage techniques may be available in the future to reduce the volume required to store hydrogen onboard the aircraft. Solid Oxide Fuel Cells (SOFC) have shown potential to allow for fuel flexibility and also generate high quality waste heat that can be combined with a gas turbine bottoming cycle to maximize system efficiency. Using SOFC technology creates a large amount of waste heat that can be recovered using a combined cycle setup, such as with a Brayton cycle. This could allow for flexibility when designing the balance of plant (BOP) in order to maximize the power-to-weight ratio of the overall system. This could also lead to a noise reduction by substituting some of the combustion noise with “quiet” heat from the SOFC system. Electric power generated from the fuel cell will allow for smaller gas turbine generators which may lead to less noise and fewer emissions. SOFC will also allow for fuel flexibility which allows other development programs to continue independently of the SOFC development plan.

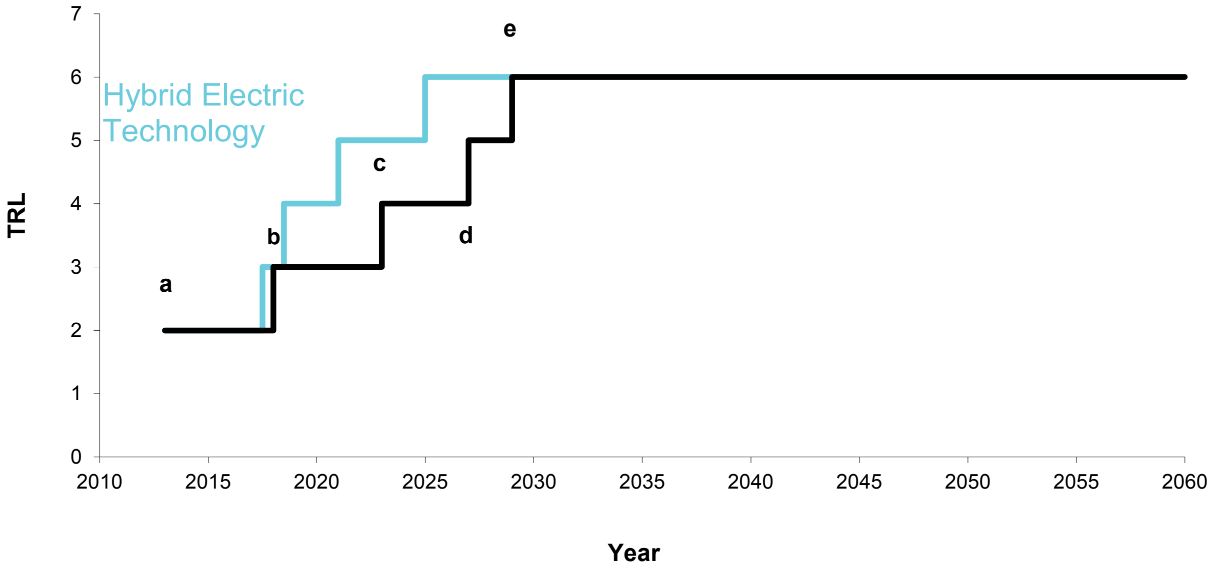
Fuel cell technology will need to be developed to increase the system specific power at least one order of magnitude over current systems in order to make it viable on future medium to long range aircraft. Since fuel cell transients can be dependent on fuel cell chemistry and operating conditions, power conversion electronics will need to be developed and tested to provide clean, constant power to the aircraft propulsor. Start-up times will need to be improved. Also, a highly integrated fuel cell system will need to be developed to reduce aircraft empty weight. Several useful references were used to help compile the technical plan.(11)(12)(13)

Risk Assessment:



If fuel cell performance and weight do not reach the required levels, this technology will not contribute to the projected benefits in fuel burn, emissions, and noise.

Major Milestones:



Maturation Plan:

TRL 2 (a) Current

Perform analysis to design system and balance of plant components, show benefit and assess life-cycle study

Perform analysis to define fuel cell specific power goals for continued development

Identify, develop, and demonstrate feasibility of advanced fuel cell materials enabling high specific powers

TRL 3 (b)

Laboratory testing of fuel cell stack technology to achieve high specific power

Design, modeling, and validation of thermal management system, reformer, and other balance of plant including heat exchangers, steam generators, and balance of plant (BOP) system integration

Design, model, and test power conversion electronics

TRL 4 (c)

A prototype power conversion system will be built and tested

A prototype highly integrated thermal management system will be built and tested with a representative low power fuel cell and appropriate balance of plant

Supporting BOP components will be built and tested

Fuel Cell Stack technology will be demonstrated on a small scale to determine if specific power targets have been met

All major components of the fuel cell system will be integrated into a low power configuration and tested

TRL 5 (d)

Demonstrate high life-cycle of high output power fuel cell stack with high robustness to thermal cycling

Ground test BOP system with full power fuel cell stack

Demonstrate and validate full-scale prototype of integrated stack and balance of plant

Demonstrate operability of fuel cell system at relevant operating conditions such as high altitude and low ambient temperatures

TRL 6 (e)

Integrate power conversion equipment into prototype aircraft power management and distribution system

Demonstrate system integrated with electric propulsion system

Dependency:

LNG aircraft systems are required to support gas turbine / SOFC hybrid architecture. Hydrogen storage and aircraft system integration is required for hydrogen powered fuel cell. If a battery is used in place of a gas turbine to supply additional system power, then battery technology and electric propulsion system technology must also be matured.

Success Criteria:

Table 6.4 – Fuel Cell Technologies Success Criteria

TRL	Success Criteria	Alternate Steps if Unsuccessful
3	Analysis shows both stack and system provide specific power required to meet goals and design shows aircraft level goals can be met	Continue design of system and components Switch to alternative technology option Consider application to smaller, shorter range aircraft
4	Tests of the fuel cell stack and BOP components show performance and weight consistent with goals. Power conversion equipment shows ability to control power fluctuations to provide safe and reliable aircraft power	Redesign components with shortfalls Switch to alternative technology option Consider application to smaller, shorter range aircraft
5	Prototype systems successfully tested in relevant operating environments and successfully integrated	Redesign system for successful operation Switch to alternative technology option
6	Full scale prototype tested including in-flight operation and partial integration into aircraft subsystems	Switch to alternative technology option

Notes:

If sufficient specific power goals are not achieved system could still be used to provide supplemental engine power or provide enhanced APU operations to increase overall aircraft energy efficiency. System could also be used on the ground to create electrical power for battery powered aircraft.

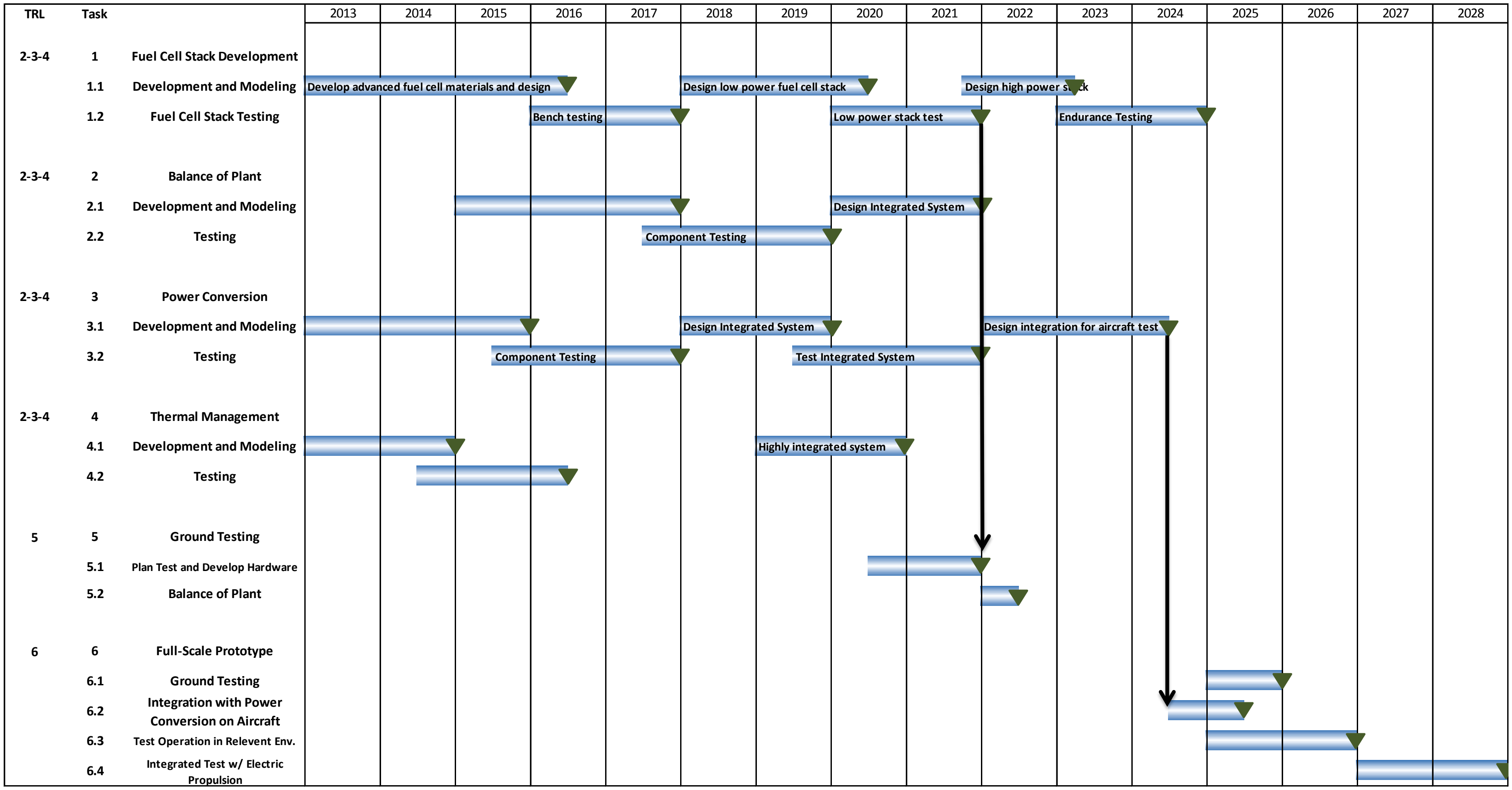


Figure 6.4 – Fuel Cell Technologies Roadmap

6.2.5 Boundary Layer Ingestion Propulsion

Goals and Objectives:

Develop boundary layer ingestion (BLI) engine installations and aircraft configurations as a means to reduce fuel burn.

Performance Area and Impact:

BLI potentially reduces the power required to produce thrust with corresponding reductions in fuel burn and emissions. BLI has potential to reduce the weight and drag of engine installations, which also helps to achieve desired reductions in fuel burn and emissions.

Upper-surface BLI configurations allow placement of engines closer to the wing surface than non-BLI engine installations, potentially resulting in better acoustic shielding for reduced noise.

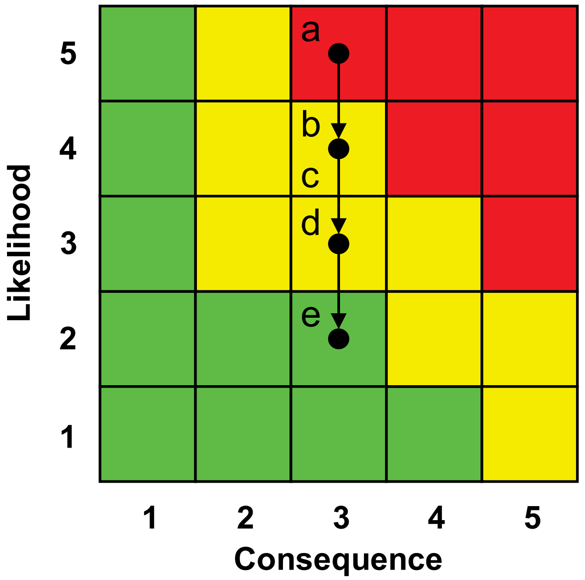
Technical Description:

In a BLI configuration, skin friction drag on bodies ahead of the engine create boundary layers that slow down the net flow ingested by the engine or the thrust-producing fan. Using BLI to slow the flow entering the fan reduces engine ram drag and offers the potential to reduce the power needed to produce thrust. The reduced ram drag allows the engine to produce less gross thrust for the same net thrust. The same net thrust can be achieved with lower fuel burn and corresponding reductions in emissions.

By locating engines closer to the surface structures on which they are mounted, BLI has the potential to reduce engine installation weight and drag. The strut or pylon, which enables the nacelle to be separated from the surface in a conventional engine installation, is reduced or eliminated, saving weight and drag. Part of the exterior surface of the nacelle gets buried in the surface structure, providing further drag reduction from BLI. Weight and drag reductions would result in reduced fuel burn with corresponding reductions in emissions.

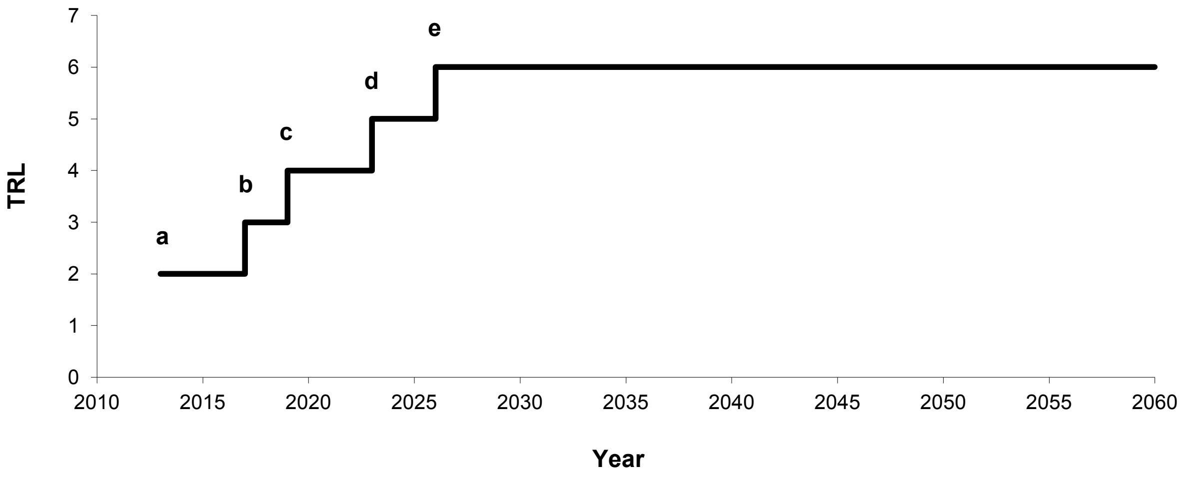
There are numerous difficulties with achieving BLI benefits. The reduced velocity from the boundary layer flow results in a drop in total pressure that will reduce engine cycle efficiency. It is important to configure the engine such that the distorted boundary layer air passes only through the fan and does not enter the engine core. In a common BLI installation with an engine placed over a planar surface, the boundary layer flow tends to collect on one edge of the fan face, which creates significant distortion. Such distortion negatively affects fan performance, so a means for reducing the distortion needs to be developed. Ideally, the low-speed boundary layer flow would be distributed evenly around the fan rim by some means, possibly vortex generators or active flow control. Finally, there are challenges to configuring a vehicle to ingest enough drag to capture a large BLI benefit. Numerous considerations limit the placement of engines, meaning that only a fraction of the airplane skin friction drag can be captured. Trades need to be evaluated between inlet drag and BLI benefit for approaches using inlet shapes and ducting to capture more boundary layer air. Hybrid-electric systems could enable distributed propulsion configurations that would allow more of the boundary layer air to be captured, realizing further fuel burn savings.

Risk Assessment:



If challenges with distortion, amount of boundary layer ingestion, and total pressure loss into engine cores are not addressed, BLI will not contribute reductions in fuel burn, emissions, and noise. Furthermore, if the design is not well integrated the system may contribute to increases in fuel burn or reduction in engine operability.

Major Milestones:



Maturation Plan:

TRL 2 (a) Current

Concepts for reducing distortion have been studied.

Some BLI configurations have been conceived.

Some studies have shown benefits for BLI.

TRL 3 (b)

A conceptual BLI aircraft configuration will be developed as a focal point for more detailed development and as target for assessment of system-level benefits.

A BLI engine installation will be designed and analyzed with goals of ingesting substantial boundary layer flow while keeping the boundary layer flow away from the engine core.

Approaches for reducing distortion from ingested boundary layer flows will be analyzed.

The BLI aircraft aerodynamic lines will be adjusted for the BLI engine installation.

Aerodynamic analysis of the integrated BLI configuration will be performed for cruise and significant off-design conditions.

BLI-compatible engines will be designed for best efficiency given the anticipated engine flows.

A concept for BLI engine structural integration will be developed and analyzed.

A system-level assessment of the benefits of BLI will be made from the results of the analysis studies.

TRL 4 (c)

Wind tunnel tests of a BLI aircraft configuration with unpowered nacelles will validate aerodynamic performance predictions and measure boundary layer characteristics entering the inlets.

Wind tunnel tests of BLI engine installations with simulated onset boundary layer flows and simulated fan flows will be performed to validate predictions of inlet flows.

Inlet flow distortion will be measured in BLI engine installation wind tunnel tests to validate performance of any approaches applied to address distortion from BLI.

Tests of BLI-compatible engine components (fans and cores) will be performed, including simulated BLI onset flow conditions.

Structural components for a BLI engine installation will be constructed and tested.

The system-level assessment of the benefits of BLI will be updated based on the results of testing.

TRL 5 (d)

Wind tunnel tests of a BLI aircraft configuration with powered nacelles will further validate aerodynamic performance predictions and boundary layer characteristics entering the inlets.

A BLI-compatible engine will be integrated and tested.

BLI engine installation structure will be integrated and tested.

Wind tunnel tests of a BLI engine installation, complete with engine, will be performed with simulated onset boundary layer flows to validate engine operability and BLI performance benefits.

Flight tests of a complete BLI engine installation may be performed for further validation of engine operability and BLI performance benefits.

TRL 6 (e)

A BLI aircraft demonstrator will be developed.

Flight tests of the BLI aircraft demonstrator will validate engine operability and BLI performance benefits for a specially-designed BLI aircraft.

Dependency:

Although not assumed in the plan, BLI technology would be improved by developments in hybrid-electric engine and distributed propulsion technology. Separating a BLI fan from its engine core provides a means to avoid ingestion of boundary layer air into the core. This separation could be accomplished with mechanical or electrical drive systems. An electrical drive system would benefit from technologies developed for the hybrid-electric engine. The hybrid-electric engine could also enable distributed propulsion systems that allow for increased boundary layer ingestion, which could lead to increased fuel burn benefits.

Success Criteria:

Table 6.5 – Boundary Layer Ingestion Technologies Success Criteria

TRL	Success Criteria	Alternate Steps if Unsuccessful
3	Analysis shows reasonable means for addressing BLI concerns (distortion, total pressure loss) and suitable performance benefits (fuel burn, emissions, noise, drag, weight)	Continue design of system and components
4	Tests of BLI system components confirm needed BLI flow characteristics (reasonable levels of distortion, low total pressure loss into engine core) and indicate performance benefits can be achieved (fuel burn, emissions, noise, drag, weight)	Redesign components with shortfalls
5	BLI system components are integrated and successfully tested with results indicating performance benefits can be achieved (fuel burn, emissions, noise, drag, weight)	Redesign system to meet goals Accept meeting reduced goals
6	A BLI aircraft demonstrator is developed and demonstrates BLI performance benefits (fuel burn, emissions, noise, drag, weight)	Accept meeting reduced goals

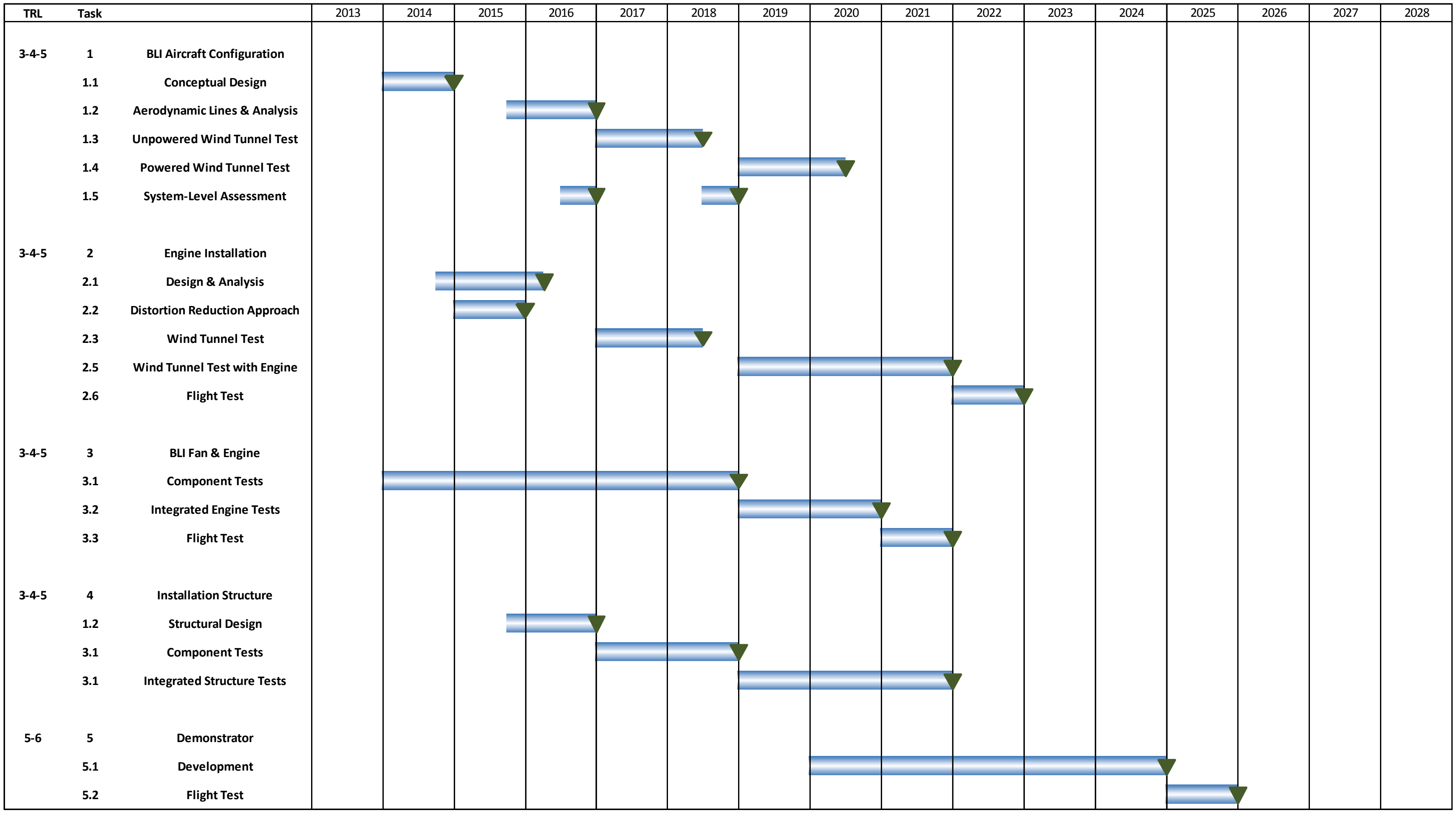


Figure 6.5 – Boundary Layer Ingestion Roadmap

6.2.6 Advanced Unducted Fans and Propellors

Goals and Objectives:

Develop high performance, light weight, and prime-reliable UDF Engine components suitable for flight propulsion applications.

Performance Area and Impact:

The unducted fan provides a fuel burn improvement by achieving propulsive efficiencies over the course of a mission well beyond those achievable with a conventional turbofan. Recent advances in blade design and acoustic analysis enable this benefit while meeting or exceeding next generation acoustic signature requirements.

Technical Description:

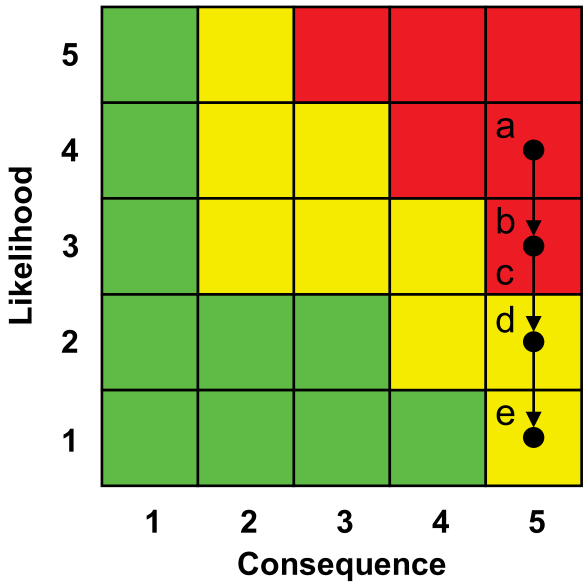
Current unducted turbofans are based on a set of counter-rotating fan bladerows. The counter-rotating bladerows make it possible to generate thrust without leaving any substantial swirl in the fan exhaust airflow. While the pressure ratio of the unducted fan propulsor is well above that of a conventional propeller, the absence of swirl in the exhaust flow allows it to be competitive with a conventional propeller in terms of propeller efficiency while occupying a smaller fan diameter.

Even with this smaller diameter, a key technological challenge for the UDF engine architecture is to efficiently provide power to the low speed fans. To accomplish this, one implementation showing promise is a high speed power turbine driving a counter-rotating differential gearbox. This architecture allows the diameter of the fan to increase for improved propulsive efficiency and acoustic characteristics while keeping the power turbine size and weight in check.

In order to operate over the wide range of subsonic flight mach numbers a commercial turbofan experiences during a flight, the fan bladerows must be capable of variable pitch. At takeoff, the blading needs to be relatively closed. At cruise, the blading needs to be relatively open. During landings, one option for thrust reverse is to rotate the fan blades through the closed position and into reversed flow. The pitch change mechanism to achieve this must be reliable and light weight, and is another key technological challenge on the road to a viable UDF product.

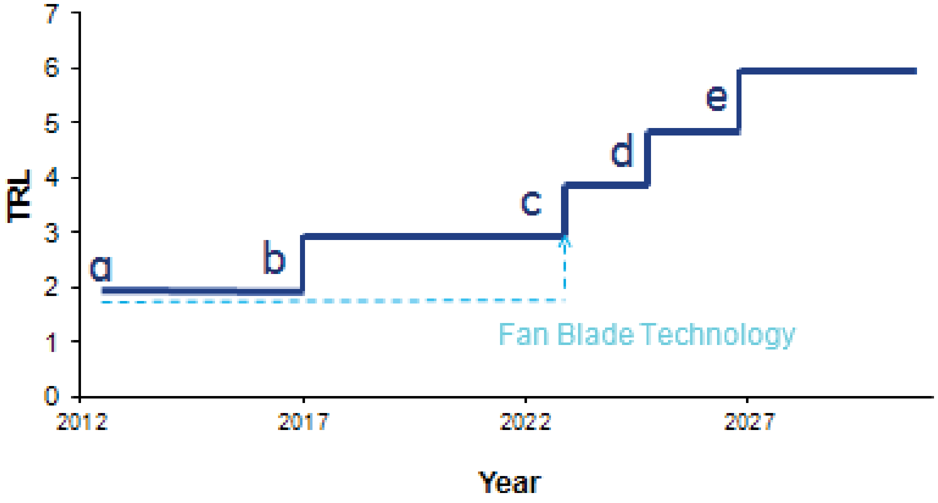
As part of task 1 activities, an evolution of the unducted fan to extreme diameters in the 20 ft class was considered for narrowbody propulsion. At this diameter, it is thought that the exit swirl produced by a single fan bladerow might be small enough to enable a high solidity single stage, low tip speed design. Since fan pressure ratio and tip speed are two main design factors influencing the noise of the propulsor, it is thought that a high diameter single stage propeller at low tip speed might yield an acoustically attractive propulsor. The requirement to operate in a high subsonic flight regime would lead the fan to remain highly swept. This, in conjunction with a relatively high solidity would likely cause the design to more closely resemble its counter-rotating cousin than the propellers of prior generations. The team has identified this as a potential topic for further investigation. At present it is beyond the scope of program funding.

Risk Assessment:



If UDF engine performance, weight, noise and safety do not reach the levels assumed in the vehicle analysis, this technology will not contribute the projected benefits in fuel burn and/or meet noise and certification requirements

Major Milestones:



Maturation Plan:

TRL 2 (a) Current

The following analyses of the engine system have been performed:

- Engine architecture study
    - Pusher vs. Puller
    - Direct Drive vs. Geared
- Performance/Aero definition
    - Hot flowpath layout
- Propulsor design
    - PCM design and integration
    - Fan blade mechanical design
- Engine dynamics
- Engine controls integration
- Engine layout
- Engine weight

Some mission and sizing analysis has been conducted to assess fuel burn.

TRL 3 (b)

A set of new design and safety requirements need to be established to address the airworthiness regulations related to this new type of propulsion system.

TRL 4 (c)

Design the UDF engine component and system integration. Evaluate and test new technologies. Provide innovate solutions to reduce the weight and the noise. Improve the reliability and reduce the maintenance

TRL 5 (d)

Integrate the components into a full-scale demonstration engine/ground test. Evaluate the engine component integration and assess the impact on the SFC

TRL 6 (e)

Integrate the components into a full-scale demonstration engine/flight test. Evaluate the engine/aircraft integration and assess the impact on fuel burn and noise.

Dependency:

A reliable and quiet fan blade is required to fully benefit from this UDF engine technology.

Success Criteria:

Table 6.6 – UDF Engine Technologies Success Criteria

TRL	Success Criteria	Alternate Steps if Unsuccessful
3	Engine technical and safety requirements meet airworthiness regulations.	Identify and conduct tests and analysis to resolve certification issues.
4	Analyses show UDF engine systems will have performance (fuel burn, emissions, noise) and weight consistent with meeting next generation goals	Redesign components with shortfalls Switch to alternative PCM. Fan Blade technology option Consider different engine architecture
5	UDF engine system components are integrated and successfully tested. Initial system performance (SFC, emissions, noise) and weight indicate next generation goals can be met with some redesign.	Redesign system to meet goals Accept meeting reduced goals
6	UDF engine system components are integrated into aircraft and successfully tested Initial system performance (fuel burn, emissions, noise) and weight indicate next generation goals can be met with some redesign.	Redesign system to meet goals Accept meeting reduced goals

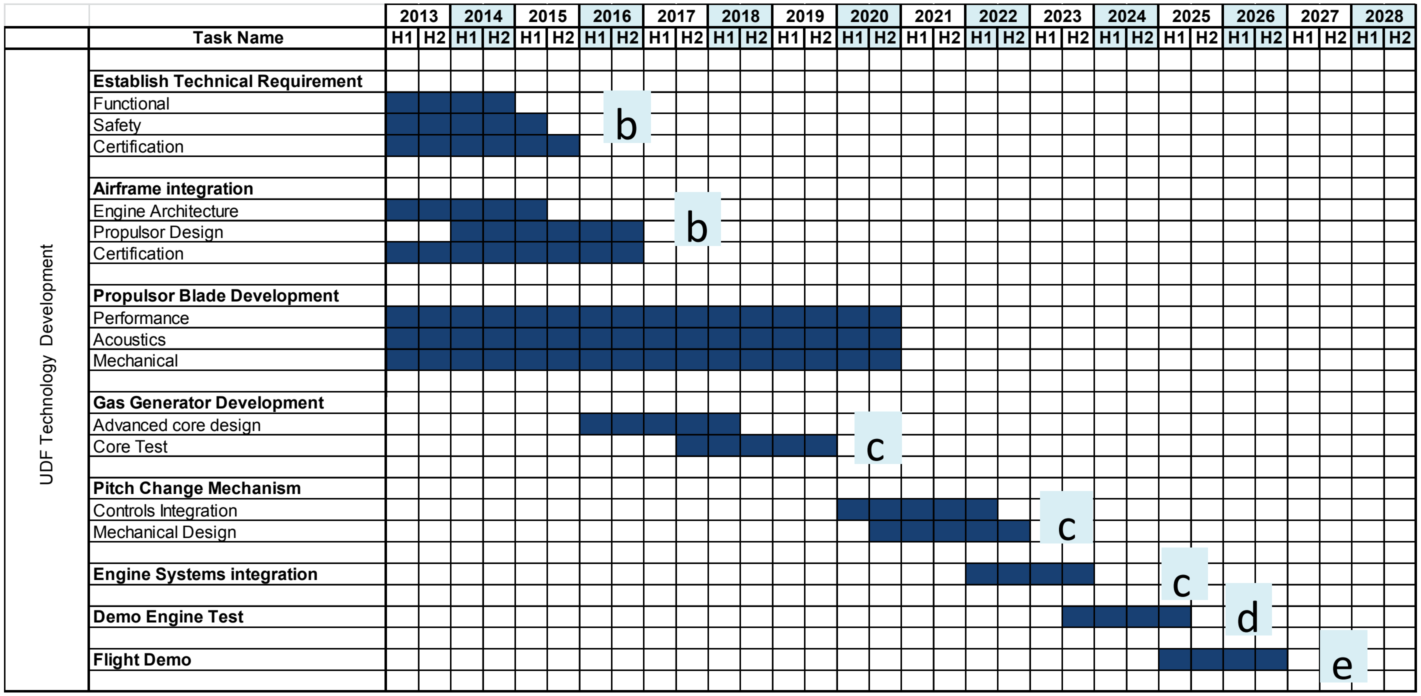


Figure 6.6 – UDF Technologies Roadmap*

* The roadmap schedule shown is notional, suitable for overall program planning purposes only, with no implied guarantee or commitment on the part of GE Aviation

6.2.7 LNG and Hydrogen Gas Turbine Engines

Goals and Objectives:

Develop technologies for LNG and hydrogen aircraft propulsion systems.

Performance Area and Impact:

Fuel burn and emissions will be reduced by using LNG and hydrogen aircraft propulsion systems.

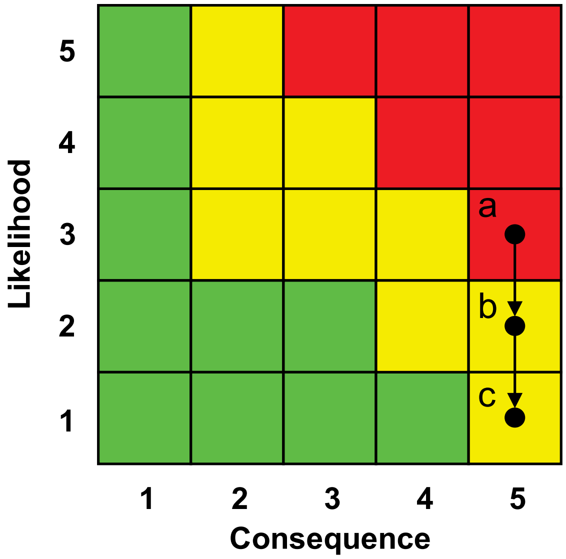
Technical Description:

LNG and hydrogen fuel systems for aircraft consist of storage tanks, a feed and distribution system and an interface fuel panel. Hydrogen is stored as a liquid at -423 deg F and LNG at -258 deg F. LNG may be stored at nearly ambient pressure owing to its high condensation temperature relative to other cryogenic fluids. From the tank, the cryogenic fuel will feed through a low pressure fuel pump in proximity to the tank for delivery from the tank to the engine main fuel pump. A relatively low pressure delivery system is desirable to avoid heavy weight piping and reduce risk to the surrounding aircraft. The vapor pressure of the fuel will also play a key role in determining the delivery pressure. At the main fuel pump the fuel is elevated to a pressure in excess of engine overall pressure prior to delivery to the combustor fuel nozzles. Cryogenic fuel provides an excellent cooling source for the propulsion system. Cooled cooling, intercooling and recuperation are examples of processes that may be employed to improve engine performance and raise the temperature of the fluid to a desirable sensible enthalpy for introduction into the combustor. At present, LNG storage temperatures are beyond the high temperature superconducting (HTS) material range. However, in the N+4 timeframe HTS materials may enable the use of LNG as a cryogenic coolant with little or no refrigeration energy.

Current marine and industrial gas turbines utilize two sets of nozzles to facilitate the introduction of a variety of fuels. One set of nozzles is used for liquid fuels such kerosene and biofuels, and the other is used for gaseous fuels such as natural gas or hydrogen. Natural gas and hydrogen based propulsion systems for aviation applications may utilize a similar dual fuel nozzle combustor to resort to operation on jet fuel at airports/bases where natural gas or hydrogen is not readily available.

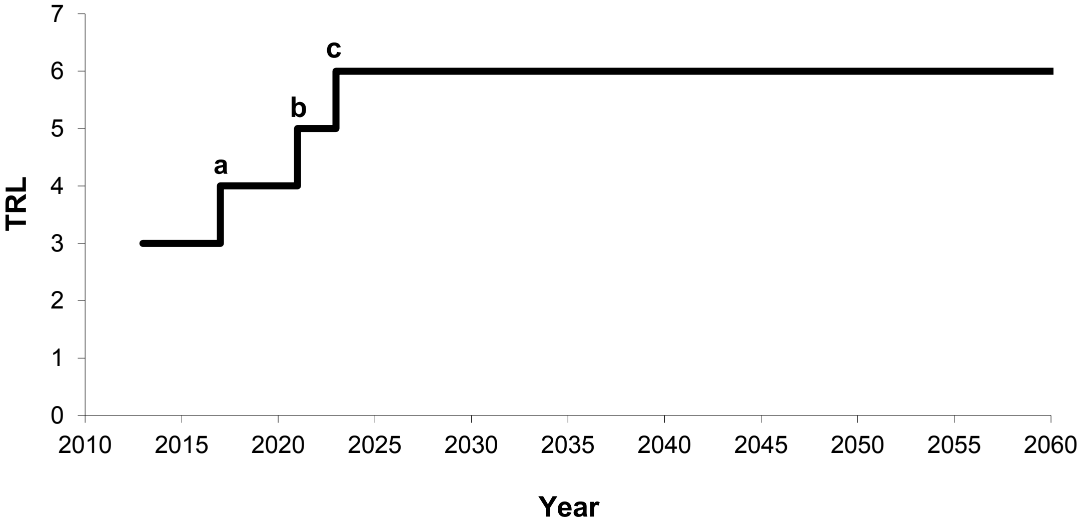
The use of hydrogen as a fuel brings additional complications for the turbomachinery designer. Hydrogen is a highly reactive gas, and as such it tends to react with the metals commonly used in engine design. This reaction leads to a phenomenon known as hydrogen embrittlement, which can substantially reduce the life of the hot section of the turbomachinery. Alternative materials capable of sustaining similar gas path temperatures, or alternative lifing strategies for existing materials will be required as a result.

Risk Assessment:



The N+4 concept engines are based on the utilization of liquefied natural gas. As natural gas fuel systems and combustors are already commercially available, the main challenges associated with utilizing natural gas are associated with establishing viable flight weight designs.

Major Milestones:



Maturation Plan:

TRL 4 (a) Current

Detailed design and test of flight worthy weight LNG main fuel pump
Detailed design and test of flight worthy heat exchangers, fuel manifold, fuel nozzles and combustor
Detailed design and test of flight worthy LNG fuel control system

TRL 5 (b)

Integration and test of fuel control system, fuel pump and combustor module

TRL 6 (c)

Integration and test of LNG based propulsion system
Integration of a flight LNG and hydrogen propulsion system on a full-scale aircraft with a full-scale demonstrator engine

Dependency:

LNG and hydrogen compatible aircraft and infrastructure are required to enable the benefits of LNG and hydrogen fueled propulsion systems.

Success Criteria:

Table 6.7 – LNG and Hydrogen Technologies Success Criteria

TRL	Success Criteria	Alternate Steps if Unsuccessful
4	Design and analysis of LNG and hydrogen based propulsion system components show performance (emissions) and weight consistent with goals	Redesign components with shortfalls Switch to alternative technology option
5	LNG and hydrogen based propulsion system components integrated and successfully tested Path to meet initial system performance (emissions) and weight goals is visible with redesign	Redesign system to meet goals Accept meeting reduced goals Switch to alternative technology option
6	LNG and hydrogen based propulsion system demonstrates performance (emissions) and weight consistent with goals	Accept meeting reduced goals Switch to alternative technology option

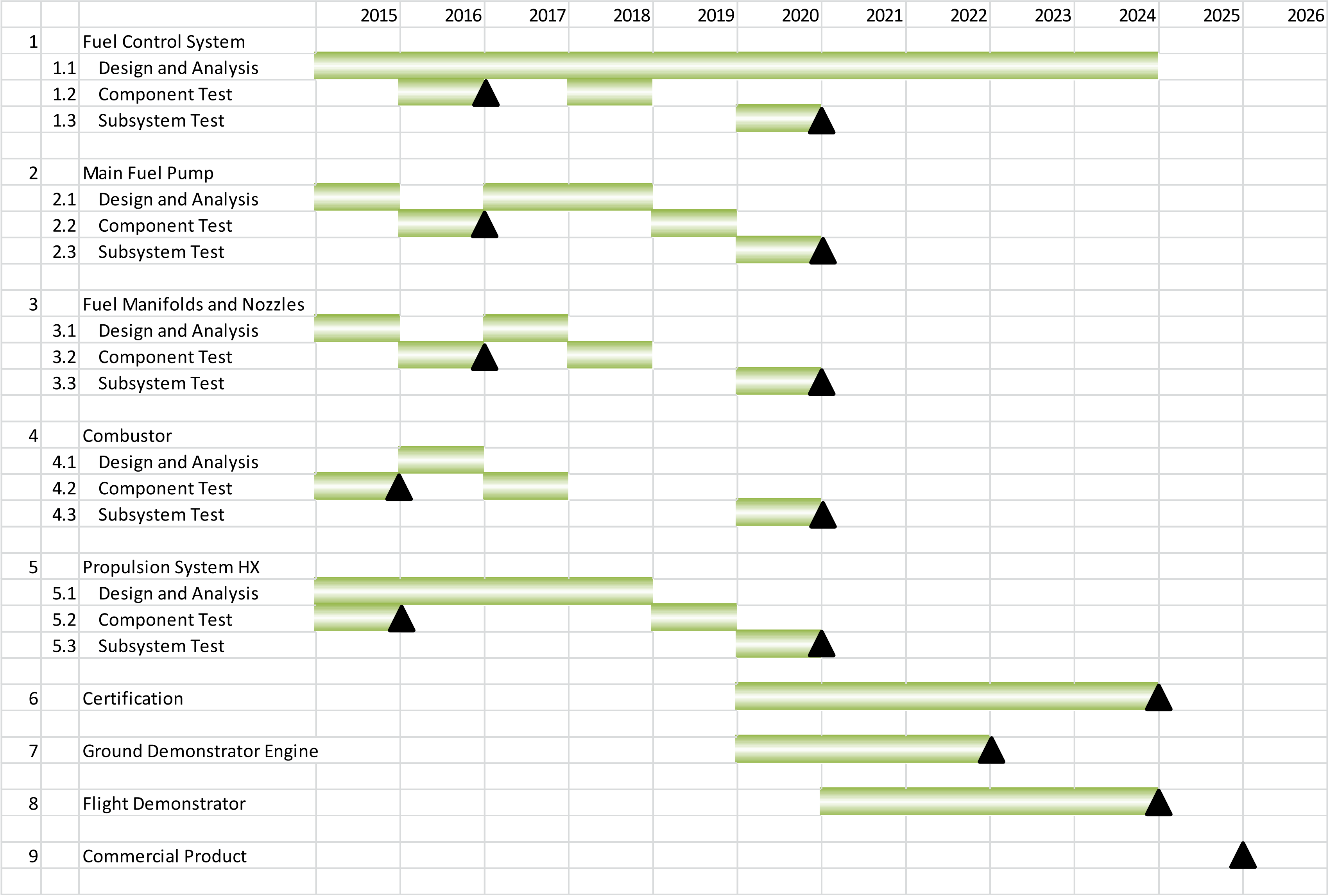


Figure 6.7 – LNG and Hydrogen Aircraft Propulsion System Roadmap

6.2.8 LNG and Hydrogen Aircraft Systems

Goals and Objectives:

Develop technologies for LNG and hydrogen aircraft systems.

Performance Area and Impact:

Fuel burn and emissions will be reduced by using LNG and hydrogen aircraft systems.

Technical Description:

LNG and hydrogen fuel systems for aircraft consist of storage tanks, a feed and distribution system and an interface fuel panel. Hydrogen is stored as a liquid at -423 deg F and LNG at -258 deg F.

Storage tanks are generally spherical or cylindrical in shape and operate at relatively low pressure (15 – 50 psia) to minimize fuel tank weight. The tanks can be foam insulated or vacuum jacketed. Foam insulation has a tendency to degrade over time with cracking due to thermal expansion/contraction and water absorption while vacuum jacketed tanks need periodic vacuum maintenance. The fuel tanks will have a quantity gauging system (capacitance gauge or point sensors) and may have internal baffles. At a minimum each tank will have fluid penetrations for filling/draining, venting and may have a separate penetration for the feed gas to the engines. The tanks will also have electrical penetrations for the quantity gauging system, pressure or temperature sensors and heaters if needed inside of the tanks. The selected insulation system will be the primary trade study. Newer technologies like vacuum insulated panels, microspheres and others will also be evaluated.

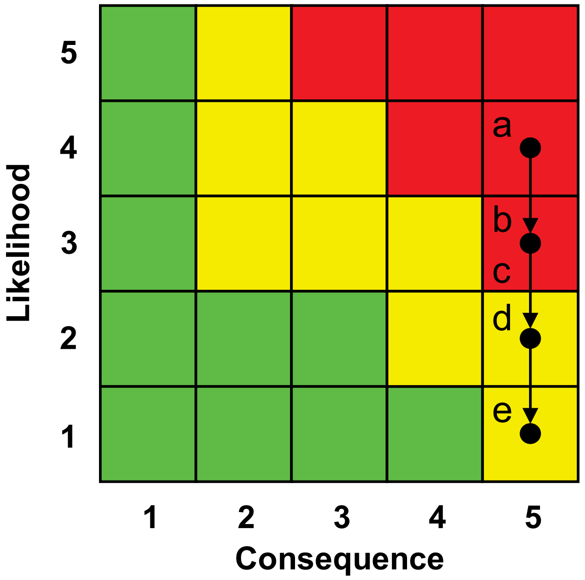
The feed and distribution system consists of all of the lines, valves, pressure and temperature sensors, heat exchangers, pumps and regulators needed to create a safe cryogenic fuel system. The feed and distribution system also allows the tanks to be filled, drained, and delivers LNG and hydrogen to the engines at the required pressure, temperature and flow rate. Anywhere that the fluid is cold, the system will use vacuum jacketed lines to eliminate frost/ice buildup and subsequent water inside the fuselage when the frost/ice melts between flights. Where vacuum jacketed lines transition to valves or other components, the non-vacuum jacketed areas will need to be foam insulated to prevent frost/ice buildup.

In general, fuel is stored at low pressure to minimize tank weight. As a result, a pump or compressor will be required to raise the pressure of the LNG or hydrogen going to the engine to provide sufficient flow. A cryogenic pump that is light weight (for flight applications) and has high reliability (long lifetime, long mean times between service, repair or replacement, and reliable operation) is an item for technology development.

The interface fuel panel will consist of disconnects for filling and draining the fuel tanks, for purging the fuel system with gaseous helium (hydrogen) or nitrogen (LNG), and any other fluid or electrical interfaces needed.

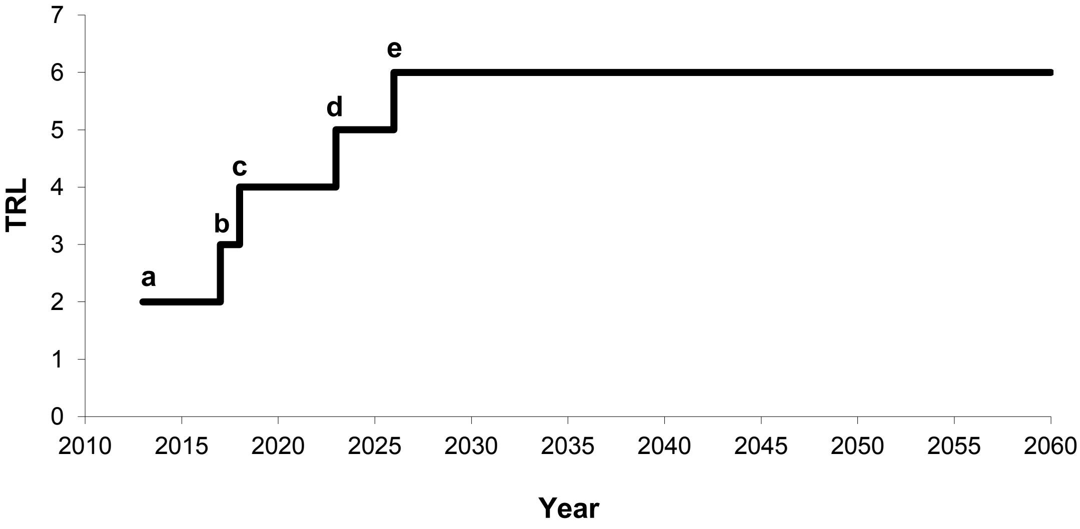
Cryogenic systems (liquid hydrogen and oxygen) have flown on the NASA Space Shuttle, delivering hydrogen and oxygen to fuel cells for the creation of electrical power and drinking water. Oxygen is used in the crew cabin environment for spacecraft applications. For aircraft applications, many military planes use oxygen for personal pilot breathing equipment, and some experimental aircraft have been fitted with liquid hydrogen tanks to allow them to run on hydrogen for short periods of time. LNG has been used in experimental aircraft and helicopters as an alternative fuel, but has not yet been used in normal service or operations. There is extensive experience operating large and aeroderivative power generation gas turbines using natural gas; however, it must be evaluated how much of that knowledge is directly applicable to aviation applications.

Risk Assessment:



If LNG and hydrogen aircraft systems weight do not reach the levels assumed in the vehicle analysis, then LNG or hydrogen aircraft will not be practical and will not contribute the projected benefits in emissions.

Major Milestones:



Maturation Plan:

TRL 2 (a) Current

Analysis of lightweight LNG and hydrogen fuel and oxidizer systems has been performed for space vehicles (launch vehicles, upper stages, spacecraft)
Large scale liquid hydrogen composite tanks have been designed, built and tested in the space industry
Large scale liquid LNG and liquid hydrogen composite tanks are being designed with up to 10 meter diameters (cylindrical tanks with hemispherical heads) for space applications

TRL 3 (b)

A study of composite liquid hydrogen and LNG tanks to operational aircraft system requirements
Preliminary studies of conformal cryogenic tankage with operational aircraft system requirements
LNG and hydrogen pump technology plan defined
Preliminary design, analysis and test of LNG and hydrogen pump

TRL 4 (c)

Design, fabrication of large test fuel systems using cryogenic tank technology
Detailed design of conformal cryogenic tankage with operational aircraft system requirements
Detailed design and test of LNG and hydrogen pump

TRL 5 (d)

Integration and test of a large test fuel system using cryogenic tank technology
Design and fabrication of a full-scale LNG and hydrogen aircraft system
Fabrication and test of sub-scale conformal cryogenic tankage with operational aircraft system requirements

TRL 6 (e)

Integration of a flight LNG and hydrogen aircraft system on a full-scale aircraft with a full-scale demonstration engine
Design, fabrication and laboratory test of a full-scale conformal cryogenic tank fuel system
Integration plan for conformal cryogenic tankage

Dependency:

LNG and hydrogen aircraft infrastructure and engine are required to enable the benefits of LNG and hydrogen fuels. LNG and hydrogen engines are needed.

Success Criteria:

Table 6.8 – LNG and Hydrogen Aircraft Systems Success Criteria

TRL	Success Criteria	Alternate Steps if Unsuccessful
3	Analysis shows LNG and hydrogen fuel system will have performance (emissions) and weight consistent with meeting goals	Continue design of system and components Switch to alternative technology option Consider application to smaller, shorter range aircraft
4	Design and analysis of LNG and hydrogen fuel system components show performance (emissions) and weight consistent with goals	Redesign components with shortfalls Switch to alternative technology option
5	LNG and hydrogen fuel system components integrated and successfully tested Initial system performance (emissions) and weight indicates goals can be met with some redesign	Redesign system to meet goals Accept meeting reduced goals Switch to alternative technology option
6	LNG and hydrogen fuel system demonstrates performance (emissions) and weight consistent with goals	Accept meeting reduced goals Switch to alternative technology option

Notes:

Implementation of operational LNG and hydrogen tankage is dependent on integration plan results and acceptance.

Hydrogen, due to increased leakage potential, may require somewhat more development time or effort. Additionally, hydrogen use will require development of a cost effective and environmentally friendly process for hydrogen production.

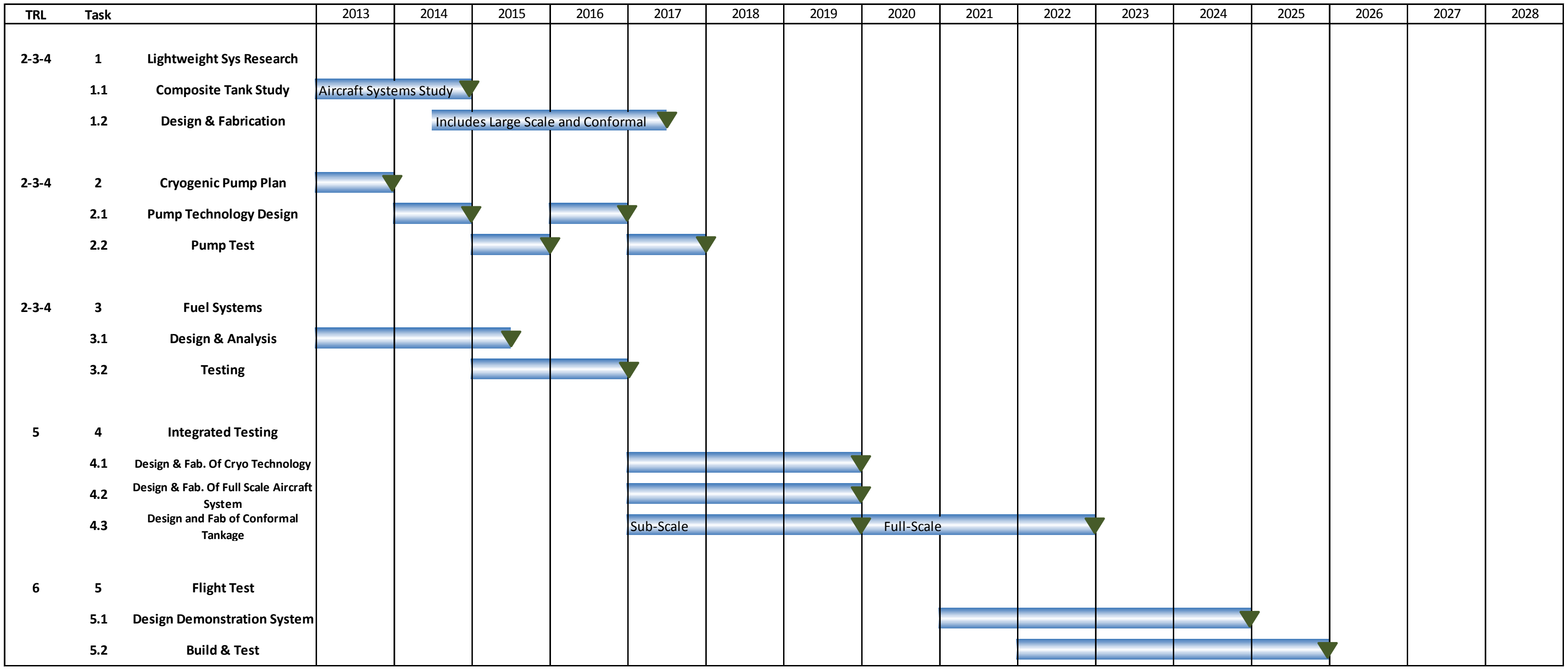


Figure 6.8 – LNG and Hydrogen Aircraft Systems Roadmap

6.2.9 LNG and Hydrogen Infrastructure

Goals and Objectives:

Develop technologies for LNG and hydrogen airport infrastructures.

Performance Area and Impact:

LNG and hydrogen airport infrastructure will enable the use of N+4 generation aircraft using LNG and hydrogen fuels to reduce fuel burn, and emissions.

Technical Description:

Airport infrastructure is the system of equipment employed at the airport used to fill the onboard fuel tanks with the needed commodity, in this case either LNG or liquid hydrogen. This also includes all delivery lines, valves, instrumentation, etc needed to make a safe cryogenic system to deliver fuel to the aircraft. Fuel storage on-board the aircraft is assumed to be a low pressure (15-50 psia) liquid in order to reduce fuel storage system weight.

A facility is required on the airport property that can store large quantities of LNG or liquid hydrogen and meet safety standards (National Fire Protection Association (NFPA) or National Aeronautics and/or Space Administration (NASA)). Commonly a 600 ft radial distance requirement between the LNG and/or liquid hydrogen storage vessels and any facilities that contain people and property lines. Usually, this would mean moving the commodity storage facility to a remote corner of the airport

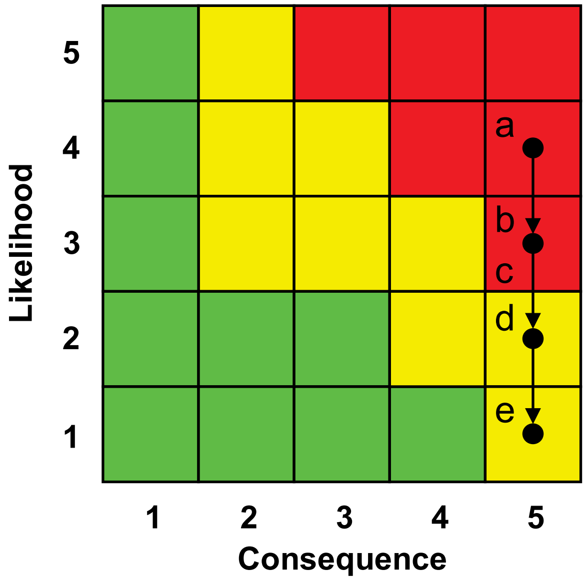
Trade Studies to be conducted include the following:

1. The most important study to be answered is: does the LNG or liquid hydrogen get transported from an on-airport storage site to the airplane or does the airplane get transported to the storage area for fueling?
   To move LNG or liquid hydrogen from the storage site to the airplane would involve a study of trucking the commodity from the storage area to the gate, common to what is currently done today with jet fuel. An alternative would be to build underground distribution systems to each parking stand. LNG and liquid hydrogen tanker trucks exist today and can already operate on any USA highway and industrialized foreign nations highways. Liquid hydrogen today is piped underground over miles of distance between plants.
2. Pumping technology must also be matured. Cryogenic pumps for LNG and liquid hydrogen need to be built to the unique requirements of an airport infrastructure and must be very reliable over long term use.
3. Insulation is needed for the commodity storage vessels and the piping to move the commodity. There are commonly used insulations like foam, vacuum jackets (dewars), and perlite that each have their own advantages and disadvantages. Foam is subject to cracking over time and moisture degradation. Dewars need periodic vacuum

maintenance and perlite will create local heat leak paths over time. There are also newer technologies to be considered like aerogels, vacuum insulated panels and microspheres.

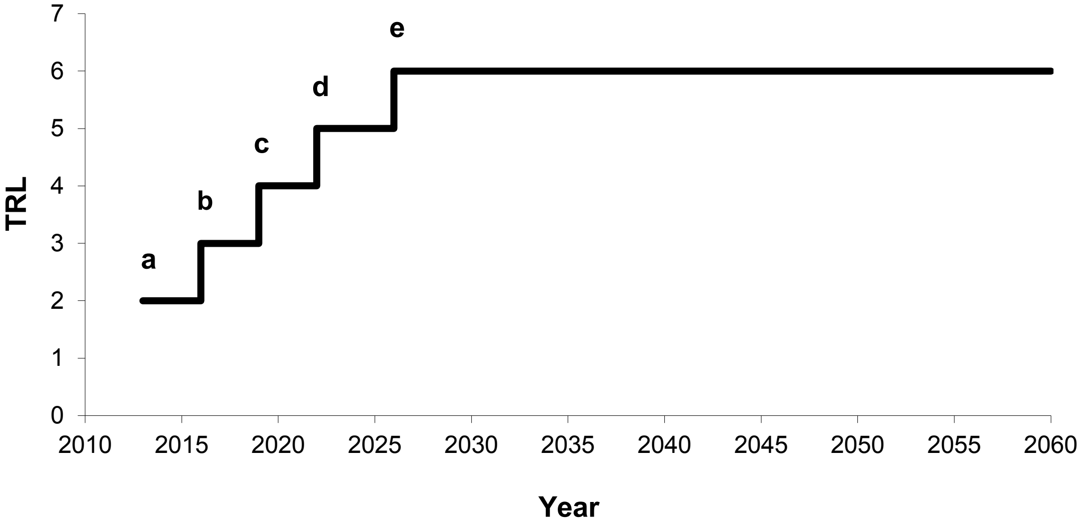
4. Another trade study that needs to be conducted is whether a commodity production facility should be operated on site or if commodity should be trucked/piped directly to the airport storage facility. There are four main methods of obtaining a hydrogen supply. First is the merchant delivery of LH2. In this method, the airport would contract with a commodity supplier like Air Products or Praxair and have them deliver a known quantity of commodity each day, week or month. The commodity would be delivered by truck or pipeline depending on the quantity. The second method is steam reforming of methane (CH4). In this process, methane is cracked with steam and hydrogen gas is formed. This would require a methane supply usually found in large quantities at oil refineries. Using this process to form hydrogen, would mean that both commodities would be available at the airport. The third method of producing hydrogen gas is to use jet fuel reforming. In this process, jet fuel is cracked to form hydrogen. And finally, there is electrolysis. This process requires large quantities of water and electricity. Based on initial environmental assessments, it is likely that only hydrogen production based on green energy sources such as wind, solar, or nuclear will be environmentally acceptable. Additionally, significant improvements in efficiency and the cost of green energy will be needed to make hydrogen a practical aviation fuel source.

Risk Assessment:



If LNG and hydrogen airport infrastructure development does not reach the levels assumed in the vehicle analysis, concurrent with the N+4 vehicle development, LNG or hydrogen fueled aircraft can not be placed in operation.

Major Milestones:



Maturation Plan:

TRL 2 (a) Current

Studies have been conducted of hydrogen airport infrastructure

TRL 3 (b)

Conduct study of LNG and hydrogen airport infrastructure
Trade study to determine if fuel is delivered to aircraft or if aircraft is brought to fueling station
Design, analysis, and fabrication study of large commercial LNG and hydrogen cryogenic pumps
Commodity (LNG and hydrogen) delivery study

TRL 4 (c)

Design, analysis fabrication and test of small-scale LNG and hydrogen airport infrastructure facility
Design study of medium-scale LNG and hydrogen infrastructure

TRL 5 (d)

Design, analysis fabrication and test of medium-scale LNG and hydrogen airport infrastructure facility
Design study of full-scale LNG and hydrogen infrastructure

TRL 6 (e)
Fabrication and operation of full-scale LNG and hydrogen airport infrastructure facility

Dependency:

LNG and hydrogen aircraft systems and engines are required to harness the benefit of N+4 aircraft technologies that reduce fuel burn and emissions. For hydrogen, a cost effective and environmentally friendly fuel production process will be required.

Success Criteria:

Table 6.9 – LNG and Hydrogen Airport Infrastructure Success Criteria

TRL	Success Criteria	Alternate Steps if Unsuccessful
3	Analysis shows LNG and hydrogen infrastructure will have performance consistent with meeting goals	Continue design of system and components Switch to alternative technology option Consider application to smaller, shorter range aircraft
4	Design and analysis of LNG and hydrogen airport infrastructure system components show performance consistent with goals	Redesign components with shortfalls Switch to alternative technology option
5	LNG and hydrogen airport infrastructure system components integrated and successfully tested Initial system performance indicates goals can be met with some redesign	Redesign system to meet goals Accept meeting reduced goals Switch to alternative technology option
6	LNG and hydrogen airport infrastructure system demonstrates performance consistent with goals	Accept meeting reduced goals Switch to alternative technology option

Notes:

Hydrogen use will require development of a cost effective and environmentally friendly process for hydrogen production.

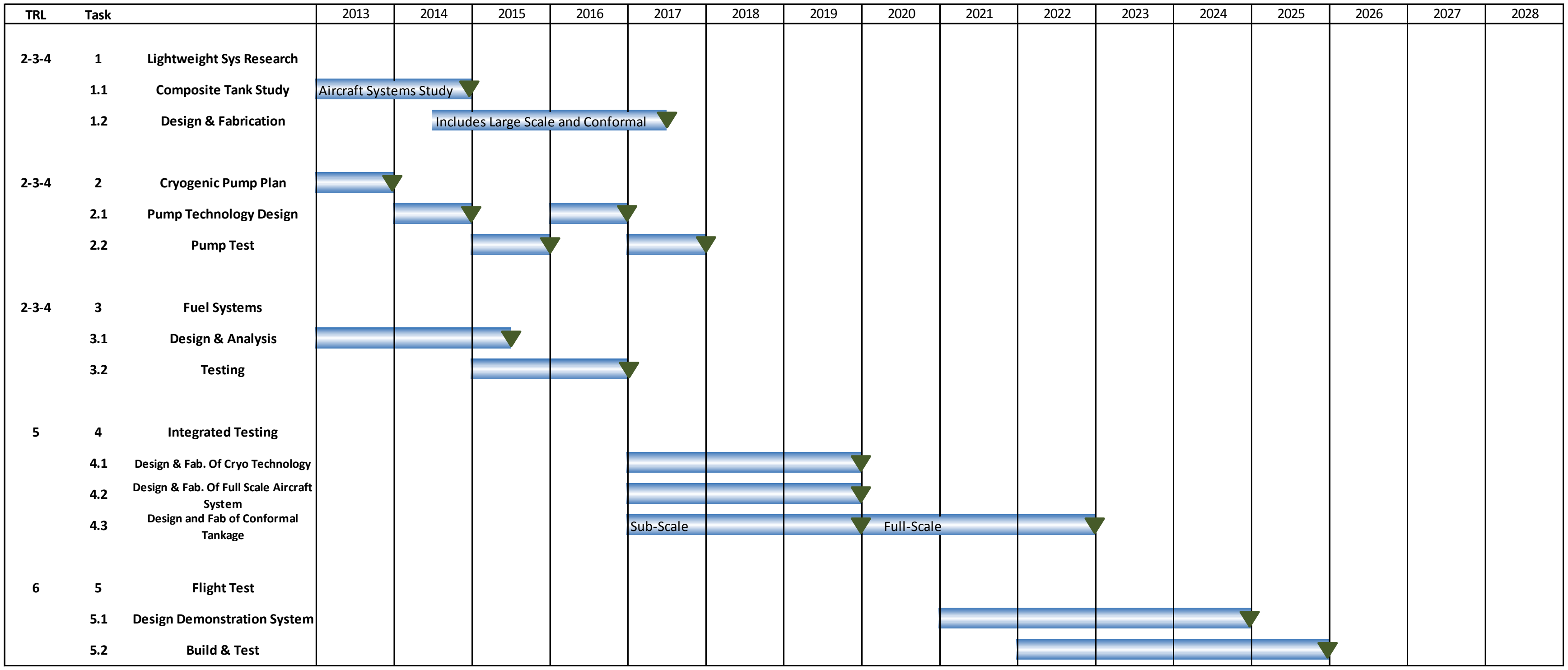


Figure 6.9 – LNG and Hydrogen Airport Infrastructure Roadmap

6.3 Technology Plans Discussion

As we project technologies further into the future, all dates become more uncertain. Additionally, many non-technical outside factors, such as research funding levels, competing energy prices, government actions and incentives, and even public acceptance could have significant influences on the pace and success of technology development.

Generally, we have used a TRL 6 date of 2025 with a corresponding operational date of 2030-2035 for N+3 technologies and a TRL 6 date of 2030-2035 with a corresponding operational date of 2040-2050 for N+4 technologies. We also have assumed that technologies are developed as soon as practical and with robust funding. Therefore, the development plans will tend to be optimistic compared to what will actually occur. The technology plans that have resulted from this effort indicate both N+3 and N+4 timeframes.

Hybrid electric propulsion was identified in Phase I as an N+3 technology and a technology plan was developed. This plan has been updated in this report and adds a specific development plan for the needed high performance modular batteries. Depending on the pace of battery development, they could be an N+3 or an N+4 technology. Also, because of their modularity, it may be possible to develop an aircraft with one kind of battery technology and replace it with another generation of batteries or even a different battery technology during the operational lifetime of the system. Even if batteries of sufficient performance are not ready in the N+3 timeframe for the assumed medium sized commercial airliner, there are likely to be other aircraft applications. Smaller general aviation, business jets, and even regional jets will likely benefit from hybrid electric technologies even at lower battery performance levels.

LNG gas turbine technology could be developed for the N+3 timeframe. The aviation infrastructure change required is very significant and likely to be the dominant influence on the timeline which could stretch into the N+4 timeframe. Hydrogen technology development is essentially similar to LNG technology development, but includes somewhat more difficult technology challenges due to lower cryogenic temperatures, material compatibility issues, and greater leakage potential. Additionally, successful development of hydrogen requires improvements in hydrogen production technology to reduce cost and environmental impact before it is a viable option for aviation. So, it is likely hydrogen is an N+4 technology, even though the hydrogen gas turbine could be developed earlier.

The general viability of LENR technology is still an issue of active research. A breakthrough in nuclear technology would have a significant impact on the entire worldwide energy structure. The technology plan assumes a reasonable “waiting period” to establish viability before beginning development of the technology for aviation.

All concepts in this report also assume the use of various N+3 technologies that were identified in Phase I. Technology plans for these other propulsion, structures, noise, and aerodynamic technologies can be found in the Phase I final report(1).

7.0 Conclusions and Recommendations

Using a quantitative workshop process, the following promising technologies were identified in the N+4 study: Methane/LNG, Hydrogen, Fuel Cell Hybrids, Battery Electric Hybrids, Low Energy Nuclear Reactors (LENR), Boundary Layer Ingestion (BLI), unducted fans and advanced propellers, and combinations. Technology development plans have been developed for these promising technologies and for the required systems and infrastructure development for cryogenic propellants.

An aviation specific life cycle energy study is needed, so the team developed an outline and recommend conducting the full study.

As an advanced technology aircraft for more detailed analysis, the team selected an LNG fueled gas turbine fuel cell hybrid configuration with an aft fuselage boundary layer ingestion propulsor.

The team then generated weight, aerodynamic, and propulsion data for a series of configurations with different combinations of N+4 technologies. Performance and sizing has been conducted for these configurations to allow comparisons on a common basis. Looking at the differences between the configurations allows quantification of the payoff of many of the N+4 technologies identified during the workshop (LNG, fuel cell topping cycle, aft fuselage boundary layer propulsor, and unducted fan).

- LNG fueled aircraft require heavier aircraft systems and larger propellant tankage compared to conventionally fueled aircraft. The higher heating value of LNG reduces the weight of fuel burned (-5.8%), but the heavier aircraft requires more total energy (+5.6%) for a given flight.
- LNG fueled aircraft have the potential for significant emissions advantages over conventionally fueled aircraft. LTO and cruise NOx are lower and less carbon dioxide is produced when it is burned.
- Use of an unducted fan increases propulsive efficiency and reduces fuel burn (-11.6%).
- Adding a topping cycle fuel cell and an aft fuselage boundary layer propulsor driven by an electric motor leads to reductions in emissions and fuel burn (-8.6%).
- The best performing architecture analyzed used LNG, a fuel cell topping cycle, an unducted fan, and an electric motor augmenting fan shaft power. Relative to the SUGAR Free Baseline aircraft, this configuration achieved a 64.1% reduction in fuel burn, beating the 60% N+3 goal. The 59.8% reduction in total energy used, effectively meets the 60% energy reduction goal. This architecture is also estimated to beat the N+3 LTO and cruise NOx emissions goals.

A summary of the technologies investigated in this study is shown in Table 7.1.

Table 7.1 – Task 1 Technology Summary

Technology	Impact	Goals	Relationships	Major Concerns
LNG	Very Significant	Fuel Burn, Emissions, (Fuel Cost), (Fuel Supply)	Enabling to Fuel Cells and Low Emission Combustors	Methane Emissions, Safety, Infrastructure
Unducted Fan	Very Significant	Fuel Burn	Enhancing	Noise, Safety
Engine Fuel Cell	Significant	Fuel Burn, Emissions	Enhancing, Dependent on LNG or Hydrogen	
BLI Aft Propulsor	Significant	Fuel Burn, Emissions, Noise	Enhancing, Dependent on power source (fuel cell or batteries) for electric motor	
LENR	Game Changing	Fuel Burn, Energy Use, Emissions, Noise	Dependent on Hybrid Technology (gas turbine or electric hybrid)	Feasibility, Safety, Weight, Customer Acceptance
Hydrogen	Very Significant	Fuel Burn, Emissions	Enabling to Fuel Cells and Low Emission Combustors, Dependent on Production Technology	Low Cost Green Production, Safety, Customer Acceptance, Infrastructure

LNG technologies should continue to be investigated as there are significant potential emissions advantages, as well as advantages in cost and energy availability. However adding LNG to the aviation propellant infrastructure would be a significant challenge. Also, active research into methane leakage during natural gas extraction, processing, storage, and use should be monitored, as this could have an additional negative environmental impact.

Unducted fans, fuel cells, and BLI are potential enhancing technologies that offer significant improvements.

LENR technology is potentially game-changing to not just aviation, but the worldwide energy mix as well. This technology should be followed to determine feasibility and potential performance.

Hydrogen technology also has potential benefits, but widespread aviation use of hydrogen requires large infrastructure changes as well as significant improvements to produce hydrogen in a low cost environmentally friendly process.

As identified in Phase I, hybrid electric propulsion with high performance batteries offers significant fuel burn, energy, and emissions advantages if large battery technology improvements occur and the technology can be adapted to aviation requirements. Hybrid electric technologies are potentially synergistic with fuel cell, BLI, and LENR technologies. Additionally, using superconducting, the cryogenic characteristics of LNG and hydrogen could be synergistic with hybrid electric technology.

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Appendix A – Propulsion Concept Information

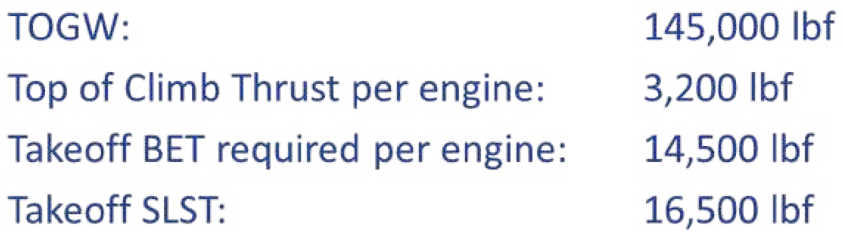
In 2011, GE was awarded a contract by Boeing to support phase II of the Subsonic Ultra Green Aircraft Research (SUGAR) program. SUGAR phase II is a three year effort funded by NASA under the N+3 Subsonic Fixed Wing (SFW) Aircraft program. The program is aimed at identifying transport aircraft and propulsion system concepts with the potential to be available in the 2030-2035 timeframe for substantial reductions in aircraft fuel burn, emissions, noise and required field length. GE's involvement in the SUGAR program as a subcontractor to Boeing represents a continuation of phase I support, where the team of Boeing, GE, Georgia Tech (GT) and Virginia Tech (VT) collaborated to identify and begin exploration of several innovative aircraft and propulsion system concepts. GE was specifically contracted in phase II to perform propulsion system conceptual design work under three tasks: 1. N+4 Advanced Vehicle Concept Study Support, 2. Truss Braced Wing Aircraft Support and 3. Hybrid Electric Aircraft Support. This N+4 final report details the analysis and results set forth in fulfillment of task 1.

Task 1 – N+4 Advanced Vehicle Concept Study Support

The N+4 Advanced Vehicle Concept study is focused on aircraft entering service in the 2045 timeframe. This task provides the airframer and engine maker with an opportunity to make aggressive technology assumptions at both the component and architectural level. In June, Georgia Tech hosted a workshop with NASA, Boeing, GE and VT to identify candidate technologies. Following a team brainstorming session, candidate technologies were ranked for their potential to positively impact the NASA SFW metrics. The hybrid fuel cell and gas turbine hybrid electric concepts ranked highly in this evaluation, but were not selected for further study due to the extensive coverage offered in the 2035 timeframe by SUGAR task 2.2. In addition to evolving GE's 2035 advanced propulsion system offering for a 2045 entry into service, GE agreed to address concepts incorporating liquefied natural gas, solid oxide fuel cells, unducted fans and aft mounted fuselage fan technologies. The novelty and shear number of the concepts to be evaluated prompted the team to utilize a design point class analysis for each engine concept. For a commercial mission, this level of analysis should be adequate to identify the potential of the concepts at a high enough degree of fidelity to understand the merits of a more detailed investigation. The results from a few key flight conditions have then been applied to scale a full flight envelope of data based on the phase II gFan+, accounting for the unique thermal, transfer, propulsive efficiency and weight characteristics associated with the new components and technologies.

N+4 Aircraft Thrust Requirements

Boeing has provided thrust requirements representative of the truss braced wing (TBW) aircraft concept for use in N+4 propulsion system studies. These requirements are shown in Figure 1. GE has provided scaling rules to resize the engine for use as the aircraft evolves, or with other narrowbody class aircraft over a reasonable thrust range.



TOGW:	145,000 lbf
Top of Climb Thrust per engine:	3,200 lbf
Takeoff BET required per engine:	14,500 lbf
Takeoff SLST:	16,500 lbf

Figure 1 - TBW Aircraft Thrust Requirements

gFan++ Advanced Turbofan(JP+2045GT+DF)

The gFan++ advanced turbofan is a direct evolution of the phase II 2035 gFan+. The details of the phase 2 gFan+ engine are outlined in the task 2.1 section of the report. The gFan+ fan pressure ratio has been adopted as a starting point for the gFan++. The key distinguishing feature of the gFan++ is the utilization of 3rd generation CMC technology, enabling a substantial increase in turbine inlet temperature while retaining an uncooled high pressure turbine. Because the turbine inlet temperature of the uncooled gFan+ is low compared to the state of the art cooled powerplant, the additional firing temperature of the gFan++ brings about a marked reduction to specific fuel consumption. It also serves to reduce the powerplant size and weight. The efficiency of the high pressure compressor (HPC) and high pressure turbine (HPT) have been penalized to approximate the effects of reduced HPC discharge blade height and HPT size in the 2045 EIS timeframe. A conceptual layout of the gFan++ is shown in Figure 2.

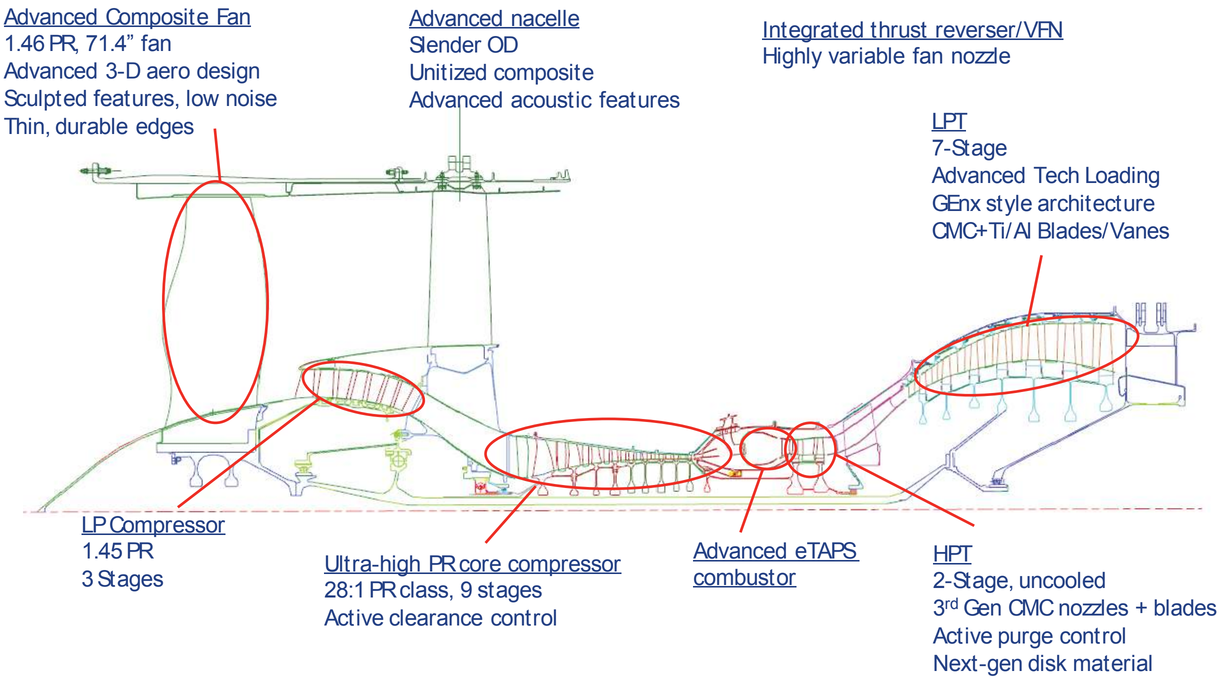


Figure 2- gFan++ (JP+2045GT+DF) Concept Layout

The key characteristics of the engine are summarized with preliminary design margins in Table 1.

JP+2045GT+DF		
Fan Diameter	71.4	In
Length	127	In
Propulsion System Weight	6379	Lbm

Performance	**Thrust (lbf)**	**SFC (lbm/lbf/hr)**
SLS	21943	0.214
Takeoff	16592	0.286
Top of Climb	3931	0.453
Cruise	3145	0.442

Table 1 – JP+2045GT+DF Key Characteristics

Liquified Natural Gas Fueled gFan++ Advanced Turbofan(LNG+2045GT+DF)

By introducing a series of well understood modifications to the combustor, the gFan++ can be converted to run on natural gas. GE has a range of LM gas turbines in service today with the capability to run on natural gas or jet fuel. A series of performance deltas were tabulated to account for the performance potential of using liquefied natural gas (LNG) and supplied to Boeing as part of the task 1 effort. These deltas account for the difference in the fuel heating value of natural gas relative to jet fuel and also make a first pass at estimating the benefits available to the propulsion system as a result of the heat sink capacity of LNG in terms of intercooling and recuperation. In the tank, LNG is stored at approximately -260F. It is unknown at the time of this report whether the engine or aircraft would make the most effective use this heat sink, so the estimated benefit of utilizing the sink in the engine was provided and the option has been left to the airframe for N+4 studies. Table 2 summarizes the key characteristics of the LNG fueled gFan++ ducted turbofan without intercooling or recuperation.

LNG+2045GT+DF		
Fan Diameter	71.4	in
Length	127	in
Propulsion System Weight	6379	lbm

Performance	**Thrust (lbf)**	**SFC (lbm/lbf/hr)**
SLS	21943	0.192
Takeoff	16592	0.257
Top of Climb	3931	0.406
Cruise	3145	0.396

Table 2 - LNG+2045GT+DF Key Characteristics

LNG Fueled gFan++ Powerplant with an Unducted Fan Propulsor (LNG+2045GT+UDF)

A promising configuration for the N+4 timeframe is the truss braced wing (TBW.) The additional room under the wing due to its high mount location on the fuselage makes it well suited to propeller and/or unducted fan (UDF) propulsor concepts. The ultra low pressure ratio of the propeller and UDF propulsors enable substantial improvements to propulsive efficiency relative to its ducted counterpart. A qualitative investigation into the pros and cons of using a propeller versus a counterrotating UDF was conducted under N+4 funding. At this time it is thought that an advanced propeller could be swept in such a manner as to enable a reasonably high flight mach (0.7) without excessive shock losses. However, the propeller leaves a small component of swirl in the exhaust stream that is inherently inefficient. To mitigate this effect and achieve a level of propeller efficiency similar to the UDF, the diameter of the propeller would have to be substantially larger. A more detailed investigation of this trade is worth consideration. The UDF was carried forward in subsequent analysis. The counterrotating fans on the UDF run at nearly a constant speed over the course of the mission and necessitate a change to the gFan++ powerplant architecture. A 2nd spool was introduced to achieve gFan++ overall pressure ratio levels and maintain operability at lower power settings. A full quantification of the details of this update were beyond the scope of the study. The thermal benefits of running on LNG, coupled with the propulsive benefits of the UDF are summarized in Table 3.

LNG+2045GT+UDF		
Fan Diameter	~144	In
Length	~194.6	In
Propulsion System Weight	7,662	lbm

Performance	**Thrust (lbf)**	**SFC (lbm/lbf/hr)**
SLS	28769	0.129
Takeoff	20193	0.186
Top of Climb	3931	0.357
Cruise	3145	0.349

Table 3 - LNG+2045GT+UDF Key Characteristics

LNG Fueled gFan++/Solid Oxide Fuel Cell (SOFC) Powerplant with UDF Propulsor

The concept of utilizing solid oxide fuel cells to augment or replace the combustor in a gas generator for aviation use was explored in phase I of the SUGAR program. The complexity of an integrated fuel cell and gas turbine arrangement may place it beyond of the N+3 timeframe. However, with an additional decade of development time, the team felt this concept warranted additional attention under the N+4 task. GE utilized internally developed SOFC analytical models to estimate the performance and sizing of the fuel cell toward N+4 applications. The model attempts to account for the inlet pressure and temperature of the fuel cell, and also adjusts cell efficiency and sizing based on the design current density selection. The process of reforming the LNG into hydrogen is assumed to occur on board the fuel cell is this time frame, eliminating a potentially heavy component. The SOFC-to-electric motor power conditioning unit specific power is assumed equal to that of the fuel cell for this study. A superconducting electric motor sits in line with the high speed LPT, and both units provide power to the geared UDF. The lapse in thrust with altitude as air density diminishes plays a major role in determining how effective the SOFC will be in improving performance throughout the mission. For the UDF based architecture, the SOFC is sized to provide roughly 40% of the overall fan power electrically at the top of climb condition. At takeoff, the power requirement of the propulsor is substantially higher, but the electric output of the SOFC only increases slightly with flight condition. As a result, the turbomachinery must provide the vast majority of the power through the LPT, and the fuel cells contribution to performance is minimalized. The off design operation of the integrated gas turbine and SOFC is a complex problem. However, given the large performance potential, GE believes it warrants continued investigation. A conceptual layout of the propulsion system is shown below in Figure 3.

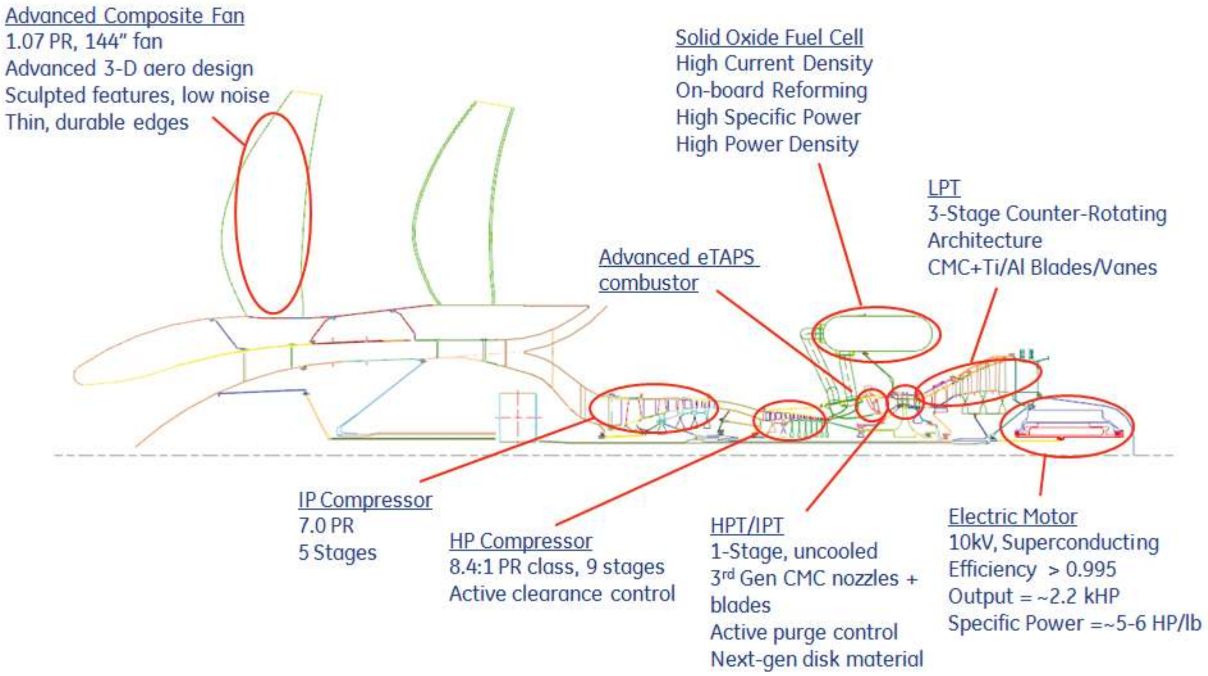


Figure 3 - LNG+2045GT+SOFC+UDF Concept Layout

The key characteristics of the propulsion system concept are summarized in Table 4.

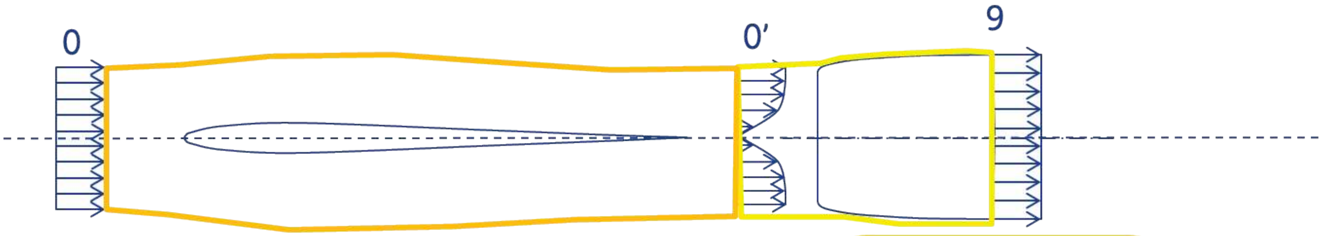
LNG+2045GT+SOFC+UDF		
Fan Diameter	144	in
Length	194.6	in
Propulsion System Weight	10162	in

Performance	**Thrust (lbf)**	**SFC (lbm/lbf/hr)**
SLS	26565	0.125
Takeoff	19077	0.176
Top of Climb	3145	0.321
Cruise	2359	0.313

Table 4 - LNG+2045GT+SOFC+UDF Key Characteristics

gFan++/SOFC Powerplant with Wing and Aft Fuselage Mounted Ducted Fans for Boundary Layer Ingestion and Wake Propulsion

The remaining technology identified by the SUGAR team for exploration under N+4 funding is that of boundary layer ingestion and wake propulsion. In a conventional commercial aircraft configuration, the propulsion system is intentionally installed at a distance from the aircraft surfaces, such that the aircraft and propulsion system interact with separate airflows. In this environment, the net thrust the engine produces is directly proportional to the difference between the velocity of the exhaust jet from the engine and the freestream velocity of the air approaching the engine. Similarly, the drag the airplane produces is directly proportional to the difference between freestream velocity and the average velocity of the wake downstream of the aircraft. The concept of boundary layer ingestion and wake propulsion is to feed the boundary layer flow from the aircraft into the propulsion system. This allows the drag created by the airplane to effectively reduce the freestream velocity of the propulsion system, also reducing the exhaust velocity required to produce a given net thrust. Two methods of bookkeeping thrust between the A/C and propulsion system were explored. The methodology the team agreed to is summarized as option 2 in Table 5.



	Option 1	Option 2
A/C Drag	A/C drag is diminished. Air scrubbing A/C and entering inlet is booked in propulsion system performance.	A/C drag is unaffected at design point (assuming no engine impact on upstream flow field.) Impact of engine on A/C drag must be accounted for off design.
Engine Ram Drag	Based on freestream flight velocity (station 0.)	Based on mass averaged velocity of fluid downstream of A/C (station 0'.)
Engine Inlet Pressure Recovery	Based on pressure loss from freestream (station 0) to fan front face (station 2.)	Based on pressure loss from downstream of A/C (station 0') to fan front face (station 2.)
Engine Gross Thrust	Based on engine exhaust (station 9.) Exhaust velocity is diminished due to reduced ram recovery.	Based on engine exhaust (station 9.) Exhaust velocity is diminished due to reduced station 0' total pressure.
Engine Net Thrust	Based on engine exhaust (station 9) and freestream (station 0) velocities.	Based on engine exhaust (station 9) and downstream of A/C (station 0’) velocities.

Table 5 - BLI/Wake Propulsion Thrust Bookkeeping

In order to evaluate the impact of the boundary layer on the effective freestream (0’) total pressure and velocity, Boeing supplied CFD based boundary layer profiles versus distance from the fuselage. The profiles were provided at altitude and takeoff flight conditions. GE post processed these profiles to arrive at representative properties for cycle design and performance prediction.

In the narrowbody thrust class, adding a third engine to ingest the fuselage boundary layer would result in smaller powerplants, leading to inefficiency in core components and forcing a trade between powerplant component efficiency and ideal thermal engine efficiency. A synergy may be possible between SOFC power production and wake propulsion. The SOFC is designed in this architecture to provide electric power to the aft fuselage fan, and to provide gas power to the wing fans. A conceptual layout of a candidate propulsion system employing boundary layer ingestion and wake propulsion in a tube and wing aircraft configuration is shown in Figure 4 and Figure 5.

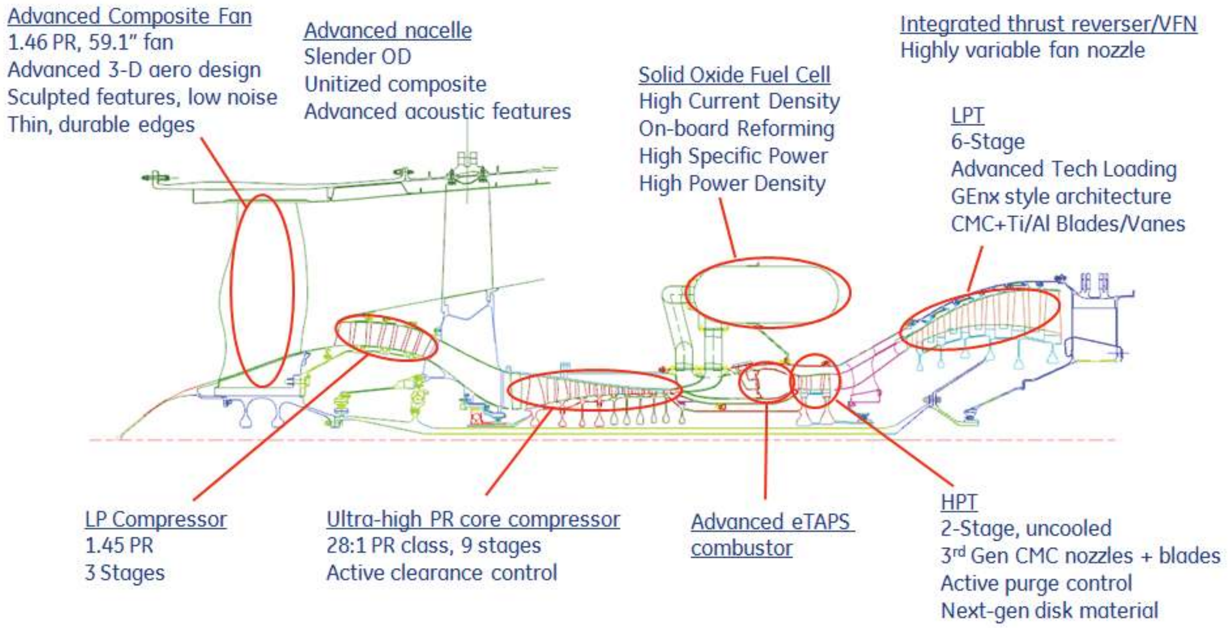


Figure 4 - LNG+2045GT+SOFC+DF+BLI (Wing Fans)

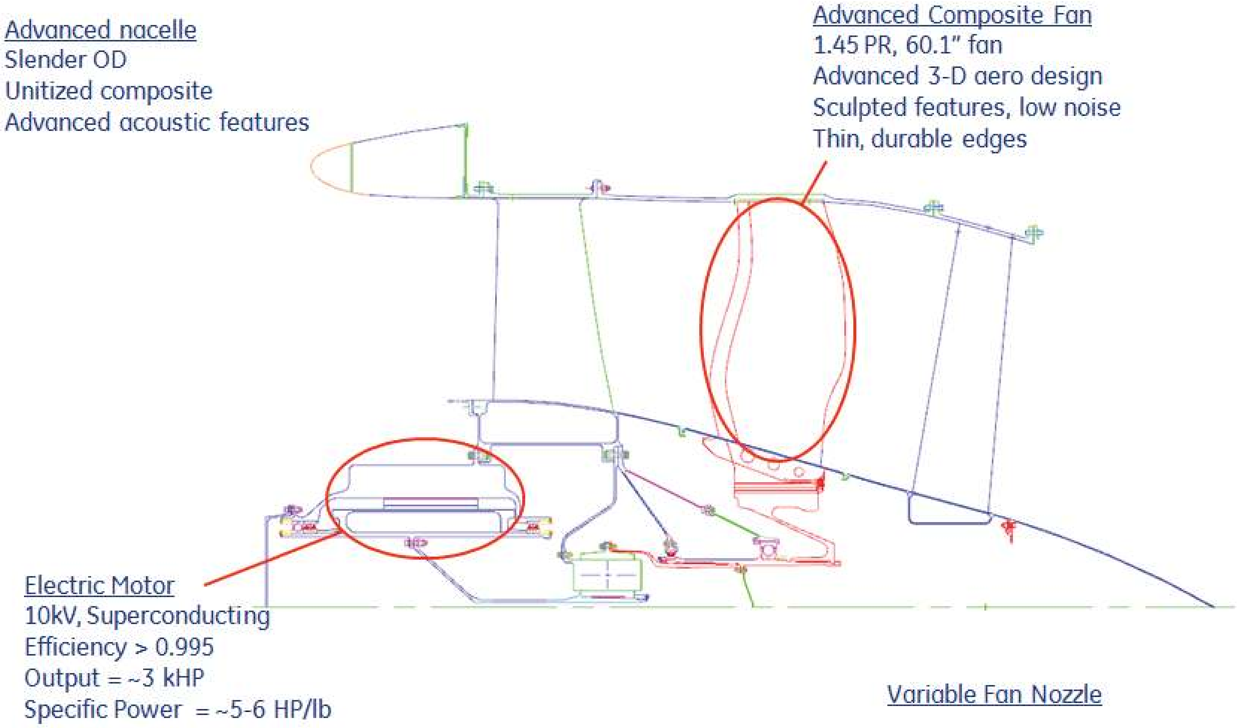


Figure 5 - LNG+2045GT+SOFC+DF+BLI (Fuselage Fan)

The key characteristics of the propulsion system concept are summarized in Table 6.

LNG+2045GT+SOFC+DF+BLI		
Fan Diameter	59.1, 60.1	in
Length	124.1, 60.3	in
Propulsion System Weight	6467, 3584	lbm

Performance	Thrust (lbf)	SFC (lbm/lbf/hr)
SLS	19106	0.188
Takeoff	15032	0.243
Top of Climb	3931	0.348
Cruise	3145	0.339

Table 6 - LNG+2045GT+SOFC+DF+BLI Key Characteristics

Following the conceptual design to varying degrees of the five N+4 engine architectures shared above, tabular datasets were developed based on design point level analyses and provided to the Boeing team, along with weights, key dimensions and scaling rules. Boeing then installed the propulsion systems on the SUGAR High Aircraft (765-095) variants TS1-5 and evaluated the combined aircraft and propulsion systems for fuel burn reduction potential. The results to this analysis are shown in Table 7, along with a qualitative assessment of the noise and emissions characteristics of the concepts.

Case	**1**	**2**	**3**	**4**	**5**	**6**	**7**	
Config. Number	765-093	765-094-TS1	765-095-TS1	765-095-TS2	765-095-TS3	765-095-TS4	765-095-TS5	
Name	SUGAR Free	N+4 Reference	N+4 High Wing Reference	SUGAR Freeze	SUGAR Freeze	SUGAR Freeze	SUGAR Freeze	
Fuel	JP	JP	JP	LNG	LNG	LNG	LNG	
Engine	CFM-56	JP+ 2045GT+ DF	JP+ 2045GT+ DF	LNG+ 2045GT+ DF	LNG+ 2045GT+ UDF	LNG+ 2045GT+ SOFC+ BLI	LNG+ 2045GT+ SOFC+ UDF	
Propulsor	Ducted Fan	Ducted Fan	Ducted Fan	Ducted Fan	Unducted Fan	DF + BLI	Unducted Fan	
				Quantitative Scoring				**Goal**
Block Fuel / Seat (900 NMI)	🟥 (Base)	🟨 -53.5%	🟨 -54.5%	🟩 -57.2%	🟦 -62.1%	🟩 -60.8%	🟦 -64.1%	**-60%[*]**
BTU / Seat (900 NMI)	🟥 (Base)	🟨 -53.5%	🟨 -54.5%	🟨 -52.0%	🟩 -57.6%	🟩 -56.1%	🟩 -59.8%	**-60%[*]**
				Qualitative Scoring				**Goal**
Noise	🟥 +3	🟥 0	🟥 0	🟥 0	🟥 +1	🟥 -2	🟥 +1	**-71 dB[†]**
LTO NOx Emissions	🟥 +3	🟨 0	🟨 0	🟩 -1	🟦 -3	🟩 -2	🟦 -4	**-80%[‡]**
Cruise NOx Emissions	🟥 +3	🟨 0	🟨 0	🟩 -1	🟩 -2	🟦 -3	🟦 -4	**-80%[*]**

[*] Relative to Baseline SUGAR Free

[†] Cum Margin Relative to Stage 4

[‡] Relative to CAEP/6

Color Legend to NASA's Goal
🟥 Far From Goal
🟨 Does Not Meet Goal
🟩 Nearly or Meets Goal
🟦 Exceeds Goal

Qualitative Ranking System

Acoustics		Emissions
Quietest	-4	Least
765-094-TS1	0	765-094-TS1
Loudest	4	Most

Table 7 - N+4 Performance, Noise and Emissions Summary

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14. ABSTRACT

This final report documents the work of the Boeing Subsonic Ultra Green Aircraft Research (SUGAR) team on Task 1 of the Phase II effort. The team consisted of Boeing Research and Technology, Boeing Commercial Airplanes, General Electric, and Georgia Tech. Using a quantitative workshop process, the following technologies, appropriate to aircraft operational in the N+4 2040 timeframe, were identified: Liquefied Natural Gas (LNG), Hydrogen, fuel cell hybrids, battery electric hybrids, Low Energy Nuclear (LENR), boundary layer ingestion propulsion (BLI), unducted fans and advanced propellers, and combinations. Technology development plans were developed.

15. SUBJECT TERMS

Aircraft; Design; Electric; Emissions; Hybrid; Hydrogen; Noise; Nuclear; Propulsion

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