Technologies and Concepts for Reducing the Fuel Burn of Subsonic Transport Aircraft

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ABSTRACT

There are many technologies under development that have the potential to enable large fuel burn reductions in the 2025 timeframe for subsonic transport aircraft relative to the current fleet. This paper identifies a potential technology suite and analyzes the fuel burn reduction potential of these technologies when integrated into advanced subsonic transport concepts. Advanced "tube-and-wing" concepts are developed in the single aisle and large twin aisle class, and a hybrid-wing-body concept is developed for the large twin aisle class. The resulting fuel burn reductions for the advanced tube-and-wing concepts range from a 42% reduction relative to the 777-200 to a 44% reduction relative to the 737-800. In addition, the hybrid-wing-body design resulted in a 47% fuel burn reduction relative to the 777-200. Of course, to achieve these fuel burn reduction levels, a significant amount of technology and concept maturation is required between now and 2025. A methodology for capturing and tracking concept maturity is also developed and presented in this paper.

NOMENCLATURE

CMI - Concept Maturity Index
CTE - Critical Technology Element
FLOPS - Flight Optimization System
HLFC - Hybrid Laminar Flow Control
HWB - Hybrid Wing Body
IPPS - Integrated Power and Propulsion
LFC - Laminar Flow Control
LTO - Landing and Takeoff
N+1 - One technology generation into the future
N+2 - Two technology generations into the future
NPSS - Numerical Propulsion System Simulation
RD^3 - Research and Development Degree of Difficulty
TSFC - Thrust Specific Fuel Consumption
T/W - Thrust-to-Weight ratio
UHB - Ultra High Bypass
WATE - Weight Analysis of Turbine Engines

1.0 INTRODUCTION

NASA's aeronautics program has set goals for significant reductions in fuel burn, noise, and emissions for future subsonic transport aircraft. These goals have been set in response to the United States' National Aeronautics Research and Development Policy [1], established in 2006 by executive order, which emphasizes mobility through the air, and aviation's role in national security, energy efficiency and environmental protection. Table 1 contains a summary of these goals as a function of time.

Table 1: NASA Subsonic Transport Performance Goals

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%

The "N+1" timeframe represents the next generation of technology, estimated to reach a Technology Readiness Level (TRL) [2] of 4-6 in 2015, supporting a 2020 entry into service. The "N+2" timeframe represents two technology generations into the future, with a predicted TRL 4-6 in the 2020 timeframe supporting a 2025 entry into service. The "N+3" timeframe represents three technology generations into the future, focusing on technologies that will not meet the TRL 4-6 maturation level until 2025. The focus of this paper is the minus 50% aircraft fuel consumption metric in the N+2 timeframe. This 50% fuel burn reduction is relative to a 777-200 baseline aircraft. Achieving this significant fuel burn reduction by the 2025 timeframe will require the successful maturation and integration of a variety of technologies. In addition, NASA's N+2 goals are intended to be met simultaneously, resulting in an even greater challenge, since fuel burn reductions can come at the expense of noise, and vice versa. Therefore, fuel burn reduction technologies are needed that do not increase aircraft noise or NOx emissions. Technologies that are capable of reducing fuel burn, noise, and NOx in a synergistic manner are ideal, if they can be developed and integrated.

This paper identifies a suite of potential fuel burn reduction technologies that also support the noise and emissions metrics, and provides estimates for the overall fuel burn reduction potential when these technologies are integrated on advanced concepts. Both advanced tube-and-wing and hybrid-wing-body (HWB) concepts are utilized to perform the fuel burn reduction assessment. Although outside the scope of this paper, a large variety of alternative advanced concepts have been proposed as well. These range from high aspect ratio trussed-braced-wing concepts [3], to concepts with boundary-layer-ingestion propulsion systems [4], to "box-wing" concepts [5]. Assessing the relative merits of these disparate concepts is challenging, but is also important so that research and development investment decisions are well informed. A methodology for assessing the relative benefits and maturity levels of this large variety of advanced concepts is developed and presented in this paper.

2.0 FUEL BURN REDUCTION TECHNOLOGIES

The following sub-sections outline potential fuel burn reduction technologies, and how their impacts are captured at the aircraft system level. All of these technologies have been, or are currently, active research projects under NASA's aeronautics research programs.

2.1 Advanced Materials

Composite materials and advanced material systems have the potential for significant weight savings relative to traditional aluminum construction. In the N+1 timeframe, a 15% reduction in the wing and tail component weights and a 5% reduction in the fuselage weight are assumed through the use of composites for construction of the primary structure. These weight reduction assumptions are consistent, and in some cases, conservative, compared to standard practice in previous aircraft system level studies, such as published by Berton and Guynn [6]. In addition, Renton, et al., [7] postulate a 20% weight savings in the N+1 timeframe when switching from an aluminum-based to a composite-based design for the wing and fuselage.

Looking ahead two technology generations to the N+2 timeframe, an additional 10% weight savings for the wing, tail and fuselage components is assumed. Advanced material systems such as stitched composites are predicted to provide this additional weight savings [8]. A recent Lockheed study [5] of subsonic transports in the N+2 timeframe also assumed a similar level of weight reduction through the use of advanced composites. For unconventional configurations such as the HWB, N+2 levels of composite technologies are required for concept viability. The HWB's non-circular fuselage configuration must simultaneously resist internal cabin pressure and buckling due to high overall bending loads, and advanced composite technology will be required to provide a structurally feasible concept for this application [9].

Finally, the ability to specifically tailor the structural characteristics of a composite wing as a function of span should enable higher aspect ratio wing designs without incurring prohibitive weight penalties. The 777-200 and 737-800 have wing aspect ratios of 9.8 and 9.4, respectively. Through the use of tailored composites, a wing aspect ratio of 11 was assumed as the upper bound for the advanced tube-and-wing designs. The 787 demonstrates progress in this direction with a wing aspect ratio of 10. This increased aspect ratio will result in a reduction of induced drag, and therefore a fuel burn reduction.

2.2 Advanced Engines

Advanced engines are a key enabler for achieving the fuel burn, noise, and emissions goals presented in Table 1. Advances in materials, aerodynamic design, integration, and architecture will contribute to the reduction of thrust specific fuel consumption (TSFC). New combustor designs targeted at reducing NOx emissions [10], and advanced liners, new engine cycles, and noise attenuating components [11] will be needed to help meet the noise and emissions goals. Both podded and open rotor engine concepts are briefly discussed below.

2.2.1 Ducted

Advanced, ultra high bypass (UHB) ratio turbofan engines are being developed for entry into service in the N+2 timeframe. These engines will have bypass ratios in the 12-18 range, and will rely on advanced propulsion technologies such as active compressor and turbine clearance and flow control, advanced cooling, gearing, regeneration, and the use of new materials that are lighter weight and have higher temperature capabilities relative to today's materials. McKay [12] provides a detailed projection of TSFC reductions for advanced engines in the 2020 timeframe based on these technologies. In addition, recent studies by Boeing and Lockheed sponsored by NASA provided advanced engine designs from Pratt & Whitney and Rolls Royce for the N+2 timeframe. Based on these sources, a cruise TSFC of 0.49 was assumed for the advanced single aisle concept, and a cruise TSFC of 0.475 was utilized for the large twin aisle thrust class. Engine thrust-to-weight (T/W) ratios of 3.4 were also assumed. This is the maximum sea level static thrust divided by the IPSS engine weight. Advanced engine models were then created utilizing NASA's NPSS [13] and WATE [14] codes and the TSFC and T/W ratio values were calibrated in NASA's sizing and performance code, FLOPS [15].

2.2.2 Unducted (Open Rotor)

According to Guynn [16] numerous studies documenting the fuel burn reduction potential of open rotor engine technology were published in the 1980's. With bypass ratios of 25 or greater, the open rotor engines generally consumed 25% less fuel than equivalent technology turbofans, for aircraft in the 100-150 passenger range cruising at Mach numbers less than 0.8. A consistent challenge, however, was increased noise. Cabin noise could be attenuated through acoustic treatments, at the cost of increased weight, but exterior noise was more challenging. Modern open rotor research has focused on reducing the noise without sacrificing the fuel consumption performance by optimizing the blade design and the propulsion airframe aeroacoustic integration, as presented by Czech and Thomas [17]. Although the open rotor engine fuel burn reduction potential is very attractive, the noise and integration challenges are significant; therefore, for the purposes of this study, only podded engine models will be utilized.

2.3 Aerodynamics

Drag reduction technologies represent another significant opportunity to lower fuel burn. Both induced drag and skin friction drag are targets for drag reduction technologies. Skin friction drag can be reduced by maximizing the amount of laminar flow on the aircraft. In areas where turbulent flow remains, drag reductions are possible through the use of riblets. The active trailing edge concept can reduce drag through wing shape optimization in flight. As discussed in the advanced materials section, induced drag can be reduced through increased wing aspect ratio.

2.3.1 Laminar Flow Control

Joslin [18] provides a comprehensive overview of LFC research covering the timeframe from the 1930s through the 1990s. According to Joslin, LFC is defined as an active boundary-layer flow control technique. This technique is usually a suction system, which is employed to maintain laminar flow at chord Reynolds numbers where the flow would otherwise be characterized as transitional or turbulent in the absence of the LFC system. An alternate concept, Natural Laminar Flow (NLF), relies on a wing design that provides a favorable pressure gradient to delay transition to turbulent flow, but it is limited in applicability to lower wing sweeps and chord Reynolds numbers relative to LFC. A key advance in this field was the development of the Hybrid Laminar Flow Control (HLFC) concept. HLFC integrates the concepts of LFC and NLF in a system that utilizes suction in the leading edge region and NLF wing design to maintain laminar flow over a portion of the wing aft of the leading edge region.

For the purposes of this study, an HLFC system was assumed for the wing and tails of the advanced tube-and-wing concepts, and for the outer wing sections of the HWB concept. The suction system will require space, weight, and power allocations that are a function of aircraft size and suction system mass flow requirements. Estimates were made for the suction system weight and horsepower requirements based on the running length of the suction system along the wing and tail leading edges. Weight and horsepower per foot metrics were utilized based on a proprietary study performed by Boeing for NASA and the Air Force

Research Laboratory in 2009. Benefits of the HLFC system were assumed to be 50% chord laminar flow along the wing upper surface, and 50% chord laminar flow on both sides of the tail surfaces. NLF was assumed to provide laminar flow on the nacelles over 50% of their length. A Krueger flap system was utilized for both the tube-and-wing and HWB concepts' leading edges, resulting in no laminar flow on the under surface of the wing due to the flap hinge line. The Krueger flap does integrate well with an HLFC system, by preventing ice and insect contamination of the wing leading edge during takeoff and climb, in addition to the high lift benefit.

2.3.2 Riblets

Riblet technology has been shown to reduce turbulent skin friction drag by up to 8 percent. Riblets are flow-aligned grooves applied to the aircraft skin in regions of turbulent flow. Walsh, et al. [19] reported a drag reduction of 6% through the use of riblets on the fuselage of a modified Learjet. Based on this flight test data, a 6% reduction in skin friction drag was assumed for the fuselage of the advanced tube-and-wing concept, and for the centerbody of the HWB concept.

2.3.3 Active Trailing Edge

An active trailing edge, utilizes a segmented flap trailing edge system that employs a combination of rotation and translation of its segments to change its shape. The shape change is optimized during transonic cruise conditions to minimize drag. Based on the work of Siclari, [20] a 1% drag reduction was assumed through the employment of a smart trailing edge system design that relies on fuel flow and flight speed measurements to continually adjust the trailing edge shape for minimum drag. In addition to drag reduction, an active trailing edge can be utilized for gust and maneuver load alleviation. Studies by Xu and Kroo [21] show how the use of trailing edge deflections can concentrate lift inboard and therefore reduce wing bending moment. Based on this work, a conservative 5% wing weight reduction was assumed for this study.

2.4 Subsystems

Advanced subsystems can also contribute towards fuel burn reductions, although not by the same magnitude as the materials, propulsion, and aerodynamics technologies. Electromechanical actuators that utilize electric motors and are mechanically coupled to the load are assumed to replace the traditional hydraulic flight control system, as described by Blanding [22]. For the purposes of this study, a 10% weight reduction was assumed relative to the traditional hydraulic system weight.

Rajashekara, et al. [23] present a hybrid solid oxide fuel cell/gas turbine (SOFC/GT) auxiliary power unit that has the potential to provide a fuel savings relative to the traditional APU and main engine generator systems in the reference aircraft, in addition to reducing harmful emissions. Through the use of this advanced APU during the cruise portion of the flight, a 1% fuel flow net benefit was assumed due to the resulting reduction in power extraction required from the main engines. The weight of the SOFC/GT APU was assumed to be equal to that of a traditional APU.

2.5 Configuration – Hybrid Wing Body

The aircraft configuration itself can be considered an advanced technology. Previous studies by Thomas, et al. [24] have established the importance for the configuration to provide shielding of the engine noise in order to achieve the overall N+2 noise goal. This shielding technology must not detract from the fuel burn performance since the goal is to meet these metrics simultaneously. The HWB configuration is attractive due to its potential to provide engine noise shielding, in addition to improved aerodynamic performance, and therefore fuel burn reduction, relative to a conventional tube-and-wing design.

3.0 ADVANCED CONCEPT SIZING AND PERFORMANCE ESTIMATION

Given the N+2 technology assumptions detailed in section 2.0, three advanced concepts were created to quantify the fuel burn reductions potentially available in the 2025 timeframe. NASA's FLOPS code was utilized to develop these three concepts. FLOPS takes as inputs the vehicle geometry, engine deck, mission definition, and, in the case of a sizing/optimization run, design variables, constraints, and the objective function. For all of the cases in this paper, FLOPS was run in optimization mode with minimum gross weight as the objective function. The design variables were wing area, aspect ratio, and engine thrust. Constraints were range, approach speed, takeoff and landing field length, missed approach and second segment climb performance, and rate-of-climb at the start of cruise. The reserve fuel is defined as 5% of the total fuel, plus the fuel required to divert 200 nm to an alternate airport, plus the fuel required to perform a 30 minute loiter before landing at the alternate airport. The engine models were developed by NASA Glenn Research Center using NPSS and WATE, and provided to NASA Langley in the form of FLOPS engine decks.

The advanced concept sizing process begins with the creation of a reference vehicle model in FLOPS based on an existing aircraft. The FLOPS model is compared to published data and, if needed, calibrated to better match the published data. Calibration can consist of adjustments to a wide variety of variables, such as weight parameters, drag parameters, or engine fuel flow. Once a satisfactory baseline model is created, the advanced technology concept is developed by adjusting input variables to reflect the advanced technology impact assumptions. The advanced technologies are also applied to the concepts in a "one-on/one-off" process to produce "waterfall" charts that show the relative contributions of each technology to the overall fuel burn reduction.

The output parameter of primary interest in this study is "block fuel". The block fuel is defined as the actual fuel burned during the mission. The total fuel is therefore block fuel plus the reserve fuel. The estimated block fuel burn for the advanced concept is compared to the reference vehicle's block fuel burn to derive the percent reduction in fuel burn.

3.1 Single Aisle Advanced Tube-and-Wing

The reference vehicle for the single aisle tube-and-wing design is a 737-800 with CFM56-7B engines. The reference mission payload/range is 160 passengers and 2875 nm. The total payload weight is 37,760 lb, which includes the weight of the passengers and their baggage. The cruise speed is Mach 0.78. FLOPS estimates that the total fuel for this mission is 46,800 lb, and the block fuel is 39,100 lb. The active constraint was the rate-of-climb at cruise altitude (this value is required to be greater than 300 ft/min). The FLOPS model outputs were compared to published data for the 737-800 [25], and were found to be within 0.25% for TOGW, 1.7% for Operating Empty Weight, and 2.5% for total fuel weight. Wing area was within 1.6%, and engine thrust within 1.2%. Given the acceptable accuracy of the initial FLOPS model, no calibration factors were utilized.

Using the reference vehicle model described above as the starting point, the N+2 technology suite was applied by utilizing the assumptions detailed in section 2.0. For this case, the active constraint was the second segment climb. Table 2 shows the parameters of interest for the advanced concept, as compared to the 737-800 reference vehicle. Note that the wing span has increased and the wing area has decreased resulting in a wing aspect ratio of 11. The block fuel burn is estimated to be 21,900 lb, a 43.9% decrease compared to the reference vehicle. Figure 1 presents the waterfall chart, showing the relative contributions of each technology area to the overall 43.9% fuel burn reduction. The advanced engines represent the largest contribution at 18.9%, with the advanced materials and HLFC comprising 11% and 9.9% respectively. The riblets, ACTE, and subsystem technologies provide the final 4.1% of the total reduction.

Table 2: Single Aisle Baseline and Advanced Tube-and-wing Parameters of Interest

	Units	FLOPS Model of the 737-800/CFM56-7B	Advanced Single Aisle Tube & Wing
Entry into Service		1998	2025
Takeoff Gross Weight	lb	174,700	141,000
Operating Empty Weight	lb	91,300	77,000
Payload	lb	37,763	37,763
Range	nm	2875	2875
Block Fuel	lb	39,100	21,900
Wing Area	ft^2	1344	1232
Wing Span	ft	112.6	116.3
Wing Aspect Ratio		9.4	11
Wing Loading	lb/ft^2	130	114.4
Cruise Mach #		0.78	0.78
Start of Cruise L/D		16.5	19.7
Start of Cruise SFC	lb/(lbf hr)	0.62	0.486
Max Thrust per Engine	lb	26,300	19,800

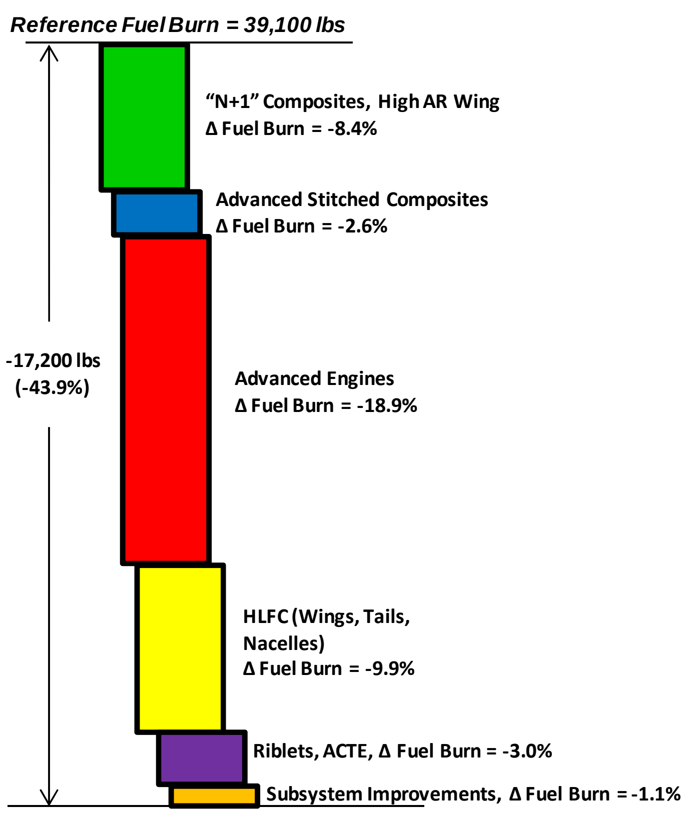

Figure 1: Advanced Single Aisle Tube & Wing Waterfall Chart

3.2 Large Twin Aisle Advanced Tube-and-Wing

The reference vehicle for the large twin aisle tube-and-wing design is a 777-200LR with GE90-110B engines. The reference mission payload/range is 301 passengers in mixed class and 7500 nm. The total payload weight is 118,100 lb, which includes the weight of the passengers and their baggage. The cruise speed is Mach 0.84. FLOPS estimates that the total fuel for this mission is 309,800 lb, and the block fuel is 279,800 lb. The active constraint was the second segment climb. Calibration factors were required to adjust the empty weight and drag. After calibration, the FLOPS model outputs matched the 777-200LR published data [26], to within 0.04% for TOGW, 0.6% for Operating Empty Weight, and 0.9% for total fuel weight. Wing area was within 1.7%, and engine thrust within 4.2%.

Using the reference vehicle model described above as the starting point, the N+2 technology suite was applied by utilizing the assumptions detailed in section 2.0. For this case, the active constraint was also the second segment climb. Table 3 shows the parameters of interest for the advanced concept, as compared to the 777-200 reference vehicle.

Table 3: Large Twin Aisle Baseline and Advanced Tube-and-wing Parameters of Interest

	Units	FLOPS Model of the 777-200LR/GE90-110B	Advanced Large Twin Aisle Tube & Wing
Entry into Service		2006	2025
Takeoff Gross Weight	lb	768,000	574,000
Operating Empty Weight	lb	342,900	275,300
Payload	lb	118,100	118,100
Range	nm	7500	7500
Block Fuel	lb	279,800	162,600
Wing Area	ft^2	4605	3787
Wing Span	ft	212.6	204.8
Wing Aspect Ratio		9.8	11
Wing Loading	lb/ft^2	167	152
Cruise Mach #		0.84	0.84
Start of Cruise L/D		19	22.4
Start of Cruise SFC	lb/(lbf hr)	0.55	0.472
Max Thrust per Engine	lb	110,000	73,200

Note that the wing span and the wing area both have decreased, with a resulting wing aspect ratio of 11. The block fuel burn is estimated to be 162,600 lb, a 41.9% decrease compared to the reference vehicle. Figure 2 presents the waterfall chart, showing the relative contributions of each technology area to the overall 41.9% fuel burn reduction. The advanced engines represent the largest contribution at 14.5%, with the advanced materials and HLFC comprising 13.2% and 10.1% respectively. The riblets, ACTE, and subsystem technologies provide the final 4.1% of the total reduction.

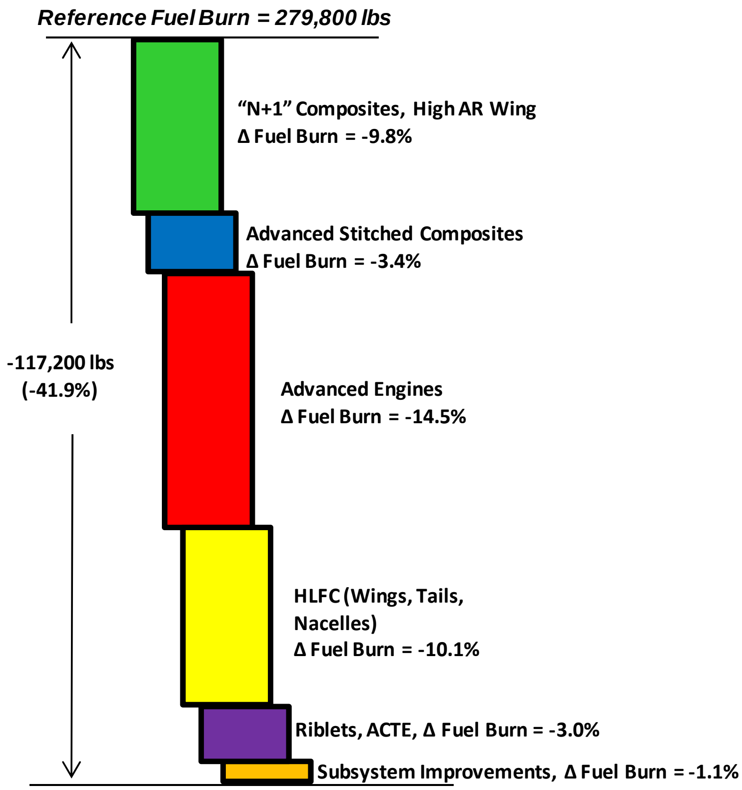

Figure 2: Advanced Large Twin Aisle Tube & Wing Waterfall Chart

3.3 Hybrid Wing Body, Large Twin Aisle Class

Following the procedures documented in Nickol [27], an HWB concept was developed for the large twin-aisle class (as shown in ref. 27, the HWB concept is attractive from a fuel burn perspective only at larger scales, so a 737 class HWB is not presented here). The 777-200 mission parameters discussed in section 3.2 were used to size the "HWB301". The centerbody sizing began with a cabin layout matched as closely as possible to the 777-200 cabin areas [26]. The 777-200 cabin geometry was used to obtain the required areas for passenger seating, aisle space, galley, lavatory, storage, cockpit, and crew rest. Figure 3 shows the 777-

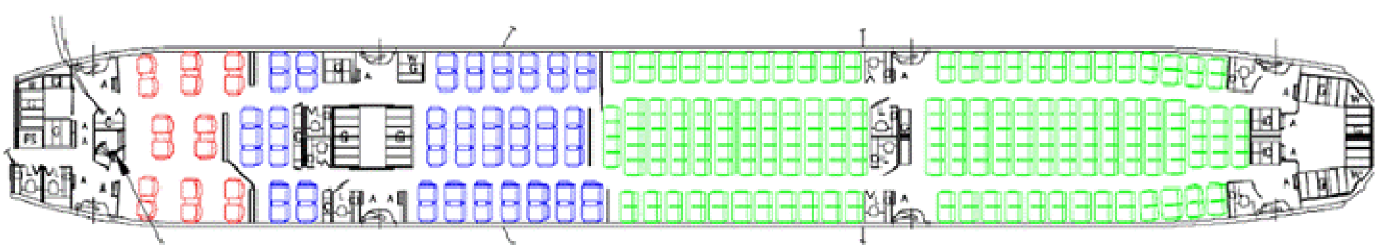

Figure 3: 777-200 cabin layout.

200 cabin layout, and Figure 4 the correlated HWB301 layout (dimensions in inches).

	Boeing 777 (ft2)	HWB301 (ft2)
Seating Area	1707.9	1553.7
Aisle	750.4	831.7
Galley	173.5	173.9
Lavatory	136.2	136.8
Cockpit	76.1	76.3
Wardrobe	35.8	39.9
Flt. Att. Seats	18	18.7
Crew Rest	83.7	81.4
Total Cabin Area	2981.6	2912.4
Total # of Exits	8	7
Total # of Middle Seats	85	115
Total # of Aisles	2	5

Figure 4: HWB301 cabin layout and associated area data (dimensions in inches)

The total cabin area of the HWB301 is within 2.3% of the 777-200. The HWB301 has one less exit than the 777-200; however, the HWB301 has five aisles compared to two for the 777-200, facilitating emergency egress. Five exits go through the bulkhead at the rear of the cabin and two through the leading edge near the front of the cabin. The HWB301 layout has 115 middle seats compared to 85 middle seats in the 777-200.

In order to move from the 2D layout to a 3D centerbody volume, several cabin cross sections were created. A pressurized cargo hold was also included with a volume equivalent to that available on the 777-200. Figure 5 shows several 2D cross sections for the HWB301. The cross section in the top half of Figure 5 shows the

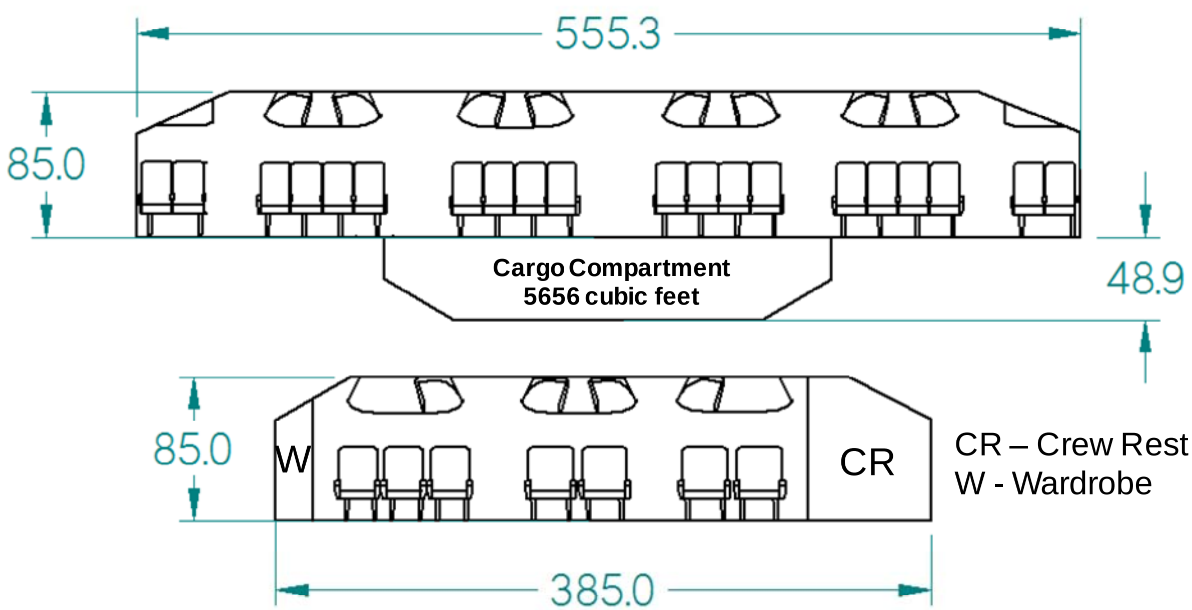

Figure 5: HWB301 cabin cross sections (dimensions are in inches)

main cabin area, the one on the bottom shows the first class area in the forward section of the centerbody, with crew rest and wardrobe spaces on the sides. The cabin height is ~7 feet, similar to the average 777-200 cabin height.

Using NASA’s rapid geometry modeling tool, Vehicle Sketch Pad (VSP) [28], a 3D centerbody was created utilizing the information from the 2D layouts. Airfoils were then tightly wrapped around the centerbody volume, with the objective of minimizing wasted space and balancing airfoil thickness and chord length. To maximize cruise L/D, wingspan is increased while minimizing wetted area. HWB configurations tend to optimize at higher wing spans than tube-and-wing concepts; however, the overall footprint of the HWB is attractive due to its significantly decreased length, relative to a tube-and-wing. Engines, fuel tanks, avionics, and landing gear were then integrated, and a longitudinal static stability analysis was completed. Details for the HWB301 concept can be found in reference 27.

Using the HWB301 vehicle model described above as the starting point, the N+2 technology suite was applied by utilizing the assumptions detailed in section 2.0 relative to an HWB concept. Table 4 shows the parameters of interest for the HWB301, as compared to the 777-200 reference vehicle and the equivalent mission advanced tube-and-wing.

Table 4: Large Twin Aisle Baseline, Advanced Tube-and-Wing, and HWB301 Parameters of Interest

	Units	FLOPS Model of the 777-200LR/GE90-110B	Advanced Large Twin Aisle Tube & Wing	HWB301
Entry into Service		2006	2025	2025
Takeoff Gross Weight	lb	768,000	574,000	541,100
Operating Empty Weight	lb	342,900	275,300	259,600
Payload	lb	118,100	118,100	118,100
Range	nm	7500	7500	7500
Block Fuel	lb	279,800	162,600	147,300
Wing Area	ft^2	4605	3787	9371
Wing Span	ft	212.6	204.8	240
Wing Aspect Ratio		9.8	11	6.1
Wing Loading	lb/ft^2	167	152	58
Cruise Mach #		0.84	0.84	0.84
Start of Cruise L/D		19	22.4	23.4
Start of Cruise SFC	lb/(lbf hr)	0.55	0.472	0.47
Max Thrust per Engine	lb	110,000	73,200	61,600

Note that the wing span of the HWB301 is 240 ft, compared with 205 ft for the advanced tube-and-wing concept. The cruise L/D of the HWB301 is 23.4 compared to 22.4 for the advanced tube-and-wing, contributing to the higher fuel burn reduction. The block fuel burn is estimated to be 147,300 lb, a 47.3% decrease compared to the 777-200 reference vehicle. Figure 6 presents the waterfall chart, showing the relative contributions of each technology area to the overall 47.3% fuel burn reduction.

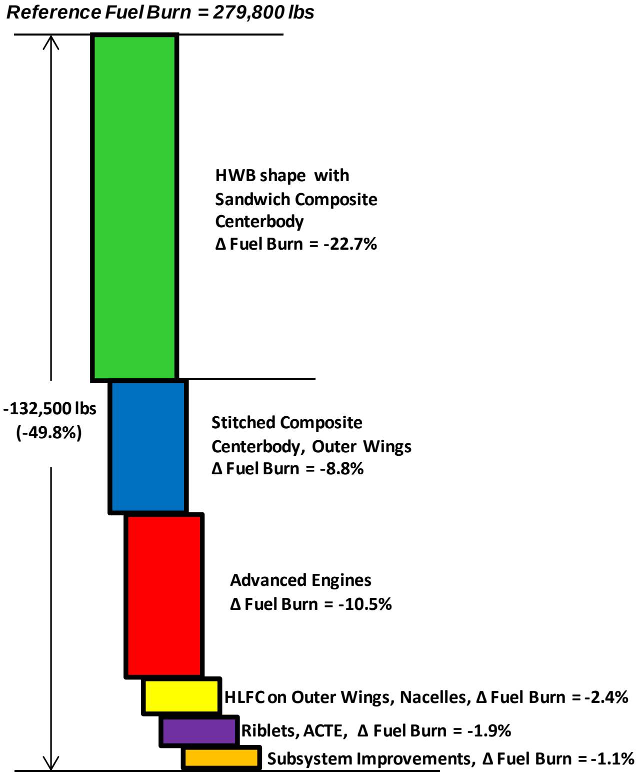

Figure 6: HWB301 Waterfall Chart

The advanced engines represent the next largest contribution at 10.5%, with the advanced materials and HLFC comprising 8.8% and 2.4% respectively. The HLFC technology is a much smaller contributor on the HWB due to the fact that it can only be applied on the outer wing sections, and covers a much smaller relative wing area than that on the advanced tube-and-wing concept. The riblets, ACTE, and subsystem technologies provide the final 3% of the total reduction. In addition to the potential fuel burn reduction, the HWB concept has the potential for significant noise reduction, due to the inherent engine shielding provided by the centerbody. Reference 24 provides analysis supporting the potential of the HWB concept to meet the N+2 noise goal. Figure 7 shows the final 3D solid model of the HWB301 concept.

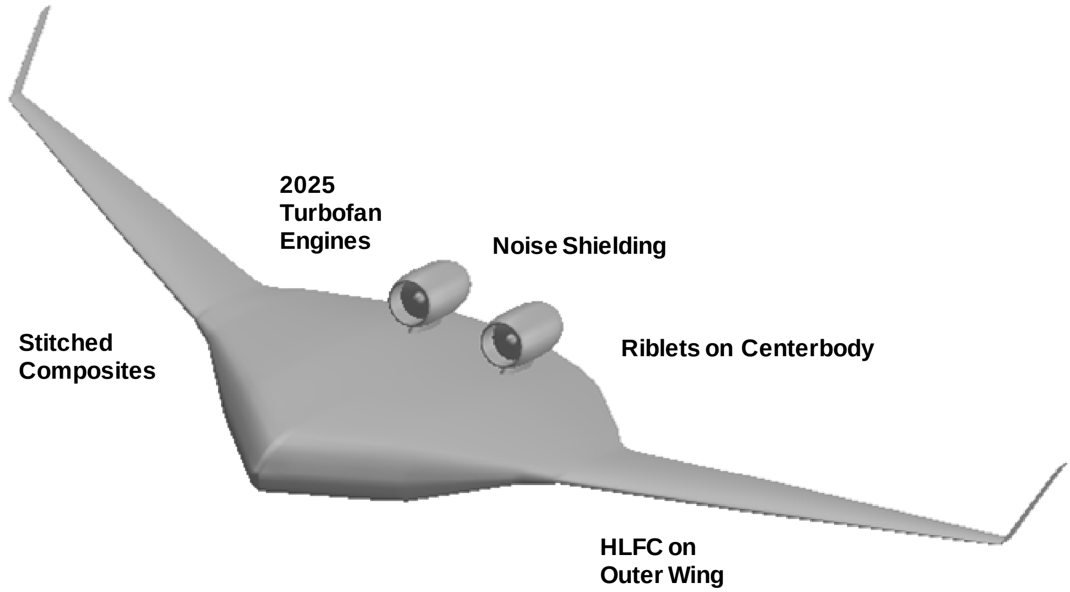

Figure 7: HWB301 Concept

4.0 METHODOLOGY FOR CONCEPT MATURITY ASSESSMENT

Both the advanced tube-and-wing and the HWB concepts require a suite of advanced technologies to deliver the estimated performance capabilities presented in the preceding section. However, the technical challenges of maturing and integrating these technologies can be a function of the configuration. For example, the HWB concept faces a technical challenge in the development of a flight weight non-circular, pressurized centerbody section, whereas the advanced tube-and-wing fuselage does not present a similar challenge. Conversely, the development of a high aspect ratio wing with acceptable aeroelastic behavior is a technical challenge for the advanced tube-and-wing, more so than the design of the HWB outer wing section. When decision makers are confronted with research & development investment choices, it is natural for them to ask for an assessment of the relative risks and benefits of the various advanced concepts that circulate in the conceptual design community. A methodology has been developed that combines several existing elements in a new way that yields a consistent approach for the relative benefit and maturity assessment of dissimilar advanced concepts. The following sections present this new methodology, and utilize the advanced tube-and-wing and HWB concepts as example cases to illustrate the application of the methodology.

4.1 Critical Technology Elements and RD^3

The first step is the identification of Critical Technology Elements (CTEs). The definition of a CTE is provided in the U.S. Department of Defense Technology Readiness Assessment deskbook [29] as follows:

> A technology element is "critical" if the system being acquired depends on this technology element to meet operational requirements (within acceptable cost and schedule limits) and if the technology element or its application is either new or novel or in an area that poses major technological risk during detailed design or demonstration.

The DoD deskbook goes on to provide a list of questions that can be asked to help identify CTE candidates:

1. Does the technology have a significant impact on an operational requirement, cost, or schedule?
2. Does the technology pose a major development or demonstration risk?
3. Is the technology new or novel?
4. Has the technology been modified from prior successful use?
5. Has the technology been repackaged such that a new relevant environment is applicable?
6. Is the technology expected to operate in an environment and/or achieve a performance beyond its original design intention or demonstrated capability?

A technology is identified as a CTE if the answer to the first question is "yes", and if the answer to at least one of the remaining questions (2 through 6) is also "yes". Candidate technologies can range from discrete hardware or software items to integration approaches or other configuration unique challenges.

After a list of CTEs is identified, the Research and Development Degree of Difficulty (RD^3) can be assessed. Mankins [30] provides definitions for five levels of difficulty summarized below in Table 5.

Table 5: Mankins Research & Development Degree of Difficulty Levels

$R\&D^3$ Level	Definition
I	A very low degree of difficulty is anticipated in achieving research and development objectives for this technology. Probablity of Success in "Normal" R&D Effort 99%
II	A moderate degree of difficulty should be anticipated in achieving R&D objectives for this technology. Probablity of Success in "Normal" R&D Effort 90%
III	A high degree of difficulty anticipated in achieving R&D objectives for this technology. Probablity of Success in "Normal" R&D Effort 80%
IV	A very high degree of difficulty anticipated in achieving R&D objectives for this technology. Probablity of Success in "Normal" R&D Effort 50%
V	The degree of difficulty anticipated in achieving R&D objectives for this technology is so high that a fundamental breakthrough is required. Probablity of Success in "Normal" R&D Effort 20%

Reference 30 provides more detailed definitions; however, the approach is relatively straightforward and each CTE should be characterized by a RD^3 score, one thru five, without undue effort. The scoring can be done in a continuous manner, that is, if the assessor feels that a particular CTE falls between level 2 and level 3, a score of 2.5 may be assigned. The RD^3 scores are then averaged to determine an overall RD^3 value.

4.1.1 Large Twin Aisle Advanced Tube-and Wing

Figure 2 is the waterfall chart for the advanced tube-and-wing concept in the large twin aisle class. The technologies that constitute this waterfall chart are good candidates to consider for classification as CTEs. The advanced UHB engine is the largest enabler for the ERA metrics, considering fuel burn, noise, and emissions. Numerous technologies are associated with the UHB engine; however, the entire engine system can be considered a CTE for this higher level assessment. The HLFC system, advanced composites, and high aspect ratio wing with ACTE technology can also be categorized as CTEs. For each of the CTEs, a TRL value is assigned, based on the TRL definitions provided by Mankins in reference 2. The goal of ERA is to advance the critical technologies to a TRL level of 6. Therefore, for the purposes of ERA, a fully mature technology is defined as level 6. RD^3 values are also assigned for each CTE. A concept maturity index (CMI) is then found by summing the current TRLs for each CTE and dividing by six times the total number of CTEs. In this case, since there are four CTEs, the divisor would be 6 x 4 = 24. Table 6 summarizes the

Table 6: CTE, CMI and RD^3 Summary for LTA Advanced Tube-and-Wing Concept

Critical Technology Elements	Current TRL	RD^3
Advanced UHB Engine Technology for Low SFC, Noise and Emissions	4	2
Hybrid Laminar Flow Control	4	2
Advanced Composite Materials and Structures	4	2
High Aspect Ratio Wing with Load Alleviation	3	2
Sum	15	8
CMI and Average RD^3	0.63	2

CTEs and the resulting CMI and RD^3 estimates for the advanced LTA tube-and-wing concept.

4.1.2 HWB301

For the case of the HWB concept, several CTEs are common with the advanced tube-and-wing, such as the UHB engine, and the HLFC system. However, there are unique challenges associated with the HWB. The propulsion airframe integration approach is a challenge due to the unconventional engine positioning and concerns relative to engine operability. The structures challenge is unique due to the requirement for the non-circular, pressurized centerbody. Finally, the HWB stability & control and flight control systems are unconventional, and qualify as another CTE. Table 7 summarizes these CTEs and the resulting CMI and RD^3 estimates for the HWB301 concept. Note that since five CTEs were identified, a fully mature concept, using the ERA definition, would have a TRL sum of 30.

Table 7: CTE, CMI and RD3 Summary for the HWB301 Concept

Critical Technology Elements	Current TRL	RD^3
Propulsion Airframe Integration / Engine Operability	2	3
Advanced UHB Engine Technology for Low SFC, Noise and Emissions	4	2
Composites/Structures for Non-circular Pressurized Centerbody	4	3
Stability & Control and Flight Control Systems	3	2
Aerodynamics, Hybrid Laminar Flow Control and Riblets	4	2
Sum	17	12
CMI and Average RD^3	0.57	2.4

4.2 Combined Benefit Estimates

The preceding discussion has focused on the challenge and difficulty of maturing and integrating technologies to enable two advanced concepts. An equally important consideration is the expected benefit of successfully maturing and integrating these technologies. As shown in Table 1, the ERA project has defined these benefits to be reduced fuel burn, noise, and emissions, and has provided metrics of success in each of these areas. The three areas are considered equally important in the context of the ERA program, and are therefore equally weighted. For the N+2 timeframe, if an advanced concept met all of these goals simultaneously, then 100% of the targeted benefit would be met. More commonly, the estimated performance will fall short in one or more areas, since these goals were intended to be very difficult to meet in order to push technology development. The relative achievement of each goal can be combined with the weighting factors and summed, resulting in a benefit index between zero and one. The benefit index would be zero if there were no estimated improvements relative to the baseline and one if all goals were met. Scores in between can provide a benefit estimate for that particular advanced concept. This formulation assumes that the benefits change in a linear manner. This assumption is not valid for the noise metric, since the change in noise performance follows a logarithmic function. Attempting to combine logarithmic and linear functions introduces unwanted and unnecessary complexity. For the purposes of this method, we can treat the noise performance metric in a linear manner similar to the other metrics. Given that we consistently use this approach for each advanced concept, the comparisons will be consistent and valid. In the following two sections the benefit index is derived for the advanced concepts to provide examples of this approach.

4.2.1 Large Twin Aisle Advanced Tube-and-Wing Concept

For the LTA advanced tube-and-wing concept, the predicted fuel burn reduction was 41.9%. Figure 15 in reference 24 shows that the expected noise performance for this type of configuration is 29 EPNdB cumulative below the Federal Aviation Administration (FAA) Stage 4 certification level (the goal is a 42 EPNdB cumulative reduction below Stage 4). The cumulative qualifier refers to the summation of sideline, approach and flyover noise, which are the three different noise measurement points defined by the FAA to support noise certification. The emissions goal is being addressed through the design of advanced engine combustors, as presented by Bulzan and Lee [31]. It is assumed that these advanced combustor designs will reach the emissions reduction goal in the N+2 timeframe.

Given the estimated benefits in each of the three areas of interest, the benefit index can be derived. Applying equal weighting to each of the three goals, and assuming linear behavior, the benefit index for this concept is 83%. Table 8 shows the derivation of this value.

Table 8: Derivation of the Benefit Index for the LTA Advanced Tube-and-Wing Concept

		LTA Advanced Tube & Wing	ERA Goal	% of Goal Achieved	ERA Weighting Factor	Weighted % of Goal Achieved
Fuel Burn	(% reduction relative to 777)	41.9	50	0.84	0.33	0.28
Noise	(margin to Stage 4)	29	42	0.69	0.33	0.23
Emissions	(% reduction relative to CAEP 6)	75	75	1.00	0.33	0.33
					Sum	**0.83**

4.2.2 HWB301

For the HWB301 concept, the predicted fuel burn reduction was 47.3%. Figure 15 in reference 24 shows that the expected noise performance for this type of configuration is 42.2 EPNdB cumulative below the FAA Stage 4 certification level. The LTO emissions performance is assumed to be identical to the tube-and-wing concept since the same engine and combustor technology will be utilized. Applying equal weighting to each of the three goals, and assuming linear behavior, the benefit index for the HWB301 is 97%. Table 9 shows the derivation of this value. Note that no credit is given for exceeding any of the goals. In this case, the noise benefit, although exceeding the goal, was rounded down to match the goal value. This is done to encourage the development of a balanced concept that does not favor one metric over the other. Giving credit for exceeding one of the goals at the expense of another will mask the shortfall in the combined benefit index.

Table 9: Derivation of the Benefit Index for the HWB301 Concept

		HWB301	ERA Goal	% of Goal Achieved	ERA Weighting Factor	Weighted % of Goal Achieved
Fuel Burn	(% reduction relative to 777)	47.3	50	0.95	0.33	0.31
Noise	(margin to Stage 4)	42	42	1.00	0.33	0.33
Emissions	(% reduction relative to CAEP 6)	75	75	1.00	0.33	0.33
					Sum	**0.97**

4.3 Visualization of Concept Maturation

Once an initial assessment of the CMI, RD^3, and benefit index is completed, the results can be utilized to support the development of a research program designed to mature the concept of interest. As the research program progresses, periodic re-assessments can be completed to track the concept's maturity and benefit progression over time. Figure 8 shows a graphical format with twin vertical axes; the left vertical axis shows the CMI, and the right vertical axis the benefit index.

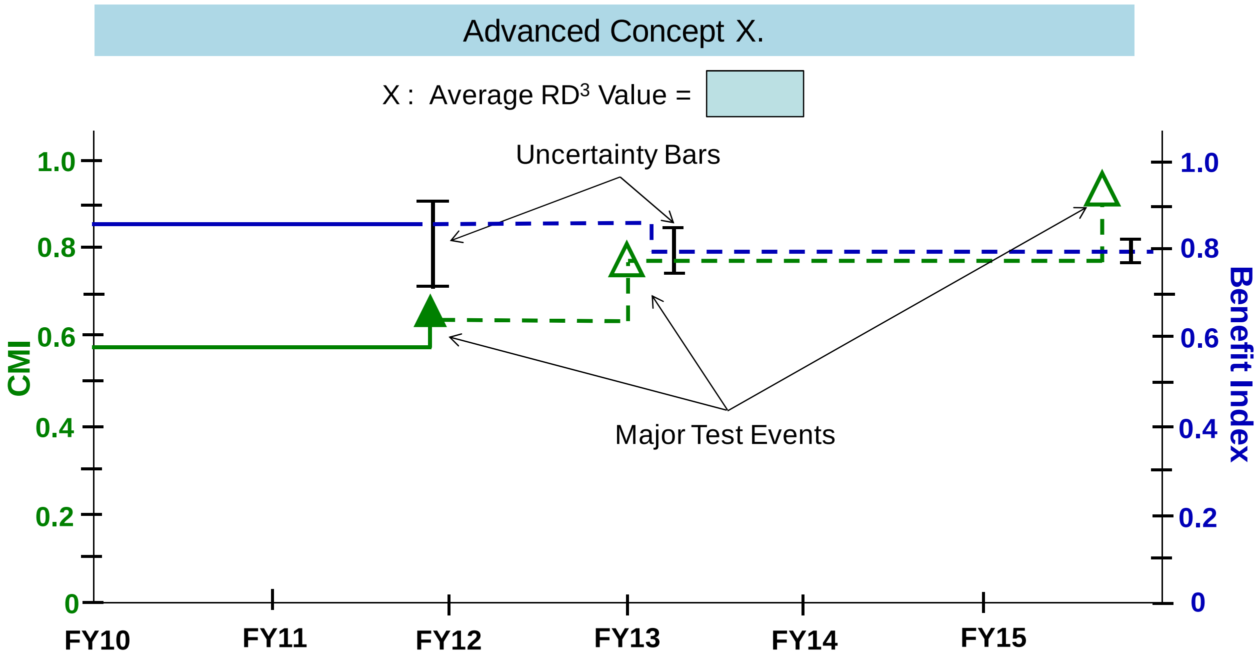

Figure 8: Example Format for Concept Maturation Roadmap

The horizontal axis is time, and the average RD^3 value is also included for reference. Although the analyses presented in this paper were deterministic, uncertainty bars are also included in this graphical format to illustrate the results of probabilistic analyses, if available. Generally, lower CMI scores will correlate with larger uncertainty bands for the benefit index. As time progresses and the technology maturation program executes, one would expect to see the CMI score increase, reflecting increasing TRLs for the CTEs. The associated uncertainty bands would shrink, and the benefit index would be updated to account for the results of the maturation efforts. In some cases, as the technology matures and the uncertainty bands shrink, the benefit index will decrease due to the replacement of optimistic assumptions with test data that accounts for "unknown unknowns" that, unfortunately, usually degrade performance. In rare cases, the benefit index may increase over time due to the discovery of previously unknown synergies or other unexpected performance increases.

4.3.1 Large Twin Aisle Advanced Tube-and-Wing Concept

Figure 9 shows a notional roadmap chart for the LTA advanced tube-and-wing concept. The point in FY12 shows the starting CMI value of 0.63 (left axis green font), and benefit index of 0.83 (right axis, blue font). An overall concept RD^3 value of 2.0 is also displayed, indicating a moderate degree of difficulty. A notional technology maturation program is executed over the next six years, and notional changes to these values are depicted. As the program progresses, this roadmap chart can be updated to track progress.

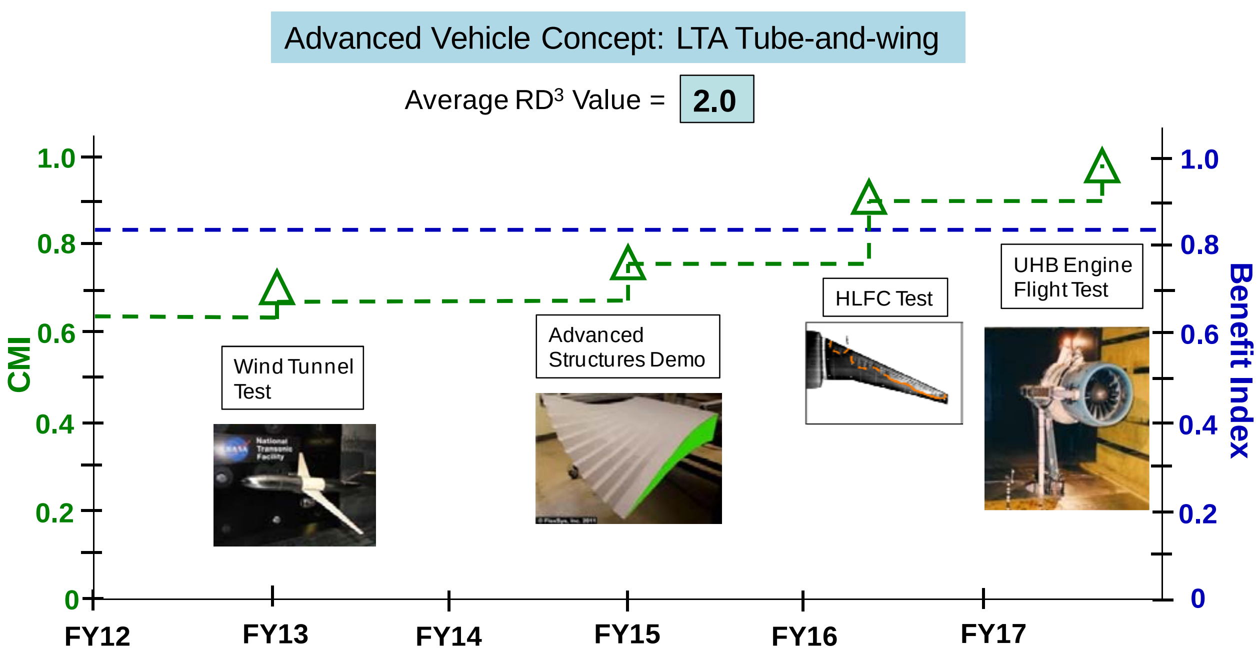

Figure 9: Notional Roadmap for LTA Advanced Tube-and-Wing Concept

4.3.2 HWB301

Figure 10 shows a notional roadmap for the HWB301 concept. Note that the starting CMI is less than that for the advanced tube-and-wing concept, indicating that the HWB301 concept will require more technology maturation. In addition, the RD^3 value is higher, indicating a more difficult technology maturation program will be required relative to the advanced tube-and-wing concept. However, the benefit index is greater for the

HWB301, illustrating its greater performance potential compared to the tube-and-wing concept.

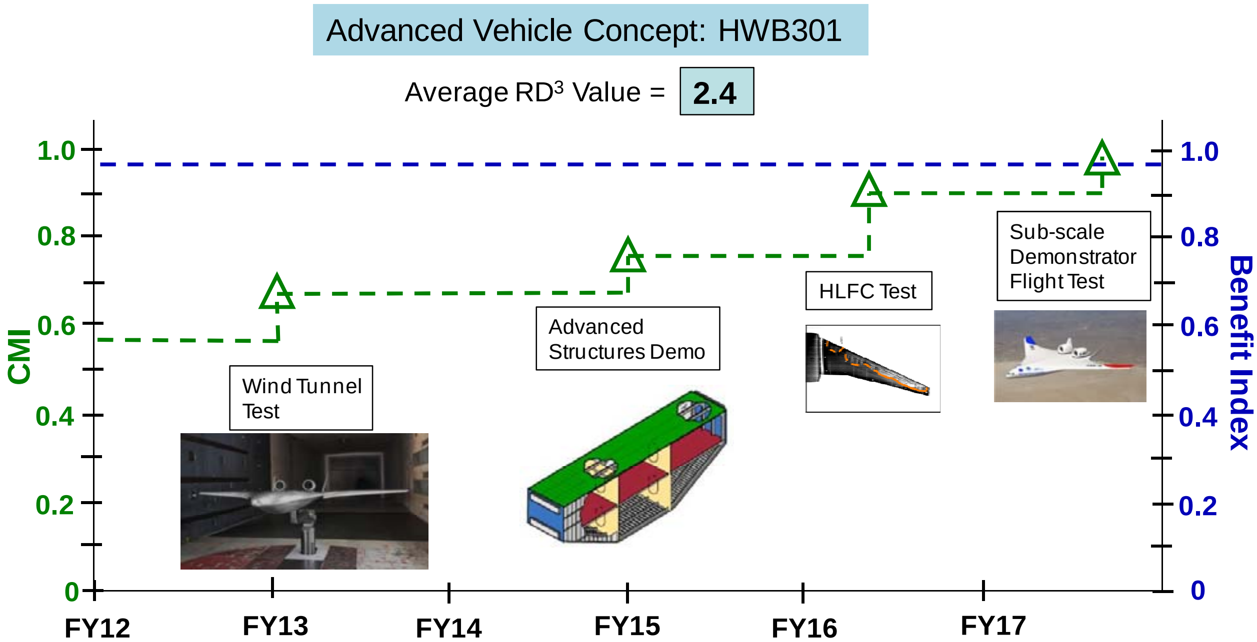

Figure 10: Notional Roadmap for the HWB301 Concept.

5.0 CONCLUSION

Significant reductions in the fuel burn of subsonic transports are possible through the introduction of advanced technologies and concepts in the 2025 timeframe. Relative to today's aircraft, advanced tube-and-wing concepts have the potential to burn 42-44% less fuel, and a large HWB concept has the potential for a 47% reduction, along with very significant reductions in noise. The critical technologies are propulsion, materials and structures, laminar flow control, and the HWB configuration itself. The ability to successfully integrate these technologies is also a key element, and should not be underestimated.

NASA's ERA goals are very aggressive, and achieving them simultaneously will require innovative concepts and highly integrated approaches. Fortunately, there appears to be no shortage of ideas and unconventional thinking from the aircraft advanced design community. The CMI index presented in this paper can be utilized to quantify the relative maturity of various advanced concepts, and track that maturity as it evolves over the course of a technology maturation effort. The roadmap chart format, examples of which are presented in Figures 9 and 10, can be utilized to present the indices of interest as a function of time, including the reduction in uncertainty surrounding the benefit index as the critical technology elements mature.

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