N+3 Advanced Concept Studies for Supersonic Commercial Transport Aircraft Entering Service in the 2030-2035 Period

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Abstract

Boeing, with Pratt & Whitney, General Electric, Rolls-Royce, M4 Engineering, Wyle Laboratories and Georgia Institute of Technology, conducted a study of supersonic commercial aircraft concepts and enabling technologies for the year 2030-2035 timeframe. The work defined the market and environmental/regulatory conditions that could evolve by the 2030/35 time period, from which vehicle performance goals were derived. Relevant vehicle concepts and technologies are identified that are anticipated to meet these performance and environmental goals. A series of multidisciplinary analyses trade studies considering vehicle sizing, mission performance and environmental conformity determined the appropriate concepts. Combinations of enabling technologies and the required technology performance levels needed to meet the desired goals were identified. Several high priority technologies are described in detail, including "roadmaps" with risk assessments that outline objectives, key technology challenges, detailed tasks and schedules and demonstrations that need to be performed. A representative configuration is provided for reference purposes, along with associated performance estimates based on these key technologies.

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1.0 Executive Summary

This is the final report by Boeing to NASA under Contract NNL08AA16B "Advanced Concept Studies for Supersonic Commercial Transport Aircraft Entering Service in the 2030-2035 Period", Paragraph 11 Deliverables/Documentation Requirements. It summarizes the work and findings, with non-proprietary information in the main report, and proprietary information in appendices.

NASA's current projects have been aimed at developing tools and technologies that will help supersonic aircraft to enter service in N+1 (2012-15) and N+2 (2018-20) timeframe. Boeing supports NASA's objective to identify and assess advanced vehicle and propulsion concepts, as well as corresponding technologies, for a new generation of supersonic commercial aircraft which could be in service by the 2030-35 timeframe ("N+3"). NASA's vision is that this new generation of commercial aircraft will extend the benefits of supersonic travel to a potential market with a broader segment of the public, carrying a larger number of passengers to improve economic viability, while meeting the increasingly stringent environmental requirements in noise and emissions anticipated being in place in 2030-35 timeframe.

The specific objective of the NASA N+3 study was to methodically identify and evaluate conventional and unconventional commercial supersonic configurations including closely integrated aircraft/propulsion concepts and prioritize technology developments needed to surmount future barriers. Results are supported by analysis and detailed assessment of the pros/cons of different approaches. This information was used to identify technology and prediction methods capability gaps, technology requirements, risks and their mitigation approaches, and to develop N+3 technology development/validation/maturation plans and roadmaps.

The initial effort under this contract was aimed at defining the design goals and metrics based on market conditions and NextGen requirements for supersonic aircraft entering service in the 2030-2035 time period. The majority of effort was devoted to defining/evaluating configurations and engine architectures, defining/evaluating enabling technologies, and prioritizing the technologies. Roadmaps of the most promising technologies and technology combinations were prepared and reported in February 2010.

Configuration ideas were distilled from the initial effort of the entire N+3 team to collect configuration and technology ideas. Forecasts of engine performance and design features by Rolls-Royce, Pratt & Whitney, and General Electric enabled initial screening of several candidate configuration and engine combinations. Technologies were identified which would enable more slender and flexible airframes, reduce engine noise, lower sonic boom, and provide improved drag and fuel consumption. Ultimately, the "Icon-II" Boeing's recommended configuration and reference engine were developed, taking advantage of expected configuration enabling technologies. Performance benefits including a 5% reduction in operational empty weight and 10% reduction in cruise drag that come from application of various advanced technologies were assumed in sizing this "concept plane". The "Icon-II" represents a low boom supersonic airliner concept of the 2030-2035 time period with 120 passengers and "trans-Atlantic+" range.

Section 2 of this report contains the Boeing forecast of the market and regulatory environment that a supersonic airliner may face in the "N+3" timeframe, and design goals that might make it feasible. The material also appears in a separate report delivered in January 2009. It concludes that a potentially viable percentage of future travelers would be willing to pay a fare premium to save time, and this could constitute an attractive business opportunity for airlines and manufacturers of future supersonic-capable aircraft. Such aircraft would require 4000-5000nmi range capability, reasonably high fuel efficiency and flexible operational characteristics in order to be economically competitive. Low emissions, noise & sonic boom will also be essential.

Section 3 describes our methodical approach to initially identifying and evaluating promising configuration directions and technological innovations. It employed a traditional brainstorming workshop, and the Interactive Reconfigurable Matrix of Alternatives (IRMA) tool at Georgia Tech to help guide the notional

application and integration of ideas. The activity identified several specific categories of configurations and technology combinations that served as the point of departure for more detailed studies.

Section 4 presents brief, non-proprietary statements from General Electric, Pratt & Whitney and Rolls-Royce regarding their forecasts of emerging engine technologies, features and performance in the N+3 timeframe. Proprietary appendices A, B, C & D contain more extensive proprietary discussion and supporting data, organized in parallel with the overall report. The proprietary Boeing Appendix A includes figures comparing engine options from all three companies, so it should not be shared with them.

Section 5 is a preliminary scoping of the requirements for an N+3 engine, based initially on the nominal aerodynamic performance and weights of the 765-072B aircraft from N+2 as a "point-of-departure". It employed the MDAO tools and methods from N+2, and provided both the nominal requirements expected for the engine, and a preliminary look at the overall vehicle performance that might be expected during the remainder of the study. This part of the study also illuminated some areas for improving the propulsion and propulsion integration through advanced technology and innovative configurations. Proprietary Appendix A presents the proprietary data and discussion associated with Section 5.

Section 6 describes the configuration and more detailed engine assessments that reveal promising avenues of technology and configuration development, and areas of greatest challenge. With some assumptions about advanced technologies and innovative configurations, some measure of their significance to developing an N+3 aircraft was gained. It includes a forecast of achievable sonic boom levels, and a preliminary assessment of the system-wide impact of supersonic operations on emissions and within the NextGen ATC framework. Proprietary data and discussion from Section 6 appears in proprietary Appendix A.

Section 7 discusses the methodology and key non-proprietary results of the technology roadmaps that are offered to guide technology development in the coming decades. Proprietary discussion and roadmaps for the propulsion system from GE appear in Appendix B, from Pratt & Whitney in Appendix C, and from Rolls-Royce in Appendix D. Airframe technology roadmapping is discussed in proprietary Appendix A, and the corresponding roadmaps are in the proprietary Appendix F. These roadmaps were discussed and presented separately in February 2010.

Section 8 presents overall N+3 conclusions.

2.0 Design Requirements (Task 3.1 & 3.2)

2.1 Market Conditions (Task 3.1)

Several key considerations are behind the market condition forecast. First is the potential market size and economic benefit. It will be a global market that depends on the world population and the global economy. Political & economic freedoms, personal & commercial financial resources, and the propensity of individuals and business to travel will dictate the demand. An international aerospace project of the future faces uncertain availability of resources—both raw materials and fuel—and must promise profitability to a variety of stake-holders worldwide.

The second key consideration is fuel prices and their volatility. Along with their commodity price and sustained availability comes an environmental impact related cost that will likely appear in the form of taxes and carbon offsets.

The final key consideration is the environment, both in terms of meeting future strict regulations, and in terms of doing the right thing for our planet. Public concerns over NOx, stratospheric water vapor addition and CO_2 emissions will argue for fuel-efficient airplanes and lower cruise altitudes (maximum 55,000ft). Contrail persistence has also become a concern, though this should not present problems at the altitudes which supersonic aircraft will be operating. Airport and community noise will be a challenge for all airplanes of the future--- more so for supersonic aircraft which require very high exhaust velocities and low effective bypass ratio at cruise. Minimizing sonic boom is an especially tough technical challenge, particularly if the boom loudness of a airliner of significant size and weight (over 150,000lbs climb weight) is to be reduced to a level acceptable for over-land supersonic cruise, at least in designated corridors.
The degree of technological success toward fuel efficiency, low noise, low emissions, and low sonic boom will to a large degree determine the ultimate viability in the future marketplace.

2.1.1 Potential Market

One estimate of the potential size of the supersonic passenger market can be made from Figure 2.1.1. Using qualitative indices that measure a passenger's willingness to pay versus the schedule and service quality he/she demands, the data shows a relatively small segment of the overall market amenable to premium airline ticket prices for supersonic travel—initially only frequent business travelers (the "Road Warriors"), and some portion of those currently using business jets. In the upper right are travelers who are willing to pay to reduce overall trip time by avoiding ordinary airport procedures. These parameters were identified in the N+2 market requirements study and carry over to the N+3 time period. One difference is that in the N+3 timeframe, a portion of the premium traffic may be already carried by supersonic (or high subsonic) business jets. Also, continued technology improvements may increase the payload-range capability of supersonic airliners and may allow supersonic over-land flight, potentially improving the market potential and lowering the price of flights for time-critical travel. If successful, this trend could potentially also attract some passengers from the full-fare economy and regular business travel price segments.

Typically, under today's conventional business model, a route with demand of at least 100 passengers per day allows an airline to justify a direct flight. Assuming supersonic flights could corner 10% to 20% of a given market, then only markets with demand above about 1000 passengers per day would support supersonic service. In Figure 2.1.2 are one recent month's worth of passenger demand (data points) versus distance of the flight, along with the number of markets (curve, right-side vertical axis) that represents. The target market is shown by the smaller oval. With the Boeing Current Market Outlook forecast as a guide, demand within this target should increase substantially by the N+3 timeframe, but it will still be a relatively small segment of the entire market. If the vehicle concept is flexible enough to also operate at lower cost and speed, the market could grow to about the area within the larger bounds (parallelogram). Somewhere between 2000nmi and 4000nmi is the shift from domestic to intercontinental ranges, and demand in this segment may not grow significantly. A similar dataset, but for long-range flights only, is

plotted in Figure 2.1.3, showing the large amount of premium airline travel just under 4000nmi, then a gap between 4000nmi and 5000nmi, and a second large group between 5000nmi and 7000nmi. It will therefore be essential for a supersonic transport to initially serve this demand for 4000nmi (+/-) range, but longer ranges should be an objective as enabling technologies mature in the N+3 (and beyond) time frame.

A poll of corporate travelers concludes that schedule is their first consideration when choosing flights. Results from that poll are shown in Figure 2.1.4, illustrating that many factors have an influence, but none as large as schedule. Aircraft type seems to have the least influence of all, but that might not be true for a unique supersonic design, especially with the recognition that "schedule" also might be served by flying faster. Historical demand for seats on the Concorde in spite of very high ticket prices is evidence of that impact. A relatively efficient supersonic aircraft, particularly one able to maintain high speed over land, might offer a segment of the market the ultimate in time-saving, point-to-point service with price that is reasonably close to traditional subsonic service. Depending on the route, it might be possible for a given aircraft (single tail number) to provide departures per day.

The argument for setting trans-Atlantic as a minimum design range is made in Figure 2.1.5, where the New York to London market stands out as having by far the largest current demand for full, business and premium fare travel. Several other trans-Atlantic and similar range markets are significant. But high utilization of a supersonic airplane becomes an issue at these ranges on east-west routes. While the airplane would be capable of flying the route several times per day, travelers might not be eager to adjust to less convenient departure or arrival times than the current subsonic fleet already supports. So efficient utilization of a long range supersonic airplane might include having the airline fly a given tail number aircraft on a variety of ranges, payloads, routes, and even speeds throughout the 24-hour day to capitalize on the operational productivity.

Actual one-way fares paid in the 3rd quarter of 2006 for NYC-LON flights are shown in Figure 2.1.6. The data demonstrate that about 75 passengers per day paid over $2000 one-way fare then, and some pay up to $5000. This was of course after the retirement of Concorde which charged substantially more for a faster supersonic flight than these premium subsonic fares. By the time of N+3, this market will have grown, and several others are expected to be substantially larger than today. A straightforward lesson from Concorde was that offering supersonic service generates demand for it, in excess of the latent demand for premium fare travel.

If additional technological successes can further improve eventual range capability, reduce fuel burn costs, and provide operational and speed flexibility (including low boom design), additional viable markets could be opened and ticket prices reduced to be more competitive with conventional subsonic flights.

2.1.2 Fuel Price

The availability of petroleum-based fuels will likely fall through the N+3 timeframe, but be replaced in part or in whole by synthetic or biological sources. But, regardless of the source, the price of fuel will most likely rise, and probably disproportionately fast when compared to other expenses incurred to manufacture, own and operate an airplane. This will place even greater importance on keeping the efficiency in seat-miles per pound of fuel (the primary performance Figure of Merit, "FOM", for N+3 aircraft) high for any aircraft of the future. The infusion of N+3 technology shows the potential to minimize the incremental fuel cost compared to subsonic aircraft to the extent that operations would still be profitable at reasonably low ticket prices.

2.1.3 Environmental Constraints

Mounting regulation of noise and emissions could render a non-compliant aircraft obsolete before it flies, so noise and emissions are critical design requirements. Taking an example from the HSCT/HSR program of the 1990's, goals then were
- No measureable adverse impact on stratospheric ozone.
- Compliance with then-year airport and community noise standards.
- No environmental damage from sonic booms.
- Compliance with all then-year requirements for low and high altitude aircraft engine emissions (including airport NOx, CO2, …).

Additionally, if transonic/supersonic flight over land is to be viable, sonic booms must not only avoid "environmental damage" to animals, humans, and property, but also be reduced in intensity to a level that the vast majority of the over-flown population agrees is not annoying or disruptive.

Fundamentally, minimizing weight and drag (required thrust) are the most important ways to minimize community noise and emissions, including CO2. But advancements in controlling the airflow and turbo-machinery noise, improved combustor technology, and shaping the aerodynamics to minimize sonic boom will be essential to meeting the ever-more challenging goals facing an aircraft designed for the N+3 time.

2.2 Design Goals (Task 3.2)

Based on the marketing assessment, and results of the N+2 studies for 2025 airplanes [1], a set of general design goals, guidelines and assumptions were initially established internally by Boeing to get the N+3 studies started. These are listed below:

- 100-150 passengers in 2-class arrangement with baseline interior (target 130)
- 1.6-1.8 Mach cruise speed
- 55,000ft or lower cruise altitude (for emissions).
- 4000nmi supersonic range (trans-Atlantic+) with 6000nmi range target for Asian routes
- 0.95 Mach or lower below 39,000ft for ATC margins
- Subsonic below 41,000ft for ATC margins
- 3.8 seat nmi/lb fuel (0.26 lb/seat/nmi) or better supersonic fuel burn
- Sonic boom as *low as practical* for an aircraft of this size
    - o Less than Concorde over water
    - o Consider "threshold Mach" over land if very low boom levels cannot be achieved
    - o Consider "boom softening" (e.g. 0.7psf) near coastal areas & and along over-land corridors if very low overpressures appear infeasible with a realistic configuration

The guidelines were then combined with the suggested design goals by NASA shown below:

- Sonic Boom: 65-70 PLdB low boom flight, 75-80 PLdB "unrestricted" flight over water.
- Airport Noise: 20-30 EPNdB cum below Stage 3
- Cruise Emissions: NOx 5g/kg fuel and particulate & water vapor mitigation
- Cruise Speed: Mach 1.3-2.0 low boom flight and unrestricted flight
- Range: 4000-5500 n.mi.
- Payload: 100-200 passengers
- Fuel Efficiency: 3.5-4.5seat nmi/lb fuel

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[1] N+2 Supersonic Concept Development & Systems Study, July 2009, final report to NASA

Using the above information and the results of the future market assessment, several conclusions were drawn to use as guidance for the remainder of the engineering activity associated with the vehicle design. The general conclusions are shown in the left side of the table 2.2.1. Based on the conclusions shown, the engineering guidelines as listed in the right side of the table were used for the vehicle design work.

2.3 Representative Program Development Schedule

To develop the technology roadmaps discussed later in this report, a representative timeline leading to the entry-into-service ("EIS") date of 2035 was required to encourage developmental milestone consistency across all study participants. The one developed and used in this study is shown in Fig 2.3.1. This timeline is a generic version of development and certification histories typical of recent commercial airliners. The chart also shows a notional set of certification and regulatory milestones relating to supersonic aircraft noise and associated "readiness levels".
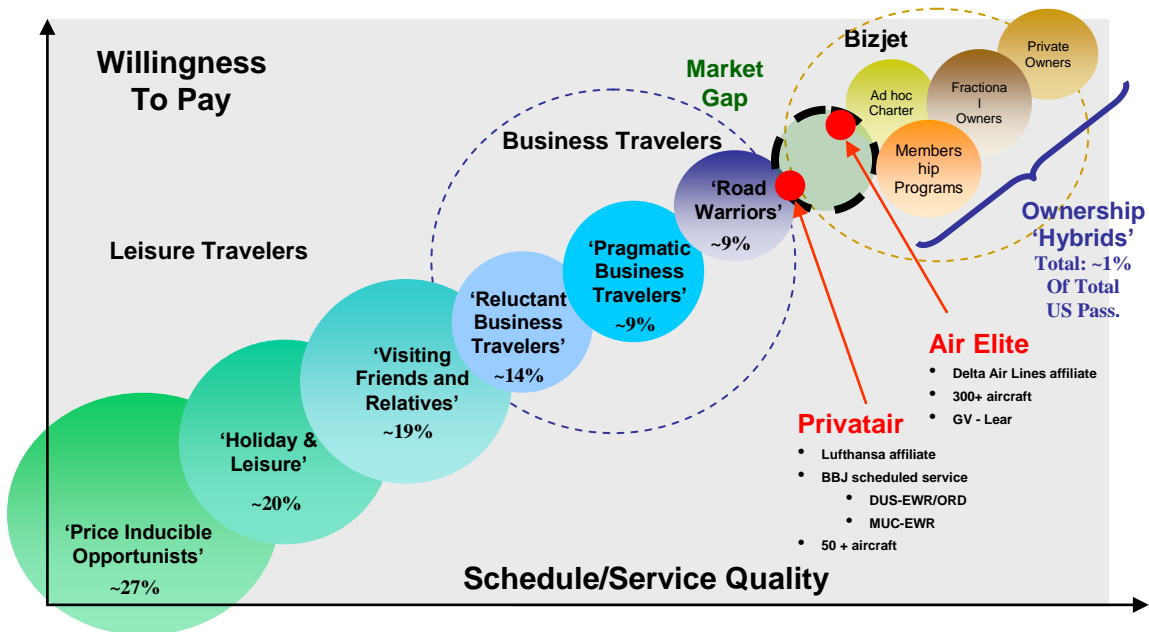
Figure 2.1.1 Willingness to pay vs schedule (and quality) demanded by customers.
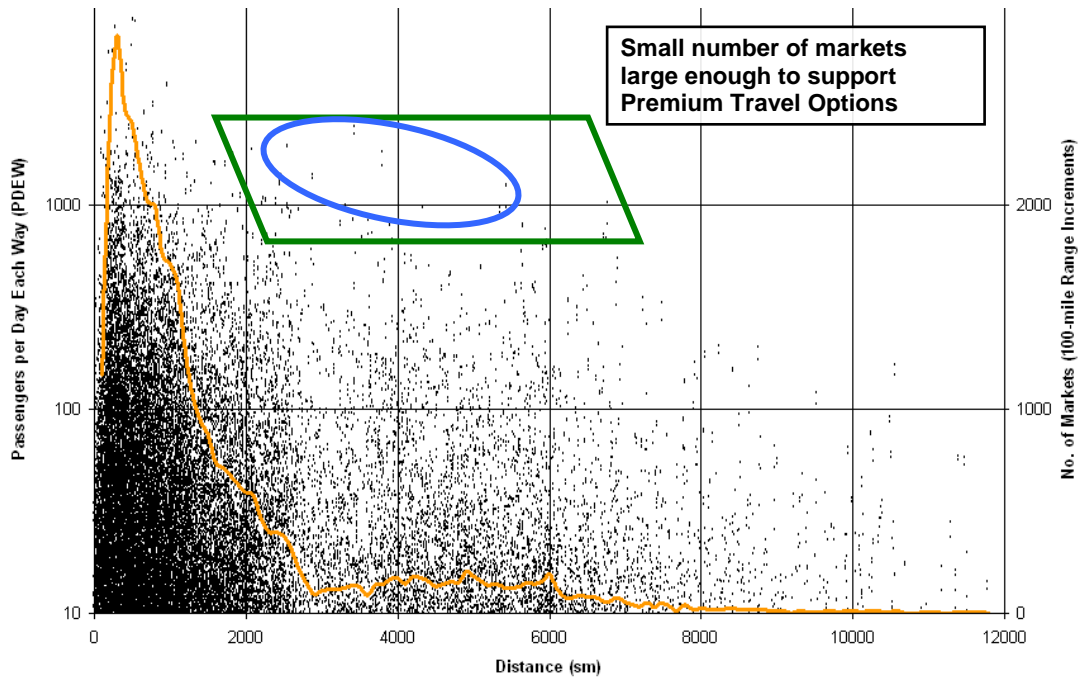
Figure 2.1.2 Measure of one recent month's demand (points) and number of markets served (curve) versus distance of a trip. Blue oval is target, green area is potential if cost & speed are flexible.
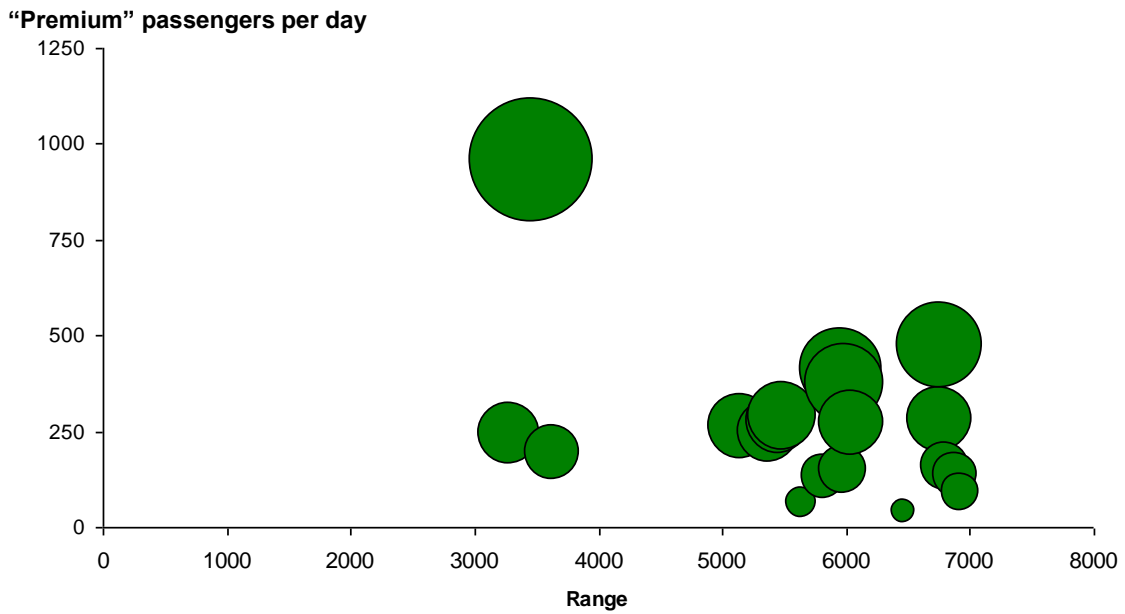
Figure 2.1.3   Number of premium passengers per day, versus range.
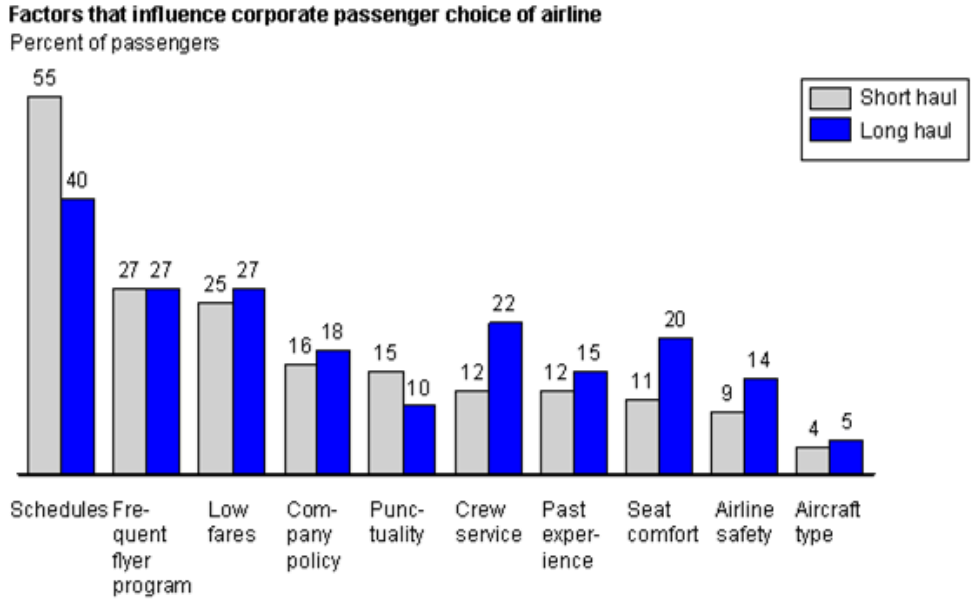
Figure 2.1.4 Corporate passengers' ranking of factors influencing their choice of airline.

a)

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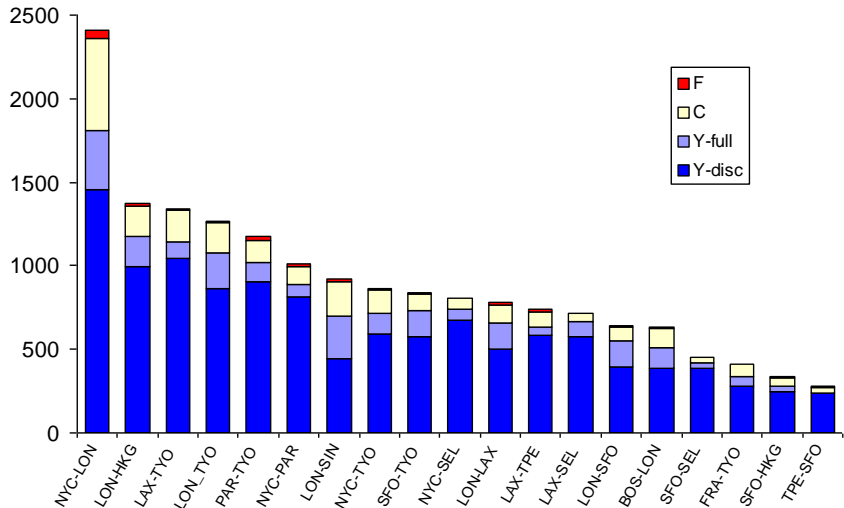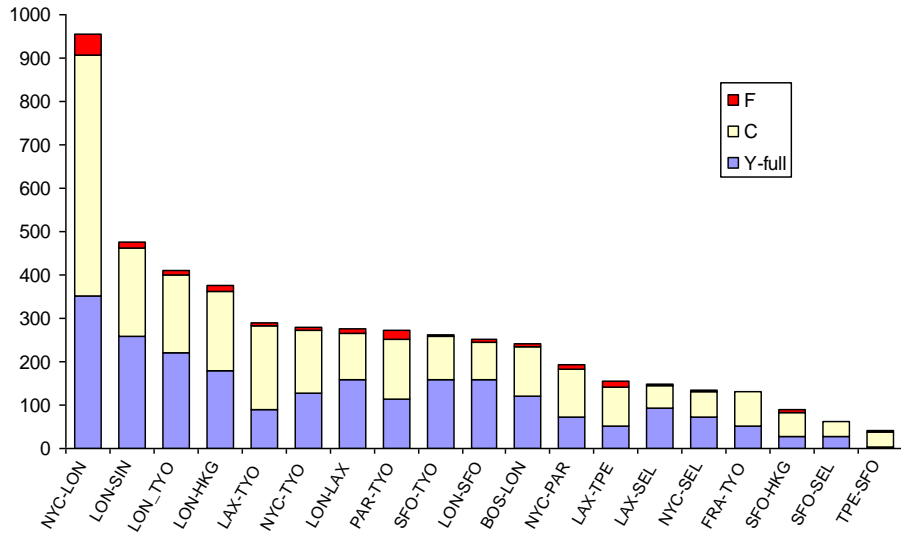
b)

Figure 2.1.5 Passenger demand each way (vertical axis) on the top 20 routes in 2006. a) Distribution of all fares. b) Distribution of full and premium fares. F=first class, C=business, Y-full=full fare coach, and Y-disc=discount fair coach.
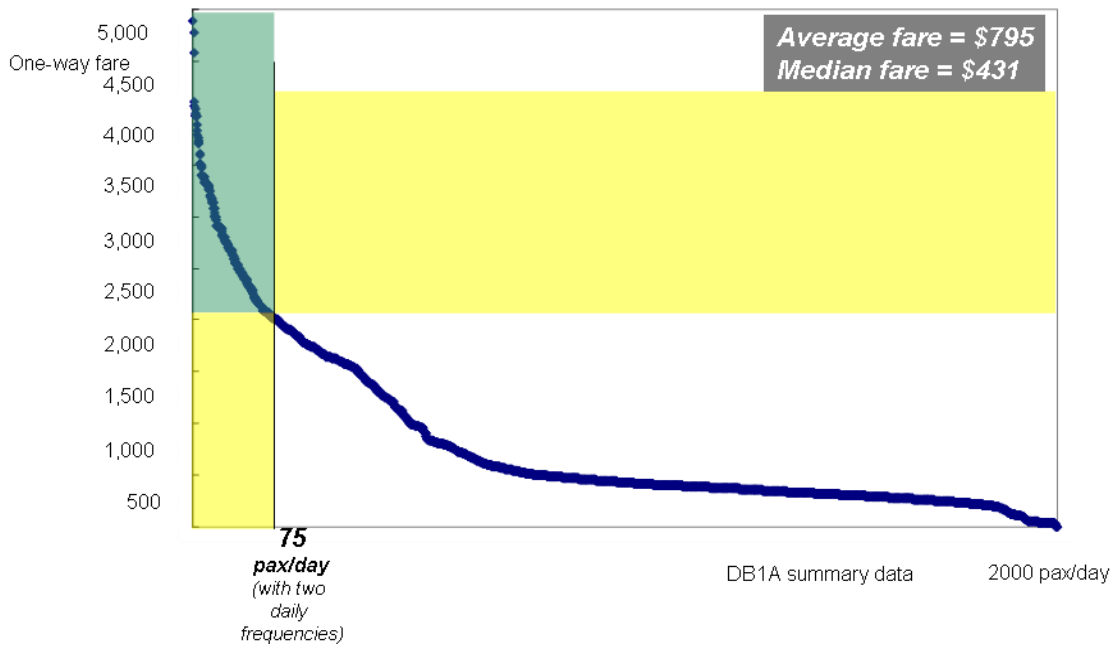
Figure 2.1.6 Actual one-way fares paid for NYC-LON for first, business and coach class seats in 3rd quarter 2006.

Table 2.2.1 Engineering Design Guidance Based on the Marketing Study.

Marketing Conclusions	Engineering Guideline
100-150 passengers (in 2-class arrangement) baseline interior, target ~130 seats	100 pass. , 130+ with optional seating
1.6-1.8 Mach cruise speed & need alternative operation plan to increase utilization (sub-sonic, hybrid ownership…)	1.8 design limit
Cruise altitude limited to 55,000ft (emissions)	<= 55,000 ft
4000nmi min. supersonic range (trans-Atlantic +) 6000nmi objective to open up Asian routes	4000 nmi minimum range
Cruise M <= 0.95 below 39Kft for ATC margins. No supersonic speeds below 41Kft for ATC margins	Compatible with ATC and traffic All SS mission
Supersonic fuel burn less than 0.26 lb/seat/nmi (3.8 seat nmi/lb) set as a plausible economic and environmental target (1% / year beyond N+2)	Study Goal for min fuel aircraft and point of reference for single metric designs
Sonic boom as low as practical (< Concorde over-water), consider "threshold Mach" over-land, and "boom softening" for operations in coastal regions and selected over-land corridors	Balanced 100 Seat config in the 80 PLdB class, "Low Boom" metric aircraft in the 70 PLdB class (eventual goal is 65-70 PLdB)
Over-land and low-yield operational solution needed	Technology Goals; low boom & good fuel efficiency vs. Mach, possibly "Threshold Mach" cruise

Reference N+3 Supersonic Timeline for Roadmaps

TRL 5: Tested in Simulated Environment
MRL 5: Manufacturing Process Developed
IRL 3: System Physical Mockup Ground Tested

TRL 6: Tested in Relevant Environment
MRL 6: Manufacturing Process Demonstrated
IRL 4: Prototype Subjected to Representative Flight Environment

TRL 8: System Proven to Work
MRL 8: Maturity Demo
IRL 5: Fab, launch and Operations

Business Case

TRL 5

TRL 6

First Flight

Feasibility

Tech Integrated in System

Certification and Delivery

Technology Development

TRL 3

Pre- Type Cert. Effort

TRL 3: Physically Validated Analytical Predictions/Not Integrated
MRL 3: Manufacturing Concepts Identified
IRL 0: N/A

TRL 4

Non-recurring

TRL 2: Basic Principles Observed
MRL 0: NA
IRL 0: NA

TRL 4: Tech components established to work together
MRL 4: Manufacturing Processes Identified—Breadboard in Lab
IRL 1: Concept Systems Analysis Completed

Authority to Proceed

Ground and Flight Test

TRL 2

Demonstrations

Propulsion System Development

Prod Engine

Prelim Concept

Initial Concept Defined

Concept Dev

Preliminary Des Cycles

First Flight

Product Development Cycles

SB Flt Demo

Mod SB Flt Demo

3+ Years

ICAO Rulemaking

Firm Config

CAEP 10
Draft Stds & Cert Criteria

2012

2020

2025

2030

2035

Years

Figure 2.3.1 Program Development Timeline Used for Reference in the Roadmap Development.
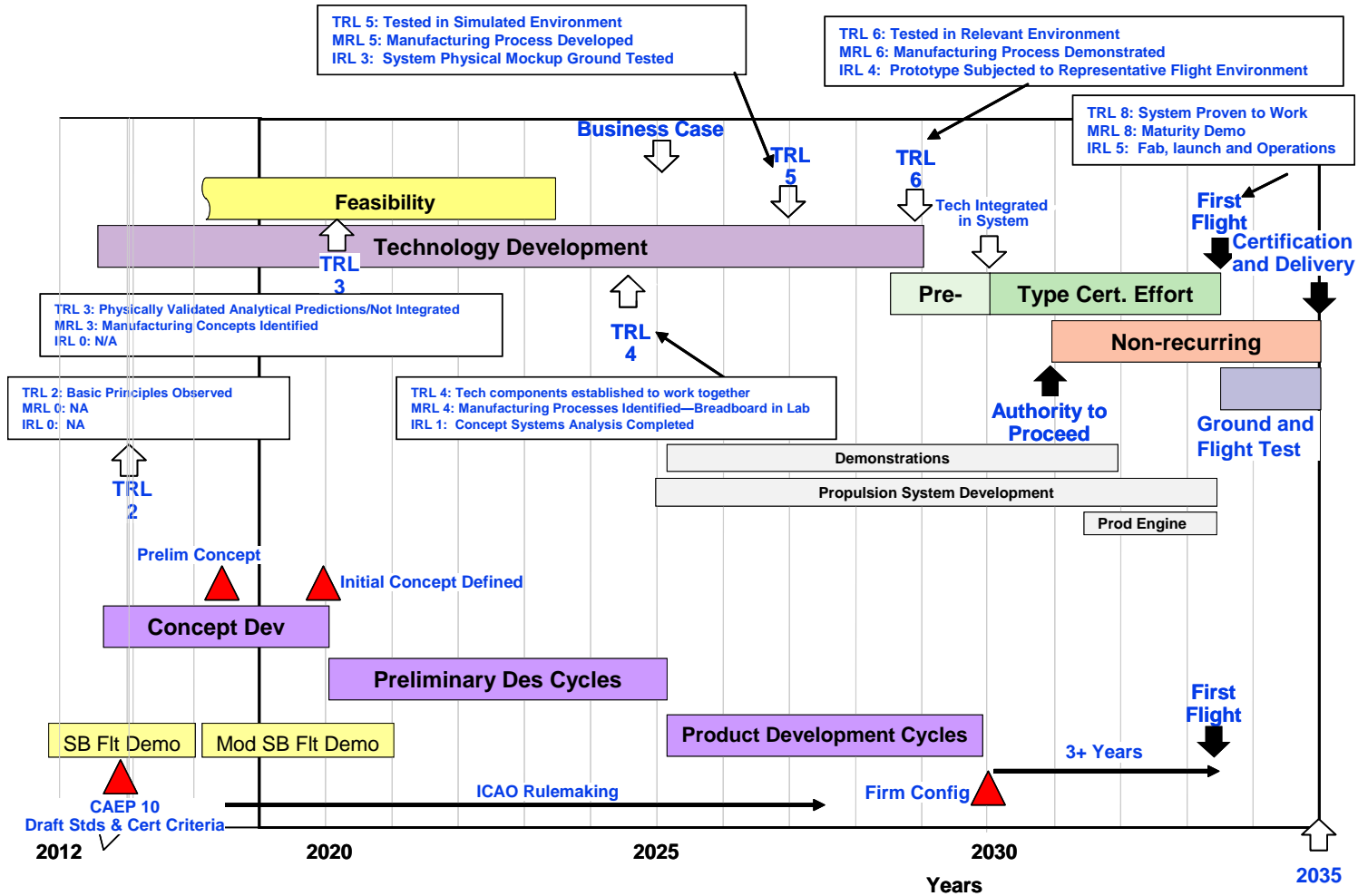
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3.0 Initial Reference Systems and Technologies (Task 3.3)

This section describes a methodical approach to initially identifying promising configurations and technological innovations. It employed a traditional brainstorming workshop, and the Interactive Reconfigurable Matrix of Alternatives (IRMA) tool at Georgia Tech to help guide the notional configuration concepts and technology ideas. Following some formal Systems Engineering processes to select configuration and technology alternatives, the activity provided several categories of preliminary configurations and technology combinations that served as the point of departure for more detailed studies.

3.1 - Process Overview and Background- Submitted by Georgia Institute of Technology

The Boeing Company solicited input from the Georgia Tech (Ga. Tech) Aerospace Systems Design Laboratory (ASDL) to facilitate a workshop for concept selection for the aircraft. Working closely with Boeing, General Electric, Pratt & Whitney, and Rolls-Royce, ASDL formalized a custom process and created tools specifically for the concept selection activity based on past experience in similar programs.

The overall goal of the workshop was to downselect a few operational, airframe and engine concepts for further analysis and study. The workshop required coordination between the partners prior to the actual events of the workshop to create the interactive tools which would aid in workshop activities.

The workshop for N+3 Supersonic concept selection was centered on using an Interactive Reconfigurable Matrix of Alternatives (IRMA) as a tool to aid in the discovery of configurations. IRMA is a systematic qualitative procedure that is unique to the conceptual design process developed by ASDL[2]. It was created to provide an "audit-trail" to define reference systems upon which quantitative analysis could be performed in a traceable, structured and systematic manner. IRMA builds on the concept of a Morphological Analysis created by Fritz Zwicky. Zwicky states that "within the final and true world image everything is related to everything, and nothing can be discarded a priori as being unimportant."[3]

Given the complexity of the new systems, there are millions of possible alternatives in the hyperspace of requirements, technologies and responses. Not all these alternatives could be quantitatively compared within the practical time limits imposed by the program management. To overcome this issue, a qualitative brain-storming exercise was developed by ASDL to prioritize and down-select the important requirements and alternatives with feedback from disciplinary experts and program management. This allowed for the quantitative process of the down-selected alternatives to be much more manageable.

The IRMA is a combination of Systems Engineering techniques such as Matrix of Alternatives, Multi-Attributes Decision Making (MADM) and Technique for Ordered Preference by Similarity to Ideal Solutions (TOPSIS).
Figure 3.1.1 depicts the Interactive Reconfigurable Matrix of Alternatives (IRMA) which was created for the N+3 Supersonic workshop. These tools provided a process for functionally decomposing the problem, identifying alternatives and technologies to meet the functions, and identifying the solutions that meet the top level needs. These tools and processes provided a mechanism for encouraging collaborative communication at the early stages of conceptual design.

The general procedure for selecting a system through the Morphological Matrix of Alternatives was as follows:
- Functionally decompose the existing system

- For each function, list all the possible ways in which it might be satisfied

- Examine the matrix for the possible new permutations

The last step offers great ambiguity, which the ASDL developed IRMA process was attempting to solve. The IRMA process included a dynamic dashboard for visualizing the effects of each decision. When a

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[2] Zwicky, Fritz, "Morphological Astronomy", The Observatory, Vol. 68, No. 845, Aug. 1948.
[3] Zwicky, Fritz, "Discovery, Invention, Research through Morphological Approach", 1969.

selection was made, incompatible options were filtered out thereby facilitating down-selection. The interactive nature of the IRMA tool allowed for the Boeing team to understand the impact of decisions at the initial point of decision making. In a collaborative group such as seen at the N+3 Supersonic workshop, this tool provided a mechanism for understanding the impacts of the order of decisions as well as facilitating discussions among group members.

3.2 – Pre-Workshop Steps

In order to create an IRMA and have a successful workshop for selecting advanced vehicle concepts, a fair amount of systems engineering activities occurred prior to the workshop.
Figure 3.1.1 depicts the necessary general steps used to create the IRMA to prepare for the workshop. This section will describe the details and major outcomes of each step.

These steps were carried through by a subset of workshop participants who had demonstrated technical competence in systems engineering techniques as well as the technical aspects for the problem at hand. The subgroup for the development of the N+3 Supersonic IRMA consisted of representatives from The Boeing Company as well as representatives from each engine company. The representatives from the engine companies provided input and guidance supporting engine technologies and integration issues.

Pre-workshop Step 1**:** Identify a set of customer requirements

Preparation for the workshop first began with understanding the needs of the customer. Supersonic commercial travel continues to offer a potentially viable, profitable option for cutting travel time and allowing for easier business and international travel. However, with the current push towards more environmentally friendly aircraft, both in the subsonic and supersonic regime, NASA has issued an aggressive set of goals which will drive next generation supersonic commercial aircraft design.
Figure 3.2.2 illustrates the various goals NASA has set for future supersonic aircraft design. The N+3 Supersonic initiative strives to develop N+3 Supersonic vehicle concepts to meet the most aggressive set of goals: reduction of sonic boom, cumulative noise, cruise emissions, and fuel efficiency. These requirements provided the initial constraints for the N+3 Supersonic initiative and direct IRMA construction.

Pre-workshop Step 2: Define problem in terms of requirements

Once the customer (i.e., NASA) had issued a set of requirements, and the overall project goal established, the requirements were translated such that the problem could later be mapped to realizable engineering characteristics. This report has discussed the need for supersonic commercial aviation and how the aircraft fleet will change as a result. This information, coupled with NASA's goals, helped formulate the overall problem: to design advanced concept, improved performance supersonic aircraft which can fit the need for commercial supersonic aviation while also meeting aggressive environmental standards. Therefore, the problem could be understood as one primarily involving aircraft architecture; changes to the aircraft architecture would either enhance or detract from the vehicle performance relative one or more of NASA's goals. In order to thoroughly address vehicle performance, the specific vehicle systems that most affect performance were identified and targeted as important areas for the conceptual design process. The Boeing team noted that design changes made to the aircraft fuselage, wing, stability and control system, propulsion, and fuel systems would most impact the vehicle's performance.

Pre-workshop Step 3: Decompose requirements in terms of functional taxonomy

Once the targeted areas of vehicle architecture were defined, it was important to break down the architecture in terms of its functional components. This was the first step in building the morphological matrix essential to IRMA. Using the sub-categories defined by Boeing (i.e. fuselage, wing, stability and control, propulsion, fuel) as a starting place, the vehicle was functionally broken down into its parts. These functional "parts" served as points of decision for each concept created. Design decisions were then made at this level of detail, ensuring that the concepts were built from the "bottom up" with much freedom to generate the N+3 concepts that would best address NASA's goals.

In order to begin vehicle decomposition, it was important to know the vehicle components which make up each subsystem as these generate decision making points in the IRMA. The functional decomposition was completed by Boeing and the engine companies in keeping with the fuselage, wing, stability and control, propulsion, and fuel categories. A complete visualization of the finished functional taxonomy can be seen in Figure 3.2.3.

Pre-workshop Step 4: Identify alternatives to decomposition and compose morphological matrix

Once the functional taxonomy was complete, each entry to the decomposition was given possible alternatives that could function in a vehicle design. For example, an airplane may realistically have 1 or 2 wings. Therefore these are the two alternatives which would populate the "number of wings" category. These alternatives served as possible "choices" in the IRMA, guiding the users in creating vehicle concepts. The alternatives were populated across a row for each entry created in the functional taxonomy. Once the alternatives were entered, the morphological matrix was complete and the backbone for the IRMA was set. The complete morphological matrix created by Boeing and the engine companies for the N+3 Supersonic workshop is shown in figure 3.2.4.

Pre-workshop Step 5.1: Create conditional relationships of functional decomposition

Once the morphological matrix was complete, the dynamic nature of the matrix was set up. This was done through the creation of a compatibility matrix which summarizes the conditional relationships within the functional decomposition. The goal of conditional relationships was to eliminate alternatives that are physically incompatible with each other. For example, if the user initially selected the aft shape of the fuselage to be a tail spike, it is physically impossible to have the propulsion system also located in the aft fuselage. Therefore, the alternatives under these categories on other rows of the matrix would be removed as alternatives for the vehicle configuration.

It is important to note that the incompatibilities dealt with merely reflect those vehicle attributes which were impossible by the laws of physics or by engineering standards. These incompatibilities did not reflect combinations of attributes which may be uncommon or suggested against. This allowed for more freedom in generating concepts. It is important that the users applied their engineering judgment when making decisions to ensure the designs were not only physically possible, but also logical, as incompatibilities cannot account for engineering logic.

The compatibility matrix was filled in by those who helped populate the morphological matrix. This matrix is symmetrical and at minimum, consists of the numbers 1 and 0. A 0 indicates that two alternatives are incompatible while a 1 indicates they are compatible. The compatibility covers alternatives in the same row as the attribute in question as well as those alternatives in other rows that affect other aspects of the vehicle architecture. Additionally, the matrix was enhanced by using the number 2 to indicate when two alternatives were not only compatible, but also that using those two alternatives together provides a benefit to using just one or the other. When an alternative was selected, any alternatives that would couple with the previously selected one and thereby improve performance were highlighted for the user to view.

A section of the compatibility matrix created for the N+3 Supersonic workshop is shown in Figure 3.2.5.

Once the compatibility matrix was completed, it was linked to the morphological matrix to enable dynamic decision making. The results of the compatibility were automatically reflected to the user with each choice made during the workshop. This can be seen in Figure 3.7. The red cells indicate those options which had been ruled out due to the incompatibility matrix. Which cells appear red was a result of choices selected previously in the decision making chain (these choices were marked with a green "yes") and helped to drive vehicle concept design. The cells that appeared purple were options that had not yet been chosen but would enhance the overall design if chosen. This reflected a number "2" in the compatibility matrix. This was a function of IRMA and will be discussed in more detail in the workshop section of this report. Note that Figure 3.2.6 does not reflect work done at the workshop, it merely indicates the functionality of the built in compatibility matrix.

Pre-workshop Step 5.2: Identify and discuss attributes of each row of the decomposition

Once the backbone of the IRMA was completed, it was important to go over the results of the functional decomposition to ensure it is comprehensive. Additionally, it was also important to discuss each attribute and alternative to ensure that the function and meaning of each was understood by all those involved. Understanding the importance of each attribute was crucial to the next pre-workshop step. Additionally, it allowed the users to scrutinize the choices they made in the functional decomposition to ensure that the problem could be adequately addressed with those attributes listed in the matrix.

Pre-workshop Step 6: Rank order decomposition based on relative importance to requirements

Using the discussions begun in step 5.2, it was important to set up the basics for IRMA scoring by identifying the importance of each functional attribute to the problem. IRMA scoring ensured that those decisions which most directly impact the NASA goals get weightings reflecting their importance. For example, fuel efficiency is highly affected by the aircraft propulsor type. Therefore, the functional attribute "propulsor type" was given a high rating such that it would count highly towards the overall score of the vehicle concept. Additionally, knowing the propulsor type was an attribute highly affecting fuel efficiency, the user was given a logical place to start the decision making process. Because of the incompatibility matrix, the order in which decisions are made affect the vehicle architecture options available towards the end of the decision making chain. Therefore, it was important to begin making decisions with those attributes that would most highly affect the vehicle's performance.

Each attribute was evaluated for its effect on each one of NASA's goals. The attributes were marked as having a high impact, medium impact, low impact, or no impact on a specific goal. The impact could be positive or negative and was accounted for during the workshop when scoring each alternative. The "high-none" scale allowed the user to think of the problem qualitatively rather than quantitatively while still capturing the importance of a specific attribute. Once the attributes were rated, the stage was set to allow for more logical, effective decision making, allowing those decisions which were more critical to vehicle performance relative to a certain goal to occur early on in the chain of decisions.

This step was performed both pre-workshop and during the workshop. Conducting this exercise prior to the workshop helped users ensure that the matrix was complete and its entries were understood. Conducting the exercise during the workshop helped check the work done before the workshop and brought all participants together. It was important that the rankings were as accurate as possible, as they ended up driving the decision making process heavily.

Pre-workshop Step 7: Select optimal suitable reference systems

Before groups could come together and begin to brainstorm unique vehicle concepts at the workshop, it was important that everyone be given a frame of reference in which they must make decisions. This frame of reference included a baseline vehicle as well as the type of mission for which the vehicle was being designed.

The baseline vehicle provided a reference system for users when they were scoring alternatives in the workshop. During the workshop, each alternative was given a score (1-10) reflecting how well they contribute to the customer goals. In this case, the score reflected how well an alternative will improve performance towards specific NASA goal. Knowing the features of the baseline, the user was able to make these decisions relative to existing systems. Additionally, choosing a reference mission was important prior to the workshop. In order to minimize confusion, it was important to stipulate reference conditions ahead of time so everyone could understand the context in which they were brainstorming. The N+3 Supersonic team selected the 765-076E as the baseline aircraft and assumed a 100 passenger aircraft for all concepts created. Having these guidelines gave structure to the workshop and ensured the participants are able to effectively contribute to the overall workshop process.

Pre-workshop Step 8: Exercise IRMA

The steps of the workshop and details on how the IRMA was used to aid dynamic decision making will be discussed in the next section of this report. A complete IRMA, ready for a workshop, is depicted in Figure 3.2.7. Again, this IRMA is a notional example and does not reflect real decisions made prior to the workshop.

3.3 – Workshop Steps

The work prepared prior to the workshop created tools and resources to facilitate a more streamlined execution of the workshop steps. These workshop steps were composed of small group breakout activities and larger group down-selection activities. This workflow is depicted in Figure 3.3.1 and this section will describe in more detail the major accomplishments of each of the steps involved in the workshop and the outcomes.

Workshop Step 1: Participant Planning and Pre-workshop review

The information provided in the pre-workshop activities contributed to the creation of the tools that will be available to the workshop participants. The IRMA, information on specific technologies, the baseline vehicle, mission requirements and the NASA goals were provided to each of the teams. The IRMA integrated the decomposition of requirements, the alternatives in the matrix of alternatives and the compatibility matrix in an interactively accessible format.

The workshop participants consisted of a subset of the individuals who participated in the pre-workshop activities and other technical experts. These participants were selected by their past experience in specific technology areas, configuration design or their broad understanding of engineering trades. The purpose of the Workshop Step 1 was to orient the participants to the mission that they are designing for and the steps that they will be required to go through during the workshop days.

An orientation for the tools that will be available to them was provided along with reference vehicle and mission information. Furthermore, each of the groups was required to select architectures that relate to each of the functional metrics. These metrics were specified by NASA and refined in the earlier phases of the program.

Workshop Step 2: Score Matrix of Alternatives

The participants were broken up into three groups consisting of an averaged level of experience both on years of experience and technical expertise. These groups worked together to identify the initial aircraft configurations for each of the NASA Goals or "Metrics of Interest" (MOI). The teams investigated a single MOI and qualitatively ranked the benefit of each characteristic relative to the MOI. The groups identified the characteristics with high benefits progressing from medium to identifying characteristics with low or no benefit to the MOI. This progressive identification of relative benefit supplied the team with a general "order of selection" to be used in the future. A snapshot of the exercise is depicted in figure 3.3.2.

Upon identifying the order of selection, the teams progressed in the specified order and ranked the alternatives associated with the metrics of interest. This ranking was then used to facilitate discussions for assessing the benefit and tradeoffs between configuration options. For a given metric, starting with the high impact characteristics, the elements within each row were scored based on their value to the specified metrics, where 1 is low and 10 is high. The teams progressed in the specified order of selection, ranking each of the alternatives. A snapshot of selected results are depicted in Figure 3.3.3 below. The teams repeated step 2 until all the MOI were evaluated. Once the order of selection was identified and the alternatives scored, the teams had the information necessary to begin exercising the IRMA to select concepts.

Workshop Step 3: Down-Select Group Concepts

For a specific MOI, each characteristic was considered in assigned order, and the team began to discuss and select alternatives for that characteristic. As alternatives were selected, any incompatible options in other characteristic rows turn red, and any enhancing options turn purple. As compatibility allows, the team, ideally, specified the highest ranked alternative on each row for a given MOI. A configuration was complete once there was an option selected for each characteristic. Figure 3.3.4 shows an example of such an intermediate result for a few characteristics. The resulting configurations represented the corners of the design space and will be used for sensitivity analysis once the workshop process is complete. Figure 3.3.5 shows the results of the configuration selection for one of the groups participating in the workshop.

Workshop Step 4: Sketch group concepts

In order to bring the concept to life and understand different interpretations of the integration aspect of the design choices, each member of the group sketched each of the proposed aircraft. The teams then compared individual sketches for each of the different aircraft and reached group consensus on what the aircraft should look like. Based on the results of the discussions, the team redrew the concepts, incorporating any changes. An example of one of the groups' original interpretations and final drawing is depicted below in Figure 3.3.6.

Workshop Step 5: Down-select among group concepts

At this stage of the workshop, there were at least three concepts to meet each of the NASA goals and in order to arrive at a select few configurations to apply technologies towards, the teams regrouped and presented their concepts. Each team presented their concept sketch and provided discussion of the rationale for their configuration selection. Since different alternatives for each of the vehicle characteristics provided advantages and disadvantages, individually as well as integrated, the teams discussed the expected pros and cons for their concepts.

Once all the groups had discussed their concepts, the large group down-selects to one or two concepts per metric. To facilitate the down-select, the group compared the concepts to each of the metrics of interest based on the perceived pros and cons of each concept. The groups then discussed commonalities amongst all concepts, configuration selection issues and integration issues which could have led to reassessing the configuration selection. Upon reaching consensus, the large group arrived at a concept or two for each metric as well as repeating the concept selection process to identify a configuration that represents a compromise between all metrics. An example of the results of the large group discussion is depicted below in Figure 3.3.7.

Workshop Step 6: Final workshop configuration and sketch workshop concepts

Upon reaching consensus amongst the larger group, the concepts were reviewed for completeness and sketches were drawn by a selected individual to bring the concepts to life. This final sketch up provided a mechanism for discussion as well as a product of the workshop. Figure 3.3.8 depicts the results from the N+3 Supersonic workshop. These drawings were used as a starting point in future steps of the contracted work.

3.4 – IRMA Process Payoff

By utilizing the ASDL created IRMA process, the N+3 Supersonic team was able to develop several alternatives for evaluation utilizing a systematic approach with documented decisions. By exercising the interactive tool, the teams were able to gain an enhanced understanding of the systems selections for the vehicle characteristics and the impacts of selecting a particular alternative without the need to exercise

lengthy and expensive analysis. The tool's dynamic nature and extensible, flexible framework allowed for the down-select process to be rapidly repeated in order to select multiple configuration alternatives. This tool also facilitated discussions related to all major components of the aircraft and the integration issues.

The process used for exercising the tool provided a systematic process to obtain a sufficient set of reference systems and a mechanism for documenting the decisions that were made over the course of the workshop. The resulting files were given to the participants for use in further analysis in the later phases of the contract or any follow-on work.

		Metrics Selection		Configuration Alternatives											
		Fuel Efficiency	Order of Selection	Alternative #1	Rank	Select	Alternatitve #2	Rank	Select	Alternatitve #3	Rank	Select	Alternative #4	Rank	Select
Fuselage	Number of Fuselages	Low		1			2								
	Wing-Body Blend	High		None			Fairing			Moderate Blend			Extreme Blend		
	Aft Shape	Med		Conventional			Tail Spike			Blended			Aft-deck		
	Nose Shape	Med		Conventional		Yes	Nose Spike			Blunted (boom)					
Wing	Number	Low		1		Yes	2								
	Location	None		Low		Yes	Mid			High					
	High Lift System	None		Conventional			Slotted Flap			Active flow control					
	Cruise aero	Low		NLF			Variable geometry			Active flow control					
	Join	High		None			Wing-Tail								
	Swing	None		None			In Flight - variable			On Ground - fixed					
	Morphing	Low		None			Planform		Yes	Variable Camber			Both		
	Winglet	Med		None			B-70 type								
S&C	Pitch Effecter	High		Conv. Horizontal			T-Tail			3-Surface			Wing TE		
	CG Control	None		None			Active								
Propulsion	Location	Low		Low Wing			Mid Wing			Above Wing			Aft Fuselage		
	Integration	Med		Podded		Yes	Embedded								
	Propulsor Arrangement	None		Single			Multiple								
	Propulsor Type	High		Variable cycle turbofan			Fixed cycle turbofan			Remote Fan					
	Energy Conversion	Med		Convent. Turbofan (Brayton)			Fuel Cell			Turbo-Generator			CVC Cycle		
	Power Augmentation	Low		None			Batteries			Fuel Cell			AB Augmentation @ pinch pts		
	Inlet Geometry	High		Fixed Area			Variable Area								
	Inlet Shape	Low		2-D			Axisymetric								
	Inlet Type	High		External Compression		Yes	Mixed Compression								
	Nozzle Geometry	Low		Fixed Area			Variable Area								
	Nozzle Shape	Low		2-D			Axisymetric								
	Nozzle Type	Med		Plug			C-D			SERN					
	Ejector	None		No			Yes								

(Clear Rankings — Vehicle Characteristics)

Figure 3.1.1 – Interactive Matrix of Alternatives for Conceptual Design Formulation
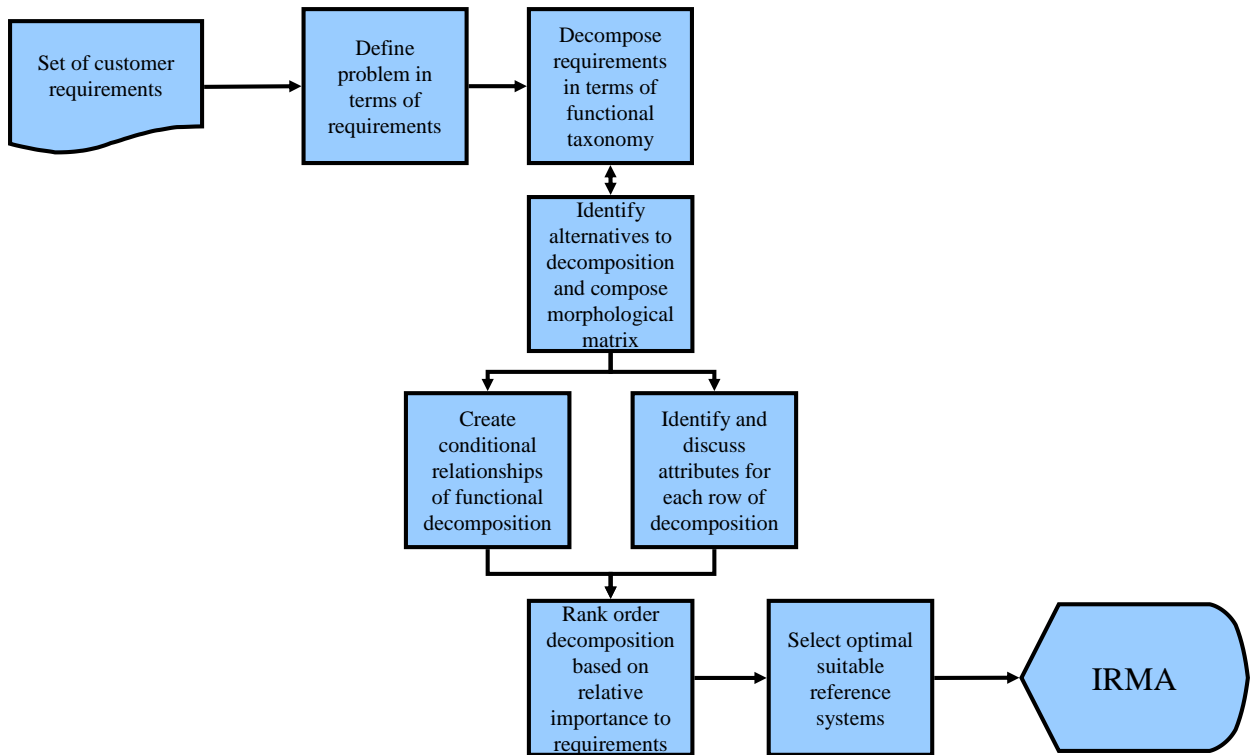
Figure 3.2.1 – Pre-Workshop Activity Sequence

Metric		N+3 Minimum Goal	N+3 Stretch Goal
Sonic Boom	Perceived Loudness - PLdB	70 - Low Boom 80 – Unrestricted	65 - Low Boom 75 – Unrestricted
Airport Noise	Cum below stage 3 – EPNdB	-20	-30
Cruise Emissions	Cruise NOx – g/kg of fuel	5	< 5 with Particulate and H2O Mitigation
Cruise Speed	Mach Number	1.3	2
Payload	Passengers	100	200
Range	Nautical Miles	4000	5500
Fuel Efficiency	Passenger-miles per lb of fuel	3.5	4.5

Figure 3.2.2 – NASA Goals for Next Generation Supersonic Aircraft

Figure 3.2.3 - Functional Decomposition of Vehicle Characteristics

Vehicle Characteristics		
Fuselage	Number of Fuselages
	Wing-Body Blend
	Aft Shape
	Nose Shape
Wing	Number
	Location
	High Lift System
	Cruise aero
	Join
	Swing
	Morphing
	Winglet
S&C	Pitch Effecter
	CG Control
Propulsion	Location
	Integration
	Propulsor Arrangement
	Propulsor Type
	Energy Conversion
	Power Augmentation
	Inlet Geometry
	Inlet Shape
	Inlet Type
	Nozzle Geometry
	Nozzle Shape
	Nozzle Type
	Ejector
Fuel	option with prop type

Vehicle Characteristics			Alternatives				
Fuselage	Number of Fuselages	1	2			
	Wing-Body Blend	None	Fairing	Moderate Blend	Extreme Blend	
	Aft Shape	Conventional	Tail Spike	Blended	Aft-deck	Body flap
	Nose Shape	Conventional	Nose Spike	Blunted (boom)		
Wing	Number	1	2			
	Location	Low	Mid	High		
	High Lift System	Conventional	Slotted Flap			
	Cruise aero	NLF	Variable geometry	Active flow control		
	Join	None	Wing-Tail			
	Swing	None	In Flight - variable	On Ground - fixed		
	Morphing	None	Planform	Variable Camber	Both	
	Winglet	None	B-70 type			
S&C	Pitch Effecter	Conv. Horizontal	T-Tail	3-Surface	Wing TE	Canard
	CG Control	None	Active			
Propulsion	Location	Low Wing	Mid Wing	Above Wing	Aft Fuselage	
	Integration	Podded	Embedded			
	Propulsor Arrangement	Single	Multiple			
	Propulsor Type	Variable cycle turbofan	Fixed cycle turbofan	Remote Fan		
	Energy Conversion	Convent. Turbofan (Brayton)	Fuel Cell	Turbo-Generator	CVC Cycle	Intercooler / Recoup Cycle
	Power Augmentation	None	Batteries	Fuel Cell	AB Augmentation @ pinch pts	
	Inlet Geometry	Fixed Area	Variable Area			
	Inlet Shape	2-D	Axisymetric			
	Inlet Type	External Compression	Mixed Compression			
	Nozzle Geometry	Fixed Area	Variable Area			
	Nozzle Shape	2-D	Axisymetric			
	Nozzle Type	Plug	C-D	SERN		
	Ejector	No	Yes			
Fuel	option with prop type	Liquid Hydro-carbon	LH2	Batteries		

Figure 3.2.4 – N+3 Supersonic Morphological Matrix

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Figure 3.2.5 – Portion of Compatibility Matrix

Figure 3.2.6 – Example of IRMA Dashboard with several selections. (Red cells indicate incompatible options. Purple cells indicate enhanced design options.)

nkings	Metrics Selection		Configuration Alternatives												
	Fuel Efficiency	Order of Selection	Alternative #1	Rank	Select	Alternitve #2	Rank	Select	Alternative #3	Rank	Select	Alternative #4	Rank	Select	Alternative #5
Number of Fuselages	Low		1			2									
Wing-Body Blend	High		None			Fairing			Moderate Blend			Extreme Blend			
Aft Shape	Med		Conventional			Tail Spike			Blended			Aft-deck			
Nose Shape	Med		Conventional			Nose Spike			Blunted (boom)						Body flap
Number	Low		1			2									
Location	None		Low			Mid			High						
High Lift System	None		Conventional			Slotted Flap									
Cruise aero	Low		NLF			Variable geometry			Active flow control						
Join	High		None			Wing-Tail									
Swing	None		None			In Flight - variable									
Morphing	Low		None			Planform			Variable Camber			Both			
Winglet	Med		None			B-70 type									
Pitch Effecter	High		Conv. Horizontal			T-Tail			3-Surface			Wing TE			Canard
CG Control	None		None			Active									
Location	Low		Low Wing			Mid Wing			Above Wing			Aft Fuselage			
Integration	Med		Podded			Embedded									
Propulsor Arrangement	None		Single			Multiple									
Propulsor Type	High		Variable cycle turbofan			Fixed cycle turbofan			Remote Fan						
Energy Conversion	Med		Convent. Turbofan (Brayton)			Fuel Cell			Turbo-Generator			CVC Cycle			Intercooler / Recoup Cycle
Power Augmentation	Low		None			Batteries			Fuel Cell			AB Augmentation @ pinch pts			
Inlet Geometry	High		Fixed Area			Variable Area									
Inlet Shape	Low		2-D			Axisymetric									
Inlet Type	High		External Compression			Mixed Compression									
Nozzle Geometry	Low		Fixed Area			Variable Area									
Nozzle Shape	Low		2-D			Axisymetric									
Nozzle Type	Med		Plug			C-D			SERN						
Ejector	None		No			Yes									
option with prop type			Liquid Hydro-carbon			LH2			Batteries						

Figure 3.2.7 – Notional IRMA Prior to Workshop
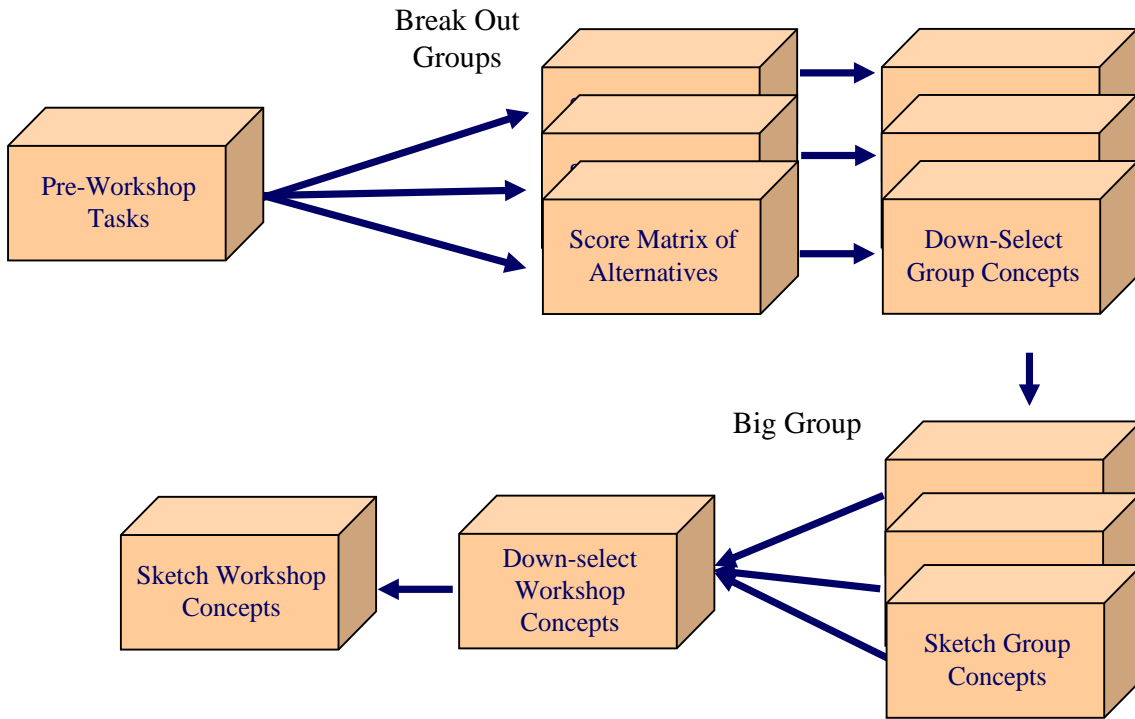
Figure 3.3.1 – Workshop Workflow Diagram

Figure 3.3.2 – Step 2: Identification of Relative Benefit

Figure 3.3.3 – Scoring the Alternatives

Figure 3.3.4 – Intermediate Results from the IRMA

Annotations in figure:
- Selections are made according to the order of selection
- As selections are made incompatible elements turn red
- Selection "yes" from the drop down box

nkings	Metrics Selection	Order of Sel	Configuration Alternatives								
	Cummulative Nois		Alternative #1	Rank	Selec	Alternatitve #2	Rank	Selec	Alternatitve #3	Rank	Selec	Alternativ
Number of Fuselages	Low	20	1	5			3					
Wing-Body Blend	Low	18	None			airing	5		Moderate Blend	5	Yes	Extreme Ble
Aft Shape	Med	13	Conventional			ail Spike	5		Blended	6		Aft-deck
Nose Shape	Low	23	Conventional	5	Yes	Nose Spike	5		Blunted (boom)	5		

Figure 3.3.5 – Team Y's Configuration Results from IRMA process

	Concept #1: Boom	Concept #2: Cumulkative Noise	Concept #3: Cruise Emissions	Concept #4: Fuel Efficiency	Concept #5: Balanced
Number of Fuselages	1	1	1	1	1
Wing-Body Blend	Conventional	Moderate Blend	Fairing	Fairing	Fairing
Aft Shape	Tail Spike	Aft-Deck	Conventional	Conventional	Aft-deck
Nose Shape	Nose Spike	Conventional	Conventional	Conventional	Nose Spike
Number	1	2	1	1	2
Location	Mid	Low	Low	Low	Low
High Lift System	Slotted Flap	Slotted Flap	Slotted Flap	Slotted Flap	Slotted Flap
Cruise aero	Variable geometry	Active flow control	NLF	NLF	NLF
Join	None	None	None	None	None
Swing	None	None	None	None	None
Morphing	Both	Both	Telescoping	None	Both
Winglet	None	None	None	None	None
Pitch Effecter	3-Surface	3-Surface	Canard	Canard	3-Surface
CG Control	Active	Active	Active	Active	Active
Location	Above Wing	Above Wing	Low Wing	Low Wing	Above Wing
Integration	Podded	Podded	Podded	Podded	Podded
Propulsor Arrangement	Single	Multiple	Multiple	Single	Single
Propulsor Type	Variable cycle turbofan	Remote Fan	Remote Fan	Variable cycle turbofan	Variable cycle turbofan
Energy Conversion	Intercooler / Recoup Cycle	Fuel Cell	Fuel Cell	CVC Cycle	Intercooler / Recoup Cycle
Power Augmentation	AB Augmentation @ pinch pts	Fuel Cell	Fuel Cell	AB Augmentation @ pinch pts	AB Augmentation @ pinch pts
Inlet Geometry	Variable Area	Variable Area	Variable Area	Variable Area	Variable Area
Inlet Shape	2-D	2-D	Axisymmetric	2-D	Axisymmetric
Inlet Type	Mixed Compression	Mixed Compression	Mixed Compression	Mixed Compression	Mixed Compression
Nozzle Geometry	Variable Area	Variable Area	Variable Area	Variable Area	Variable Area
Nozzle Shape	Axisymetric	2-D	Axisymetric	Axisymetric	Axisymetric
Nozzle Type	C-D	SERN	C-D	Plug	C-D
Ejector	Yes	No	No	No	No
option with prop type					

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Figure 3.3.6 – Concept sketches

Number of Fuselages	Team Z: Cumulative Noise	Team Y: Cumulative Noise	Team Z: Cumulative Noise		Compiled Team: Cumulative Noise
Wing-Body Blend	1	1	2		1
Aft Shape	None	Moderate Blend	Fairing		Moderate Blend
Nose Shape	Conventional	Aft-Deck	Body Flap		Aft-Deck
Number	Conventional	Conventional	Conventional		Convenventional
Location	2	2	1		1
High Lift System	Low	Low	Low		Low
Cruise aero	Slotted Flap	Slotted Flap	Slotted Flap		Slotted Flap
Join	Active flow control	Active flow control	Active Flow Control		Active Flow Control
Swing	None	None	None		None
Morphing	IN flight-varible	None	IN flight- variable		IN flight- variable
Winglet	Both	Both	Both		Variable Camber
Pitch Effecter	None	None	None		None
CG Control	Canard	3-Surface	Canard		3-Surface - put engines inside VT
Location	Active	Active	Active		Active
Integration	Above Wing	Above Wing	Above Wing		Above Wing
Propulsor Arrangement	Embedded	Podded	Embedded		Podded
Propulsor Type	Single	Multiple	Multiple		Multiple
Energy Conversion	Variable cycle turbofan	Remote Fan	Variable cycle turbofan		Remote Fan
Power Augmentation	Intercooler/Recoup Cycle	Fuel Cell	conentional turbofan (Brayton)		Intercooler / Recoup Cycle
Inlet Geometry	None	Fuel Cell	None		None
Inlet Shape	Variable Area	Variable Area	Variable Area		ixed Area - due to external compressio
Inlet Type	2-D	2-D	w-D		2-D
Nozzle Geometry	External Compression	Mixed Compression	External Compression		External Compression
Nozzle Shape	Variable Area	Variable Area	Vairable Area		Vairable Area
Nozzle Type	2-D	2-D	2-D		2-D
Ejector	C-D	SERN	SERN		SERN
option with prop type	Yes	No	Yes		Yes

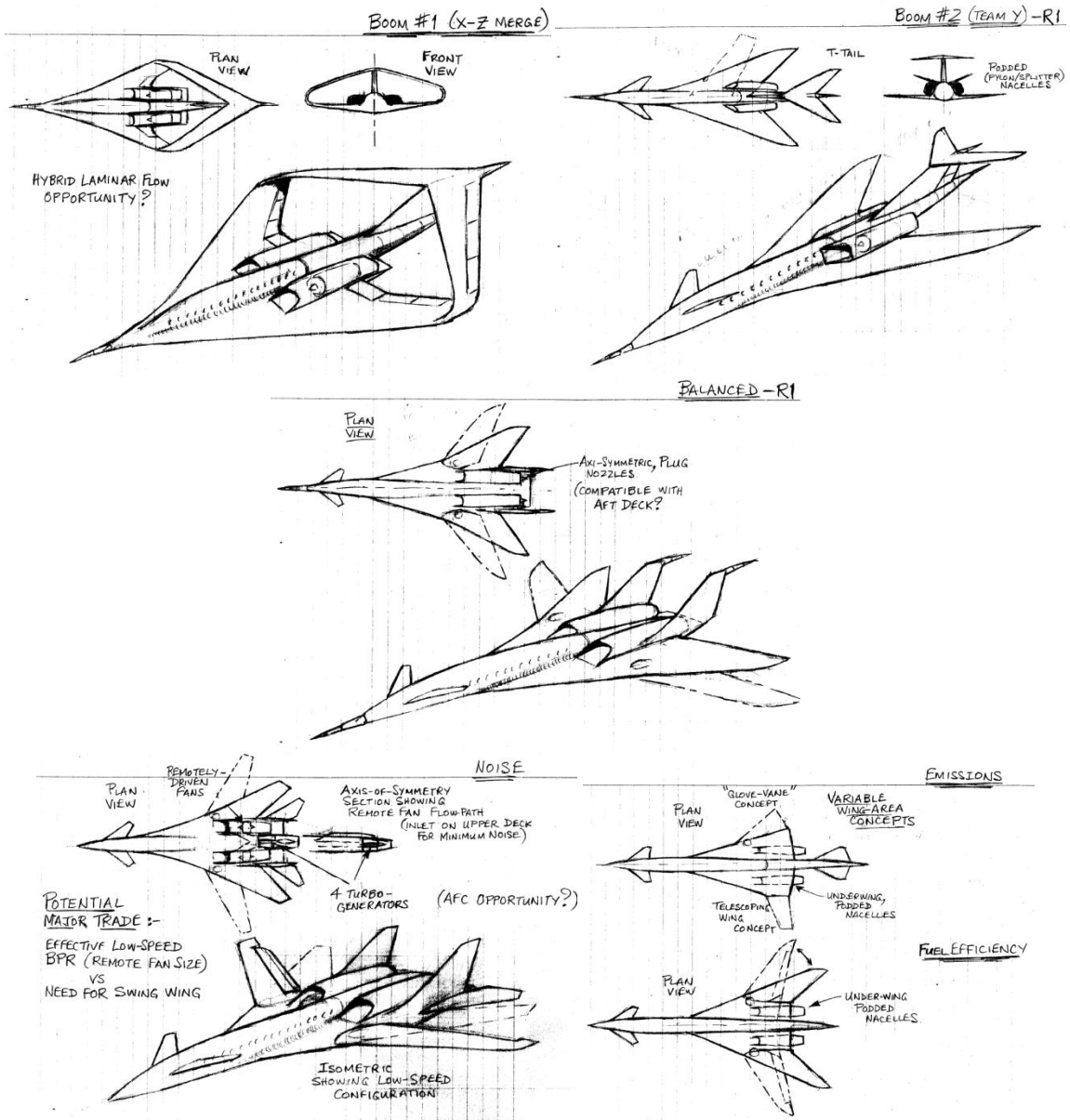**Figure 3.3.7 – Large group configuration down-selection**

Figure 3.3.8 Concept Category Sketches as a Point of Departure for Further Development.

4.0 Engine Development and Technologies (Task 3.3 & 3.4)

This section contains non-proprietary discussion of the engine development and technologies by General Electric, Pratt & Whitney, and Rolls-Royce U.S. (Liberty Works). Sub-sections 4.1, 4.2 and 4.3 were prepared and submitted independently by the respective engine companies, and formatting and content are not strictly consistent. Independent proprietary discussion and data are found in Appendices B, C & D.

4.1 General Electric Engine Technology Inputs

4.1.1   General Electric Introduction

GE Global Research and Aviation supported Boeing's contract from NASA on these N+3 Supersonic System Studies. GE's support included propulsion system support through the development of an advanced variable cycle engine (VCE) propulsion system to meet the vehicle requirements and environmental goals. The overall goals are shown in Figure 3.2.2. They cover sonic boom, airport noise, fuel efficiency, and emissions. The sonic boom, cruise speed, payload, and range were essentially used by Boeing to set the propulsion requirements that GE used to design the propulsion system. The airport noise, cruise emissions, and fuel efficiency were targets that GE assessed based on the propulsion system developed.

The baseline propulsion system was a variable cycle engine with advanced technology assumptions appropriate for a 2025-30 TRL 6 technology availability date. The engine architecture includes features such as:
- Variable Cycle Technologies
- Advanced Thermal Management
- Axisymmetric Plug (Axi-Plug) Exhaust with Noise Reduction Technologies
- Transonic Thrust Augmentation

Together these technologies provide an advanced propulsion system anticipated to meet the vehicle requirements and environmental goals.

Assessments of the jet noise produced by the propulsion system during takeoff were made to ensure the propulsion system meets the targets provided by Boeing such that the overall airport noise goal is met. The exhaust system proposed in this study provides very high performance due to the Axisymmetric plug configuration, and jet noise reduction features to take advantage of the capabilities of the variable cycle engine to allow higher jet exhaust velocities to be achieved with lower noise levels.

Emission levels are estimated based on the engine cycle and anticipated operational limits of the current TAPS combustor. The emission assessment was likely the most difficult to perform as very limited emission data exists at the very aggressive engine conditions used in this study. It was required to reduce the operating temperature of the propulsion system to meet the current emission goals. It will be required to move to an alternate combustor concept during future studies to retain the highest thermal efficiency possible with this system.

The fuel efficiency goal is targeted through the high thermal efficiency of the engine, smaller diameter, and lighter weight due to the variable cycle features and the high performance exhaust, as well as using moderate thrust augmentation during transonic operation.

A number of trade studies were made looking at ways to reduce the combustor temperature while maintaining the high thermal efficiency of the propulsion system. These included intercooling and interturbine combustion. The results indicate the best trade for the propulsion system to meet the emissions goal was to reduce the operating temperature and accept a small SFC and weight impact.

Roadmaps were developed for the most critical technologies and a list of future work efforts was included.

All of these items are covered in detail in Appendix B

4.1.2   General Electric Propulsion System Overview

The advanced Variable Cycle Engine uses advanced level technologies, and other technologies aimed at an entry into service (EIS) date of 2035. The engine architecture includes variable cycle features and advanced thermal management. The high performance Axi-Plug exhaust includes jet noise reduction technologies.

The advanced thermal management system enables the engine to be designed at a higher overall pressure ratio (OPR) for improved thermal efficiency and enhanced engine life while operating at sustained high core temperature during cruise.

Also, as part of this program, advanced low NOx combustor concepts and technologies were investigated to determine the ability of the propulsion system to achieve the N+3 cruise emission goal. The combustor concepts and technologies and the impact on cruise NOx emissions are discussed in Appendix B. The impact of the combustor exit temperature (T4) on cruise NOx emissions, engine performance, and weight is also discussed in Appendix B.

The exhaust system is critical for supersonic vehicles since the nozzle performance strongly impacts the efficiency of the propulsion system as well as enabling jet noise technologies. The VCE propulsion system also features an Axi-Plug exhaust system. The exhaust has variable area capability to ensure high performance throughout the flight envelope. The exhaust system also provides for a thrust reversing system.

The exhaust also has a feature that augments the mixed temperature of the exhaust by a moderate amount. This system has minimal impact on exhaust performance. Due to the low augmentation temperature and use of advanced materials, no additional cooling is required when the augmentation is on.

4.2 Pratt & Whitney Engine Technology Inputs

4.2.1 Pratt & Whitney Initial Aircraft and Propulsion Concepts

Initial propulsion and aircraft concepts were generated through a joint brain storming session with Boeing, Pratt & Whitney, General Electric, and Rolls-Royce. This effort was conducted at Georgia Institute of Technology and employed various qualitative assessment techniques. The outcome of this activity identified six aircraft concepts that addressed the key N+3 supersonic metrics. These concepts are described in section 3 of this report. From this effort several critical propulsion observation were made that set the technology direction pursued by Pratt & Whitney.

Observation 1: A low boom aircraft design is essential for meeting overland supersonic noise requirements. Low boom aircraft designs are inherently long and slender such that aerodynamic loading and compression characteristics are distributed to reduce the ground level boom. From a propulsion airframe integration perspective this suggested that engine length is a design degree of freedom that could be exploited for overall system advantage.

Observation 2: Low airport noise is critical. Current N+1 (2013-2018 EIS) subsonic engines under development by industry will drive bypass ratio higher to minimize noise and reduce fuel burn. Pratt & Whitney's gear technology will allow this trend to continue without incurring the weight penalties associated with high bypass ratio. By the N+3 time frame subsonic aircraft will likely have bypass ratios on the order of 20-30 and far exceed the N+3 supersonic airport noise goals. Any supersonic system will need to meet, or more likely, exceed N+3 supersonic airport noise goals.

Observation 3: In a high energy cost future, fuel burn dominates aircraft cash operating cost per seat mile and CO2 production goes directly with fuel burn. Therefore, reducing fuel burn can be used as a surrogate for reducing CO2 and improving economics. NOx production will be a challenge, but is not unique to supersonic aircraft and can be assumed to be solved by subsonic technology efforts.

From these three observation Pratt & Whitney focused its efforts on innovating solutions that met boom, airport noise, and fuel burn/CO2 goals. The design implications of satisfying low airport noise and efficient low boom supersonic flight drive the engine in diametrically opposed design directions. Low airport noise requires an engine with high bypass ratio while efficient supersonic flight requires an engine with low bypass ratio. Pratt & Whitney focused primarily on finding solutions to this dichotomy.

4.2.2 Pratt & Whitney Propulsion Concepts

Pratt & Whitney engaged in an internal brainstorming activity to identify propulsion concepts that align with the direction described in the P&W proprietary section 4.1 of Appendix C. The concepts were qualitatively developed based on historical experience, physical review, and innovative brainstorming. Each concept was then categorized by the four elements of a jet engine (inlet, propulsor, gas generator, and nozzle) and performance estimated. These concepts are discussed and prioritized in the Pratt & Whitney proprietary Appendix C. The most promising of these concepts were then refined, quantified, and integrated with the vehicle as described in section 5.0

4.2.3 Pratt & Whitney Analysis & Trades

The traditional approach for executing designs with diametrically opposed requirements is to optimize the system to a Pareto front at which point any further improvement with respect to one goal must come at the expense of the other. If none of these compromise solutions are acceptable from a business or environmental perspective then investment in technology is required to move the pareto front. To date, technology has been insufficient to meet a minimum threshold of acceptability for commercial operations and after a half century of research, there are no commercial supersonic transports in service. Congruent with NASA N+3 goals, Pratt & Whitney pursued concepts and technologies that will enable diametrically opposed goals to be met or exceeded.

The challenge of meeting both low airport noise and low fuel burn supersonic flight was assessed by point designing engines at the extreme of the Pareto front defined by current technology. Conceptually this is illustrated in figure 4.2.1. These two design solutions are referred to as Pareto limit engines. The difference in the design characteristics between these two engines represents the physical barriers that need to be overcome with new technology. The magnitude of the gap determines the closure strategy. If the gap is narrow then it is likely that combinations of incremental technologies can close it. If on the other hand the gap is large then fundamentally new and innovative approaches will need to be pursued.

The two Pareto limit engines were obtained by mining the Pratt & Whitney N+2 supersonic parametric data base established in 2008. An engine was selected that maximized the economic figure of merit (seat*nmi / block fuel) without concern for airport noise and then a second engine was identified that minimized airport noise without regard for economics. These two engines showed that economical supersonic (M=1.6) flight required engine fan pressure ratios on the order of ~3, and conversely, low airport noise required the jet velocity to be less than 1100ft/s and a fan pressure ratio on the order 1.7. These engine attributes were then enforced as requirements and both engines re-evaluated at the N+3 base aircraft mission-thrust profile. Results are shown in the Pratt & Whitney proprietary Appendix C. This activity demonstrated that an N+3 engine must be able to vary its fan airflow and fan pressure ratio almost 2X to satisfy both low airport noise and efficient supersonic flight. Conventional fan architectures can not meet this design range and new propulsor concepts are required.

Concepts that potentially allow a 2X fan flow and meet the required fan pressure ratio range were identified. See Pratt & Whitney proprietary Appendix C. An observation of these systems is that they increased frontal area, i.e., when the engines are in low bypass mode there is significant frontal area that does not swallow flow and results in drag. This is true whether the fans are remote off the engine axis or concentric similar to emerging military 3rd stream concepts. Figure 4.2.2 shows an integrated propulsion aircraft assessment of an auxiliary fan arrangement. The auxiliary fans are remote and are engaged only for around the airport operations and cocooned with an aerodynamic fairing at supersonic cruise. Vehicle assessment showed that the net drag of the vehicle increased 10% at supersonic cruise due to the increased frontal area. This translates into a 10% thrust increase to offset the drag and at constant fuel flow this

would require turbine specific fuel consumption to be reduced ~10%. This TSFC short-fall potentially could be made up with a variety of the candidate gas generator technologies identified in section 4.0. However, these gas generator technologies will pertain to any vehicles in the N+3 time frame, subsonic or supersonic. Therefore, as a practical matter, technologies that negate the drag need to be identified for N+3 supersonic transports if they are to be competitive economically and acoustically. Technologies that reduce the drag associated with auxiliary fans are discussed in Pratt & Whitney proprietary Appendix C along with propulsion airframe integration solutions.

In addition to the propulsor concepts described above several gas generator technologies were investigated. Since gas generator technologies are equally applicable to subsonic, supersonic, industrial, and marine application, they were not studied in as much detail. Pratt & Whitney primarily focused on refining discriminating supersonic technologies. However, of the gas generator technologies identified in section 4.0 of Appendix C, two stood out as having twice the potential of the other technologies. These two technologies are discussed in greater detail in the Pratt & Whitney proprietary Appendix C.

4.2.4 Pratt & Whitney Technology Prioritization.

Boeing accessed the aircraft system impact of the initial engine technologies provided by Pratt & Whitney by applying sensitivity coefficients. The engine technologies that had the greatest system potential were then refined through quantitative analysis and integration with the vehicle. This refinement was conducted by applying the NASA NPSS engine modeling environment. Integration with the vehicle was conducted by providing Boeing with traditional data packs for various groupings of technologies. This approach was used because the physical characteristics of very low TRL technologies were not sufficiently developed to parametrically model in NPSS across the flight envelope. Also, it was not practical within the scope of this contract to assess technologies individually one at a time because of their confounded nature, dimensionality, and limited physics modeling for low TRL concepts. Therefore, the technologies were grouped into bundles that were independent based on physics mechanisms. Three data packs were provided that reflected:
- Baseline enabling concept (data pack STF1841)
- Advanced gas generator concepts → Technology Bundle 1 (data pack TB1)
- Advanced propulsor/inlet concepts → Technology Bundle 2 (data pack TB2)

The details each technology bundle is described in the Pratt & Whitney proprietary Appendix C

4.2.5 Pratt & Whitney Road Mapping

Roadmaps for the baseline and technology bundles were established and are provided in the Pratt & Whitney proprietary Appendix C. These roadmaps were developed to give a holistic view of the activity required to mature each technology. It should be emphasized that the technology concepts as put forth are still very notional. The roadmaps emphasize 5 elements that need to be executed. They are:

- Develop physics models for each concept. These models need to be able to address design and off design performance from an aerodynamic, thermal, structural, kinematic, and controls perspective.
- Propulsion Airframe Integration Optimization. Parametric exploration of the best mission, aircraft, engine, and integration. Establish the relevant environment for technology development and validation.
- Analysis-of-Alternatives (AOA). Assess concept alternatives as physics is refined and integration issues identified.
- TRL Progression Testing from bench tests through supersonic flight demonstrators
- Engine development leading to a 2035 entry into service.

4.3 Rolls-Royce Engine Technology Inputs

4.3.1 Rolls-Royce Process

Rolls-Royce was asked to develop an engine solution for Boeing's -072B supersonic civilian cruiser. In order to meet mission requirements the engine needed to meet three critical sizing points as shown in Table 4.3.1. Other requirements for the mission were to have a 1100 ft/sec jet velocity at takeoff and demonstrate lower NO_x emissions from the N+2 levels. Emissions were assessed at takeoff, subsonic climb and supersonic cruise. It was directed by Boeing that the NASA NO_x emission index method be used

$$NOxEI = 0.0041941 \cdot \left(\frac{P_3}{439}\right)^{0.37} \cdot e^{\left(\frac{T_3 - 1471}{345}\right)} \cdot T_4$$

Since many advanced engines lead to higher pressures and temperatures an amended version of the relation can be found in the proprietary Appendix D. Additional customer requirements were a 0.5 high-pressure bleed as well as an 80 hp power extraction. Generic inlet and exhaust curves were supplied by Boeing in order to provide installed engine performance.

In order to meet or exceed each of the requirements set by Boeing and NASA, new technologies needed to be defined for the 2035 timeframe. A large list of new or updated technologies was initially assessed at a qualitative level before a technology solution was defined and resulted in a subset of the original list. The truncated list was then incorporated into a full engine model where a design space of overall pressure ratio (OPR), fan pressure ratio (FPR), turbine inlet temperature (HPT RIT) and other parameters were defined and explored. Using this process an optimum solution was found and still met all requirements. Once an engine was defined data and scaling rules were sent to Boeing to assess the engine at the aircraft level. The scaling rules were supplied so that the engine could be made larger or smaller as the aircraft requirements changed.

4.3.2 Rolls-Royce Technology Prioritizing, Selection, and Roadmapping

An essential part of the NASA N+3 studies was to assess each technology's worth to the engine system. Once an acceptable engine was chosen a sensitivity study commenced. For the sensitivity study each technology was assessed in terms of drag, weight, fuel burn and noise. The fuel burn was assessed by looking at the cruise condition, the drag has been assessed to be just a function of engine diameter and finally the emissions and noise were assessed at the takeoff condition. Only the takeoff condition was used for emission assessment during the sensitivity study. There were two reasons the delta at takeoff, rather than the supersonic condition, was applicable to the study. First during the optimization of the cycle in 4.3.1 it was noted that the variation in NOxEI did not change much across environmental conditions when comparing different technology suites. Secondly the amended version of the NOxEI equation is baselined to a sea-level static condition. Using the sensitivities found in the technology assessment a prioritized technology list was generated which highlighted what technologies needed to be roadmapped for future development. It should be noted that the technologies chosen were found to be specific to supersonic engines. Specific data associated with the prioritizing, selection and roadmapping efforts are shown in the Rolls-Royce proprietary Appendix D.
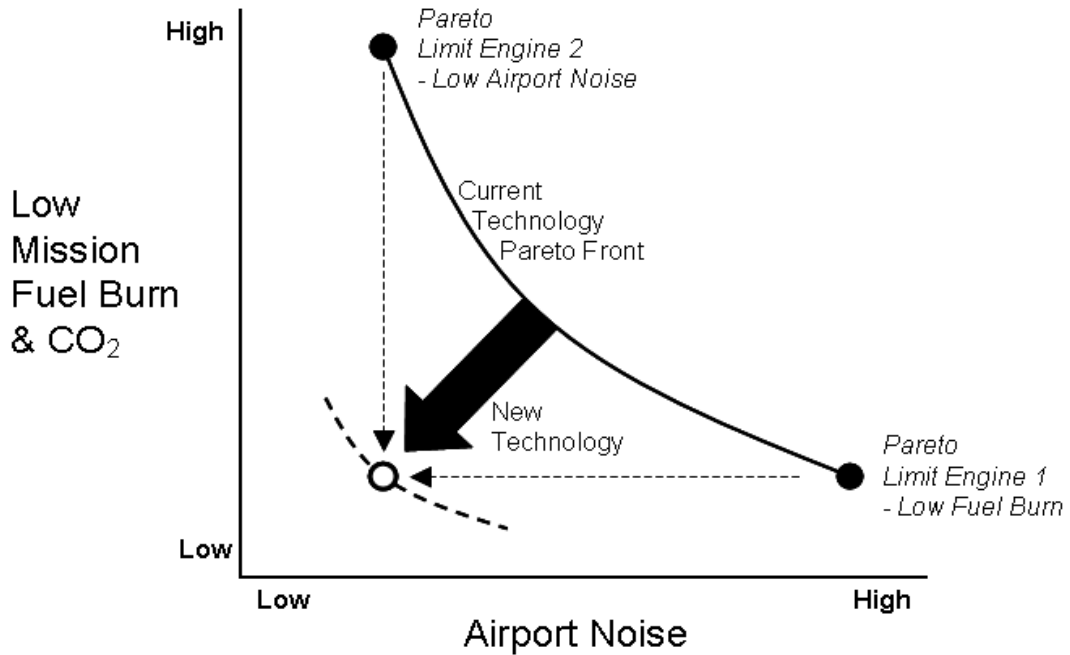
Figure 4.2.1 P&W, Interrogating designs at the Pareto limits provide insight to the magnitude of the technologies required to satisfy both airport noise & low fuel burn.
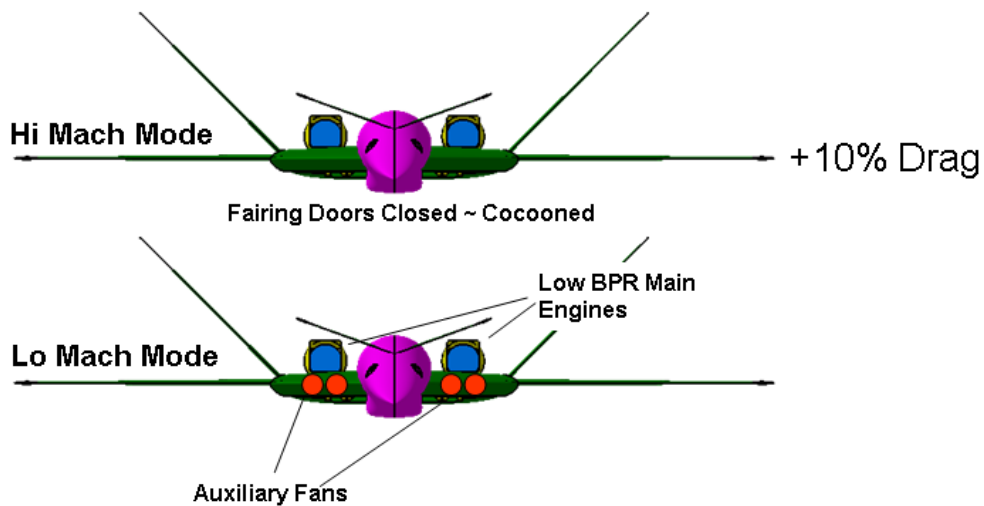
Figure 4.2.2 P&W Cocooned auxiliary fans increase drag 10% and require a 10% SFC improvement to overcome the drag (hold Mach) with 10% more thrust at constant fuel flow

Table 4.3.1 Engine Requirements

Condition	Altitude [ft]	Mach No.	ΔTamb [deg F]
Cruise	55000	1.6	0
Pinch Point	40550	1.13	0
Takeoff	0	0.25	27

40

5.0 Preliminary Engine Analysis and Trades (Task 3.5)

Non-Proprietary

5.1 Point of Departure Vehicle

The N+2 765-072B configuration[4], Figure 5.1, and corresponding optimum NPSS engine definition were used as the point of departure vehicle for assessing the impact of N+3 engine technologies. The -072B concept is a 100 passenger vehicle capable of 4000nmi total range, with a cruise M=1.6 and a TOGW of approximately 300,000lb.

In order to provide context for the results of the N+3 studies, the background of the N+2 -072B vehicle is summarized in the following discussion. This vehicle was the product of a detailed series of N+2 system level trade studies. In order to capture the interactions between the various analysis disciplines (geometry, aero, weights, propulsion, mission performance, takeoff performance), an in-house MDAO model was employed. The system level trades considered passenger count, cruise Mach, cruise range, and engine cycles over a defined supersonic non-stop mission profile.

For the engine cycle trades, a series of candidate engines cycles from engine manufacturers were evaluated. These were provided to the MDAO model in the form of installed thrust and fuel flow tables for a reference thrust. Jet velocity (Vj) served as a surrogate for propulsion noise. It was generally understood that a low diameter engine is needed for best supersonic aerodynamic performance, and a low Vj to minimize the jet noise. However, because of the fundamental physics of turbine engines, minimizing Vj results in a large diameter engine, and vice versa. A trade study was performed on several engine cycles having low diameter, low Vj, or a compromise between diameter and Vj. Following the trades, a preferred concept was selected. The N+2 -072B / NPSS configuration optimized for minimum jet velocity is the point of departure vehicle and source for the initial thrust requirements.

5.2 Initial Engine Requirements

Each engine company (OEM) was provided with the same set of thrust and SFC targets, inlet and nozzle performance schedules, bleed and HPx off-takes, and flight profile data. Relevant inputs are summarized as follows:

A) Key cycle points
  - Cruise (sizing Point): 55,000 ft, Mach 1.6, ISA
  - Pinch Point: 40,550 ft, Mach 1.13, ISA
  - Takeoff: Sea Level, Mach 0.25, ISA + 27 deg F

B) Customer Requirements
  - 80hp extraction
  - 0.50 pps high pressure bleed

C) Installation/Integration
  - The baseline inlet design is an external compression tailored 3D inlet of fixed geometry. Reference inlet recovery, spillage drag, bleed drag maps were supplied.
  - The baseline nozzle design is a two-dimensional convergent-divergent nozzle with variable area ratio. Data supplied included drag coefficients and gross thrust coefficients.
  - The inlet and nozzle data were used at the discretion of each engine manufacturer, depending upon their configuration.

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[4] N+2 Supersonic Concept Development & Systems Study, July 2009, final report to NASA

D) Mission Definition
- The supersonic mission profile is displayed in Figure 5.2

The engine OEMs would then provide data packs of key engine data. They provided engine size, weight, and scaling exponents. Several iterations were made with the OEMs, based on changes to cycle settings and/or geometry.

The values for power extraction and bleed airflow in the Customer Requirements, above, are reference values. In actuality they would be highly dependent on airplane size and systems architecture details. The reference values used represent optimistic levels for a generic small future airliner at cruise conditions, assuming technology progress in the future energy efficiency of airplane systems, cabin systems, and vehicle thermal management. If scaled current year (~787 type) airplane systems were assumed, the resulting engine performance would likely show increases in SFC up to 0.3-2.4% (depending on airplane size and mission profile) relative to the decks supplied by the engine companies based on the reference levels shown. All airplane level performance in the N+2 and N+3 studies was computed based on propulsion decks using the reference extraction levels which were held constant regardless of airplane size or configuration details being considered. This assumption has made the primary configuration and technology increments under study easier to track.

5.3 Engine & Vehicle Sizing Process

The Boeing medium fidelity parametric airplane model, along with the provided engine data, was modeled in the similar MDAO environment as was used on the N+2 studies. The engines were nominally considered to be under-wing podded engines on the -072B configuration.

For each of the trade study points, the concept was re-optimized through "sizing" to maximize the cruise efficiency Figure of Merit (FOM) = Seat*nmi/lbs of block fuel, by varying the wing area and engine size (reference thrust). Each engine and airplane combination was sized holding range and payload constant, allowing TOGW to vary. The MDAO model resized the airframe as the engine, wing and fuel load changed. When the wing area is scaled, the MDAO model recalculates all the aerodynamics, weights, and resulting performance. When the reference thrust is scaled, the MDAO model changes engine size/weight, along with the thrust and fuel flow tables. When the engine size changes (diameter, weight, length) the nacelle will also change. So the aerodynamics must be recalculated. All of these will affect the performance.

The aircraft optimization was subjected to the following constraints:
- Greater than 300 fpm rate of climb (ROC) anywhere in the mission
- Less than 10,000 ft balanced field length with noise derate (tradable)
- Sufficient fuel volume in the wing (desired) or wing and fuselage (required)
- Less than 78 psf wing loading (W/S) maximum wing loading @ T/O
- 4000 nmi range with a 100 passenger, cabin, 1.6Mach cruise speed

The implication of using the N+2 modeling method for the N+3 studies is the following. Because range is held constant, for a parametric model this means that the vehicle can scale down. Therefore, vehicle weight and required thrust goes down. Since the engine configurations offered for the N+3 studies had the potential for higher performance than the N+2 reference engine, the vehicle could be resized by several thousands of pounds, leading to fairly substantial changes in vehicle performance.

When it was initially noticed that vehicle performance was in some cases significantly beyond the goal, an investigation was performed into the feasibility of the MDAO model results. The investigation confirmed the powerful compounding effects of the optimization method. For instance, a lower SFC means less fuel used during a mission, leading to lower weight and drag. A smaller fan diameter due to higher specific thrust results in lower drag. Therefore, when the vehicle and engine are resized, the lower drag leads to less

fuel, resulting in lower weight, and therefore lower wing area. The outcome of the investigation confirmed that the MDAO was predicting reasonable results.

5.4 Overall Engine and Vehicle Performance Assessment With -072B Configuration

Efficiency

All engine concepts demonstrate innovative approaches to achieving an adaptive cycle capable of high performance for the given requirements. They have aggressive cycle parameters such as high OPR and turbine temperatures. All engine concepts resulted in efficiency FOM values which exceeded the goal of 3.5, ranging in values from 18% to 38% better than the goal. Such fuel efficiency increases could be feasible with technologies such as sophisticated inlet flow management, advanced materials, efficient thermal management systems, and transonic thrust augmentation, which enables reductions in engine size.

TOGW

All configurations resulted in vehicles with TOGW's well below the N+2 optimum baseline of ~300,000 lbs. They were between about 220,000 – 280,000 lbs. The un-scaled fan diameters range from about 76 to 91inches; when resized during the optimization process, the fan diameters ranged from about 60 to 80 inches. This compares favorably to the optimized N+2 fan diameter of about 95in. The un-scaled engine weights range from about 8200 to 12000 lbs; when resized during the optimization process, the weights were in general much lower than the optimized N+2 weight of nearly 12000lbs. The ability of the engine concepts to resize well below the N+2 optimum reflects the benefits of the advanced technologies which were incorporated. However, it was found that, much below 270,000lb TOGW, the proportions of the 100-passenger body relative to the wings and nacelles made it impossible to re-draw a reasonable configuration with the predicted sizing (i.e. the sizing re-optimization would drive the configuration into a part of the design space where the vehicle would no longer re-integrate). In such a case, the design range was increased above the 4000nmi minimum before re-cycling the configuration.

Emissions

All configurations noted challenges with achieving the emissions targets. The OEMs were given the following empirical equation to calculate emissions, based on legacy programs such as HSR:

$$NOxEI = 0.0041941 \cdot \left(\frac{P_3}{439}\right)^{0.37} \cdot e^{\left(\frac{T_3 - 1471}{345}\right)} \cdot T_4$$

Although initially used, this equation was considered not entirely applicable to the N+3 studies. To reduce the potential for over predictions, the results were factored down based on literature research and consultation with subject matter experts. Other calculation methods were also employed. While some reduction relative to N+2 was found, it was generally concluded that the goal could be met only if cycle temperatures were reduced. This would, however, adversely affect efficiency FOM.

Noise

In general, the engine configurations were sized such that a Vj target of 1100 ft/s or less was met at sideline noise conditions. If the Vj target was exceeded and additional noise-mitigating technologies were included, further acoustic assessments were performed to justify having sufficient potential to meet the noise targets with deeper derates, more aggressive nozzle designs, and/or changes to the airframe.

Design Weight is 300,000lbs
Design Mach=1.8
Overall Length 241
Design payload is 100 passdual class
Payload 25,000lbs

Body Volume Updated
(Net Body volume decreased to
14282cuft or 142cuf/pass)

Nacelle contain
83.55' Fan Hi-BPR
60,000lbs SLST/engine
• 2-D inlet
• 2-D Nozzle

Vertical Only
aftbody

Wing Reference
Area=3988sqft

Wing/Body fairing houses
two post 4wheel truck

Figure 5.1 Configuration 765-072B low fuel burn configuration from NASA N+2 study.

Mission

Supersonic
Cruise / Climb
Constant Mach,
Optimum Altitude
(53k ft limit)

Climb and Accelerate to
Optimum Supersonic
Cruise M & h

Descend and decelerate

See specified
climb / descent
Schedule to right

Taxi Out (9 Minutes)

Takeoff to 35 ft

Climbout and Accelerate
to 1,500 ft & 250 kts

Approach and Land (4 Minutes)

Taxi In (5 Minutes from Reserves)

Still Air Range

Block Time & Fuel

Mission Profile	ALTITUDE (FT)		MACH		Notes
	Initial	Final	Initial	Final	
CLIMB	1500	10000	0.39	0.45	Climb at 250 KCAS from 1500 ft to 10,000 ft
CLIMB	10000	10300	0.45	0.69	Accelerate to 375 KEAS at roughly constant altitude (10,300 ft)
CLIMB	10300	20774	0.69	0.85	Climb at constant 375 KEAS to Mach 0.85 (~20,800 ft altitude)
CLIMB	20774	35000	0.85	0.85	Climb at constant Mach 0.85 to 35,000 ft
CLIMB	35000	39000	0.85	0.95	Climb and accelerate to Mach 0.95 at 39,000 ft
CLIMB	39000	41000	0.95	M-crz	Climb and accelerate to Supersonic Cruise Mach (1.6 to 2.0) at 41,000 ft
CLIMB	41000	h-opt	M-crz	M-crz	Climb to optimum initial cruise altitude
					Climb / cruise with 53,000 ft maximum altitude
DESCENT	53000	39000	M-crz	0.95	Descend & decelerate to Mach 0.95 @ 39,000 ft
DESCENT	39000	34960	0.95	0.85	Descend to Mach 0.85 and 273 KEAS (altitude ~ 35,000 ft)
DESCENT	34960	20774	0.85	0.85	Descend at Mach 0.85 and 375 KEAS (altitude ~20,800 ft)
DESCENT	20774	10300	0.85	0.69	Descend at constant 375 KEAS to ~10,300 ft
DESCENT	10300	10000	0.69	0.45	Decelerate to 250 KCAS at roughly constant altitude (10,000 ft)
DESCENT	10000	1500	0.45	0.39	Descend to 1500 ft at constant 250 KCAS

Figure 5.2: Supersonic Mission Profile

6.0 Airframe/Engine Analysis and Trades (Task 3.5)

Preliminary brainstorming for configuration features and technologies identified several configuration categories and several technologies that influenced the specific study airplanes. Configuration features of interest included very long and slender bodies, minimum thickness lifting surfaces, variable geometry wings, and over-wing inlets. With sufficient development, such features and several generally applicable technologies could advance substantially and become practical within the N+3 timeframe. This section describes a variety of configurations assembled to serve the dual purposes of evaluating these features and technologies, and selecting the most promising N+3 configuration. Two more radical alternative configurations, an oblique "scissor" wing and a joined wing concept, are also briefly examined in light of the expected enabling N+3 technologies.

6.1 Configuration Development

High body fineness is one of the general features expected in the N+3 generation of supersonic airplanes. While a long slender body has some potential for wave drag reduction, the primary appeal is the opportunity to shape and minimize the sonic boom. But weight and flexibility are concerns that will put practical limits on what degree of configuration slenderness for boom is realistic. Rather than using extra material or adding internal structural components, the most promising remedy allowing significant slenderness increases seems to be active structural mode control and aerodynamic load (e.g. gust & maneuver) alleviation as part of an integrated flight control system. A relatively smaller but important benefit can be expected from using tailored stiffness materials that might be developed. A slender body would unfavorably reduce the cross-section of the flight deck and obstruct pilot vision, likely demanding a full-time forward external vision system (XVS).

Higher fineness ratio wing planforms (minimum thickness and greater quarter chord sweep angles) are required for minimizing the sonic boom of N+3 airplanes, presenting flexibility problems similar to those of slender bodies. Such surfaces can be expected to have flutter and limit cycle oscillation (LCO) issues. Low-frequency "hump mode" flutter may exist at points in the normal operating envelope, and on very long bodies the structural mode frequencies may be on the same order as the frequencies of the flight control system. As the aircraft structure deflects, alignment of the engine inlets and nozzles may change, and structural vibrations of the lifting surfaces may couple with oscillating deflections of the fuselage. Tailored structural concepts and materials will help, but the most promising solutions are also likely to require the addition of active control of the structure and loads. A very slender N+3 airplane would probably need a complete aero- propulso- servo- elastic (APSE) control system to stabilize the aircraft and structure, relieve gust and maneuver loads, and avoid flutter throughout the flight envelope.

A configuration feature identified as being of potential interest is variable wing geometry in the form of variable sweep. While it offers some promise of "fine-tuning" the configuration for climb, acceleration, cruise and any boom control phases of flight, the most attractive feature of variable sweep is a potential improvement in low-speed performance (e.g. take-off field length, engine-out climb, approach speed, take-off and approach thrust requirements). An interesting alternative to symmetrical swing-wings is the oblique "scissor" swing-wing which could offer the same low speed advantages and capture fuel burn savings at lower supersonic Machs. Such a concept could even offer efficient flight at "threshold Mach", thereby offering an alternative "no boom" operational solution over land.

Nacelles for all the study airplanes for N+3 are over the wing. It sacrifices the favorable supersonic interference potential that is inherent in lower mounted nacelles, and requires inlets and engines to be more tolerant of distortion. But over-wing nacelles promise better shielding of noise sources from inlets, turbomachinery, nozzle and jet exhaust, and allow more freedom to integrate the area and lift distributions during the sonic boom design tailoring. The inlets for N+3 study airplanes project the use of "diverter-less" nacelles, relying on alternate upstream or internal boundary layer management through a combination of shape optimization, suction panels and active flow control (AFC) devices. These features may be combined

with aerodynamically tailored 3D inlets that offer high pressure recovery and compact (shorter, lighter) installations with minimal moving parts.

Some technologies required for a swing-wing or oblique "scissor" wing airplane (e.g. reliable, fail-safe & compact bearings and actuation systems) are applicable to those configurations exclusively. But most structural, aerodynamic, boom reduction and systems technologies for N+3 would benefit any configuration by roughly the same amount. The net benefit however, is not always easy to quantify for an individual technology. For example, some technologies are *enabling* technologies rather than ones that directly provide weight, L/D or SFC improvements. For example, the APSE control system mentioned above would essentially add weight, volume and complexity to an airplane, and save weight on only heavy, slender structures. But it might *enable* an otherwise infeasible slender body and wing combination, for which the payoff comes in design options that lead to a better overall configuration solution. Other examples of enabling technologies are lightweight shaped composite armor for firewalls and containing a burst engine rotor, which is key to enabling podded or other close side-by-side engine arrangements; high toughness/low density material that reduces weight in lightly loaded areas of minimum gage; and materials for high temperature & acoustic loads for aft decks, noise shielding and nozzles.

6.2 Detailed Studies of Selected Concepts and Technologies

This section outlines selected configurations employing technologies representing promising and addressable concepts from the preliminary Georgia Tech workshop which are shown in Figure 6.2.1. The first is configuration 1C that has a variable sweep "arrow" wing. Its promise is low fuel burn that might result from tailoring the performance across the flight envelope, and low boom. Next is configuration 2C, a scaled-up version of the model 765-076E reference low boom airplane from the N+2 study[5]. It has a fixed wing and a V-tail expected to help tailor the sonic boom and to shield aft engine and exhaust jet noise. Configuration 2C is the basis for "Icon-II", the Boeing recommended N+3 reference airplane which will be discussed at length later. A joined wing and oblique "scissor" wing configuration are used to explore significantly different configuration alternatives. Finally, "remote fan" technology is applied to a generic supersonic airframe to explore its potential. Note: the number designations for these configurations signify nothing more than the order of their original graphical layout, and the letters signify revisions (typically minor) of the original "A" model.

A central task of the N+3 project is to assess the impact of technology. It could affect the choice of engine, the choice of airframe, and determine the ultimate performance of the airplane. With several engines and several airframes under consideration, answering some preliminary questions about matching, and sizing optimization is necessary to properly balance the performance. At one extreme, using each combination for every study and assessment would be comprehensive, but could be formidable, and, at the other, a hasty reduction to a single combination or single condition could hide important results. A series of preliminary sizing studies help answer some important questions about how to proceed with the broader engine/airframe studies. Proprietary engines from each of the engine companies are employed. Their weight, size and performance represent the engine companies' forecasts for technology at the N+3 level and under N+3 noise, performance and emissions requirements. Each engine and its performance is described in more detail in the separate appendices B, C & D. NPSS engines from the 765-076E (scaled) and the 765-072B from N+2 are also used for reference. For these preliminary studies, the airframe technology is assumed to be at the outer limits of "N+2" in light of the aggressive general arrangement of the "-076" type, with thin surfaces, novel engine integration, and high body fineness ratio. Some important questions about how to proceed can be addressed using these preliminary studies.

First, does the choice of configuration have a large effect on the relative evaluation of the engines? The answer is no, based on results from sizing the thrust to maximize range for the 765-072B and 765-076E airplanes from N+2 using each of 4 engines, including the N+3 study engines supplied by the three engine companies. Because these results are based on proprietary engine company data, they appear together in Proprietary Appendix A, and separately in Appendices B, C & D. For each airplane, MTOGW was fixed

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[5] N+2 Supersonic Concept Development & Systems Study, July 2009, final report to NASA

(300,000lb for the -072B and 180,000lb for the -076E) and wing area was fixed (3988 sq ft for the -072B and 2516 sq ft for the -076E). The relative range achieved using the various engines is about the same for each airplane, demonstrating that the configuration does not strongly affect the engine evaluation.

Does the choice of cruise Mach number have a large effect on the relative evaluation of the engines? No, not according the results from sizing thrust for maximum range on the 765-072B, with each of four engines, at 1.6 & 1.8 Mach. The relative range from each of the engines is about the same at the two cruise Machs. Results are in Proprietary Appendix A.

Does wing area have a large effect on the relative evaluation of the engines? Again, no, based on similar thrust sizing results where wing area of Configuration 1C was first held fixed at 4700 sq ft (sufficient for carrying nearly all required fuel in wing tanks), then changed to 3800 sq ft (nominally the value that maximizes range, but requires fuel tanks within the fuselage). These results can be found in Proprietary Appendix A.

These preliminary results provide some confidence that a study using a single engine/airframe combination should provide a general result without much risk of overlooking some unique benefit or issue arising from a specific combination. Thus, a single configuration, 2C, is used for the incremental technology effects assessment with an expectation that the results will be generally applicable. The choice of Configuration 2C is discussed later.

6.2.1 Low Fuel Burn/Low Boom Swing "Arrow" Wing: Configuration 1C.

Configuration 1C is described in Figure 6.2.2, with details of the planform and a three-view in Figure 6.2.3. Table 6.2.1 summarizes the features of this configuration. The swing-wings have the potential to nearly double the overall wing span of the configuration at lower subsonic Mach, resulting in nearly 4 times the aspect ratio. As configured here, 1C has three surfaces for trim, and only forward noise shielding is provided by the over-wing nacelle installation since there is little aft deck area. 5000lb is estimated for the wing pivot and actuation system, and 15,000lb is estimated for the relatively high aspect ratio movable outboard panels. A complete breakdown of the weight is provided in Table 6.2.2. Some fuel volume in the wing is lost due to the pivot joint and actuator, and overall volume increases because of the thickness assumed for the pivot. The swing-wing geometry assumed is based on in-house experience with variable sweep concepts incorporating lessons learned from the design of the B-1 bomber and more recent in-house design studies. The strake has constant sweep located to avoid shedding a vortex that might be ingested by the engine. High aspect ratio and sweep of the moveable wing panels, and the absence of an aft deck to support the engines suggest that APSE might be a challenge for this configuration.

Variable sweep configurations show lower drag in the transonic speed range, and large potential drag reduction at landing and takeoff conditions (along with an increase in low-speed lift at alpha which improves approach/touchdown attitudes). To fully exploit the advantages, re-optimized engine cycles should be matched to the airframe, but that was not within the scope of the present activity. As a result, the ultimate integrated benefit of variable sweep remains unmeasured, but the significant costs can already be estimated. A comprehensive evaluation would require significant design, engine-airframe MDO, and multi-point aero optimization efforts.

Unfortunately, many low-boom supersonic configurations are not sized by low-speed performance exclusively, since the wing loading can be constrained by climb profile and boom considerations, and the low supersonic "thrust pinch" often sizes the engine. So the principal advantages of variable sweep are not always realizable. While some improvements in wing pivot bearing and actuation design have been made since aircraft like the F-14 and B-1, variable sweep still requires relatively heavy and bulky bearings and actuation systems that will inevitably reduce the available fuel volume within the wing, and add to the overall configuration cross-section and weight. Compared to a contemporary fixed planform selected to provide a good compromise between high and low speed performance (e.g. the 2C or -072 types), a swing-wing of similar size provides only a modest aerodynamic advantage anywhere in the mission profile except

in the mid-subsonic to low speed regime the wing can be nearly unswept. A lower landing speed does become possible and engines may be de-rated further to meet takeoff noise goals (without the need for airframe shielding). Some future applications of a "swing-wing" general arrangement can't be entirely ruled out. However, if sufficient noise reduction can be obtained through variable cycle engines, airframe shielding, and low-impact suppressor nozzles, and field performance is automatically met by the relatively low wing loading required for low sonic boom designs, then the overall incremental benefit of the variable sweep wing may not be worth the added risk and complexity.

6.2.2 Configuration 2C, 100 passenger scaled 765-076E from N+2.

Configuration 2C is described in Figure 6.2.4, with a three-view and characteristics in Figure 6.2.5. It is essentially the 765-076E configuration from N+2 but scaled and re-integrated to accommodate 100 passengers at 300,000lb MTOW. Notable features are the V-tail for noise shielding and boom control, and the fin-tip pods for housing ballast to tune the V-tail structural dynamics and potentially help volume tailoring for low boom. The planform represents a typical compromise of a fixed-wing for supersonic cruise and low speed performance and handling. The 2C represents technology closely tied to the levels assumed for the final N+2 reference configuration, but some elements of this larger cousin would require "N+2+" enablers (e.g. materials mix and APSE flight controls) even prior to any application of specific N+3 advances. The characteristics in Table 6.2.3 and the weight breakdown in Table 6.2.4 show further details. Configuration 2C will serve as the point-of-departure for developing the N+3 "Icon-II" Boeing recommended study airplane. The 2C is designated configuration 765-107A as shown here, and becomes 765-107B after developing into the "Icon-II" concept which rolls in all applicable N+3 technologies and an increase in payload to 120 passengers and cargo.

6.2.3 Alternate Concept: Joined Wing (3B)

The joined wing concept shown in Figure 6.2.6, detailed in Figure 6.2.7, was identified for its possible structural efficiency, stiffness in structural modes important for dynamic conditions, and an unexplored potential to favorably affect the boom by directing shocks aft of the otherwise trailing re-compression. Characteristics of the configuration are in Table 6.2.5.

As this joined wing concept was studied further, it was realized that an undesirable feature of the high tail is that it would reflect some engine noise downward. More significantly, the promised structural advantages are not certain. Thin supersonic tail surfaces offer little buckling resistance from end-loads, and the inherent relief of critical high static loads through bending of an ordinary cantilever wing is limited by this stiff arrangement. The stiffness of the nacelle attached to the wing might not be improved over an aft-deck alone. A more detailed Finite Element Model (FEM) structural analysis and design would be necessary to identify and maximize any structural advantages of a joined wing. Table 6.2.6 is a breakdown of the weight, with no advantage assessed for the joined structure. This particular weights summary also includes a heavier, older technology engine than the others, but if a credible structural weight assessment and design could be made of the joined wing concept, then its performance could be compared to other configurations by installing equivalent engines.

Optimizing the twist and camber of the wing and tail for minimum drag in Tranair changes the lift distribution by an amount comparable to what was achieved using the same process for the 765-076F in the N+2 study. Figure 6.2.8 shows these results at 1.8 Mach and 0.12 CL for configuration 3B. A drag reduction of 8 counts is achieved by reducing peak Mach numbers over the wing slightly, and shrinking the area over which they appear, evident in Figure 6.2.9. Nearly 30 counts remain between the drag of this highly constrained optimum and the forecast, but tail size and other features of the integrated configuration have not been refined from their initial values. It is likely that a simultaneous design for drag and boom would be necessary to explore the low sonic boom potential of this concept—an effort significantly beyond the scope of the present study.

The trial drag optimization resulted in a more aft center of lift, as shown in Figure 6.2.10, creating a challenge to balancing the airplane, payload and fuel. So, while the aft area in the joined tail might be good for boom, and maybe for supersonic trim, it is unfavorable for subsonic trim and loadability. A canard or longer strake might help, but would add wetted area and drag at their intersection with the body. It is also possible that the extra wetted area of the tail (a source of both weight and drag) would offset any potential APSE benefit of the joined wing arrangement, and that any boom advantage would be realized over only a small range of operation. A significant effort of CFD and FEM analysis and design would be required before assuming the advantages.

6.2.4 Alternate Concept: Oblique "Scissor" Wing (4B)

The oblique "scissor" wing configuration is an attractive and somewhat radical alternative for a supersonic transport. An example in configuration 4B is shown in Figures 6.2.11 and 12. It offers the possibility of nearly twice the lifting length as a conventional wing of comparable size. A straight load path across the wing root, potential to align the center of lift with the payload, and the ability to transform from a nearly optimum unswept flapped low speed wing at high lift conditions to a highly swept supersonic configuration with an entirely subsonic leading edge make this an attractive alternative to the traditional "swing-wing".

But the oblique "scissor" wing was originally aimed at low supersonic cruise, so most supersonic design and testing has been done at Mach numbers less than about 1.4, and most early CFD analysis (typically Euler) neglected important viscous effects. A significant concern on this concept was that "real flow" viscous effects could limit the maximum Mach number at which this type could cruise efficiently and without airframe buffet. A brief CFD study was conducted to understand this risk issue. Figure 6.2.13 shows viscous CFD results from CFD++ at 1.4 Mach and 3 deg AOA on a wing-body representative of the 4B. 40 million grid elements are used for a solution at a flight Reynolds number of 2 million/ft. With the wing swept 60 degrees (for a normal Mach number near 0.7 across the airfoil), the boundary layer on the trailing edge of the downstream wing is separating. Any higher Mach would require higher sweep, and the problem would be exacerbated. Careful design could help minimize the affect, but probably not eliminate it unless other sacrifices were made.

While the oblique "scissor" wing offers nearly twice the lift length of a conventional configuration, and, therefore, some natural reduction in boom overpressure and PLdB, it offers few design alternatives for shaping the boom beyond simply reduced over-pressure "N-wave". Therefore, an optimized "conventional" configuration that exploits all of the advances through the N+3 timeframe remains the more promising concept if true low-boom is to be achieved.

Employing the oblique "scissor" wing concept for operation at threshold Mach is attractive. It could be a fall-back position in case boom regulation is strict. At lower supersonic speeds, there is potential for higher efficiency, particularly if landing or takeoff conditions size the wing area, and boom considerations would not influence the wing loading or any other characteristics of the supersonic design. The highest possible threshold Mach would probably be chosen, both for the obvious advantage of speed, and for the less obvious advantage of avoiding the increasing sensitivity of focused booms to maneuvering near the speed of sound. The ability of the "scissor" wing to provide so much low-speed performance (i.e. L/D) from a configuration with favorable supersonic drag might allow simpler and lighter engines, having both performance and cost advantages. But the true performance potential would be realized only after matching the engine characteristics to the airframe, similar in scope to what was done on the HSCT, and that is not a part of this N+3 study. Future studies should consider re-visiting this concept for supersonic flight at shorter ranges (e.g. U.S. trans-continental) with reduced fuel burn potential if reduced cruise Mach is an option.

6.2.5 Preliminary Airframe Comparisons

Comparing the aerodynamic performance of the these candidate concepts in Figure 6.2.14, all can achieve about the same lift-to-drag ratio at a point (e.g. Mach 1.8 cruise) except the joined wing 3B that, as drawn,

has significantly more wetted area in the large joined tail. The consequent skin friction drag hinders the performance of the joined wing 3B at all Mach numbers. At subsonic Mach, the aerodynamic advantage of variable sweep is evident in the "swing-wing" increment for the 1C configuration, shown with and without variable sweep. Variable sweep is also responsible for part of the advantage of configuration 1C over 2C at low supersonic Mach, but a significant portion of the advantage at supersonic speeds is achievable from varying camber with simple flaps on the aft deck. Configuration 2C is shown without optimum aft deck flap deflections, but could roughly match configuration 1C at low supersonic Mach. The scissor wing 4B appears to have significantly higher L/D at all Mach below cruise, especially at subsonic Mach. Not apparent at this level of analysis, however, is whether the range factor Mach*L/D/SFC could be as high at lower supersonic Mach as at cruise Mach of 1.8, where all aircraft of this study were aimed. As the brief CFD study demonstrates, the promise of an oblique scissor wing configuration is tempered by the risk of buffeting and potential stability and control issues arising from viscous flow effects. The data shown for the scissor wing also presumes a joint and fairing between the wing and body that does not compromise the aerodynamics at any condition. With these challenges in mind the likely maximum practical cruise Mach number for the Configuration 4B is set at 1.4. The two curves for the 765-107A and 107B "Icon-II' will be discussed later. Area+thrust sizing "thumbprint" charts for configurations 1C and 2C are in Figures 6.2.15 and 6.2.16 as examples of the information available to assess the airplanes. For both configurations, cruise range could be increased if the wing area and thrust were lowered from their original values, but fuel volume, second-segment climb gradient, and thrust margin constrain the area and thrust to remain about the same as their original values. Additionally, the aggressive sonic boom targets for N+3 would probably add another constraint in the form of a lower bound on wing area that still offers potential for sufficient boom reduction.

6.3 "Icon-II" Airframe and Engine, Configuration 765-107B.
-- Description of Preferred Designs

6.3.1 Icon II Airframe
Considering the costs, penalties, and uncertain benefits of variable geometry or the other alternative configurations considered, configuration 2C became the point of departure for developing the "Icon-II", Boeing's reference N+3 technology concept airplane. Because the alternative configurations 3B and 4B would have required extensive detailed design, and potentially reconsideration of the basic requirements (e.g. cruise Mach for the scissor wing 4B) in order to fairly assess their potential, both were not considered to be viable reference aircraft. Between 1C and 2C, the swing-wing 1C seemed attractive for the possibly lower approach speed, improved climb-out performance and noise, and lower thrust required for thrust pinch. But a large part of the advantage of 1C would have to come from sizing the wing down. Not only would a smaller wing require significant volume in the body for fuel tanks, but raising the cruise wing loading might prevent achieving the aggressive boom goals. Any aerodynamic advantages must overcome the increased structural weight of the pivot and highly swept outboard wing to realize a net performance advantage, and that performance advantage must be large enough to justify the complexity and cost of designing, building and maintaining the joint and actuator. Considering these challenges facing the 1C, and the fact that 2C has comparable cruise performance, along with another cycle of more detailed design and analysis of a similar configuration for the N+2 Experimental Validation project, 2C was selected as the basis for "Icon-II" reference airplane.

A first step in developing the "Icon-II" was doing a preliminary sizing and incorporating the best performing N+3 engine. Results are shown in Table 6.3.1. The first result is from sizing only thrust to maximize range for Configuration 2C at Mach 1.6 with wing area and MTOGW fixed. The resulting range is 4600 nmi. Using preliminary estimates of 10% reduction in operational empty weight (OEW) and 6% potential reduction in cruise drag, and sizing both the wing area and thrust to minimize weight at fixed 4000nmi range, the theoretical takeoff gross weight is reduced substantially. Unfortunately, the configuration is not feasible because the over-wing nacelles and landing gear do not integrate into such a small wing. Using 5000nmi range instead, and repeating the sizing relieves some of the integration challenge, but not all. The cruise speed sensitivity proved to be relatively flat; changing from 1.6 Mach to 1.8 Mach has little effect, assuming that equally efficient over-wing inlets can be designed using similar technology.

From an airline's perspective, the most promising resolution would likely be to maintain the original 300,000 lb design MTOGW and trade away some of the range (nearly trans-Pacific, as shown in the last two lines of Table 6.3.1) for an increase in cabin size. This would immediately improve the seat nmi/lb figure of merit through additional seats, with initially modest cost in total fuel burn. On this basis, the vehicle was re-drawn for a 120 passenger dual-class version, and now the impact of technology can be more carefully assessed.

Structural concepts from N+3 applied to the "Icon-II" airplane include some advanced materials, as shown in Figure 6.3.1. Also assumed is an active APSE control system to alleviate gust and maneuver loads, tailor the configuration (e.g. spanload) for optimum efficiency, control the flexible airframe, and actively suppress flutter. In addition to the materials and control system advancements, authority to design and certify the structure based on reliability, rather than allowable stress as is traditional, is assumed. The weight saved should be comparable to that saved by advanced materials and an APSE control system. Progress in airframe optimization is expected to deliver some additional reduction in weight by the N+3 timeframe.

At the top of the list of aerodynamic technologies applied to the "Icon-II" is hybrid laminar flow control (HLFC) on at least the wing, and possibly the tail. Riblets would cover all other surfaces for reduced turbulent skin friction. In addition to their basic drag reduction, application of HLFC and riblets would have the favorable side effect of eliminating some excrescence by smoothing over some manufacturing seams. Flex hinges and morphing flap geometry would also address some excrescence, particularly when controls are deflected. Progress in CFD-based design should provide overall improvement, and specific assistance in integrating the propulsion system and optimizing in the presence of propulsion induced flow-fields. Some unfavorable aspects of over-wing inlets should be mitigated by improvements to design methodology. Active control systems should permit significantly aft CG, and fine-tuned drag reduction throughout the envelope. Advancements in high-lift aerodynamics might contribute to maximum lift and drag reduction through configuration sizing relative to field performance, approach speeds, and community noise constraints.

Airframe noise is improved by some of the same features that reduce drag. Some examples are flex hinges, sealed & morphing leading edge geometry, flush antennas & air data system sensors, and streamlined landing gear fairings. Noise from the propulsion system is reduced by the wing shielding inherent in over-wing nacelles, acoustic liners for the inlet and nozzle, chevrons or actively controlled exhaust jet edge flow-field, and shielding by the V tail.

Boom is addressed in N+3 primarily through airplane general arrangement and the assumption of improved simultaneous optimization for drag and boom, and slender configurations that offer design freedom. Over-wing nacelles also offer some design freedom to affect boom with minimum consequences elsewhere. A nose boom for adding forward body length might be beneficial. Even more nose length could be added by using a retractable probe like the Gulfstream "Quiet Spike", at some penalty in weight and complexity. But, there is generally little to be gained in PLdB for front shock reduction below the level attainable in the rear of the aircraft. Regulation and certification criteria are unknown, but expected to be challenging. Advanced design methods and configuration strategies provide hope that the challenge can be met.

A careful "bottoms up" estimate of the benefit of these technologies applied to Configuration 2C results in about 5% reduction in OEW, and 10% reduction in cruise drag. These values are the basis for performance improvements between the "N+2+" levels assumed for the initial N+3 study airplanes, and the final "Icon-II", designated 765-107B. Comparing the 765-107B "Icon-II" to configuration 765-107A (i.e. an intermediately refined configuration 2C with 100 passenger body and no aft deck flap optimization), Figure 6.2.13 demonstrates the advantage in lift-to-drag ratio afforded by this reduction in drag.

A three-view of the "Icon-II" configuration, 765-107B, is shown in Figure 6.3.2. It is essentially the Configuration 2C, but with ride control vanes, a moderate fixed nose boom, and a slightly broader fuselage that accommodates 120 passengers in a dual class arrangement, shown in Figure 6.3.3. The cabin accommodates 50 passengers in a spacious "executive" interior arrangement, as shown in Figure 6.3.4,

demonstrating one of the alternative cabin utilization concepts. If seating comfort were reduced for an "all tourist" charter type configuration, around 130 passengers could be accommodated.

The drag of the 765-107B is explained in Figure 6.3.5. It shows that scaling the 765-076E up to the 100 passenger Configuration 2C changed the cruise lift-to-drag ratio (L/D) a small amount, from 8.3 to 8.47. The cruise L/D increases to 9.46 once the 10% drag reduction from N+3 technology is applied and the fuselage has been grown to accommodate 120 passengers. Comparing the L/D of the 765-107B to some of its predecessors, Figure 6.3.6 shows better L/D for the HSR 2015TC[6], but a pretty close match to a 2015TC with revised technology predictions and scaled 76% to be about the same size (i.e. airplane size plays a significant role in L/D differences due to Reynolds number and excrescence scaling). The benefit of N+3 technology over N+2 is evident when compared to the 765-072B from N+2.

6.3.2 Icon II Engine

6.3.2.1 General Description

The N+3 goals call for low cruise emissions (~5 g/kg NOx), high range (4000-5500nmi), and high fuel efficiency (3.5-4.5 seat nmi/lb fuel at 4000-5000nmi). For trade study purposes, "stretch goals" beyond the NASA N+3 goals, partly based on desirable market economics, were specified for the "Icon-II" vehicle configuration. These called for, among other things, increased range (4800-5000nmi) and fuel efficiency (4 - 5 seat nmi/lb fuel). The Icon-II vehicle sizing was performed for fixed wing area and a fixed TOGW of 300k lb (tied to approach speed limits and top-of-climb boom design point). The engines were resized to maximize range.

The "Icon-II" airframe was paired with an N+3 technology level reference engine (referred to as the "Icon" engine). This is a notional engine meant to represent the most promising combinations of technologies disclosed by the engine OEMs, and is used as a concept engine for trade studies only. The Icon "composite" propulsion concept represents no particular OEM's design and does not imply commitment from any OEM to design or develop such an engine, especially regarding weight and geometry. As described later, this notional engine provides projected propulsion performance levels which enable the Icon-II airframe to meet the basic N+3 performance requirements and even approach the "stretch" goals.

6.3.2.2 Methodology

To create the Icon engine configuration, all engine technologies were reviewed in order to determine which technologies were a) common, and b) most beneficial. The performance data for the Icon engine is based on the N+2 -072B NPSS data. Factors were applied to the data such that its vehicle range would meet the N+3 stretch goals. Further details are in proprietary Appendix A.

6.3.2.3 .Results

An overview of the engine configuration can be seen in Table 6.3.2 and Figure 6.3.7.

6.3.3 Icon II Performance

Figure 6.3.8 is a thumbprint sizing chart showing the as-drawn 765-107B "Icon-II" having some margin in wing area and thrust (de-rated as required to meet projected noise) in the configuration. Where the approach speed and second segment climb gradient constraints meet, a small advantage in increased range, reduced thrust, reduced wing area, and improved seat nmi/lb fuel FOM could be achieved if another sizing cycle had been allowed. Changing the wing area and thrust to achieve this would be a first step in the

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[6] High Speed Civil Transport—2015 Technology Baseline Airplane Configuration, D6-82527-3, April 2000, NAS1-20220

development of this configuration. The table in Figure 5.2 presents the mission profile used to evaluate the airplane.

6.3.4 Icon II Noise

As described in Section 6.3.1, advances in noise reduction, suppression and efficiently integrated shielding should give the N+3 generation of aircraft an advantage over the N+2 generation. Starting at the levels of airport and community noise predicted for the study aircraft of the N+2, the Icon-II gains from better high lift performance, light weight and low impact ejector/suppressor nozzles and effective shielding that is more efficiently integrated into the configuration. The noise level of the "Icon-II" is expected to keep pace with the ever more strict noise requirements.

6.3.5 Icon II Structural Arrangement

The structural arrangement assumed for the 765-107B "Icon-II" is essentially the same as for the 765-076E from the N+2 study, with appropriate adjustments for the effects of airplane size and passenger cabin dimensions on the floor height, window spacing, stowage bins, landing gear sizing, fuel tank volume allocations, etc.. The wing has multiple spars and the thin outboard wing has little volume for anything but structure. The wing tip and tail tip are solid. A torque box gives rigidity to the thin aft deck, allowing it to resist and transmit tail loads, but supplemental external keel structures in the aft deck, as on the 765-076E, might be unavoidable. The fuselage is essentially monocoque, but a supplemental internal keel beam is likely. Landing gear will match those described in Table 6.2.3 for configuration 2C, and the main gear bays demand innovative structure to route wing carry-through loads, and articulate mechanisms to ensure compact stowage with minimum fairing.

6.3.6 Progress toward the goals

A comparison of the capabilities of the "Icon-II" 765-107B against the goals is shown in Table 6.3.3. In every category, the airplane is forecast to exceed the minimum goals, and often reaches the stretch goals.

6.4 Technology Trade Studies

6.4.1 Aeroelastics & Material Trades (submitted by M4 Engineering)

The initial assessment of technology benefits was based on experience with previous vehicle development activities. Technologies selected in the loads and aeroelasticity area included; active gust load alleviation (GLA) and maneuver load alleviation (MLA), active flutter suppression, and aero-propulsive-servo-elasticity (APSE).   In order to better quantify the benefits associated with aeroelastic and material technologies on flutter, detailed analyses were conducted on a relevant configuration. The starting point for these analyses was the final FEM from the NASA NRA N+2 studies. The model was first modified to provide a more relevant baseline for the N+3 analyses where the structural layout was modified to improve load paths. The model is shown in Figure 6.4.1. The baseline titanium strength sized model was provided to M4 Engineering Inc. for aeroelastic studies to assess flutter margins and to determine potential benefits of active flutter suppression. A range of materials was considered, including the baseline titanium design, aluminum, a baseline composite and an advanced composite.   The material properties are shown in Table 6.4.1.

The flutter speed margins were based on the flight envelope of the N+2 system studies as shown in Figure 6.4.2. Starting with strength sized models for all four materials, flutter analyses were conducted to establish margins.   The titanium and aluminum configurations did not meet flutter margin requirements.   The composite configuration vehicles are stiffer and suppress the flutter mechanism present in the more flexible metallic configurations. The details of these analyses are provided in the M4 Final Report provided as an attachment.   The titanium and aluminum configurations then went through a resizing process using the aeroelastic optimization capability in MSCSoftware NASTRAN to meet both the strength and flutter

requirement. Table 6.4.2 summarizes the results. The column marked 'Baseline' shows the structural weight for the 4 configurations sized for both strength and flutter. The column marked with 'FSS', for Flutter Suppression System, shows the structural weight with just strength requirement, and provides an upper bound of weight reduction when implementing a flutter suppression system.   The addition of the flutter constraint to the sizing of the all titanium vehicle results in the addition of 7282 lb of structural weight (6.3% OWE) to the baseline vehicle.   For an all aluminum construction, the flutter penalty is 34,390 lb of structural weight (19.7% OWE). The flutter characteristics present in these configurations could be mitigated through the use of an active flutter suppression system, which could result in a significant avoidance of structural weight.   The details of the analysis are provided in the M4 final report and this report has been provided as an attachment in Appendix G.

Based on the technology assessments and detailed analyses performed, a roadmap has been developed for developing and improving the technologies to support the N+3 timeframe as shown in section 7.

6.4.2 Sonic Boom

The forecast sonic boom levels for the N+3 vehicle concepts represent a mix of classical Jones-Seebass-George-Darden theory of sonic boom minimization, emerging N+2 technology advancement, and predictions of future N+ 3 developments assuming the appropriate investments are made.

The basic principles of how to reduce the sonic boom of supersonic aircraft with classical signature shaping has been available for decades. Seebass and George published "Sonic boom Minimization Including Front and Rear Shock Waves" in 1969. This paper laid out the basic principles and theory, and proposed the minimum sonic boom an aircraft concept might achieve as a function of aircraft weight, length, Mach and altitude. What was absent at the time was:
1. Definition of what sonic boom loudness would be acceptable to the public at large
2. Significant innovation in the areas of aerodynamics, propulsion, and structures (to minimize aircraft physical size and weight)
3. Technological progress in flight controls and in various ASE disciplines (to handle the required long, slender, thin-winged aircraft designs)
4. Validated, high fidelity analysis tools to accurately predict a configuration's sonic boom level at all regions of its supersonic flight envelope
5. Flight verifications of the shaping theory
6. Definition of a feasible compromise between aircraft features selected for sonic boom minimization criteria and features to meet performance, safety, emissions, and noise requirements.

Much of the subsequent HSR sonic boom related work in the 1990's, and a substantial portion of the NASA and industry funded sonic boom research since then, has been directed toward addressing each of these areas. In addition, research has also focused on the MDO problem of defining aircraft features like weight, length, planform, general arrangement that would place a concept design space where the high speed lines could potentially be optimized to achieve the configuration's low boom objectives with the available design tools. In 1998, Seebass revisited minimum achievable sonic boom as defined by the classical Jones-Seebass-George-Darden theory, with his paper on "Sonic Boom Minimization" presented at the Special Course on "Fluid Dynamics Research on Supersonic Aircraft" held at the von Karman Institute for Fluid Dynamics (VKI). For reference, based on the method of that paper, an aircraft of the "Icon-II" size, length, Mach, and altitude, would have a "Seeb minimum" potential boom loudness level of 79PLdB.

Our expectation is that between now and the technology readiness date for an N+3 supersonic airliner, assuming the continued necessary investment in sonic boom mitigation technology, significant progress will be made in at least three more recent promising areas of sonic boom design development research. These progress areas would include:

- Expanded use of MDO and higher order tool suites (CFD, FEM's) applied to classical Jones-Seebass-George-Darden theory of sonic boom minimization. This approach focuses on

minimizing the sonic boom on a "macro" level by changes to the overall lift and volume distribution. This is done by maximizing the effective length and minimizing the weight of the aircraft with effective MDO design, as well as tailoring the general arrangement of the aircraft to achieve target lift and volume distributions with minimal compromises to overall performance parameters.

- Enhanced use of emerging optimization capabilities coupled with advances in computing power to work both full configuration and configuration component features on a "micro" level to take advantage of near-field aerodynamics and exploitation of non-linear effects. This potential resides in using wave interference, wave cancellation, nacelle shaping and positioning, etc. to manipulate the near-field signature well before the fully formed far-field signature develops and "freezes" on its way to the ground.

- Developments in harnessing the potential of active flow control, unsteady aerodynamics, energy manipulation, active geometry morphing, etc… at a micro level for the benefit of sonic boom mitigation

It is important to recognize that although we expect significant progress to be made in sonic boom design capability, we also believe a trade will remain between utilizing the emerging technology for the exclusive purpose of sonic boom reduction versus the purpose of improved performance, reduced emissions, reduced costs and so forth. Consequently we have only forecast the "Icon-II" as having boom levels at ~77PLdB, even though its optimum signature is assumed to be distinctly non-SEEB. While we foresee the possibility of an aircraft in the same size/weight category of the "Icon-II" possibly achieving a lower bound of 65-70pldb if all the sonic boom technology potential is realized, the 65-70PLB level may come at a substantial performance /economic /fuel-burn penalty which may constitute an unfavorable compromise.

In addition to Boeing's own assumptions as to the future pace and direction of low boom design technology, Wyle Labs has proposed fine-tuning the source/multi-pole distribution, as demonstrated in the Wyle Labs GENGS tool (see non-proprietary Appendix E), to drive that boom level down to the goal. Translating the theoretical description of the off-body pressure field into practical aircraft geometry or load is among the many challenges facing development of low boom technology maturity in the N+3 timeframe.

6.4.3 NextGen System Wide Environmental Assessment of Technology Impacts (submitted by Wyle Labs)

Pursuing advanced aircraft designs and NAS technologies is a vital component of a comprehensive strategy to reduce aviation environmental impacts, including those related to climate forcing. The aviation industry is pursuing various transformational concepts for environmentally-friendly subsonic and supersonic aircraft to be introduced into the NAS within the NextGen framework and beyond. N+3 vehicle concepts presently offer the most ambitious targets in terms of environmental impact reduction from the source. In terms of emissions and fuel burn, NASA's Subsonic N+3 program (Table 6.4.3) aims to achieve a set of highly stringent targets:

- More than 80 percent reduction in LTO Nitrous Oxide (NOx) emissions compared to CAEP 2 standards,
- Mitigation of contrail formation, which have a climate forcing effect,
- More than 70 percent improvement in fuel efficiency compared to current Stage 4 aircraft,
- The preponderance of alternative fuel use.

These stringent goals for emissions and fuel burn are to be pursued in concert with an equally stringent goal to reduce noise at the source. What is more, the Boeing Team N+3 Supersonic concepts and Technology Programs under study are targeting a supersonic transport vehicle—injecting additional environmental considerations, namely sonic boom and stratospheric emissions. Hence, even though achieving win-win outcomes for all the environmental effects associated with future aircraft is possible, there are several design tradeoffs and operational constraints that make aggressive NextGen goals for environmental impact

mitigation challenging and require further development in order to achieve a technology readiness level suitable for incorporation into a viable future supersonic aircraft.

There are notable gaps in the current body of aviation climate change research and there is further progress to be had on the accurate modeling of cruise emissions, especially stratospheric emissions, which would be relevant to the vehicle concepts considered under this study. Wyle modeled the emission distribution across the NAS (Figure 6.4.3) for a 2025 NextGen condition that would likely only see the introduction of a few N+1 and N+2 concepts[7]. This modeling exercise showed that cruise emissions by a select vehicle class (Single-aisle/medium-haul) produce over 60 percent of domestic US emissions. The modeling of a supersonic business jet with a frequency of 85 daily operations proved to contribute less than 1 percent of total NAS emissions.[7] This shows that from a system-level perspective, the largest impacts, and the potential for their mitigation currently lies within a particular market segment and a smaller supersonic transport market is unlikely to alter that picture. Yet other concerns with high altitude supersonic operations, namely climate forcing issues remain.

There is still an ongoing effort to understand and accurately model non-CO2 climate forcing effects by aircraft emissions during the cruise phase of flight, where emissions are directly injected into Upper Troposphere (UT) or the Stratosphere as would be the case for high altitude supersonic transport operations. These emissions, including SO2, Particulate Matter (PM), H2O, have local and transient effects on irradiative forcing, through reactions that impact ozone, formation of contrail and other direct/indirect PM effects. PM is of particular concern for aviation due to its direct effects on human health, including respiratory and cardiac complications.[8]

The total climate forcing effect of non-CO2 emissions is believed to equal the CO2 emissions produced by aircraft operations.[9] However, the scientific community still lacks a thorough understanding of these interactions at high altitude. Further observational and modeling research is needed before their effects on climate change can be accurately accounted for. Despite these gaps, the cruise emissions that Wyle modeled for a separate NRA provide a good start for understanding the proportionality and distribution of emissions across the NAS and the effects of introducing advanced supersonic vehicles on NextGen goals for environmental mitigation. Such an approach can also serve to help prioritize the various emissions and performance technology programs by providing a system wide assessment of their contributions and benefits relative to one another.

Another approach to evaluate the environmental performance of advanced vehicles is to measure their impacts in relation to their productivity in the NAS and/or the capacity they serve. We generally found that this becomes a challenge for supersonic vehicles of which the value served in the NAS is one of time saved.[10] It is exceedingly difficult to quantify the value of time saved in the NAS as a result of supersonic operations and compare those benefits to the environmental footprint of the vehicle. Hence, analyzing the emissions and climate change effects of future supersonic aircraft currently faces two analytical challenges: (a) existing gaps in scientific understanding and modeling of stratospheric emissions, and (b) the difficulty of concluding an effective tradeoff metric for the vehicle that communicates its benefit in relation to its impact.

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[7] Rachami J., Page J., Zhou L., "Environmental Modeling of Advanced Vehicles in NextGen", AIAA 2009-6981, 9th AIAA Aviation Technology, Integration and Operations (ATIO) / Aircraft Noise and Emissions Reduction (ANERS) Conference, September 2009.

[8] Environmental Protection Agency (EPA). Health and the Environment. Available: http://www.epa.gov/particles/health.html

[9] Intergovernmental Panel on Climate Change (IPCC) (2000). Aviation and the Global Atmosphere, chap 6, Potential Climate Change from Aviation.

[10] Rachami, J., and Page, J., "Sonic Boom Modeling of Advanced Supersonic Business Jets in NextGen", 48th Annual AIAA Aerospace Sciences Meeting, AIAA 2010-1385, January 2010.

- Low fuel burn/low boom swing "arrow wing" (1C)

- Reference N+2 low boom -076 scaled up (2C)

- Alternate Concept: Joined Wing (3B)

- Alternate Concept: Scissor Wing (4B)

- Remote fan proposal
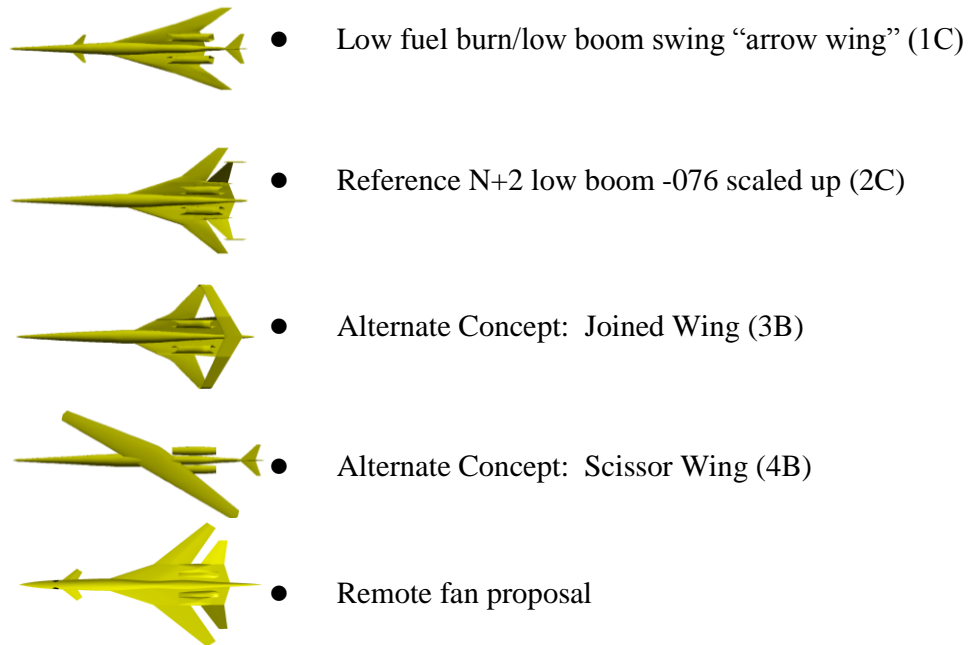
Figure 6.2.1 Preliminary configurations for study.

Forward noise shielding by wing

Swing wing 5000lb

High AR and sweep 15000lb

Constant sweep strake to avoid vortex ingestion.

Wing/Body fairing houses two axle 4-wheel truck

Challenges: APSE issues arise from high AR, high sweep and minimal aft deck to support engines.
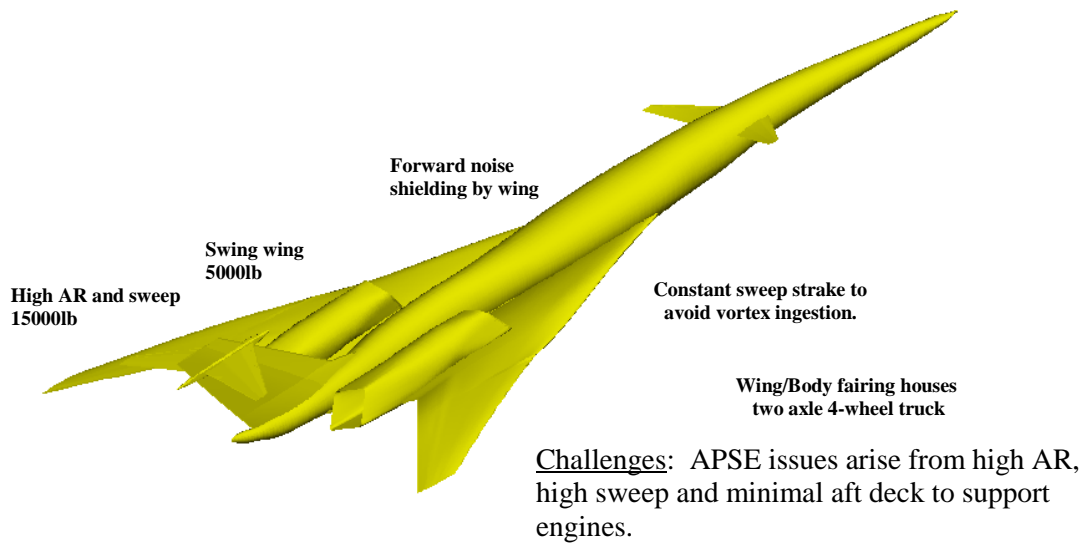
Figure 6.2.2 Walk-around chart of Configuration 1C, 3 surface swing "arrow" wing.

model	DATA TABLE (as drawn airplane)				
N+3 Concept 1C	Wing		Canard	Horizontal	Vertical
ITEM	ESDU	Total		Tail	Tail
Area to CL	4700.924	4808.2			
Exposed			161.99	300.84	581.67
Reference	4700.924		161.99	300.84	581.67
Aspect Ratio	1.64	1.61	3.15	3.15	2.00
Taper Ratio	0.126		0.250	0.25	0.387
LE Sweep angle	71.98		48	48	62
Dihedral, TE	12	12	10	0	0
T/C	0.024	0.024	0.030	0.030	0.030
Tail Volume		0.129	0.046	0.082	0.0791
Span , in	1054.3	1054.27	271.1	184.7	289.4
Root Chord, In	1140.5		137.7	187.6	420.3
Tip Chord, in	143.6		34.4	46.9	165.4
M.A.C. IN	771.1	869.7	96.4	131.3	315.9
X 1/4 mac	1939.9	1887.8	900.3	2931.9	2613.9
Y, Zmac	195.4		96.2	79.9	145.4
Tail Arm, IN.			1039.6	992.0	674.0

89.8ft

259.4 ft
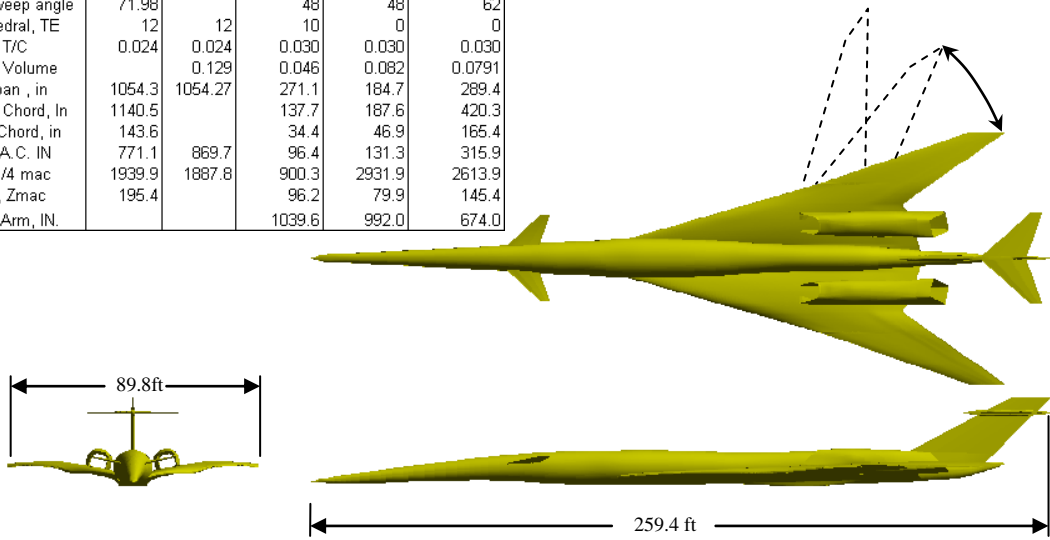
Figure 6.2.3 Three-view and characteristics of Configuration 1C, swing "arrow" wing.

Table 6.2.1 Characteristics of Configuration 1C, swing "arrow" wing.

N+3 Concept 1C	
Weights (Targets)	
Maximum Taxi Weight (MTW) (lb.)	303,000
Maximum Takeoff Weight (MTOW) (lb.)	300,000
Maximum Landing Weight (MLW) (lb.)	240,000
Engine Type	
SLST (lb)	60,000
Fan diameter (in.)	86.44
Overall Dimensions	
Overall Length (ft., in.)	242.0
Fuselage Length (ft., in.)	242.0
Passenger Cabin Length (ft)	96
Wing	
ESDU Reference Area (sq. ft.)	4701
Span (ft.)	87.9
Outboard LE Sweep (°)	71
ESDU Reference Area LE Sweep (°)	71.98
Empennage and Canard	
Horizontal Stabilizer Area (ref., sq. ft.)	300.8
Combined Vertical Tail Area (exposed, projected, sq. ft.)	581.7
Combined Canard Area (exposed, projected, all-moving, sq. ft.)	162.0
Passenger and Baggage Capacities	
Pass. Count	100
Total Cargo Capacity (cuft)	900cuft
Landing Gear	
Wheel base (ft., in.)	1402
Main Landing Gear Track (ft., in.)	423
Main Landing Gear Truck Size (width x length, in.)	Dual Tandem
Main Landing Gear Tire Size	H40x14.5-19
Nose Landing Gear Tire Size	H22x8.25-10

Table 6.2.2 Preliminary, un-cycled weights for Configuration 1C, "swing–wing".

	Model N+3 Concept 1C Rev. INITIAL, MCTCB, N+3, LONG CON-DI		
		Growth 300,000 lb	
FC	Description	Weight	CG
01	Wing Structure	57660	2247
02	Horizontal Tail Struture	2490	2920
03	Vertical Tail Structure	3390	2686
04	Fuselage Structure	16700	1372
05	Main Landing Gear	7400	2049
07	Nose Landing Gear	1010	443
08	Forebody Controls	940	904
	Structure Total	**89590**	**2069**
09	Inlet Structure and Systems	4620	2220
10	Cowling	2160	2362
11	Pylon/Strut	1820	2354
12	Engine	18940	2333
13	Nozzle	5680	2505
14	Installation (incl. fairings)	1340	2354
15	Engine Accessories, Controls, & Start System	200	2377
	Propulsion Pod Total	**34760**	**2350**
23	Fuel System	4490	2205
24	APU/EPU	120	1204
27	Instruments	830	867
28	Surface Controls	3140	1890
29	Hydraulic Power System	2560	1829
30	Pneumatic System	0	0
32	Electrical System	2330	1484
33	Electronics	510	1885
34	Flight Provisions	760	400
35	Passenger Accomodations	10440	1552
37	Cargo Compartment	580	2647
38	Emergency Equipment	600	1541
39	Environmental Control Systems	1180	2281
40	Ice Protection	210	2517
49	Exterior Markings	650	1722
50	Load and Handling	0	0
55	Customer Options	800	6320
	Systems & Fixed Equipment Total	**29200**	**1855**
	Manufacturer's Empty Weight (MEW)	**153550**	**2092**
97	Standard and Operational Items	5360	1635
	Operational Empty Weight (OEW)	**158910**	**2076**
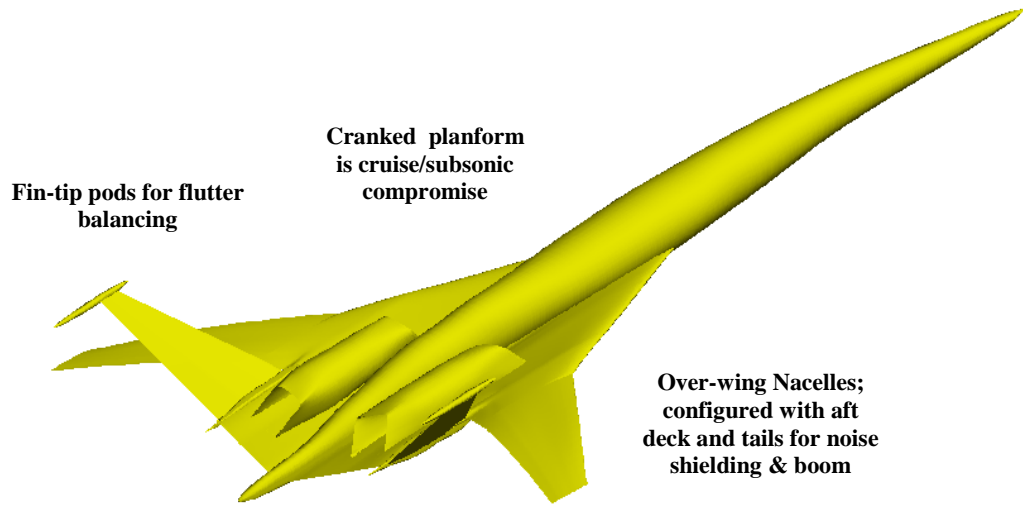
Figure 6.2.4 Walk-around chart of 100 passenger Configuration 2C /"765-107A", (scaled from N+2 765-076E)

model	DATA TABLE (as drawn airplane)				
N+3 Concept 2C	Wing		Horizontal		Vertical
ITEM	ESDU	Total	Projected		Projected
Area to CL	3964.224	4230.2			
Exposed			420.47		420.47
Reference	3964.224		420.47		420.47
Aspect Ratio	2.92	2.74	3.15		3.15
Taper Ratio	0.170		0.198		0.198
LE Sweep angle	57.40		48		48
Dihedral, TE	12	12	45		45
T/C	0.024	0.024	0.030		0.030
Tail Volume		0.103	0.103		0.0411
Span , in	1291.3	1291.29	519.4		519.4
Root Chord, In	755.6		275.3		275.3
Tip Chord, in	128.6		54.4		54.4
M.A.C. IN	516.2	685.1	189.5		189.5
X 1/4 mac	2043.2	1918.2	2544.1		2544.1
Y, Zmac	246.5		317.0		317.0
Tail Arm, IN.			500.8		500.8

107.6

242 ft
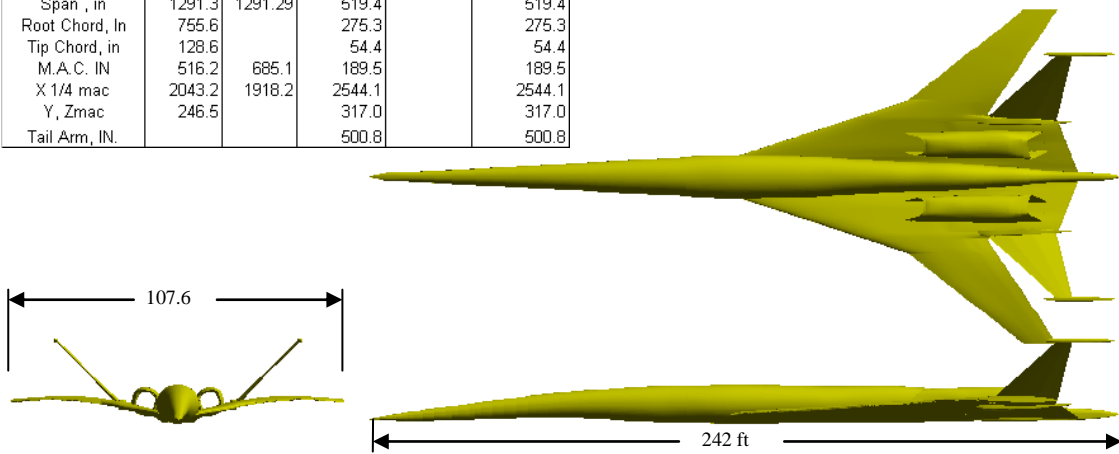
Figure 6.2.5 Three-view and characteristics of Configuration 2C

Table 6.2.3 Characteristics of Configuration 2C.

N+3 Concept 2C	
Weights (Targets)	
Maximum Taxi Weight (MTW) (lb.)	303,000
Maximum Takeoff Weight (MTOW) (lb.)	300,000
Maximum Landing Weight (MLW) (lb.)	240,000
Engine Type	
SLST (lb)	60,000
Fan diameter (in.)	86.44
Overall Dimensions	
Overall Length (ft., in.)	242.0
Fuselage Length (ft., in.)	242.0
Passenger Cabin Length (ft)	96
Wing	
ESDU Reference Area (sq. ft.)	3964
Span (ft.)	107.6
Outboard LE Sweep (º)	52
ESDU Reference Area LE Sweep (º)	57.40
Empennage and Canard	
Horizontal Stabilizer Area (ref., sq. ft.)	420.5
Combined Vertical Tail Area (exposed, projected, sq. ft.)	420.5
Combined Canard Area (exposed, projected, all-moving, sq. ft.)	0.00
Passenger and Baggage Capacities	
Pass. Count	100
Total Cargo Capacity (cuft)	900cuft
Landing Gear	
Wheel base (ft., in.)	1564
Main Landing Gear Track (ft., in.)	305
Main Landing Gear Truck Size (width x length, in.)	Dual Tandem
Main Landing Gear Tire Size	H40x14.5-19
Nose Landing Gear Tire Size	H22x8.25-10

Table 6.2.4 Preliminary, un-cycled weights for Configuration 2C

Model N+3 Concept 2C Rev. INITIAL, MCTCB, N+3, LONG CON-DI		
	Growth 300,000 lb	
FC Description	**Weight**	**CG**
01 Wing Structure	40460	2213
02 Horizontal Tail Struture	4570	2611
03 Vertical Tail Structure	1740	2306
04 Fuselage Structure	15720	1452
05 Main Landing Gear	7400	2109
07 Nose Landing Gear	1010	1004
08 Forebody Controls	0	0
Structure Total	**70900**	**2044**
09 Inlet Structure and Systems	4620	2245
10 Cowling	2160	2388
11 Pylon/Strut	1820	2380
12 Engine	18940	2359
13 Nozzle	5680	2531
14 Installation (incl. fairings)	1340	2380
15 Engine Accessories, Controls, & Start System	200	2403
Propulsion Pod Total	**34760**	**2376**
23 Fuel System	4110	2117
24 APU/EPU	610	1060
27 Instruments	830	1099
28 Surface Controls	3460	1998
29 Hydraulic Power System	2210	1901
30 Pneumatic System	0	0
32 Electrical System	2330	1483
33 Electronics	510	1885
34 Flight Provisions	760	600
35 Passenger Accomodations	10340	1552
37 Cargo Compartment	580	2647
38 Emergency Equipment	600	1541
39 Environmental Control Systems	1190	2279
40 Ice Protection	210	2497
49 Exterior Markings	590	1722
50 Load and Handling	0	0
55 Customer Options	800	6318
Systems & Fixed Equipment Total	**29130**	**1856**
Manufacturer's Empty Weight (MEW)	**134790**	**2089**
97 Standard and Operational Items	5360	1660
Operational Empty Weight (OEW)	**140150**	**2072**
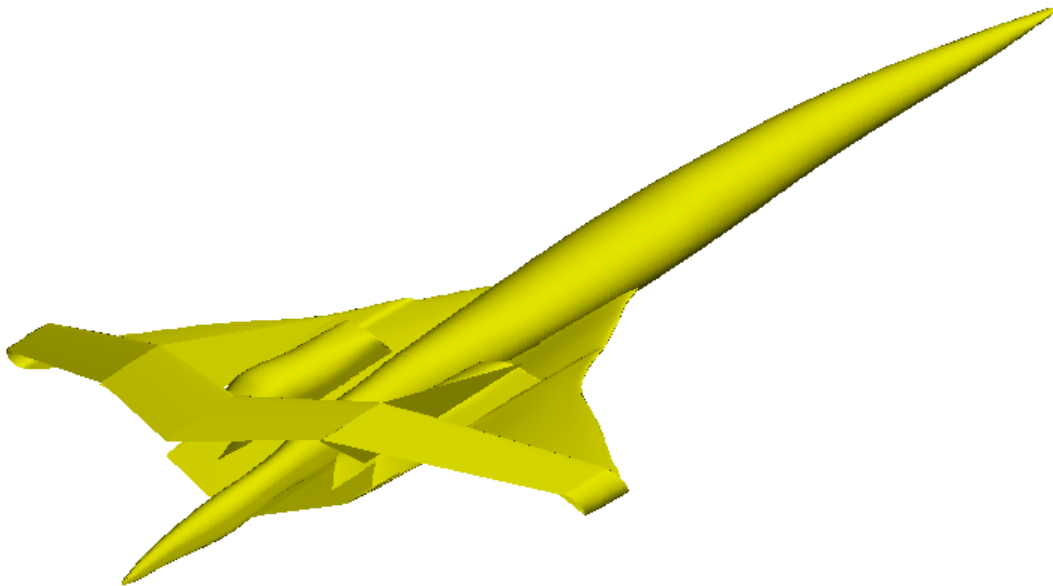
Figure 6.2.6 Configuration 3B, preliminary Joined Wing.

model	DATA TABLE (as drawn airplane)				
N+3 Concept 3B	Wing		Horizontal	Canard	Vertical
ITEM	ESDU	Total			Tail
Area to CL	3224.646	3415.5			
Exposed			1071.4		477.8
Reference	3224.646		1071.4		477.8
Aspect Ratio	3.10	2.93	7		0.77
Taper Ratio	0.199227		0.6		0.616
LE Sweep angle	50.67		-25		54.49
Dihedral, TE	12	12	-8.76		26.14
T/C	0.024	0.024	0.030		0.030
Tail Volume		0.442	0.442		0.0457
Span , in	1200	1200	1200.0		163.0
Root Chord, In	645.3449		214.3		235.7
Tip Chord, in	128.57		128.6		188.6
M.A.C. IN	444.4695	552.580	175.0		251.9
X 1/4 mac	1868.346	1791.132	2460.1		2238.2
Y, Zmac	233.2259		275.0		155.1
Tail Arm, IN.			591.8		369.9

104.6ft

242 ft
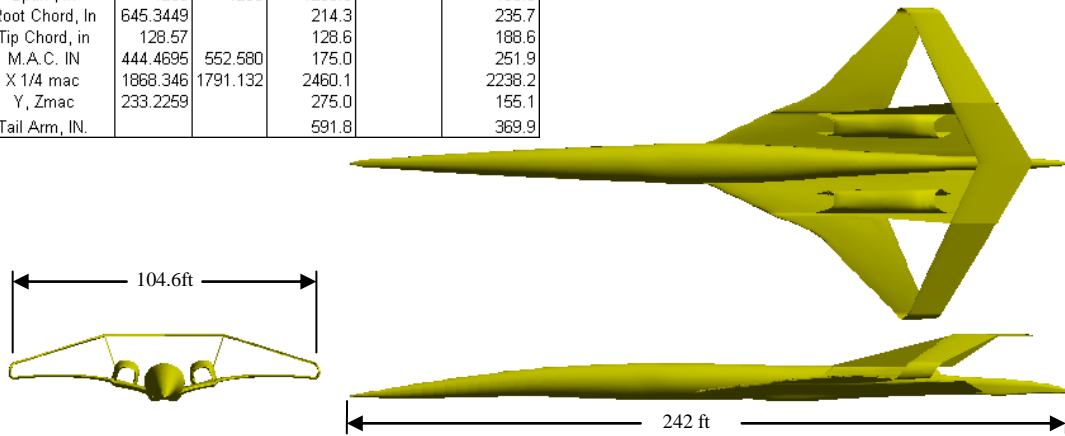
Figure 6.2.7 Three-view and characteristics of Configuration 3B, preliminary Joined Wing.

65

Table 6.2.5 Characteristics of Configuration 3B, preliminary Joined Wing.

N+3 Concept 3B	
Weights (Targets)	
Maximum Taxi Weight (MTW) (lb.)	303,000
Maximum Takeoff Weight (MTOW) (lb.)	300,000
Maximum Landing Weight (MLW) (lb.)	240,000
Engine Type	
SLST (lb)	60,000
Fan diameter (in.)	83.55
Overall Dimensions	
Overall Length (ft., in.)	242.0
Fuselage Length (ft., in.)	242.0
Passenger Cabin Length (ft)	96
Wing	
ESDU Reference Area (sq. ft.)	0.0
Span (ft.)	114.0
Outboard LE Sweep (°)	45
ESDU Reference Area LE Sweep (°)	1684.5
Empennage and Canard	
Horizontal Stabilizer Area (ref., sq. ft.)	1071.4
Combined Vertical Tail Area (exposed, projected, sq. ft.)	477.8
Combined Canard Area (exposed, projected, all-moving, sq. ft.)	0.02
Passenger and Baggage Capacities	
Pass. Count	100
Total Cargo Capacity (cuft)	900cuft
Landing Gear	
Wheel base (ft., in.)	1346.88
Main Landing Gear Track (ft., in.)	429.9
Main Landing Gear Truck Size (width x length, in.)	Dual Tandem
Main Landing Gear Tire Size	H40x14.5-19
Nose Landing Gear Tire Size	H22x8.25-10

Table 6.2.6   Preliminary, un-cycled weight breakdown of Configuration 3B, preliminary Joined Wing. Note: No weight advantages assessed for joined structure. Engine is a heavier, N+2 technology model.

FC	Description	Weight	CG
Model N+3 Concept 2B Rev. INITIAL, MCTCB, N+3, LONG CON-DI			
		Growth 300,000 lb	
01	Wing Structure	47730	2121
02	Horizontal Tail Struture	940	879
03	Vertical Tail Structure	2750	2600
04	Fuselage Structure	18200	1501
05	Main Landing Gear	7400	2109
07	Nose Landing Gear	1010	1004
08	Forebody Controls	1910	2621
	Structure Total	**79940**	**1978**
09	Inlet Structure and Systems	4680	2243
10	Cowling	2420	2399
11	Pylon/Strut	1700	2391
12	Engine	30920	2359
13	Nozzle	1620	2531
14	Installation (incl. fairings)	2200	2391
15	Engine Accessories, Controls, & Start System	200	2414
	Propulsion Pod Total	**43740**	**2358**
23	Fuel System	4110	2117
24	APU/EPU	610	1060
27	Instruments	830	867
28	Surface Controls	3250	2062
29	Hydraulic Power System	2700	2035
30	Pneumatic System	0	0
32	Electrical System	2330	1483
33	Electronics	510	1885
34	Flight Provisions	760	400
35	Passenger Accomodations	10440	1552
37	Cargo Compartment	580	2647
38	Emergency Equipment	600	1541
39	Environmental Control Systems	1230	2264
40	Ice Protection	210	2456
49	Exterior Markings	580	1722
50	Load and Handling	0	0
55	Customer Options	800	6320
	Systems & Fixed Equipment Total	**29540**	**1862**
	Manufacturer's Empty Weight (MEW)	**153220**	**2064**
97	Standard and Operational Items	5360	1659
	Operational Empty Weight (OEW)	**158580**	**2051**
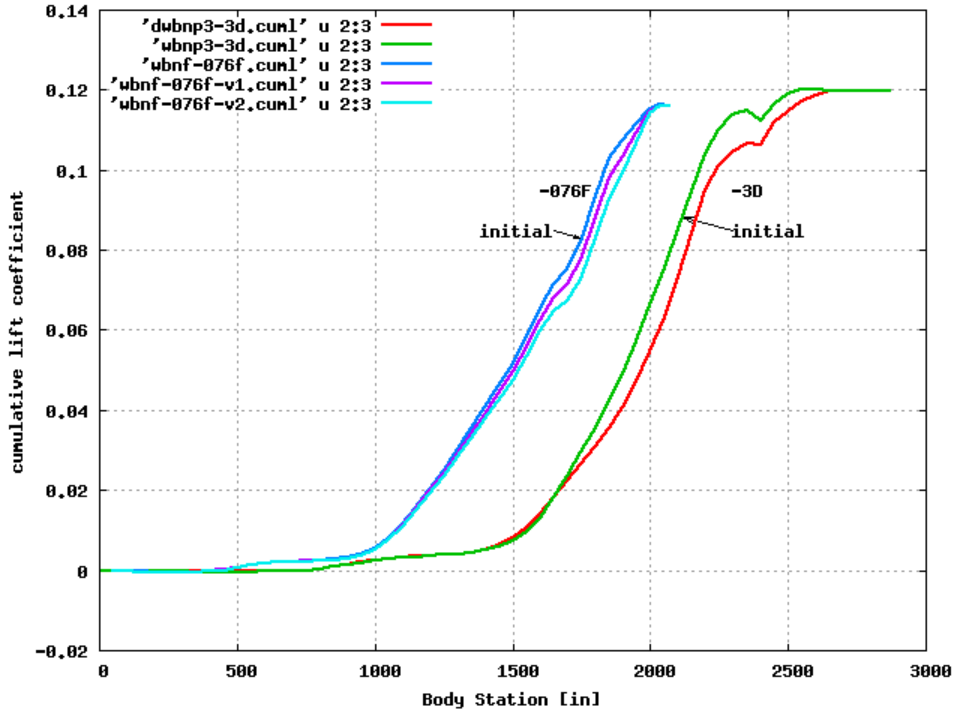
Figure 6.2.8 Cumulative lift distributions on the Joined Wing config 3D and the N+2 config 765-076F, before and after Tranair design of twist and camber for minimum drag. Mach=1.8, CL=0.12

Twist & camber of wing & tail designed to minimize drag (pressure + skin friction) at M=1.8, cruise CL=0.12

Figure 6.2.9 Mach contours before ("Seed") and after Tranair design of twist and camber on the wing and tail at 1.8 Mach and 0.12 CL.

Figure 6.2.10 Center of lift on seed and drag optimized configurations. Balancing payload fuel & airframe would be more challenging on the optimized configuration.
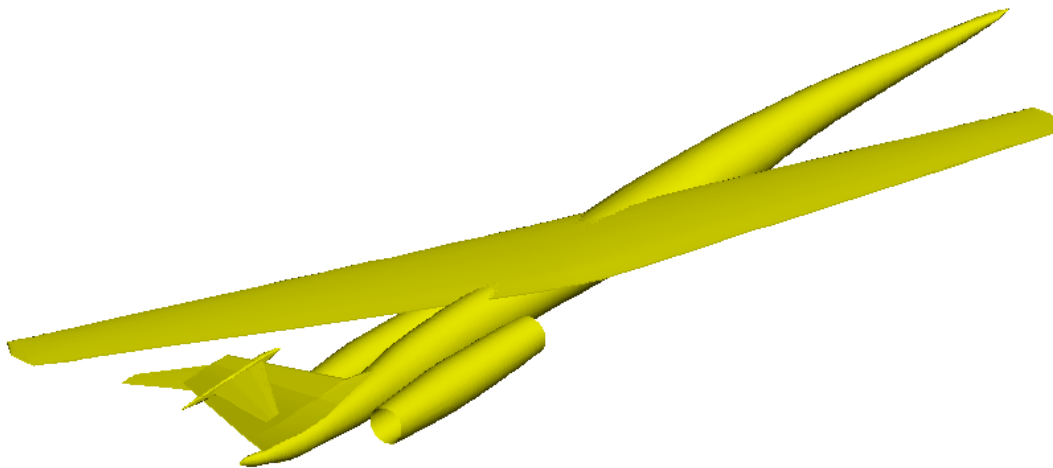
Figure 6.2.11 Configuration 4B Oblique "Scissor" Wing.

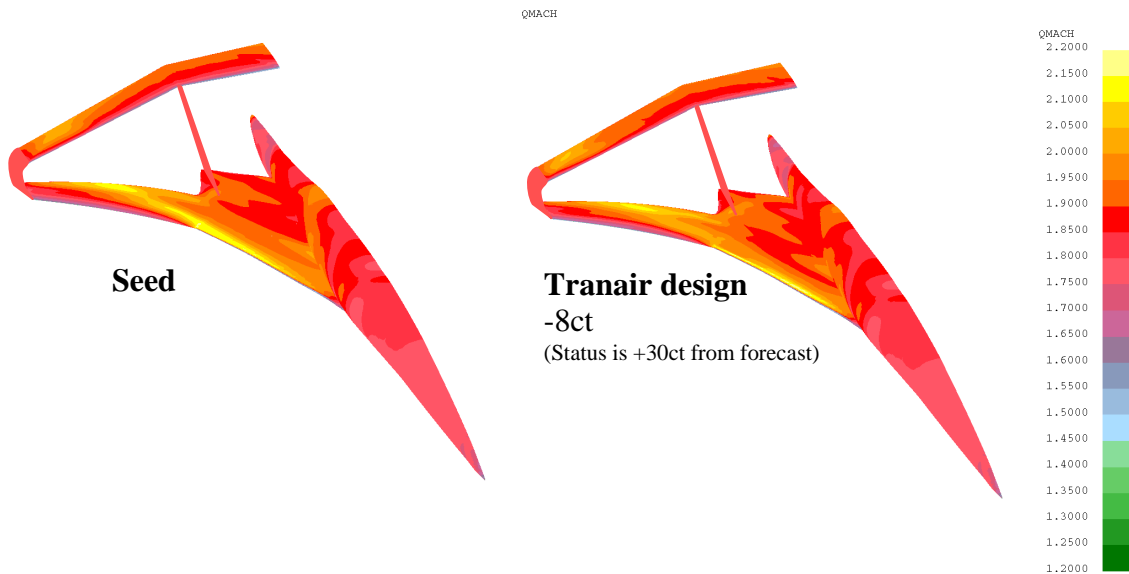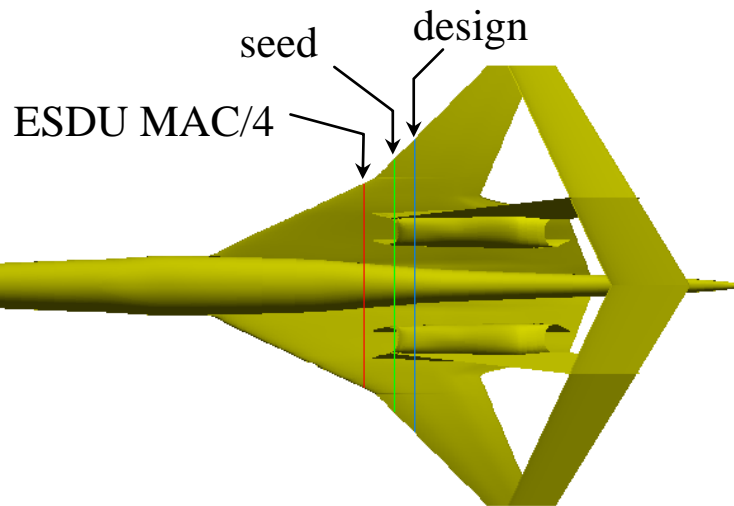| model	DATA TABLE (as drawn airplane)				
N+3 Scissor Wing	Wing		Horiz		Vertical
ITEM	ESDU	Total			Tail
Area to CL	3832.318	3799.2			
Exposed			555.39		581.67
Reference	3832.318		555.39		581.67
Aspect Ratio	3.28/11.33	3.31/11.42	3.15		2.000
Taper Ratio	0.445197		0.25		0.387
LE Sweep angle	0.00		48		62
Dihedral, TE	0	0	0		0
T/C	0.024	0.024	0.030		0.030
Tail Volume		0.635	0.635		0.0362
Span , in	1346/2500	1346/2500	501.92		289.42
Root Chord, In	305.483		254.95		420.31
Tip Chord, in	136		63.74		165.38
M.A.C. IN	231.5855	225.930	178.46		315.93
X 1/4 mac	1957.896	1956.483	2973.10		2553.91
Y, Zmac	545.0219		106.385		145.37
Tail Arm, IN.			1015.21		596.0186

112.2 ft
208.3 ft unswept

259.4 ft
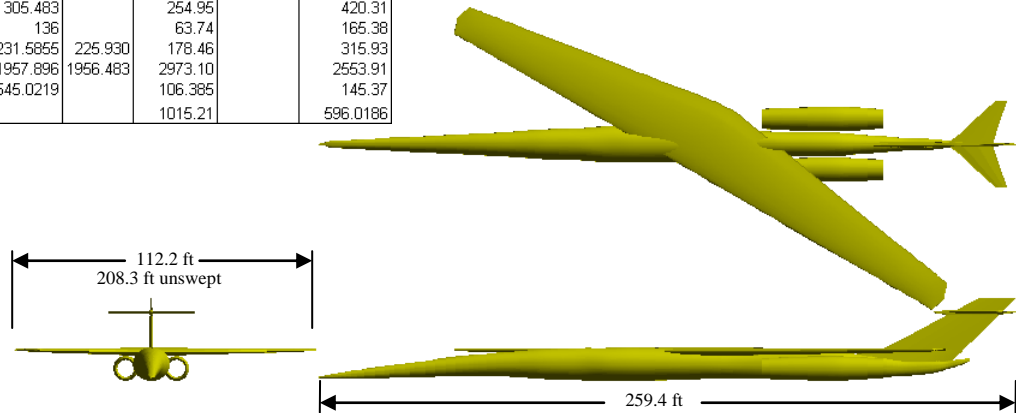
Figure 6.2.12 Scissor Wing dimensions

Scissor Wing config. 4B, M=1.4, AOA=3deg
Surface Streamlines

CFD++ analysis
40M grid elements
Re 2M/ft
(Full-scale flight)

flow

Optimal/variable
fairings a challenge

Flow separation
indicated along
down-stream wing

Figure 6.2.13 CFD++ viscous analysis of an oblique "scissor" wing & body like config 4B. Mach 1.4, angle of attack 3 deg, 40 million grid elements, Reynolds number 2 million/ft.
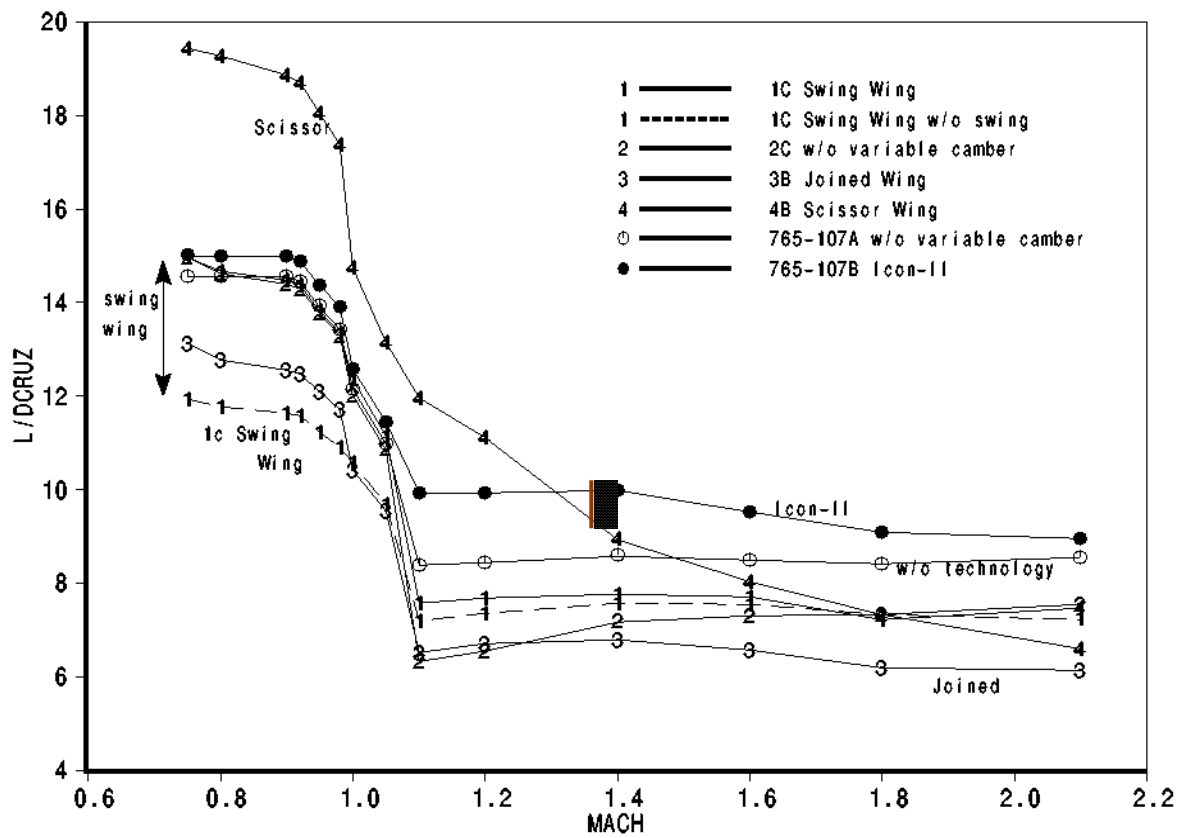
Figure 6.2.14 L/D vs Mach for a nominal climb, accel. and cruise flight profile. (Carlson-Middleton linearized panel solution + calibration factors and flight adjustments)

Figure 6.2.15 Area+thrust sizing "thumbprint" of configuration 1C.

N+3 Concept2a
NPSS 072B Engine
Mach 1.60

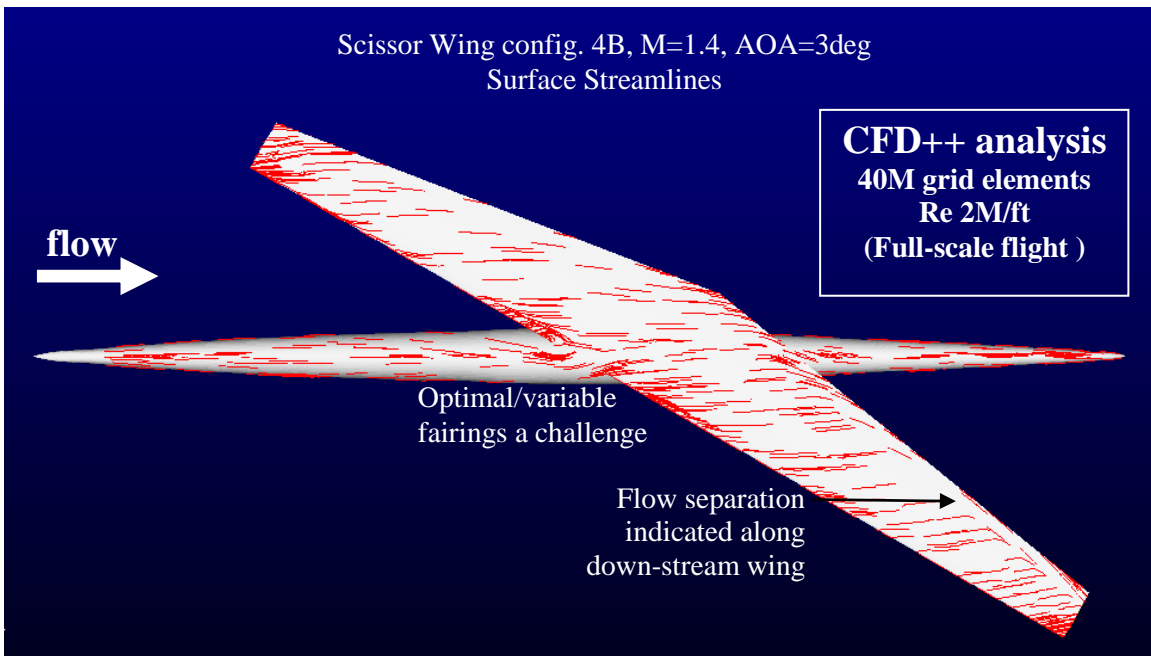|		
MTOW..........lb	300000
Sw.........sq.ft	3750
Sh..........sq.ft	0
Sv..........sq.ft	0
SLST Thrust....lb	63500
Range..........nm	3428.6
Payload........lb	20000
SLST/eng.......lb	63500
BET/eng........lb	57280
OEW............lb	144378
Block Fuel.....lb	113684
Reserve Fuel...lb	23040
Fuel Vol Req...lb	136356
Fuel Vol Avail.lb	123924
Block Time.....hr	4.49
Climb Time....min	58.86
ICAC..........ft	51692.00
Thrust ICAC....ft	51692
Buffet ICAC....ft	99999.00
Fact AE TOFL...ft	6227
NOTE: 1st and 2nd Seg Grad	
based on 10000 ft FL	
1st Seg Grad.....	0.0270
2nd Seg Grad.....	0.0243
Takeoff LE ..deg	30.00
Takeoff TE ..deg	10.00
Landing LE ..deg	0.00
Landing TE ..deg	30.00
Approach CL.....	0.8503
Vappr.......keas	149.1

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Figure 6.2.16   Area+thrust sizing "thumbprint" of configuration 2A, predecessor to 2C, the seed to the eventual "Icon-II.

Table 6.3.1 Thrust and Area + Thrust sizing of Configuration 2C, with and without preliminary estimate of weight and drag reduction via technology.

	Weight (lbs)	Range (nmi)
Engine change alone Mach 1.6	300k	4600
With Preliminary Weight & Drag Projections	**10% OEW Reduction (preliminary estimate)**	**6% Cruise Drag Reduction (preliminary estimate)**
Mach 1.6	220k	4000
Mach 1.6 **Mach 1.8**	275k 277k	5000 5000
Mach 1.6 **Mach 1.8**	300k 300k	5400 5350

Mini canard/RCV for trim and structural mode control

Advanced Metals/MMC/CMC (nose & main landing gear, hot wash)

High Strength/Modulus composites

Tough, low density composites

Tailored stiffness

Light Weight Composite Armor

Light weight thermal protection
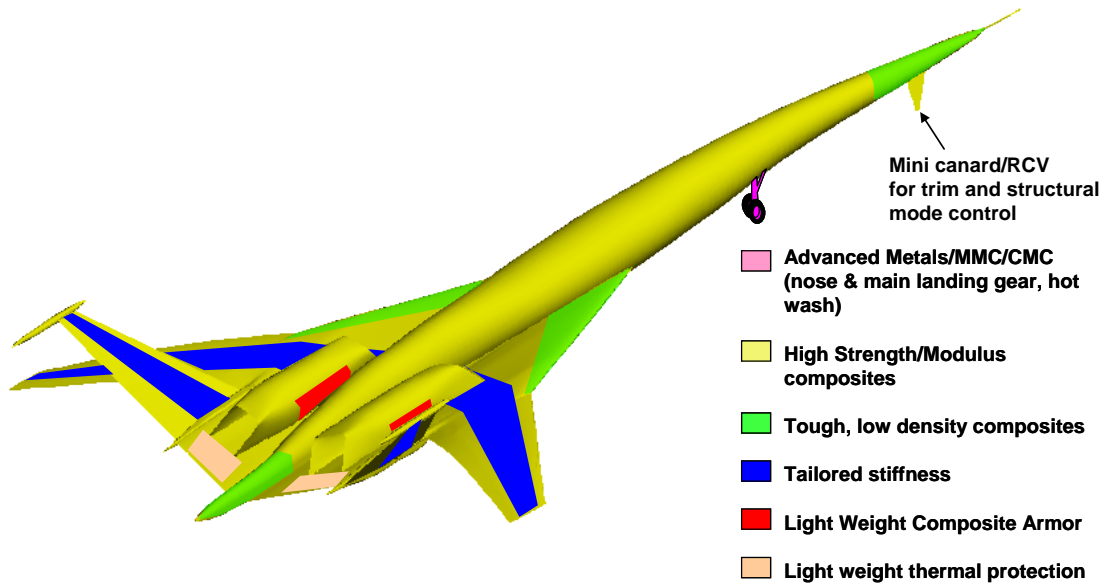
Figure 6.3.1 Advanced materials & structural concepts assumed for N+3.

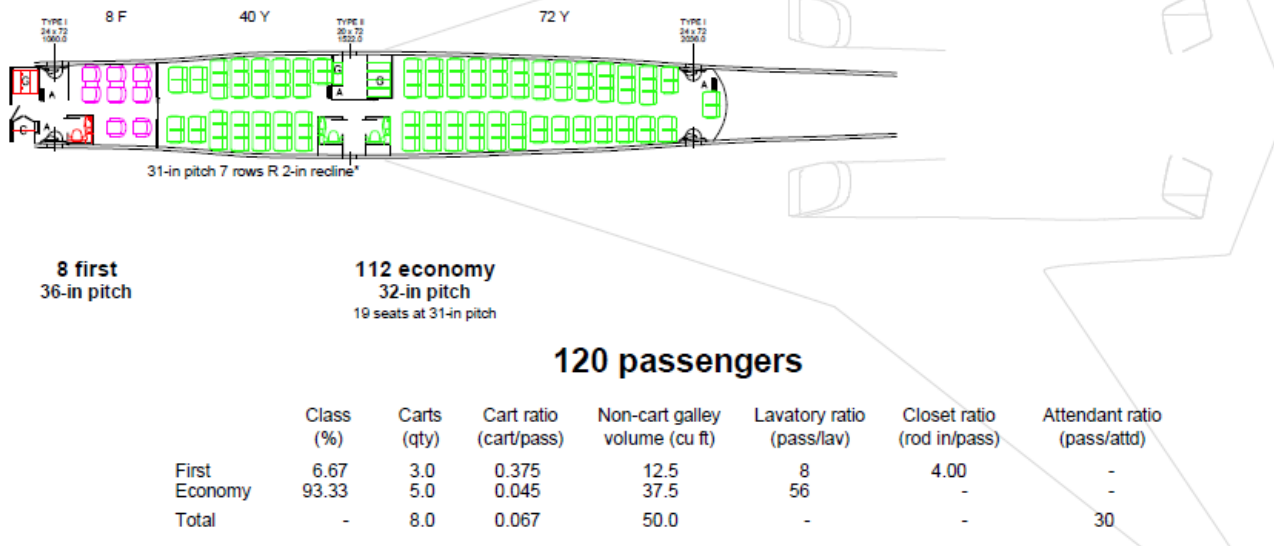| Model	DATA TABLE (as drawn airplane)				
N+3 765-107B	Wing		Horizontal	RCV	Vertical
ITEM	ESDU	Total	Projected		Projected
Area to CL	4200	4471.1			
Exposed			445.48	78.13	445.48
Reference	4200		445.48	78.13	445.48
Aspect Ratio	2.90	2.72	3.15	2.00	3.15
Taper Ratio	0.169		0.198	0.20	0.198
LE Sweep angle	57.59		48	58	48
Dihedral, TE	12	12	45	-20	45
T/C	0.024	0.024	0.030	0.030	0.030
Tail Volume		0.102	0.102	0.066	0.0413
Span , in	1323.6	1323.6	534.6	75.0	534.6
Root Chord, in	782.1		283.4	125.0	283.4
Tip Chord, in	131.8		56.0	25.0	56.0
M.A.C. in	534.1	703.9	195.1	86.1	195.1
X 1/4 mac	2196.6	2071.4	2711.6	293.9	2711.6
Y, mac	252.4		335.7	41.2	335.7
Tail Arm, in.			515.0	1902.7	515.0

110 ft 4in

262 ft
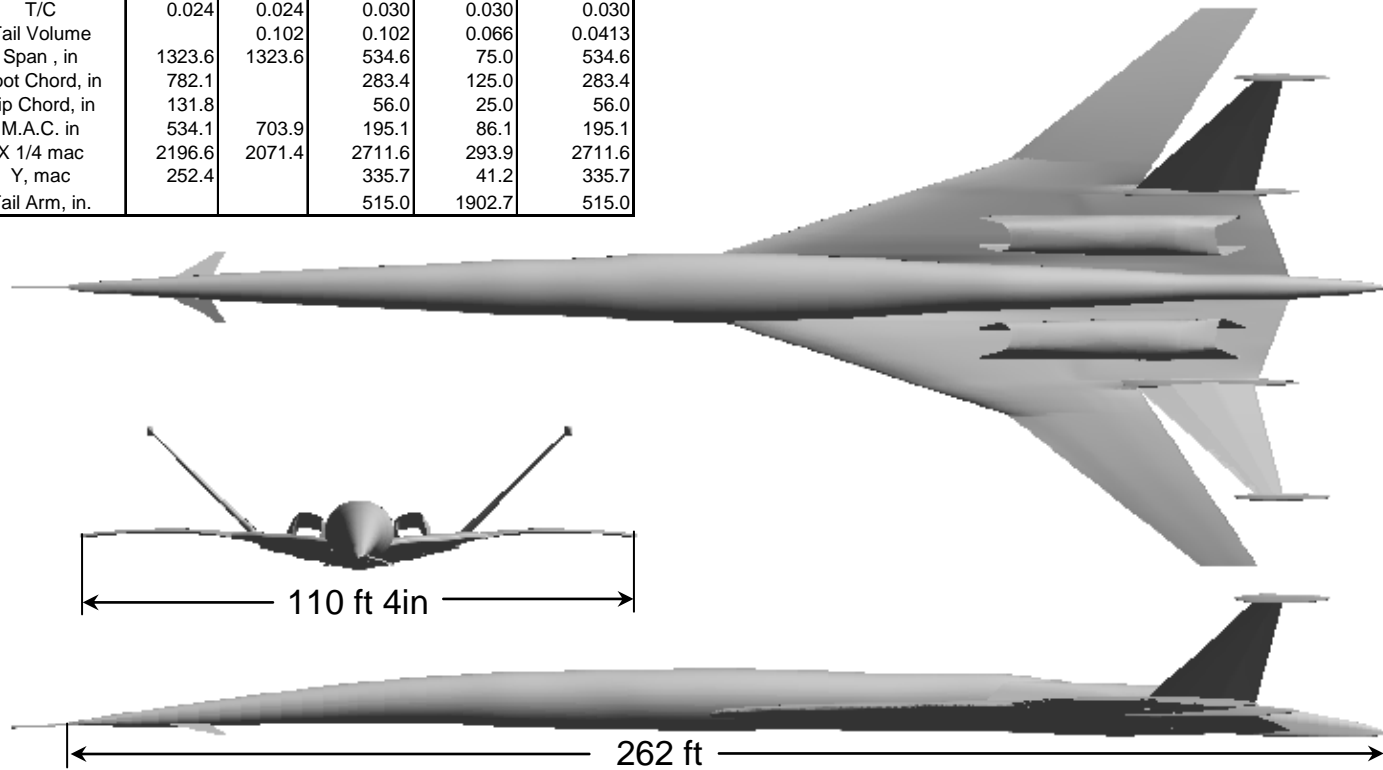
Figure 6.3.2 Three-view of the "Icon-II" 765-107B.

Interior Arrangement
IAC Short/Medium Range Rules - 1992

Product Development Study

765-107B

8 F 40 Y 72 Y

TYPE I 24 x 72 1060.0 TYPE II 20 x 72 1020.0 TYPE I 24 x 72 2056.0

31-in pitch 7 rows R 2-in recline*

8 first
36-in pitch

112 economy
32-in pitch
19 seats at 31-in pitch

120 passengers

	Class (%)	Carts (qty)	Cart ratio (cart/pass)	Non-cart galley volume (cu ft)	Lavatory ratio (pass/lav)	Closet ratio (rod in/pass)	Attendant ratio (pass/attd)
First	6.67	3.0	0.375	12.5	8	4.00	-
Economy	93.33	5.0	0.045	37.5	56	-	-
Total	-	8.0	0.067	50.0	-	-	30

Attendant visibility subject to FAA approval
* Recline space available last row only
Concerns: Passenger stowage volume
Economy seat setback does not meet 16g HIC requirements

F/C - 48-in setback, 8-in recline
E/C - 43-in setback, 6-in recline
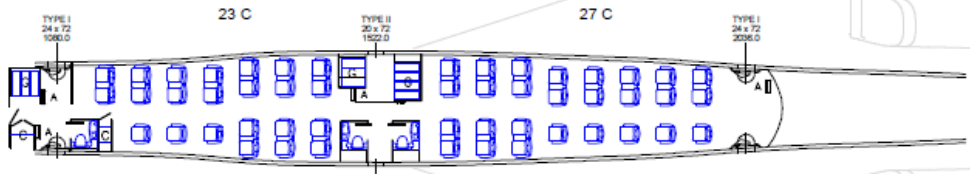
Drwn: gjo
Appd: ___

TBC

NAPD0590
rev. -
02-09-10

Figure 6.3.3 Cabin layout for 120 passengers, dual class, in "Icon-II" 765-107B.

Interior Arrangement

Executive/All First Class

Product Development Study

765-107B

23 C

TYPE I
24 x 72
1080.0

TYPE II
20 x 72
1522.0

27 C

TYPE I
24 x 72
2036.0

50 business
50-in pitch

50 passengers

	Class (%)	Carts (qty)	Cart ratio (cart/pass)	Non-cart galley volume (cu ft)	Lavatory ratio (pass/lav)	Closet ratio (rod in/pass)	Attendant ratio (pass/attd)
Business	100.00	10.0	0.200	82.0	17	1.36	-
Total	-	10.0	0.200	82.0	-	-	13

Attendant visibility subject to FAA approval
* Recline space available last row only
Concerns: Passenger stowage volume

B/C - 52-in setback, 10-in recline

TBC

Drwn: gjo
Appd: ___

NAPD0596
rev. -
02-15-10

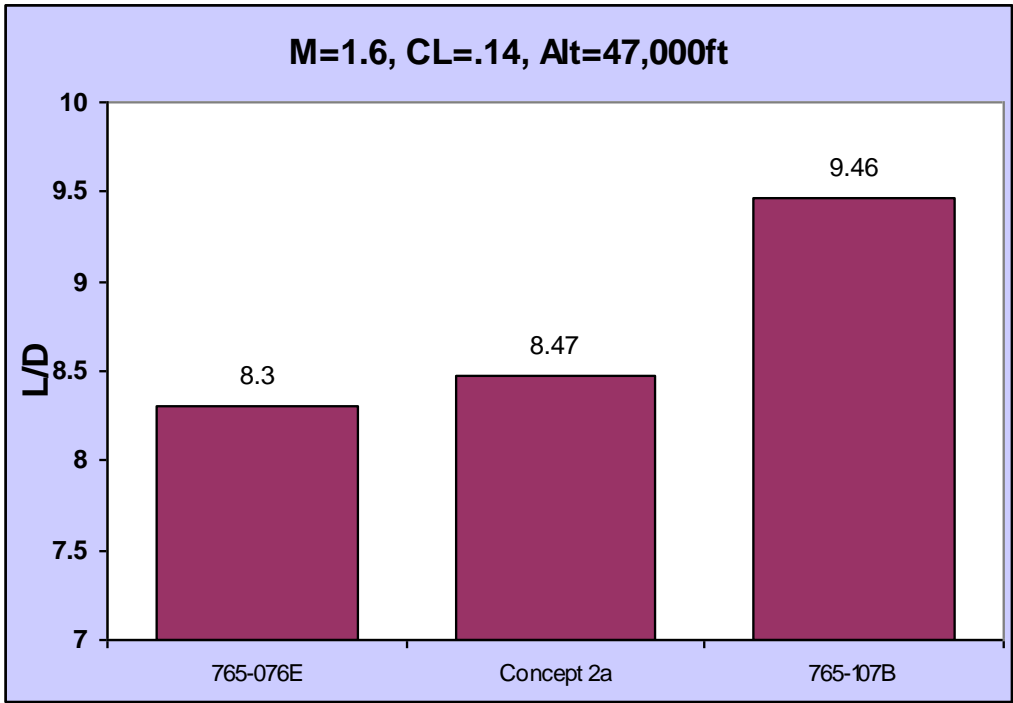**Figure 6.3.4 Cabin layout for 50 passenger, executive class "Icon-II" 765-107B.**

Figure 6.3.5 Drag tracking from 765-076E to Concept 2A to 765-107B "Icon-II".
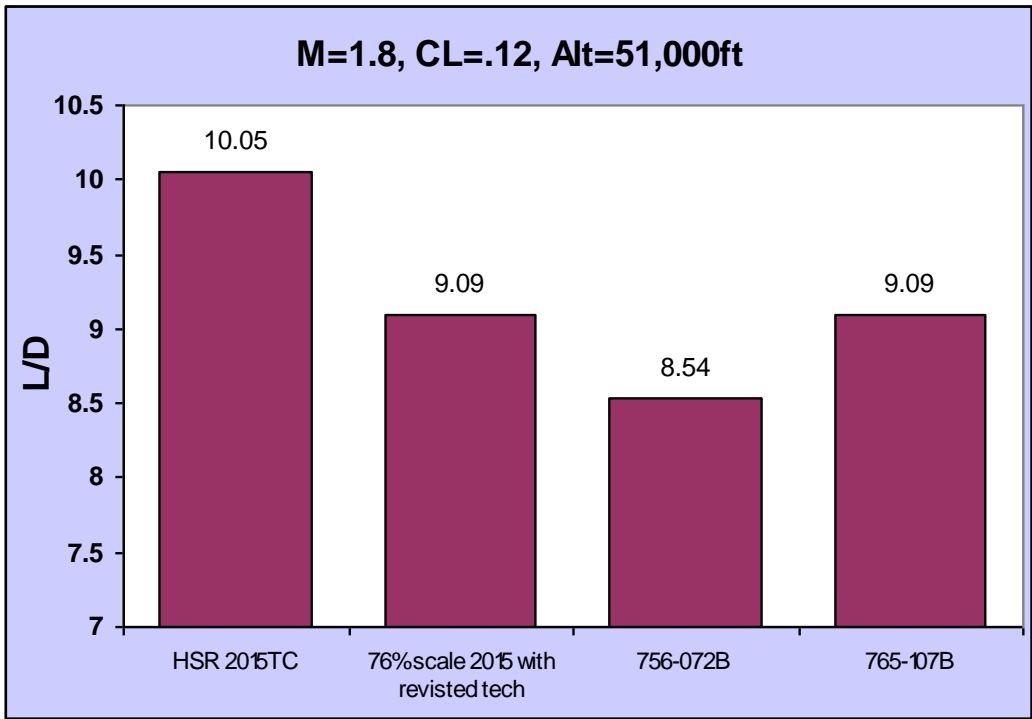
Figure 6.3.6 Drag tracking from HSR 2015TC and N+2 765-072B.

Table 6.3.2 Configuration parameters of the "Icon-II" engine (un-scaled).

Ref. Thrust (27F, SLS, Augm.) [lbf]	66000 - 68000
Ref. Thrust (27F, SLS, Non-Augm.) [lbf]	57000 - 59000
Cruise SFC (50k, M1.6, 90% power) [lbm/hr/lbf]	0.77 - 0.79
Diameter [in]	81 - 84
Total Length [in]	560 - 570
Engine+Nozzle Weight [lbm]	11000 - 11300

Figure 6.3.7:   Icon Engine Configuration Chart

```
N+3 ICON 765-107B
BRT ICONx03
Mach 1.80
```

FOM = 4.95   FOM = 4.90   4.85   5.0

```
MTOW...........lb    300000
Sw..........sq.ft    4200
Sh..........sq.ft    0
Sv..........sq.ft    0
SLST Thrust....lb    68000

Range..........nm    4930.7
Payload........lb    27000
SLST/eng.......lb    68000
BET/eng........lb    86134
OEW............lb    134540
Block Fuel.....lb    121057
Reserve Fuel...lb    18359
Fuel Vol Req...lb    139097
Fuel Vol Avail.lb    134530
Block Time.....hr    5.43
Climb Time....min    26.03
ICAC...........ft    50359.00
Thrust ICAC....ft    50359
Buffet ICAC....ft    99999.00
Fact AE TOFL...ft    6360
NOTE: 1st and 2nd Seg Grad
      based on 8000   ft FL
1st Seg Grad.....    0.0146
2nd Seg Grad.....    0.0350
Takeoff LE ..deg    30.00
Takeoff TE ..deg    10.00
Landing LE ..deg    0.00
Landing TE ..deg    30.00
Approach CL.....    0.8720
Vappr.......keas    139.1

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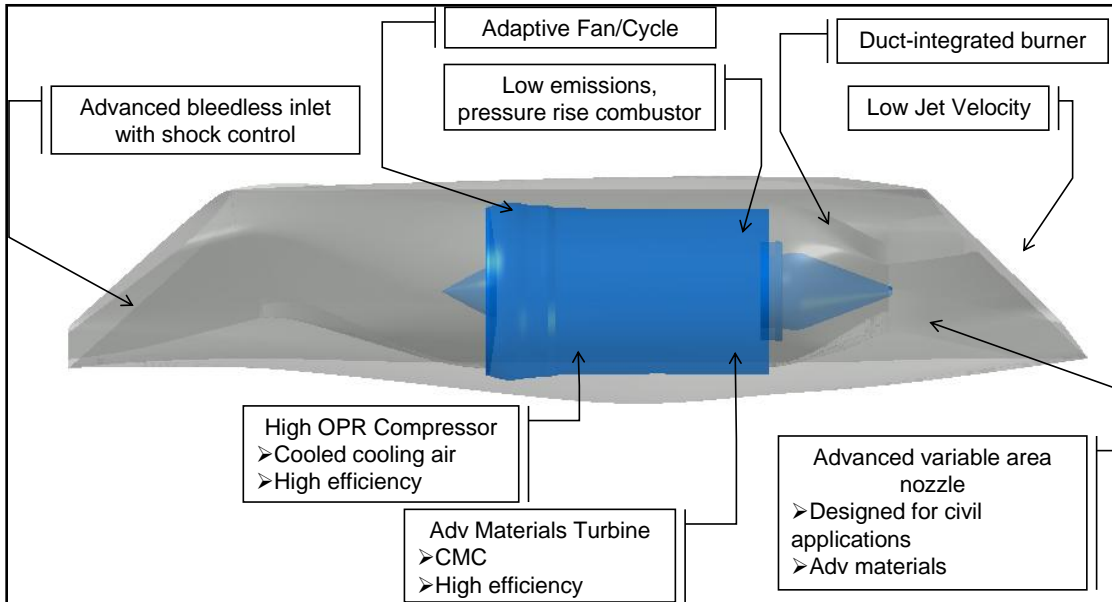
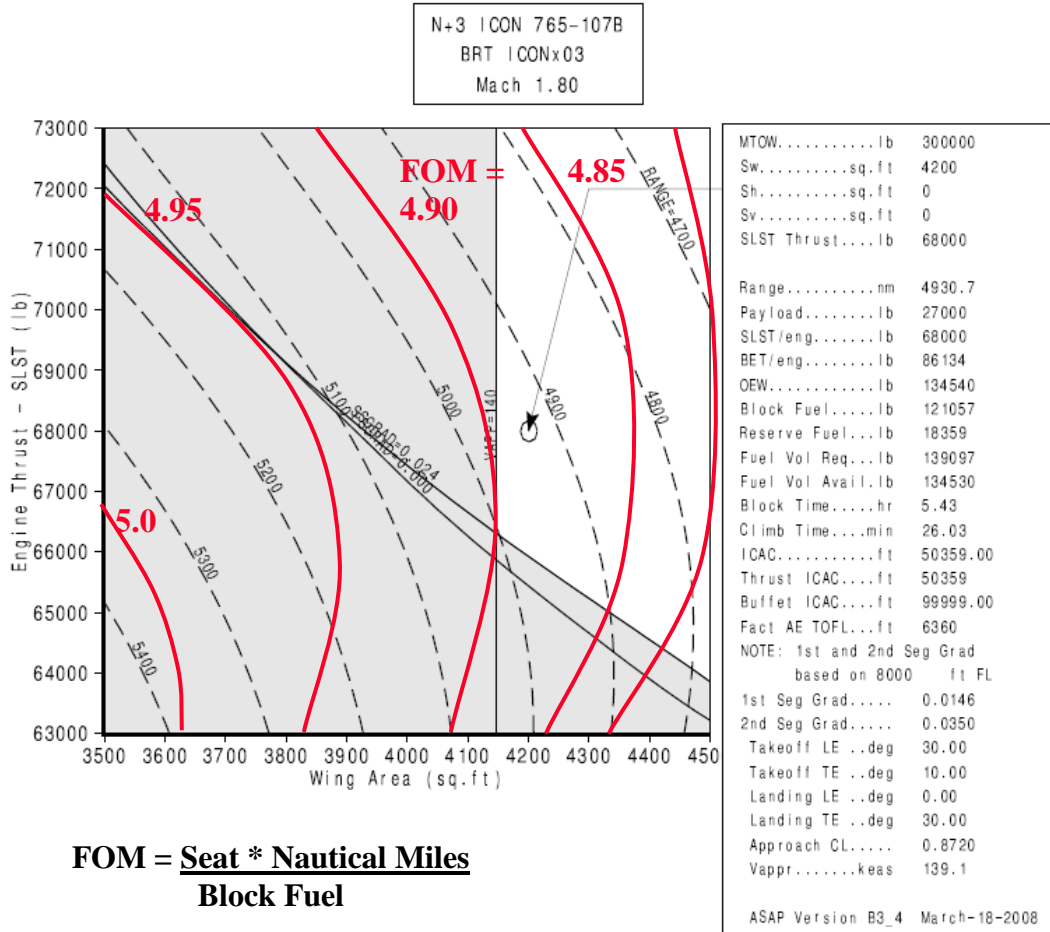$$FOM = \frac{Seat * Nautical\ Miles}{Block\ Fuel}$$

Figure 6.3.8   Thumbprint sizing chart for "Icon-II" 765-107B.   Thrust is de-rated as required for estimated noise.

Table 6.3.3   Comparison between N+3 goals and forecast for "Icon-II" 765-107B.

Metric	Min Goal	Stretch Goal	Icon-II
Sonic Boom	70-80	65-75	65-75
Noise	-20	-30	-30
Cruise Emissions	5	<5	~5
Speed	1.3	2	1.6-1.8
Range	4000	5500	5900-4800
Payload	100	200	50-130
Seat-nmi/lb fuel	3.5	4.5	4-5
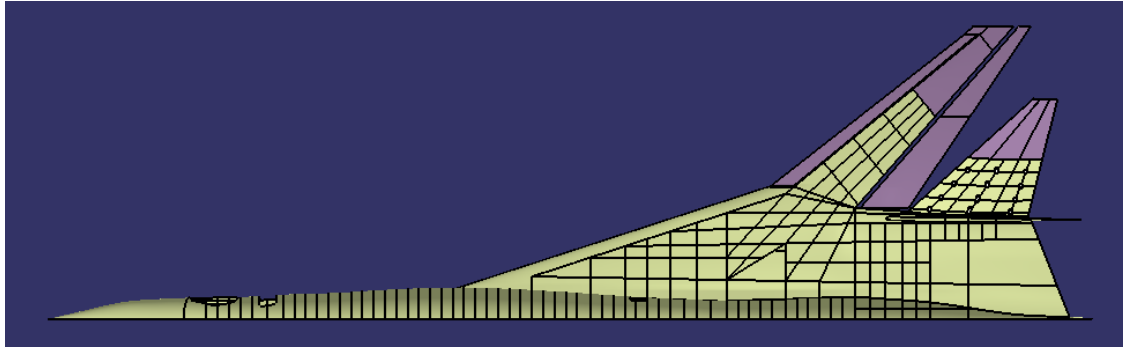
Figure 6.4.1 Structural Layout

Table 6.4.1 Material Properties

		Al	Ti	Baseline Comp	Improved Comp
		2024-T62	5AI-5V-5Mo-3Cr	11/11 email	11/11 email
E	Msi	10.6	16.0	30.6	39
E (q-iso)	Msi	10.6	16.0	11.1	13.9
Ftu	ksi	63		56	68
Fty	ksi	50	180	37	45
εall (Limit)	in/in	0.004717	0.011250	0.003363	0.0032614
rho	lb/in^3	0.10	0.16	0.056	0.056

Figure 6.4.2 Flight Envelope

Table 6.4.2 Structural Weight Summary

	Baseline	With FSS
Aluminum	104,956	70,566
Baseline Composite	48,791	48,791
Improved Composite	45,556	45,556
Titanium	46,587	39,305

Table 6.4.3 – NASA Subsonic N+3 Program Goals

Criteria / Technology	N+1 Generation: Conventional Tube & Wing (2010)	N+2 Generation: Unconventional Hybrid Wing Body (2020)	N+3 Generation (2030-2035)
Noise (Cumulative below Stage 4)	- 32 dB	- 42 dB	Better than - 71 dB (55 LDN at average airport boundary)
LTO NOx Emissions (below CAEP 2)	-70%	-80%	Better than -80% plus mitigate formation of contrails
Performance: Aircraft Fuel Burn	-33%	-50%	Better than -70% plus non-fossil fuel sources
Performance: Field Length	-33%	-50%	Exploit metroplex concepts

Source: Adapted from NASA Overview of NRA solicitation (N+3 Pre-Proposal Conference)
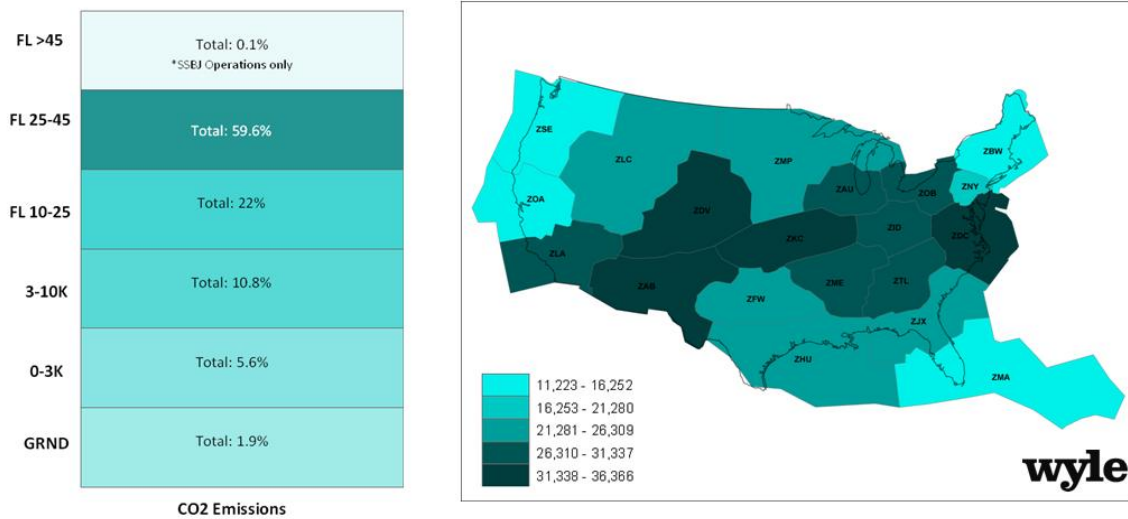

Figure 6.4.3 – NAS-Wide Emission Distribution for Modeled 2025 Scenario (Baseline NextGen and N+1 and N+2 Subsonic and Supersonic Fleet and Operations)

7.0 Technology Prioritization, Selection and Roadmapping (Task 3.6)

7.1 Propulsion Technologies

7.1.1 Background

The goal of Task 6 is to calculate an aggregated benefit at the vehicle level. This benefit is composed of the individual benefits or decrements that a technology offers in terms of propulsion-specific quantities. "Propulsion-specific" refers to the engine itself, in addition to integration technologies such as inlets and nozzles. The fundamental quantities of interest were changes in engine weight, diameter (or drag for inlets and nozzles), SFC, noise, emissions, and thrust. The respective engine OEM's assessed the fundamental quantities for engine technologies, whereas Boeing assessed the nozzle and inlet technologies with a few exceptions.

7.1.2 Methodology

Sensitivities were calculated based on variations in parameters on a resized engine from the -072B baseline. This exercise was performed in order to determine, for instance, the effect of a 1% change in engine thrust, diameter, or SFC on vehicle FOM and TOGW. Then the following equation was employed:

$$\Delta Param = \frac{\partial Param}{\partial Fn} \times \Delta Fn + \frac{\partial Param}{\partial Wf} \times \Delta SFC + \frac{\partial Param}{\partial W} \times \Delta W + \frac{\partial Param}{\partial D} \times \Delta D$$

Where

Param	=	Vehicle-level parameter (FOM, TOGW)
Fn	=	Net thrust
Wf	=	Fuel flow
SFC	=	Specific Fuel Consumption
W	=	Weight (engine)
D	=	Diameter (engine)

and

Param	$\dfrac{\partial Param}{\partial Fn}$	$\dfrac{\partial Param}{\partial Wf}$	$\dfrac{\partial Param}{\partial W}$	$\dfrac{\partial Param}{\partial D}$
FOM	2.366	-2.05	-0.238	-0.694
TOGW	-1.503	1.161	0.285	0.571

The emissions and noise benefits were not explicitly calculated, but considered inputs from engine OEM analyses.

After calculation of vehicle-level benefits, statistical analyses were performed. The first section of the analysis consisted of constructing histograms that indicated which technologies showed the most benefit. An example histogram is shown in Figure 7.1. In the second section of the statistical analysis, the cost and risk indices (i.e. low, medium, or high) were assigned values, and the benefits were then divided by the indices. These indices were 1 for low, 3 for medium, and 5 for high risk or cost. An example of such a chart can be found in Figure 7.2. Such a chart is meant to delineate which technologies show the best balance between benefit, risk, and cost; essentially, the further out a technology lay on the horizontal and vertical axes, the more promising it is. For the simplified example in Figure 7.1 and Figure 7.2, Tech 1 shows high benefit, low risk, and low cost; in contrast, Techs 5-7 show low benefit, high risk, and high cost. Therefore, the cluster of Techs 5-7 would be eliminated from further consideration. An "overall weighted benefit" metric was defined which aimed to combine the benefits of reductions in sonic boom, noise, and emissions, and increases in fuel efficiency. These benefits, if available, were individually multiplied by weighting factors and then summed. The weighting factors were 1 for sonic boom reduction, 1 for noise reduction, 1 for fuel efficiency increase, and 0.2 for emissions reduction. The reason for assigning 0.2 to the emissions

reduction was because technologies which had emissions benefits were typically significantly higher than the other benefits, and could have skewed the data. The technologies, changes to fundamental values, and vehicle aggregated benefits are contained in the proprietary Appendices A through D.

7.1.3 Technology Families

Approximately 90 propulsion-related technologies were considered and analyzed per the described process. Of these technologies, approximately 25% were deemed for consideration for detailed roadmapping. A typical reason for exclusion is that a technology could represent significant benefits in terms of SFC and emissions, but also demonstrated a weight penalty which far outweighed the overall potential fuel efficiency benefit.

Upon analyzing all technologies which were considered for detailed roadmapping, technology groups or "families" were evident. These shall now be described.

7.1.3.1 Adaptive Fan/Cycle

The constraints of the design space for this vehicle call for propulsion systems which are met with competing requirements. For instance, the engines must be low-noise during take-off, which implies traditional high BPR turbofans, which also require high mass flows. However, during cruise, the engines must have high thrust in proportion to inlet area, which implies a smaller diameter and low BPR (i.e. a turbojet). To address these competing demands, advanced configurations should adapt mass flow and/or effective fan pressure ratio.

The broad classification of "Adaptive Fan/Cycle" is meant to describe configurations in which the inlet mass flow is adjusted during operation, the variation of which enables high cycle performance. This can be achieved by several means. Whereas in traditional turbofans the fan flow is distributed between the bypass and core, such advanced concepts may result in an additional diversion, generating a separate mass flow which enables advanced thermal and noise management. By varying the flow in an optimal manner, significant potential for reductions in engine diameter, weight, and noise exist.

Less than five technology concepts were roadmapped in detail. The primary affected goal is fuel efficiency, with benefits greater than 10% but less than 25%. The secondary goal affected is sonic boom reduction, due to reductions in TOGW on the order of 15-20%. Additionally, Adaptive Fan/Cycle systems are seen to have potential benefit for noise reduction during take-off.

7.1.3.2 Compressor

Advances in material technology for compressor components are deemed to have the potential for significant performance improvements. The family of "Compressor" describes these material technology advancements. Improving the microstructure of discs could lead to higher compressor operating temperatures and therefore higher discharge pressures. This results in higher OPRs for engines of smaller diameter and weight. Less than five technology concepts were roadmapped in detail. The primary affected goal is fuel efficiency, with a benefit between 5 and 10%; the secondary affected goal is sonic boom, due to reductions in TOGW on the order of 5%.

7.1.3.3 Turbine

Advances in turbine technologies are primarily in the field of materials development. Fundamentally, high temperature materials enable the turbine to run at much higher temperatures. With the increase in temperature capability, the turbine requires less cooling. Reductions in cooling, along with the higher turbine temperature, increase thermal efficiency while also reducing engine weight. Of the few technologies which were roadmapped, an example is CMC components. The primary goal affected was fuel efficiency, with benefits between approximately 10 and 20%; the secondary affected goal is sonic boom, due to reductions in TOGW on the order of 5-15%.

7.1.3.4 Combustor

The family "Combustor" describes advanced combustion concepts which can significantly improve emissions and fuel efficiency. Examples of such concepts would be those in which combustion occurs such that volume is maintained and therefore pressure is increased. These concepts might also include high temperature-capability materials and advanced controls on ignition and mixing to ensure the leanest possible ignition. Less than 5 technologies were roadmapped in detail. The primary goal affected was emissions, with estimated benefits of greater than 70% reduction. The secondary goal affected was fuel efficiency, with up to 5% improvement due to SFC reductions.

7.1.3.5 Cycle/System

The term "Cycle/System" is a broad classification for those technologies which offer optimized cycle performance. Improving compressor and turbine efficiencies through advancements in modeling and materials could lead to large SFC reductions. Other examples of Cycle/System technologies are advanced thermal management systems such as cooled cooling air, and increasing the ability of fuel to retain heat prior to combustion. Five technologies were roadmapped, and they primarily affected fuel efficiency, up to 25%. A secondary affected goal was emissions, with more than an 80% improvement.

7.1.3.6 Inlet

As the mission for this vehicle requires sub- and supersonic flight phases, the propulsion system must be able to adapt for maximum performance and operability. The term "Inlet" refers to technologies which ensure sufficient mass flow to the engine and high pressure recovery, while minimizing noise, SFC, and distortion effects throughout all flight conditions. Some technologies such as auxiliary inlet doors enable the inlet to meet the mass flow demands of low speed, high power situations. Other technologies would enable aggressive flow turning to shorten the diffuser length, or changing the shape of the nacelle during flight through the use of advanced materials and control systems. Four technologies were roadmapped. They primarily benefitted fuel efficiency, with benefits between 5-10%. Due to potential for weight reductions, the secondary goal affected was sonic boom, with an average of 1% improvement.

7.1.3.7 Nozzle

To perform efficiently, provide sufficient take-off thrust, and still meet stringent noise requirements, the propulsion system must have a sophisticated exhaust system. The family "Nozzle" refers to these technologies. Nozzle technologies must be able to operate efficiently at subsonic speeds, where fixed geometries have had a successful history, and at supersonic high altitude conditions, where variable geometries enable a broad range of operating capabilities. While variable area configurations have been successfully applied to military platforms, further steps are required to apply similar technologies for a commercial application. Some nozzle technologies show potential for the shielding of jet velocity noise through the use of innovative mass flow channeling afforded by adaptive cycle engines. This category also encompasses technologies which augment the thrust at certain Mach number ranges, enabling lower dry thrust, therefore reducing engine size and weight and increasing vehicle efficiency over a given flight range. Five nozzle technologies were roadmapped. They primarily benefit fuel efficiency, up to 20%. The secondary benefit is in noise reduction, with near 10% improvements.

7.2 Airframe Non-Proprietary

7.2.1 Technology Identification, Screening and Prioritization

The airframe technology items were identified and developed building off the results of the Initial Reference System and Technologies workshop described in Section 3.0. Each Engine Company developed their own technologies items and all are covered in detail in the respective proprietary Appendices.

Boeing started from a company-wide survey of ongoing technology and vehicle development work, past studies such as HSR and other industry efforts such as that from NIA. The goals and objectives of the N+3 supersonic vehicle study program were reviewed with the appropriate personnel working on the

technologies with the request to identify the items that would be applicable to this N+3 supersonic work. This activity generated about 100 technology items that were then grouped under the following categories:

- Safety and Airworthiness
- Sonic Boom
- Noise
- Engine Efficiency and Durability (covered in Section 7.1)
- Aeroelastics and Flight Controls
- Airframe Structures and Materials
- Aerodynamic Efficiency
- Systems
- MDO (Multidisciplinary Optimization)

The 100 items were reduced to 34 through an initial screening process that considered the most promising and applicable technologies for this application. The following criteria were used during the initial screening process:

- Fuel Efficiency
- Development time to TRL 6
- Fundamental Quantity Benefit i.e. Drag, noise etc
- Tech Rank relative to each of the Concepts shown in Section 3
- Risk
- Integration Issues
- Current TRL
- Description
- Cost for TRL 6

Following the initial screening process, more detailed quantitative values were assigned to each technology for the criteria shown above.

Resized mission performance for the 072B reference configuration was evaluated by incrementally varying each of the fundamental quantity items of drag, empty weight (OEW), thrust and SFC. The following equation, similar to that shown in Section 7.1, was then developed based on the resizing results and the partial derivative values determined as shown below:

$$\Delta Parameter = \underset{2.366}{\frac{\partial(Parameter)}{\partial(Thrust)}} \times \Delta Thrust + \underset{-2.05}{\frac{\partial(Parameter)}{\partial(Fuel\_Flow)}} \times \Delta SFC + \underset{-1.325}{\frac{\partial(Parameter)}{\partial(OEW)}} \times \Delta OEW + \underset{-1.5909}{\frac{\partial(Parameter)}{\partial(Drag)}} \times \Delta Drag$$

FOM

These results are therefore based on a direct impact on the fuel burned FOM. The assessed values for each of the 34 technologies were used with the above equation to get an overall FOM (figure of merit, seat*nmi/fuel burned) and the results used to rank the technologies from best to worst to obtain the top items for further study. The top 34 items ranked in order is shown in Table 7.1. Then as discussed in Section 7.1, histograms were constructed that indicated which technologies showed the most benefit and the risk indices were assigned values, and the benefits were then divided by the indices and histograms were constructed as illustrated in Figs 7.1 and 7.2.

The detailed results of the technology evaluations are contained in Appendix A.

7.2.2 Affordability Analysis

An attempt was made to determine the best-value of the technologies by applying NASA's Process Based Economic Analysis Tool (P-BEAT). This process is summarized in Figure 7.3. A few technologies were identified to test the ability to apply the process. Needed quantities were identified to execute the process. Based on the far term nature of the work the necessary information was not available in sufficient detail to make the analysis meaningful. So the effort was discontinued.

7.2.3 Roadmaps

The top technologies indicated in Table 7.1 were then combined with related technologies identified in the discussion of Section 7.2.1 and grouped into categories. These categories were:

1. Sonic Boom—Design Methods
2. Sonic Boom– Active Technology Mitigation
3. Noise—High Lift
4. Propulsion Integration—Inlet and Nozzle
5. Aeroelastics & Flight Controls*
6. Composites & Metals*
7. Structural Concepts*
8. Aerodynamic Efficiency
9. Aircraft Systems*

The supersonic technologies were compared side-by-side with the Subsonic Super Ultra Green Aircraft Research (SUGAR) work being done by Boeing in an attempt to highlight the exclusively supersonic items. They were compared on the basis of Subsonic Only, Mixed and Supersonic only. We built the supersonic technology roadmaps with this as a point of departure and focused on the supersonic only and the supersonic applications for the mixed. But we found that some can't be segregated and those are identified by the * in the roadmap listing above.

The resulting roadmaps are presented in the proprietary Appendix F. However the key milestones over the first five years from the roadmaps are shown figure 7.4.

Table 7.1 Results of the Technology Ranking

| FOM Rank	Technolgy
1	Reliability-Based Design and Certification
2	Active Laminar
3	Structural Health Management
4	Active GLA/MLA
5	Riblets (limitied application)
6	Low-speed High-Lift devices
7	Aero-Servo-Propulsive-Elasticity (ASPE)
8	Reliable CG Control
9	Passive Laminar
10	Morphing bumps (Control Cp Distribution)
11	Synthetic Jets Fuselaage
12	Plasma
13	Structurally Integrated Energy Management
14	Highly efficienct and flexible, thin film solar cell
15	High-Efficiency Thermal-Electric Energy Harvesting
16	AFC High Lift
17	Synthetic Jets Wing
18	Advanced Metals
19	Hingeless Control Surfaces
20	Tailored Structural Stiffness
21	Active Flutter Suppression
22	Highly Integrated Subsystems (multifunctional structures)
23	Ultra-High-Modulus, Ultra-High-Strength Fibers
24	Thermoplastic Composites
25	High-Temperature Polymer Composites
26	Multifunctional Nano-Composite
27	Nano-electronics
28	Very Tough Composites
29	Metal-Matrix Composites
30	Active TE
31	Hingeless Control Surfaces with Fowler Motion
32	Control Surface Deflection through LE or TE Warping
33	Supersonic Microjets
34	Off-Body Energy Addition
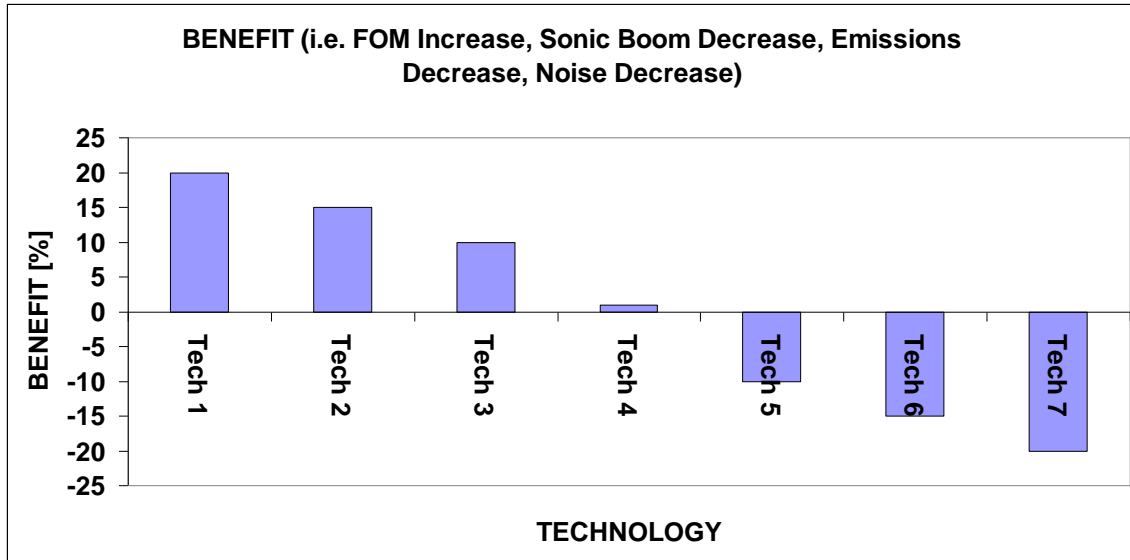
Figure 7.1: **Example Histogram**
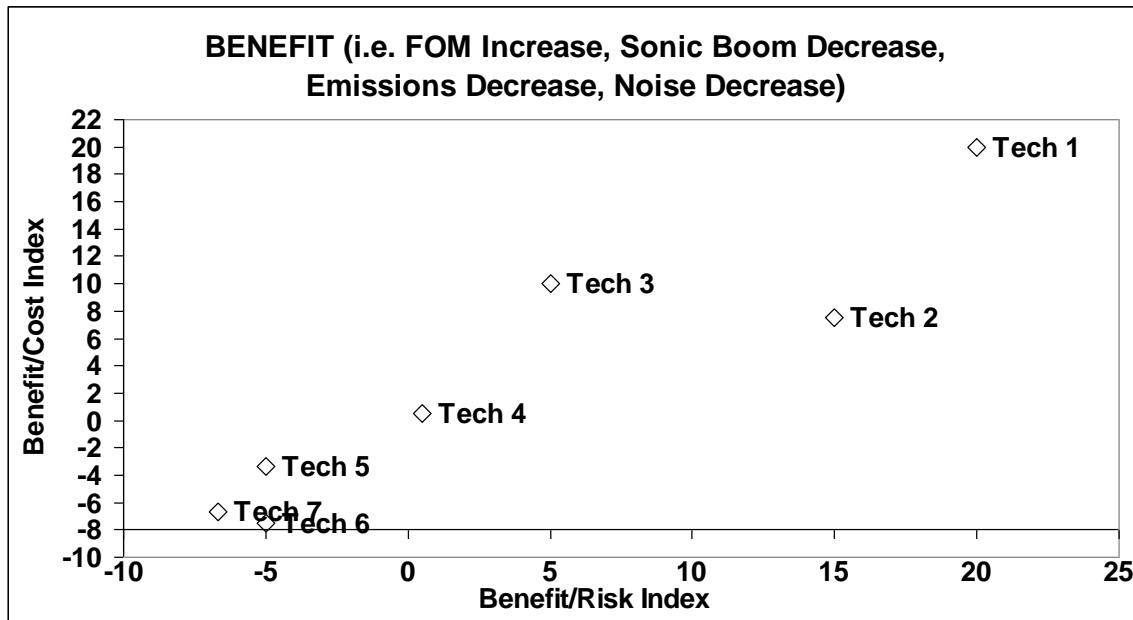
Figure 7.2: **Example Benefit/Cost vs. Benefit/Risk Chart**

N+3 Affordability Task Progression
("Affordability" = Cost vs. Benefit)

- N+3 Supersonics Metrics & FOMs
- Vehicle Technologies Morph Matrix

- Vehicle Characteristics Morph Matrix
- Performance & Sizing Analysis
  (Subsystem-level information)

Boeing Performance Engineering

Boeing Affordability Engineering

Qualitative Technology Value Analysis

Subsystem-Level Vehicle Cost Estimates & Drivers

Quantitative Vehicle Concept Value Analysis

Task 5
Technology Evaluation

Task 6
Vehicle Evaluation

Figure 7.3 Summary of Affordability Process

	2011	2012	2013	2014	2015

SONIC BOOM

- Initial SB Framework
- Obj Ftns and Constrains
- OBH Benefit ana
- MJ WT Test go-ahead
- MJ Shock mods
- Current Contract Commplete
- Final SB Framework
- Para Geom and CFD
- MJ 3-D wt demo
- OBH WT demo
- Propogation Aero and FEM
- Parametric Requirements
- Otimization Technique
- OBH Pwr Sys & demo plan
- MJ FS sys des & demo plan

CUMULATIVE NOISE

- HCl Prelm Conceps Feasability
- Cont. Mold Line Lip (CMLL) Sys Req.
- Adaptive Cycle Test
- CMLL feasibility
- HCl WT Test
- Augmentation Dev for Adv Nozzle
- Adaptive struct low rate deformation
- Noise reducing nozzle
- CMLL Bench Test
- Ejector Noz sys reqmts

CRUISE EMISSIONS

- Low Emissions Combustor Test
- Adv. Combustor Rig Test
- Compressor w/ heat exchanger

FUEL EFFICIENCY

- ASE real time algorithims
- Mat target applications
- Sys cand techs and risk
- ASE Lidar gust sensor
- RBD and SHM benetift ana
- Mat cost benefit ana
- RBD metrics and des app
- Struct integrated antennas
- Inlet fluidic feasability
- Variable Area Noz sys reqmts
- Inlet fluidic control reqmts
- Riblets app studies
- Sys tech dev plan
- ASE physics, CFD Structure
- ASE benefit ana
- SHM hot spot monitoring
- Variable Area Noz trade study
- Active LF extent and location
- Sys tech feasability demo
- ASE hingeless cont surf
- MAT new forms & processes
- Struct powr retern and EME
- MDO BL stability morphing ans camber
- Active LF veh assessmt
- Inlet fluidic bench test
- ASE Active wing control
- ASE Improved actuators
- Passive LFC WT Test
- Active LF breadbd bench tests
- Sys tech maturation status
- Variable Area Noz layout & control
- Inlet mold line lips bench test

Legend:
- AERODYNAMICS
- STRUCTURE
- PROPULSION
- AIRCRAFT SYSTEMS
- (ENGINE OEM-SPECIFIC)

Figure 7.4 Key Milestones from the Roadmaps
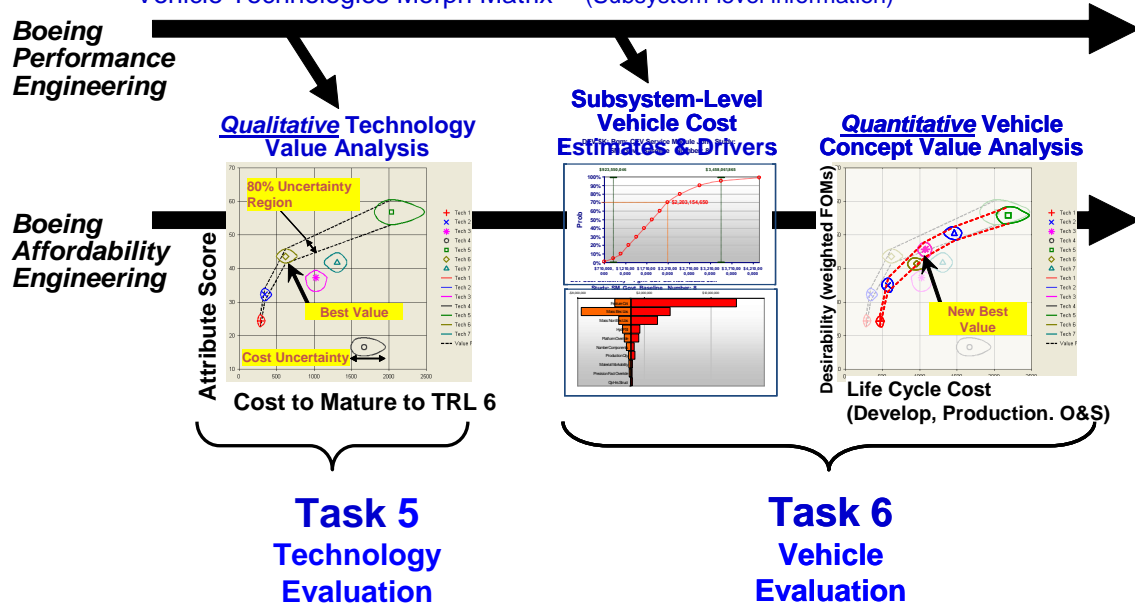
8.0 Conclusions

The objectives of this study were to define and evaluate integrated configuration and propulsion concepts for supersonic aircraft entering service in the 2030-2035 timeframe, to identify and prioritize key technologies to enable such aircraft, and to develop corresponding technology development roadmaps. A study was conducted to determine potential market and regulatory conditions in the time frame of interest, and those results were used to determine the design requirements and performance and environmental goals for the study aircraft. A separate contract with Sensis provided involvement, input to and requirements from their studies for the NextGen airspace system. Using the design requirements thus determined, configurations and technologies were identified early in the program to set the vehicle categories and top level technology areas for study. This was done in a group setting with all program participants contributing to the results.

Following the initial configuration and technology identification exercise—each engine company and the airframe team members proceeded to develop: (1) a more detailed set of appropriate vehicle concepts, (2) representative engine architectures, and (3) a detailed set of technologies that would be applicable to these vehicle configurations and engine architectures. Trade studies were conducted using size-optimized vehicle mission performance to identify the primary candidates in all areas.

Conceptual design studies resulted in the recommendation of a fixed wing configuration with V-tails and upper surface engines as the technology reference concept plane for N+3. This vehicle, Boeing model number 765-107B, was nicknamed "Icon-II". Sizing and mission analysis of the Icon-II concept showed that if the constituent enabling technologies achieved their projected levels, similar aircraft should have the potential to meet or exceed all the N+3 goals set out at the beginning of the study.

As shown in Figure 8.1, near-term technological progress should enable technically viable SuperSonic Business Jets (SSBJ's) with a reasonable degree of sonic boom reduction within the next decade (N+1). With roughly another ten years of development, progress should be sufficient to allow a type of relatively fuel-efficient supersonic airliner of roughly 100 seats or a low-boom airliner of somewhat smaller size (at some fuel efficiency penalty).   The Boeing models -072B and -076E, respectively, represented concept planes for each of those categories in the previous N+2 study. The N+3 studies have identified a path whereby an aircraft like the Icon-II would have the potential to provide 100 or more passengers in capacity, increased range, lower boom, reduced takeoff noise, and significantly increased fuel efficiency by the N+3 time frame.

The Icon-II concept plane is configured to carry 120 passengers in a two class, single aisle interior, cruise at Mach 1.6-1.8 with a range of about 5000 nmi. At design range, the concept showed a fuel efficiency of more than 4.5 seat-nautical-miles/pound of block fuel. Recent advances in low-boom shaping technology indicate that a configuration with the design features of Icon-II is projected to achieve a sonic boom environmental goal level of 65-75 PLdB, airport/community noise levels potentially quieter than 30 EPNdB cumulative below Stage III/Chapter 3, and attain cruise NOx emissions of EI= 5g/kg.

To achieve these performance levels, the highlights of the technologies incorporated in the vehicle concept are:
- Improved metallic and composite materials and structural concepts (including improved ballistic protection for airplane systems and structure for engine disk burst, rim release,and FOD), reliability based design, active load alleviation and active aeroelastic (APSE) control
- Aerodynamic devices including hybrid laminar flow, riblets, morphing leading and trailing edges and selective use of active flow control
- Noise-shielded upper surface nacelles, employing advanced liners and duct treatments, and potentially low-impact/low NPR suppressor nozzles,
- Optimized low sonic-boom design coupled with multi-point drag optimization and configuration refinement based on improved Multi-Disciplinary Optimization (MDO)

- Advanced light weight, high energy efficient airplane systems including electronic forward external vision systems, automated CG monitoring/control, and thermal management
- Advanced light weight bleedless inlets with compact light-weight diffusers, high distortion tolerance, and variable area nozzles with low jet velocities and a duct integrated burners
- Adaptive fans and other variable cycle engine features, low emission pressure rise combustors, high OPR compressors, and turbines with advanced materials/ advanced cooling

A prioritized list of engine and airframe technologies has been determined using mission performance based trade factors. The top 34 airframe technologies, broad engine technologies and a 5 year milestone summary for all technical areas is included in Section 7 of this report. Because of the competitive nature of the roadmaps, details of the roadmaps are contained in a series of Proprietary Appendices to this non-proprietary document.
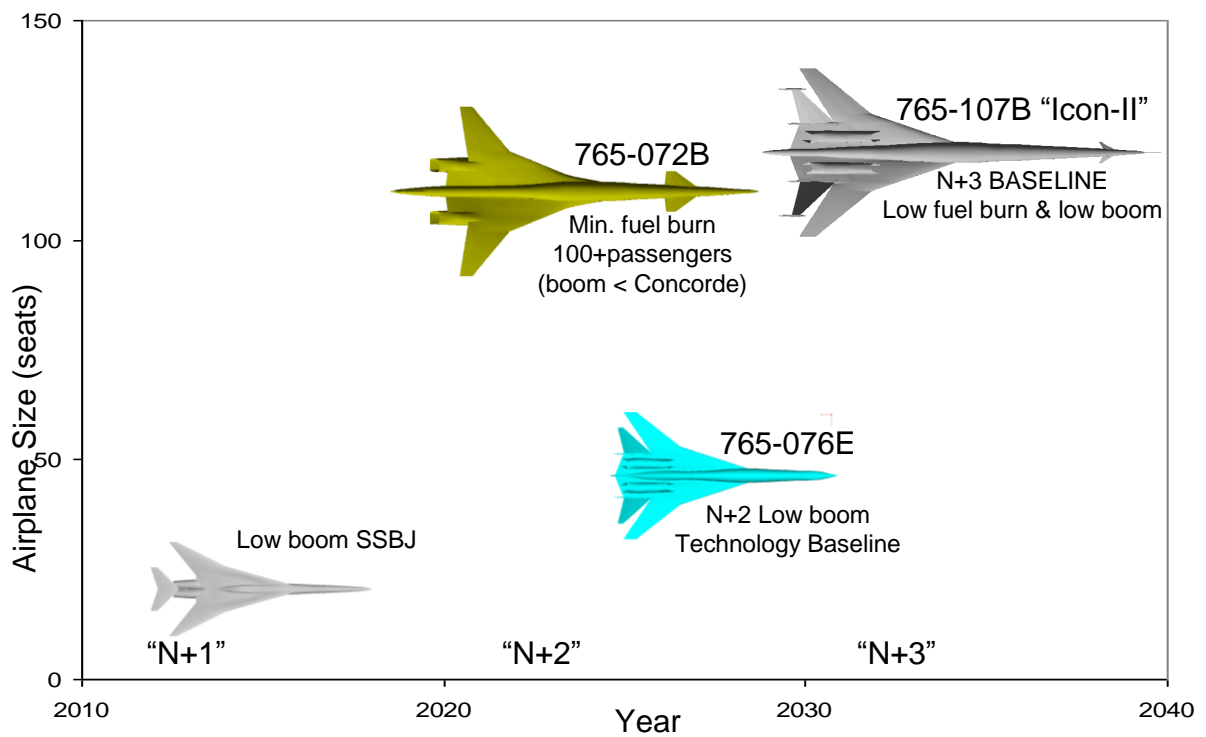
Figure 8.1 Supersonic Technology Horizons.

Appendix A: Boeing Engine Summary Results and Airframe Roadmaps

(NOT INCLUDED)

Appendix B: General Electric Engine Development and Roadmaps

(NOT INCLUDED)

Appendix C: Pratt & Whitney Engine Development and Roadmaps

(NOT INCLUDED)

Appendix D: Rolls-Royce Engine Development and Roadmaps

(NOT INCLUDED)

Appendix E: Achievable Sonic Boom Levels Through Continued Configuration Studies (Wyle Labs)

NASA has introduced a set of supersonic technology goals (Figure E.1). In order to achieve these goals, a set of design and analysis tools must be developed and refined and integrated into an effective integrated state of the art knowledge base: Sonic Boom minimization Technology. At present, various elements of the design, integration, optimization and analysis toolset have been prepared, but significant work remains to bring the technology to a readiness level suitable for serious design consideration. The remaining sections of this chapter will discuss the current state of the art in sonic boom tools, an application of the optimization technology (conducted under the current contract) to a realistic supersonic transport configuration, and a discussion of the various elements of the sonic boom technology roadmap. Where possible the nomenclature used in the Sonic Boom Technology Roadmap (long term schedule and short term schedule and costs) are *referenced in bold italics*.

	N+1 Supersonic Business Class Aircraft (2015)	N+2 Small Supersonic Airliner (2020)	N+3 Efficient Multi-Mach Aircraft (Beyond 2030)
Environmental Goals			
Sonic Boom	65-70 PLdB	65-70 PldB	65-70 PLdB low boom flight 75-80 PLdB unrestricted flight
Airport Noise (cum below stage 3)	10 EPNdB	10-20 EPNdB	20-30 EPNdB
Cruise Emissions (Cruise NOx g/kg of fuel)	Equivalent to current Subsonic	< 10	< 5 & particulate and water vapor mitigation
Performance Goals			
Cruise Speed	Mach 1.6-1.8	Mach 1.6 -1.8	Mach 1.3 - 2.0 low boom flight Mach 1.3- 2.0 unrestricted flight
Range (n.mi.)	4000	4000	4000 - 5500
Payload (passengers)	6-20	35-70	100 - 200
Fuel Efficiency (passenger-miles per lb of fuel)	1.0	3.0	3.5 – 4.5
Table 1. NASA's Initial Environmental Targets and Performance Goals for Future Supersonic Civil Aircraft			

Figure E.1 – NASA Supersonic Vehicle Goals

State of the Art, 2010 and Future Technology Needs

Sonic Boom Prediction

Considerable resources have been applied to the refinement of sonic boom prediction methodologies. One such model whose development has been funded in a large part by NASA is the PCBOOM propagation model[11]. PCBoom is a full ray trace sonic boom program that calculates sonic boom footprints and signatures from flight vehicles performing arbitrary maneuvers. It computes detailed ground signature shapes starting from a variety of near-field signature definitions. PCBoom has its roots in the NASA sonic boom program written by Thomas[12] in the early 1970s. Initial development consisted of adding focus

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[11] Page, J.A., Plotkin, K.J., and Wilmer, C.W., "PCBoom Version 6 Technical Reference and User Manual", Wyle Research Report WR 09-20, August 2009.

[12] Thomas, C.L., "Extrapolation of Sonic Boom Pressure Signatures by the Waveform Parameter Method," NASA TN D-6832, June 1972.

boom prediction capability[13]. Further development, through a series of versions,[14,15,16] extended the original code (which computed boom on a single ray for a single flight condition) to handle full maneuvers and a variety of aircraft source inputs. There have been improvements to the algorithms, such that boom aging is now handled by waveform steepening and shock fitting,[17] rather than Thomas's waveform parameter method.[18] Three dimensional ray tracing algorithms[19] have replaced Thomas's original flat earth layered ray equations, although Thomas's original ray equations are present as an option and much of the logical flow is retained.

PCBoom6 has the following capabilities:

- Specification of the vehicle as an F-function, a data line of Δp/p, via data from a CFD solution, as a simple form from a library of aircraft, or as a blunt hypersonic body. There is a launch vehicle mode, which includes the effect of the vehicle itself plus the effect of an underexpanded rocket plume.
- Matching of CFD solution inputs to mid-field via an Euler full potential code.[20]
- Ray tracing through a 3-D stratified atmosphere over either flat earth or over a WGS-84 ellipsoidal earth.
- Specification of arbitrary maneuvers in either local Cartesian coordinates or in geographic latitude and longitude.
- Calculation of superboom signatures at focal zones, and also the secondary post-boom signatures a distance away from the geometric focus.
- Calculation of boom along particular rays, or on rays across the full width of the boom carpet.
- Calculation of shock structures, either as a simple Taylor structure or via molecular relaxation absorption processes.
- Calculation of spectra and a variety of loudness metrics for ground booms.
- Calculation of the effect of finite ground impedance on boom signatures.
- Effects of wind and terrain on boom propagation.

There still remain areas where further research is required. In the Sonic Boom Technology Roadmap these are referred to as *Analysis Tools*. These Analysis Tools are further refined in the near term roadmap as *Sonic Boom Propagation Tools* whose elements are explained in more detail in the following paragraphs.

Focusing – This area requires detailed investigation of the nature of sonic boom focusing for low-boom aircraft and to assess and improve the adequacy of methods to model focused sonic boom waveforms under realistic conditions. To date, analysis of focusing from candidate low boom aircraft has been limited and has not adequately accounted for the complexity of their F-functions including off-design F-functions. A NASA NRA program has been established to investigate sonic boom focusing analytically and experimentally and to assess the suitability of current modeling techniques and physical understanding for focused sonic boom signature prediction.

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[13] Plotkin, K.J., and Cantril, J.M., "Prediction of Sonic Boom at a Focus", Wyle Laboratories Research Report WR 75-7, October 1975. Also, AIAA Paper 76-2, January 1976.

[14] Plotkin, K.J., "PCBoom3 Sonic Boom Prediction Model, Version 1.0e", Wyle Research Report WR 95-22E, October 1998.

[15] Plotkin, K.J., and Grandi, F., "Computer Models for Sonic Boom Analysis: PCBoom4, CABoom, BooMap, CORBoom," Wyle Research Report WR 02-11, June 2002.

[16] Plotkin, K.J., Page, J.A., and Haering, E.A. Jr., "Extension of PCBoom to Over-The-Top Booms, Ellipsoidal Earth, and Full 3-D Ray Tracing," AIAA 2007-3677, May 2007.

[17] Middleton, W.D., and Carlson, H.W., "A Numerical Method for Calculating Near-Field Sonic-Boom Pressure Signatures," NASA TN D-3082, November 1965.

[18] Thomas, C.L., "Extrapolation of Wind-Tunnel Sonic Boom Signatures Without Use of a Whitham F-Function," NASA SP-255, *Third Conference on Sonic Boom Research*, Schwartz, I.R., (Ed.), October 1970, pp.205-218.

[19] Schulten, J.B.H.M., "Computation of aircraft noise propagation through the atmospheric boundary layer," NLR TP 97374, December 1997.

[20] Kandil, O.A., Yang, Z., and Bobbitt, P., "Prediction of Sonic Boom Signature Using Euler-Full Potential CFD with Grid Adaptation and Shock Fitting," AIAA-2002-2543, June 2002.

Weather – A thorough investigation of the effects of weather on sonic booms needs to be explored. Current models include the effects of stratified atmospheric temperature, wind and humidity profiles, but little validation work has been done investigating the propagation of sonic booms through varied atmospheric conditions such as rain and clouds. While methodologies exist for predicting sonic boom ground impacts from winds aloft, no comprehensive analysis of the impacts of gross climate features, such as the jet stream on both operations and subsequent sonic boom cumulative impacts has been performed. Previous NASA studies assessing the impacts of future vehicles on the NextGen concept of operations and computation of system wide environmental impacts should be extended to include the cumulative environmental impacts of weather features. System wide modeling tools exist today in a suitable form that analyses could be accomplished in the short term which account for such items as the impact of seasonal jet stream variation and the impact of contrail avoidance trajectory rerouting on CONUS cumulative sonic boom impacts. Atmospheric turbulence has been addressed in recent work; however limited empirical datasets exist with high fidelity atmospheric turbulence data, with which to validate and assess current turbulence modeling. Also a more comprehensive understanding of the impact realistic turbulent environments (seasonal, regional, local terrain effects) have on sonic boom signatures is needed.

Over the Top Booms – Propagation tools for prediction of OTT booms have been established.[21] Assessments of OTT sonic booms from Concorde operations have been performed but experimental validation datasets including comprehensive weather data are limited.

Terrain – Incorporation of terrain capability in PCBoom includes the effects of ground altitude and impedance changes on predicted ground boom signatures. At present there are no benchmark datasets from which to compute validation studies of propagation over varying ground impedance and altitude terrain. Methodologies for propagation of sonic booms into canyons (natural or urban) from which one would expect sound reflections do not currently exist. Consideration of potential regulatory requirements to minimize human audibility in areas such as the Grand Canyon National Park could conceivably necessitate development of such a propagation model. Anecdotal observations of recent NASA sonic boom testing such as the House Vibes experiment[22] indicate that reflections of sonic booms off residential homes (especially garage doors or other flat surfaces) create sounds that could impact human subjective response. Models for predicting reflected or secondary acoustic elements in urban or natural environments do not currently exist.

Transmission of Booms Indoors – The potential for acceptable supersonic flight lies in the concept of sonic boom minimization through shaping sonic booms, whose shocks (and associated loudness) are lower than those of conventional N-waves. The benefit of shaping for direct outdoor listening has been well demonstrated in the laboratory, and is fully consistent with mainstream understanding of hearing and perceived loudness. The indoor perception of sonic booms is more complex[23], with three components:
• The audible and perceptible (felt) indoor boom, which is simply the outdoor boom filtered by the noise reduction characteristics of the building
• Tactile motion of the building, which is governed by the structural response characteristics of the structure
• Rattling of the building and of objects inside the building. This is a secondary effect, dependent on both building structural response and the nature of items which can potentially rattle.
Current state of the art has identified methods for prediction of the onset of window rattle[24,25] but significant work remains in the assessment of suitable indoor metrics which are reflective of human response.

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[21] Reference to Boeing Zyphrus (?) Code for OTT / Secondary Booms

[22] Klos, J. et all, "Vibroacoustic response of residential housing due to sonic boom exposure: a summary of two field tests", Noise Con 2008, July 2008.

[23] Plotkin, K.J., Sizov, N.V., and Morgenstern, J.M., "Examination of Sonic Boom Minimization Experienced Indoors", AIAA Aerospace Sciences Meeting, AIAA 2008-0057, January, 2008.

[24] Sizov, N. et all, "Measured rattle threshold of residential house windows", Noise-Con 20078.

[25] Sizov, N.V., and Scholl, D.J., "Wavelet-based detection for rattle of residential house windows", Inter-Noise 2009, August 2009.

Threshold Mach – Some of the current designs for supersonic business jet and transport aircraft[26] target overland slightly supersonic cruise flight at conditions such that the sonic boom will not reach the ground. This is known as supersonic flight below Mach Cutoff (typically Mach 1.0 – 1.2). It is a flight speed below the speed of sound at the ground, and under certain atmospheric and operational conditions where atmospheric refraction due to inherent temperature gradients will cause the sonic boom to curve upwards before intersecting the ground, thereby avoiding the creation of a sonic boom. The physical phenomena of Threshold Mach has been demonstrated; however the practical application in the NextGen system needs to be examined in more detail in order to assess the viability of such a concept. Examination of the benefits of dynamic routing on such operations, a realistic assessment of time based weather changes on system wide flights as well as a more detailed experimental benchmark dataset from which to validate the 3D ray tracing and prediction of Threshold Mach is needed.

Euler Full Potential Mid-Zone Method

In order to more accurately predict the aerodynamic field surrounding the vehicle and obtain a better representation of the sonic boom source function, it is customary to utilize Computational Fluid Dynamics, such as an Euler solver. While this often improves the order of the sonic boom modeling (from simple linearized volume and lift to incorporation of higher order acoustic sources such as multipoles), it comes with a significant computational cost. Today's CFD codes principally consider uniform atmospheric environment and are valid locally in the vicinity of the aircraft. A propagation model such as PCBoom is required to compute the effects of propagation of the vehicle signature through a varying atmosphere. When working with CFD flowfield solutions, the critical issue is coupling the highly detailed numeric near field into locally axisymmetric ray tracing. In the past, Ting and Darden's MMOC[27] and Page and Plotkin's multipole method[28,29] provided partial solutions. These are basically one or two zone methods, with two zone methods generally having an interface to ray tracing. MMOC was a two zone method where near field CFD was coupled to Method of Characteristics propagation. Plotkin[30] outlined a possible three-zone method, with full CFD interfacing to a second order CFD-like region and then to ray tracing.

An alternate technique to the multipole method which has been incorporated into PCBoom, employs a 3D Euler-Full Potential (EFP) code developed by Eagle Aeronautics and Old Dominion University.[31] This is a computationally accurate method for bridging the gap between CFD acoustic near-field predictions and linearized far-field acoustic propagation. It propagates signatures from CFD near-field to the far-field based on the full-potential equation with a grid adaptive shock fitting scheme. The EFP method extracts flowfield data from a CFD solution for either structured or unstructured CFD codes and propagates it to the acoustic far-field where a pressure cylinder is extracted and provided to PCBoom for continued propagation to the ground using geometrical acoustics.

Far-field CFD for Sonic Boom – To date very limited flight measurement data and corresponding CFD predictions are available for validation of the near-field CFD[32], the mid-field EFP propagation and

[26] Rachami, J., and Page, J., "Sonic Boom Modeling of Advanced Supersonic Business Jets in NextGen", 48th Annual AIAA Aerospace Sciences Meeting, AIAA 2010-1385, January 2010.

[27] Darden, C.M., "An Analysis of Shock Coalescence Including Three-Dimensional Effects With Application to Sonic Boom Extrapolation," NASA Technical Paper 2214, 1984.

[28] Page, J.A., and Plotkin, K.J., "An Efficient Method for Incorporating Computational Fluid Dynamics Into Sonic Boom Prediction", AIAA-91-3275, Sept. 1991.

[29] Plotkin, K.J., and Page, J.A., "Extrapolation of Sonic Boom Signatures from CFD Solutions," AIAA-2002-9022, January 2002.

[30] Plotkin, K.J., "Theoretical Basis for Finite Difference Extrapolation of Sonic Boom Signatures," 1995 NASA High-Speed Research Program Sonic Boom Workshop, NASA Conference Publication 3335, edited by D.G. Baize, July 1996.

[31] Kandil, O.A., Yang, Z., and Bobbitt, P., "Prediction of Sonic Boom Signature Using Euler-Full Potential CFD with Grid Adaptation and Shock Fitting," AIAA-2002-2542, June 2002.

[32] Haering, E.A., et all, "Airborne Shaped Sonic Boom Demonstration Pressure Measurements with Computational Fluid Dynamics Comparisons", 43rd AIAA Aerospaces Sciences Meeting, AIAA 2005-0009, January 2005.

ultimately the far-field ground sonic boom signature for shaped low-boom vehicles. Some wind tunnel measurements and corresponding CFD predictions have been performed for shaped sonic boom vehicles.[33] Further refinement of the CFD prediction models and gridding algorithms need to be investigated in order to improve the off-body CFD prediction capability, improve modeling fidelity, avoid numerical dispersion of shocks and improve computational efficiency.

<div align="center">

Low Boom Optimization – Goals and Targets

</div>

Boom Optimization Tool
The key concept to minimizing sonic boom is vehicle shaping, such that the boom at the ground is a mid-field shape that has not yet evolved into a far field N-wave.[34] George and Seebass[35,36] showed that an optimal low boom F-function is that shown in Figure E.2. The signature begins with a delta function, which Jones[37] had shown is the optimal for arbitrarily far N-waves. Since one is looking for a mid-field signature, some of the energy from the delta can be "hidden" behind it, in a region with slope gentle enough that it does not steepen into a shock. The F-function is defined by five or six constants, defined in the equation at the top of the figure. The equivalent area is algebraically related to the F-function, and is defined by the equation at the bottom of Figure E.2.
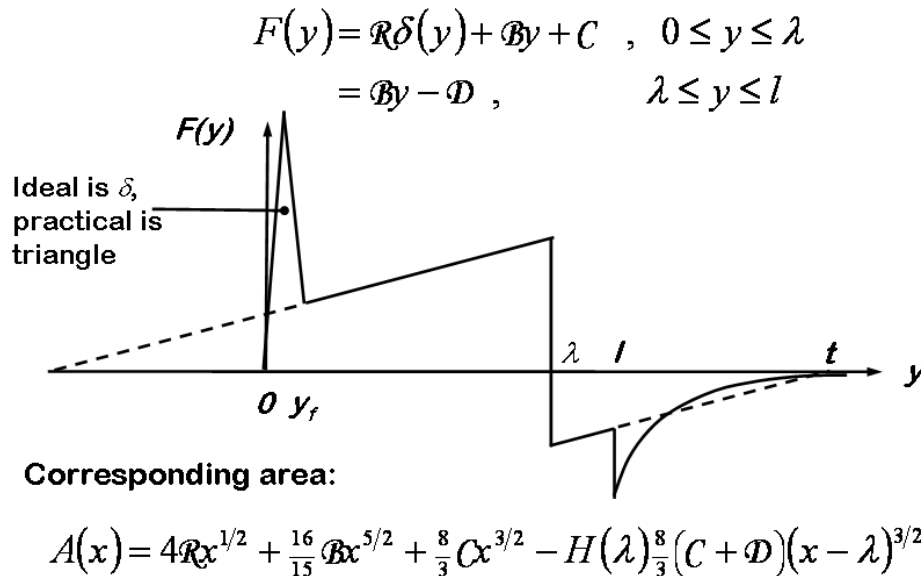
$$F(y) = \mathcal{R}\delta(y) + \mathcal{B}y + C \quad , \quad 0 \le y \le \lambda$$
$$= \mathcal{B}y - \mathcal{D} \quad , \qquad \lambda \le y \le l$$

Corresponding area:

$$A(x) = 4\mathcal{R}x^{1/2} + \tfrac{16}{15}\mathcal{B}x^{5/2} + \tfrac{8}{3}Cx^{3/2} - H(\lambda)\tfrac{8}{3}(C+\mathcal{D})(x-\lambda)^{3/2}$$

Figure E.2 – George-Seebass minimum boom solution, including front and rear shocks

The F-function in Figure E.2 will, at its design point, yield a ground signature that falls into a family illustrated in Figure E.3. George and Seebass showed that, for a given weight and length, this model yielded the optimal lowest shock strength. They also established the minimum length needed to obtain a shockless boom.

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[33] Graham, D.H., et all, "Wind Tunnel Validation of Shaped Sonic Boom Demonstration Aircraft Design", 43rd AIAA Aerospace Sciences Meeting, AIAA 2005-0007, January 2005.

[34] McLean. F.E., "Some Nonasymptotic Effects on the Sonic Boom of Large Airplanes," NASA TN D-2877 (1965)

[35] George. A.R., and Seebass, R, "Sonic Boom Minimization Including Both Front and Rear Shocks", AIAA Journal **9** (1971) 2091-2093.

[36] Seebass. A.R, and George, A.R, "Design and Operation of Aircraft to Minimize Their Sonic Boom," J.Aircraft, **11** (9), 509-517, September 1974.

[37] Jones, L.B., "Lower Bounds for Sonic Bangs", Journal of the Royal Aeronautical Society **65** (1961) 1-4
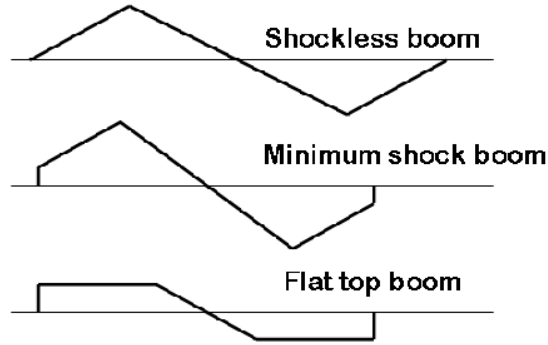
Figure E.3. Family of booms in George-Seebass optimal model

There are two limitations to George and Seebass's theory. The first is that it is ideal, with the vehicle geometry restricted to shapes defined by the equation at the bottom of Figure E.2. The second is that it is written only for the total boom, the sum of volume and equivalent lift volume, under the aircraft. Sonic boom is three dimensional, with boom off-track being just as important as on-track, and for a given configuration the mix of volume and lift will change with off-track azimuth angle.

These limitations are relaxed in the Generalized George-Seebass (GENGS) model developed by Wyle.[42,41] There are two generalizations. The first is to define the F-function as an arbitrary number of segments, as sketched in Figure E.4. The equation at the top of E. 2 then becomes

$$F(y) = \sum_{i=1}^{n} (B_i y + C_i) H(y - \lambda_{i-1})$$

(1)

where B_i, C_i and λ_i are segment-by-segment generalizations of the original single parameters and H is the Heaviside step function. The nose delta is not a separate element, but is defined by a pair of segments forming a triangle. Equation (1) is not ideal, but allows for realistic requirements such as engines and empennage. Its deviation from ideal can be quantified by comparison with the original form. The equivalent area is then

$$A_e(x) = 4 \sum_{i=1}^{n} [B_i I_3(x; x_{i-1}, l) + C_i I_2(x; x_{i-1}, l)]$$

(2)

where I_2 and I_3 are closed form algebraic expressions similar to the elements in the equation at the bottom of Figure E.2.
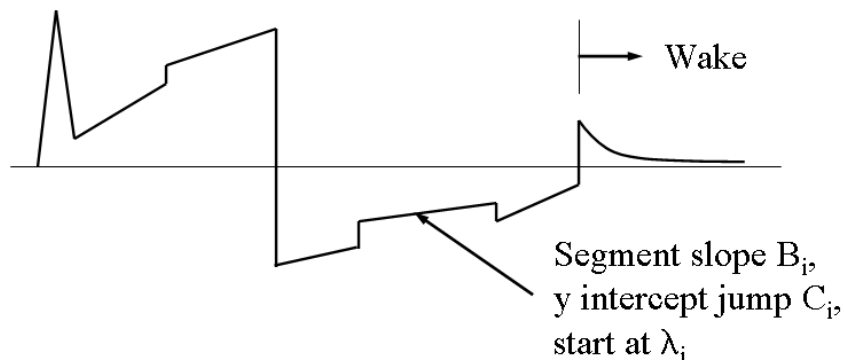

Figure E.4. Generalized multi-segment F-function

The second extension is to allow azimuthal variation. A true three dimensional F-function can be decomposed into distributions of multipoles.[38] This is a logical extension of Walkden's original lifting body theory[39] which represented the F-function as volume (monopole) and lift (dipole) components. Equation (1) is further generalized to

$$F(y,\theta) = \sum_{i=1}^{k} \sum_{n=0}^{\infty} \cos(n\theta)(B_{in} y + C_{in})H(y - \lambda_{in-1})$$

(3)

where the decomposition is both in longitudinal segments i and azimuthal harmonic order n, There are now many more components to solve for, but there are also many more constraints since minimum shock strength is sought off track as well as on track.

This generalized method has been implemented in graphical interactive version used for manual steering of optimization, Figure E.5, and a batch version suitable for use in an automated optimization system.
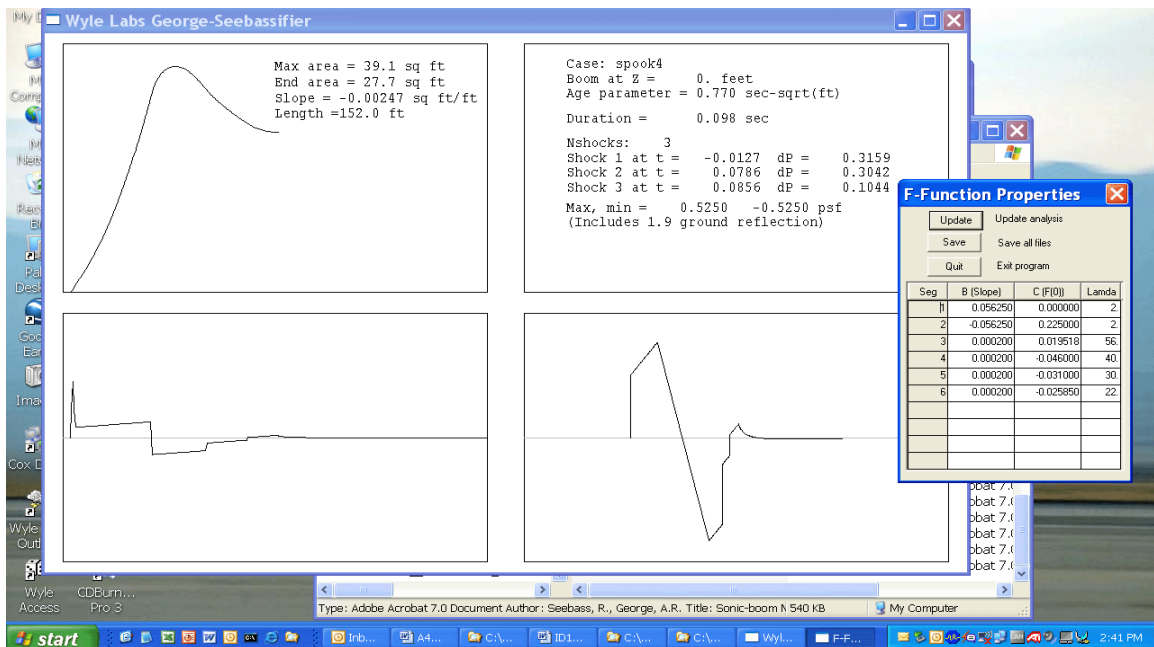

Figure E.5. Graphical manually steered generalized George-Seebass model (GENGS)

Application of the Manually Steered Optimization Analysis

The 3D Generalized George-Seebass analysis methodology described in the previous section was developed for NASA under a separate NRA effort and leveraged in this study. GENGS serves as a constraint based on the physical reality of the optimum George-Seebass solution. The GENGS methodology was executed using manual steering to obtain a target low-boom concept F-function and associated ground sonic boom metrics. This process was applied in order to demonstrate application of the Low-Boom Technology Optimization and better understand its role in low-boom configuration development and provide deeper insight in order to effectively develop the low-boom technology roadmap.

Vehicle sonic boom characteristics for the configuration -2A vehicle (Figure E.6) was provided to Wyle by Boeing in the form of an Excel file containing undertrack centerline lift and volume distributions (Figure

[38] George, A.R., "Reduction of Sonic Boom by Azimuthal Redistribution of Overpressure", AIAA Journal, **7**, 2, February 1969.
[39] Walkden, F., "The Shock Pattern of a Wing-Body Combination, Far From the Flight Path", Aeronautical Quarterly, **IX** (2), 164-194, 1958.

E.7) predicted by linear aerodynamic analyses. This vehicle starting point is not an optimized low-boom vehicle; however it is reflective of a closed and sized configuration and is the result of incorporation of boom reduction concepts, such as slender airframe, highly swept swing wings, integrated nacelles and aft deck, into the configuration. The source characteristics include airframe features such as tails and nacelles are lumped in with the appropriate lift and volume pieces.
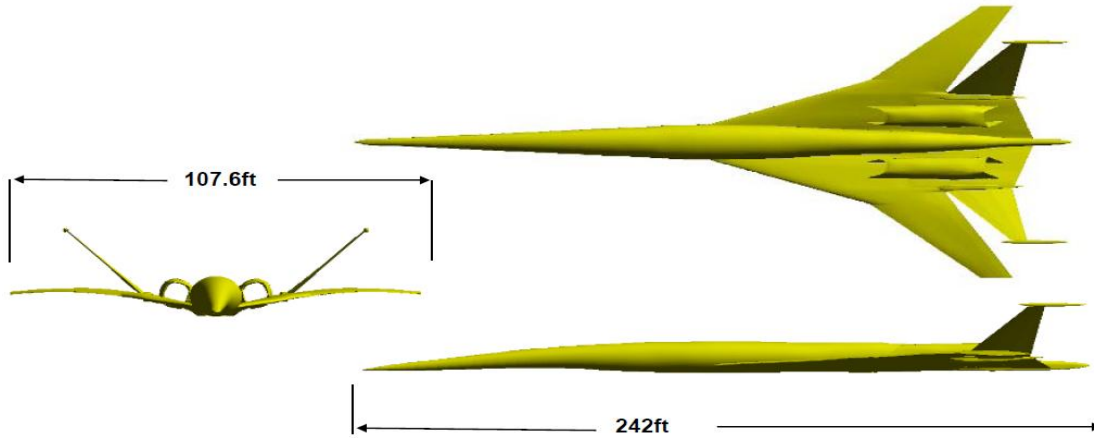

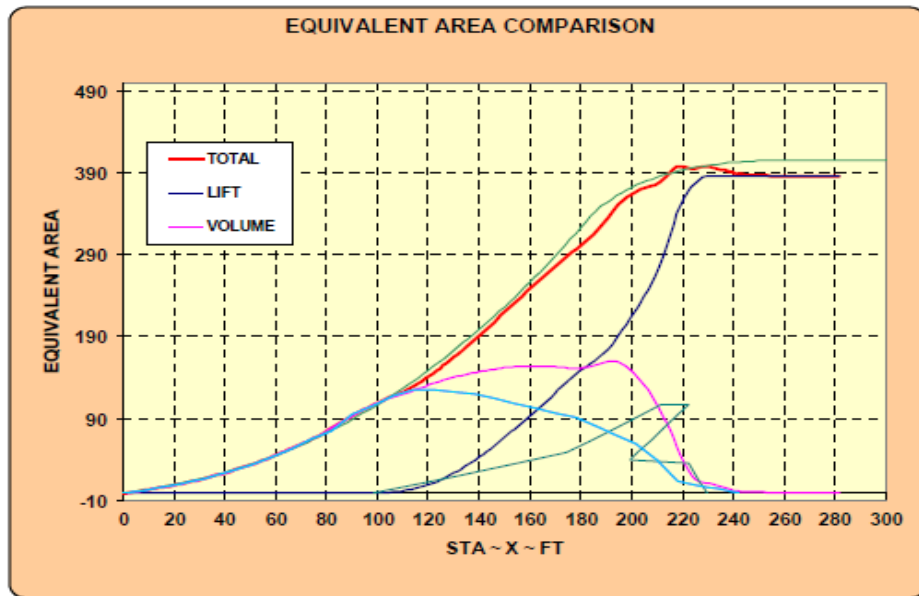**Figure E.6 –Configuration -2A**[40]

Figure E.7 – Configuration – 2A Sonic Boom Linearized Aero (Lift and Volume) Source Description

The optimization process was developed to provide suggested source target improvements including higher order poles as would be present in a CFD solution. For this analysis we did not have CFD results available, so a starting cylinder was created analytically from the linearized undertrack data. The data was manipulated by using a Cosine(azimuth) function to estimate the lift component at other roll angles (Figure E.8). The lift and volume were summed and converted to an F-function for all roll angles in 1 degree increments. The F-function was scaled back to dP/P and a complete pressure cylinder was created.

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[40] A description of the -2A vehicle is provided in Section 6.2
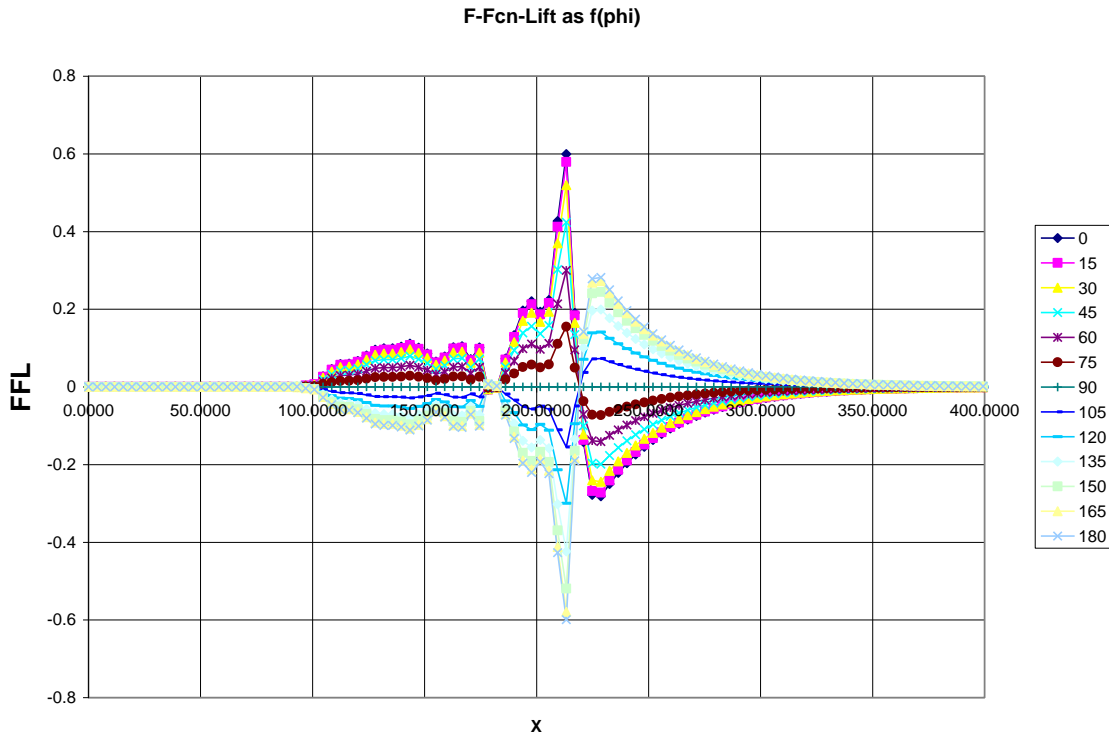
F-Fcn-Lift as f(phi)

Figure E.8 – Starting pressure cylinder

The original provided pressure distribution (dP/P) is based on a radius of 1000 Ft. This is too large for the GENGS Cylinder optimization process because much of the initial aging (where there are a lot of dramatic changes) are not included in a 1000 Ft radius cylinder, and hence lost. Since our starting point contains only the n=0 and n=1 multipole terms, reducing the cylinder radius did not require a full multipole analysis. The sonic boom source description was reworked so that the dP/P is representative of a cylinder with radius of one-half body length. In the case of the -2A vehicle, this is 121 Ft. The scaling from F-fcn to dP/P is provided in Equation 4.

$$\frac{\gamma M^2}{\sqrt{2\beta R}} \tag{4}$$

where $\gamma = 1.4$ and $\beta = \sqrt{M^2 - 1}$ and $R = 121 ft$

The GENGS optimization process is designed to start with a CFD solution with the axial coordinate origin located at the noise of the aircraft. So the first axial coordinate of the initial pressure rise (nose cone) in the Cylinder file was adjusted aft along the Mach angle representing the undertrack intersection of the nose shock with the cylinder at the 0.5 R/L radius.

The strength of the starting multipoles present in the cylinder may be computed using the GENGS preprocessor program Poles. The order 0 (volume) and 1 (lift) multipoles are provided in Figure E.9 for the configuration -2A concept vehicle for the undertrack azimuth. The black lines indicate the numerical multipole fit to the source dP/P data while the red lines are the approximated finite number of multipole segments used for the starting point in the optimization process.
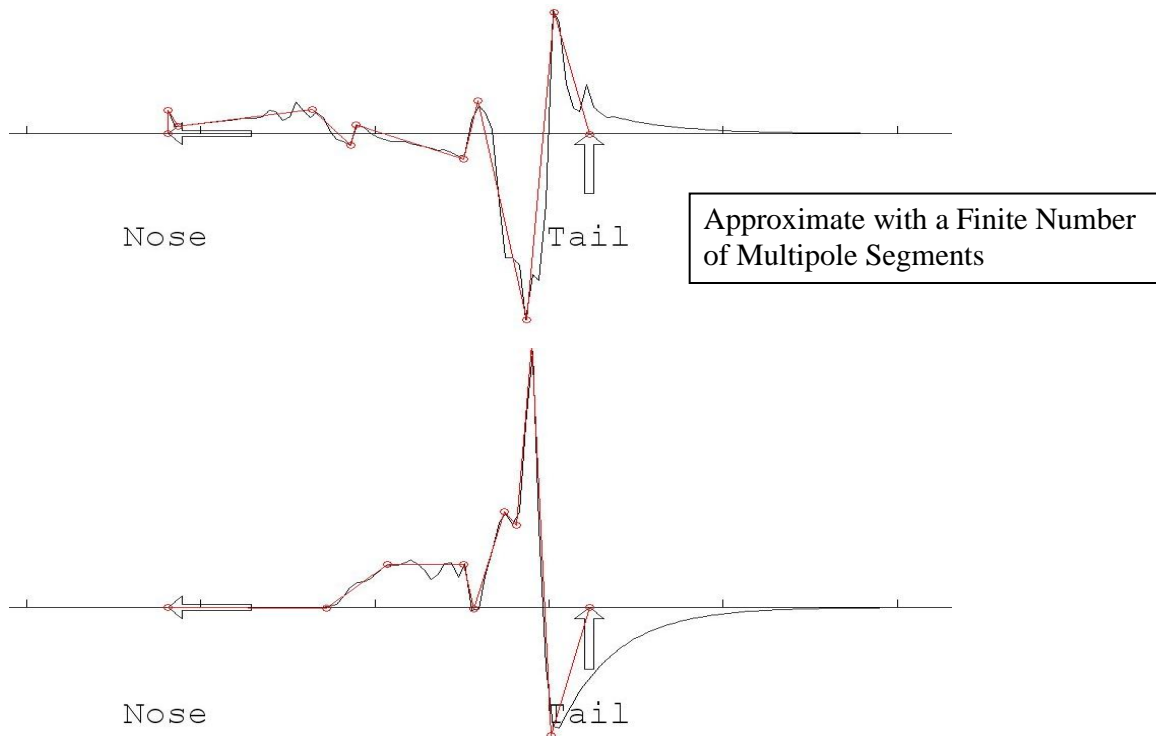
Figure E.9 – Configuration -2A multipoles of order 0 (volume) and 1 (lift)

With the starting configuration defined, the interactive (human steered) process of undertrack optimization can begin. This analysis leveraged a recently completed Wyle NASA NRA[41,42] entitled "Low Boom Supersonic Vehicle Shaping Tools" under NASA Task Order No. NNL08AA27T. This technology is outlined earlier in this section. The manually steered optimization allows one to interactively edit the source multipole distribution and visualize the ground signature and loudness. For this process the signature aging characteristics were created based on flight at Mach 1.8 at 51,000 Ft through the US Standard atmosphere using PCBoom[43].

The manually steered optimization process concentrated only on the undertrack signature and relied on the introduction of higher order multipoles to achieve reduced ground booms. Figure E.10 documents the starting source F-function parameters (top left quadrant) the starting source F-function (bottom left quadrant), the ground boom signature parameters (top right quadrant) and ground boom signature (bottom left quadrant). This is based on the finite number of segments fit to the n=0 and n=1 order poles. For this source F-function, the maximum shock is at the rear of the aircraft of magnitude 1psf and is driving the loudness level to 90.69 PLdB. Optimization will therefore attempt to better shape the aft segment of the F-function and reduce the rear shock by introducing higher order multipoles (order n=2, quadrupoles). Examination of CFD solutions for slender supersonic configurations suggested that quadrupoles contain initially a negative pulse followed by a positive and a second negative pulse.

[41] Plotkin, K. J., "Sonic Boom Shaping in Three Dimensions", 15th AIAA / CEAS Aeroacoustics Conference, AIAA 2009-3387, May 2009.

[42] Plotkin, K. J., "Low Boom Supersonic Vehicle Shaping Tools, Including Three-Dimensional Effects", Wyle Research Report WR 09-15, June 2009.

[43] Page, J.A., Plotkin, K.J., and Wilmer, C.W., "PCBoom Version 6 Technical Reference and User Manual", Wyle Research Report WR 09-20, August 2009.

Update — Update analysis
Save — Save all files
Quit — Exit program

Seg	Volume (n=0) B (Slope)	C (F(0))	Lamda	Lift (n=1) B (Slope)	C (F(0))	Lamda	Quadrupole (n=2) B (Slope)	C (F(0))	Lamda
1	-0.006513	0.056569	6.	-0.000019	0.000000	91.	0.000003	0.000000	242.
2	0.000528	0.014325	77.	0.002919	-0.267357	35.	0.000000	0.000000	0.
3	-0.003923	0.383732	22.	0.000000	0.100403	44.	0.000000	0.000000	0.
4	0.016439	-1.754247	3.	-0.017319	3.044711	6.	0.000000	0.000000	0.
5	-0.001335	0.165344	62.	0.013365	-2.355783	17.	0.000000	0.000000	0.
6	0.017604	-3.054264	8.	-0.004529	1.097802	7.	0.000000	0.000000	0.
7	-0.018877	3.439382	28.	0.046968	-9.201615	9.	0.000000	0.000000	0.
8	0.046404	-10.008609	16.	-0.083101	17.982893	11.	0.000000	0.000000	0.
9	-0.014734	3.563932	20.	0.013610	-3.293624	22.	0.000000	0.000000	0.

```
Case: Cyl-2a
Boom at Z =    0. feet, phi =    0.00 degrees
Age parameter = 0.843 sec-sqrt(ft)
Duration =    0.221 sec
Nshocks:   6
Shock 1 at t =  -0.0104  dP =   0.2963
Shock 2 at t =   0.0132  dP =   0.5230
Shock 3 at t =   0.0507  dP =   0.2232
Shock 4 at t =   0.0829  dP =   0.2448
Shock 5 at t =   0.1307  dP =   0.1833
Shock 6 at t =   0.2105  dP =   0.9995
Max, min =    1.1433
@Grnd     0.58 PsfMax   90.69 PLdB
 113.16 dB  71.39 dBA  94.28 dBC
```
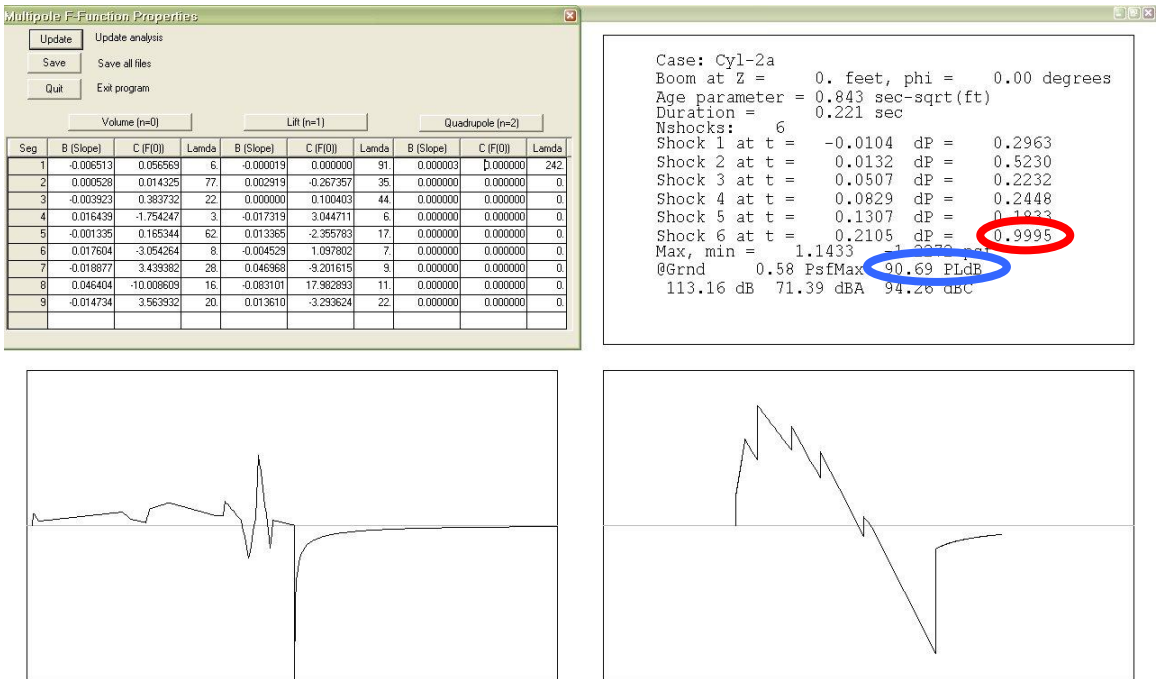
Figure E.10 – Starting -2A Source and Ground Boom Signature and Loudness

After several interactive iterations, it was determined that introduction of the quadropole terms shown in Figure E.11 (top left inset) created a multi-step aft shock. Further refinement of the multipole source distribution (Figure E.12) eventually yielded a target F-function which obtained balanced front and rear maximum shock strengths (approximately 0.5 psf) and resulted in a reduced loudness level of 84.9 dB, a reduction of almost 6dB from the starting point. An illustration of the undertrack signature evolution as it advances and ages through the atmosphere is provided in Figure E.13. Evident is the evolution of the higher order multipoles into an aft "sawtooth" like signature, reminiscent of the quiet spike technology responsible for significant reduction of sonic boom levels from the front half of the ground boom signature.
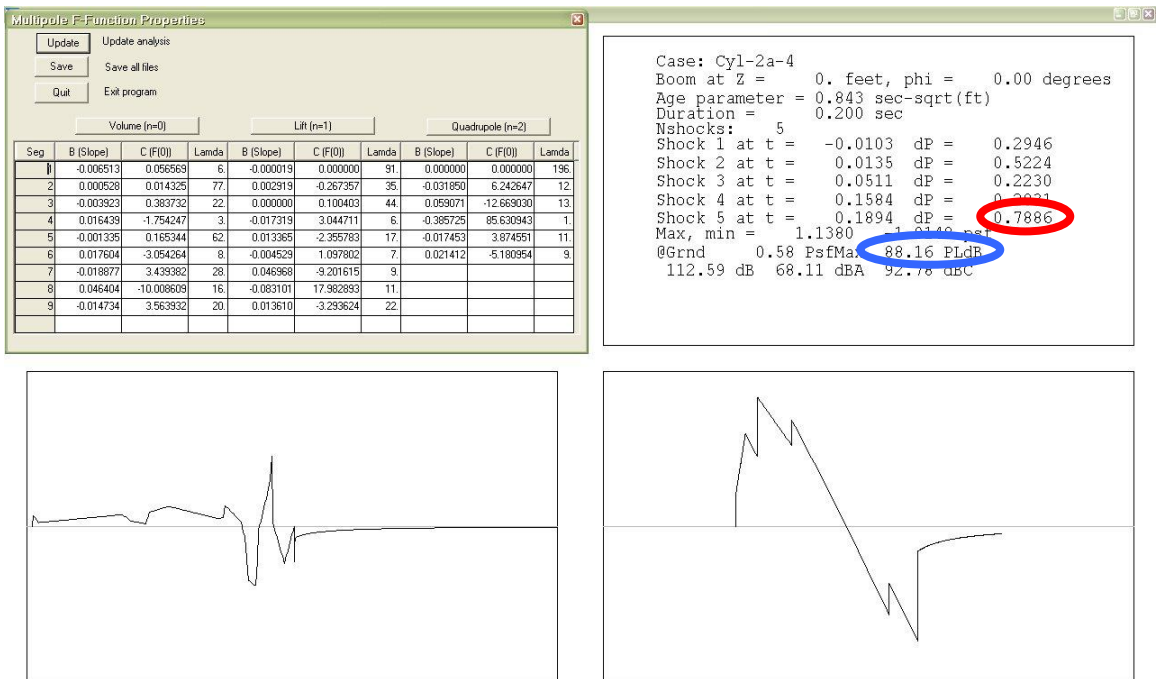
Update — Update analysis
Save — Save all files
Quit — Exit program

Seg	Volume (n=0) B (Slope)	C (F(0))	Lamda	Lift (n=1) B (Slope)	C (F(0))	Lamda	Quadrupole (n=2) B (Slope)	C (F(0))	Lamda
1	-0.006513	0.056569	6.	-0.000019	0.000000	91.	0.000000	0.000000	196.
2	0.000528	0.014325	77.	0.002919	-0.267357	35.	-0.031850	6.242647	12.
3	-0.003923	0.383732	22.	0.000000	0.100403	44.	0.059071	-12.669030	13.
4	0.016439	-1.754247	3.	-0.017319	3.044711	6.	-0.385725	85.630943	1.
5	-0.001335	0.165344	62.	0.013365	-2.355783	17.	-0.017453	3.874551	11.
6	0.017604	-3.054264	8.	-0.004529	1.097802	7.	0.021412	-5.180954	9.
7	-0.018877	3.439382	28.	0.046968	-9.201615	9.			
8	0.046404	-10.008609	16.	-0.083101	17.982893	11.			
9	-0.014734	3.563932	20.	0.013610	-3.293624	22.			

```
Case: Cyl-2a-4
Boom at Z =    0. feet, phi =    0.00 degrees
Age parameter = 0.843 sec-sqrt(ft)
Duration =    0.200 sec
Nshocks:   5
Shock 1 at t =  -0.0103  dP =   0.2946
Shock 2 at t =   0.0135  dP =   0.5224
Shock 3 at t =   0.0511  dP =   0.2230
Shock 4 at t =   0.1584  dP =   0.2031
Shock 5 at t =   0.1894  dP =   0.7886
Max, min =    1.1380
@Grnd     0.58 PsfMax   88.16 PLdB
 112.59 dB  68.11 dBA  92.78 dBC
```

Figure E.11 – Intermediate -2A Source and Ground Boom Signature and Loudness

Update | Update analysis
Save | Save all files
Quit | Exit program

Volume (n=0) | Lift (n=1) | Quadrupole (n=2)

Seg	B (Slope)	C (F(0))	Lamda	B (Slope)	C (F(0))	Lamda	B (Slope)	C (F(0))	Lamda
1	-0.006513	0.056569	6.	-0.000019	0.000000	91.	0.000000	0.000000	192.
2	0.000528	0.014325	77.	0.002919	-0.267357	35.	-0.031850	6.242647	16.
3	-0.003923	0.383732	22.	0.000000	0.100403	44.	0.059071	-12.700000	13.
4	0.016439	-1.754247	3.	-0.017319	3.044711	6.	-0.385725	85.630943	3.
5	-0.001335	0.165344	62.	0.013365	-2.355783	17.	-0.017453	3.874551	9.
6	0.017604	-3.054264	8.	-0.004529	1.097802	7.	0.021890	-5.180954	9.
7	-0.018877	3.439382	28.	0.046968	-9.201615	9.	0.000000	0.000000	0.
8	0.046404	-10.008609	16.	-0.083101	17.982893	11.	0.000000	0.000000	0.
9	-0.014734	3.563932	20.	0.013610	-3.293624	22.	0.000000	0.000000	0.

```
Case: Cyl-2a-4
Boom at Z =     0. feet, phi =    0.00 degrees
Age parameter = 0.843 sec-sqrt(ft)
Duration =    0.194 sec
Nshocks:    7
Shock 1 at t =   -0.0103   dP =    0.2946
Shock 2 at t =    0.0135   dP =    0.5224
Shock 3 at t =    0.0511   dP =    0.2230
Shock 4 at t =    0.0525   dP =    0.0857
Shock 5 at t =    0.1742   dP =    0.2524
Shock 6 at t =    0.1786   dP =    0.1937
Shock 7 at t =    0.1835   dP =    0.513
Max, min =    1.1380   -1.0537 psi
@Grnd     0.58 PsfMax   84.87 PLdB
  112.75 dB   64.06 dBA   90.75 dBC
```

Figure E.12 - Final -2A Manually Steered Source and Ground Boom Signature and Loudness

P(t) at 51kFt

P(t) at 40kFt

P(t) at 50kFt

P(t) at Ground

Figure E.13 – Final Manually Steered and Optimized Configuration Propagation History

An integral part of the optimization process is retention of the key configuration characteristics such as weight and length. The length of the vehicle is represented by the F-function length and preserving this value retains the original configuration length. Weight is represented by the integration of the lift from the vehicle and is manifest by the integral of the axial lift term from the n=1 multipole. Since the n=0 and n=1 multipoles were essentially preserved during this manually steered optimization process, these key configuration characteristics were retained.

Higher order multipoles beyond n=2 were not exploited in this analysis. Potential improvements to the azimuthal redistribution of boom might be found by introducing additional terms. The software suite provides for this analysis using optimizer steering – a task unsuitable for "human" (manual) steering. A parametric investigation of sonic boom target shaping with automated optimizer steering could help to better understand the potential improvements such poles will provide, specifically when considering boom signature across the entire carpet and not just undertrack. Development of the knowledge base for potential higher order multipole benefits as well as an understanding of the applicability across configuration types (smaller business jets, larger transports, symmetric and asymmetric configurations and vehicles with non-planar lifting surfaces such as joined wings) is required to advance the technology readiness level of the sonic boom optimization target development.

Preferred objective functions and targets – is how the sonic boom source optimization technology is referred to in the sonic boom technology roadmap. The current optimization methodologies employed in this study explained in the previous section, focused on perceived loudness (PLdB) as the metric of choice. However at present, the regulatory framework for future commercial supersonic flight remains undefined. Considerations of cumulative sonic boom impacts and possible indoor and outdoor listening environments have the potential to introduce additional metrics into the optimization process. The proper balance between objective functions and targets when considering ground boom metrics must be explored further.

Survey Potential Objective Function Parameters – When exploring GENGS optimization using automated rather than manually steered optimization, a series of objective function parameter boundaries must be defined. A systematic investigation of these functions for various classes of supersonic low-boom aircraft should be performed. It is conceivable that different sets of objective functions are more effective for smaller vehicles such as business jets than for larger transport aircraft. Also conventional symmetric slender wing-body aircraft will require different optimization guidance than novel concepts such as oblique wing or joined wing low-boom aircraft.

An expansion of the GENGS optimization concept to other flight altitudes (such as cruise-climb profiles), to other Mach numbers (such as would be encountered for lower range missions) and the incorporation of flight over different terrain conditions (mountains, over water flight etc…) is needed. Expansion of the optimization from a single operating condition across the carpet width, to a full mission based optimization and ultimately a system-wide optimum will be needed in order to guide the detailed design process. Expansion of the optimization technology will be required before any significant low-boom design investment will be made.

Integrate tools to define targets – At present the link between the configuration parameters and the GENGS optimization targets does not exist. There is a distinct decoupling of the vehicle surfaces and the off-body target pressure distribution. The first step is to integrate the existing design suite of tools with the optimization targets so that achievable and reasonable configuration changes are driving the optimization process, not just the intermediate pressure or F-function distribution. The configuration shape responsible for yielding an aerodynamic pressure solution with the optimized and desired higher order poles is not defined by this process. Additional configuration shaping design work is required to determine the changes required in the lifting surfaces which will yield the desired non-linear effects. The development of multidisciplinary design optimization toolsets which will permit rapid design of alternate configurations which can produce these desired higher order multipole signatures is a one of the technology areas requiring additional investment.

Configuration and Target Links Understood – With the integrated configuration – optimization target tool developed, systematic configuration perturbations can be explored in order to better understand the full three-dimensional higher order impact configuration changes have on the higher order multipoles from the sonic boom perspective. An examination of these relationships will lead to potential rapid prototyping improvements in the design methodology and more robust vehicle designs.

Appendix F: Boeing Airframe Technology Roadmaps

(NOT INCLUDED)

G.1 Introduction

The SOW between Boeing and NASA contains the following description in Task 3.6: "The contractor shall conduct detailed studies on the most promising technologies and technology combinations determined in task 3.5. … The contractor shall … use a higher order level of analysis tools to ensure benefit and penalty trends are not a function of tool fidelity." M4 is supporting this effort by extending the trade study process with detailed analysis using higher fidelity structural models. The approach taken is to perform multiple aeroelastic analyses including FEM based weight prediction to quantify effect on weight of technologies and configuration parameters. This work is based on Boeing's N+2 FEM with updates for the N+3 effort. This model is for the 765-076E configuration described in reference 1 and shown in Figure G.0.1.

Figure G.0.1: 765-076E general arrangement [2]. This figure depicts the vehicle planform with an initial structural layout. The structural layout was revised for use in the analyses in this effort.

G.1.1 Performance Summary

Based on the aeroelastic FEM received from Boeing, the baseline FEM for this study has been developed. This work is described here:

Task 1: Establish Sensitivity of Vehicle Weight to Active Flutter Suppression Technology
- Completed
    - Strength analysis
        - Received strength sized FEM from Boeing
        - Define regions not included in global sizing (Detail design of local reinforcements not addressed in this effort)
    - Flutter analysis
        - Flutter analysis of strength sized vehicle
        - Add local panel stiffness to remove local modes
    - Optimization setup
        - Definition of design regions for use in trade studies
        - Definition of minimum gage
    - Structural sizing with flutter constraints to quantify effect of flutter suppression technology

Task 2: Establish Sensitivity of Vehicle Weight to Material Property Technologies
- Completed
    - Material trade study for four materials with and without flutter constraints

G.1.2 Issues/Concerns

No reportable technical issues exist at this time.

G.2 Strength Analysis

G.2.1 Assumptions

The following assumptions are made in the N+3 strength analysis:
- Basic load set of 8 cases
- Linear aerodynamics and linear structure
- Minimum gauge thickness of 0.040"
- Local reinforcements not addressed in this effort
- 270 property regions grouped in the eighteen portions of the structure shown in Figure G.0.2 through Figure G.0.10

a)   b)
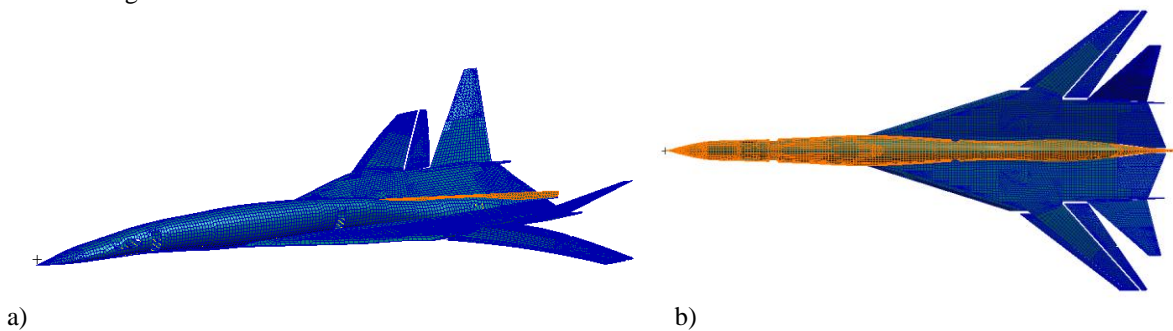
Figure G.0.2: (a) Fuselage Spine, (b) Fuselage Skin

a)   b)
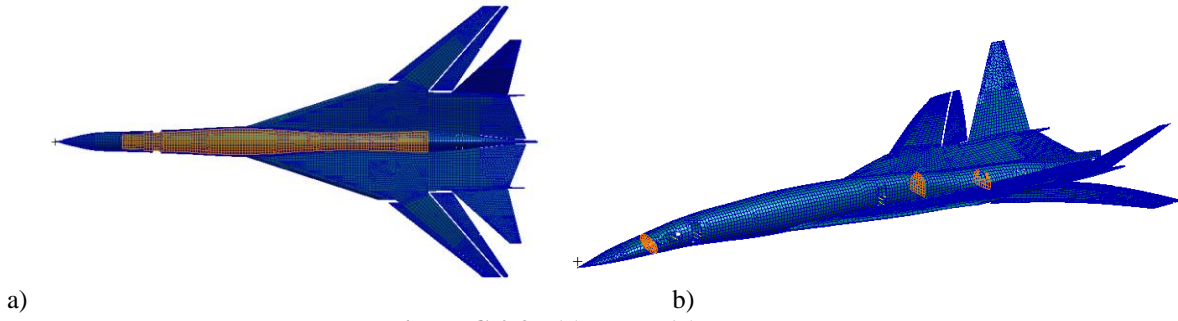
Figure G.0.3: (a) Floor, (b) Bulkheads

a)   b)
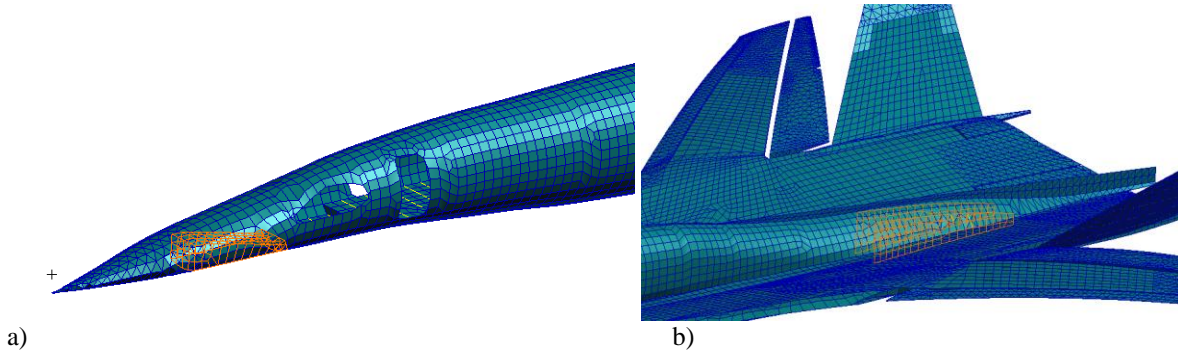
Figure G.0.4: (a) Forward Landing Gear Bay, (b) Aft Walls

a)   b)
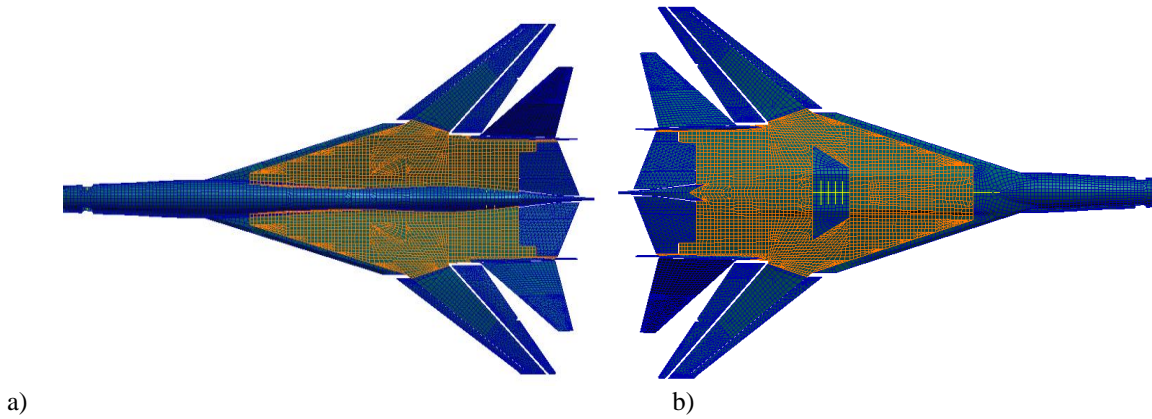
Figure G.0.5: (a) Inboard Wing Upper Skin, (b) Inboard Wing Lower Skin

a)   b)
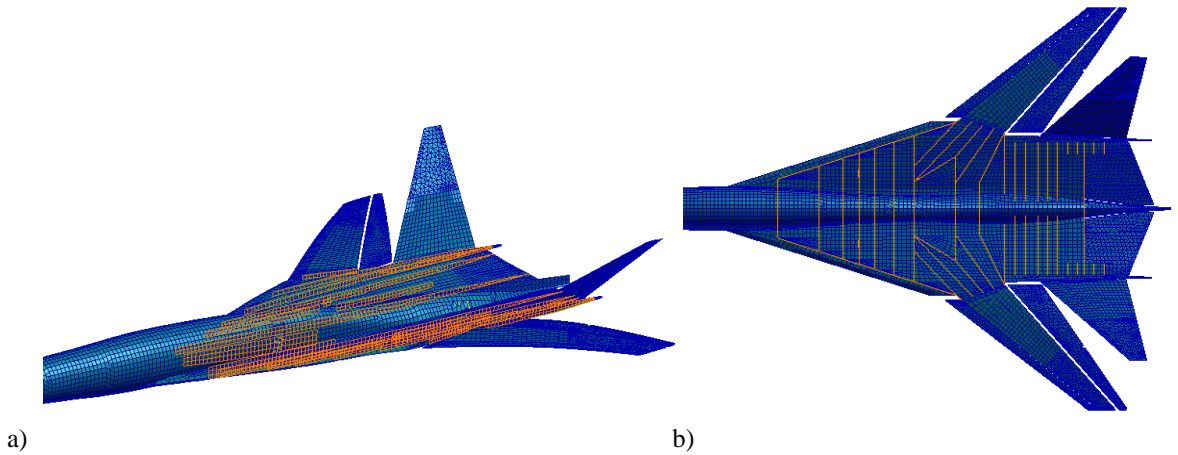
Figure G.0.6: (a) Inboard Wing Ribs, (b) Inboard Wing Spars (Forward Carry-through and Aft)

114

a)   b)
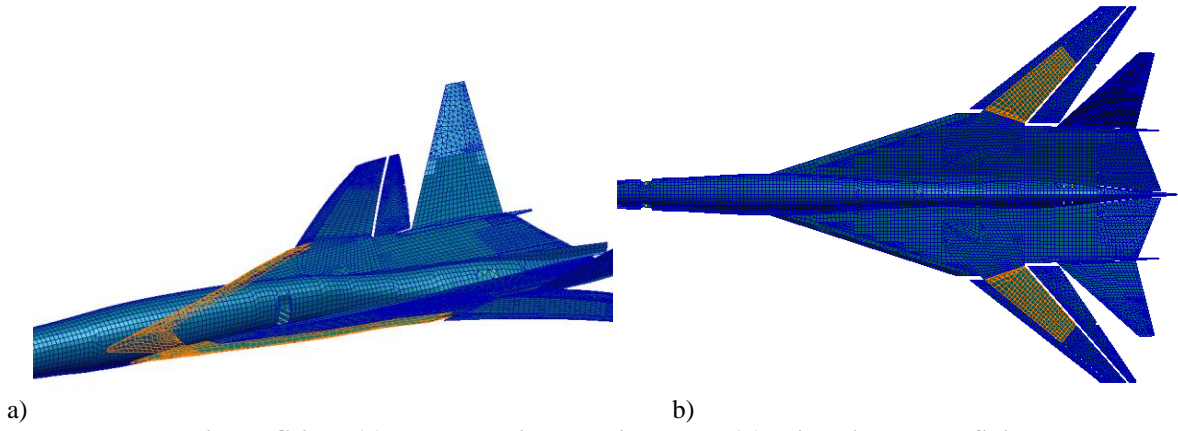
Figure G.0.7: (a) Inboard Wing Leading Edge, (b) Mid Wing Upper Skin

a)   b)
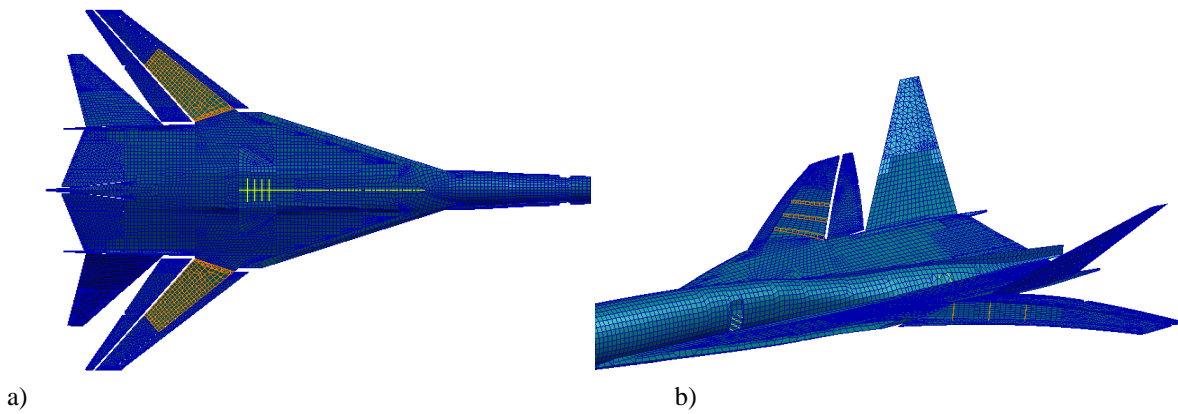
Figure G.0.8: (a) Mid Wing Lower Skin, (b) Mid Wing Ribs

a)   b)
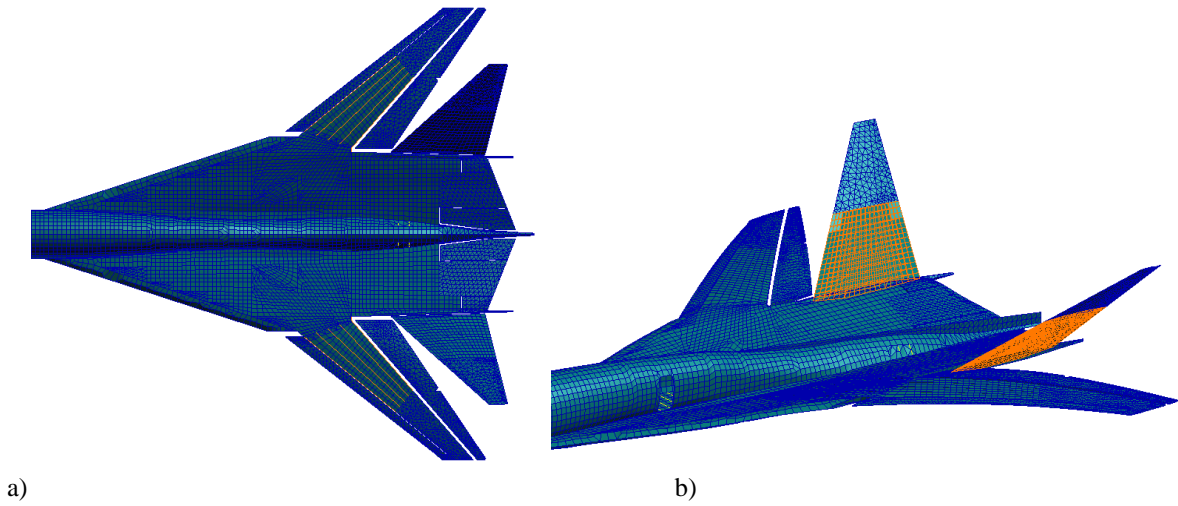
Figure G.0.9: (a) Mid Wing Spars, (b) Fins

a)   b)
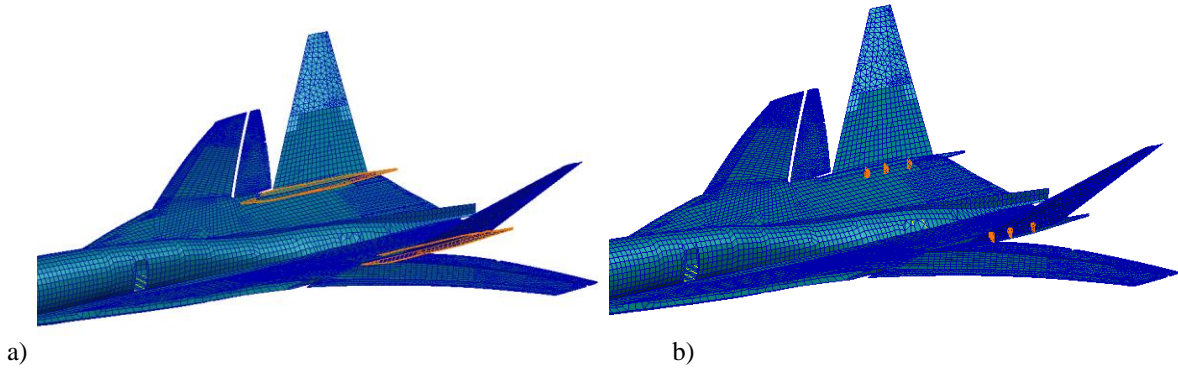
Figure G.0.10: (a) Skin Below Fins, (b) Spars Below Fins

G.2.2 Load Conditions

The load conditions used in this study were developed by Boeing [3]. These include both symmetric and anti-symmetric maneuvers as well as landing, a lateral ground maneuver and a simple gust condition. The load conditions (Limit loads) are:

- +2.5/-1.0G subsonic
- +1.2/-0.0G supersonic
- 25°/sec roll subsonic
- Landing
- 0.5G lateral ground maneuver
- 1.5G pitch-up supersonic

The strength requirement enforced is:

- No material yielding at limit load

G.2.3 Material Properties

Materials considered in the material trade study include a conventional Aluminum, an Advanced Titanium, as well as baseline and improved Graphite Epoxy materials. The properties used for these materials are shown in Table G.0.1.

Table G.0.1: Material properties used in N+3 material trade study.

		Al	Ti	Baseline Comp	Improved Comp
		2024-T62	5Al-5V-5Mo-3Cr	11/11 email	11/11 email
E	Msi	10.6	16.0	30.6	39
E (q-iso)	Msi	10.6	16.0	11.1	13.9
Ftu	ksi	63		56	68
Fty	ksi	50	180	37	45
εall (Limit)	in/in	0.004717	0.011250	0.003363	0.0032614
rho	lb/in^3	0.10	0.16	0.056	0.056

G.2.4 Stress Results for Titanium Configuration

As discussed in the Interim Report [4] elements in the wing/fuselage joint region with stress greater than 180ksi were removed from consideration for the optimization studies. Additionally the minimum gauge thickness was set to 0.040". To decrease the time the optimization analysis took to run, design regions, as provided by Boeing, that resulted in similar optimized thickness were grouped together. This reduced the total number of design regions to optimize from 535 to 270. Figure G.0.11 shows the von Mises stress envelope of the eight load conditions for the strength optimized upper and lower skin (note that the set of elements removed are not included in the results).

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Fringe: Derived Maximum, Optimized, Stress Tensor, , von Mises, (NON-LAYERED)

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default_Fringe :
Max 180136. @Elm 31110028.1
Min .000000 @Elm 41310030.1

a)

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Fringe: Derived Maximum, Optimized, Stress Tensor, , von Mises, (NON-LAYERED)

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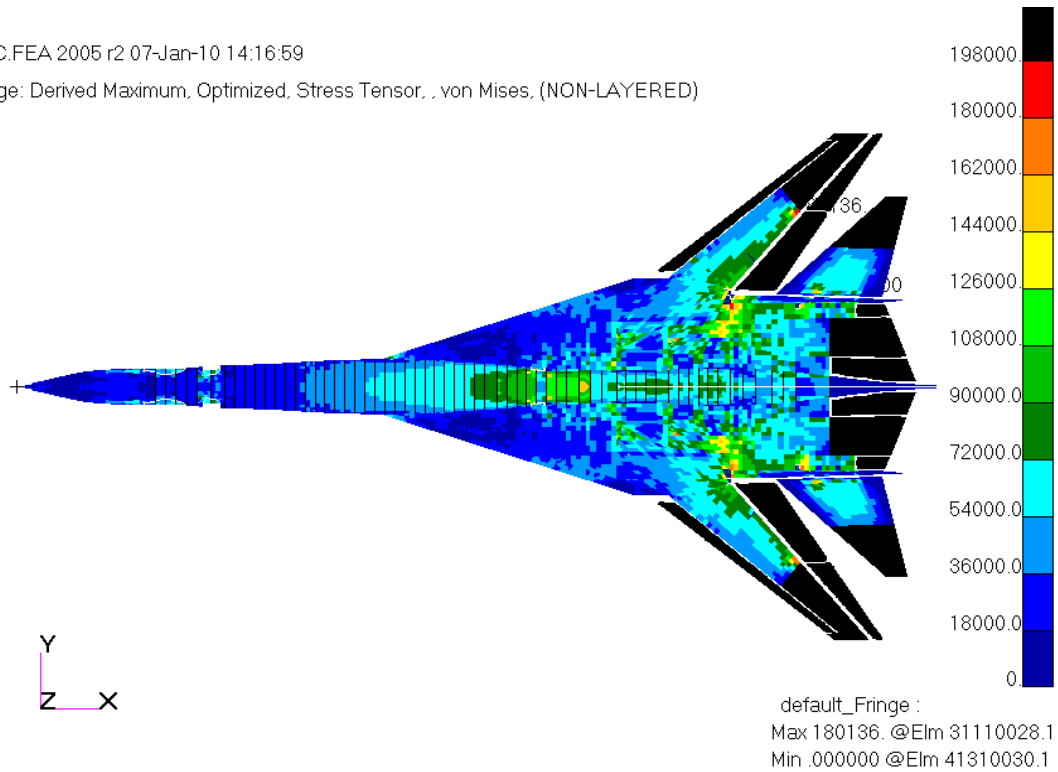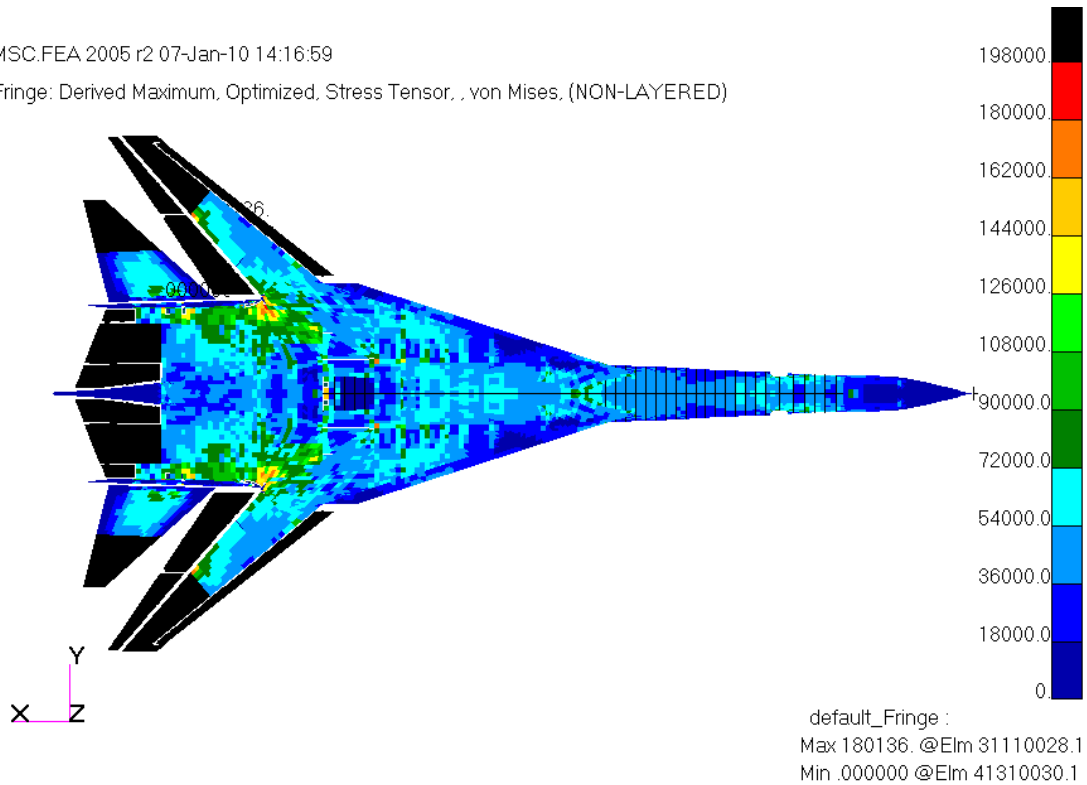
b)

Figure G.0.11: Stress results showing maximum von Mises stress across all load conditions for (a) upper skin, and (b) lower skin. (Limit loads)

G.3 Flutter Analysis

G.3.1 Assumptions

The following assumptions are made in the N+3 flutter analysis:
- Linear aerodynamics and linear structure
  - Character of linear results at transonic conditions were confirmed to be similar to those at high subsonic conditions
- Actuator compliance not modeled at control surfaces (preliminary nature of configuration)
- One mass condition considered
- 2 percent structural damping (g) assumed

G.3.2 Flight Conditions

The flight conditions for flutter analysis are derived from the N+2 flight envelope as shown in Figure G.0.12. The flutter requirement is:

- No flutter below 1.15 times the dive speed for all Mach numbers in the flight envelope.
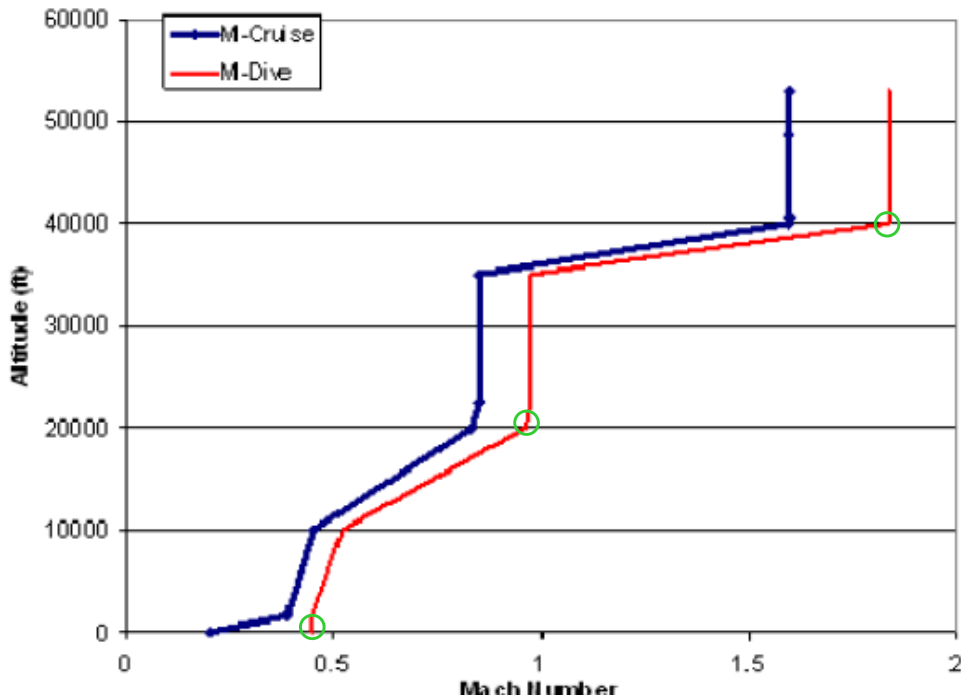
Figure G.0.12: N+2 flight envelope [1] with conditions identified as critical for flutter identified in green.

G.3.3 Flutter Results

Based on the results presented in the Interim Report [4] a transonic flutter case and a supersonic flutter case were defined to determine the weight penalty to satisfy the flutter constraint.

Transonic (Mach 0.99)
- Velocity (in/sec): 11501.1   11560.5   13033.6
- Q (lb/in^2):   8.5696E-9   3.5600E-8   9.7554E-8

Supersonic (Mach 1.8)

- Velocity (in/sec): 20911.1   20911.1   21948.0
- Q (lb/in^2):   6.8557E-9   2.8323E-8   4.5629E-8

The last flight condition listed above represents 1.5 times the dive speed (events highlighted in Figure G.0.14).

Using a conservative flutter constraint of 0% damping for modes 7 through 15, as well as the strength constraint, the structure was optimized for each of the eight strength analyses and the two flutter analyses. For the Titanium material, the resulting structural weight is 18.5% larger than the strength only optimized structure (46,587 lbs).

Flutter analysis results of the strength only sized configuration and the strength and flutter sized configuration for Titanium are shown for various Mach numbers in Figure G.0.13 and Figure G.0.14. These results show frequency and damping as a function of equivalent airspeed and have vertical lines indicating the dive speed and flutter requirement. For each of these analyses, flutter is identified within the flight envelope for the strength only sized configuration. This is seen as crossing of 2% damping at speeds below the dive speed. The strength and flutter sized configurations show flutter does not occur below the dive speed for these Mach numbers. The flutter mode shape for the strength only sized configuration is shown in Figure G.0.15.

While the strength sized metallic configurations exhibited flutter within the flight envelope, the composite configurations did not. A comparison of the flutter data for the critical aeroelastic modes is shown in Figure G.0.16. It is noted that the composite configuration exhibits higher wind-off frequencies with a similar frequency ratio to that of the Titanium configuration.

Strength Sized

Strength/Flutter Sized
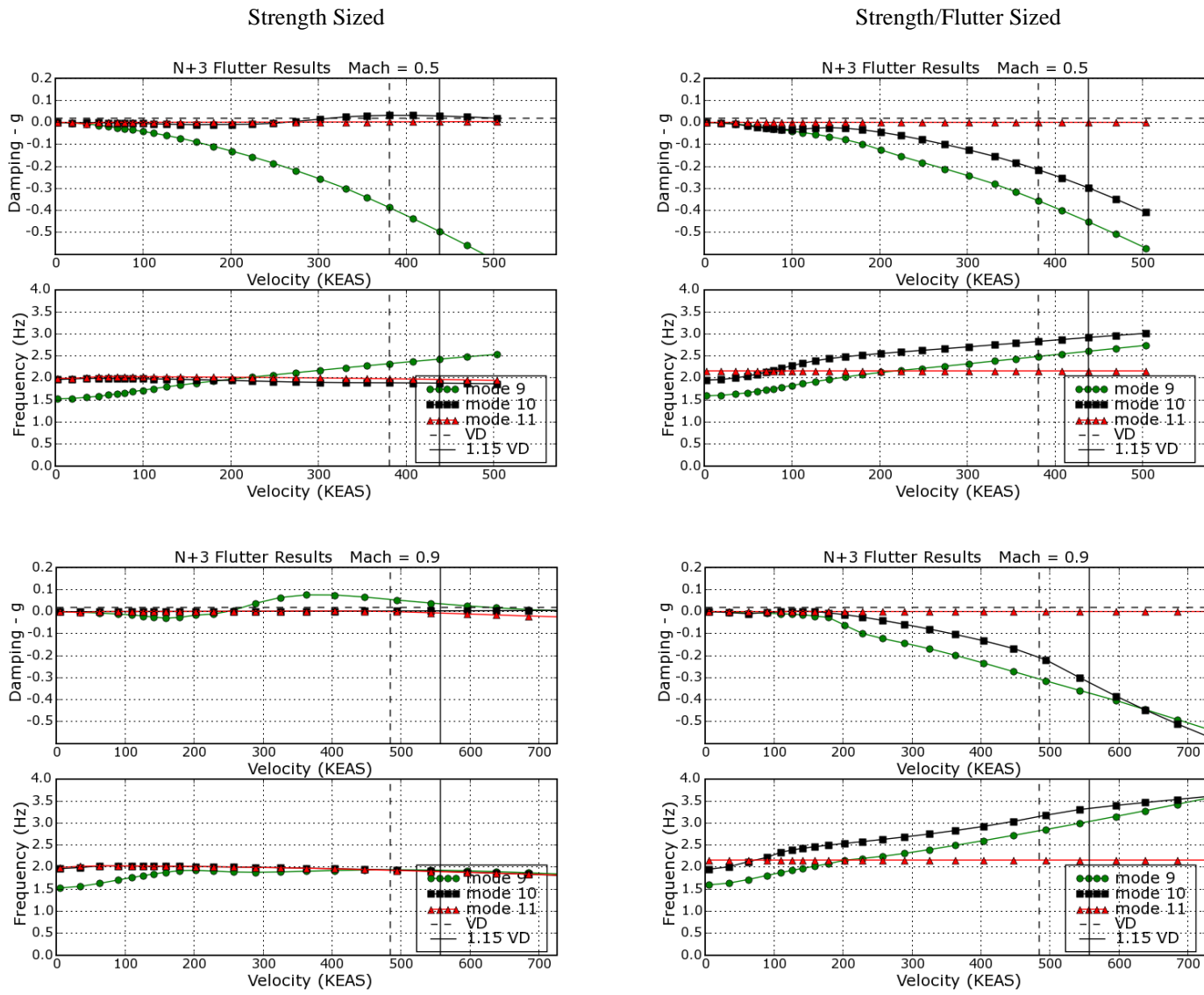
Figure G.0.13: N+3 flutter results for strength sized and strength/flutter sized configurations.

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Strength Sized

Strength/Flutter Sized
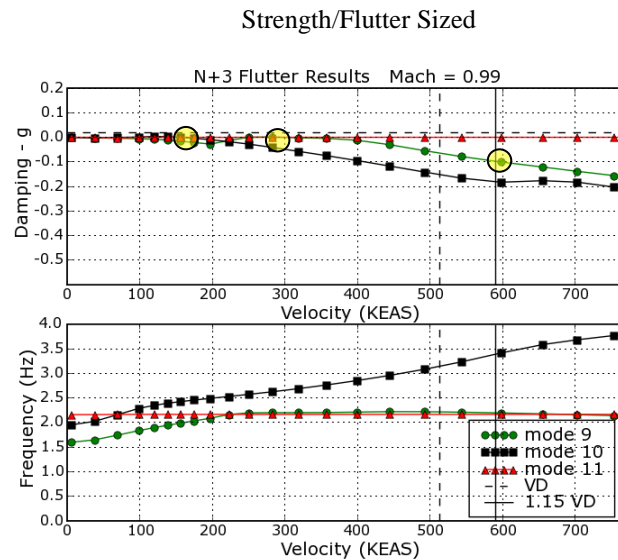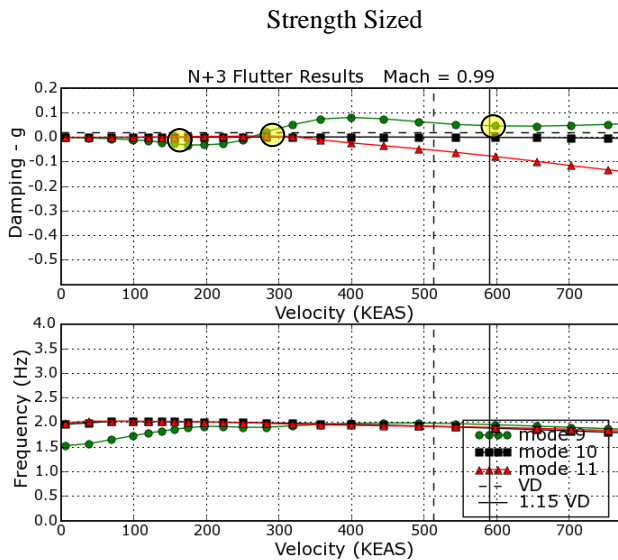
c)
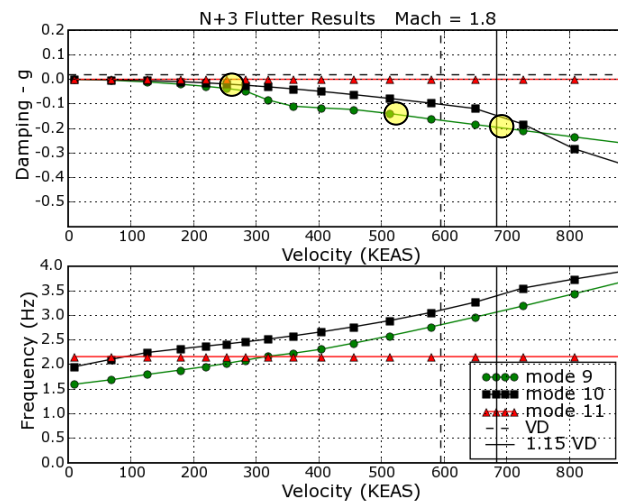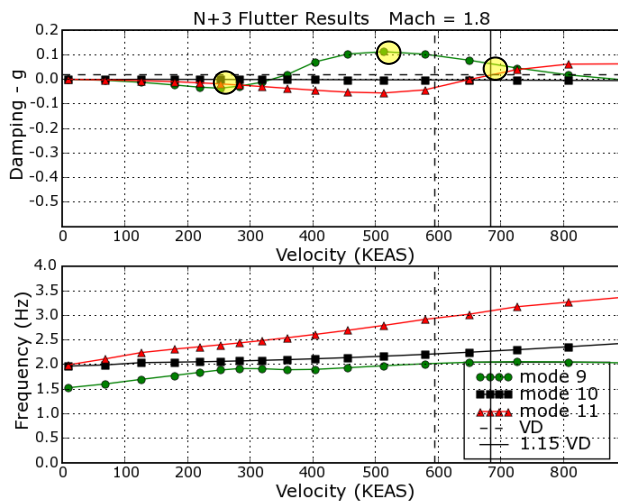
d)

Figure G.0.14: N+3 flutter results for strength sized and strength/flutter sized configurations (events specified for optimization highlighted).
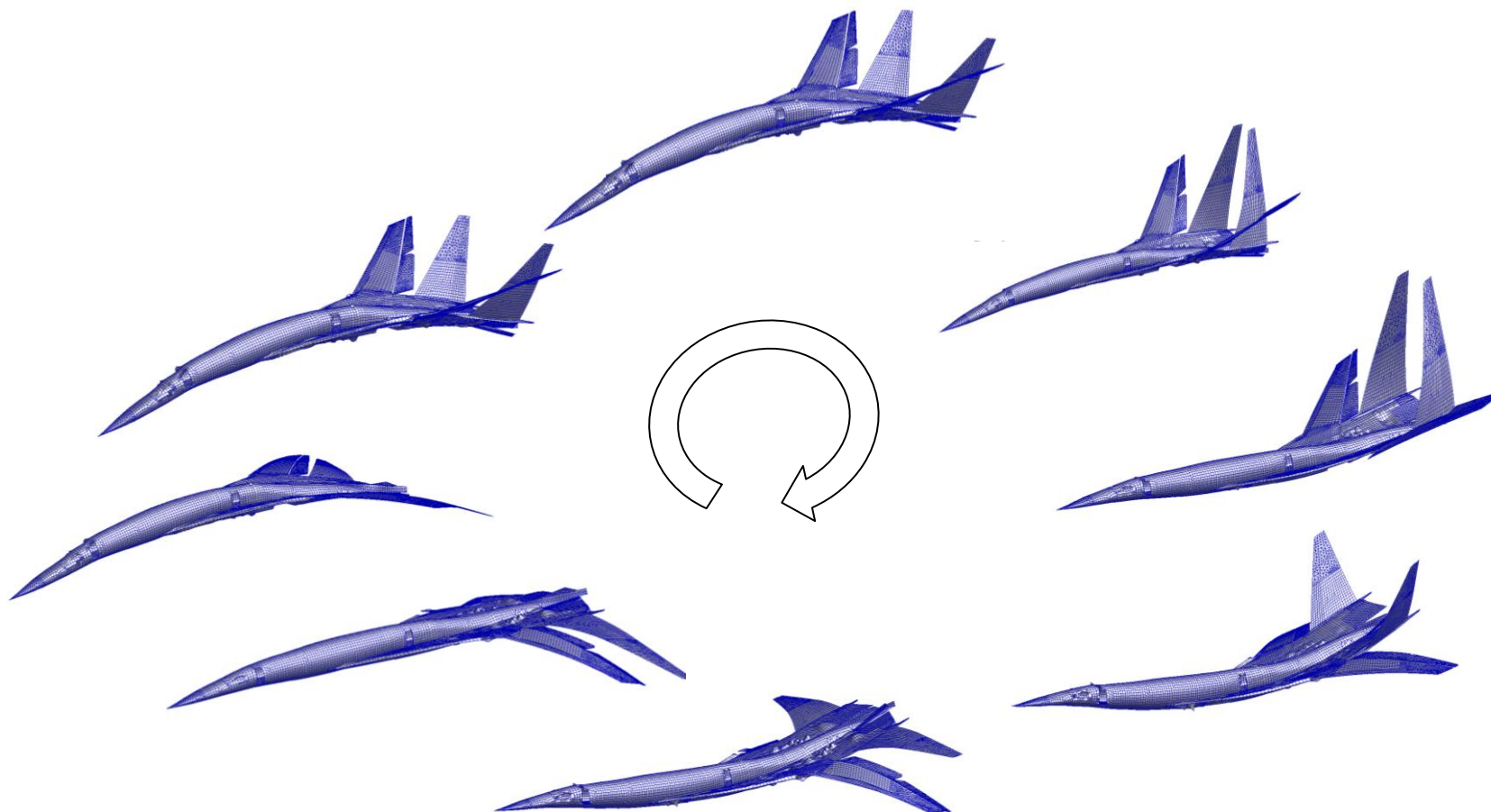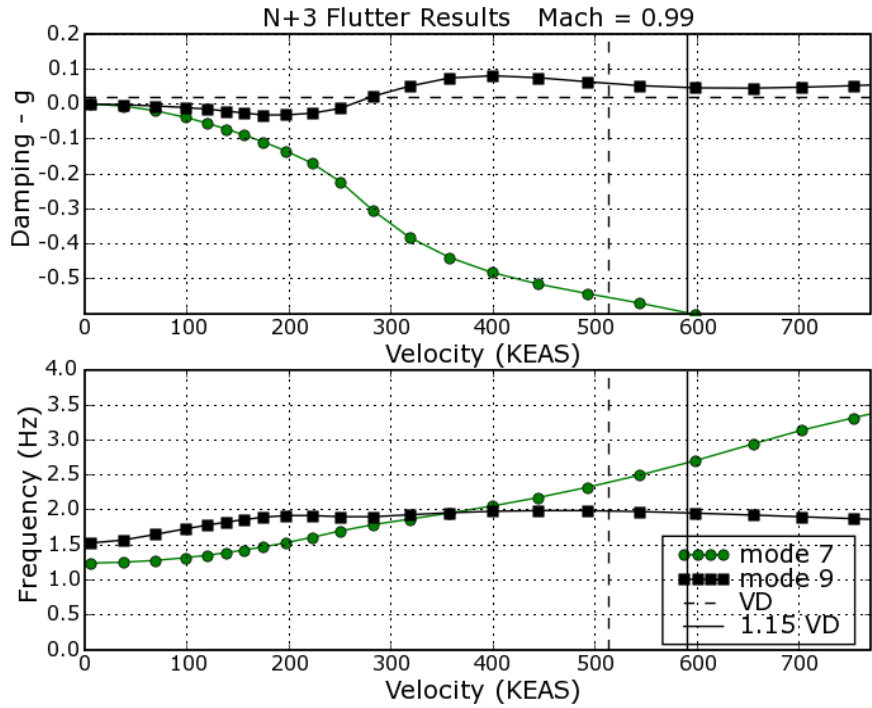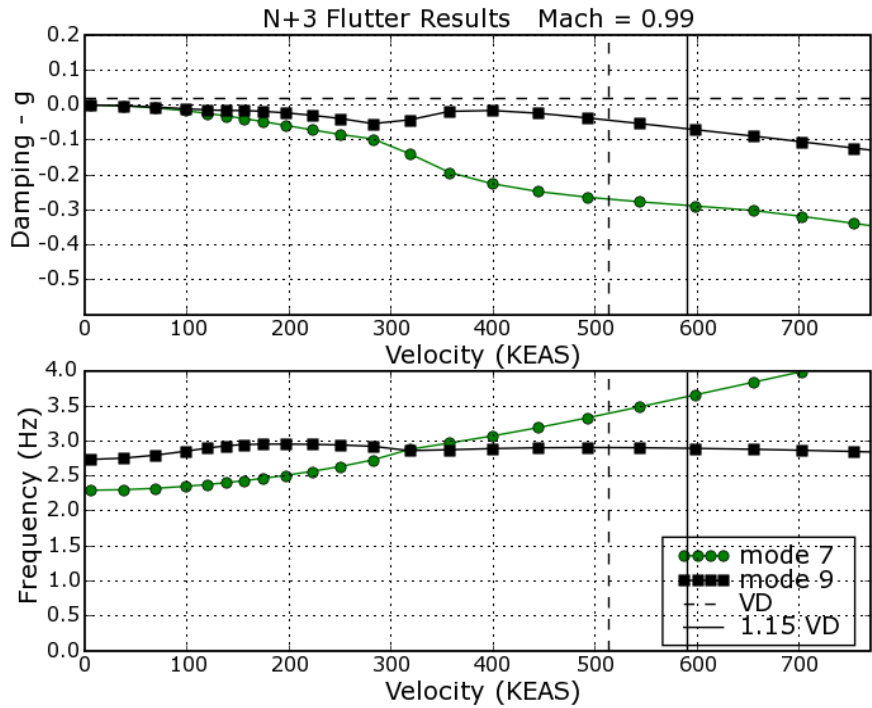
Figure G.0.15: N+3 flutter results for strength sized configurations (M_∞=0.99, V_∞=400KEAS).

a)

b)

Figure G.0.16: N+3 flutter results for strength sized configurations: a) Titanium, b) baseline composite (M$_\infty$=0.99).

G.4 Optimization Results

The structural weight comparisons for all four materials with and without flutter constraints are shown in Table G.0.2. Note that the configurations sized without flutter constraints are representative of an ideal flutter suppression system (FSS). Note that while the Titanium material results in the lightest weight for the cases with FSS, the composite materials achieve comparable weights when flutter constraints must be satisfied by the airframe.

Figure G.0.17 through Figure G.0.20 show the breakdown of the weight of the different portions of the structure for each of the materials. The weight of the inboard wing and fuselage skin increases significantly to meet the flutter requirement in for both metallic materials.

Table G.0.2: Optimization results for structural weight (lb).

	Baseline	With FSS
Aluminum	104,956	70,566
Baseline Composite	48,791	48,791
Improved Composite	45,556	45,556
Titanium	46,587	39,305
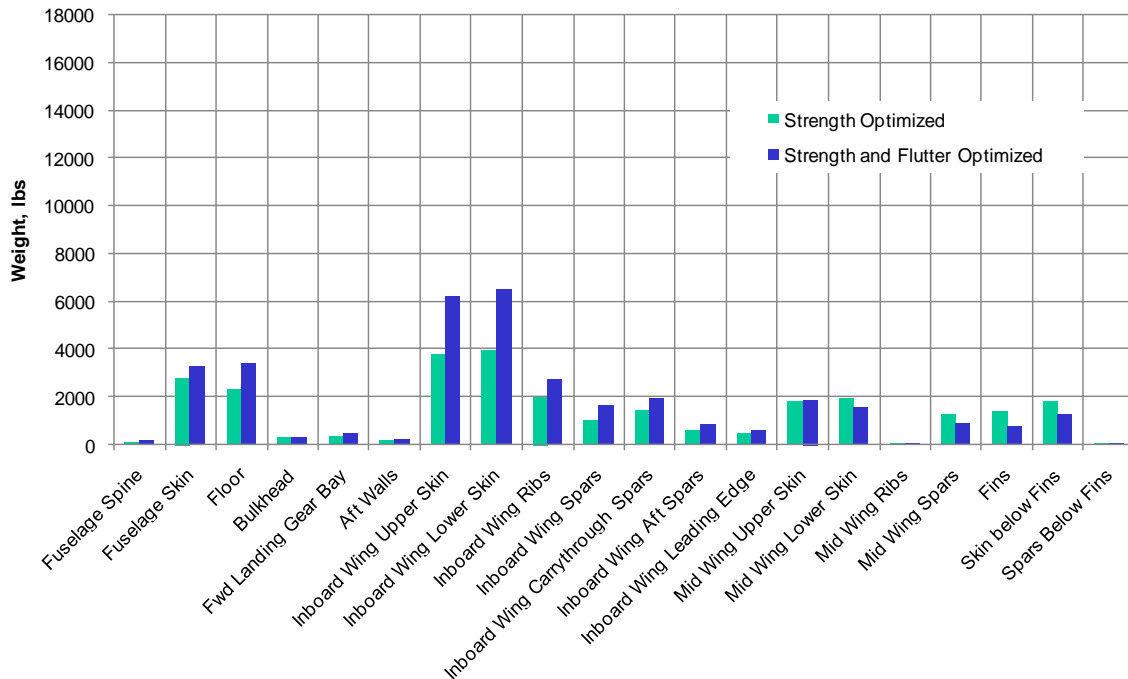
Figure G.0.17: N+3 Weight Summary for Titanium Material.
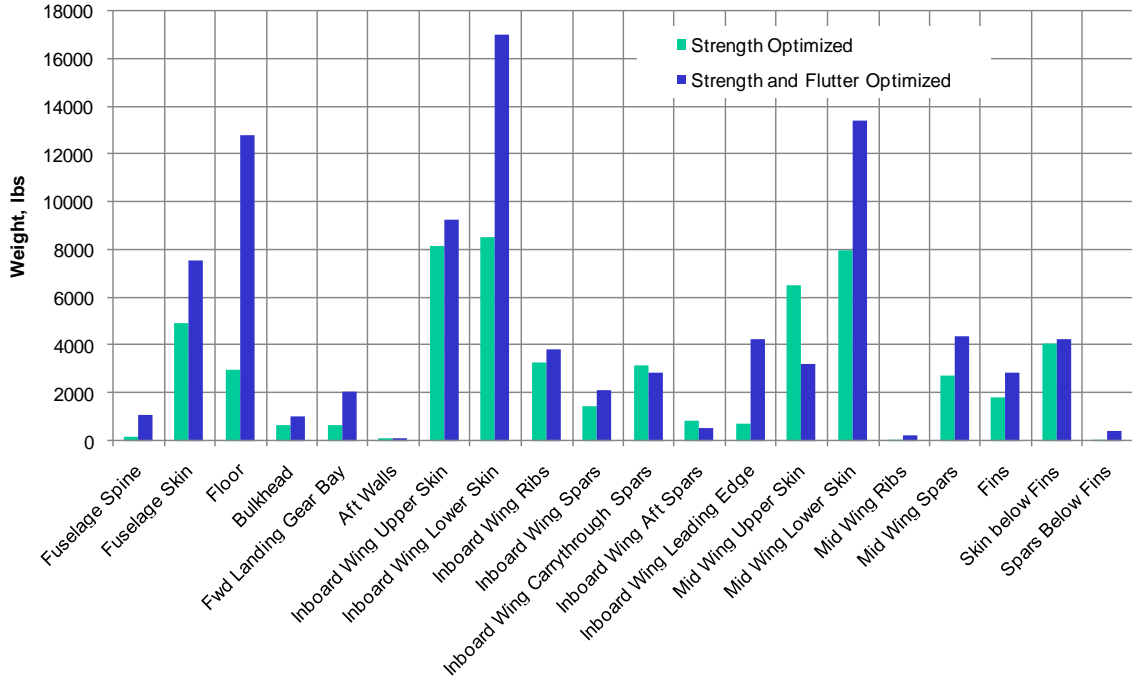
Figure G.0.18: N+3 Weight Summary for Aluminum Material.
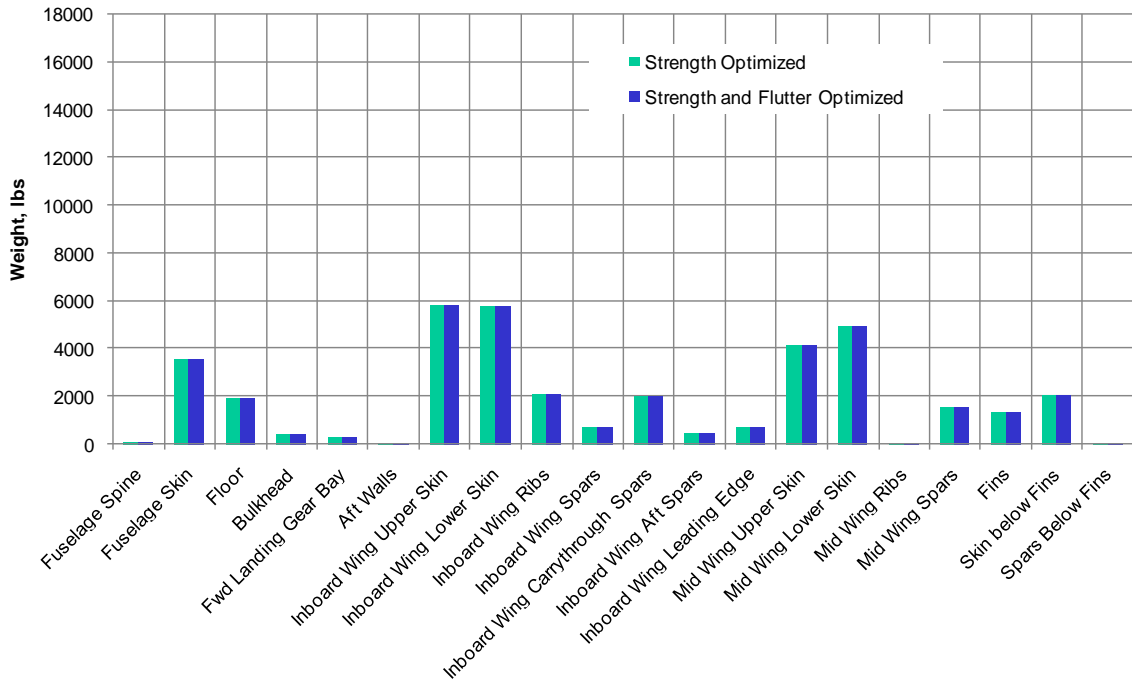
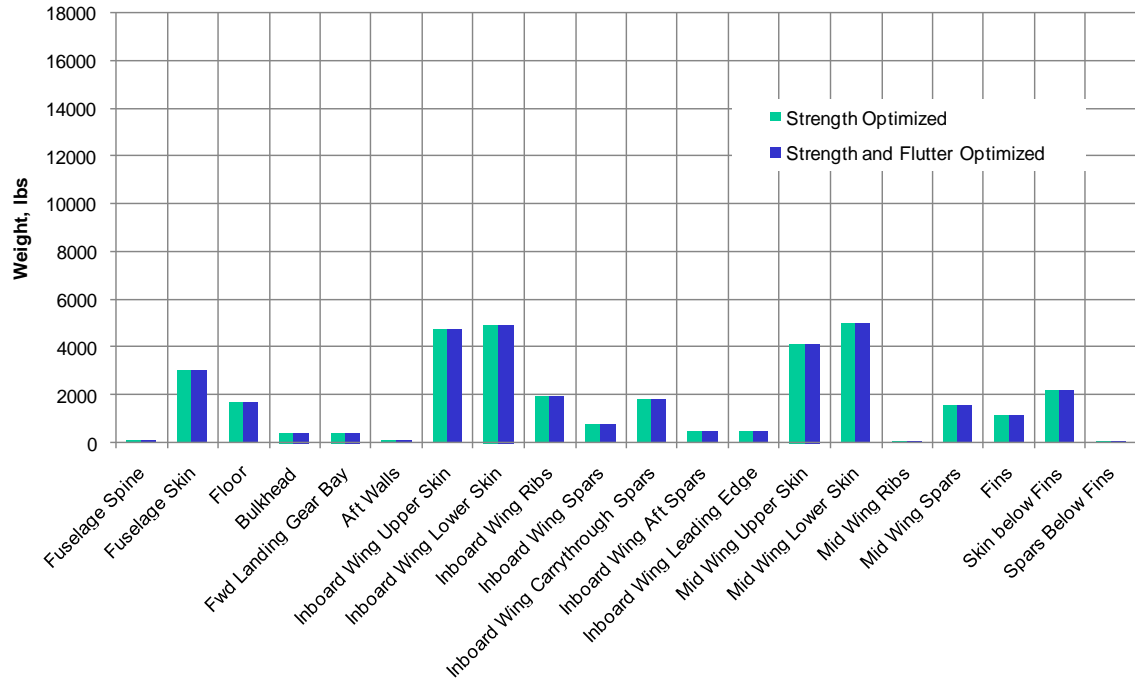**Figure G.0.19: N+3 Weight Summary for Baseline Composite Material.**

Figure G.0.20: N+3 Weight Summary for Improved Composite Material.

G.5. Conclusion

Material trade studies have been performed for the Boeing N+3 configuration. There materials included consideration of strength and flutter constraints. The weight savings relative to a conventional Aluminum material are shown in Table G.0.3. The following conclusions are made:

1. Strength sized configurations for both metallic materials were found to have flutter within the flight envelope.
2. The lightest weight structure is achieved for the Titanium structure in which flutter constraints are satisfied by a flutter suppression system. Recent active aeroelastic control research suggests such a flutter suppression control law might be achievable [5].
3. Sizing results for composite structure show significant weight savings relative to an Aluminum configuration. This is especially true for the case in which flutter constraints must be satisfied by the structure.

Table G.0.3: Optimization results for structural weight.

	Baseline	With FSS
Aluminum	N/A	-33%
Baseline Composite	-54%	-54%
Improved Composite	-57%	-57%
Titanium	-56%	-63%

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14. ABSTRACT

Boeing, with Pratt & Whitney, General Electric, Rolls-Royce, M4 Engineering, Wyle Laboratories and Georgia Institute of Technology, conducted a study of supersonic commercial aircraft concepts and enabling technologies for the year 2030-2035 timeframe. The work defined the market and environmental/regulatory conditions that could evolve by the 2030/35 time period, from which vehicle performance goals were derived. Relevant vehicle concepts and technologies are identified that are anticipated to meet these performance and environmental goals. A series of multidisciplinary analyses trade studies considering vehicle sizing, mission performance and environmental conformity determined the appropriate concepts. Combinations of enabling technologies and the required technology performance levels needed to meet the desired goals were identified. Several high priority technologies are described in detail, including "roadmaps" with risk assessments that outline objectives, key technology challenges, detailed tasks and schedules and demonstrations that need to be performed. A representative configuration is provided for reference purposes, along with associated performance estimates based on these key technologies.

15. SUBJECT TERMS
Advanced concepts; Aircraft performance; Aircraft configurations; Aircraft design; Supersonic aircraft

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