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Final Report for the Advanced Concept Studies for Supersonic Commercial Transports Entering Service in the 2030 to 2035 Period, N+3 Supersonic Program

John Morgenstern, Nicole Norstrud, Marc Stelmack, and Craig Skoch
Lockheed Martin Aeronautics Company, Palmdale, California

August 2010

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Executive Summary

Lockheed Martin Aeronautics Company (LM Aero), working in conjunction with seven industry and academia sub-contracting teammates, executed an 18 month program responsive to the NASA sponsored "N+3 NRA Advanced Concept Studies for Supersonic Commercial Transports Entering Service in the 2030 to 2035 Period" contract. The key technical objective of this effort was to generate promising supersonic concepts for the 2030 to 2035 timeframe and to develop plans for maturing the technologies required to make those concepts a reality. The N+3 program is aligned with NASA's Supersonic Project and is focused on providing alternative system-level solutions capable of overcoming the efficiency, environmental, and performance barriers to practical supersonic flight.

In addition to FAA regulations, the Next Generation (NextGen) Air Traffic System (ATS) congestion levels are a concern as they are expected to increase by a factor of 1.5 to 2.5 in the 2025 timeframe. Understanding how supersonic aircraft affect future congestion levels requires a system of systems analysis that integrates vehicle design, operating environment, and economic interaction into a single process. LM Aero worked with a sister company, Transportation Security and Solutions (TSS), and Purdue University to assess the value that a supersonic transport concept vehicle brings to the NextGen ATS. A fast time modeling and simulation study done by TSS revealed that commercial supersonic vehicles will not impact future airport capacity. However, supersonic air vehicles in the 2030 timeframe will exert additional demand for airport operations. Purdue University simulated numerous future Civil Air Transport System scenarios, allocating N+3 vehicles to maximize system-wide productivity while also computing fleet-wide emissions and direct operating costs. These results showed that the total value of time saved by passengers on N+3 supersonic transports will likely exceed the added operating costs incurred by the aircraft. These system-level scenarios showed that supersonic transport is a viable solution for increased productivity and promotes the renewed viability of supersonic travel.

Our extensive team designed a preferred supersonic configuration and developed plans for maturing the identified, enabling technologies required to meet the N+3 performance and environmental goals. Working in conjunction with GE Global Research Center (GRC), John Hansman from MIT, Helen Reed and Bill Saric from Texas A&M, Wyle Laboratories, Purdue, and Penn State—an initial low-boom, supersonic configuration was used to assess potential airframe and propulsion technologies that were projected to meet or exceed the future supersonic boom, noise, emissions, cruise speed, range, payload, and fuel efficiency goals. Multi-Disciplinary Analysis and Optimization (MDAO) showed it was possible to achieve the N+3 boom goal with an "inverted-V", engine-under wing configuration. Further sizing and quantified analysis proved that using revolutionary technologies enabled this configuration to achieve the range, payload, and cruise speed goals.

Based on LM provided requirements and targets, GE developed an Variable Cycle Engine (VCE) propulsion system and a conventional Mixed Flow Turbo Fan (MFTF) propulsion system expected to meet or exceed the environmental goals set by NASA, as well as an MFTF optimized solely for cruise efficiency. These propulsion systems take advantage of an Advanced Thermal Management System (ATMS) to extend the overall pressure ratio (OPR) of the engine and increase thermal efficiency. A low noise, high performance exhaust system takes advantage of the innovative jet noise reduction features that work synergistically with the VCE features to reduce the exhaust jet noise. Augmented transonic thrust allows the propulsion system to be favorably sized with potential take-off noise abatement. Analysis shows that this propulsion system, along with integrated technology sets, meets the N+3 airport noise, emissions, and fuel efficiency goals.

Our integrated airframe and propulsion system, along with identified/enabling technologies, is projected to meet or exceed *all* N+3 targets. Results of the environmental and performance characteristics of our advanced vehicle concept are summarized in Table 1.

Through a collaboration effort, LM Aero and GE GRC identified N+1, N+2, and N+3 technologies critical to meet or surpass the N+3 goals. N+1 and N+2 shaping technologies were considered to be "endemic" or inherent to the baseline design. These configuration technologies were not included in the final technology roadmap, but other N+2 technologies were included to provide a comprehensive

technology list. As a result, technology roadmaps were created for all prioritized, airframe technologies to demonstrate the maturation efforts required to raise each technology to a Technology Readiness Level 6 (TRL 6).

TABLE 1.—LM'S PREFERRED CONCEPT WITH TECHNOLOGY INPUTS MEETS OR SURPASSES ALL N+3 GOALS

	NASA N+3 Efficient Multi-Mach Aircraft (Beyond 2030)	N+3 Goal Status
Environmental Goals		
Sonic Boom	65 to 70 PLdB low boom flight 75 to 80 PLdB unrestricted flight	70 to 76 PLdB KEY GOAL
Airport Noise	20 to 30 EPNdB (cumulative below stage 3)	18.4 (32.2 jet only) KEY GOAL
Cruise Emissions (g/kg fuel)	<5 EINOx Plus particular and water vapor mitigation	5 EINOx
Performance Goals		
Cruise Speed	Mach 1.3 to 2.0 low boom flight Mach 1.3 to 2.0 unrestricted	Mach 1.6
Range	4000 to 5500 nmi	4850 nmi
Payload	100 to 200 pax	100 pax
Fuel Efficiency	3.5 to 4.5 (pax-nmi/lb-fuel)	3.64 (pax-nmi/lb-fuel) KEY GOAL

Recommended future work includes Phase 2 testing and Phase 3 maturation efforts to provide a technology set necessary to realize a vision vehicle serviceable in the 2030-2035 timeframe.

Current N+2 efforts allow us to reasonably assume that N+2 technologies will be developed during those N+2 program efforts, and the developed technologies will be available for application on the N+3 vehicle. Concentration on N+3 technologies provides a clear roadmap to achieving and surpassing the stated N+3 goals while providing an exciting solution to supersonic travel. Figure 1 highlights the comprehensive technology set for both airframe and propulsion systems.

Future work recommendations for airframe technologies include:

- Low cost, high impact tools and methodologies such as Low Boom Shaping Fidelity and CFD-based MDAO to address boom mitigation
- Distributed roughness with plasma augmentation to ensure laminar flow at supersonic conditions
- Adaptive geometry technologies including lift distribution control and inlet flow control technologies to address the N+3 fuel efficiency goals

Future work recommendations for propulsion technologies include:

- Continued development of VCE technologies
- Development of the Transonic Thrust Augmentation device—critical technology to meeting N+3 goals
- Alternate combustor/combustion concepts need to be explored, as these propulsion systems are developed to take advantage of the full thermal capability of the system. The currently funded NASA Supersonics Low Emissions combustor program will provide key validation data for high temperature NOx levels, and the maturation of some enabling technologies
- Predictive and design tool development in many areas need to be continued to be developed including:
  - Aero-acoustics for both fan and jet noise
  - Combustion and emissions

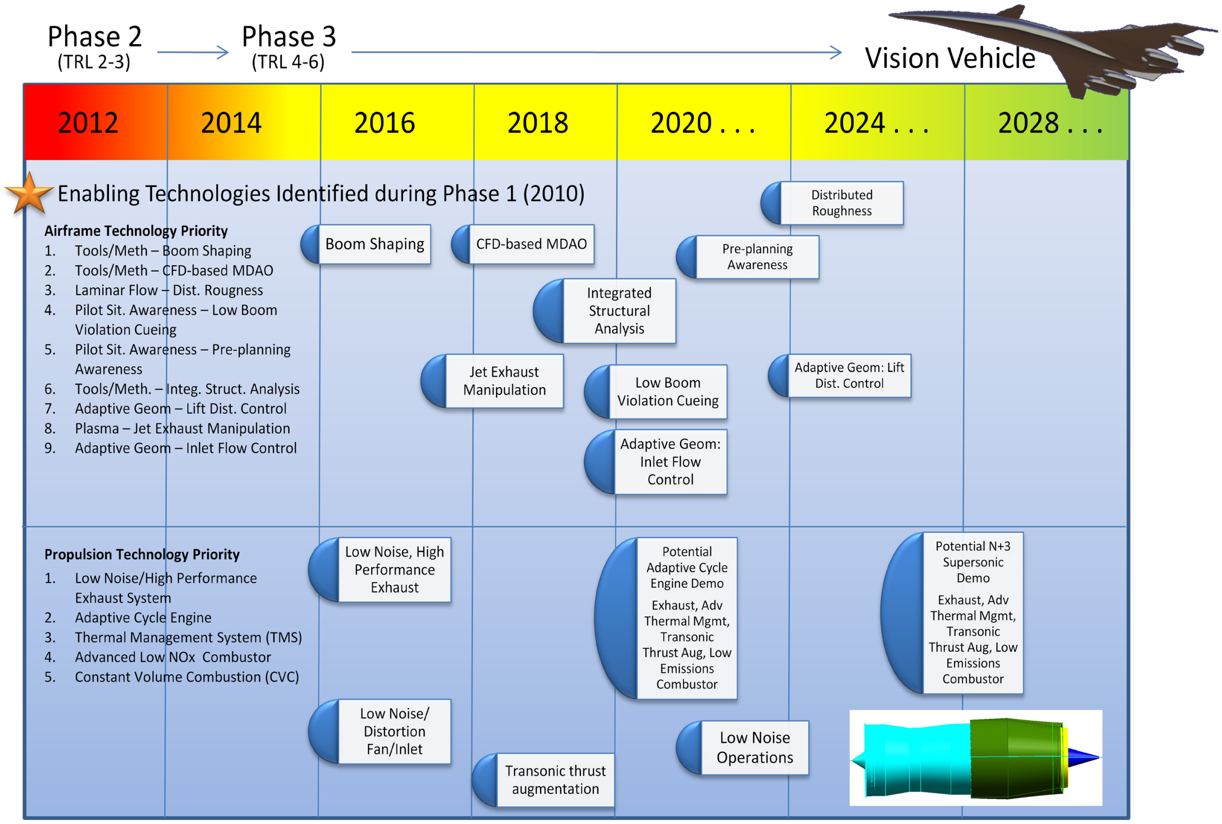


Figure 1.—Technology roadmap for N+3 enabling technologies.

Contents

List of Tables

List of Figures

1.0 Introduction

1.1 Subject of the Report

Research in the area of Advanced Supersonic Transport (AST) has been a focus area for NASA since 1960s, driven by maintaining U.S. leadership in the area of commercial transport. According to a 1980 Open Travel Alliance (OTA) report (Ref. 1) on the impact of advanced air transport technology, the business case in favor of ASTs results from improved aircraft productivity (measured in seat miles generated per unit time) and its capability to transport twice the number of passengers on long distance flight. Higher cost of operations, concerns over environmental impact due to noise and emissions, and restrictions to fly supersonic on land due to sonic boom are some of the technological issues that need to be addressed for production and deployment of ASTs. NASA's research efforts for the advancement of AST are dedicated to address these technical challenges and the AST technology is being matured under N+1, N+2 and N+3 projects. The goal of the N+3 project is to explore a conceptual design for multi-Mach aircraft in 2030 timeframe that has low sonic boom, is environmentally acceptable, fuel efficient, and able to fly at supersonic speed above land. Other, integrated design concerns include:

- Sonic Boom Reduction
- Cruise Efficiency
- Aero-Propulso-Servo-Elasticity
- Airport Noise
- Light Weight Structure for Airframe/Propulsion Systems
- High Altitude Emissions

A complimentary area for NASA research is the Next Generation Air Transportation System (NextGen) (Joint Planning and Development Office, 2009 (Ref. 2)). The U.S. Air Traffic Management (ATM) system is today operating at the edge of its capabilities, handling the real-time planning and coordination of over 50,000 flights per day. Although air traffic has seen a decline in the recent year due to severe economic downturn, the recent numbers suggest that traffic is currently stabilizing (Official Airline Guide, 2009 (Ref. 3)) however, per market forecasts by MITRE (Ref. 4) and Boeing (Ref. 5) (2009) a strong growth in air traffic is expected in both short and long term. Additionally, Boeing's long term market forecast cites that the air transportation industry is resilient and has survived many economic downturns in the past. It has grown at 5 percent annually and by year 2029 the number of airplanes flying in the National Air Space will be more than double. To address this concern, the Federal Aviation Administration (FAA) along with NASA and other government and industry partners are charting the NextGen.

One of the strategic objectives outlined in the NextGen plan is to have a system scalable enough to respond quickly and efficiently to increase in demand and is flexible enough to incorporate new types of airframe for example, Unmanned Aircraft System (UAS), Very Light Jets (VLJs), Large Civil Tiltrotor (LCTR), ASTs, and others. Since supersonic transports provide a step increase in passenger mobility by speed of travel, their incorporation within the NextGen ATS could potentially provide alternative methods of operation, subsonic to supersonic transition regulations, and unforeseen hazards. NASA is focused on providing vehicle designs and identifying enabling technologies that can meet the nation's need for effective, efficient and safe air travel.

Overall, the supersonics project is designed to develop knowledge, capabilities, and identify innovative solutions for supersonic air vehicles. Sonic boom, environmental concerns, and NextGen ATS integration are major concerns for commercial supersonic travel. Revolutionary solutions are required to generate viable, supersonic solutions.

1.2 Purpose

The purpose of this final report (PMF–01403) is to respond to the NASA sponsored program "N+3 NRA Advanced Concept Studies for Supersonic Commercial Transports Entering Service in the 2030 to 2035 Period." The N+3 program is focused on generating promising supersonic concepts for the 2030 to 2035 timeframe and to develop plans for maturing the technologies required to make those concepts a reality. An additional system-level focus includes understanding how a supersonic civil transport would integrate and operate within the 2025 NextGen ATS.

This program is committed to overcoming significant performance (cruise speed, range, payload and fuel efficiency) and environmental (sonic boom, airport noise, and cruise emission) challenges. The NASA stated N+3 goals are illustrated in Table 2.

TABLE 2.—N+3 ENVIRONMENTAL AND PERFORMANCE GOALS

	N+1 Supersonic Business Class Aircraft (2015)	N+1 Small Supersonic Airliner (2020)	N+1 Efficient MultiMach Aircraft (beyond 2030)
Environmental goals			
Sonic boom	65 to 70 PLdB	65 to 70 PLdB	65 to 70 PLdB low boom flight 75 to 80 PLdB unrestricted flight
Airport noise (cum blow Stage 3)	10 EPNdB	10 to 20 EPNdB	20 to 30 EPNdB
Cruise emissions (cruise NOx g/kg of fuel)	Equivalent to current subsonic	<10	<5 and particulate and water vapor mitigation
Performance goals			
Cruise speed	Mach 1.6 to 1.8	Mach 1.6 to 1.8	Mach 1.3 to 2.0 low boom flight Mach 1.3 to 2.0 unrestricted flight
Range (nmi)	4000	4000	4000 to 5500
Payload (passengers)	6 to 20	35 to 70	100 to 200
Fuel efficiency (passenger-miles per lb of fuel)	1.0	3.0	3.5 to 4.5

Meeting or surpassing these goals stimulates innovation and advances the pursuit of revolutionary conceptual designs. System-level multi-disciplinary analysis and optimization (MDAO) and out of the box thinking allows for revolutionary technology identification. This fosters an environment of innovation and generates excitement for future supersonic travel.

Overall, the N+3 effort is driven by the need for alternative solutions capable of overcoming the efficiency, environmental, and performance barriers to practical supersonic flight. Results from these studies aid in upcoming research efforts and provides a roadmap for future supersonic funding.

1.3 Scope

LM Aeronautics conducted research, testing, trade studies and sensitivity analysis in support of the NASA's N+3 Supersonic Vehicle effort. A combination of advanced design and an integrated system analysis was taken to define a conceptual vehicle capable of meeting the environmental and performance goals. Viable technology development paths were produced by the design, engineering, and test capabilities of our team. In addition, core technology trades were performed to provide estimates of the advanced vehicle concept's noise, emissions and performance characteristics. LM was also responsible for the coordination and management of all subcontractors and resulting work. LM is committed to helping NASA successfully achieve their goals of first understanding what is necessary in 2030 to 2035, generating a suite of enabling concepts and technologies to meet those needs, and socializing that vision with the broadest possible audience.

2.0 Work Breakdown Structure (WBS)

LM Aeronautics was responsible for the overall design, development, and technology identification necessary to realize a visionary vehicle capable of achieving the supersonic N+3 environmental and performance goals. A combination of advanced design and an integrated system approach was required to define an advanced concept vehicle serviceable in the 2030 to 2035 timeframe (Task 3.1). Design of the vehicle included configuration layout, design, analysis, and definition to produce a concept tightly integrated with airframe and propulsion technologies. Using a system-level design space, LM Aeronautics was also tasked to perform various trade and sensitivity studies to understand how a future Next Generation (NextGen) scenario with supersonic transports drove design requirements (range, noise, emissions, boom, fuel, and mobility). The interplay of design constraints was modeled and analyzed in physics based multi-disciplinary analysis and optimization (MDAO) process using Rapid Conceptual Design (RCD). Task 3.2 included RCD model development, integration with technology inputs, quantified analysis, and technology benefit/impact assessments. After multiple design iterations and system-level analysis of the preferred configuration, LM Aeronautics was responsible for developing a technology roadmap of enabling technologies for the N+3 vehicle. This roadmap includes a list of key technologies, definition of roles and quantification of impacts on the concept vehicle, traceability to N+3 goals, baseline TRLs, proposed TRL maturations schemes for future N+3 phases, and prioritization. Overall, LM Aeronautics was ultimately responsible to optimize complex multi-variable combinations of airframe and propulsion technologies while iterating, maturing, identifying, and ultimately down-selecting critical technologies required to realize an N+3 vehicle. Figure 2 illustrates the overall WBS of the tasks and duties required for the program.

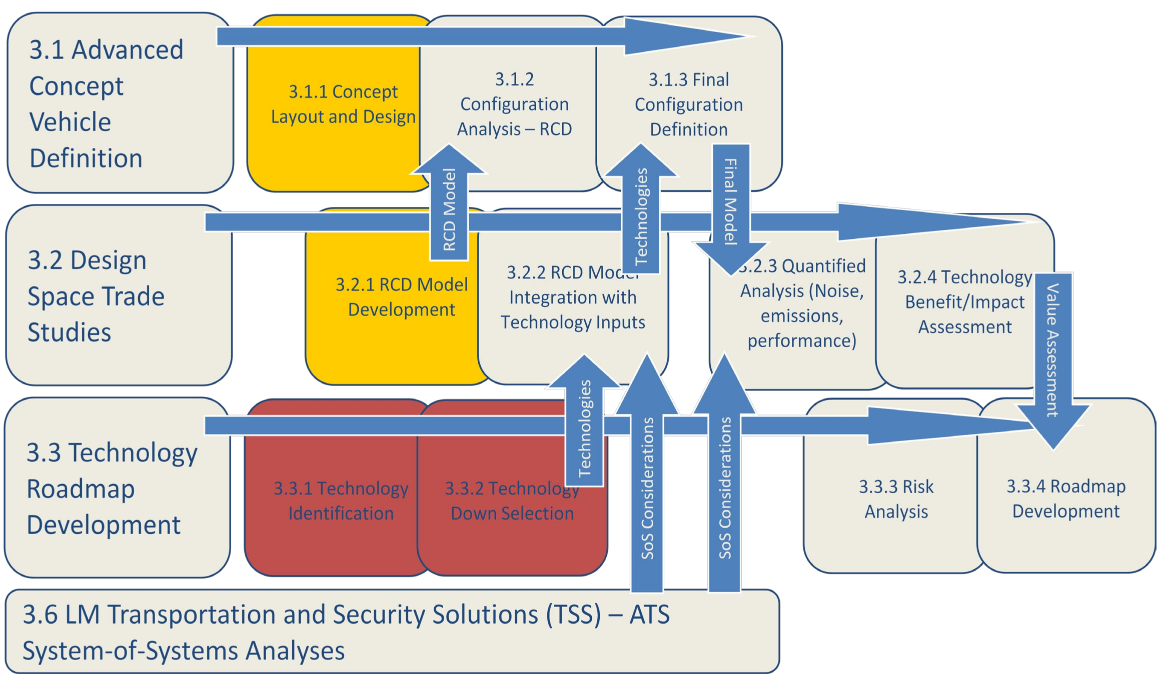


Figure 2.—LM WBS for N+3 Phase 1 program.

Our efforts focused on four major tasks: Advanced Concept Vehicle Definition (Task 3.1), Design Space Trade Studies (Task 3.2), Technology Roadmap Development (Task 3.3), and ATS System-of-Systems Analysis (Task 3.6). LM was also responsible for the management and coordination of seven subcontractors to provide subject-matter data and expertise to the program. Collaboration included teaming with GE Global Research Center (GRC) with GE Aviation for advanced propulsion concepts as well as fuel efficiency and emissions, Penn State for jet noise reduction, Purdue for system of system analysis, MIT for green initiatives, Wyle labs for real-world loudness effects and boom guidance, LM Transportation and Security Solutions for air traffic analysis, and Helen Reed and Bill Saric for laminar flow analysis. All required tasks include subsequent subtasks that align with the main task. The WBS encompasses all work necessary to oversee and direct the execution of the N+3 Phase 1 Program.

3.0 Tasks and Trade Studies—Airframe Systems

3.1 Advanced Vehicle Concept (WBS 3.1)

3.1.1 Concept Layout and Design (WBS 3.1.1)

3.1.1.1 Description

Before laying out a configuration, we looked at the N+3 goals and addressed design methods and strategies necessary to meet those challenges. Based on our past history designing and analyzing supersonic configurations, we first focused our energy on the sonic boom requirement. The N+3 sonic boom goal of 65 to 70 PLdB is significantly lower than the state of the art 107 PLdB of the (408,000 lb, 100 passenger) Concorde with a shock strength of 2 psf, or the 102 PLdB of the (12,000 lb—33 times lighter than Concorde) F-5 with a shock strength of 1.3 psf. Meeting the sonic boom goal requires a minimum shock (ramp signature) shock strength of 0.12 to 0.17 psf. One way of meeting this goal is increasing the fuselage length used by SEEB to calculate the minimum shock signature, as shown in Figure 3. In order to reduce the length required, it is anticipated that the perceived level of noise on the ground can be reduced through shock blending, as shown in Figure 4, and through taking into account real world absorption and turbulence. Results from Wyle's analysis on *Effects of Atmospheric Propagation on Low-Boom Shaped Signatures* can be seen in Section 3.2.5.

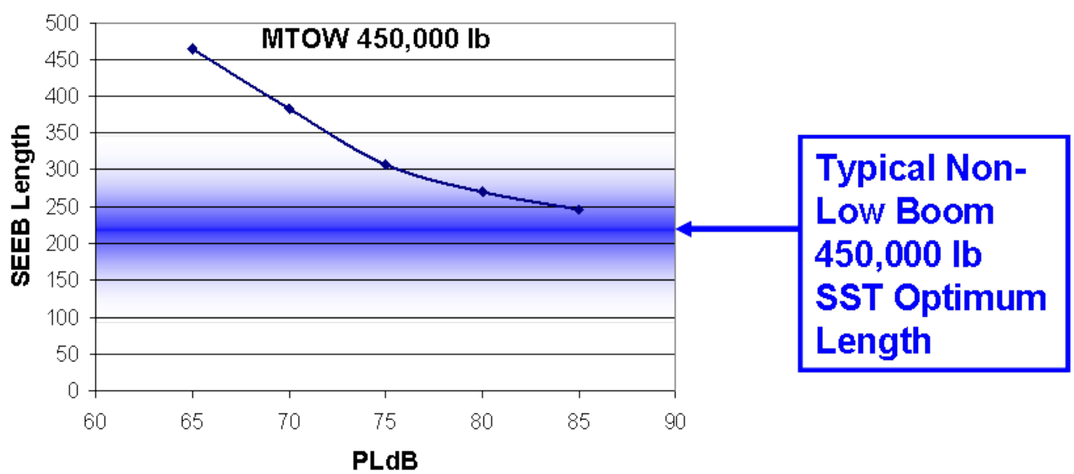


Figure 3.—Relation between vehicle length and perceived level of noise (PLdB).

The other noise challenge was meeting the airport noise goal of 20 to 30 EPNdB cumulative below FAR36 Stage 3 limits. Current subsonic airplanes, like the Boeing 777–200 with GE 90–85B and the Airbus A380 with RR Trent 970, already meet this goal at 23 EPNdB and 26 EPNdB cum below Stage 3 respectively. However, it is more of a challenge for supersonic aircraft. Using the Concorde as a state-of-the-art (SOA) comparison, its supersonic transport status is 45 EPNdB cumulative above Stage 3. Our strategy for meeting the noise goal was to first require GE to meet sideline –3 EPNdB at 90 percent power also known as PLR (programmed lapse rate), use the GE VCE, and optimize takeoff procedures. Second, reduce approach noise with a low-noise fan design, inlet liners and inlet flow choking. Third, investigate other promising advanced technologies.

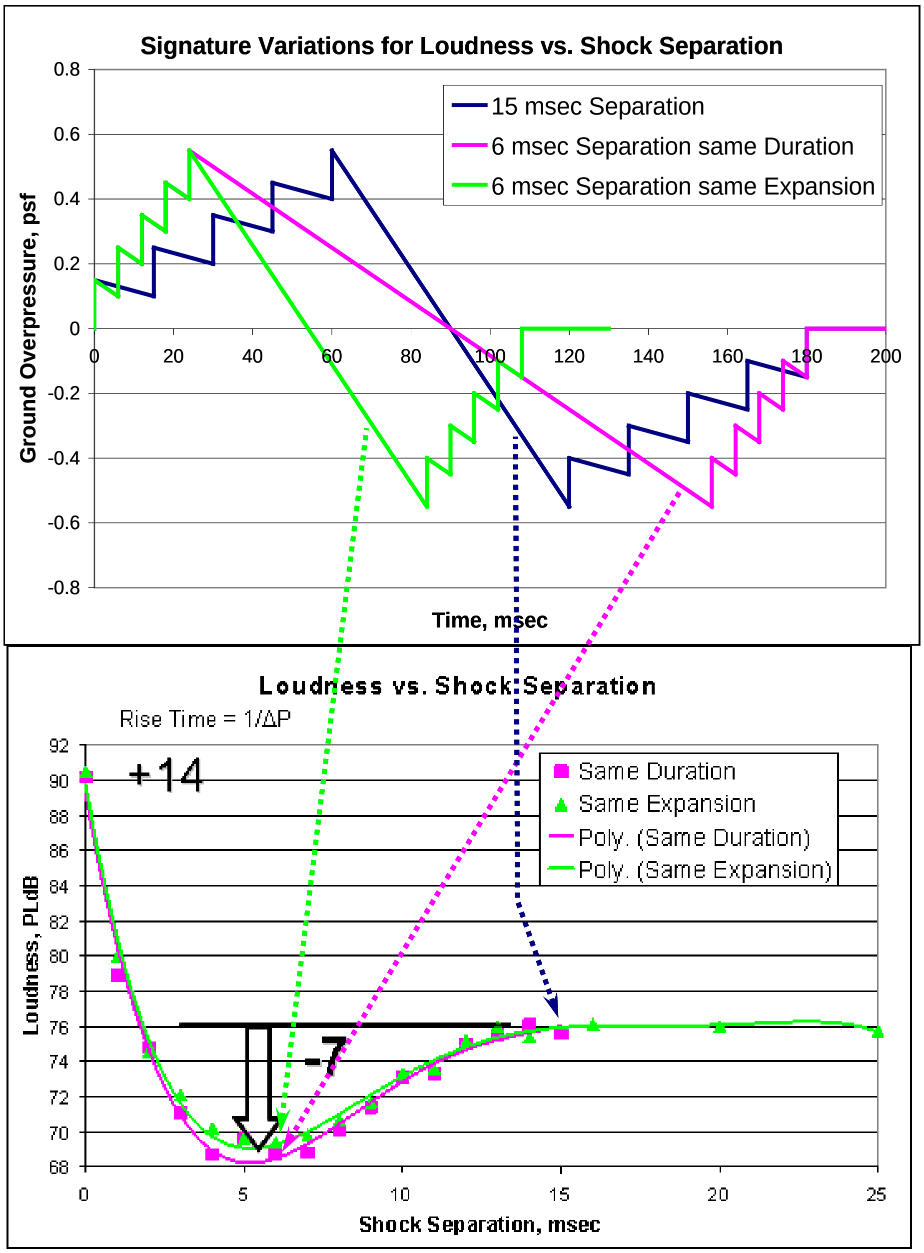


Figure 4.—Effect of shock separation on loudness.

	lb	fraction
Empty Weight	148,000	0.492
Payload Weight	22,440	0.075
Fuel Weight	130,200	0.433
Max Take-Off Weight	300,600	
	pax-Nmi/lbfuel	
Efficiency	3.07	

Reference Mission
100pax
4,000 Nmi range
Mach 1.6, 50,000 ft altitude

Figure 5.—Initial sizing for reference mission.

As part of the iterative design process, we looked at a number of different vehicle concepts that would integrate features necessary to achieve the N+3 mission requirements and performance goals. Desirable configuration features included items that would provide low boom, low drag, low weight, and good aeroelasticity performance for cruise and off-cruise conditions. Drawing on previous Quiet Supersonic Transport (QSST) experience, our process started with applying the desirable configuration features to a modified inverted-V, "QSST-like" concept. The four-engine inverted V-tail concept was proposed to better capture advantages of the inverted tail concept—particularly greater wing bending moment relief.

Preliminary vehicle sizing with QSST and historical data established the weight breakdown necessary to determine engine thrust, wing sizing, and fuselage length for boom. A slight improvement was assumed, giving an L/D of 10 and an SFC of 0.95 lb fuel/lb thrust/hr. These assumptions were applied to the reference mission of 100 passengers, 4000 nmi range, and Mach 1.6 cruise. This resulted in a Max Take-off Gross Weight (MTOW) of just over 300,000 lb, with an efficiency of 3.07 pax-nmi/lb fuel, as shown in Figure 5. However, this did not meet the requirement of efficiency between 3.5 to 4.5 pax-nmi/lb fuel. It was calculated that the efficiency could be raised to 3.97 pax-nmi/lb fuel if the L/D increased to 11, the SFC improved to 0.90 lb fuel/lb thrust/hr, and empty weight reduced by 5 percent. This quantified the N+3 vehicle improvement values to achieve NASA's desired performance goals. These values were status indicators as opposed to targets. N+3 technologies were sought to maximize performance as much as possible and potentially go beyond these goals.

3.1.1.2 Results

The initial configuration was sized with an assumed MTOW approximately equal to 300,000 lb, resulting in a wing area approximately equal to 3,000 ft^2, and a take-off thrust approximately equal to 100,000 lb The benefits of this low-boom configuration include stretched boom signature due the inverted V-tail and nose droop, favorable aerodynamic interference and compression lift for aft-under-wing mounted engines, efficient propulsion integration due to the planform trailing edge sweep and airfoil reflex, aerodynamic efficiency for wing planform design, reduced wing gull roll penalties due to wing tip and inverted V-tail anhedral, and structural flexibility suppression due to inverted V-tail wing bracing. Once designed, these specific elements were considered endemic to the configuration and always a part of the initial configuration technology set. The design was used as the "yardstick" to compare other potential configurations. Figure 6 highlights the overall initial configuration definition and design features that were modeled within CATIA V5.

Once the initial concept was defined, an initial inner mold-line (IML) cabin volume constraint was determined to insert passengers within the loft. The initial configuration held 101 passengers including future projected economy seat sizing comfort improvements relative to the Concorde and other regional jets plus the provision for 10 percent first class seats. The cabin layout included one galley, two lavatories, one supplemental space, and three emergency constraints. The boom constraints on the fuselage outer mold line (OML) forced cabin camber and cross section pinching on each end. This limitation required one first class seat to be removed from the forward section of the cabin, and a unification of the next set of seats. Nine rows in the aft section of the cabin changed from four across to three across while the cabin was lengthened. Cambered cabin slopes less than 5 percent have to be reconciled in a future design phase. Figure 7 demonstrates a realistic cabin layout that establishes fuselage IML constraints for the initial configuration.

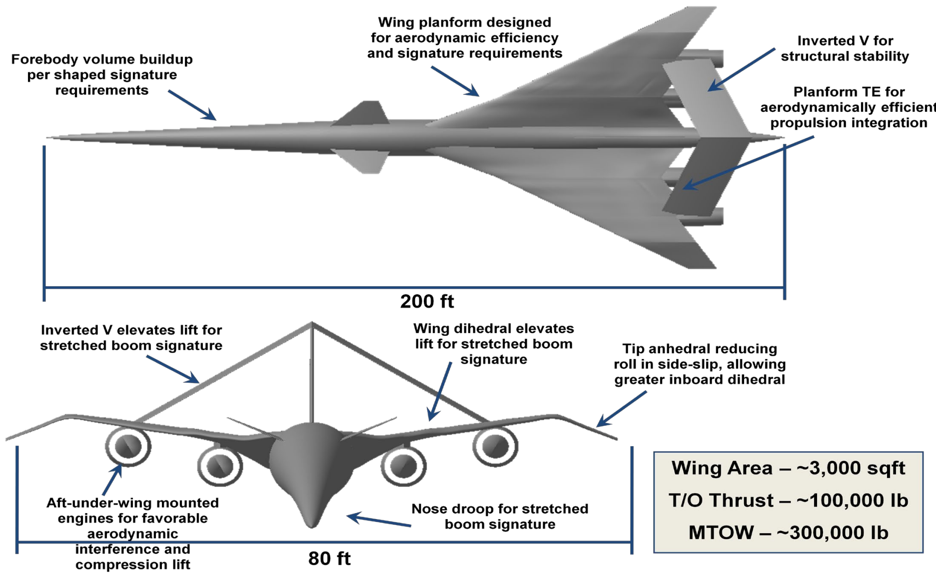


Figure 6.—Initial configuration definition.

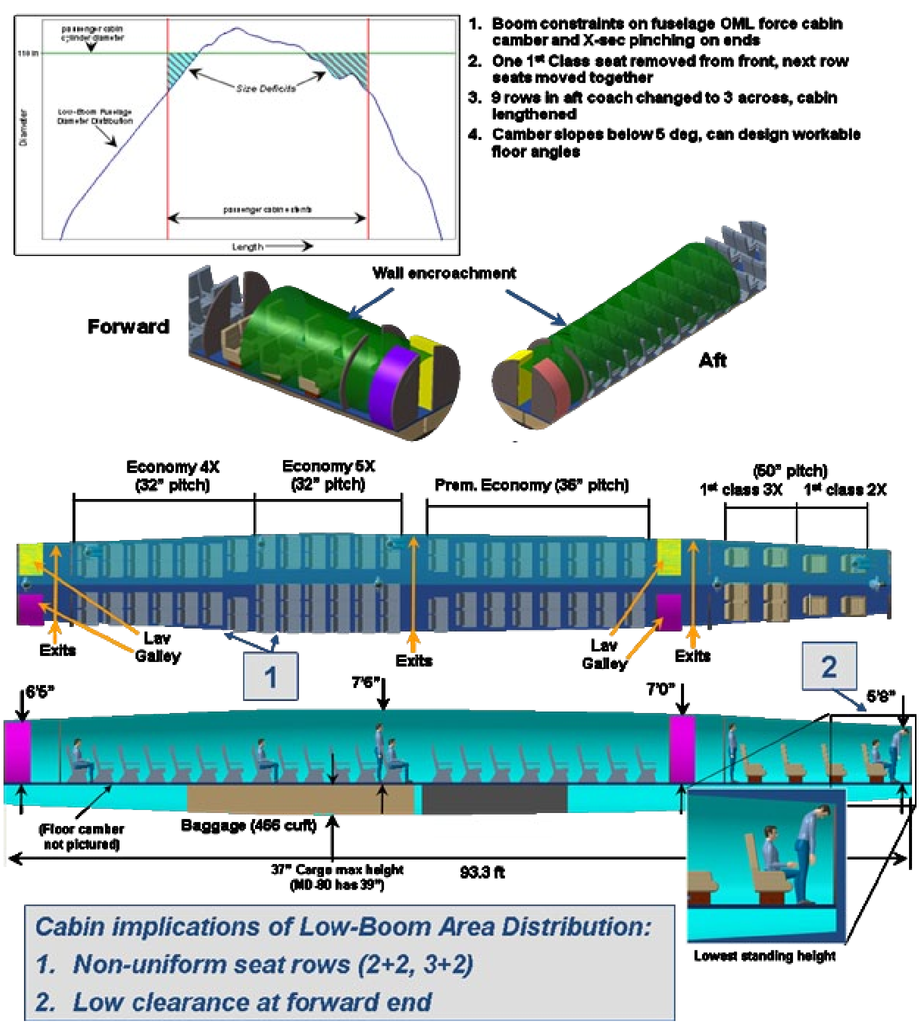


Figure 7.—Area-ruled cabin layout.

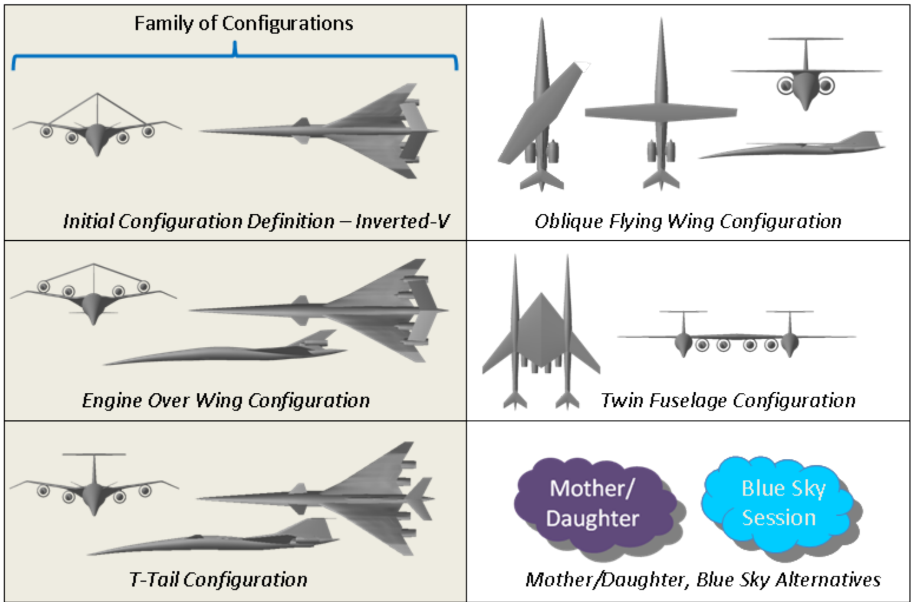


Figure 8.—Alternative configuration concepts chosen for further analysis.

3.1.2 Alternative Configurations (WBS 3.1.1)

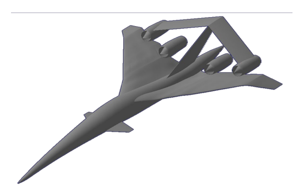
3.1.2.1 Description

The N+3 concept vehicle definition also included exploration of alternative concepts, both conventional and unconventional, to investigate all potential configuration solutions. Figure 8 highlights the various configurations that were studied starting with the family of inverted-v tail configurations and branching off to an oblique wing, a twin-fuselage concept, and a variety of brainstorming concepts.

3.1.2.1.1 "Blue Sky" Configurations

After the initial ideas listed above were considered, further brainstorming sessions, called "blue sky," were conducted with leading experts from outside the program, to identify more revolutionary concepts. However, no further configurations were discovered that could reasonably outperform those concepts already being considered.

3.1.2.1.2 Engines-Over-Wing Configuration



The engine-over-wing configuration was considered to address potential structural benefits (shorter landing gear) and noise level reductions possible with engine placements above the wing. When the engines are placed over the wing, engine spillage shocks are blocked from the ground by the wing. However, this results in higher pressure on the upper surface of the wing predicted to reduce L/D by 2 points.

In order to assess the need for noise reduction with the engines over wing configuration, it needed to be determined how low the noise could be for the engine under wing configuration. This was done through a wing configuration study to address propulsion/airframe integration (PAI) issues of a low-boom design. Figure 9 exhibits the trailing edge design study used for favorable interference drag. The wing trailing edge was swept to capture maximum nacelle shock compression lift and airfoil reflex for shock (and drag) cancellation. The nacelle shock was substantially countered; it met a 65 to 70 PLdB equivalent area target as easily as above the wing engine placements. The high pressure caused by the nacelle shock on the lower surface of the wing resulted in higher efficiency (lower angle-of-attack) through an increased L/D. Since it was possible to meet the sonic boom requirement with the higher efficiency of the engines-under-wing concept, further development of the engines-over-wing configuration was discontinued.

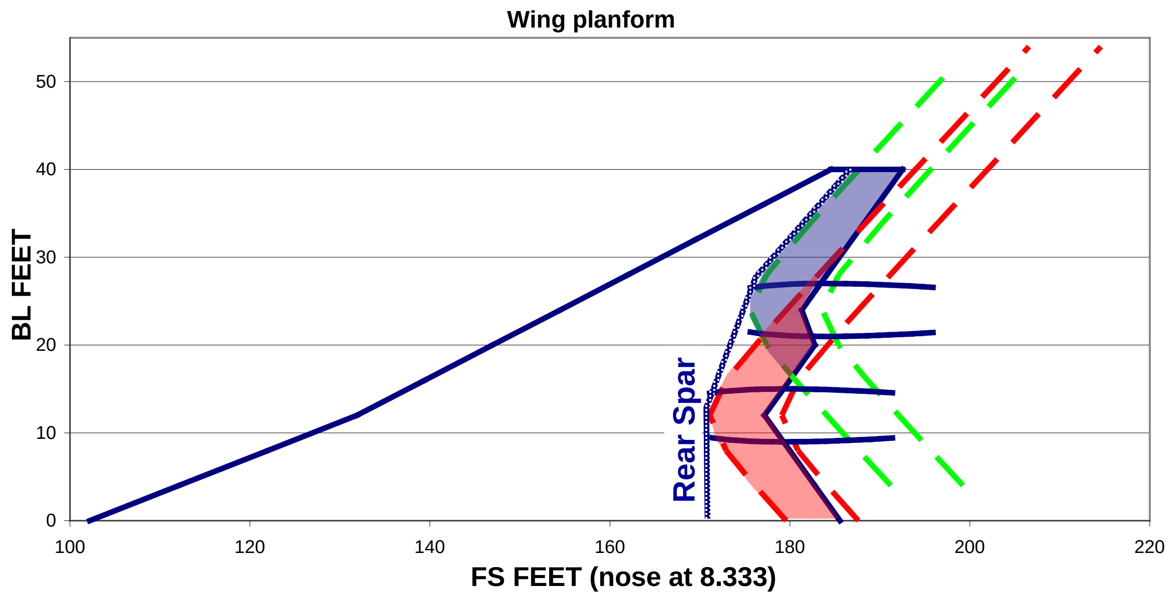
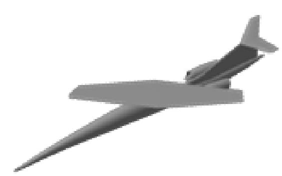


Figure 9.—Wing trailing edge swept to maximize compression lift and shock (and drag) cancellation from airfoil reflex.

3.1.2.1.3 T-Tail Configuration

The T-tail configuration was considered in order to raise the aft lift and stretch the boom signature. The configuration reduces interference drag and eliminates the inverted-V structure. A set of coarse geometry trades was performed to reduce the T-tail's sonic boom level while minimizing adverse impacts to drag. These trades followed the same approach used on the inverted V-tail, which is described in Section 3.2.1. Results for both configurations are provided in Table 4 in that section. This configuration was not considered further, however, because it also entailed an increase in wing weight (because the T-tail does not help support the wing as the inverted V-tail does), possible flutter issues, and a larger fin.

3.1.2.1.4 Oblique Wing Configuration



Oblique wings have been studied since the 1970s and have been proven to provide good aerodynamic performance at supersonic and subsonic speeds. The variable sweep allows better aerodynamic optimization at a variety of Mach numbers. If the takeoff constraint is driving the wing size, this would allow for a smaller wing with good low-speed, transonic, and supersonic performance. The smaller wing would require less thrust, possibly requiring fewer engines. However, an oblique wing design complicates the boom design and introduces a weight penalty with the wing pivot mechanism. Analysis of the area distributions was performed to determine whether the complications to the boom design could be overcome.

Figure 10 shows area distributions at Mach 1 for the components and area distributions for the combined vehicle at Mach 1.6 for roll angles from 0° to 180°. The Mach 1 area distribution shows one of the benefits of the oblique wing, in that the area of the wing is spread over a greater length of the vehicle than a traditional wing, which can help reduce wave drag. The Mach 1.6 area distributions show that there are some smile angles that are better than others. For a smile angle that causes the Mach angle to align more closely with the wing, the wing appears quickly in the area distribution, increasing that angle's contribution to wave drag.

Figure 11 shows the lift distributions for different angles. At 49°, which is opposite the angle of the wing, the lift distribution is spread out over a greater length of the vehicle at about 1250 lb/ft. For the opposite –49° angle, the lift is concentrated over a much shorter length, at almost 3000 lb/ft. This results

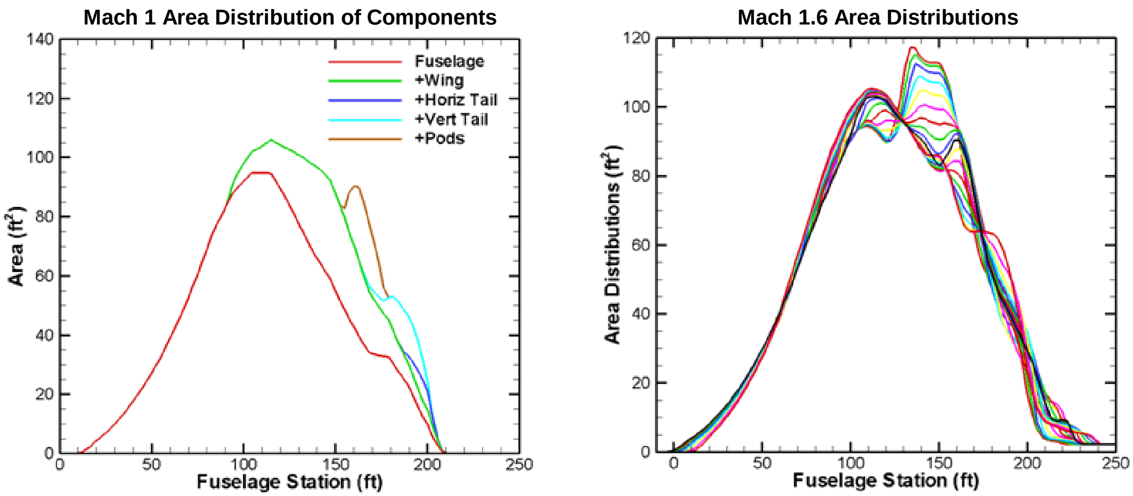


Figure 10.—Component and Mach 1.6 area distributions for roll angles 0° to 180°.

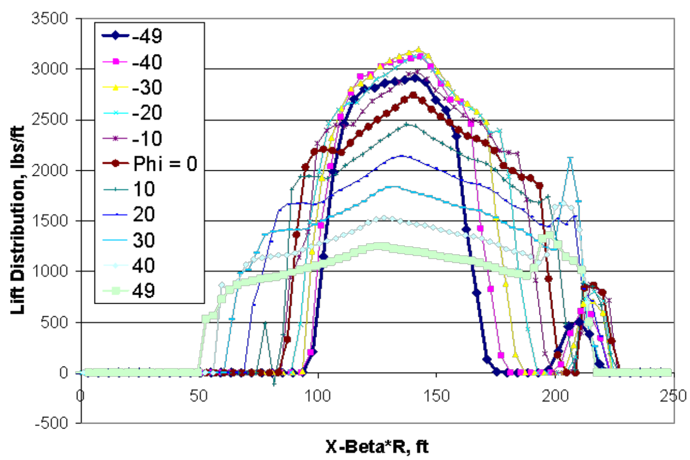


Figure 11.—Lift distributions at different angles.

in an asymmetric sonic boom signature, where the vehicle is quieter on one side and louder on the other. In Figure 12, the equivalent area distribution is shown compared to the baseline configuration. On the left plot, the undertrack distribution for the oblique wing is better than for the baseline, since it does not have the overshoot. The right plot shows the equivalent area distributions off to the sides compared to the baseline. At +49°, this again shows that the oblique wing has a better distribution than baseline, but on the other side at –49°, the area distribution is significantly worse.

The oblique wing configuration allows for improved signature in some areas at the expense of others. The efficiency can be higher at off-design Mach numbers through rotations; however, since the vehicle spends the majority of the time at the design cruise Mach number, this has a limited benefit. Unsweeping the wing makes it easier to meet takeoff requirements. However, takeoff is not predominantly limiting the baseline design, so this benefit is likely to be attenuated using the engine cycle matched to the baseline. In addition, the weight penalty of the rotation mechanism counters the off-design benefits. In conclusion, the supersonic transport mission spends more than 85 percent around the cruise condition, so cruise efficiency while maintaining a low sonic boom disturbance is the predominant characteristic for the best supersonic transport design. While the boom constrained cruise efficiency analysis is incomplete, it does show both advantages and disadvantages. At this point, the asymmetry inherent to this design makes it more challenging and resource intensive without a clear benefit indicated to justify the extra work. The

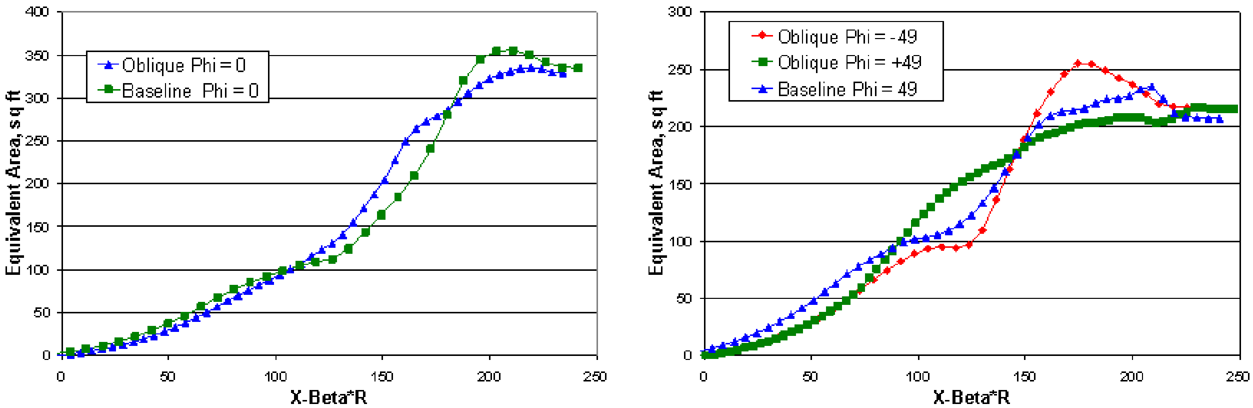
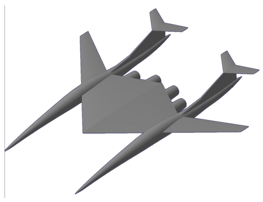


Figure 12.—Equivalent area distribution undertrack (left), and side (right) for oblique wing and baseline configuration.

show oblique wing appears to be a viable design alternative at this depth of analysis; however, it was not chosen as a baseline design.

3.1.2.1.5 Twin Fuselage Configuration



The twin fuselage configuration is another proposed N+3 configuration but presented fuel efficiency and boom design complications. The benefit of the twin fuselage configuration is the favorable interference between the fuselages that reduce drag. The fuselage weight is also split on the wing, reducing bending moment and wing structural weight. With the separation distance between the two fuselages, the far-field method would not accurately predict wave drag. Using an appropriate near-field method, the twin fuselage's favorable interference at optimal separation was small (less than 2 percent drag reduction) while the minimum practical cabin cross-section created a large fineness ratio penalty for the 100 to 200 passenger size. The twin fuselages' increased surface area skin friction and increased cross-section wave drag overwhelmed the possible wing structural benefit, prompting the elimination of this configuration.

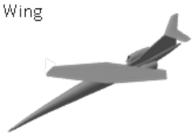
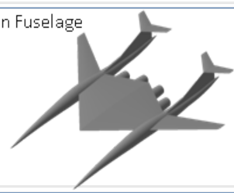
3.1.2.1.6 Mother/Daughter Configuration

The mother/daughter concept involves two vehicles: a "daughter" optimized for cruise (high wing loading, thrust sized for cruise) and not subject to any takeoff field constraints, and a "mother" optimized for takeoff and landing performance (low wing loading, thrust sized for takeoff) without prioritizing cruise efficiency. Operations would involve the two vehicles taking off in tandem, relying partly on the mother's thrust for takeoff and climb. The pair then separates upon attaining cruise altitude, at which point the daughter cruises efficiently and the mother returns to its home airport, most likely to serve several daughters and perhaps returning unmanned. The daughter could similarly rendezvous with another mother at its destination airport if additional power is needed for landing. Comparison of the baseline configuration and a daughter (nontakeoff constrained) version of it, developed for this purpose, showed that takeoff was not a strongly limiting constraint. In other words, the takeoff and cruise thrust requirements of the baseline were closely balanced. Entirely new airframe and engine designs that did not already mitigate takeoff requirements would be required to understand the full benefits of no takeoff requirements. Since the mother/daughter configurations would require different propulsion systems, aerodynamics, etc., a judgment was made that the added complexity of a second vehicle did not warrant further investigation.

3.1.2.2 Results

Analysis and consideration of each alternative configuration resulted in each one's elimination. Table 3 summarizes the pros and cons of each alternative configuration as it was compared and analyzed in regards to the initial configuration design. Within the family of configurations, the T-tail configuration was eliminated due to a lack of substantial benefits, and the engine over wing design was eliminated due to a two point reduction in L/D. The oblique wing configuration promised high aerodynamic performance, but the design was ultimately eliminated due to the weight penalty of the rotation mechanism and the sonic boom design difficulties. The twin fuselage configuration provided potential weight savings, but these benefits were not enough to outweigh the boom design complications to achieve the N+3 sonic boom goal. And finally, the mother/daughter configuration was eliminated due to complexity. As a result, the “as-drawn” initial configuration was used to perform additional sizing and mission analysis and lofted in CATIA V5 as the final configuration as seen in Section 3.3.

TABLE 3.—PROS AND CONS OF EACH ALTERNATIVE CONFIGURATION
AS COMPARED TO THE INITIAL CONFIGURATION

Configurations	Pros	Cons
T-Tail 	•Eliminate inverted v structure •Raise aft lift and stretch boom signature •Less interference drag	•Wing weight •Flutter •Larger fin
Engines-Over-Wing 	•Eliminate nacelle shock contribution to boom •Shield inlet fan noise with wing •Lower inverted V-tail angle, less concern for transonic choking	•Propulsion efficiency •No compression lift
Oblique Wing 	•Smaller wing, good low-speed performance •Less thrust, can move to twin •Better transonic performance (lower fineness ratio) •Efficient multi-mach capability	•Wing pivot weight and reliability •Propulsion integration •Landing gear integration •Complicates boom design (lift starts earlier)
Twin Fuselage 	•Drag benefits (lower overall fineness ratio, Busemann biplane interference) •Less wing structure required to hold engines (no cantilevers)	•Only works for larger numbers of passengers (50 pax per fuselage inefficient) •Low-boom configuration requires as much length as possible, twin fuse spreads volume out laterally
Mother/Daughter 	•Removes takeoff requirements for cruise vehicle	•Requires two separate vehicles be designed, built, and operated

3.2 Design Space Trade Studies With RCD (WBS 3.2)

3.2.1 RCD Low Boom Design Approach (WBS 3.2.1)

The first set of trade studies defined the inverted V-tail in terms of its longitudinal location, span, area, dihedral and leading edge sweep angles, and thickness-to-chord (t/c) ratio. An analogous set of trades was performed to define the geometry of the T-tail configuration as mentioned in Section 3.1.2. The approach was to identify the configuration that minimized drag, then adjust each geometry parameter individually to reduce sonic boom. By focusing on both drag and sonic boom, these trades constituted the first step in reducing the sonic boom associated with the inverted V-tail and T-tail configurations.

This initial set of trades transitioned the inverted V-tail configuration from a purely minimum-drag design to one with reduced sonic boom. It defined the planform and provided the starting point for the subsequent shape optimization process, which further reduced boom through finer adjustments in the shape of the lifting surfaces and ultimately enabled the inverted V-tail configuration to meet the N+3 noise goal.

3.2.2 RCD Model Development (WBS 3.2.1)

3.2.2.1 Aero/Boom Shape Optimization

3.2.2.1.1 Description

Rapid Conceptual Design (RCD) was used to modify the lift distribution of the as-drawn configuration such that its boom signature conformed to the prescribed target. This model included induced and wave drag, ground signature, and equivalent area analyses to enable shaping to account for both drag and boom. This shape optimization was performed with the planform fixed in accordance with the results of the tail-location trade described above. Its goal was to ensure that the configuration could be shaped to meet the N+3 sonic boom goal of 70 PLdB.

3.2.2.1.2 Results

The resulting improvement in the as-drawn configuration's sonic boom signature is illustrated in Figure 13. The left-hand plot corresponds to the sonic boom signature of the configuration prior to optimization (which resulted from coarse geometry trades performed previously). It was characterized by the large, 1.38-psf shock (increase in overpressure) occurring at 200 msec. The sonic boom signature corresponding to the resultant configuration, in which the maximum shock strength has been reduced to 0.29 psf, is shown in the right-hand plot in Figure 13.

The consequence of this improvement in sonic boom signature was a reduction in L/D from 10.1 to 8.0 (at beginning of cruise). This decline incurred because the initial shape did not meet the constraints required for sonic boom. The aero/boom shape optimization process yielded the five Pareto points in Figure 14, which represent the trade space between sonic boom and L/D.

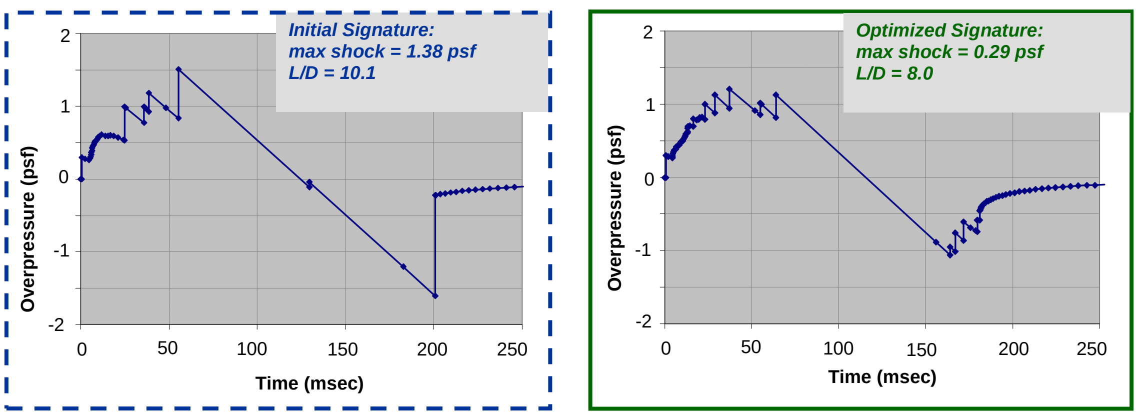


Figure 13.—Undertracking ground signatures, before and after aero/boom shape optimization.

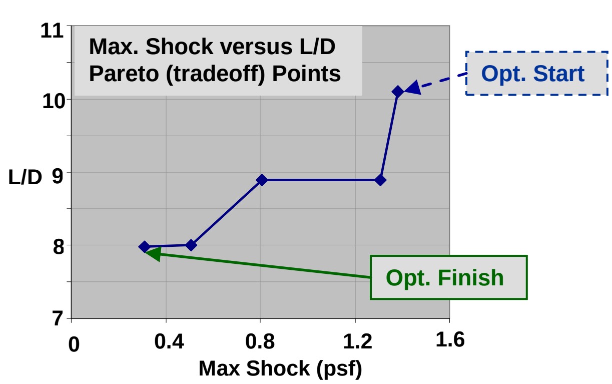


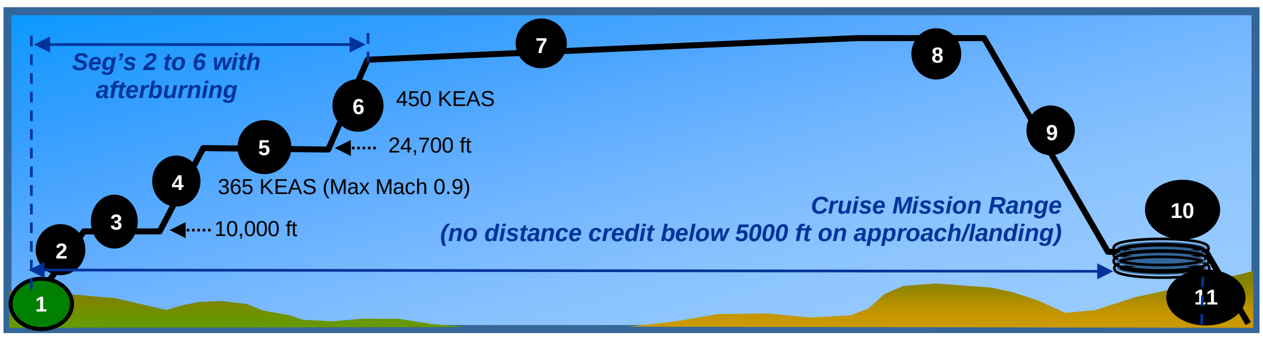
Figure 14.—Shock strength versus L/D tradeoff points.

This aero/boom shape optimization yielded two important results regarding the ability of the N+3 vehicle to meet its goals. First, it verified that the aircraft's lifting surfaces can be shaped to meet the 70-PLdB boom target. Second, it quantified the aerodynamic cost of doing so in terms of L/D. The latter result, shown to be a 21 percent reduction (from 10.1 to 8.0), can be offset by aerodynamic technologies such as Natural Laminar Flow (NLF) (to be described in Section 3.2.4.2) to enable a low-boom configuration to continue to meet N+3 range goals of over 4000 nmi.

3.2.2.2 Sizing and Mission Performance

LM's Rapid Conceptual Design (RCD) process was also used to size the as-drawn configuration to achieve maximum range subject to fuel volume and takeoff performance constraints. The integrated, multidisciplinary sizing model included multiple aerodynamic components (profile, induced, and wave drag), a parametric weights buildup, and mission performance and balanced field length (BFL) analyses. In addition to sizing, it facilitated assessments of N+3 technology benefits at the system (vehicle) level.

The sizing mission for the N+3 vehicle is illustrated in Figure 15 and consisted of the following segments:



1. Warm-up and takeoff—3 min at idle + 1 min at max power
2. Subsonic climb to 10,000 ft at 250 kn calibrated air speed (KCAS) (with afterburning)
3. Level acceleration at 10,000 ft: Mach 0.45 to Mach 0.66 (365 kn equivalent air speed (KEAS)) (with afterburning)
4. Subsonic climb and acceleration (maximum Mach 0.9) to 24,700 ft (with afterburning)
5. Level transonic acceleration to 450 KEAS (constant q=685 psf) (with afterburning)
6. Supersonic climb and acceleration at 450 KEAS until Mach 1.6 (with afterburning)
7. Cruise at Mach 1.6
8. Level deceleration to Mach 0.9
9. Descend at 4000 ft/min to 5,000 ft (constant 250 KEAS from 10,000 to 5,000 ft)
10. 5 min loiter awaiting clearance (no distance credit)
11. Descend to land (no distance credit)
12. Climb to 5000 ft (250 KCAS) after wave-off (no distance credit)
13. 5 min Loiter awaiting clearance (no distance credit)
14. Subsonic climb to 35,000 ft diversion altitude (250 KCAS to 10,000 ft, then 250 KEAS)
15. Diversion at best cruise mach
16. Descend at 4000 ft/min to 5,000 ft (250 KEAS above 10,000 ft, then 250 KCAS)
17. Descend to land (no distance credit)
18. Land with fuel reserves to loiter 30 min at 5,000 ft

Figure 15.—N+3 sizing mission.

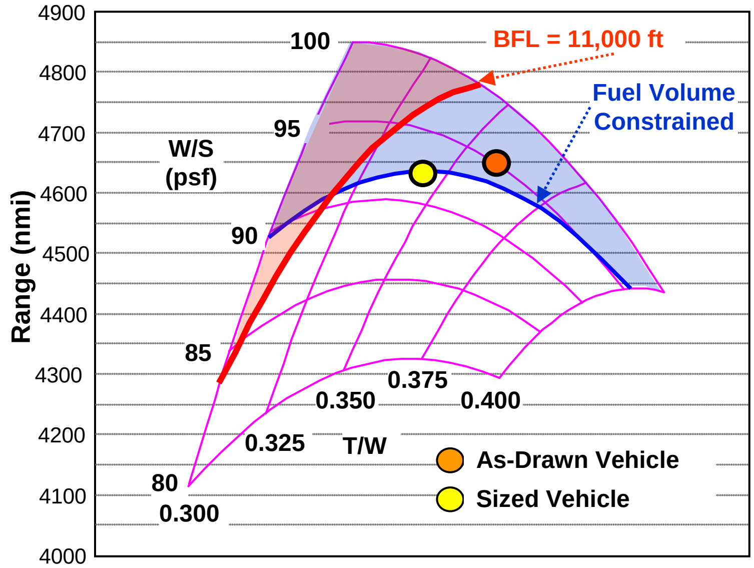


Figure 16.—N+3 Sizing space and results.

At a gross takeoff weight (GTOW) of 285,000 lb, the sized N+3 configuration achieved a range of 4640 nmi using conventional fuel tanks (i.e., without expanding fuel capacity through Biologically Inspired Morphing Structure or other technologies). Its thrust-to-weight ratio (T/W) and wing loading (W/S) were 0.34 and 92 psf, respectively. This range lies well within the N+3 goal bounds of 4000 to 5500 nmi. The two-dimensional sizing design space (T/W, W/S) is shown graphically in Figure 16, on which the orange and yellow circles correspond to the as-drawn and sized configurations, respectively. As indicated on the graph, the sized configuration is fuel volume constrained; its internal fuel volume, when full, corresponds to exactly 285,000 lb. GTOW. Configurations in the shaded blue area of the graph have insufficient fuel volume to take off at this weight. Configurations in the red shaded area of the graph in Figure 24 had balanced field lengths (BFL) exceeding 11,000 ft; the sized configuration's BFL was 9,770 ft. Its all-engines-operating (AEO) and FAR 25 takeoff field lengths were 9040 and 10,400 ft, respectively. Therefore, while sizing based on FAR25 field length would reduce margin relative to the 11,000 ft limit, doing so would yield the same (sized) configuration in terms of T/W and W/S. Table 4 details the sized configuration's mission performance according to individual segments.

TABLE 4.—SIZED N+3 CONFIGURATION MISSION PERFORMANCE

Phase	Initial alt (ft)	Initial Mach	Initial wt. (lb)	Phase dist (nmi)	Phase time (min)	Phase fuel (lb)	Avg. L/D	Avg. SFC [(lb/hr)/lb]
1. Warm-up and takeoff	0	0	285,000	-------	-----	851	------	------
2. Climb to 10,000	0	0.381	284,149	8	2	2,913	10.6	1.08
3. Level accel	10,000	0.453	281,236	4	1	951	10.5	1.12
4. Climb and accel	10,000	0.665	280,285	24	3	3,892	10.5	1.20
5. Transonic accel	24,700	0.900	276,393	10	1	1,239	10.3	1.26
6. Supersonic accel	24,700	1.11	275,154	40	3	4,083	11.5	1.28
7. Supersonic cruise	*40,500*	*1.60*	*271,116*	*4,447*	*293*	*104,127*	*8.71*	*0.881*
8. Level decel	53,600	1.60	166,989	40	3	147	9.24	0.105
9. Descend and decel	53,600	0.900	166,842	77	12	921	10.8	1.72
10. 5-min loiter	5,000	0.343	165,921	-------	5	902	10.9	0.707
11. Descend to land	5,000	0.342	165,019	-------	4	440	11.2	1.21
12. to 18. Diversion and reserves	0	-------	164,579	200	68	12,849	------	------
Mission totals	-------	-------	----------	4,850	395	133,270		

The sensitivity of the sized N+3 vehicle's range to changes in maximum takeoff weight (MTOW) is illustrated in Figure 17. The blue line on the figure illustrates the nearly linear relationship between MTOW and range. Each 1000 lb. of additional weight yields approximately 11.2 nmi of added range; this translates to 89.3 lb per mile. The red line and right-hand axis on Figure 17 denote passenger-miles flown per lb. fuel on each mission, an efficiency metric which decreases with additional weight. The configuration was re-sized in accordance with the fuel volume and takeoff field constraints to produce the results in Figure 17. Extrapolating the red (efficiency) line on the plot suggests that ranges up to 5000 nmi, which would correspond to a MTOW of approximately 320,000 lb, are possible while meeting or exceeding N+3's minimum efficiency goal of 3.5 pax*nmi per lb. fuel.

Reducing the maximum allowable takeoff field, which was originally 11,000 ft during sizing, has no impact until the requirement falls below the sized configuration's takeoff field length of 9.970 ft. As the field performance gets more restrictive, it requires increasing the thrust-to-weight ratio and decreasing wing loading, as shown in Figure 18. Both of these lead to inefficient cruise, decreasing the achievable mission range as illustrated in Figure 19. This analysis was performed with a constant MTOW of 285,000 lb.

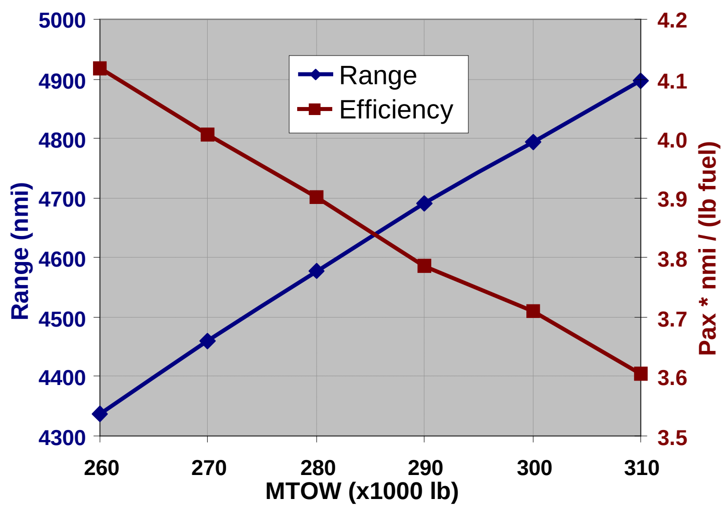


Figure 17.—Range and efficiency versus MTOW.

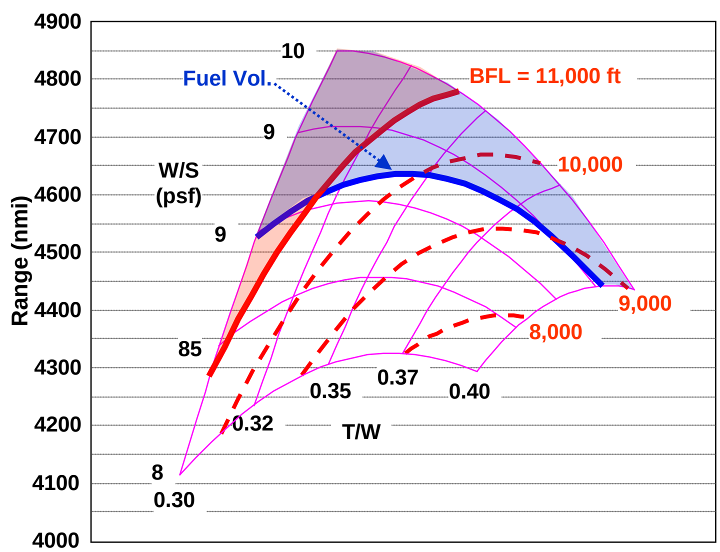


Figure 18.—Sizing design space with takeoff field contours.

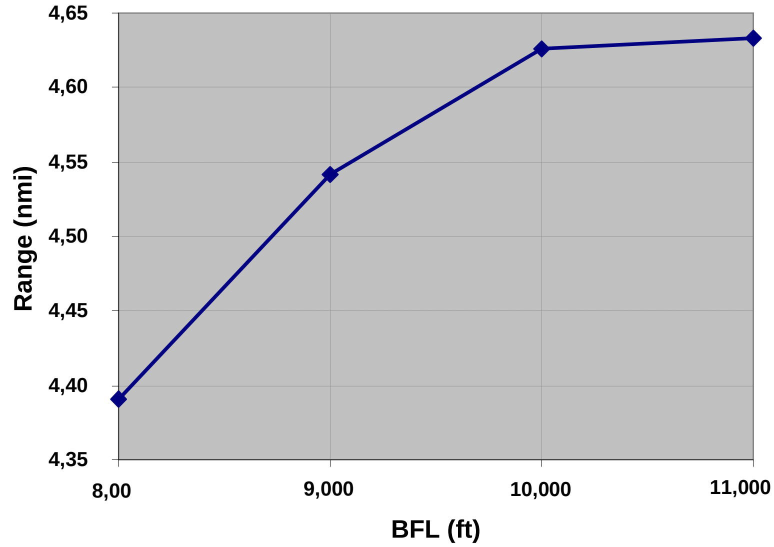


Figure 19.—Range versus takeoff field length for MTOW = 285,000 lb.

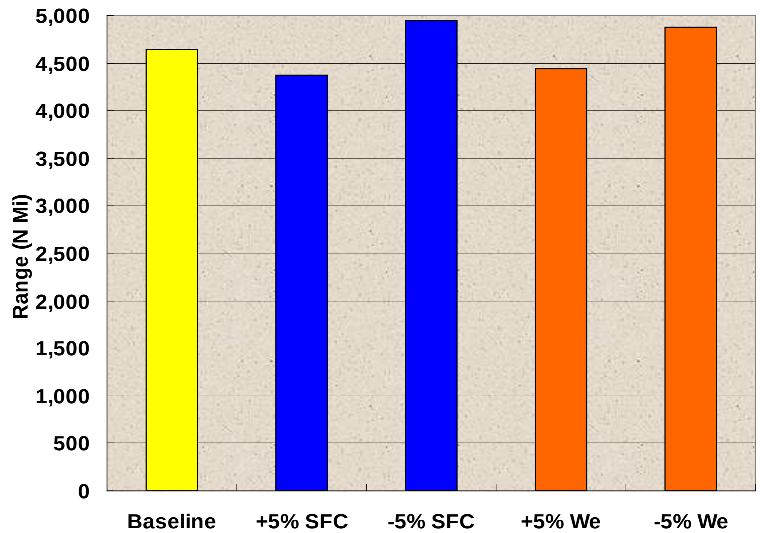


Figure 20.—Technology impacts to sized configuration mission range.

Finally, the sensitivities of the sized N+3 configuration's range to changes in empty weight and specific fuel consumption (SFC) were evaluated by perturbing each of those quantities by 5 percent and resizing the vehicle to the same constraints. The results of this study are summarized in Figure 20. A 5 percent increase or decrease in SFC resulted in a range of 4370 or 4940 nmi, respectively. The resultant range due to a 5 percent increase or decrease in empty weight was 4440 or 4880 nmi, respectively. The corresponding, local sensitivities are thus –57 nmi per percent increase in SFC, and –44 nmi per percent increase in empty weight.

3.2.3 RCD Model Integration with Technology Inputs (WBS 3.2.2)

3.2.3.1 Description

The same N+3 vehicle model used for sizing also incorporated analysis components specific to some of the technologies that will enhance the vehicle's performance. Namely, GE's VCE and the aerodynamic benefits of NLF were represented in the sizing RCD model itself.

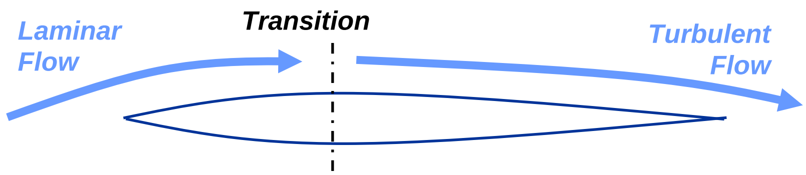


Figure 21.—NLF schematic.

RCD integration of the FLF4-L1 engine was achieved by including a cycle deck provided by GE directly in the mission performance component of the model. Also, takeoff thrust was evaluated based on that deck and accounted for in the takeoff field performance analysis within the sizing model. The effects of NLF were captured using a friction drag analysis that supported both laminar and turbulent flow assumptions on all surfaces, top and bottom. Transition points, illustrated schematically in Figure 21, were varied parametrically and the aircraft's friction drag based on appropriately weighted sums of laminar and turbulent skin friction coefficients.

3.2.3.2 Results

Results of this task are described in the following Section 3.2.4.

3.2.4 Technology Benefit/Impact Assessment (WBS 3.2.4)

3.2.4.1 GE VCE

3.2.4.1.1 Description

Performances of both the initial and sized configurations were evaluated using GE's VCE, which helps the N+3 vehicle meet its goals in two ways. First, it is lighter than a similarly-powered turbofan. This reduces the aircraft's empty weight fraction, thereby permitting an equal increase in fuel fraction and longer range, compared to a vehicle designed for a conventional engine.

3.2.4.1.2 Results

GE's VCE impact on range performance was investigated by sizing an alternate configuration, based on a GE turbofan engine, to the same fuel volume and takeoff constraints. A comparison of the sized N+3 configuration, with its VCE, and the turbofan-based alternate is summarized in Table 5.

TABLE 5.—VCE VERSUS TURBOFAN SIZED CONFIGURATION PERFORMANCE

	VCE	Alternate Turbofan
Range	4640 nmi	4400 nmi
T/W (total thrust)	0.34 (98,000 lb)	0.38 (108,000 lb)
W/S (wing area)	92 (3090 ft^2)	94 (3040 ft^2)
Empty weight	129,600 lb	131,500 lb
Mean cruise SFC (cruise fuel)	2.32% more than AT	2.27% less than VCE
BFL	9,770 ft	8,720 ft
Time to M0.9 / M1.6 (with AB)	5.8 min / 10.1 min	4.9 min / 8.1 min

As shown in the table, the VCE yields greater range compared to the turbofan, 4640 nmi versus 4400, primarily due to the increased weight of the turbofan. Even though the VCE does cruise at a slightly higher SFC, fixing the GTOW (285,000 lb) resulted in more fuel available for the corresponding configuration. In re-sizing for the turbofan, the consequent weight gain was partially offset by shrinking the wing slightly (W/S increased from 92 to 94 psf), which also improves cruise efficiency slightly. However, further increases in W/S result in a net loss of range due to reduced fuel volume. The turbofan's power does reduce time to Mach 0.9 and 1.6 by 1 and 2 min, respectively, and reduce BFL by approximately 1000 ft, but the VCE more effectively helps the N+3 vehicle meet its range performance goal.

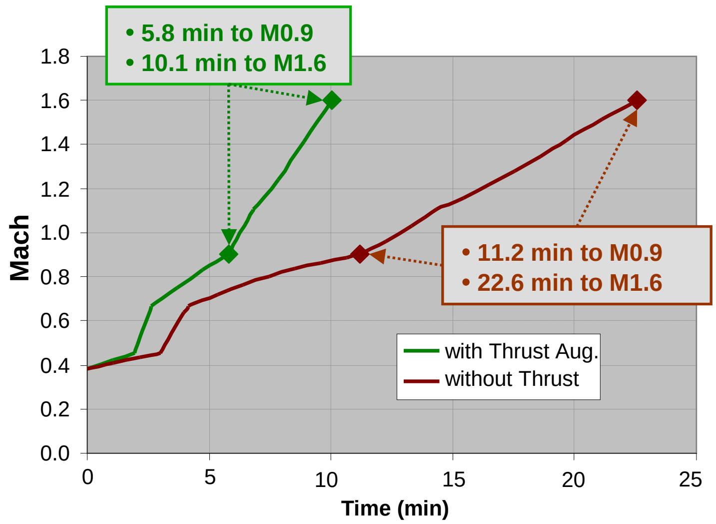


Figure 22.—Time to Mach with and without thrust augmentation.

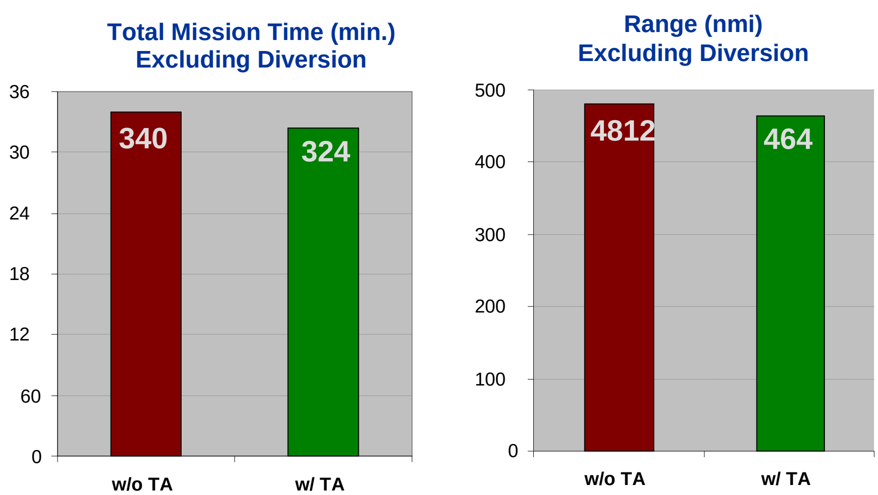


Figure 23.—Thrust augmentation (TA) impact on sizing mission time and range.

Mission performance was evaluated using the thrust augmentation technology during the climb and acceleration segments of the sizing mission (Figure 15, segments 2 to 6). Comparing this performance with that attained using max dry power showed that thrust augmentation reduced the time from takeoff to beginning of cruise by over 50 percent. As shown in Figure 25, thrust augmentation enables the N+3 vehicle to reach Mach 1.6 10.1 min after takeoff. Doing so via the same climb profile would take 22.6 min using max dry power. Similarly, the aircraft reaches Mach 0.9 (the beginning of its transonic acceleration phase) in 5.8 min using the thrust augmentation and 11.2 min without them.

The impact of employing thrust augmentation during climb and acceleration on overall range and mission fuel is illustrated in Figure 23. An analogous mission flown entirely on max dry power takes 16 min longer (340 versus 324 min.) and reaches 172 miles farther (4812 versus 4640 nmi) than the sizing mission as flown (i.e., with thrust augmentation). The 3.7 percent increase in range is attributable to fuel savings achieved by limiting operations to max dry power.

In terms of operational flexibility, the more important benefit of thrust augmentation technology is that it allows the level transonic acceleration to be moved above commercial jet traffic if necessary. This is exhibited in Figure 24, which shows the time necessary to reach altitudes up to 40,000 ft by following

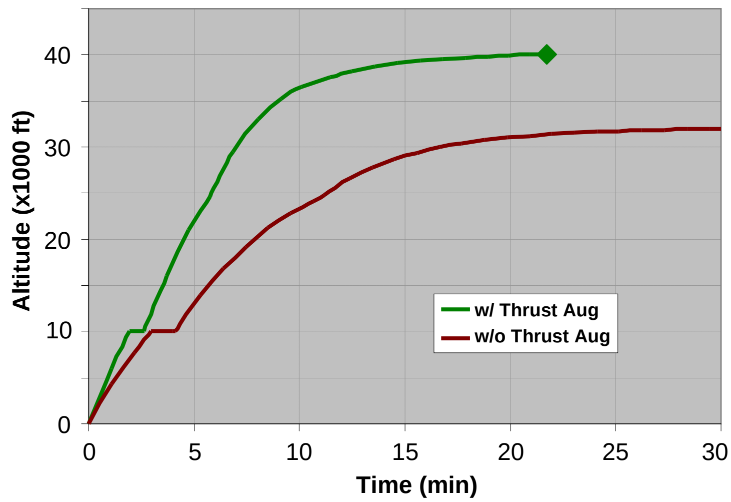


Figure 24.—Time to altitude, with and without thrust augmentation.

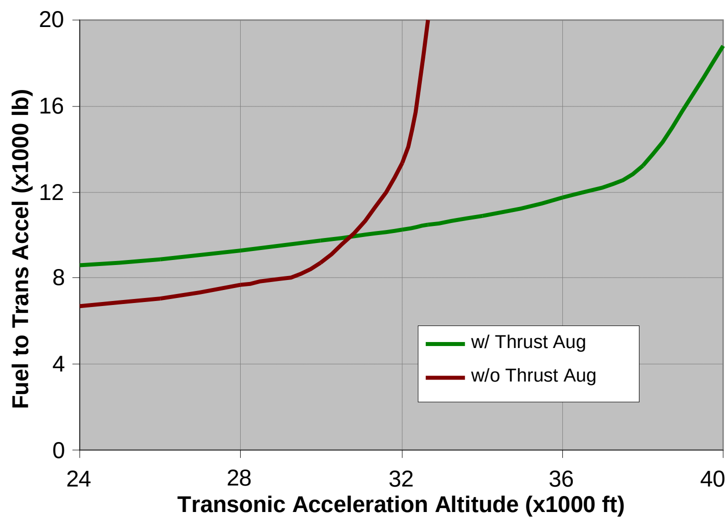


Figure 25.—Fuel to transonic acceleration, with and without thrust augmentation.

the sizing mission profile to 10,000 ft and climbing at Mach 0.9 thereafter. As indicated by the green line on the graph, the N+3 vehicle with thrust augmentation activated reaches 40,000 ft in only 22 min. Conversely, absent the thrust augmentation, the vehicle is effectively forced to cruise-climb starting from near 32,000 ft. A direct consequence of this is that, as the transonic acceleration is delayed to 32,000 ft or higher, the climb phase accounts for a substantially larger fraction of mission time and available fuel, as illustrated in Figure 25. The plot on that figure depicts the total fuel consumption, from takeoff through subsonic climb, as a function of the altitude at which acceleration takes place. As the time and fuel spent during the subsonic climb grow to dominate the mission, the ultimate effect is to compromise total mission range. This undesirable result is shown on the plot of mission range versus transonic acceleration altitude in Figure 26.

These results demonstrate that, if supersonic flight were sometimes restricted by ATC (air traffic control) limitations until above most subsonic traffic, thrust augmentation is necessary to do so without compromising the N+3 vehicle's speed and range. This is particularly important in light of the airport and airspace analysis performed by LM Transportation and Security Solutions (to be described in Section 3.4.2), which showed that the greatest potential for conflicts between N+3 vehicles and existing subsonic

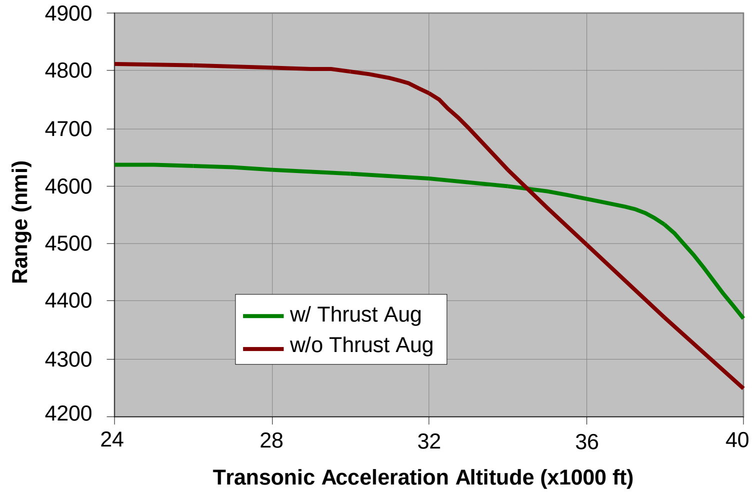


Figure 26.—Sizing mission range, with and without thrust augmentation.

traffic exists during transonic acceleration and supersonic climb. The VCE can minimize this risk by moving these segments above existing traffic while still enabling the N+3 vehicle to meet its range goal.

3.2.4.2 NLF

3.2.4.2.1 Description

Experimentation by Bill Saric and Helen Reed from Texas A&M showed that the use of Distributed Roughness Elements (DREs) can delay flow transition to produce significant regions of swept wing laminar flow. The impact of this technology and unswept NLF on the sized N+3 configuration was investigated by parametrically varying the transition point, in terms of percent of chord, in analyzing the aircraft's friction drag. For each aircraft component (wing, fuselage, etc.), skin friction coefficients were computed for both laminar and turbulent flow. Each component's total skin friction and drag coefficients were calculated using a sum weighted according to the assumed transition point.

3.2.4.2.2 Results

The effects of laminar flow on the N+3 vehicle's friction drag coefficient and total drag polars is visible in Figure 27 and Figure 28, respectively. Both were evaluated at a cruise condition of Mach 1.6 and 50,000 ft altitude. Of particular interest was the improvement in lift-to-drag ratio (L/D) attained through NLF. Without this technology, the N+3's cruise CL at 50,000 ft during its sizing mission is 0.145. As highlighted on Figure 28(b), inducing laminar flow over 40 percent of chord length leads to an L/D increase of 2, which would offset the drop in lift-to-drag ratio (L/D) observed as a result of shaping for sonic boom (described previously in Section 3.2.2.1). Therefore, this technology is critical in ensuring that a vehicle shaped to comply with the N+3 noise goal of 70 PLdB can also achieve the sized configuration's range of over 4600 nmi.

The performance benefits of friction drag reduction achieved through NLF are summarized in Figure 29 and Figure 30. The first figure is a graph of mission range and passenger efficiency, again defined as passenger-miles per lb. Fuel, as a function of the flow transition point with GTOW fixed at 285,000 lb The solid blue line shows the increase in mission range if the sized configuration's T/W and W/S are maintained at 0.34 and 0.92, respectively, while the dotted blue line depicts the additional range benefit that would result from re-sizing the configuration to the same constraints. In the latter case, the range benefit of additional fuel volume outweighs the detriment of more wetted area, which is lessened by maintaining laminar flow. This is evidenced by the slightly increased wing size (reduced W/S). Finally, the solid and dashed red lines show the increase in passenger efficiency, again corresponding to maintaining and resizing T/W and W/S, respectively.

NLF also has the effect of reducing the fuel, and consequently the gross takeoff weight, of a fixed-length mission, as shown in Figure 30. The dark and light blue lines on the plot correspond to the sized configuration's GTOW and fuel weight, respectively, for its 4640-nmi mission. The red line depicts the consequent increase in efficiency, which is attributable entirely to the decrease in fuel required.

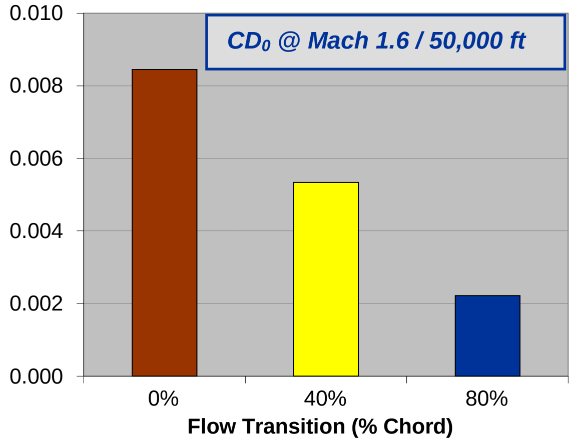


Figure 27.—Cruise friction drag coefficient for 3 levels of natural laminar flow.

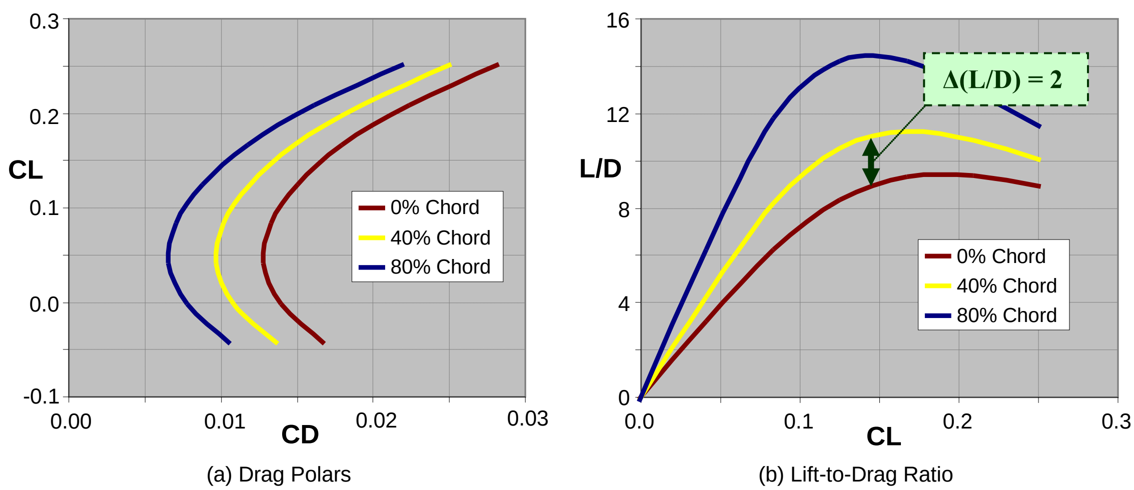


Figure 28.—Cruise drag polars for 3 levels of natural laminar flow

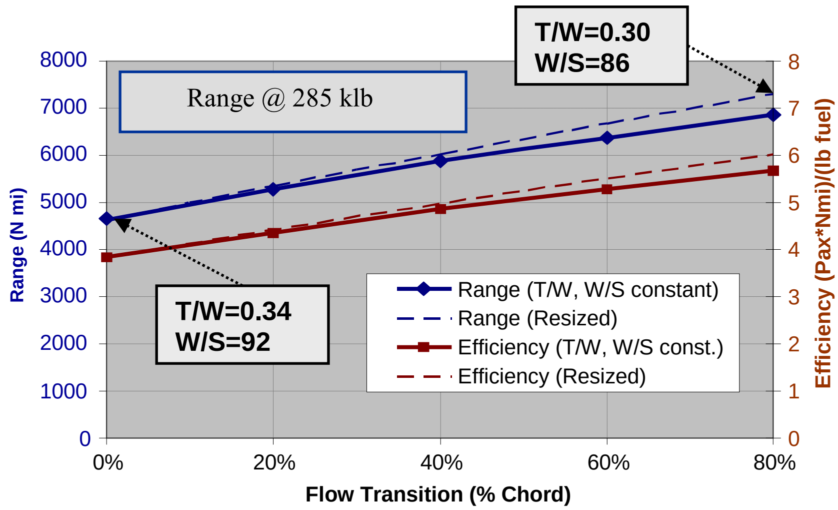


Figure 29.—Range and efficiency [pax*nmi / lb fuel] benefits of natural laminar flow—constant GTOW.

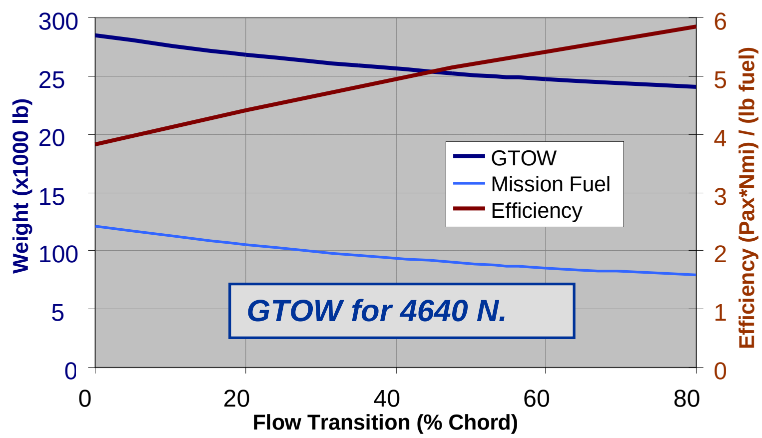


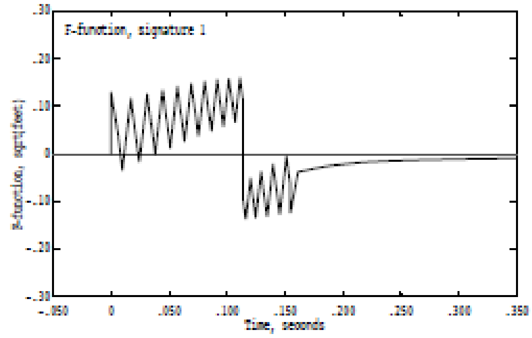
Figure 30.—Weight savings from natural laminar flow—constant range.

3.2.5 Quantified Analysis (WBS 3.2.3)

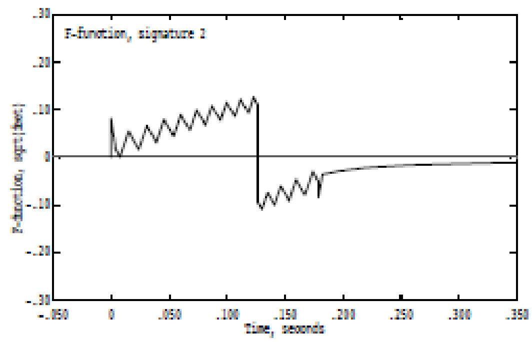
3.2.5.1 Description

The sonic boom ground signatures of the N+3 aircraft were originally computed by modeling shock waves as either thin shocks or as simple "1/P Taylor structure" shocks. In an additional study by Wyle Laboratories and Penn State University, the boom signatures were completed by calculation of actual shock structures accounting for molecular relaxation effects, and the variations associated with atmospheric turbulence. The effect of lateral offset of the boom, i.e., propagation off track as well as under track, was examined. The key result of this analysis was perceived loudness, PLdB, of the booms accounting for those real world effects.

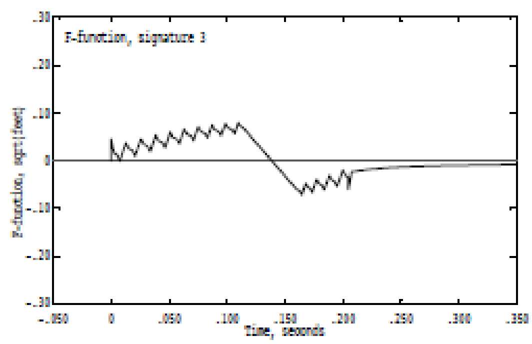
Three near-field signatures provided by LM to Wyle and PSU and served as the starting point for this analysis. Specifically, they were target (desired) signatures derived from SEEB corresponding to loudness levels of 80, 75, and 70 PLdB in accordance with N+3 goals. The first two were undertrack signatures while the last one was derived off-track at 40° azimuth. Figure 31 shows those signatures, normalized as F-functions. The shorter names noted in the figure captions ("denoted Sig1," etc.) are to refer to these signatures in this report. Flight conditions for all three are Mach 1.6 at 48,000 ft in the standard atmosphere (Ref. 6).



a. LMBin_N3sig1.txt, denoted Sig1



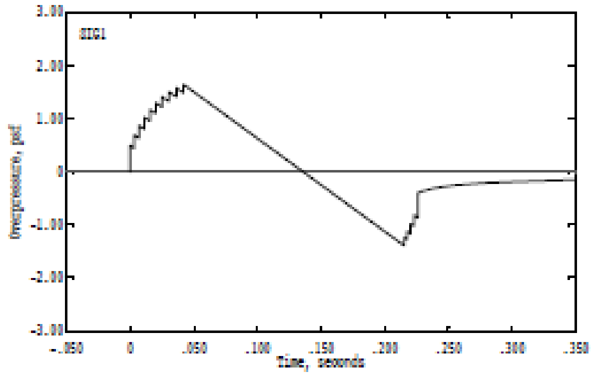
b. LMBin_N3sig2.txt, denoted Sig2



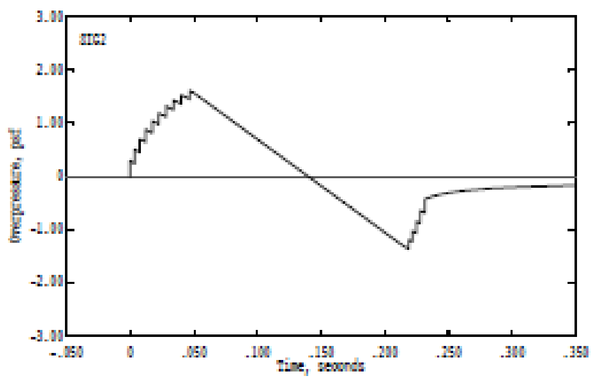
c. LMBin_N3sig3.txt, denoted Sig3

Figure 31.—F-functions for three configurations.

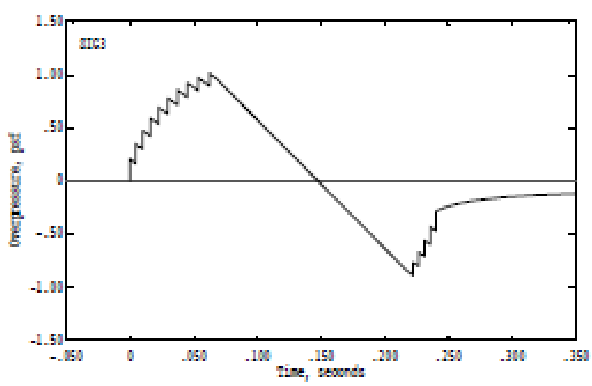
Figure 32 and Figure 33 show nominal ground booms. These were computed using PCBoom3, 4 for those flight conditions. Figure 32 shows booms with thin shocks, while Figure 33 incorporates 1/P Taylor shock structures. Both include a ground reflection factor of 1.9. Note that the individual shocks in the F-functions are still distinct: they have not coalesced. Thickening (Figure 33) smoothes them so that the ground booms have the appearance of ramp signatures. The Perceived Loudness levels should be regarded as qualitative, since the frequency content of a Taylor shock is not the same as that of a relaxation shock.



a. Sig1

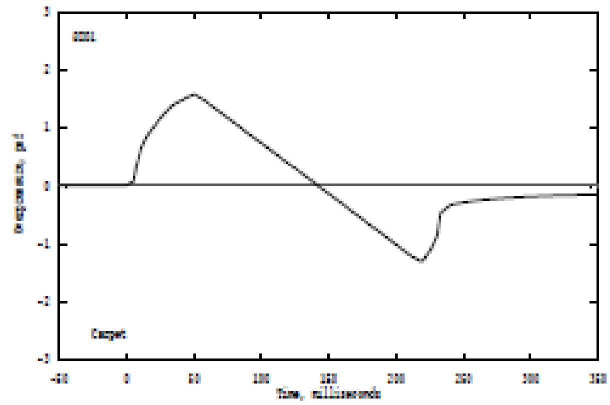


b. Sig2

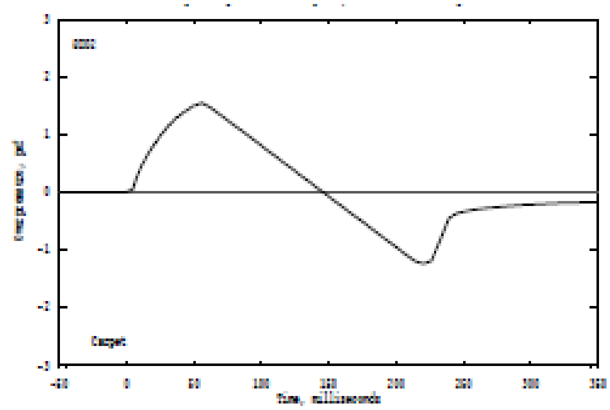


c. Sig3

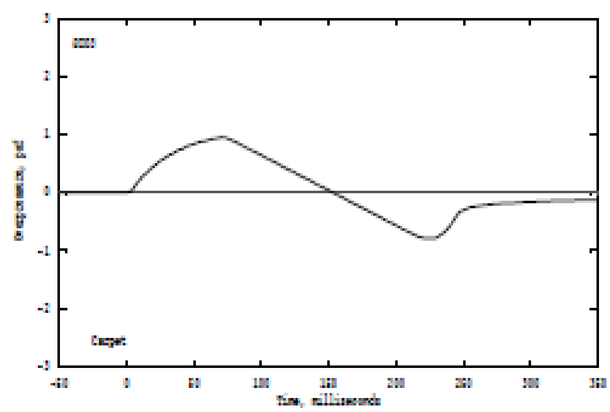
Figure 32.—Thin shock ground booms (no thickening).



a. Sig1, 1/P Taylor shocks, 89.4 PLdB



b. Sig2, 1/P Taylor shocks, 82.9 PLdB



c. Sig3, 1/P Taylor shocks, 76.3 PLdB

Figure 33.—Nominal ground signatures from PC-Boom, 1/P Taylor shock structures.

Three propagation effects were considered and are addressed in Sections 3.2.5.2, 3.2.5.2.2 and 3.2.5.2.3:

- Shock structures due to molecular relaxation atmospheric absorption
- The effects of turbulence
- The effects of off-track propagation.

3.2.5.2 Results—Effects of Molecular Relaxation

3.2.5.2.1 Effects of Molecular Relaxation

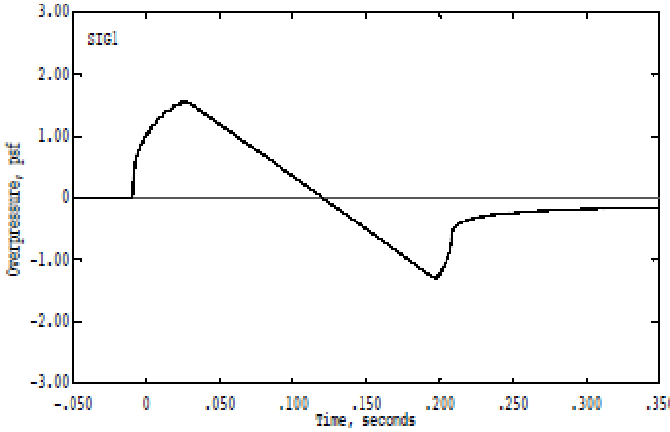
Loudness of sonic booms (Ref. 7) is determined primarily by the structure of the shock waves, which contain the high frequency audible components. The structure is governed by a balance between nonlinear steepening and molecular absorption, quantified by the Burgers equation (Ref. 8). PCBoom6 (Ref. 9) contains a Burgers solver, which uses a mixed time and frequency domain algorithm similar to that devised by Anderson (Ref. 10). Molecular absorption is defined by the current ANSI/ASA standard (Ref. 11).

The three signatures have been processed by PCBoom6's Burgers solver to obtain ground signatures for two humidity conditions: 50 percent, representing a typical low-absorption condition that occurs most of the time, and 5 percent, representing dry, high-humidity conditions. The analysis procedure is to first compute the thin-shock solution at 47,000 ft (1000 ft below the flight altitude), then begin the Burgers calculation. The reason for beginning the calculation a short distance away from the flight path is to avoid anomalies associated with the Anderson-like algorithm in regions of very high wave pressure.

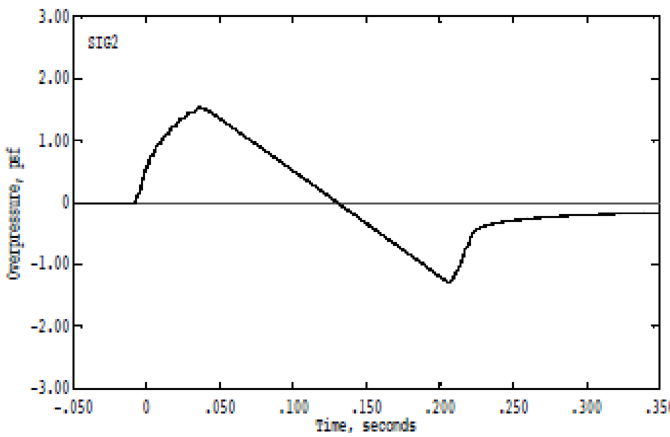
Figure 34 and Figure 35 illustrate the booms for the 50 and 5 percent humidity cases. Note that their appearance is similar to the Taylor-thickened booms: the same shape as the thin shock solutions (Figure 33) but with the shocks smoothed. Table 6 summarizes the loudness of the three booms and three types of thickening. Booms under dry (high absorption) conditions are considerably less loud, by about 8 dB for these examples, than under moist (low absorption) conditions. The nominal 1/P Taylor structure booms fall about midway between the extremes.

TABLE 6.—SUMMARY OF LOUDNESS, PLdB

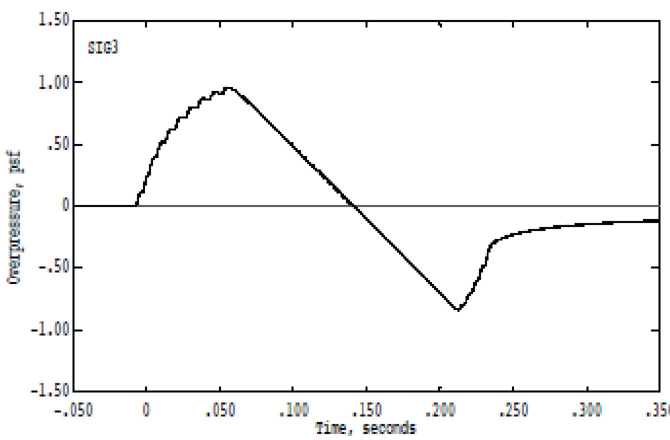
Shock Type	Sig1	Sig2	Sig3
Taylor	89.4	82.9	76.3
50% RH	94.1	87.6	82.7
5% RH	85.8	79.7	74.6



a. Sig1, 94.1 PLdB

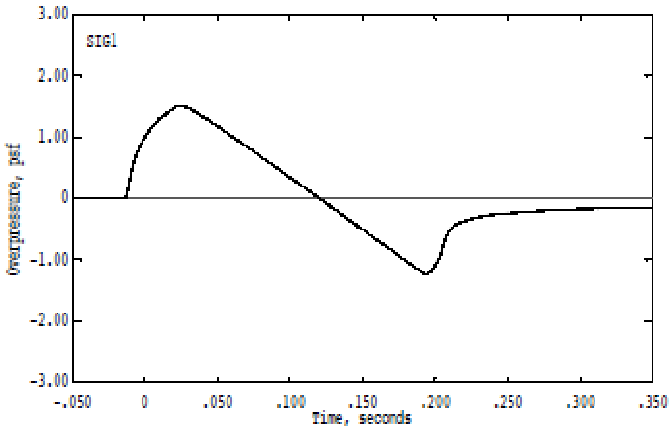


b. Sig2, 87.6 PLdB

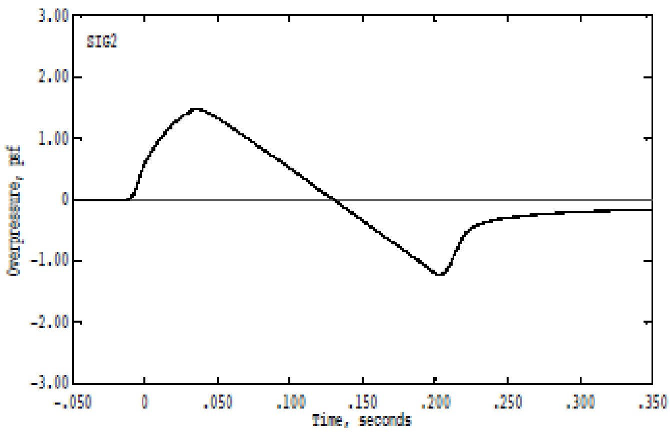


c. Sig3, 82.7 PLdB

Figure 34.—Ground Booms at 50 percent relative humidity.



a. Sig1, 85.8 PLdB



b. Sig2, 79.7 PLdB

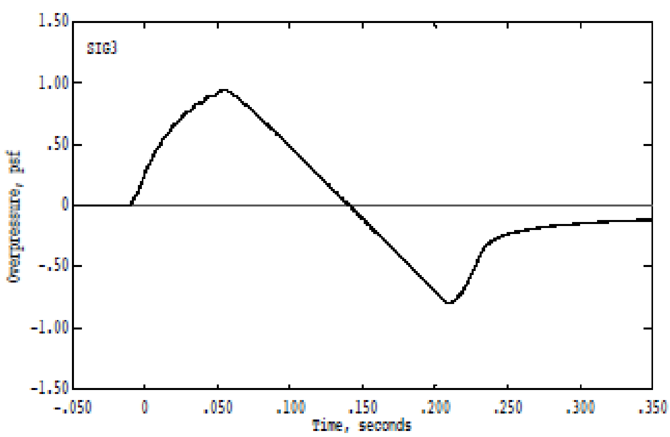


Figure 35.—Ground booms at 5 percent relative humidity.

3.2.5.2.2 Effects of Atmospheric Turbulence

Atmospheric turbulence is known to distort sonic booms. Figure 36 is a classic NASA measurement result, showing booms measured under calm and turbulent conditions (Ref. 12). There is a considerable body of literature and analysis on the specific effects of turbulence on booms. Early predictive models tend to be statistical in nature, which makes it difficult to the estimate of the effects on loudness.

Empirical filters have, however, recently been developed for the effect of individual realizations of turbulence (Refs. 13 to 15), the loudness of which can be computed. Ten such filters have been applied to each of the relaxation-thickened booms in Figure 37 and Figure 38. Figure 37 shows two of these applications, a “peaking” and a "rounding" instance applied to Sig 1, 50 percent humidity. The original boom, from Figure 37(a), is drawn in blue and the turbulent-distorted boom is drawn in black.

Table 7 shows the Perceived Loudness for all six ground signatures (Sig1, Sig2 and Sig3, each at 50 percent and 5 percent relative humidity) and the ten realizations. The minimum, maximum, average and standard deviation (sigma) are shown for the ten turbulence realizations. Note that the average of each of the turbulent-distorted booms is always less than that of the corresponding nondistorted boom. The range of loudness from minimum to maximum for each boom is up to 10 dB. It should be noted that the turbulence filters are based on flight test data that, in general, had less distortion than seen in other tests such as that shown in Figure 36. While it is expected that the average loudness of booms would follow the trend of small reduction (or possibly no reduction), variations of individual booms may be greater than computed here.

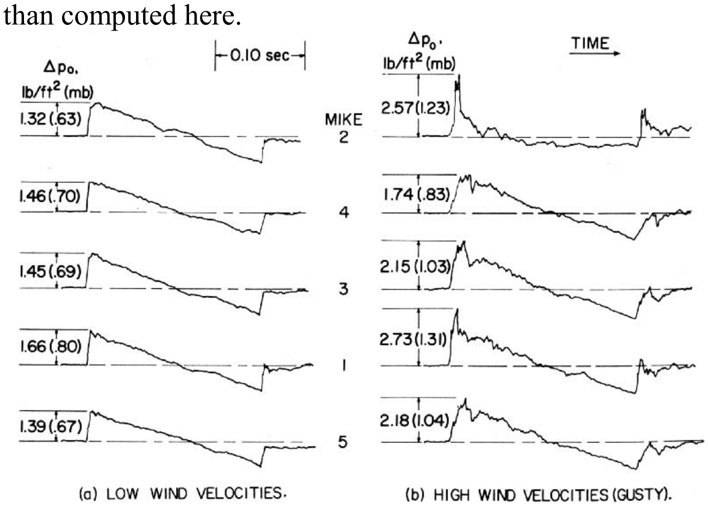
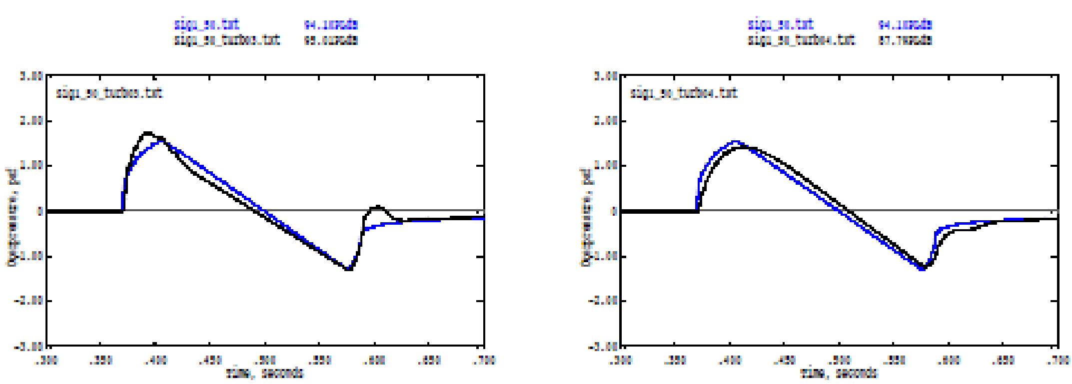
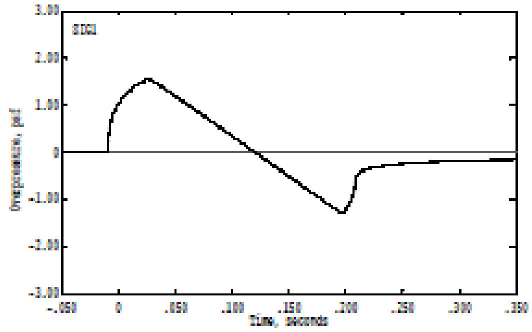


Figure 36.—Distortion of sonic booms by turbulence.

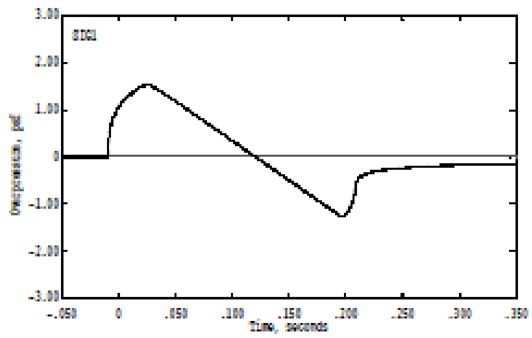


a. "Peaking" turbulence applied, 95.0 PLdB b. "Rounding" turbulence applied, 87.8 PLdB

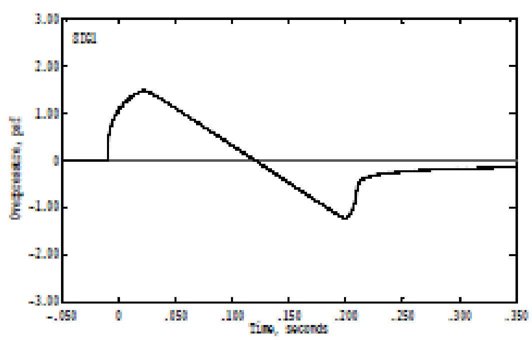
Figure 37.—Sig1, 50 percent humidity, with peaking and rounding turbulence.



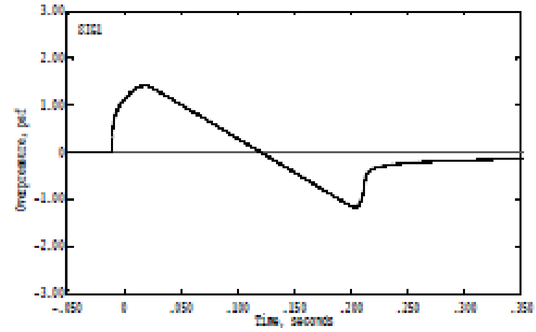
a. Phi = 0 degrees. Pmax = 1.56, PL = 94.10



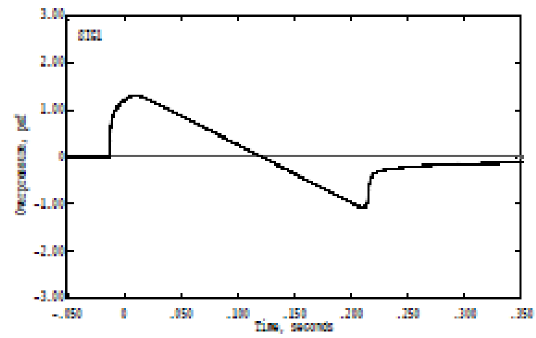
b. Phi = 10 degrees. Pmax = 1.54, PL = 95.16



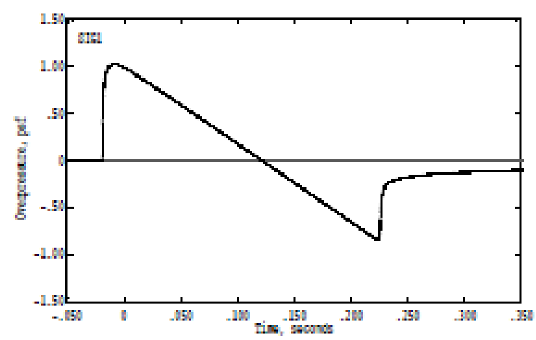
c. Phi = 20 degrees. Pmax = 1.50, PL = 95.63



c. Phi = 30 degrees. Pmax = 1.43, PL = 96.84



e. Phi = 40 degrees. Pmax = 1.31, PL = 98.51



f. Phi = 49.8 degrees. Pmax = 1.03, PL = 99.48

Figure 38.—Signatures, peak overpressures and perceived loudness across the carpet, Sig1 50 percent RH.

TABLE 7.—LOUDNESS FOR ALL GROUND SIGNATURES, VARIOUS TURBULENCE REALIZATIONS

	Signature and relative humidity					
Turbulence	Sig1, 50%	Sig1, 5%	Sig2, 50%	Sig2, 5%	Sig3, 50%	Sig3, 5%
None	94.10	85.81	87.56	79.72	82.70	74.64
1	92.28	85.50	85.77	79.58	81.13	73.37
2	87.16	81.01	80.99	75.60	74.85	67.91
3	95.01	88.50	89.19	82.90	84.76	77.62
4	87.79	79.83	81.43	74.19	76.78	68.26
5	92.40	83.43	84.80	76.65	81.04	72.62
6	92.99	86.00	85.20	78.99	81.87	74.48
7	94.17	86.46	86.60	79.95	83.33	75.55
8	94.43	86.34	86.36	79.61	83.49	75.71
9	94.55	86.99	87.11	80.25	83.88	75.91
10	93.73	85.71	85.80	78.88	82.79	74.96
Minimum	87.16	81.01	80.99	74.19	74.85	67.91
Maximum	95.01	88.50	89.19	82.90	84.76	77.62
Average	92.40	84.95	85.29	78.61	81.33	73.60
Sigma	2.65	2.59	2.36	2.41	3.03	3.07

3.2.5.2.3 Off-Track Booms

Off-track boom propagation was predicted by using the under-track F-functions at lateral azimuths, in 10° increments, out to lateral cutoff of 49.8°. Physically, roll angles off-track generally have a substantial reduction in impulse due to lift reducing with the cosine of the roll angle degrees from under-track. Therefore actual off-track sonic boom generally decreases in impulse; however, shaped booms (non N-wave) can decrease or increase in loudness depending on how well their shaping is maintained at other roll angles (a very configuration-specific dependency). The following indicates just one difficulty of maintaining good off-track shaping: an F-function that works under-track may work (Sig3) or may not work off-track (Sig1 and Sig2). Figure 41 shows the ground signatures for Sig1 50 percent humidity. The peak overpressure and perceived loudness of each boom is presented in Table 8. Note that the peak pressure progressively decreases across the carpet (due to the longer propagation distance), as expected, but that loudness increases. The reason for this is apparent from the signatures in Figure 38: the off-track positions, with their longer propagation distances, are beyond the design point for the under-track ground signature. The individual steps, which did not coalesce under track, progressively coalesce off-track. At the carpet edge most of the steps at the bow of Sig1 and all of the steps at the tail have coalesced into single shocks. The same coalescence occurs for Sig2, with peak pressure and perceived loudness shown in Table 9. On the other hand, Sig3 was intentionally designed with a lower slope in its ramp because it was shaped for the roll angle furthest off-track, which also results in good shaping at lower coalescence everywhere else. Table 10 shows the peak pressure and perceived loudness of Sig3 across the track. Both decrease toward the carpet edge. Note that this is a coalescence issue, independent of the humidity and shock structure.

The off-track calculation is approximate because a single under-track F-function was used at all azimuths, while a physical configuration's F-function changes off-track both from the cosine drop-off in overall lift and from asymmetric changes in the distribution of lift and volume at each roll angle. It is important that optimal designs be developed off-track as well as under-track.

TABLE 8.—BOOM MAGNITUDE ACROSS CARPET, Sig1 50 PERCENT HUMIDITY

ϕ (°)	Pmax (psf)	Loudness (PLdB)
0	1.56	94.10
10	1.54	95.16
20	1.50	95.63
30	1.43	96.84
40	1.31	98.51
49.8	1.03	99.48

TABLE 9.—BOOM MAGNITUDE ACROSS CARPET, Sig2 50 PERCENT HUMIDITY

ϕ (°)	Pmax (psf)	Loudness (PLdB)
0	1.53	85.91
10	1.52	85.89
20	1.48	85.69
30	1.41	86.68
40	1.29	90.44
49.8	1.02	96.03

TABLE 10.—BOOM MAGNITUDE ACROSS CARPET, Sig3 50 PERCENT HUMIDITY

ϕ (°)	Pmax (psf)	Loudness (PLdB)
0	0.97	82.70
10	0.96	81.11
20	0.93	80.25
30	0.88	78.65
40	0.81	76.79
49.8	0.64	76.50

3.2.5.3 Conclusions

Ground booms accounting for molecular relaxation shock structure, at 50 and 5 percent relative humidity, have been computed for three nearfield signatures. Thin shock and 1/P Taylor shock signatures were also presented for comparison. Loudness results are presented and discussed. Humidity has a clear effect on the loudness of booms. Under dry conditions (5 percent RH) the sample booms are about 8 dB less loud than under moist/typical (50 percent RH) conditions. Loudness of the nominal 1/P Taylor shock booms is about midway between moist and dry relaxation shock booms.

The effect of turbulence was evaluated by applying filters to the under-track booms for ten realizations of turbulence. This turbulence set yielded a slight decrease in average loudness, but with individual variations of up to plus or minus 5 dB. The sample turbulence set is modest in amplitude, and real-world turbulent variations may be bigger. The turbulence model used (Ref. 13 to 15) should be expanded to cover a wider range of atmospheric conditions.

Off-track propagation was examined, assuming the under-track F-functions applied at all azimuths. For booms Sig1 and Sig2 the longer propagation distances off-track resulted in partial coalescence of shocks, losing the shaping effect and yielding higher perceived loudness than under track. Coalescence did not occur for the lower amplitude Sig3, so its loudness did decrease off-track across the carpet. These off-track trends used to same F-function for all roll angles, but a real configuration's F-function changes considerably since lift drops off with cosine of roll angle and the distribution of volume and lift changes at every roll angle. Still, it illustrates that low boom shaping must be developed off-track as well as under-track. Finally with regard to low boom, variations in humidity, and mild turbulence were investigated. Variations of +2 PLdb (turbulence peak) to –15 PLdB (turbulence and humidity rounding) were seen relative to 50 percent humidity Burgers analysis. Strong turbulence has changed N-wave average loudness as much as –6 PLdB along with greater scatter in loudness. While humidity variations are on average close to the 50 percent humidity level, there are other uncertainties (atmospheric winds, greater rounding/over-prediction of N-waves, ground reflection arrival time rounding) that seem to all push in the quieter direction. Since this result comes to us at the end of the program, hereafter we will carry a –4 to –16 PLdB uncertainty in "real" loudness relative to molecular relaxation loudness calculations (or more approximately +2 to –11 PLdB uncertainty from 1/dp Taylor loudness).

3.3 Final Configuration Definition (WBS 3.1.3)

3.3.1 Loft

3.3.1.1 Description

Sizing and mission performance from Section 3.2.2.2 drove the final configuration loft. The drooped nose in the initial configuration reduced the vehicle length, but this was not enough to overcome the added complexity of the shape. A straighter nose may cause difficulties with pilot visibility, but this will be solved with the use of Synthetic Vision as the design moves closer to reality. As a result, the final configuration is shown with a reduction in the drooped nose.

3.3.1.2 Results

The RCD process was also used to size the final configuration to meet the mission, as detailed in Section 3.2.2.2. The final configuration was sized to have a gross takeoff weight was 285,000 lb, with a thrust to weight ratio of 0.34 and a wing loading of 92 psf. The final configuration with all included changes is shown in Figure 39.

The final wing, canard and tails were optimized to reduce the sonic boom with minimal aerodynamic efficiency reduction. The Rapid Conceptual Design (RCD) model and results for this boom optimization are detailed in Section 3.2.2.1. This optimization resulted in a reduction of the 1.38 psf max shock to 0.29 psf, and a reduction in L/D from 10.1 to 8.0.

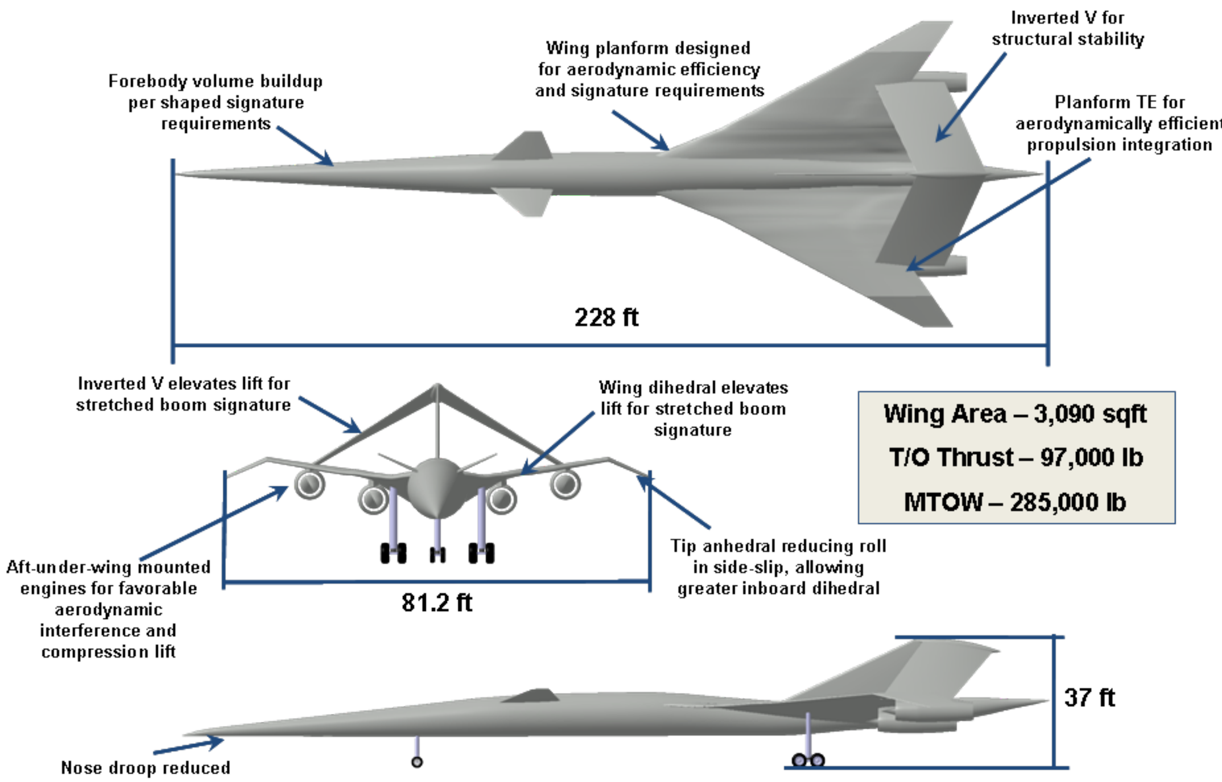


Figure 39.—Final configuration three-view.

3.3.2 Fuel Arrangement

3.3.2.1 Description

Initially, the fuel arrangement was performed by only placing fuel within the final configuration's wings. However, this fuel placement was ultimately inadequate and fuel had to be placed in the forward fuselage and V-tail. The internal fuel assessment was performed in CATIA V5.

3.3.2.2 Results

The fuel volume was found by examining space for fuel tanks in the vehicle, as shown in Figure 40. The fuel tanks included a small tank in the fuselage to allow for some trimming of the CG through fuel placement. The total fuel available is 133,900 lb.

3.3.3 Aerodynamics

3.3.3.1 Description

Cruise drag of the sized N+3 configuration was consisted of 3 induced, profile, and wave drag. These items are plotted in Figure 41. The profile drag does not include shaping for low boom.

3.3.3.2 Results

The total drag polar at Mach 1.6 and 50,000 ft altitude, a flight condition near mid-cruise, is shown in Figure 42(a). Figure 42(b) depicts a breakdown of profile drag by component (total profile drag at this condition is CD0 = 0.0843). Again, these results do not reflect shaping for low boom, as it is anticipated that the N+3 technologies described in Sections 9.0 and 10.0 will offset the aerodynamic penalties from doing so. Finally, the takeoff drag polars in and out of ground effect (IGE, OGE) are shown in Figure 43.

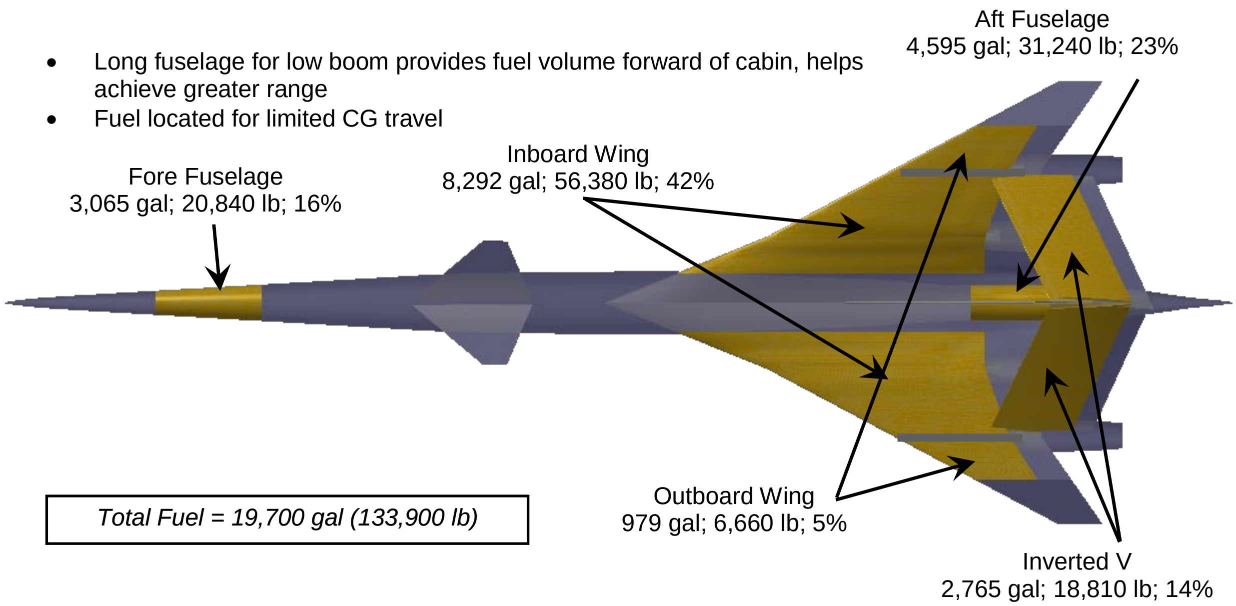
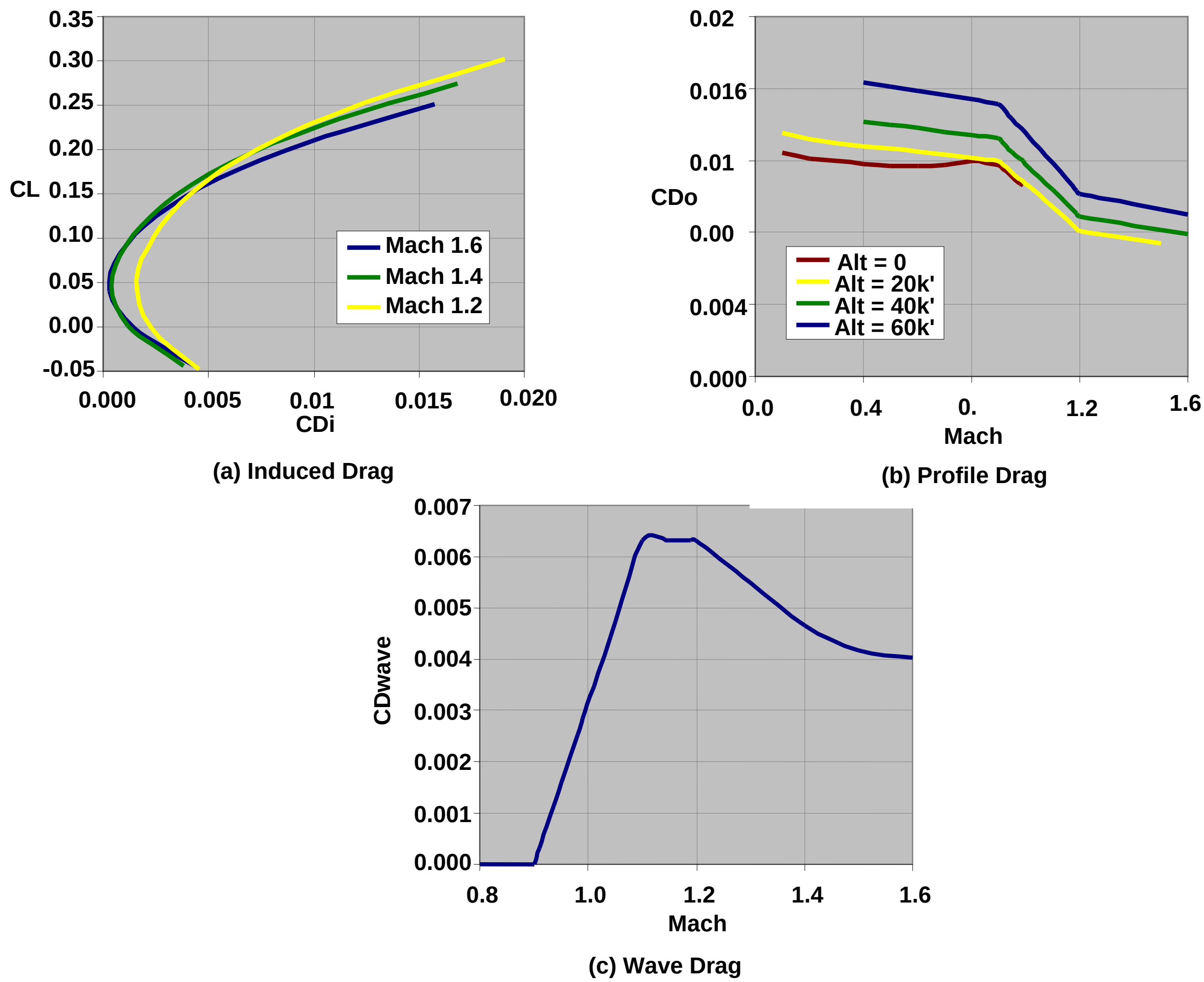


Figure 40.—Fuel packaging for final configuration.

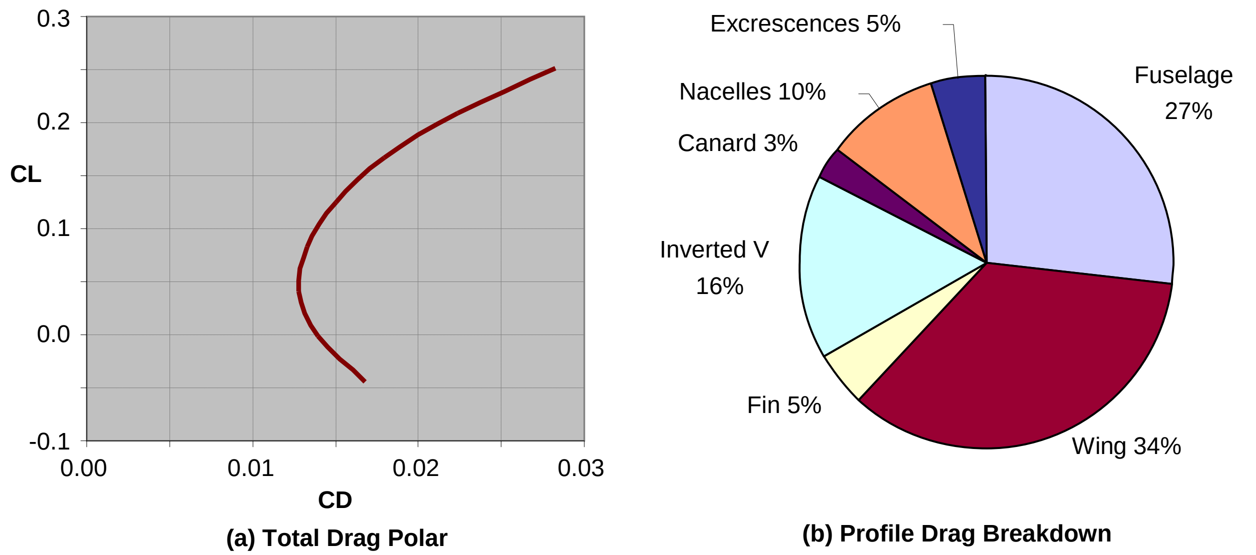


(a) Induced Drag

(b) Profile Drag

(c) Wave Drag

Figure 41.—N+3 cruise drag components.



(a) Total Drag Polar

(b) Profile Drag Breakdown

Figure 42.—Aerodynamic performance at Mach 1.6, 50,000 ft.

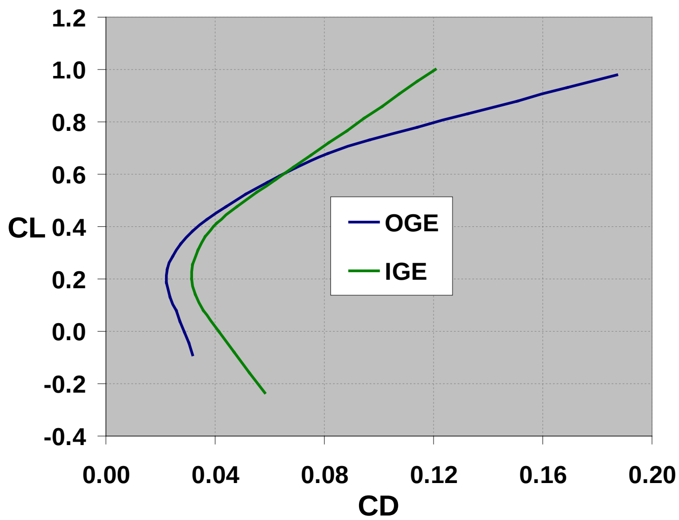


Figure 43.—Takeoff drag polars.

Structure	**75,275**	**Operating Items Weight**	**10,212**	
Wing	23,944	Std. Oper. Items (Crew+Gear)	3,663	
Fuselage	20,733	Outfitting Allowance	5,000	
Canard	1,246	Unusable Fuel and Oil	1,549	
Inverted V Tail	5,599			
Vertical Fin	2,110	**Payload**	**21,500**	
Nacelles	10,408	Passengers	17,000	
Landing Gear	11,235	Baggage	4,500	
Propulsion	**22,050**	**Fuel**	**133,928**	
Engines	19,482	Inboard Wing Tank	56,382	
Accessories	412	Outboard Wing Tank	6,656	
Fuel System	2,156	Inverted V Tail Tanks	18,808	
		Fore Fuselage Tank	20,838	
Systems	**15,264**	Aft Fuselage Tank	31,243	
Flight Controls	3,375			
APU	877	**Manufacturer's Empty Weight**	**119,344**	
Instruments	266	**Operating Empty Weight**	**129,556**	**45.5%**
Electrical/Avionics	4,483	**Zero Fuel Weight**	**151,056**	
Hydraulics	3,189	**Fuel Weight**	**133,928**	**47.0%**
Furn./Equip./Handling	588	**Payload Weight**	**21,500**	**7.5%**
Environmental Control	2,486	**Takeoff Gross Weight**	**284,984**	
6% Empty Weight Margin	6755			

Figure 44.—Sized N+3 configuration weights statement.

3.3.4 Weights

3.3.4.1 Description

Weights of the sized N+3 configuration were based on LM Aero parametrics.

3.3.4.2 Results

A summary weights statement of the sized N+3 configuration appears in Figure 44.

3.4 System of System Analysis (WBS 3.6)

3.4.1 Purdue

Following N+3 configuration sizing, LM provided aircraft performance data to Purdue University, which performed a system-of-systems analysis of the vehicle's effects on a future civil air transport system (ATS). The goals of this study were to quantify the SSTs' contributions to and impacts on the ATS as a whole.

3.4.1.1 Description

Purdue's system-of-systems study predicted the effects of adding SST's to an all-subsonic fleet, beginning in 2030 and occurring at a constant annual rate through 2050. The baseline fleet, to which SST's were added, consisted of six subsonic aircraft, each in service in 2005 and representing a unique capacity class, ranging from 20 seats (Embraer ERJ145) to over 300 (Boeing 777–200ER).The model ATS included those routes in the WWLMINET Network (Ref. 16) that either originated or terminated in the U.S., thereby including 180 airports. Passenger demand was modeled by increasing 2005 levels by a fixed annual percentage. Different demand scenarios were created by varying the yearly rates of STT addition to the fleet (either 25 or 50) and passenger demand growth (from 1 to 5 percent in 1 percent increments).

For each future scenario, defined by specific levels of passenger demand and SST availability, Purdue investigated two allocations of aircraft: one maximized ATS productivity (passenger * knots), the other block-hours saved by SST passengers. The latter was calculated by comparing the SST's block time on each route it flew to that of a subsonic aircraft. Fleet-wide carbon dioxide (CO_2) and nitrous oxide (NOx) emissions were computed to gauge SSTs' environmental impacts on the ATS. Finally, fleet direct operating costs (DOC) were calculated based on estimates of each aircraft's DOC.

3.4.1.2 Results

Initial studies established the trade space between SST performance benefits and environmental impact, such as that illustrated in Figure 45. This graph shows the maximum productivity achievable as an allowable limit of CO_2 is increased; they are shown in billions of passenger*knots and billions of lb, respectively. The values listed correspond to year 2050 in a scenario in which aircraft were allocated to maximize productivity based on 3 percent annual passenger demand growth SST's added at 50 per year starting in 2025.

Subsequent studies investigated the increase in fleet DOC attributable to the SST's as well as the routes to which they were assigned and the number of passengers on them. Figure 46 illustrates this DOC difference for a scenario based on 3 percent annual passenger demand growth. The left-hand graph (Figure 46(a)) is a plot of DOC versus year for fleets in which SST's are added at 25 and 50 per year starting in 2025; DOC growth of an all-subsonic fleet is also included for comparison. The increase in DOC attributable to the SST's was calculated as the difference between the DOC of a fleet including them to that of the baseline (all-subsonic) fleet. Figure 46(b) shows this DOC increase versus year from 2025 to 2050. The nonsmooth nature of the DOC increase is due to their being allocated in different numbers and to different routes as they comprise more of the ATS fleet.

Figure 46 depicts DOC in millions of 2005 dollars and includes estimates of crew, landing and navigation fees, maintenance, depreciation, interest, and insurance costs based on a 1995 NASA report (Ref. 17). Given the sensitivity of DOC to the underlying assumptions and the volatility of individual costs (esp. fuel), further research is necessary to refine these cost estimates and gauge them against the value of passengers' time saved by using SST's.

Figure 47 contains information about the use of SST's in the air traffic system. The left-hand plot, Figure 47(a), shows the number of routes to which SST's were allocated and the number of passengers on them for the same scenario (3 percent annual passenger demand growth). The left-hand axis corresponds to the former, while the right-hand axis corresponds to the latter and was based on an assumption of 90 passengers per flight.

Finally, Figure 47(b) shows the average range of SST routes within the ATS. While the routes and ranges varied as demand grew and more aircraft were added to the system. The average range was consistently between 3,000 and 5,000 nmi. This indicates that aircraft meeting the N+3 range goal of 4,000 nmi will likely be well-suited for incorporation into the civil air transport system.

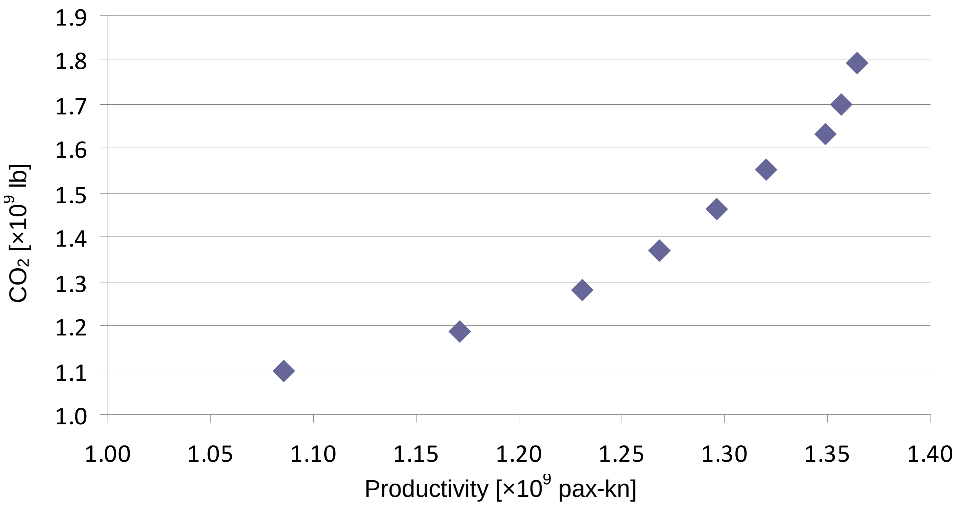
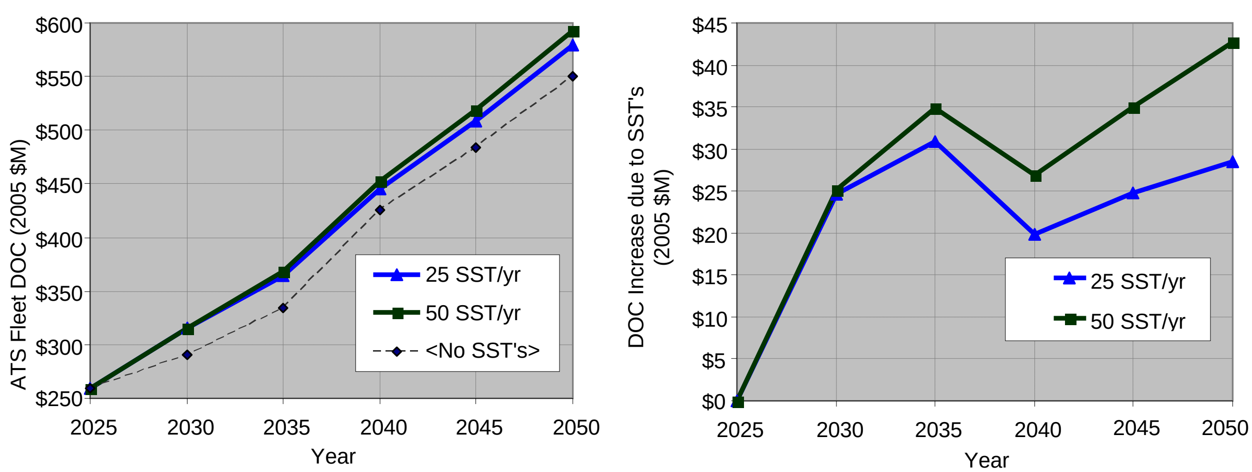


Figure 45.—ATS productivity versus carbon dioxide.



(a) DOC versus Year

(b) DOC Increase due to SST's

Figure 46.—DOC growth and increase attributable to SST's.

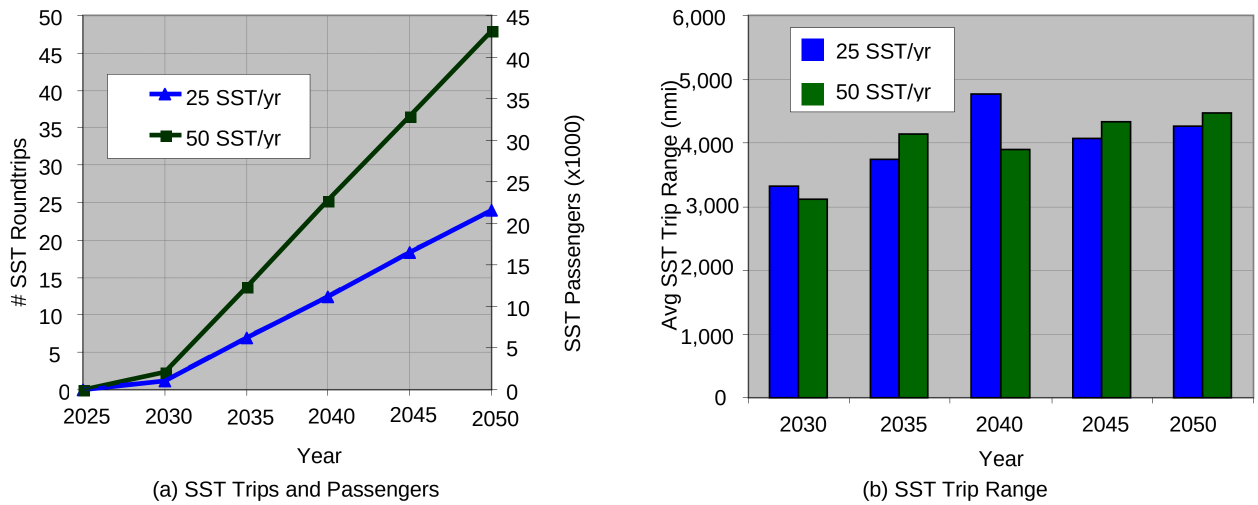


Figure 47.—SST trips, passengers, and range within ATC.

3.4.2 Transportation and Security Solutions

The impact of N+3 Supersonic Transports (SST's) on airport terminal and en-route environments was investigated by LM Transportation and Security Solutions (LM TSS). This study assessed SSTs' impact on airport and airspace capacity requirements, their interaction with subsonic traffic during arrival, departure, and subsonic climb and descent phases, and consequent increases in air traffic complexity and controller workload.

3.4.2.1 Description

LM TSS's studies were based on the RAMS Plus air traffic modeling and simulation environment, which simulates traffic from a macro-to-micro level (gate-to-gate movements) based on the flights, sectors, airports, airspace and air traffic, controllers, procedures that define an ATC environment. This tool enabled an assessment of 4–D trajectory based operations in a future ATC environment in which controllers maintained required separation standards. The study was conducted as follows:

1. Potential routes for N+3 SST operation were identified.
2. Target SST Introduction date and anticipated supersonic operations were based on traffic forecasts
3. Modeled en-route air traffic, airport and terminal area operations.
4. Analyzed demand, conflict, workload and complexity assessment metrics using the RAMS Plus simulation tool.
5. Assessed new processes and aircraft types in the future National Air Transportation System (NAS).

3.4.2.1.1 SST Climb Profiles

The N+3's climb profile is defined by segments 2 to 6 of the sizing mission described in Section 3.2.2.2. They are expected to climb in a similar manner to standard aircraft (Boeing 777, Airbus 340 etc) during the initial climb out from the runway to around 10,000 ft. On reaching 10,000 ft the aircraft will level off and undergo a first acceleration leg lasting around 80 sec during which the aircraft will accelerate from around 290 to 450 kn.

Following the initial acceleration phase, the aircraft will resume its climb and continue to accelerate through the lower/middle airspace to reach 535 kn at around 24,000 ft. There it will level off a second time and enter the second acceleration phase which lasts approximately 125 sec, during which the aircraft will accelerate up to 719 kn (Mach 1.09). Thereafter the aircraft will climb rapidly towards its expected cruise altitude of 61,000 ft, accelerating during the entire climb portion to reach its top speed of 917 kn (Mach 1.6).

A comparative analysis was done to ensure that the N+3 profile generated by RAMS Plus is consistent with the one developed by LM-Aero. Figure 48 and Figure 49 show that the two profiles are closely calibrated. Also for the purposes of comparison a representative climb profile for subsonic transport (A320) is depicted. As can be seen in Figure 51, from the performance standpoint the trajectory of N+3 intersects with conventional aircraft as N+3 climbs to supersonic speed and final cruise altitude. This could potentially create additional conflict as the flight overtakes the slower, conventional aircraft at higher flight levels.

Figure 51 indicates that RAMS Plus profile is closely calibrated with conceptual vehicle designed by LM Aero. It also shows comparison between N+3 and subsonic climb profiles.

3.4.2.1.2 Supersonic Descent Profiles

The N+3's descent phase corresponds to segments 9 to 11 of the sizing mission (Section 3.2.2.2). LM SST's analysis was based on a constant rate of 3500 ft/min from the end of cruise (this rate was subsequently adjusted to 4000 ft/min to maximize mission range). The aircraft decelerates rapidly during the initial descent between the Cruise level and the entry to the transitional (middle) airspace around 36,000 ft, decreasing from supersonic cruise at 719 to 470 kn around 36,000 ft. Below that level, the AST will decelerate at a rate similar to that of conventional aircraft.

Comparative analysis ensured that the N+3 profile generated by RAMS Plus was consistent with the sizing mission; Figure 50 and Figure 51 show they are closely calibrated. A representative descent profile for subsonic transport (A320) is also depicted for comparison.

Figure 50 indicates that RAMS Plus profile is closely calibrated with N+3's mission profile. It also shows comparison between N+3 and subsonic descent profiles.

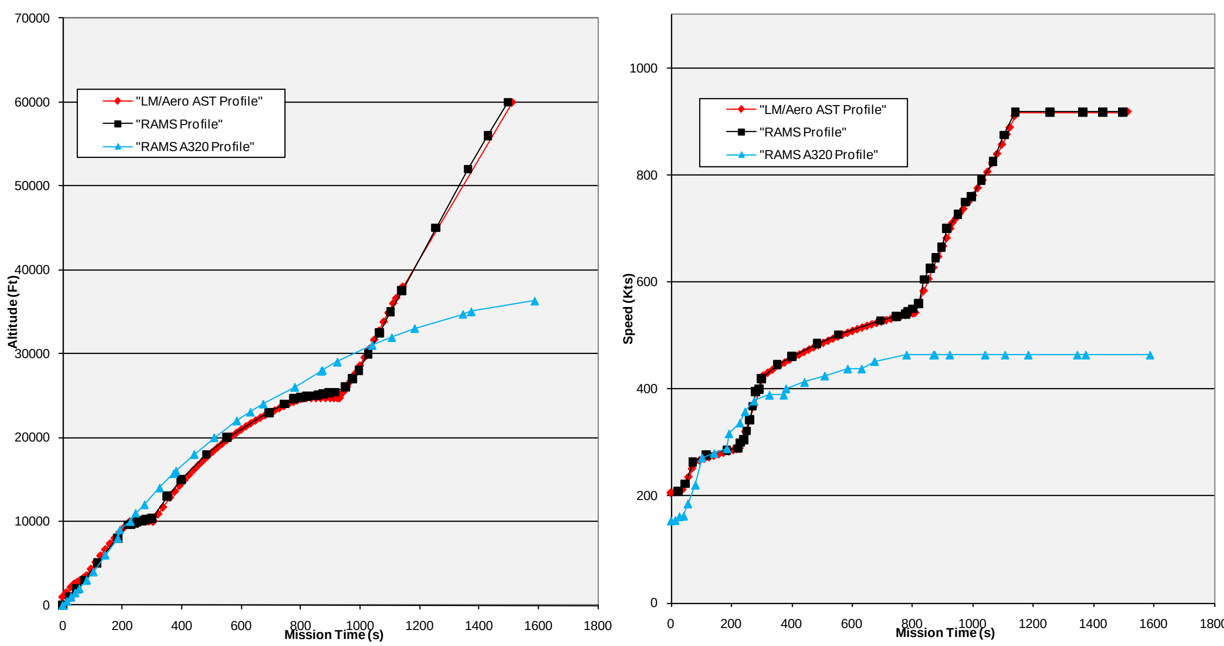


Figure 48.—N+3 climb profile.

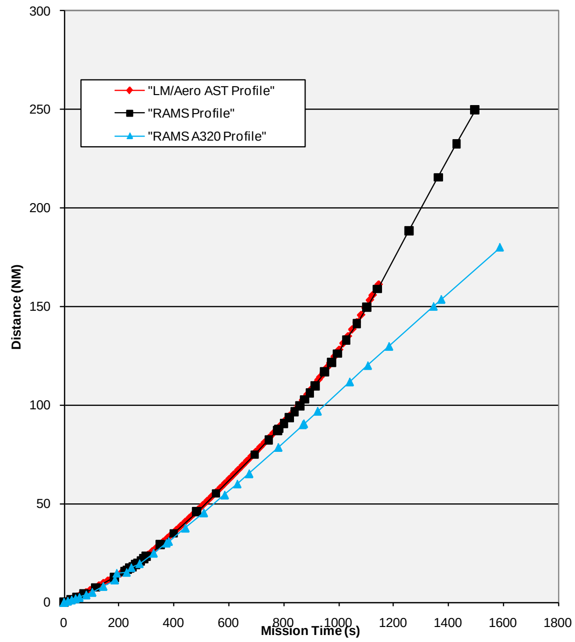


Figure 49.—N+3 mission profile (climb phase).

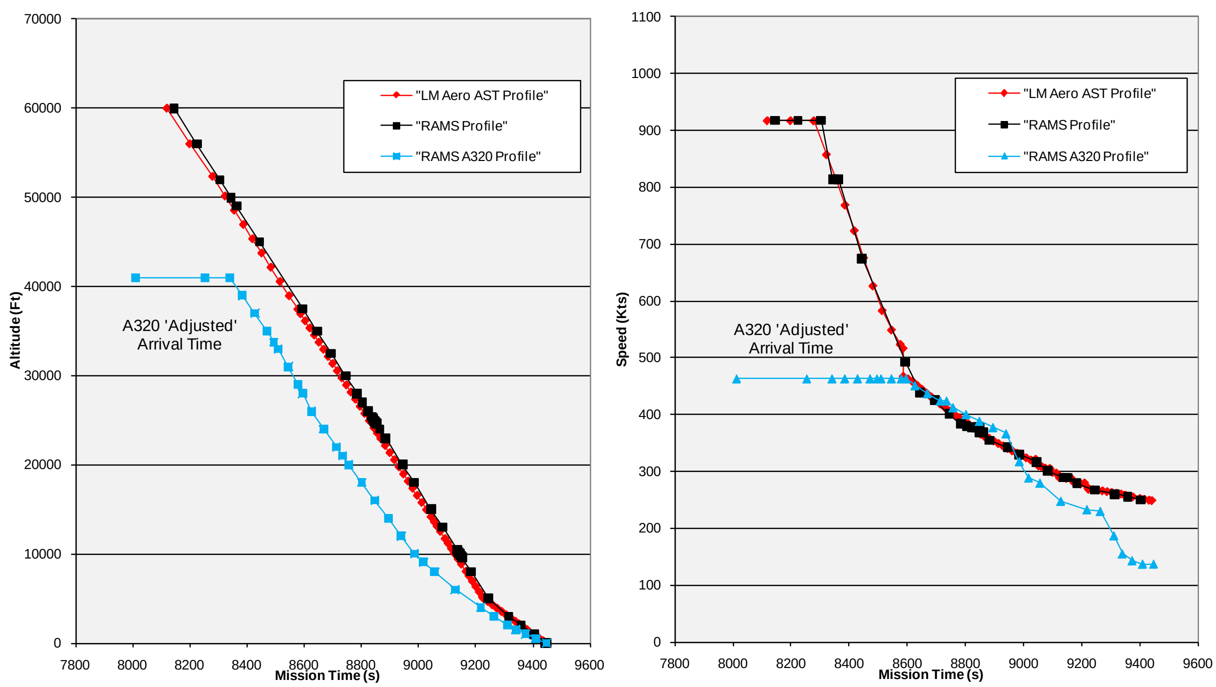


Figure 50.—N+3 descent profile.

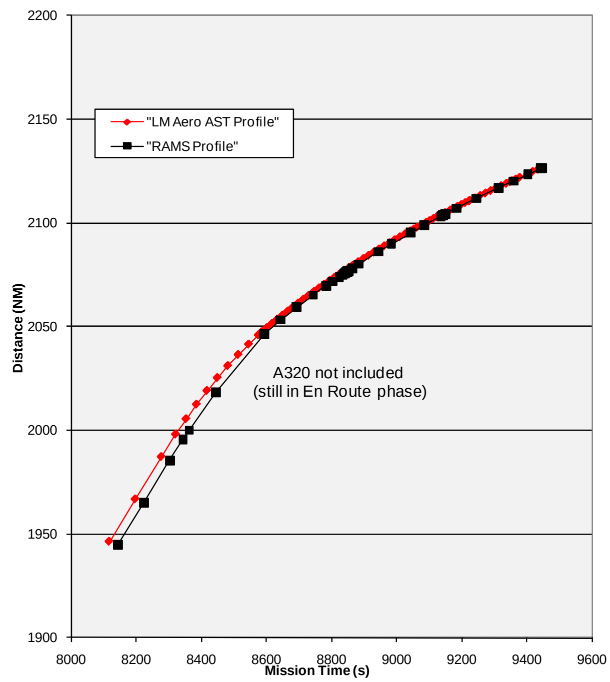


Figure 51.—N+3 mission profile (descent phase).

3.4.2.2 Potential SST Routes

With expected technology improvements in the environmental and fuel efficiency of the N+3 SST, it is anticipated that the aircraft is not constrained to fly only oceanic routes and can fly supersonic over land. This makes the aircraft ideally suited for economically viable domestic routes and major international routes. Additionally, the multi-mach N+3 aircraft will be capable of flying at speeds of up to 2 Mach, will have a maximum range of 6000 nmi, and can carry up to 200 passengers.

Research from the 1980 U.S. OTA report on the Impact of Advanced Air Transport Technology, Chapter 3 (Variables Affecting a Supersonic Transport Market) (Ref. 1) suggests that “an aircraft’s product is passenger (/ cargo) miles”. On this basis N+3 can improve productivity using faster aircraft with the same number of ‘seats’ but with significantly shorter flying time thus achieving higher passenger miles per hour than a conventional operation. Additional factors also come into play, particularly relating to economic or social factors for key city-pairs or flight operations. For the purpose of this study it was decided to constrain the route allocation based on the aircraft productivity measure of passenger miles per hour, without distinguishing different passenger value.

In order to evaluate the value of operations, a passenger factor was produced comparing the passenger loads for two N+3 operations (a return trip) against a one-way conventional operation to produce a passenger productivity factor. In addition to the time for a return trip, a sufficient turn-around window of 40 min was included in the calculation for the N+3.

The passenger factor for any city pair could be calculated as follows:

- PaxFactor = [[2* SS_time] + 40-min] * SS_Pax_load / [Conventional_Time] * Conventional_Pax_load
- PaxFactor = Passenger factor
- SS_time = Time taken by supersonic transport between city pair
- SS_Pax_load = Supersonic passenger load
- Conventional_time = Time taken by conventional aircraft between city pair
- Conventional_Pax_load = Conventional passenger load
- 40 min = Supersonic turnaround time

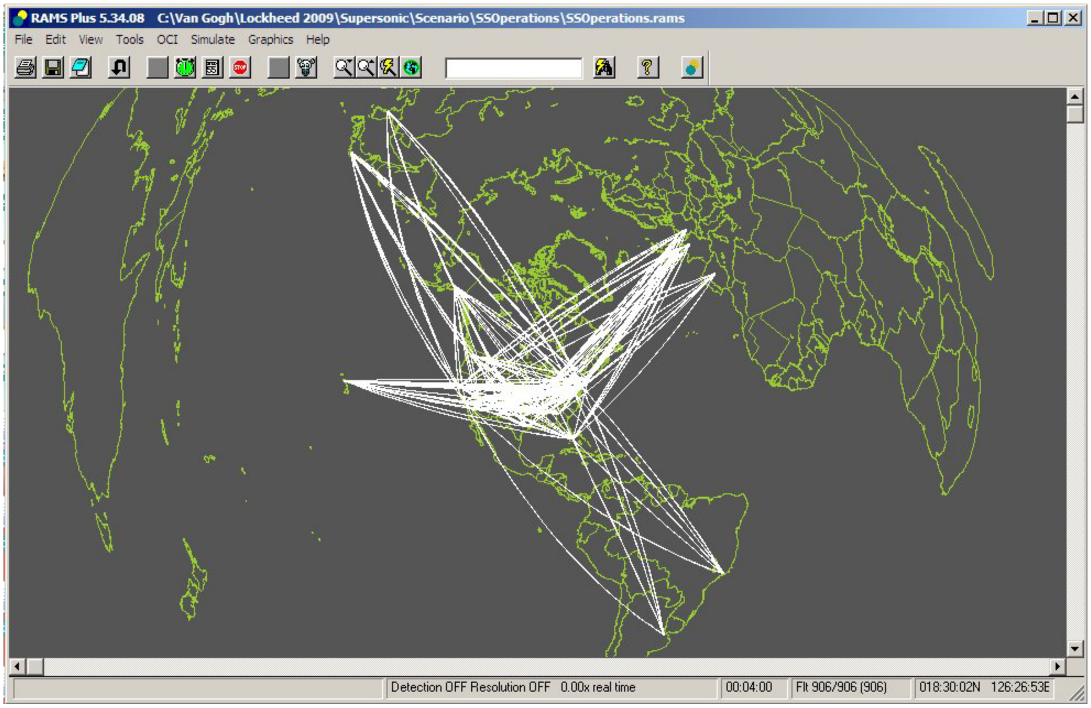


Figure 52.—Potential N+3 route network.

As shown in Figure 52, the city-pairs (domestic and international) with the best passenger factor were selected based upon the results of the calculations. Once the city pairs were identified, arrival and departure times were adjusted to allocate suitable supersonic arrival and departure banks based on local departure and arrival times. Twenty major U.S. Airports and 11 international destinations were identified for potential N+3 operations. Not all of the possible origin-destination pairs are viable for N+3 due to shorter route distance. The productivity of N+3 reduces with the shorter route distance to below 60 percent at 1000 nmi due to time lost on surface, climb and descent (Ref. 1). For example Los Angeles to Newark and San Francisco to Newark are suitable but operations between Los Angeles and San Francisco are not. For each viable city-pair, between four and six daily operations are included depending on the arrival/departure banking calculations (adapted to local times) and N+3 journey time.

3.4.2.3 Modeling Air Traffic Operations

3.4.2.3.1 Scenario

To generate the scenario, Aircraft Situation Display to Industry (ASDI) data from August 24, 2007, containing arrivals and departures from top 35 U.S. airports was used as a starting point. ASDI is a subset of the Enhanced Traffic Management System (ETMS) and contains flight data from all scheduled carrier and business jets. To create a traffic scenario representative of 2030 traffic levels, additional operations were added based on the 2 percent annual growth rate predicted in MITRE’s Fleet Forecast. The N+3 operations were included based on the methodology described above. The resulting traffic sample included 906 N+3 supersonic operations among the 44,000 total flights (subsonic and supersonic, domestic and international) on a single day considered in the study.

Figure 53.—Sector adaptation for U.S. airspace in 2008.

3.4.2.3.2 Airspace and Procedures

The airspace considered for these experiments is based on the 2008 NAS adaptation and contained 960 En Route sectors as can be seen Figure 53. No assumptions about future airspace changes or modifications are considered in the scope of this study, for example big airspace (Ref. 18) that aim to consolidate terminal area with en route arrival sectors. In the terminal area we assumed precision RNAV (P-RNAV) and RNP procedures will be in use. The N+3 will be capable of executing P-RNAV and will fly great circle distance between city pairs. **Area Navigation** (RNAV) is a method of Instrument Flight Rules (IFR) navigation that allows an aircraft to choose any course within a network of navigation beacons, rather than navigating directly to and from the beacons. This can conserve flight distance, reduce congestion, and allow flights into airports without beacons.

It was assumed in the study that NextGen airport management technology will be in place to permit traffic to achieve the airport demand being forecasted, through a combination of precision navigation, RNAV sequencing and merge capabilities, and Time/trajectory Based Flow Management tools. Given that supersonic traffic performs like conventional traffic in the arrival and departure phases, it was concluded that no special procedures would be required in the airport and terminal regions.

3.4.2.3.3 Air Traffic Controllers

Each of the En Route control sectors has a single Radar (R-Side) Controller allocated in the simulation. Planning Controllers or Assistants are not taken into consideration in the studies.

3.4.2.3.4 Separations

Each ATC Controller in the model is allocated 5 nmi separation requirements and flight level separation using RVSM separation standards. The RAMS Plus simulation tool provides a fully adaptable set of ATC rules that can be used to provide separation assurance within any airspace volume, as well as to manage ATM-based flow/sequence management in airspace and arrival/departure/airport systems. Controller rules are allocated to each and every control element in the system, and in the airborne phases, uses projected 4–D airspace tubes to predict when conflicts occur. A forward-chaining production rule expert system provides the tool with a set of potential resolution actions which have been tuned to represent generic Air Traffic Controllers. In the event that separation problems are identified in the simulation involving supersonic and nonsupersonic traffic, the model has been tuned to allow supersonic aircraft to continue unimpeded to mimic performance based services concept.

3.4.3 Results

Analysis was performed on an air traffic simulation based on 2030 projected traffic levels including N+3 aircraft. Additional supersonic transports are added through 2050 would be expected to yield additional arrival and departure operations. The results are described on the basis of phase of flight.

3.4.3.1 Airport and Terminal Area Operations

Despite a slight increase in the number of airport operations due to the introduction of N+3 traffic, we do not anticipate that they will have any significant impact on the airport capacity as their performance is very similar to subsonic transport. Research in the design of N+3 conducted by LM Aero suggests that they will fall into either medium or heavy wake category for runway separation standards. They will not have to be procedurally separated from other subsonic traffic in the terminal area as it is anticipated that N+3 will be equipped with precision—RNAV and capable to execute optimized arrival and departure procedures in the terminal area. In the arrival phase, N+3 will exploit advanced NextGen sequence and merge capabilities and perform in the same way as conventional traffic. Similarly, in the initial departure phase (up to 10000 ft) the N+3 traffic will operate with similar characteristics as conventional aircraft.

Since a subsonic operation might be replaced by 2 or 3 N+3 operations (the journey time is close to half in many cases) the arrival and departure rates increase slightly over the 24-hr period, particularly during peak arrival and departure periods.

A sliding view of departure demand is shown in Figure 54 and Figure 55 for selected U.S. airports where supersonic operation was defined. In both figures, blue bars represent conventional aircraft and orange represent N+3 operations. For example, the departure rate shown at 10:40 represents the number of departures for the period from 10:40 to 11:40 Zulu. As can be seen in most cases, the introduction of N+3 aircraft will require some additional departure capacity at major U.S. airports during the peak hours of conventional operations. The general trend suggests that most N+3 departures are scheduled for early morning and will utilize unused airport capacity as during that time the demand for conventional operations is relatively low. An exception was Honolulu airport (HNL) where introduction of N+3 will require a higher departure capacity during the peak hours of conventional traffic.

Similar to departure demand, a sliding view of arrival demand is shown in Figure 56 and Figure 57 for selected U.S. airports where supersonic operation was defined. Again, the blue and orange bars in both figures represent conventional and N+3 aircraft operations, respectively. For example, the arrival rate shown at 10:40 represents the number of arrivals for the period from 10:40 to 11:40 Zulu. As can be seen in most cases, the introduction of N+3 aircraft will require minimal additional arrival capacity at major U.S. airports with exception of HNL where higher arrival capacity might be required.

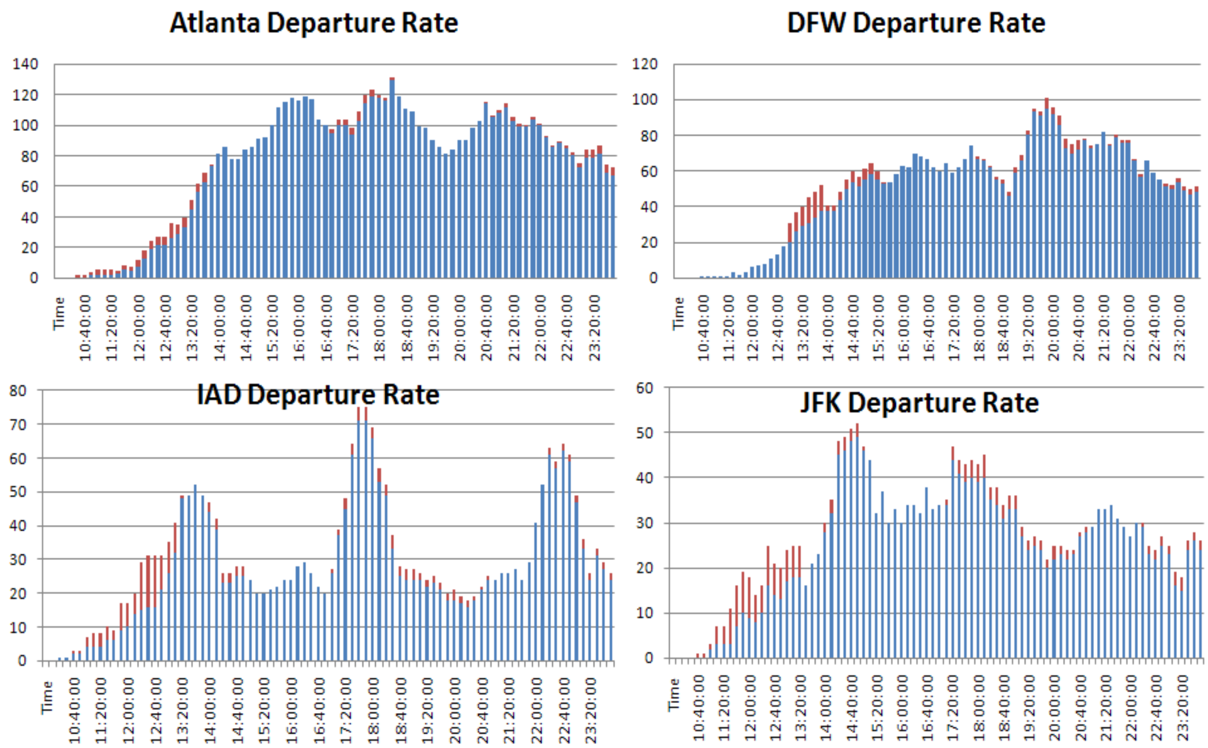


Figure 54.—Departure rate for selected U.S. airports. (Blue bars represent conventional aircraft and orange represent AST operations.)

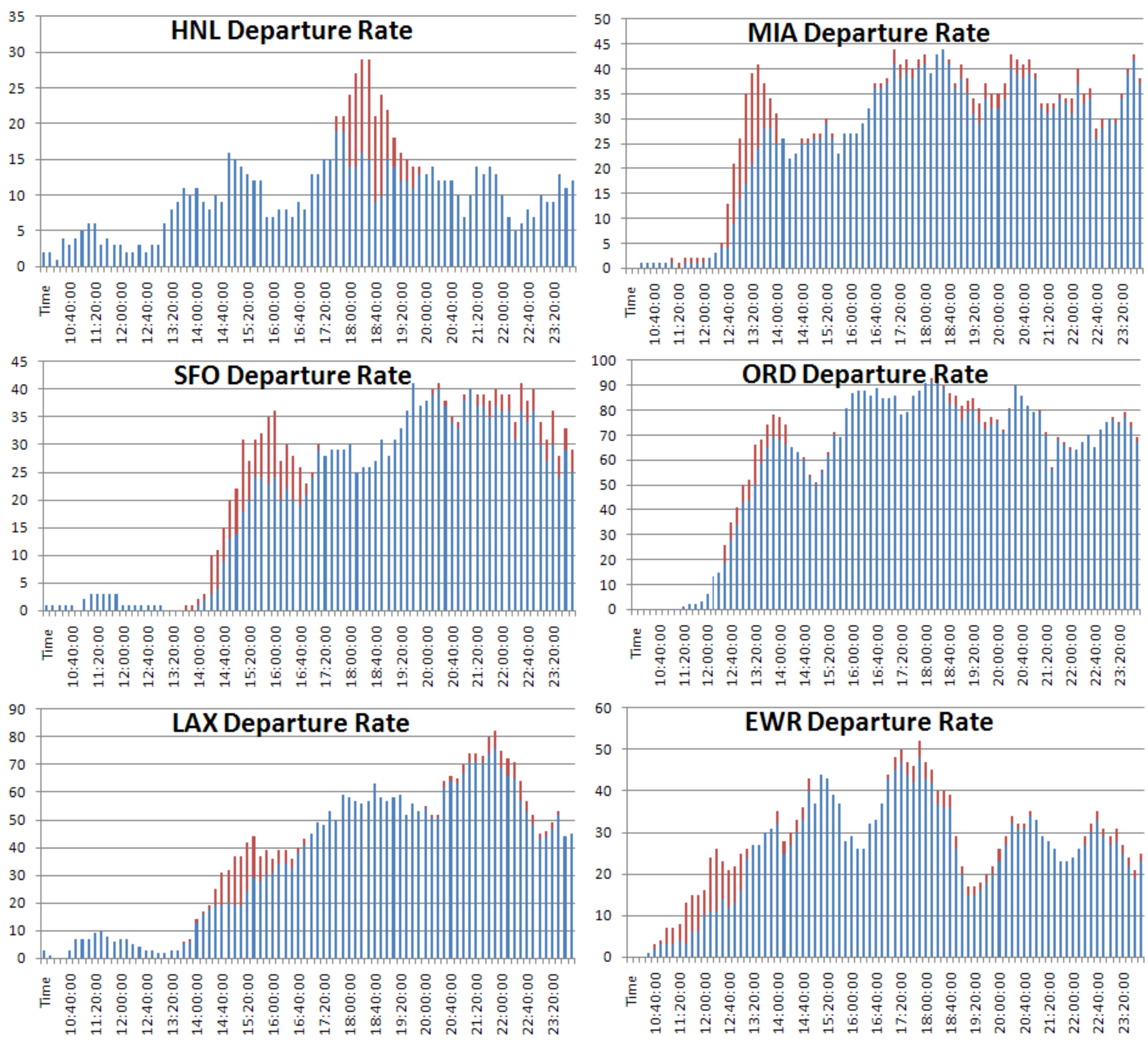


Figure 55.—Departure rate for selected U.S. airports. (Blue bars represent conventional aircraft and orange represent AST operations.)

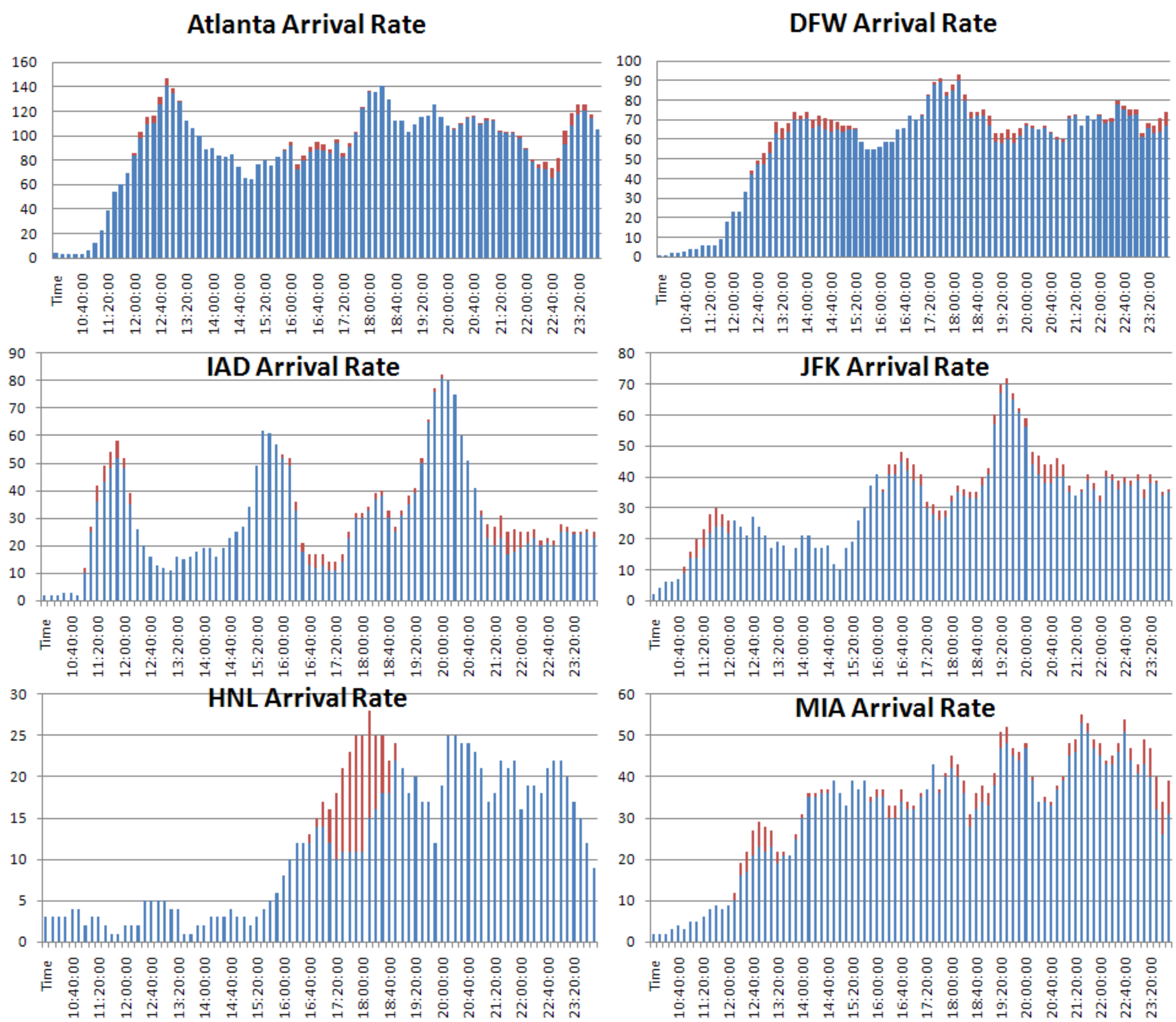


Figure 56.—Arrival rate for selected U.S. airports. (Blue bars represent conventional aircraft and orange represent AST operations.)

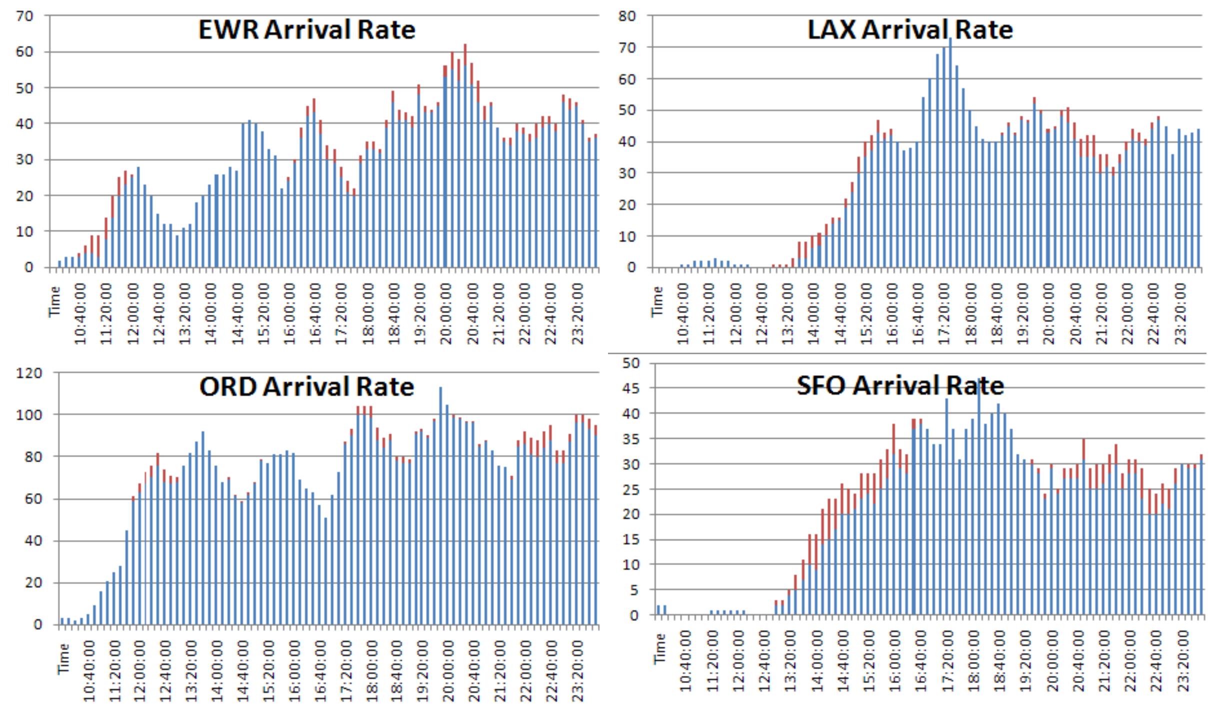


Figure 57.—Arrival rate for selected U.S. airports. (Blue bars represent conventional aircraft and orange represent AST operations.)

3.4.3.2 Transition Airspace Operations

Departures: The most significant impacts are expected to be observed in the transition airspace—in particular during four key phases of the supersonic flight profile in the departure phase:

Phase 1: At around 10000 ft the N+3 will level off and undergo the first acceleration phase (from 280 to 400 kn in around 75 sec).

Phase 2: Following the initial acceleration. N+3 will climb to a second transition level around 24000 ft.

Phase 3: At 24000 ft the aircraft undergo their second acceleration phase (from 500 to 750 kn in around 130 sec).

Phase 4: Steep supersonic climb to the ultra high airspace (typical cruise levels between 58000 and 61000 ft).

Figure 58 shows the route network analysis across different departure phases (identified using different colors) for N+3 aircraft departing from the NAS-CONUS using 4-D trajectories. The potential route network was described previously in Section 3.3.2.2 and assumes that great circle routings for N+3 aircraft are enabled by NextGen. Figure 59 shows route network for east coast. This figure suggests that the route network is well separated across Phases 1, 2 and 3, and departures from one airport do not interfere with the others. The result is consistent for even busy east coast multiplex airspace (multiple hub airports in close proximity, for example JFK, EWR, PHL, BOS and IAD).

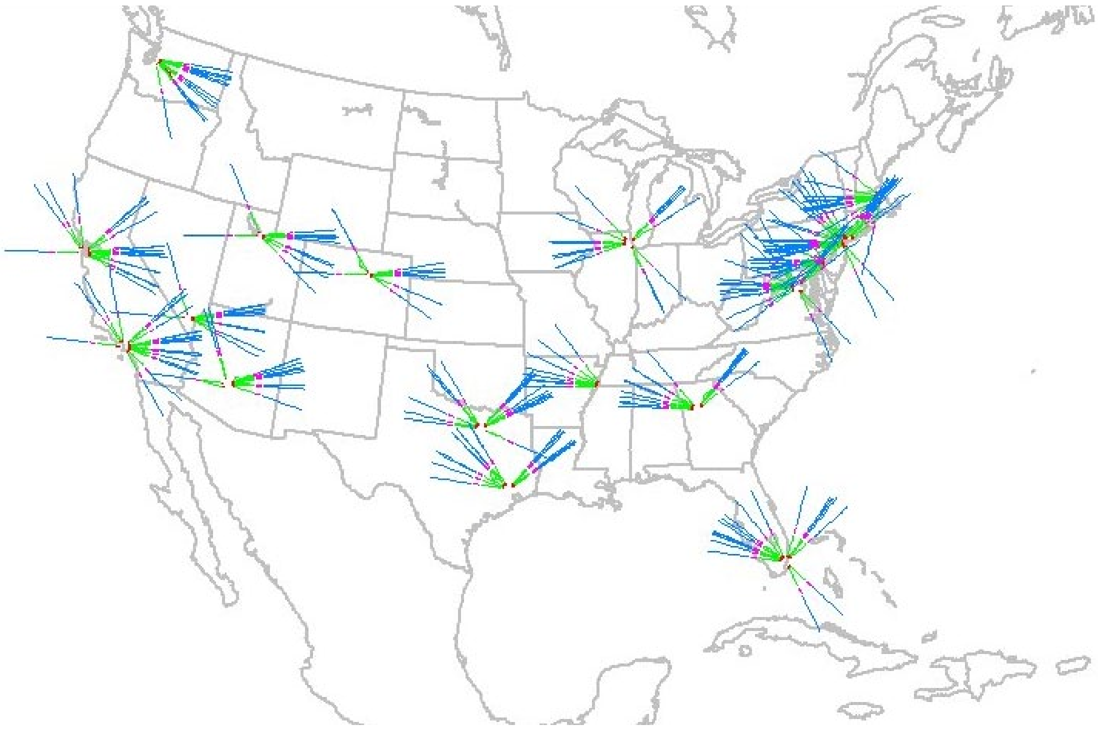


Figure 58.—AST route network analysis across four AST departure phases.

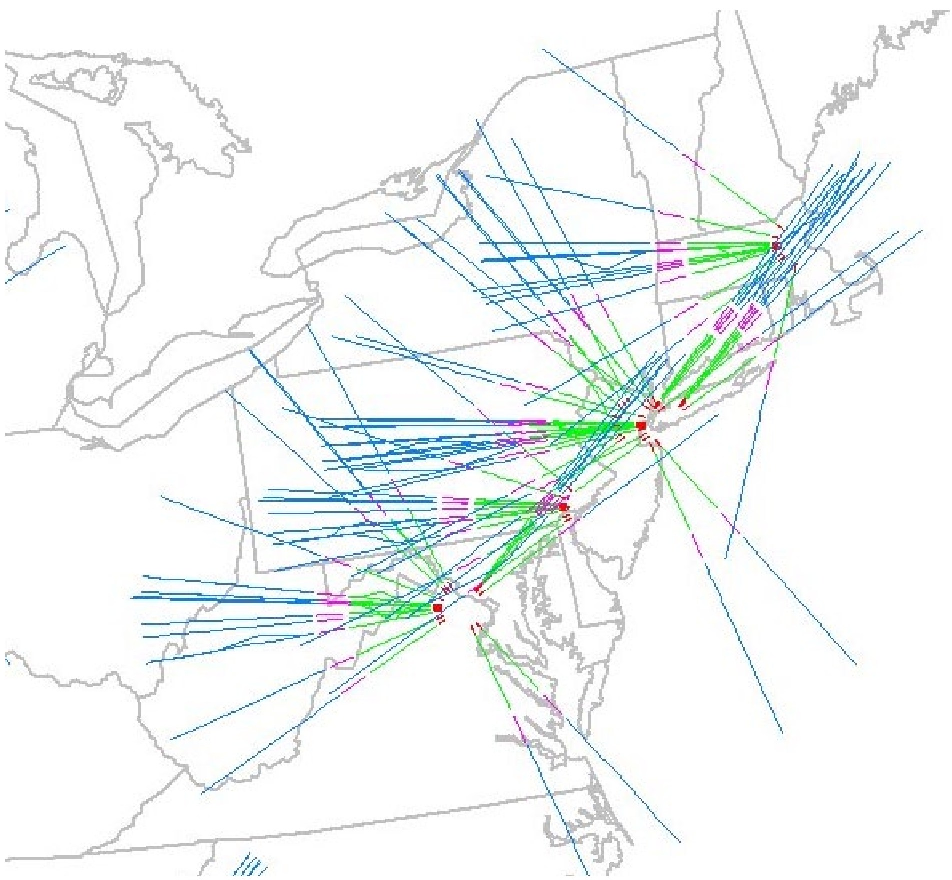


Figure 59.—AST route network for the East Coast.

3.4.3.2.1 Initial Acceleration Around 10,000 ft

Phase 1 acceleration occurs early in the N+3 profile at an altitude of 10,000 ft. As a result, during this phase the aircraft are in dedicated departure sectors which have managed throughput and present little or no risk of interaction with other traffic (flights follow one another out of the airport and are managed as a sequence into higher transition sectors). It is further assumed that in a NextGen environment, departure management capability such as Departure Flow Manager (DFM), currently in prototype stages, is available and assists controllers with the management of a variety of departure operations.

Phase 1 supersonic operations in the NAS are restricted to only 21 departure sectors. Figure 60 shows analysis of N+3 Phase 1 operations and conventional operations for selected departure sectors in New York, Los Angeles and Fort Worth. The Figure indicates that although some additional sector capacity will be required to handle N+3 operations, overall operations occur during periods with lower conventional traffic operations. This is due to slightly earlier departure times for N+3's to allow for multiple return operations across a 24-hr period. This suggests that capacity exists in the departure sectors to allow for the management of Phase 1 operation of N+3's. As can be seen the number of operations in these departure sectors are high as is typical of the low airspace and does not pose a significant problem as all flights are managed in a controlled sequence (unlike upper airspace where traffic can be mixed).

In order to evaluate the potential impact of air traffic complexity and controller workload due to N+3 operations, a RAMS Plus Controller workload model was used. The model is based on a set of generic ATC tasks generated during the simulation in response to discrete events that occur during the simulation (e.g. entry to an ATC sector will record a number of 'real-world' ATC tasks such as coordination, transfer of control, initial clearances etc.). Additionally task weights can be modified according to dynamic conditions. For example, a conflict between flights with a slow rate of convergence will require different workload than one with a high convergence rate. During the simulation, controller tasks of varying lengths are recorded at different times with metrics produced to evaluate the percentage loading in the next 60-min period every 15 min during the simulation.

Figure 61 shows mean and maximum air traffic complexity and controller workload for departure sectors impacted by N+3 operations. As can be seen, differences in air traffic complexity and controller workloads due to Phase 1 operations are minimal with average controller workload marginally higher across most sectors and small percentage increases in maximum percent load, which remains below 80 percent.

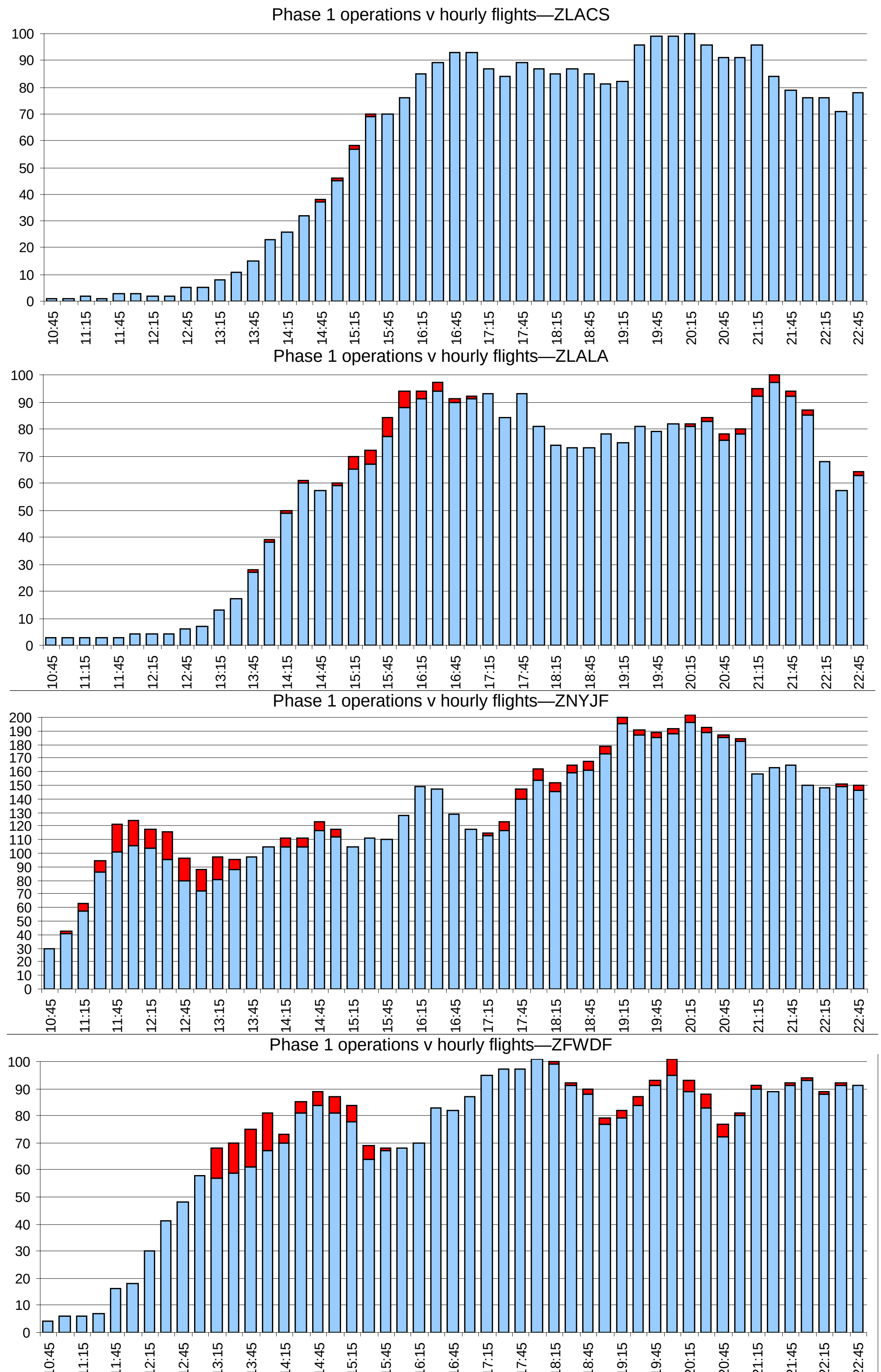


Figure 60.—Phase 1 analysis for selected departure sectors.

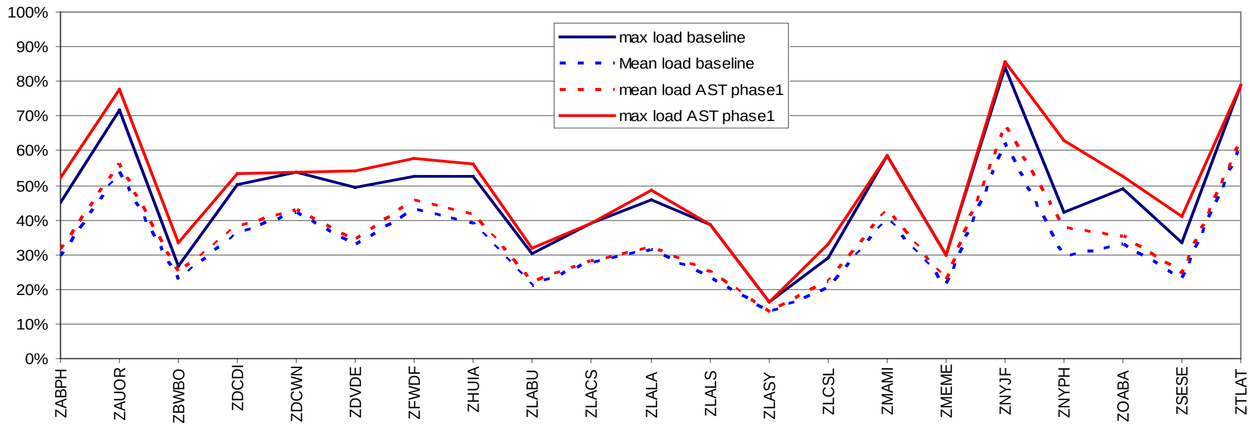


Figure 61.—Phase 1 air traffic complexity and controller workload.

3.4.3.2.2 High-Speed Climb to Supersonic Acceleration Flight Level

Phase 2 of the N+3 operations consists of a high speed climb following the initial acceleration phase between 10000 and 23000 ft. The climb is contained within the same low level departure sectors as Phase 1 operations. Analysis reveals that for all N+3 departures from U.S. CONUS airports, only a small percentage of departing traffic traverses more than 1 ATC sector during Phase 1 (acceleration) and Phase 2 (climb)—only 9 sectors more than the original 21 Phase 1 sectors have Phase 2 operations occurring in them. As shown in Figure 62, Phase 2 operations occur nearer periods of peak traffic load.

As is shown in Figure 63, workload impacts remain low during Phase 2 operations. Similar to Phase 1, workload is generally 3 to 5 percent higher, with some larger increases in peak workload relating to management of several N+3 departures during the same departure bank. As these aircraft are procedurally separated and do not intersect with one-another, managing the N+3 traffic during Phase 2 may cause marginal increase in controller workload. In Phase 2 operations air traffic remains organized as departure management systems are expected to assist in the sequencing and management of flights as they are delivered to the departure transition airspace.

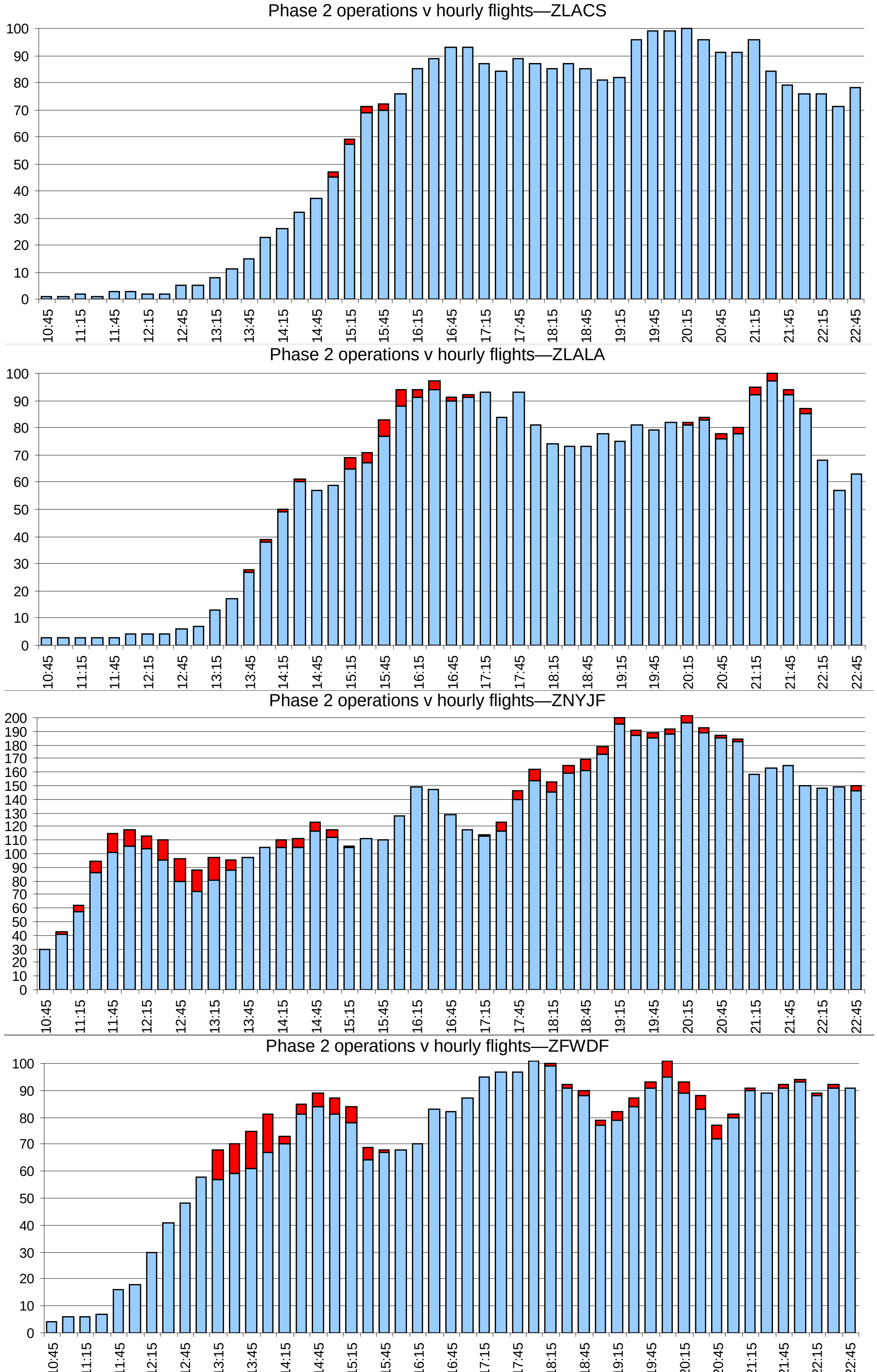


Figure 62.—Phase 2 analysis for selected departure sectors.

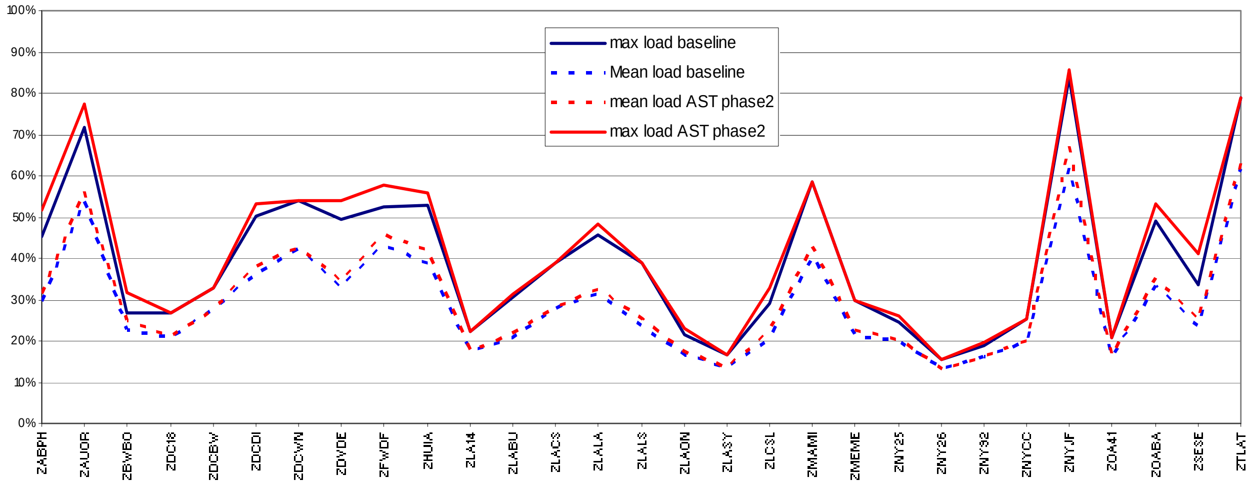


Figure 63.—Phase 2 air traffic complexity and controller workload.

3.4.3.2.3 Phase 3: Acceleration toward Supersonic at 24000 ft

At 24,000 ft the N+3 aircraft levels off and accelerates from 500 to 750 kn in around 130 sec. This particular phase occurs in mid level en route sectors and the Phase 3 operations are dispersed across several NAS sectors. Figure 64 shows analysis of selected sectors in the Boston, Washington DC, New York and Houston En Route ATC centers. As can be seen in the figure, N+3 operations do not significantly increase the number of operations in these sectors over conventional operation numbers.

Figure 65 shows air traffic complexity and workload for sectors that are involved in Phase 3 operations. The air traffic complexity and controller workload is considerably higher in these sectors with N+3 operations compared to the baseline. The increase in workload could be attributed to additional load involved with managing rapid acceleration of supersonic aircraft.

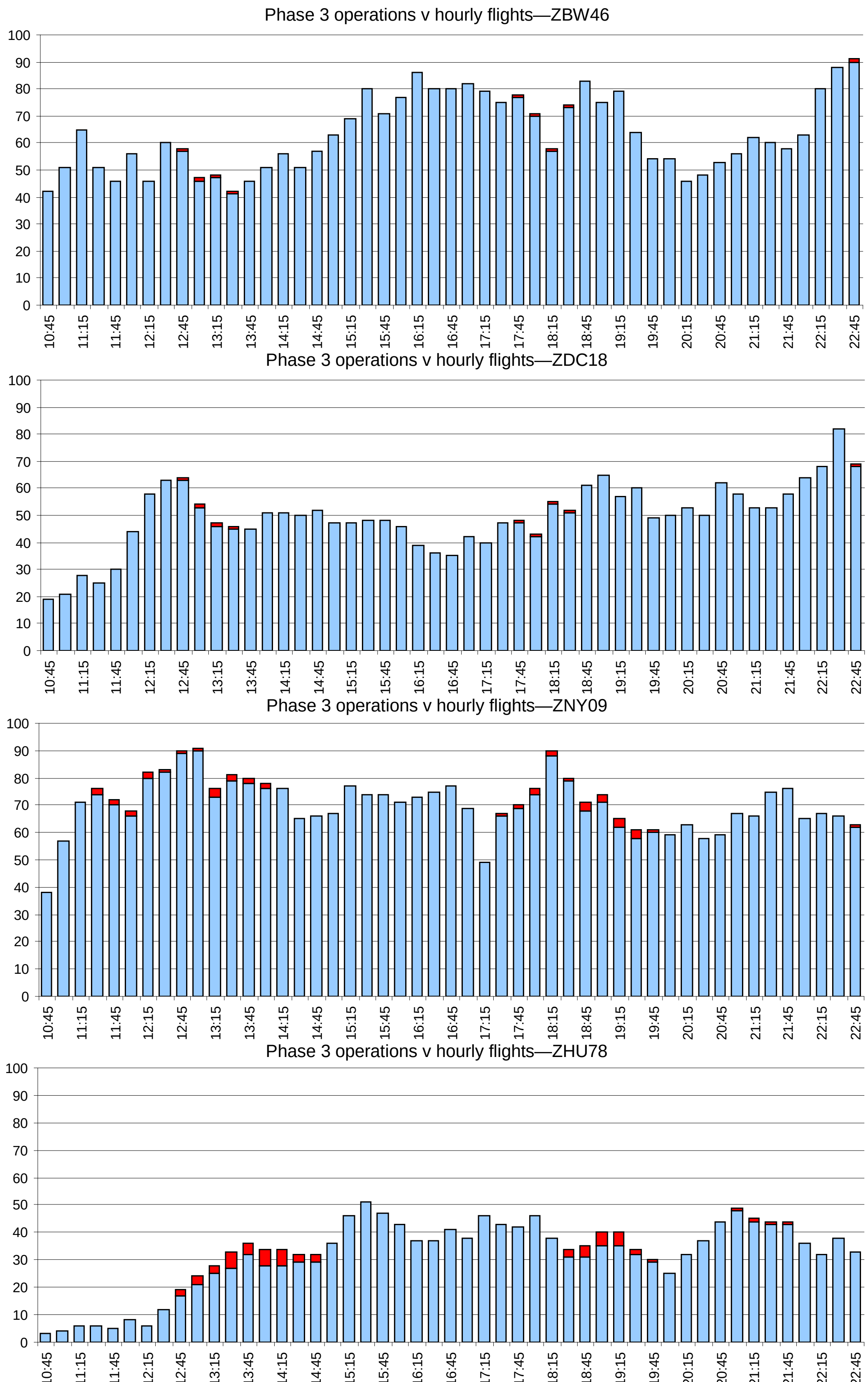


Figure 64.—Phase 3 analysis for midlevel en route sectors.

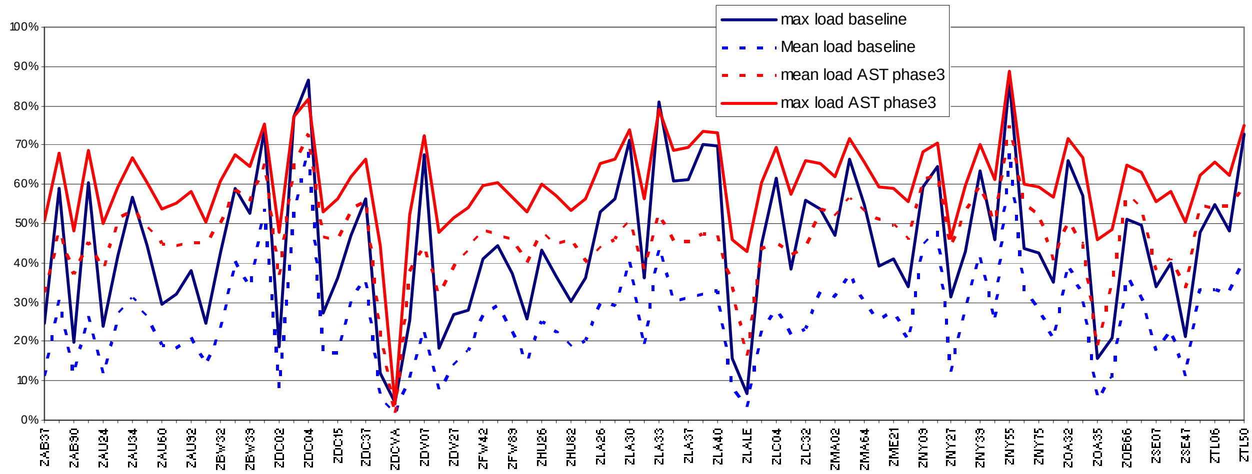


Figure 65.—Phase 3 air traffic complexity and controller workload.

3.4.3.2.4 Phase 4: Supersonic Climb to Cruise Flight Level

Following Phase 3 acceleration, the N+3 climbs at supersonic speeds to its cruise altitude. In this phase, it climbs through other flight levels occupied by conventional traffic flying at significantly lower speeds. Figure 66 shows controller workload across all sectors in which N+3 supersonic climb occurs. As can be seen, the workload is considerably higher in the scenario with N+3 operations compared to the baseline. The results are consistent with research in the area of air traffic complexity (Ref. 19) and suggest that situations involving overtaking aircraft can cause a greater level of complexity. Sridhar, Seth and Grabbe (1998) (Ref. 20) suggest that speed differences of greater than 150 kn from average speed of all aircraft in the sector increases complexity.

Analysis of conflicts between N+3 operations and conventional traffic was conducted during Phase 3 acceleration and Phase 4 supersonic climb phases. Figure 67 shows the number of conflicts identified during Phase 3 acceleration and Phase 4 supersonic climb using a standard 5 nmi separation. As expected, a majority of conflict situations involving the N+3 are found in the 34,000 to 39,000 ft. bands ("AST" in the figure title connotes "Advanced Supersonic Transport," or the N+3 aircraft). These flight levels are most commonly used as cruising altitude for conventional aircraft. A comparison with the current number of subsonic conflicts is suggested as an area for further investigation.

For the 12 hr period being considered in the scope of this initial study, conflict counts are relatively low, peaking just over 50. The conflict situations are further classified by conflict characteristics, crossing, in track, or opposite. While this is encouraging, it is felt that further detailed studies of the interaction between N+3 and conventional traffic in these flight levels would be of great benefit. It is also important to further evaluate the type and geometry of conflict as these factors have different impact on complexity and controller workload.

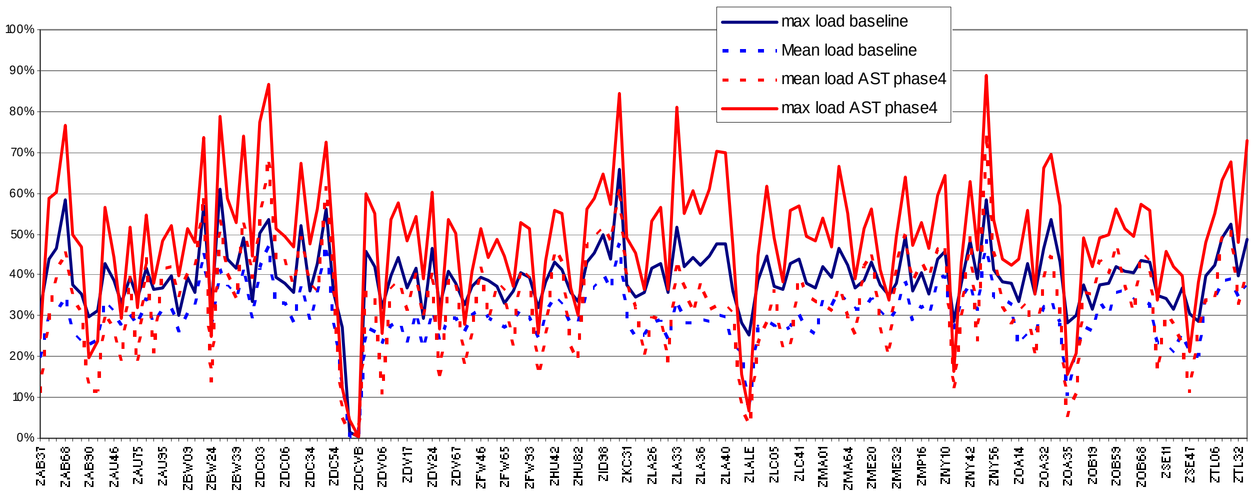


Figure 66.—Phase 4 air traffic complexity and controller workload.

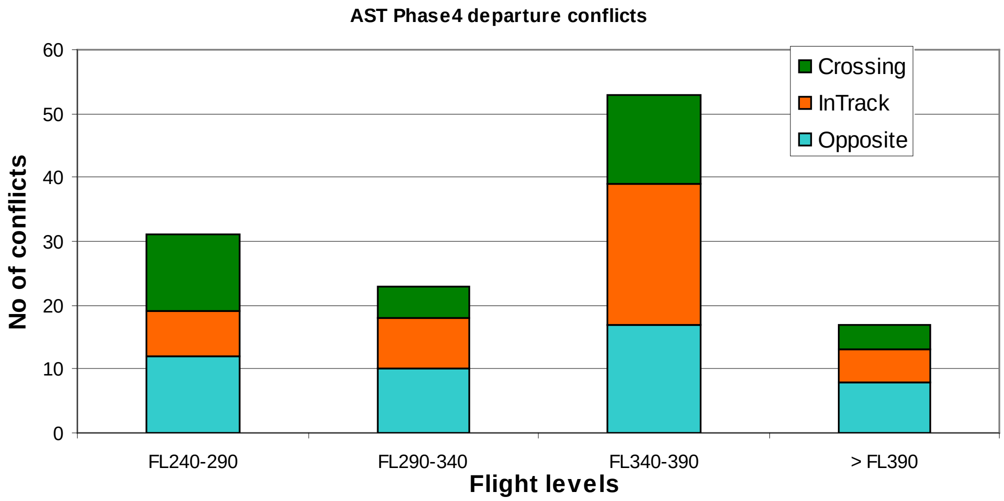


Figure 67.—Phase 4 conflict analysis.

3.4.3.3 En Route Operations—Phase 5

N+3's will use flight levels significantly higher than conventional traffic (over 50,000 ft) as their final cruise altitude. At these altitudes the traffic density is expected to be relatively low therefore no significant impact on operations is anticipated. ATC activities during this phase are also expected to be low. For these reasons a detailed analysis of N+3 operations was not attempted during this study; one is recommended as future work.

3.4.3.4 Arrival Operations—Phase 6

In the descent phase, N+3 will descend rapidly from its supersonic cruise, decelerating until reaching the more conventional flight levels around 36,000 ft with speeds similar to conventional traffic at that level. Because the N+3 will have to merge with conventional traffic for arrival operations, arrival (Phase 6) interactions with those flights were considered.

Figure 68 shows the analysis of type of conflict by flight level bands for N+3 operations during arrival phase (again referring to the vehicle as an "AST"). As it descends into the conventional airspace (>FL 39,000 ft) crossing or opposite conflicts are predominant. Sequence and merging conflicts (InTrack) become more pronounced as the N+3 descends toward the transition and arrival airspace below 29,000 ft. A comparison with the current number of subsonic conflicts is again suggested as an area for further investigation.

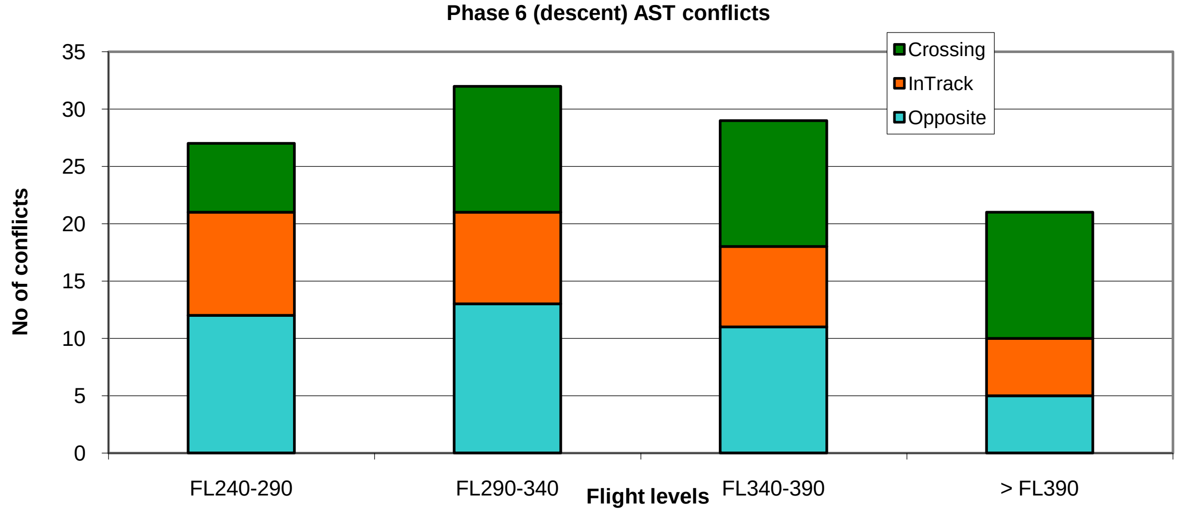


Figure 68.—Phase 6 conflict analysis.

3.4.4 Conclusions

An investigation of how N+3 operations impact the demand for airports and airspace, based on its performance characteristics, has been conducted. Results suggested that N+3 operations will require some additional airport capacity during peak hour hours at certain airports; however, most operations are likely to be scheduled during the periods of nonpeak conventional operations and will therefore utilize the unused airport capacity. Furthermore, N+3 route networks between various airports are fairly well separated (assuming they are able to fly great circle routings) even for busy air corridors. During departure, N+3 Phase 1 operations (climb to 10,000 ft) are contained within 21 National Air Traffic System (NAS) departure sectors and nine additional sectors for Phase 2 (high speed climb from 10,000 ft to 23,000 ft) operations. During Phase 1 and 2 of N+3 operations a marginal increase in air traffic complexity and controller workload is predicted. Phase 3 operations occur in mid-level, en-route sectors and are more dispersed across the NAS. Although the number of operations in these sectors increased marginally, air traffic complexity and controller workload was much higher. A significant increase in controller workload and complexity is anticipated during Phase 4 N+3 operations, which involves supersonic climb from 24,000 ft to cruising altitude. Analysis of conflict during supersonic climb, Phase 4, indicates that most conflicts occur between flight levels 34,000 to 39,000 ft; however, the overall numbers of conflicts were low for the duration of the study.

4.0 Tasks and Trade Studies—Propulsion Systems

Three propulsion system models were delivered to LM as part of this program. The first two were designed to meet all of the N+3 Supersonic goals, fuel efficiency, airport noise, and emissions. The last was “optimized” solely for cruise efficiency while ignoring the airport noise and emissions goals.

4.1 Technical Description

4.1.1 VCE Propulsion System

The advanced VCE uses advanced 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 advanced noise reduction technologies.

4.1.2 Conventional Mixed Flow Turbofan (MFTF) Propulsion Systems

The variable cycle features were eliminated from the turbofan that met the environmental goals along with the "Optimized" cruise engine that met or exceeded the performance goals without meeting any of the environmental goals. However these MFTF engines still had the other advanced technologies and the high performance Axi-Plug exhaust without the noise reduction technologies.

4.1.3 ATMS

The ATMS enables the engine to be designed at a higher OPR for improved thermal efficiency and enhanced engine life while operating at sustained high core temperature during cruise.

4.1.4 Advanced Low NOx Combustor

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 Section 4.7. The impact of the combustor exit temperature (T4) on cruise NOx emissions, engine performance, and weight is also discussed in Sections 4.4.1.3 and 4.7.

4.2 Exhaust System

The exhaust system is very important for supersonic vehicles since the nozzle performance is critical to the efficiency of the propulsion system as well as enabling jet noise technologies.

4.2.1 VCE Exhaust

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 with advanced jet noise reduction features. The exhaust has variable area capability to ensure high performance throughout the flight envelope. The exhaust system also provides for a thrust reversing system. Ceramic Matrix Composites (CMC) and other advanced composite materials are used extensively in the exhaust to minimize cooling requirements and weight.

4.2.2 Conventional MFTF Exhausts

For the two other turbofan engines designed without VCE features, the cooling scheme and advanced materials for the exhaust were the same. However, the advanced jet noise reduction technologies are not used in the exhaust. For the engines without VCE features, the core and bypass streams are conventionally mixed and then exhaust through an Axi-Plug nozzle, so the convergent section tended to be longer to provide the additional mixing length required for this higher BPR engine. This extra length is beneficial for noise as the two streams have more mixing length and plenty of room for acoustic suppression. The Axi-Plug exhaust also helps with the noise due to the increased radius ratio.

4.2.3 Transonic Thrust Augmentation

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.

4.2.4 Exhaust Variable Geometry Features

The exhaust has variable throat and exit area capability to ensure high performance throughout the flight envelope. The translating cowl also provides for a thrust reversing system.

4.3 Airframe Requirements

4.3.1 NASA N+3 Goals

For the NASA N+3 Supersonic transport (SST) study, LM used a Mach 1.6 cruising, 100 PAX vehicle of approximately 300 klb While the propulsion system does not have a strong impact on Sonic Boom other than minimizing the size of the engine and the overall aircraft, it does strongly impact airport noise, cruise emissions, and overall mission efficiency.

To best reflect overall mission efficiency, NASA also developed a fuel efficiency Figure of Merit (FOM) around specific range and passenger load (PAX). The FOM is #PAX * (range / block fuel). Range/block fuel is specific range or V0 / fuel flow. Specific range can also be presented in terms of V0 *(L/D)/(SFC)/Weight. The engine obviously has a direct impact on SFC, but the size of the engine can also impact aircraft L/D and weight.

4.3.2 Thrust Requirements

LM provided thrust requirements for their NASA N+3 SST design. For sizing the initial engine, takeoff and transonic thrust targets were set along with a Mach 1.6 TOC thrust target that would provide a 300 ft/m ROC margin. Since the GE variable cycle propulsion system has additional noise suppression capability over a regular turbofan, the target Vjet at 10 percent Programmed Lapse Rate PLR was initially set higher than what would be set for a typical turbofan

4.3.3 Customer Installation Effects

LM requested that propulsion installation effects be included in the installed engine data. To model these losses LM provided inlet performance updates. LM provided data is used directly in the cycle model to model the inlet. Along with the inlet recovery table, LM provided inlet critical additive drag (Cdcrit). The inlet drag is represented in the installed thrust.

The GE variable cycle propulsion system has the Axi-Plug exhaust with excellent nozzle performance and acoustic suppression capability. Since the nozzle has variable A9 capability, the area ratio can vary and therefore peak performance can be maintained at most all flight conditions. Tests and CFD analysis have shown that final exhaust performance is relatively unaffected by the noise reduction features in the exhaust.

There should be very little throttle dependent drag from the Axi-Plug nozzle, so nozzle drag was left out of the installed thrust.

For customer offtakes, LM provided the table shown in Figure 69, 1.5 lb/s compressor interstage bleed, 1.25 lb/s Fan Stream bleed, and 80 hp taken from the HP shaft. The fuel lower heating value for the study was assumed to be 18400 Btu/lb.

Engine bleed and horsepower extractions—Nominal (Per engine)	
Horsepower	80
Engine bleed—Fan	1.25 lbm/sec
Engine bleed—Intermediate	1.5 lbm/sec

Figure 69.—LM NASA N+3 bleed and horsepower extraction requirements

4.4 GE VCE Propulsion System

4.4.1 Propulsion System Design

4.4.1.1 Description

The core is initially sized to keep max cycle average T41 under the T41 limit throughout the flight envelope. The core pressure ratio (CPR) is set to keep the maximum cycle average T3 under the T3 limits. Section 4.4.1.3 shows the propulsion system impact of dropping core temperatures and Section 4.7 discusses the impact of core design temperatures on the NOx emissions goal. As will be shown in Section 4.4.1.3 the final design maximum cycle average T41 can be reduced by several hundred degrees to improve cruise NOx emissions, without having a significant impact on engine performance.

The engine total airflow size is set to yield the Mach 1.6 TOC thrust requirement. The Transonic Thrust Augmentation device typically provides sufficient margin to meet transonic and takeoff thrust requirements. At max power, the fan is running at 100 percent corrected speed. The Transonic Thrust Augmentation device can either be on or off depending on demand. The Axi-Plug exhaust has partially variable A8 and A9, which can be adjusted to accommodate the modest temperature bump from augmentation and still maintain near peak efficiency across the operating range.

The initial design space exploration to determine the best FPR and CPR for the N+3 engine started with an engine from a previous internal study, which could meet noise requirements with no margins. This engine was updated with an advanced high-pressure ratio core while still limiting max cycle average T3 to the N+3 timeframe limit.

To design the engine, thrust available was tracked at SLS takeoff, Mach 0.3 SL and 1,000 ft, transonic, and Mach 1.6 TOC. These were the critical flight conditions discussed in Section 3.2.2.2. Maximum power with and without the Transonic Thrust Augmentation device is observed at all conditions other than Mach 1.6. Vjet at 90 percent takeoff power to represent a Programmed Lapse Rate (PLR) for sideline noise measurement is also tracked to check the engines ability to meet acoustic requirements.

4.4.1.2 Results

An initial design trade study was performed to examine the effects of FPR, and dry versus Transonic Thrust Augmentation device operation on engine size. Engines were designed over a range of FPR’s to meet thrust requirements with and without the Transonic Thrust Augmentation device. The CPR and core size were rescaled for each engine targeting the max cycle average T3 and T41. The study showed that without the Transonic Thrust Augmentation device, the engines were sized at the takeoff or transonic condition, providing excess thrust at TOC. Conversely, when using the Transonic Thrust Augmentation device, the engine was always sized at TOC and was smaller.

The results from these preliminary trade studies are shown in Figure 70. The previous GE internal studies had already shown that the highest FPR engine should be able to meet NASA’s N+3 acoustic goals. So, any lower FPR engine should also be able to meet the acoustic goals. All engines sized to meet Takeoff thrust at Mach 0.3 ISA +36 °F with or without the Transonic Thrust Augmentation device. The Transonic Thrust Augmentation device was always used to meet transonic thrust requirement, particularly at the lower FPR. Although sensitivities to assess overall mission impact were not available at this point in the studies, it was felt that the highest FPR engine would be an appropriate propulsion system for this program; it was the smallest and lightest engine. It did not appear that the SFC penalty for the higher FPR would have as near an impact as the size impact. Therefore, the higher FPR was chosen for the initial baseline VCE design. The cycle data is used to design the Flowpath for the engine and the exhaust.

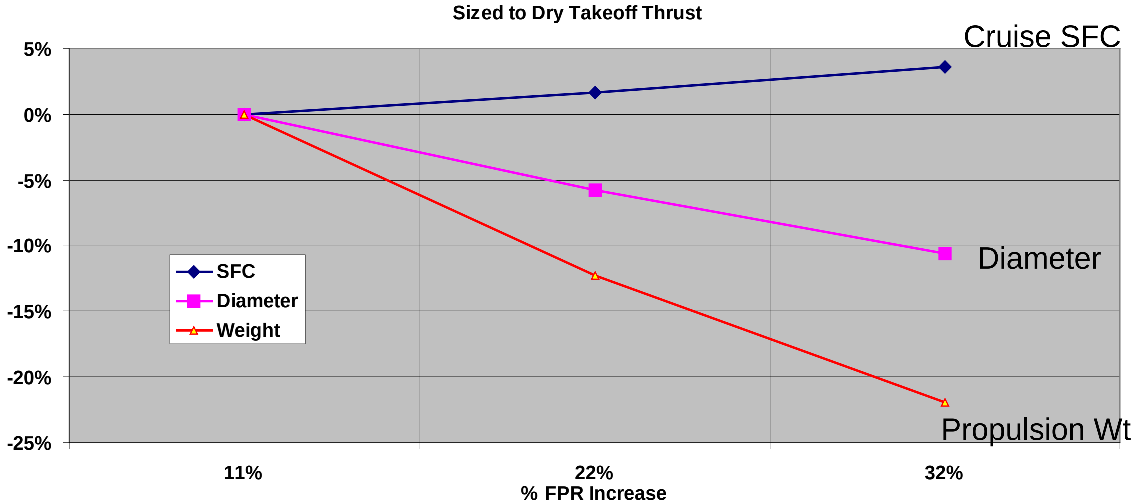


Figure 70.—Results from preliminary FPR Design Space Exploration Trade Study.

The engine matches the Mach 1.6 thrust requirement exactly. The Transonic Thrust Augmentation device is required to meet takeoff and transonic thrust requirement. The cycle data for this engine was used to estimate takeoff noise levels for this baseline configuration. The takeoff noise level prediction for this baseline configuration is discussed in Section 4.3.2.

An engine datapack with mission and takeoff data was generated covering the envelope LM requested. Cycle performance data includes: 1.5 lb/s compressor interstage bleed, 1.25 lb/s fan stream bleed, and 80 hpx (60 kw) extracted from the HPC and GE's Axi-Plug exhaust system performance with a variable A8 and A9.

4.4.1.3 Impact of Core Temperature on Engine Size and Performance

The engine core temperature has a significant impact on performance, weight, life, and NOx emissions. HPC discharge temperature (T3) and combustor exit temperature (T4) have a strong impact on combustor emissions, as shown in (Ref. 21). HPT rotor inlet temperature (T41) determines how much energy per pound of flow is available from the HPT and therefore core size. T3 and T41 set overall thermal efficiency and therefore strongly impact SFC. T3 has the strongest impact on SFC, typically the higher the better. There is also an optimum T41, above which T41 has little impact on SFC.

T3, T4, and T41 also set cooling flows for the core components. The ATMS and the advanced CMC materials system allow the engine to operate at high T3 with less cooling flow impact, but the T41 or T4 still impact required cooling flows. T4 is the gas path temperature for the HPT nozzle inlet and T3 is the temperature of the cooling air. From these, the required cooling flow for the HPT nozzle is set. The amount of cooling flow and T3 then set turbine rotor inlet temperature (T41). T41 is a mass average of the cooling flow for the nozzle at T3 and gas flow through the nozzle at T4. At the extreme, if a material was available that could survive at T4 temperatures, then no cooling would be required and T4 would be equal to T41. T3 and T41 also set cooling flows for the HPT and T3 and T49 cooling flows for the LPT. Even though for an ideal Brayton cycle, higher core temperatures are better for thermal efficiency, the required cooling flows tend to diminish the benefit. Once the gas path temperature gets below the bulk metal temperature capability of the material, then the cooling flows will no longer change as T4 and T41 drop.

Figure 71 shows the impact of T4 on the VCE propulsion system concept, adjusting cooling flows appropriately as temperature drops. As can be seen, the T4 can be initially pulled back minimal impact on SFC. The T4 impact on propulsion weight tends to be somewhat linear. Although as T4 drops further, the propulsion penalties start to increase more significantly.

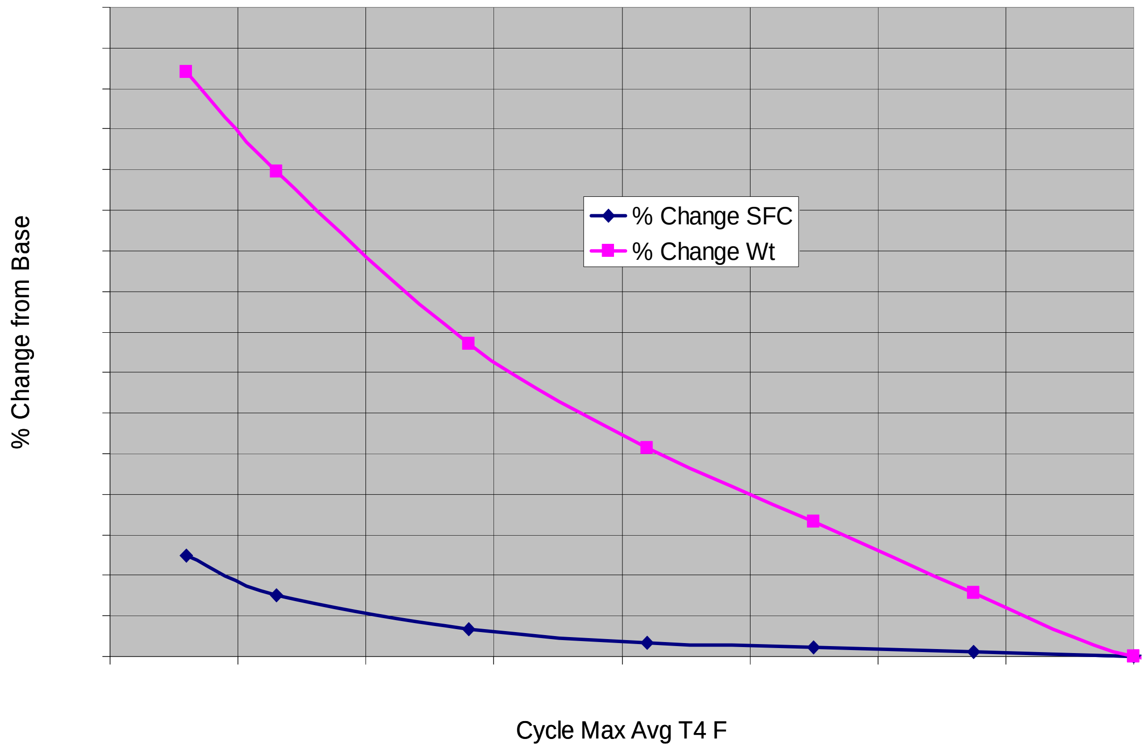


Figure 71 —T4 impact on weight and SFC

4.4.1.4 Impact of Plug Size in Axi-Plug Nozzle

LM had expressed some concern about the high nozzle closeout angles (boattail) on the GE Axi-Plug exhaust. It was noted that increasing the size of the plug could reduce the boattail angles on the exhaust. Since the Axi-Plug exhaust was leveraged form earlier internal studies, a CFD input file already existed that could be used to determine the impact of plug size on exhaust performance.

For this quick CFD study two flight conditions were analyzed, takeoff with the Transonic Thrust Augmentation device on and Mach 1.6 TOC. Two Plug sizes were investigated, the original and 50 percent larger.

Overall the study showed that the larger plug might decrease CFG by a slight amount. Although, it was felt that reductions in this loss would be possible with more time to optimize the geometry. The study also showed that the CFG could be improved by a modest amount at takeoff cutback.

4.4.2 Noise Assessment

4.4.2.1 Description

The noise goals for the supersonic N+3 application are 10 to 20 EPNdB cumulative margin below Stage 4 (or 20 to 30 EPNdB cumulative margin below Stage 3). LM provided the take-off gross weight (TOGW) target, number of engines and thrust requirements. GE made assumptions regarding the remaining information required to perform noise assessments. GE provided three different propulsion systems, two of which were intended to meet the noise goal and one which was designed solely for cruise efficiency. Noise assessments were only performed on the two propulsion systems intended to meet the noise goal. All of the noise assessments performed in this study are preliminary and no margins are applied. GE provides these as guidance only and implies no guarantees or commitments.

The first propulsion system developed was a VCE that enables the advanced jet noise reduction features in the exhaust. The exhaust system incorporates a number of proven noise reduction technologies for supersonic exhaust nozzles and combines them into one innovative exhaust system.

4.4.2.2 Results

Jet noise is typically the dominant propulsion system noise component for the take-off monitor locations and usually the lateral, sideline monitor location will be the most difficult noise level to achieve so the initial acoustic assessment was limited to this condition. Based on previous internal work with LM an appropriate fan pressure ratio was chosen that should meet the noise goal. However, the previous studies did not include any thrust augmentation capabilities so the initial noise study looked at the propulsion system with and without augmentation during the sideline monitoring location. Figure 72 shows the results of this noise study, the points on this chart are all under the Sideline Stage 3 requirement. The methodology followed to obtain the noise estimates are outlined below:

- Jet noise estimate of the equivalent ideally mixed exhaust
  - Assumes appropriate altitude, 1,476 ft sideline
  - External velocity appropriate for take-off
- Scaled jet noise levels from experimental database of three configurations for a range of mixed jet velocities:
  - Conic nozzle equivalent ideally mixed exhaust
  - Jet Noise Reduction Technology 1
  - Jet Noise Reduction Technology 2
- Determine benefit of the Jet Noise Reduction configurations by subtracting from equivalent ideally mixed exhaust conic nozzle
- Account for number engines
- Account for engine-engine jet noise shielding based on installation
- Compare to the sideline Stage 3 requirement to obtain sideline margin

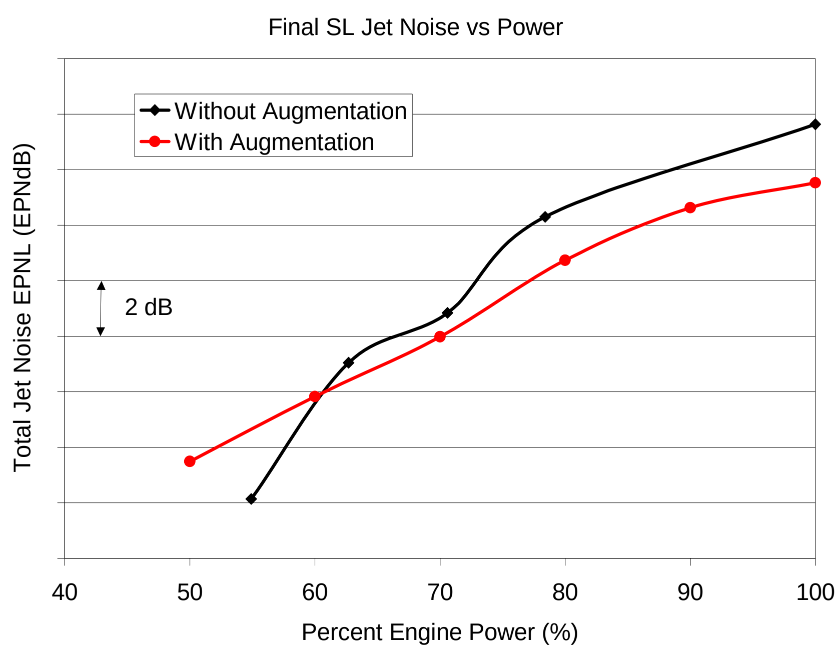


Figure 72.—Total jet noise level for sideline monitor location for VCE engine for different power setting with and without augmentation.

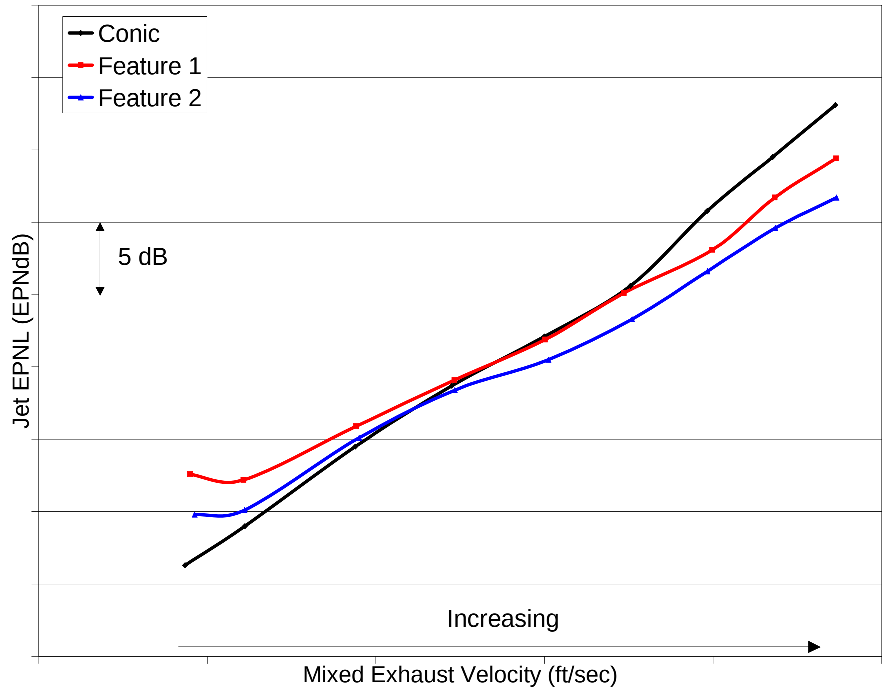


Figure 73.—Typical jet noise level for jet noise reduction features versus mixed velocity scaled experimental data.

This figure shows the percentage of engine power versus the sideline jet noise estimate for the total propulsion on the aircraft. An important observation from this is that the augmentation provides a benefit over the higher range of engine power. This is because the jet noise reduction feature is highly dependent on the exhaust velocity range. As the velocity increases the benefit of this feature typically improves, such that although the primary jet noise associated with the higher exhaust velocity may be higher, the improved performance of the feature may result in a lower final jet noise level. Typically for the same thrust the augmentation results in a higher temperature and thus higher exhaust velocity. Figure 73 demonstrates this effect; showing scaled experimental data for a conic nozzle, and configurations with the jet noise reduction features. There is clearly a level of the exhaust velocity where the features show a benefit once above. This figure shows a typical result of scaling existing scale model data, for one engine and before any system corrections have been applied.

This study showed sufficient margin for the sideline or lateral monitor location jet noise with augmentation during take-off. A more detailed noise assessment was conducted for all three of the monitor locations, sideline, flyover or cutback, and approach. Propulsion noise estimates were made for the jet noise and the fan inlet radiated noise. The fan exhaust radiated noise was not included due to uncertainty in its prediction as well as the significant room for acoustic suppression treatment through the relatively complex exhaust. Airframe noise levels were crudely estimated using an existing preliminary design tool as no better estimates were provided. The methodology for the jet noise estimate has already been summarized. The fan inlet radiated noise component was estimated using a GE version of the Heidmann code that has been validated with a similar fan system under a previous program. This estimate includes all of the features of the VCE fan module, and a conservative estimate of acoustic suppression treatment in the inlet. Additional assumptions are listed below:

- Flyover/cutback
  - Assumes thrust cutback to an appropriate level
  - Assumes cutback altitude
  - Appropriate external velocity

Based on these noise assessments the VCE propulsion system is expected to meet the program goal. The take-off profile should be assessed to improve the cutback procedure and a better estimate of the airframe noise is needed. The airframe noise levels used in the current study contribute 4 to 5 EPNdB to the cumulative margin.

The fan inlet radiated noise also makes a significant contribution to the cumulative margin. Alternate propulsion/airframe integrations should be assessed to mitigate this. There are alternate exhaust configurations that could take advantage of airframe shielding and much more highly integrated installations.

4.5 Conventional Mixed Flow Turbofan (MFTF) Propulsion System

4.5.1 Propulsion System Design

4.5.1.1 Description

LM requested that GE design a moderate BPR Mixed Flow Turbofan (MFTF) without variable cycle features or the associated special acoustic features in the exhaust that would still meet the NASA N+3 acoustic requirements for the program. The FPR for the MFTF was chosen based on previous internal studies. While the special acoustic features in the exhaust were no longer available without the variable cycle features, the Transonic Thrust Augmentation device was still deemed possible although a greater challenge due to the reduced fan stream temperatures.

4.5.1.2 Results

The initial configuration chosen was designed with the same core temperatures and technologies as the VCE baseline. The CPR was increased to make up for the loss of boost to get as much OPR as possible without adding a booster stage. Both the MFTF and VCE were designed to produce the required TOC thrust, but the MFTF makes more augmented thrust at takeoff and transonic, because of the greater thrust lapse.

The airflow capacity of the MFTF engine is 1/3 greater than the VCE engine, so the fan inlet is greater in diameter, the engine longer, and heavier. The nozzle exhaust duct is quite long to accommodate the large mixer that would be required for the higher BPR engine. In the end the MFTF engine showed only a slight improvement in SFC over the VCE concept. LM mission results indicated that the MFTF lost 240 nmi in range relative to the VCE.

4.5.2 Noise Assessment

4.5.2.1 Results

For the conventional MFTF noise assessment jet noise and fan inlet noise estimates were made both with and without augmentation, the airframe noise components are the same as the VCE engine since the vehicle weight didn't change for the noise assessment. The assumptions for the monitor locations were also consistent. The jet noise assessment was fairly different from the previous assessment for the VCE propulsion system since the exhaust system was very different. The conventional MFTF uses conventional mixing of the core and bypass flows before reaching the Axi-Plug nozzle, shown in Figure 74. The methodology for estimating the jet noise was as follows:

- Jet noise prediction for fully mixed exhaust
- Appropriate penalty since lobed mixers generate high frequency noise and don't result in fully mixed flow
- Appropriate noise reduction due to the plug
- Consistent engine and system corrections as VCE assessment

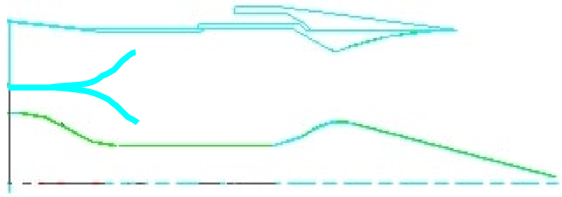


Figure 74.—Conventional MFTF mixed flow and axisymmetric plug nozzle exhaust.

From this assessment both the cases, with and without augmentation, met the noise goal but the no augmentation case provided more cumulative margin. This is consistent since there are not technologies included in this exhaust system which perform significantly better at higher velocities. Therefore the conventional MFTF propulsion system would not have an acoustic benefit for using the augmentation during the take-off operations.

4.6 "Optimum" Cruise Conventional MFTF Propulsion System

4.6.1 Propulsion System Design

4.6.1.1 Description

GE was also requested to design an "Optimum" cruise engine ignoring all other program goals. The propulsion system development and refinement sought an N+3 Supersonic design with the highest cruise efficiency without regard to any noncruise design requirements, specifically, acoustics and emissions.

To design the engine the same advanced technology assumptions with a 2025 TRL-6 Technology Availability Date were used. The engine architecture has no variable cycle features but does includes other advanced technology features appropriate for the time period, including the Axi-Plug Exhaust with Transonic Thrust Augmentation device. The Optimized cruise engine is a conventional MFTF like the previous one, only with a higher FPR and lower BPR.

4.6.1.2 Results

For the Optimized cruise engine study, Lockheed sensitivities were provided in the form of range, drag, and weight sensitivity data in a spreadsheet. These were used to determine the impact on vehicle range due to variation in diameter, SFC and weight.

Figure 75 shows the results from the cruise engine optimization study. As part of the optimization process, it was discovered that the Fan inlet diameter could be reduced somewhat, which improved range by approximately 1 percent for the baseline.

Impact On Range				
	VCE	MFTF		
	Baseline	Moderate FPR	high FPR	higher FPR
Inlet Diameter (inches)	0.0	-1.1	-4.6	-7.1
Range increase/decrease due to Diameter (nm)	**0.0%**	**0.7%**	**3.2%**	**4.9%**
SFC	0.0%	-1.2%	-0.5%	0.7%
Range increase/decrease due to SFC (nm)	**0.0%**	**1.5%**	**0.5%**	**-0.8%**
Total Quote Weight (lb)	0.0%	2.7%	-6.8%	-13.1%
Range increase/decrease due to Weight (nm)	**0.0%**	**-0.4%**	**1.0%**	**2.0%**
Total % Range increase/decrease	0.0%	1.8%	4.7%	6.1%

Largest gain in range

Figure 75.—Impact to range based on LM sensitivities.

The next step in the study was to define the cruise “optimized” MFTF with approximately the same mass averaged FPR as the baseline VCE, resulting in a moderate FPR MFTF. Since the previous conventional MFTF study showed a decrease in range performance with lower FPR, it was decided to investigate turbofans with higher FPR’s. The high FPR MFTF showed a significant gain in range over the moderate FPR MFTF. Next a higher FPR MFTF was designed and the sensitivities still showed an increase in range, although the increase was much less, indicating that the trade for size for SFC was leveling off. The higher FPR MFTF was chosen for the “Optimized” cruise engine to deliver to LM.

The max inlet airflow capability for the higher FPR MFTF is much less than the VCE baseline, because it makes the same thrust at a higher FPR. All engines were designed to make the same TOC thrust, but the ”optimized” MFTF makes less augmented thrust at takeoff and transonic, because of the smaller thrust lapse. With transonic augmentation, this engine is almost perfectly balanced at takeoff and TOC. The fan diameter is much smaller and the weight comes out lower than VCE baseline, but is not expected to meet the N+3 acoustic and emissions goals.

4.7 Emissions status

Cruise NOx emissions were estimated using an analytical method developed by GE Aviation. This method simulates the combustion process in the Twin Annular Premixed Swirler (TAPS) combustor (Figure 76) used in the propulsion system under study. It should be noted that this methodology was previously also used for estimating EINOx for the N+1 supersonic combustor program. It uses Chemkin to calculate a laminar lean premixed opposed flow flame to represent the well-mixed portion of the combustion, and a rich premixed opposed flow flame to represent the diffusion flame from the pilot. Jet-A was the fuel, and the chemical kinetic mechanism was obtained from GE Aviation. Figure 77 shows the flow configuration.

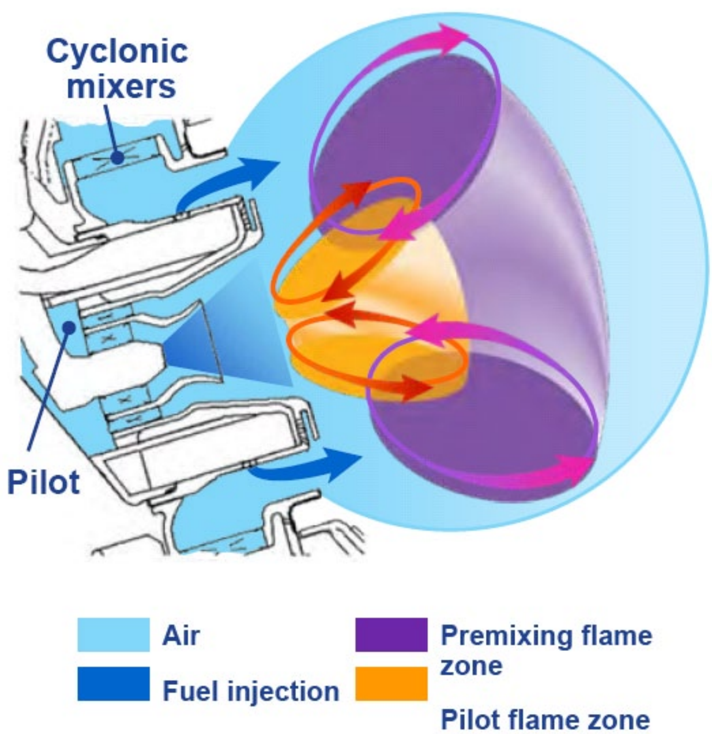


Figure 76.—GE Twin Annular Premixed Swirler (TAPS) combustor.

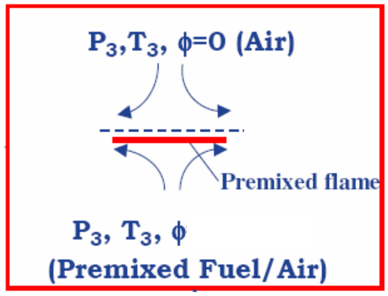


Figure 77.—Opposed flow flame calculated using Chemkin with Jet-A.

Some assumptions have been made to estimate GE62 NOx levels for the N+3 time frame. Starting with assumptions being used in an ongoing Low Emissions Combustor Program for Supersonic Aircraft additional assumptions are made in terms of cooling flow, residence time, and pilot level for the N+3 timeframe. Using these levels and adjusting the T4 level down based on the discussion in Section 4.4.1.3 the emissions goal of 5 EINOx is projected to be met.

4.8 Efficiency (FoM) status

Based on the propulsion system cycle data GE provided to Lockheed-Martin and the results of Lockheed-Martin's sizing studies the final version of the GE propulsion system resulted in an FOM exceeding the N+3 goal.

4.9 Technology Trades and Studies

4.9.1 Low-Emissions Combustor

4.9.1.1 Description

Meeting the N+3 emission goal of cruise EINOx = 5 g/kg fuel using a TAPS-type combustor has been one of the most challenging aspects of the supersonic N+3 program. To achieve the NOx goal, even more aggressive technology development targeting an N+3 timeframe is necessary in regards to reducing combustor residence time, cooling flow, pilot, and fuel/air mixing time. Figure 78, Figure 79, and Figure 80 show the variation of EINOx with different levels of mixer air, mixedness and amount of pilot, respectively, for different values of T4.

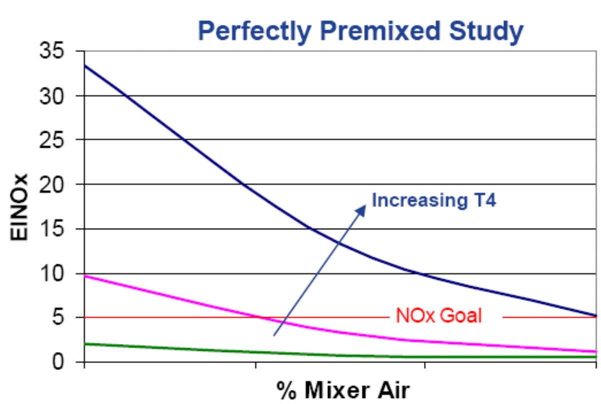


Figure 78.—Effect of amount of mixer air on EINOx with different values of T4.

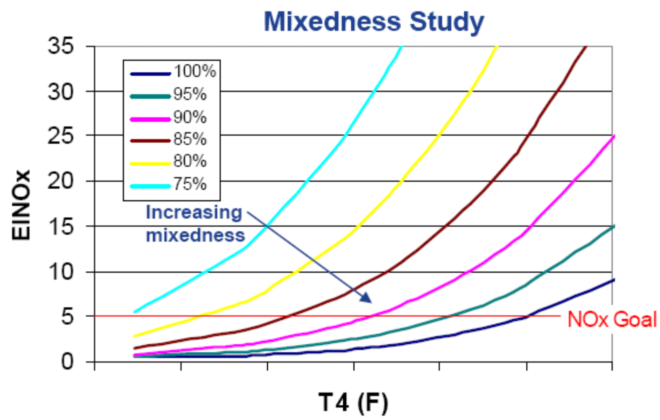


Figure 79.—Variation of EINOx with different levels of mixedness versus T4.

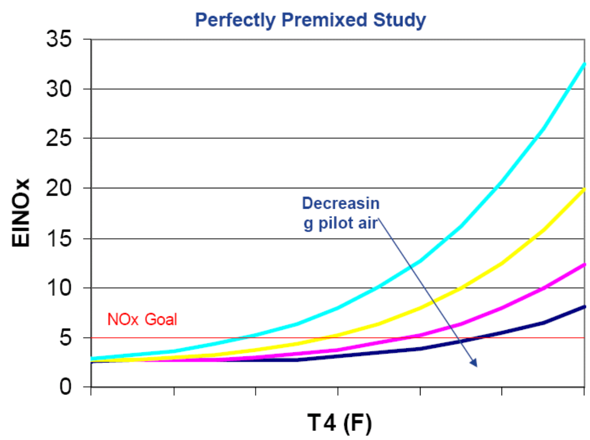


Figure 80.—Variation of EINOx with different levels of pilot air versus T4.

4.9.1.2 Results

A significant reduction in residence time is beneficial. To enable this, a significantly shortened combustor will be required. However, a shortened combustor will have high emissions of CO at low power (e.g. idle) conditions due to incomplete combustion. A shortened combustor may also not have sufficient volume for reliable operability. Additional technologies will be required to address this deficiency in operability. Therefore, a variable geometry combustor might be necessary, where the combustor is relatively long at low power conditions, and is then shortened during cruise.

A significant jump in cooling and material technologies is also required. The liner and dome cooling flows should be reduced significantly and more air can be directed to the mixer. Significant advances in material development would be necessary to achieve this.

4.9.2 Intercooler

The principal challenge for an intercooler (IC) is coming up with a lightweight low loss Hx system to remove heat from the compressor gooseneck (T25). The larger the temperature difference between the hot stream (T25) and the cooling source, the smaller the Hx required. The larger the Hx system, the greater the size, weight, and associated pressure losses.

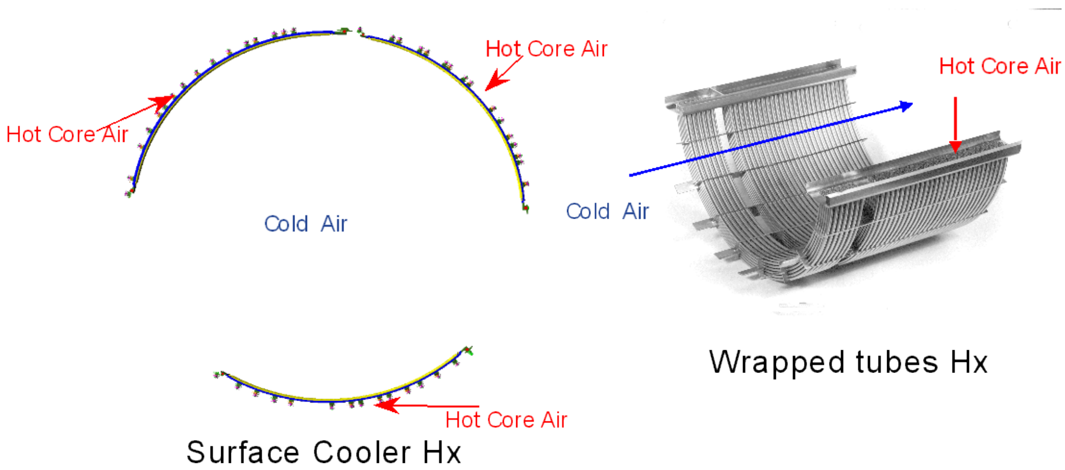


Figure 81.—Two notional types of heat exchangers.

4.9.2.1 Description

This study explored entitlement for the IC in the GE baseline VCE. Most of the complexities of the Hx system were ignored to see if the system would work with no losses and provide sufficient benefit to be worth a more detailed investigation. The analysis accounted for the amount of heat that needed to be transferred to obtain a certain drop in T25 and then the amount of Hx surface area required to achieve this heat transfer.

Typically, the purpose of an intercooler is to take heat out of the air entering the compressor (T25) to reduce core temperatures T3, T4, and T41. Once T3 is reduced the CPR can be increased driving T3 back up to further improve thermal efficiency. Also, with an intercooler, core size could be dropped increasing BPR and driving T4 and T41 back up, again improving thermal efficiency. For these supersonic N+3 studies, one of the most difficult environmental goals to achieve is the cruise NOx emissions goal. T4 and somewhat T3 have a strong impact on NOx emissions. For this analysis, the IC was used only to reduce T25 dropping core inlet temperature to reduce NOx cruise emissions, while maintaining thermal efficiency.

To perform this study, the VCE was designed with IC at the inlet to the core. It was assumed all gooseneck air passes through the notional heat exchanger to maximize the amount of heat that can be transferred and the drop in T25.

In the study two types of Hx were investigated, a surface cooler and tube style Hx as shown in Figure 81. The surface cooler is the lightest heat exchanger with the minimum amount of losses, but overall it requires more room to get the same amount of Hx surface area as the tubed. The tube style Hx has more losses, because they actually obstruct the flow going through the array of tubes and the flow going though the tubes have losses due to the passage through the small tubes. The tubes can however get more Hx exchanger area into a smaller space.

4.9.2.2 Results

The cycle analysis showed that to achieve about a reasonable drop in T4 requires about a small F drop in T25. From an ideal analysis the GE baseline could achieve a small drop in T25, but the calculation for Hx surface area showed that the required size was prohibitive.

Another alternative to the air-to-air Hx is to use the fuel as a heat sink. This would require an Air/Fuel Heat Exchanger or Air/Oil/Fuel Exchanger. A simple calculation of the thermal load from the gooseneck air to get the small F T25 drop showed that simplistically the fuel temperature would have to increase a significant amount to take all the heat due to the small quantity of fuel relative to gooseneck air.

Realistically this would not work as the fuel temperature increased the delta T would drop reducing the heat transfer and eventually the fuel temperature would reach T25.

The final conclusion was that using the IC to reduce T25 was not practical, the Hx would not fit in the engine. As was shown in the T4 core sizing trade study, the loss in performance for a reasonable drop in T4 was only a slight increase in SFC and small increase in weight. If the losses in the IC Hx system were fully accounted for there would likely be a much greater impact on SFC and the weight of the required Hx would be prohibitive.

4.9.3 Interturbine Combustor

Another attempt at reducing T4 for NOx cruise emissions was to introduce some burning between the HPT and LPT. A simple analysis performed by adding a small burner between the two turbines showed that T4 could be reduced. However burning in this lower pressure zone is much less efficient. The SFC penalty was significant. Again as in the intercooler nozzle, even this larger reduction in T4 could be obtained by simply designing the core to the same lower T4 with a smaller system impact.

4.9.4 Constant Volume Combustor (CVC)

CVC technology is being investigated to improve the efficiency of gas turbine engines. These configurations rely on pressure-rise constant volume combustion rather than constant-pressure deflagration currently used in today's gas turbine engines. Notional thermodynamic CVC cycles show increased thermodynamic efficiency greater than Humphrey (constant volume) and Brayton (constant pressure) cycles as a result of the pressure-rise associated with constant volume combustion.

4.9.4.1 CVC Modeling Approach

The following section describes the modeling approach of the CVC module within the engine. In the architecture considered, the regular deflagration-based (Brayton cycle) combustor is replaced with a CVC in the hot-gas path, Figure 82. The CVC would accept compressor-discharge air, detonate, and then exhaust into the high-pressure turbine through a nozzle. Such an architecture would potentially allow de-staging the compressor (since some of the pressure-rise is achieved by the combustor), but would likely require a very different turbine design. Furthermore, the design of this transition piece, and in particular the area ratio, is very important in optimizing the performance of the engine.

The CVC was modeled in NPSS by modifying the standard deflagration burner module in the engine model to include constant-volume combustion pressure-rise multiplier, Figure 82. The CVC pressure-rise map was generated separately using a quasi-1–D gas-dynamic code and inserted into NPSS as a lookup table in the functional form PR = function (T3, T41). Previous trade studies showed that the pressure-rise from a CVC (once the geometry was defined, including the area ratio) was primarily a function of these two parameters. The baseline VCE engine was used as a starting point for the present study.

The performance of a CVC is strongly a function of the physical geometry of the combustor. For this reason, it is important to understand the assumptions used in generating the pressure-rise map. The assumptions in generating are as follows:

1. CVC with 4:1 area ratio nozzle.
2. Gaseous C_2H_4 fuel with reduced mechanism two-step chemistry.
3. Includes steady-flow pressure losses.
4. Adiabatic walls.
5. "Rubber" inlet geometry so that each point is optimized for "on-design" operation.
6. Same compressor/HPT maps as simple cycle.

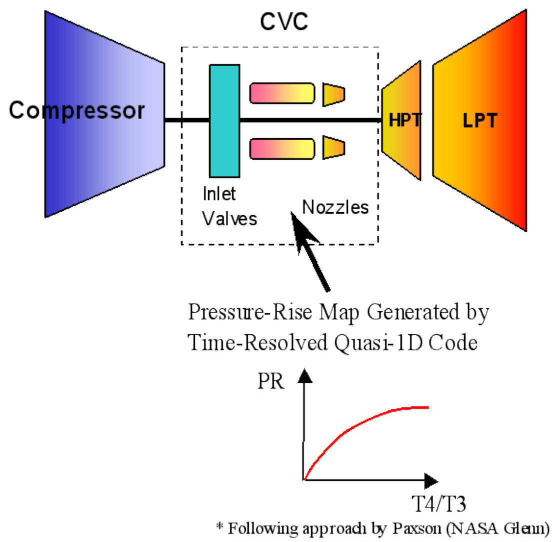


Figure 82.—Schematic diagram showing implementation of PDE in NPSS model.

4.9.4.2 CVC Trade Study Results

The main impact of the CVC is to enable a higher OPR engine using a simpler, lower CPR compressor. The study was performed with and without the Transonic Thrust Augmentation device. The engine was sized using the same temperature limits as the VCE and thrust-matched at the cruise thrust requirement. Thrust matching at cruise resulted in excess thrust at take-off. Furthermore, the thrust benefit of the CVC was an adder on top of the Transonic Thrust Augmentation device in the baseline engine. The specific fuel consumption benefit is approximately 3.2 percent for the CVC across the flight envelope, and is also an adder to the Transonic Thrust Augmentation device. One of the main observations with constant volume combustion is that the pressure-rise achieved is a strong inverse function of the initial temperature (or compressor discharge temperature). In particular, as the compressor pressure ratio increases (and T3 increases as well), the benefit of the pressure-rise combustion is reduced

An additional case was considered where the compressor was intercooled, so that the engine could benefit from the increased P_3, but the CVC could maximize its pressure-rise due to a lower intercooled T_3. This has a slight benefit over the CVC alone. The addition of the intercooler provides an additional SFC benefit, with a total benefit of 4.7 percent over the baseline VCE engine. The benefit of intercooling (with CVC) is seen to be reduced at lower OPR.

At this early stage, the CVC technology seems promising in that it can offer up to 5 percent improvement in SFC above and beyond the advanced N+3 baseline VCE engine. The TRL level of CVC technology, however, is relatively low and further development work is required to be considered for implementation.

4.9.4.3 Future Work

The present trade study represents a preliminary assessment of incorporating CVC technology into an advanced N+3 supersonic engine architecture. CVC technology is still in early stages of development, and many of the methods and design tools require further work. Future assessments should include the following improvements:

1. Refined CVC pressure-rise map with Jet-A fuel properties.
2. Further trade studies on the impact of CVC geometry on pressure-rise and an optimization of the geometry within the engine architecture. In particular, nozzle area ratio is known to have a big impact.

3. Improved turbine maps specific to CVC flows (when available).
4. Further parametric variations of T3, T41 and turbine efficiency.
5. Perform preliminary weight estimates and trade studies to understand impact of weight to SFC.
6. Impact of CVC operation at part-power conditions.

5.0 Technology Roadmap Development—Airframe (WBS 3.3)

The overall strategy to develop technology roadmaps began with technology identification. Each technology was assessed for viability, applicability, and duplication. The down selected technologies were then analyzed and ranked in terms of benefit, probability of success, and total program development costs. This resulted in a prioritized list of enabling technologies. A description and risk assessment, including a TRL maturation plan, is included for each prioritized technology in Section 9.0 New Technology.

5.1 Technology Identification (WBS 3.3.1)

The process used by LM, to identify enabling technologies for the N+3 vehicle, combined resources and research activities to define and develop a comprehensive technology list. The LM technology identification process is highlighted in Figure 83.

The process initiated with research on LM heritage, on-going NASA, and on-going LM resources to identify potential enabling technologies. All used sources for technology identification include:

- Heritage QSST/QSP information—Configuration shaping and inlet technologies
- Subcontractor input—GE GRC, Penn State, Reed/Saric, Purdue University, and J. Hansman from the program kick-off meeting held on December 12, 2008
- NASA information from the 2008 Supersonic Funding Portfolio
- Revolutionary Technology Programs (RTP) technology capabilities
- Tech Fair—Jet Exhaust Manipulation and Webcore Technologies
- Brainstorming sessions—Three sessions conducted during Phase 1

Each resource was thoroughly researched by the N+3 team to identify potential technologies capable of enabling an N+3 advanced vehicle concept.

LM conducted additional research activities to identify technologies from small businesses and subject matter experts. On December 8, 2008, LM conducted a Tech Fair to engage small businesses and the academic community to further identify enabling technologies. LM sent out over 30 solicitations and ultimately received three participants within the fair. Each participant was required to submit a half hour presentation that outlined their specific technologies and the research that had been done to date. LM selected two out of the three technologies presented as potential enabling technologies. Those two participants include Webcore Technologies, based out of Miamisburg, Ohio and Dr. Mo Samimy from Ohio State University. Webcore Technologies specializes in innovative materials and composite manufacturing which aligned with the same 2030 vision required for the N+3 vehicle. Dr. Samimy's current research is on the application of plasma in jet engine exhaust to modify flow levels for noise reduction. Three brainstorming sessions were conducted during the first quarter of the program to encompass all technology possibilities. These sessions were held with LM subject matter experts and other LM personnel to provide insight for identifying a comprehensive technology list.

Once all resources and activities were completed, each technology was categorized and captured in a comprehensive spreadsheet. The four technology categories include:

- Individual bolt-on techs
- Airframe and propulsion configurations

- Tools and methods
- Materials and generic technologies

Each technology was divided by source, category, benefits, drawbacks, N+3 goals addressed, and readiness. Figure 84 demonstrates a sample of the technologies compiled.

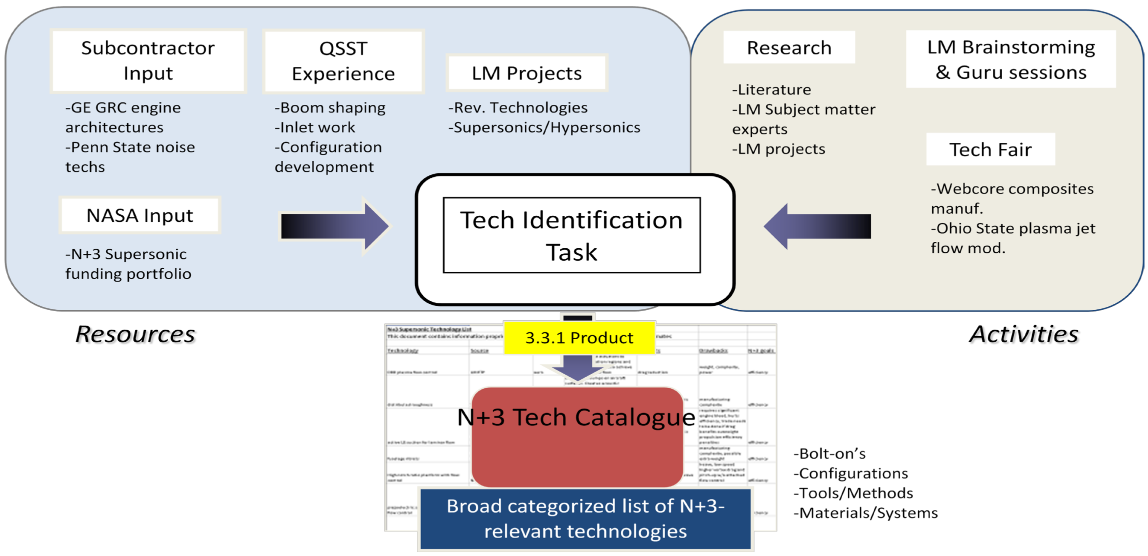


Figure 83.—Technology identification process used to construct the technology roadmaps.

N+3 Supersonic Technology List							
Configuration							
Technology	Source	Category	Description	Benefits	Drawbacks	N+3 goals addressed	Readiness
High notch ratio planform with flow control	N+3 proposal	Aero	Wing with high notch ratio (high TE sweep)	Low induced and wing wave drag	Heavy, low speed higher vortex drag and pitch-up without attached flow control	Efficiency	Idea. Would need to develop and test specific design
Synthetic cockpit vision	LM proposal brainstorming session	Avionics	Use TV camera system to give pilot better visibility where nose is in way	Eliminates need for folding nose or any other design compromises necessary for the pilot to see the runway	None	Efficiency	Needs development but research activities are on going
Swing canard	LM configuration brainstorming session	Configuration	Deploy canard only at low speeds to control trim and stability	Lower drag, better boom	Weight and complexity Of retraction	Efficiency, boom	Would have to be designed in
Wing tip tanks	LM configuration brainstorming session	Configuration	Strategically shaped wing tip tanks	Structural stability, span load alleviation, area ruling	Weight	Efficiency, boom	TRL-9, airplanes have employed them before
Configuration shaping	LM proposal brainstorming session	Configuration	Shape configuration to close fore and aft shock to acceptable levels using advanced MDO techniques	Constrain sonic boom while maintaining efficiency and trim	Efficiency is compromised if it has to be balanced against boom requirements	Boom, efficiency	Has been done for QSST, more research to be done
Variable sweep outboard wing panels	N+3 kickoff meeting brainstorm	Configuration	Vary sweep of wing using pivots or other mechanical system	Easier to balance low speed takeoff requirements with high speed drag and boom goals, less weight than full variable sweep wings since it's just outboard panels	Large weight penalties in pivots and mechanical systems	Efficiency, noise, boom	TRL-9, done before on F14, F111, and B1
Quiet spike	N+3 kickoff meeting brainstorm	Configuration	Extending and retracting spike, extends for cruise to increase effective length of airplane, retracts for better landing	Reduces boom	Weight and complexity of retraction mechanism	Boom, efficiency	Tested on F-15 for mechanical reliability
Knight's lance nose	N+3 proposal	Configuration	Similar to quiet spike but would be nonretractable	Reduces boom	Weight, landing slap-down considerations	Boom, efficiency	Idea

Figure 84.—Technology catalogue excerpt used to define space of possible technologies, provide input for down selection, and disseminate ideas.

5.2 Technology Down Selection (WBS 3.3.2)

Once all proprietary and nonproprietary enabling technologies had been identified, they were then down selected to provide a focused, manageable list of technologies to analyze for vehicle integration. The overall process is illustrated in Figure 85.

The LM technology down selection process started with the catalogued N+3 technology set and was scrubbed with five factors in mind to reduce the overall list. Those factors include:

- Research—subject matter experts, other LM projects, literature
- Weighted Pugh Matrix Analysis
- N+0, 1, 2 technology duplication
- Subsonic/supersonic duplication
- Techs already supported elsewhere

Each technology was initially gauged by N+3 team members and LM subject matter experts to determine if the technology passed a “sanity” check. Technologies that were not applicable to the N+3 goals, determined to be ineffective through other and heritage LM projects, or duplicated through N+1 efforts were eliminated. Duplicated N+2 technologies were included in the next stages of the down selection process; however, they were noted as being N+2 technologies and were directly applicable to the N+3 goals. The remaining technologies were then put into a weighted Pugh Matrix to determine the overall benefit for an advanced, supersonic vehicle.

The Pugh Matrix analysis weighed different measures of merit such as L/D, empty weight, SFC, boom, noise, emissions, safety, pax comfort, and cost to determine a net benefit value for each technology. This net benefit value was ultimately used to determine the overall prioritization set. Within the Pugh Matrix, numbers of –9, –6, –3, 0, +3, +6, or +9 were assigned to a measure of merit (efficiency, environment, and practicality) to determine if a technology “helped” or “hurt” and by how much. A value was not assigned unless the technology had a direct and significant impact on the measure of merit. Differentiating and assigning a value to a specific measure of merit allowed an explicit analysis of each technology in regards to vehicle impacts. In addition, it was assumed that the technologies put through the analysis were “bolted” onto a baseline vehicle. This baseline vehicle was assumed to have been designed to meet the noise, emissions, and efficiency goals. As a result, configuration technologies were considered to be endemic or already installed on the baseline vehicle, and technologies would be “bolted-on” or simply added to the baseline design. The reasoning is that the configuration technologies were judged to be high-payoff with low impact and necessary to achieve the N+3 goals. Figure 86 illustrates the baseline configuration with endemic technologies highlighted.

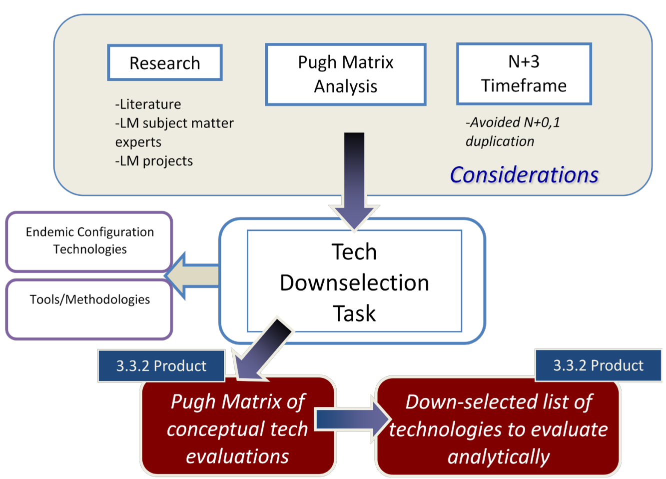


Figure 85.—Technology down selection process that produced manageable list of technologies to further evaluate and create roadmaps.

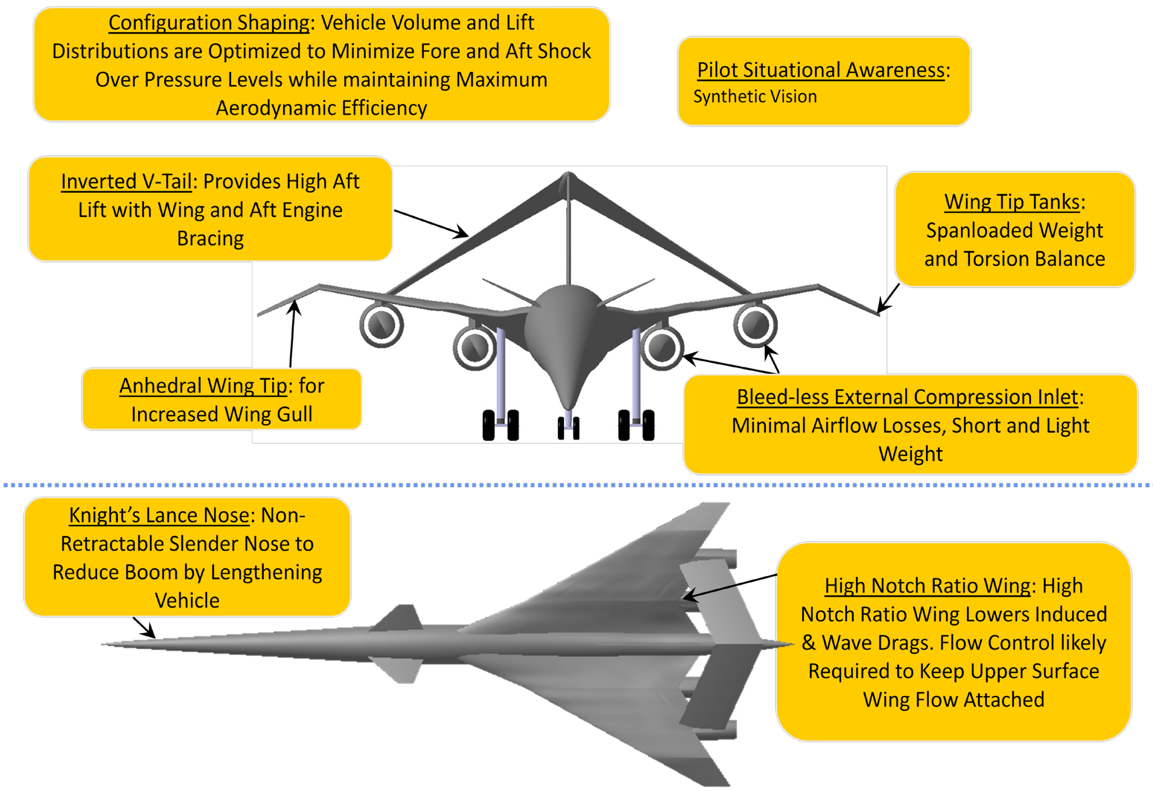
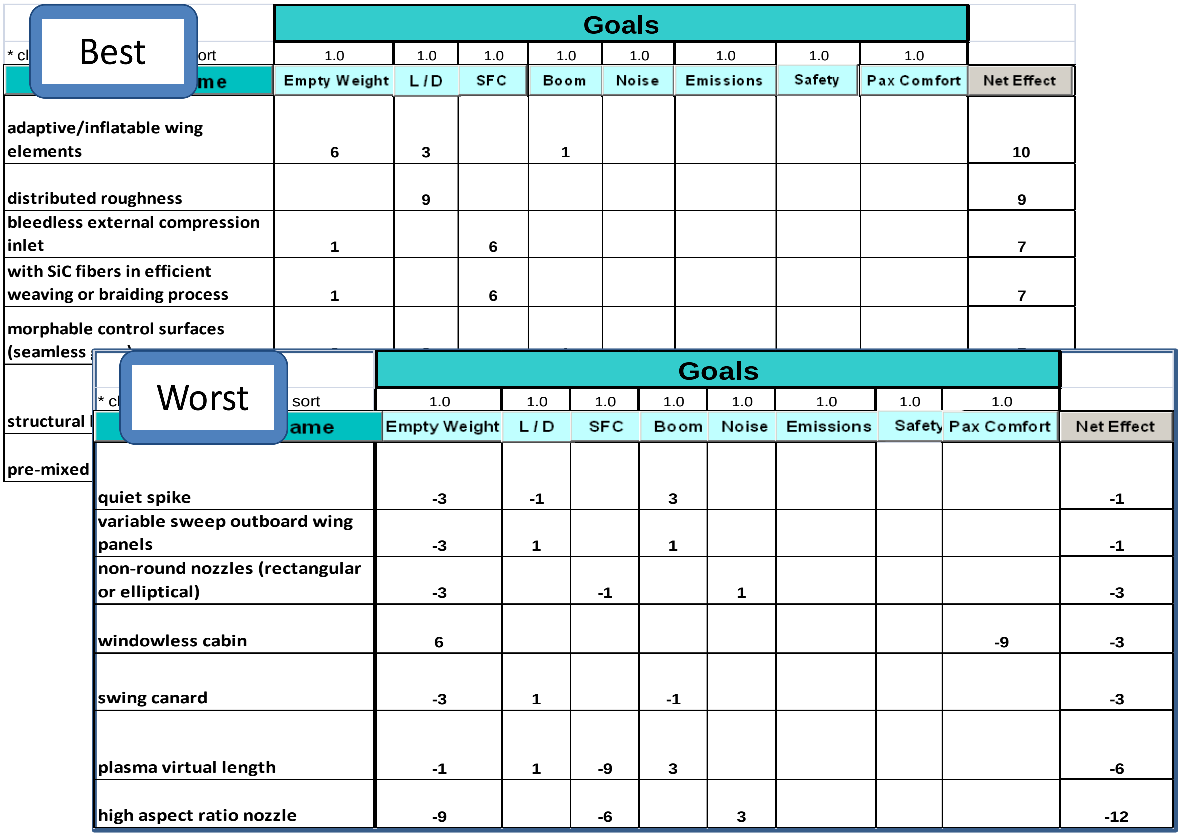


Figure 86.—Configuration technologies assumed to be designed into the advanced vehicle concept.

Other Pugh Matrix ground rules and assumptions include:

- Number defines whether technology "helps" or "hurts" a specific vehicle measure of merit
- Secondary technology effects were ignored unless they were significant
- L/D and SFC refer to long-term cruise values, not short-term low speed
- Emissions includes NOx, CO_2, and water contrails
- Noise is community noise on the ground at takeoff and landing, it does not include boom or cabin noise
- Cabin noise falls under the category of "passenger comfort"
- Some technologies are already considered to be on the baseline (e.g., Inverted V).
- Cost/Complexity refers to how much more or less "complicated" the vehicle becomes as the result of adding a technology
- Gray areas and exceptions were unavoidable due to the nature of assigning values to each technology
- The baseline vehicle has been designed to meet the noise, boom and emission constraints as best as possible

Once the rankings of each technology had been accomplished, a weighted product function determined the overall net benefit values. Based on these values, we were then able to sort the technology based on high and low values. Figure 87 highlights the best and worst results from the Pugh Matrix effort.



* cl... ort	Goals								
	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
...me	Empty Weight	L / D	SFC	Boom	Noise	Emissions	Safety	Pax Comfort	Net Effect
adaptive/inflatable wing elements	6	3		1					10
distributed roughness		9							9
bleedless external compression inlet	1		6						7
with SiC fibers in efficient weaving or braiding process	1		6						7
morphable control surfaces (seamless ...									
structural ...									
pre-mixed ...									

* cl... sort	Goals								
	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
...ame	Empty Weight	L / D	SFC	Boom	Noise	Emissions	Safety	Pax Comfort	Net Effect
quiet spike	-3	-1		3					-1
variable sweep outboard wing panels	-3	1		1					-1
non-round nozzles (rectangular or elliptical)	-3		-1		1				-3
windowless cabin	6							-9	-3
swing canard	-3	1		-1					-3
plasma virtual length	-1	1	-9	3					-6
high aspect ratio nozzle	-9		-6		3				-12

Figure 87.—Observations and insights from rankings contributed to prioritization.

Technologies rated the highest included adaptive/inflatable wing elements, distributed roughness, and the jet noise technology. Adaptive geometry produced a net Pugh Matrix benefit equal to +10. The reason adaptive geometry scored so high was due to the technologies broad range of potential applications. Control augmentation, inlet flow control, and adaptive OML were the major applications considered for adaptive geometry. This was the highest score followed by distributive roughness with a net benefit value equal to +9. Distributed roughness scored high because it had a positive impact on L/D with no negative impacts on other measures of merit. Further research and analysis proved that distributed roughness could provide a 1.0 to 1.5 point increase in L/D with minimal increase in system complexity. The jet noise technology set scored a net benefit value of +7 because the technologies are instrumental in reducing the overall noise levels to reach the N+3 goals.

Technologies that were rated the worst include the high aspect ratio nozzle and plasma virtual length. The high aspect ratio nozzle scores low because it had a small noise benefit but has a high negative impact on weight and efficiency. The technology's overall score equaled –12. Plasma virtual length scored a –6 because of the complexity issues associated with an additional system and its large power requirements. Most of the vehicle impacts from negatively scored technologies were small and only 7 out of 51 technologies resulted in values from –3 to –1.

As a result, the following table (Table 11) demonstrates the nonprioritized list of technologies that were down-selected for further analysis. Each technology was selected based on a judgment call, the Pugh Matrix, and considerations to ultimately apply these technologies to an N+3 demonstrator.

A technology that did not make the list, but is recommended for further study and analysis is aircraft take-off assist (Table 12). Take-off Assist, under aircraft operations, uses a subsonic vehicle to assist a supersonic vehicle during take-off in a similar manner to a glider being towed. The goal is to reduce the overall noise levels at take-off. Both vehicles would then land by themselves. This type of operation could also potentially increase efficiencies within the configuration design. This technology scored reasonably high (Pugh Matrix value = +5), but the impacts of this system within the future ATS are unclear. The system requires further research and analysis to understand the full impact.

TABLE 11.—NONPRIORITIZED OF PUGH MATRIX TECHNOLOGIES DOWN SELECTED FOR FURTHER ANALYSIS

Category	Technology	Source	Description	Benefits	Drawbacks	Benefit value (Pugh matrix analysis)
Laminar flow	Distributed roughness	Reed/Saric	Distributed bumps on a/c surfaces. Creates acoustic disturbances out of phase with cross-flow disturbances and maintains laminar flow.	Lower drag at supersonic speeds	Manufacturing complexity	+9
Adaptive geometry	Inlet flow control	LM RTP	Vary inlet geometry to choke flow in the inlet at low speeds	Reduced inlet fan noise	Complexity of using variable geometry	+3
	Lift distribution control	N+3 Kick-off brainstorming session	Ability to conform portions of configuration/ control lift surfaces	Ability to control lift, decreased drag, lower noise	Potential difficulties to create drag at low speeds	+7
Plasma	Jet exhaust manipulation	Tech Fair—Ohio State	Plasma actuators on nozzle lip to play with jet characteristics to reduce noise	Jet noise reduced about 2 to 3 dB	Power required for plasma	+3
Pilot situational awareness	Low boom violation cueing	LM	Heads up display illustrating maneuver and acceleration limits for low boom operation	Mitigate boom and operate a/c within FAA limitations		+9
	Boom/noise preplanning awareness	LM	Route planning for noise abatement	Intelligent route finding to apply noise to specific areas	Performance and efficiency decrease to abate noise/boom	+9
Tools/ Methods	Boom shaping	LM	Shapes lifting surfaces to low boom targets	Higher fidelity solution	Computational Requirements	+9
	CFD-based MDAO	LM/Stanford/ NASA	Shapes lifting surfaces to low boom targets	Higher fidelity solution	Computational Requirements	+9
	Integrated structural analysis	LM	Integrated analysis that accounts for flutter and other ASE concerns	Higher fidelity/ integrated solution	Computational Requirements	+9

TABLE 12.—RECOMMENDED ENABLING TECHNOLOGIES FOR FURTHER RESEARCH AND ANALYSIS

Category	Technology	Source	Description	Benefits	Drawbacks	Benefit value (Pugh matrix analysis)
Aircraft operations	Take-off assist	LM	A minimalist autonomous takeoff assistor would tow the supersonic aircraft by cable through take-off up to launch altitude. The supersonic aircraft would have its engines at partial throttle during takeoff to stay within noise limits and to be controllable. The supersonic aircraft would land on its' own.	Reduces community noise on takeoff	Potential operation problems within future ATS	+5

The technology down selection process produced a manageable list of promising technologies for further evaluation and identified enabling technologies suitable for the technology roadmaps. Nonproprietary results from the Pugh Analysis are posted in Appendix B.

5.3 Technology Prioritization (WBS 3.3.4)

Technology prioritization was done by calculating value in terms of the overall benefit of the technology to the air vehicle, probability of success, and the cost to develop that technology to a TRL 6. The equation used is highlighted below:

$$\text{Rank} = \frac{\text{Benefit} * \text{Probability of Success}}{\text{Cost to Develop}}$$

The results from the Pugh Matrix analysis were used to determine a benefit value for each technology, and referenced subject matter experts within LM were used to determine the probability of success and the overall program costs to mature each technology. Each technology was then prioritized and put into the following roadmap format, Table 14, to illustrate the enabling airframe and propulsion technologies required to realize an environmentally friendly vision vehicle.

The down selected technologies have applications to N+2 and N+3 air vehicles. Different technologies, including low boom violation cueing and preplanning awareness, first have application to the N+2 vehicle but will also be used on the N+3 vehicle to achieve the N+3 performance and environmental goals. It was reasonably assumed that these N+2 technologies, highlighted in Table 13, would be developed during subsonic N+2 programs and would not be a focus for future N+3 technology development. As a result, these technologies were prioritized and technology roadmaps were developed for completeness. However, it is assumed that these technologies will be developed in other efforts first and are not recommended for future N+3 development efforts.

We recommend that future airframe development should concentrate on N+3 specific tools/methodologies, laminar flow, and adaptive geometry technologies. The order of importance is outlined in the table and follows the priority ranking provided.

TABLE 13.—PRIORITIZED LIST OF ENABLING TECHNOLOGIES NECESSARY TO ACHIEVE N+3 PERFORMANCE AND ENVIRONMENTAL GOALS

Priority no.	Category	Prioritized, enabling N+3 technology	Addressed N+3 goal	Vehicle benefit	Current TRL level	Vehicle application	Availability timeframe (TRL = 6)
1	Tools/ methods	Boom shaping	Boom mitigation	Optimized boom configuration capable of achieving 70 PLdB	1-2	N+2 and N+3 supersonic application	~2015
2	Tools/ methods	CFD-based MDAO	Boom mitigation	Optimized boom configuration capable of achieving 70 PLdB	2-3	N+3	~2016
3	Laminar flow	Distributed roughness with plasma aug.	Fuel efficiency, range	L/D +1 to 1.5, Increased efficiency at higher Machs, less friction/drag, reduction in aircraft wt.	3	N+2 and N+3 supersonic application	~2022
4	Pilot situational awareness	Low boom violation cueing	Boom mitigation	In-flight boom intelligence, reduced sonic boom, operation within FAA limits	1-2	N+2	~2018
5	Pilot situational awareness	Boom/noise preplanning awareness	Boom mitigation	Intelligent/Boom conscience route finding, operation within FAA limits	1-2	N+2	~2020
6	Tools/ methods	Integrated structural analysis	Efficiency	Optimized empty weight design	1-2	N+3	~2017
7	Adaptive geometry	Lift distribution control	Efficiency, noise	Adaptive airfoils to optimize range	2-3	N+3	~2018
8	Plasma	Jet exhaust manipulation	Noise	Reduced nozzle PLdB noise by 6-8 dB	2-3	N+3	~2016
11	Adaptive geometry	Inlet flow control	Noise, efficiency	Reduced inlet fan noise with improved efficiency (+10% inc in take-off thrust and transonic thrust. Plus 10% subsonic SFC improvement)	2-3	N+3	~2018

6.0 Technology Roadmap Development—Propulsion

6.1 Technology Identification—Potential Enabling Technologies

6.2 Technology Down Selection/Prioritization

Early in the program a list of propulsion technologies were compiled and prioritized, shown in Table 14. This prioritization was in terms of engineering judgment as to the benefit to the program, the chance of the technology succeeding if it was fully developed, and the cost of development of the technology. This prioritized list was used as the program developed to guide the choice of technologies to be evaluated in the propulsion system. As the assessments relative to the goals became clearer and as the configurations LM was focusing on became evident, some of these technologies made more sense and some were no longer appropriate to include. As discussed in Section 4.1, the advanced VCE, as well as the conventional MFTF use many advanced technologies aimed at 2025 TRL 6 Technology Availability Date and EIS date of 2035. The main advanced technology features of the propulsion system broken out for more detailed evaluation and trade studies are the VCE architecture engine, the ATMS, the Axi-Plug Low Noise Exhaust, and the Transonic Thrust Augmentation device. There is also an Advanced Low NOx Combustor concept capable of meeting the N+3 cruise NOx emission goal. There were also some additional technologies evaluated that were not part of the baseline propulsion system. The additional technologies aimed at reducing T4 to meet the cruise NOx emissions goal were intercoolers, interturbine combustion, and to improve SFC, constant volume combustion. These trade studies will be summarized in the following sections.

TABLE 14.—PROPULSION SYSTEM TECHNOLOGY MATRIX

Priority	Technology	Benefit to program	Chance of success	Cost to develop	Ranking
1	Exhaust noise reduction technologies	9	9	1	81
1	ATMS	9	9	1	81
1	Transonic thrust augmentation	9	3	1	27
2	Premixed combustion	9	3	1	27
2	Active control combustion	9	3	1	27
1	VCE	9	9	9	9
1	Advanced low NOx combustor	9	3	3	9
1	High OPR gas turbine	9	9	9	9
5	Over-wing mounted engines	3	3	1	9
7	Constant volume combustion	9	3	3	9
13	Cross-shafted auxiliary fans	3	3	3	3
3	Ceramic matrix composite exhaust	3	3	3	3
4	Inter-cooler	3	3	3	3
6	Embedded engines	3	3	3	3
8	Counter-rotating fan	3	3	3	3
10	Indirect Brayton cycle	3	3	3	3
12	Auxiliary turbofans	9	1	9	1
		9 = high, 3 = medium, and 1= low			

7.0 GOTCHA Analysis (WBS 3.3.3)

Using a NASA tool, each enabling technology was evaluated as to how it addressed an N+3 goal, and this path was then mapped using GOTCHA charts. Each N+3 goal (sonic boom, airport noise, cruise emissions, cruise speed, range, payload, and fuel efficiency) was laid out with corresponding technical challenges and resulting approach to solve those objectives. The results, which prove traceability for each technology to an N+3 goal, are shown in Figure 88 and Figure 89.

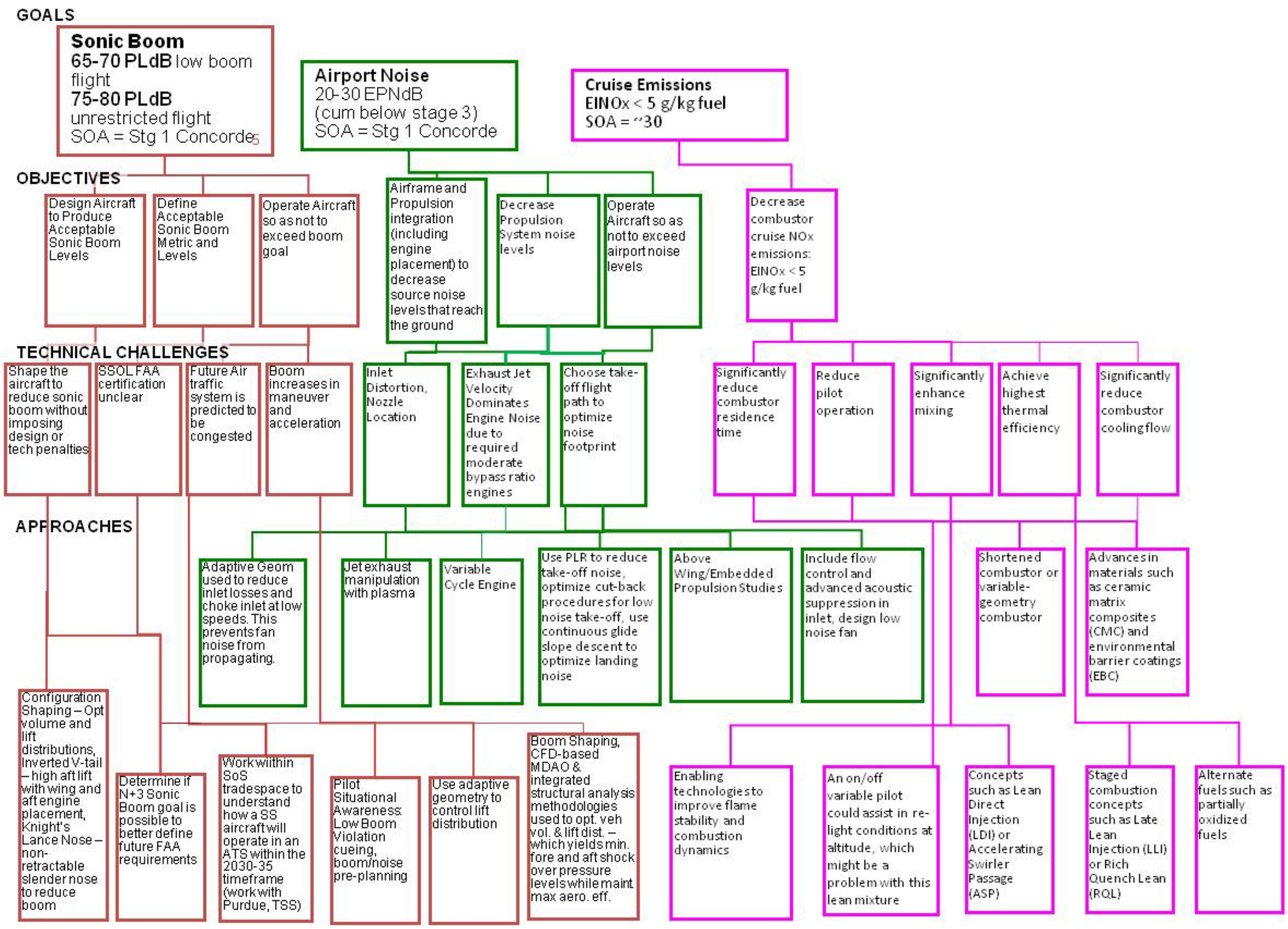


Figure 88.—GOTCHA successfully traces prioritized technologies to N+3 environmental goals.

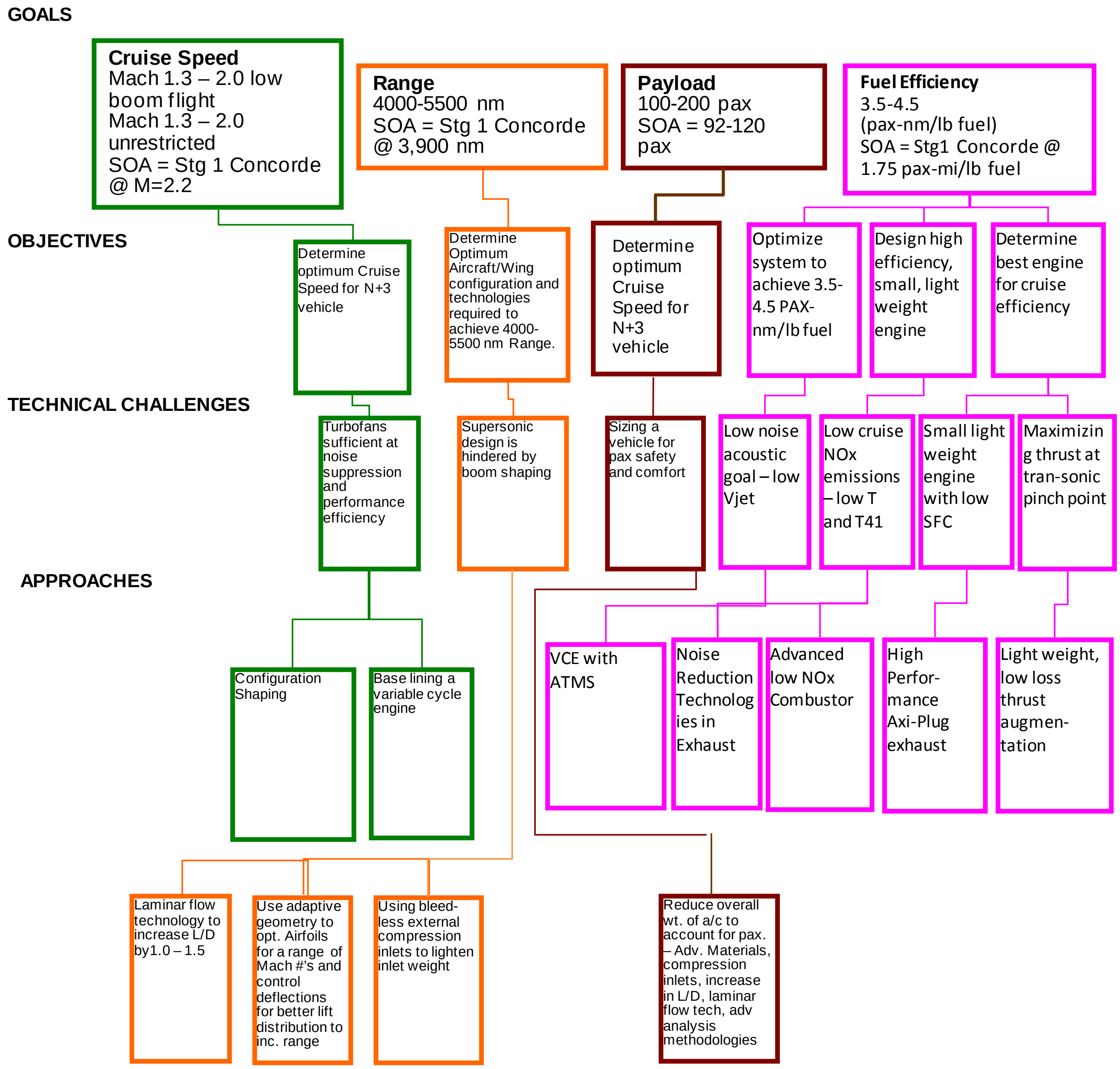


Figure 89.—GOTCHA successfully traces prioritized technologies to N+3 performance goals.

8.0 New Technology—Airframe (WBS 3.3.3, 3.3.4)

The following section describes each prioritized technology and establishes which N+3 goal the technology addresses. Waterfall charts were also generated for each enabling technology to demonstrate the maturation plans for Phase II and Phase III efforts. All technology plans illustrate the maturation cycle up to TRL 6 and are grouped according to category. Each technology was assessed by considering the technology's current TRL and an understanding of the resources that would likely be needed to raise the TRL. The results show that all technologies can achieve TRL 6 within the 2030 to 2035 timeframe and major risk items are identified.

8.1 Tools /Methodologies—Low Boom Shaping Fidelity

8.1.1 Addressed N+3 Goals

- Boom mitigation

8.1.2 Description

Current low sonic boom design and analysis methods have less fidelity (to various degrees) than is needed to achieve low boom loudness goals with the best aerodynamic performance simultaneously possible. Where possible, fast low fidelity methods will be replaced or modified with enhanced accuracy methods including more faithful geometric modeling. Low fidelity methods will work incrementally from high-fidelity methods in mixed-fidelity and multi-fidelity frameworks. Improved investigation and optimization schemes will find better solutions and better Prato fronts for trading-off between objectives. CAD incorporation is desired for parametric geometry modifications that maintain smoother and more producible shapes, are better for other disciplines, and still achieve near optimum aero/boom performance. Improvements in CFD analysis accuracy and speed will be implemented through coding automation, more efficient gridding, improved propulsion boundary conditions, wind tunnel and flight measurement validations and propagation beyond the near-field. Additional enhancements to propagation methodology include rounding, turbulence, maneuvering and additional flexibility in inverse minimization targets.

8.1.3 Roadmap

Figure 90 delineates a broad course of action necessary to mature and develop these boom shaping enhancements. The main maturation efforts include parallel work with NASA on multiple means and methods of fidelity improvements for modified-linear tools, multi-fidelity frameworks and CAD integration, CFD improvements and inverse design targets. Once complete, verification and validation needs to be performed to ensure usability by personnel within the aerospace industry.

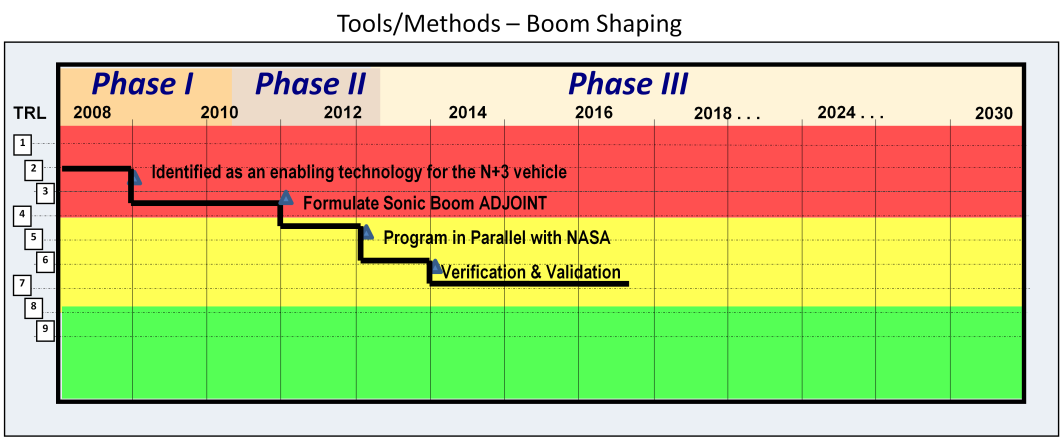


Figure 90.—Roadmap for tools/methods—low boom shaping fidelity.

Tools/Methods – CFD-Based MDAO

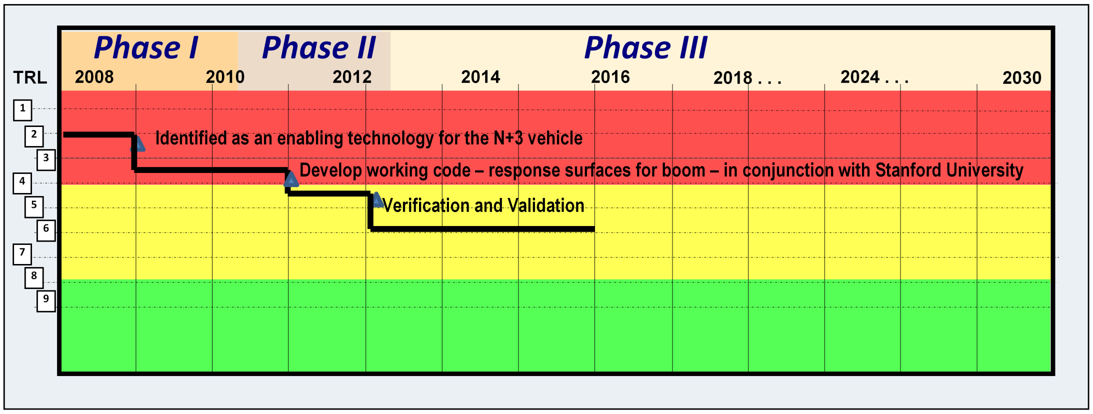


Figure 91.—Roadmap for tools/methods—CFD-based MDAO.

8.2 Tools/Methodologies—CFD-Based Adjoint Shape Optimization

8.2.1 Addressed N+3 Goals

- Efficiency
- Sonic Boom

8.2.2 Description

CFD has been identified as the necessary tool for accurate low sonic boom prediction. The implementation of an effective adjoint of sonic boom in CFD will greatly improve the effectiveness of low boom CFD-based design. Achieving low sonic boom with the highest performance efficiency possible requires final refinement of configurations with CFD-based design. Strong integration with CAD geometry definition will also be part of the process to insure geometric fidelity and final shapes practical for all disciplines, like smooth shapes for efficient structure.

8.2.3 Roadmap

The waterfall chart in Figure 91 shows the general outline of CFD-Based sonic boom adjoint MDO maturation plans from TRL 2-3 to TRL 6. Development of the tool is ideally done in conjunction with Universities and NASA, and then it must go through the verification and validation process. Total code development verification matures the technology to TRL 6 in approximately 2016.

8.3 Laminar Flow—Distributed Roughness with Plasma Augmentation

8.3.1 Addressed N+3 Goals

- Drag reduction
- Fuel efficiency

8.3.2 Description

The distributed roughness technology consists of distributed bumps on wing surfaces to create acoustic disturbances out of phase with cross-flow disturbances to maintain laminar flow on swept surfaces. This technology anticipates extending the laminar flow to the majority of the vehicle’s surface. Laminar flow reduces friction drag by 80 percent for the portion of the surface where it can be attained, greatly increasing fuel efficiency and range.

During the Phase II extension of the Quiet Supersonic Platform program conducted by DARPA, the Arizona State University research team headed by William Saric and Helen Reed conducted a series of tests in the NASA Langley 4 by 4 Unitary plan tunnel (UPWT) culminating during the period of January to February 2004. The UPWT work was designated as Task 6 of the overall ASU effort. The purpose of this task was to achieve NLF on a swept wing at Mach 2.17 using spanwise-periodic discrete roughness elements (now known as DRE)—a technology pioneered by William Saric and used in both high-speed and low-speed flow. The results at higher unit Reynolds numbers are encouraging and justify a continuation of this program of using DRE for NLF in supersonic flow sometime in the future.

Further technology development of distributed roughness is currently being conducted with Helen Reed, Bill Saric, and the Air Force Research Lab (AFRL) using plasma generation and spacing control of DREs to maximize NLF on the Revolutionary Configuration for Energy Efficiency (RCEE) program. The plasma can be generated with any desired roughness spacing for optimal effect at all flight conditions. This technology could also be used to prevent separation with shock/boundary layer interactions to improve efficiency. In addition to increased control for maximizing NLF, the plasma generator has many good operational features. It requires little power, has no moving parts, is flush mounted, is compact in size, and can be varied at high frequency.

8.3.3 Roadmap

Figure 93 highlights the maturation plan for plasma assisted natural laminar flow. Currently, wind tunnel work on the RCEE program in conjunction with AFRL and Reed/Saric at Texas A&M augments the overall maturation plan. Three additional maturation tests are required to bring the TRL from 3 to a 6. The first step is a subsonic flight test at Texas A&M. The second is a transonic flight test using a wing glove on a business jet. The third test, occurring well into Phase 3, includes a large scale supersonic flight test to push to TRL 6.

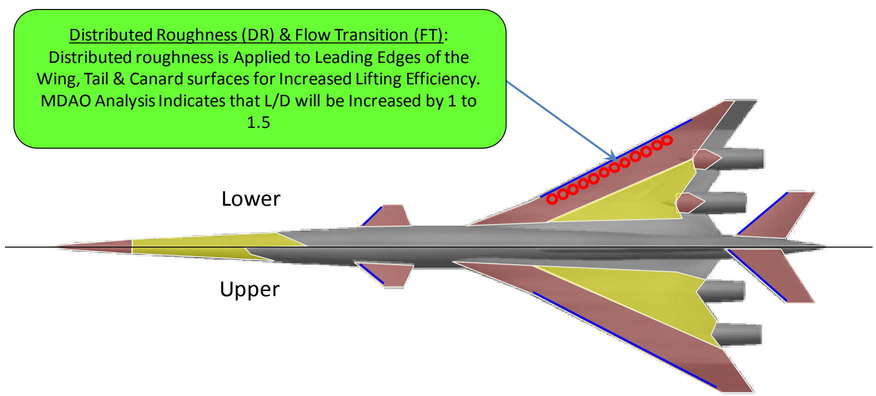


Figure 92.—Laminar flow technology benefits applied to advanced vehicle concept.

Laminar Flow – Plasma Augmented Distributed Roughness

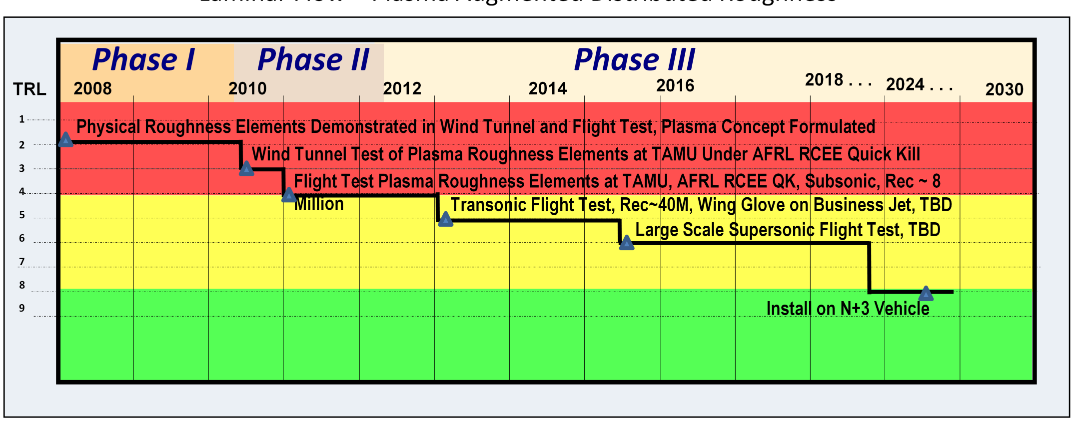


Figure 93.—Roadmap for laminar flow technology—plasma augmented distributed roughness.

Pilot Situational Awareness – Low Boom Violation Cueing

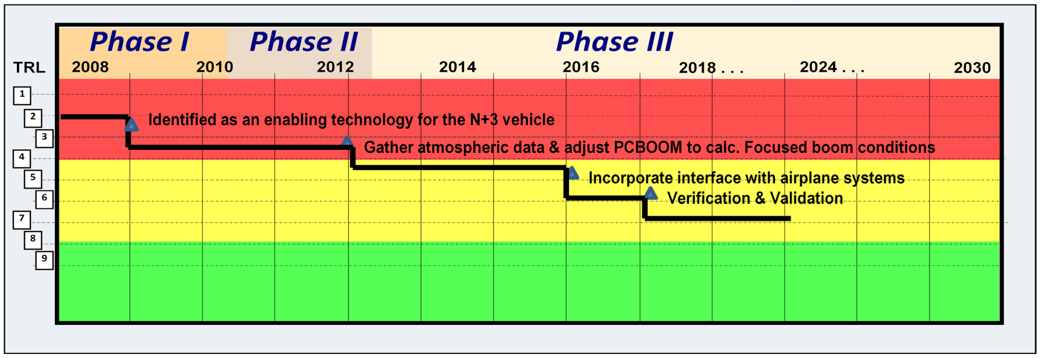


Figure 94.—Roadmap for pilot situation awareness—low boom violation cueing.

8.4 Pilot Situational Awareness—Low Boom Violation Cueing

8.4.1 Addressed N+3 Goals

- Boom Mitigation

8.4.2 Description

Low Boom Violation Cueing is a pilot situational awareness tool that is assumed to be developed first for the N+2 vehicle. It is included within this list because it has N+3 applicability's. The tool provides warnings on a heads-up display about maneuvers, turning rate limits, and accelerations that could trigger a breakdown of the vehicle's low boom characteristics. It also provides mach cut-off indication for flying without boom on the ground to further help minimize boom impact. This will enable lower speed supersonic flight even before acceptable low boom level regulations are implemented.

8.4.3 Roadmap

Figure 94 shows the general development plan for low boom violation cueing. The first step to mature the technology includes gathering atmospheric data, taking many ground measurements to quantify statistical scatter from predictions and adjusting PCBOOM code to calculate focused boom conditions. Results from that effort will be incorporated with airplane system interfaces. Lastly, verification and validation matures the code to TRL 6.

8.5 Pilot Situational Awareness—Preplanning Awareness

8.5.1 Addressed N+3 Goals

- Boom Mitigation
- Noise

8.5.2 Description

Preplanning awareness is a route planning and pilot situation awareness tool that is assumed to be developed for the first low boom vehicle, N+2. It is included within this list because it has N+3 applicability's. Preplanning awareness provides information about noise levels and flight path data to reduce boom impact over land. The tool can optimize over land operation and help plan routes to minimize sonic boom noise annoyance. Later incarnations can also help optimize airport noise abatement procedures for specific community routing, runways and engine throttling.

Pilot Situational Awareness – Boom/Noise Pre-planning Awareness

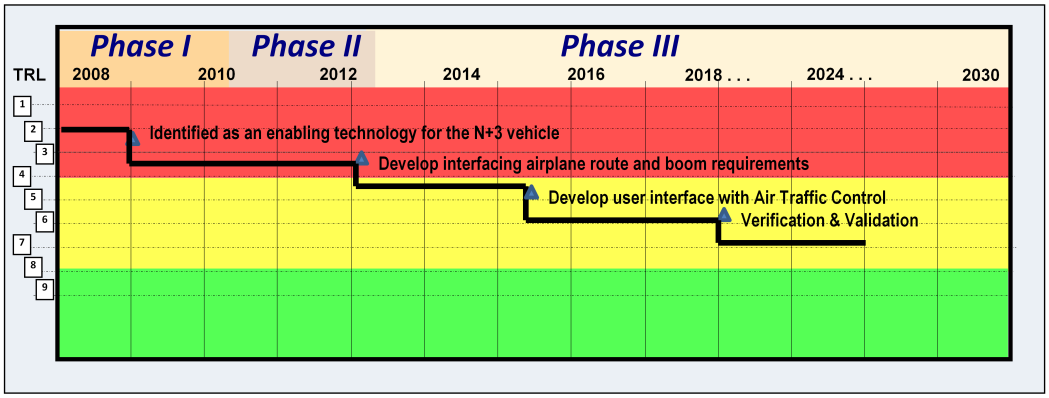


Figure 95.—Roadmap for pilot situation awareness—preplanning awareness.

8.5.3 Roadmap

Figure 95 highlights the maturation plan necessary for preplanning awareness. The first step is to develop prediction capabilities. Next, determine pilot interface and system interfacing requirements. Finally, pilot interfaces with ATC need to be developed, implemented and ultimately verified.

8.6 Tools/Methods—Integrated Structural Analysis

8.6.1 Addressed N+3 Goals

- Efficiency

8.6.2 Description

Low sonic boom design and optimization is initially performed simultaneously with aerodynamic optimization. Any method that provides the lift needed for boom also provides the drag and moment needed for aerodynamic efficiency. While both boom and aerodynamics are greatly dependant on vehicle surface geometry, another discipline is also greatly dependant on that geometry—structures. Structural strength and stiffness are even higher power functions (third and fourth) of thickness than drag (second) and rolls up into overall efficiency through structural weight. Further, since length and weight are primary parameters affecting boom, structural optimization is not only of primary importance to surface geometry design but strongly interacts with boom and aerodynamics. Based on their strong geometry design dependence, sonic boom, aerodynamics and structures will benefit from and employ the most sophisticated optimization methodology possible. Based on their strong interactions, further benefit should be achievable by optimizing all three disciplines in an integrated framework. Additionally, the particularly slender configurations of low boom designs will often need to employ more sophisticated structural analyses for flutter suppression, aeroelastic control, aero-servo-elasticity (ASE and even APSE, which adds propulsion interactions in designs without a tail or braced nacelle mount). The best methods for these sophisticated analyses need to be integrated into the low boom design framework so that all critical structural limitations are accurately addressed. Past commercial aircraft program trends have shown that investments in better initial design phases tends to pay-off greatly in reduced rework, lower overall development cost, lower recurring cost and better aircraft performance.

Tools/Methods– Integrated Structural Analysis

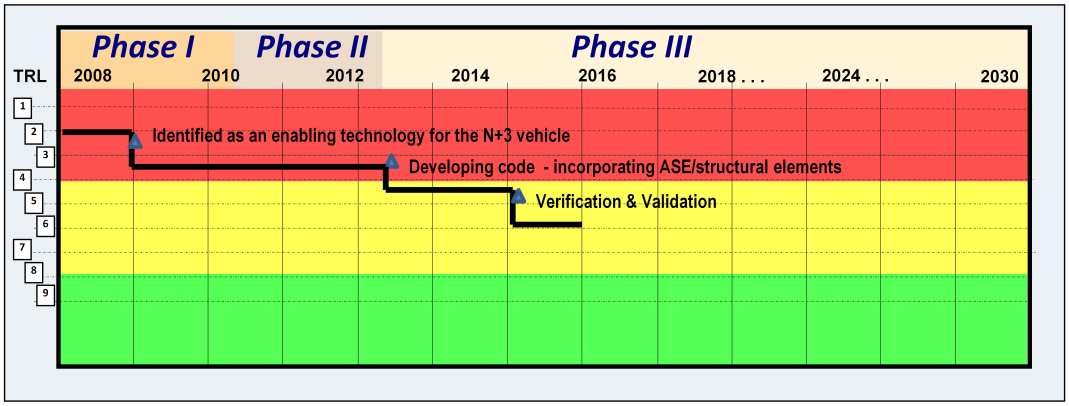


Figure 96.—Roadmap for tools/methods—integrated structural analysis.

8.6.3 Roadmap

Figure 96 illustrates a high-level maturation plan for integrated structural analysis. Much of the plan relies on the integration of structural tools developed outside of this supersonic program. Most structural tool development will be provided by third party software developers. They may need some guidance to insure that their tools can be integrated into the low boom design framework. Validation of software analysis needs to be performed on a representative low boom design. Following development needs to be requested from the third party software developers for any validation cases with unsatisfactory results. Additional support may be needed from the third party software vendor to integrate their tools effectively into the low boom framework.

8.7 Adaptive Geometry—Lift Distribution Control

8.7.1 Addressed N+3 Goals

- Efficiency
- Noise

8.7.2 Description

Adaptive geometry—lift distribution control is performed using shape-memory alloys or piezoelectric actuators to bend flexible surfaces without gaps. This adaptive geometry can improve control efficiency and reduce the overall airframe noise. Airfoils could also be optimized for over-water operation for improved lift distributions to increase range. Future research is needed to develop the methods and materials.

8.7.3 Roadmap

Figure 97 demonstrates the developments needed to mature lift distribution control. The first step is to demonstrate autonomous adaptive wing materials including tension/compression structures and tunable modulus composites. Next, the development of integrated shear stress sensing materials along with a wind tunnel demo of the 2–D integrated system brings the technology to TRL 4. TRL 6 is achieved with a 3–D system design, fabrication and a demonstration.

Adaptive Geometry – Lift Distribution Control

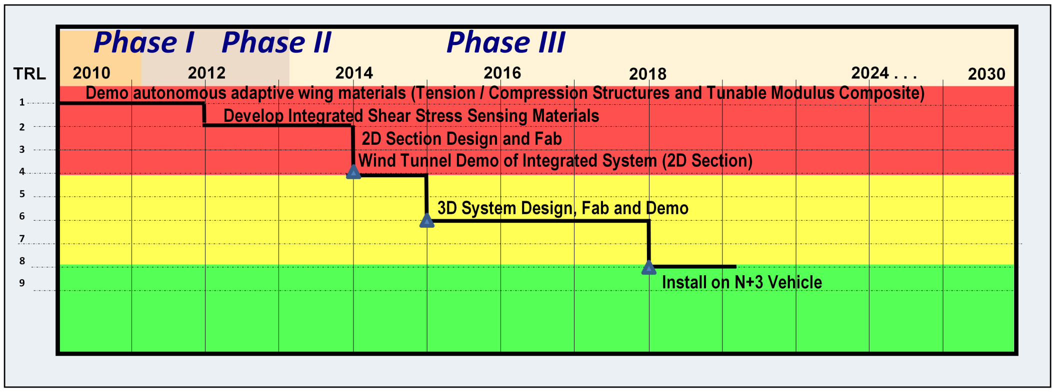


Figure 97.—Roadmap for adaptive geometry—lift distribution control.

8.8 Plasma—Jet Exhaust Manipulation

8.8.1 Addressed N+3 Goals

- Noise

8.8.2 Description

Jet Exhaust Manipulation uses high bandwidth and amplitude plasma actuators on the nozzle lip to adjust flow in such a way to reduce jet noise (and perhaps sonic boom). The technology development is currently being conducted by Dr. Samimy from Ohio State University. Research is needed to develop the most effective system: reduce power requirements, determine best amplitude, flow stream depth and circumferential location, frequency and circumferential modulation, and optimize integration with acoustic liners. The plasma effectiveness on the exhaust flow and mixing is enhanced by matching the natural eddy formation frequency. Further enhancement is achieved with circumferential variations and variation in strength, nozzle position and depth of plasma location. These parameters are just starting to be investigated on a simple conical jet. Thereafter, development will need to advance to the 3-stream nozzle flow of proposed VCEs (with perhaps a greater effectiveness potential).

8.8.3 Roadmap

Figure 98 demonstrates jet exhaust manipulation maturation plans continuing the simple nozzle studies with improved hardware to investigate the full range of effective power, position and frequency. Parallel efforts will model the flow effects and help to identify the most optimum plasma configuration, particularly for transition to the proposed multi-stream nozzle flow and integration with acoustic liners. Testing with the multi-stream nozzle set-up follows with multiple entries and final testing at near flight exhaust conditions and temperature and Reynolds number.

Plasma – Jet Exhaust Manipulation

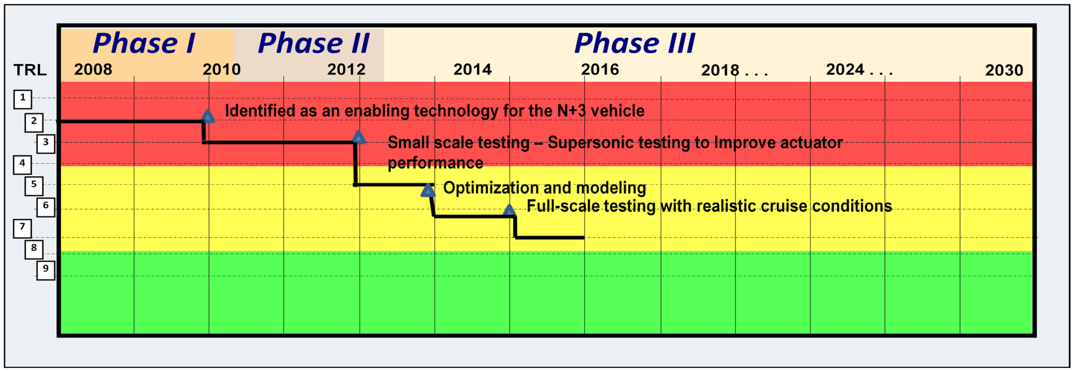


Figure 98.—Roadmap for plasma—jet exhaust manipulation.

Adaptive Geometry – Inlet Flow Control

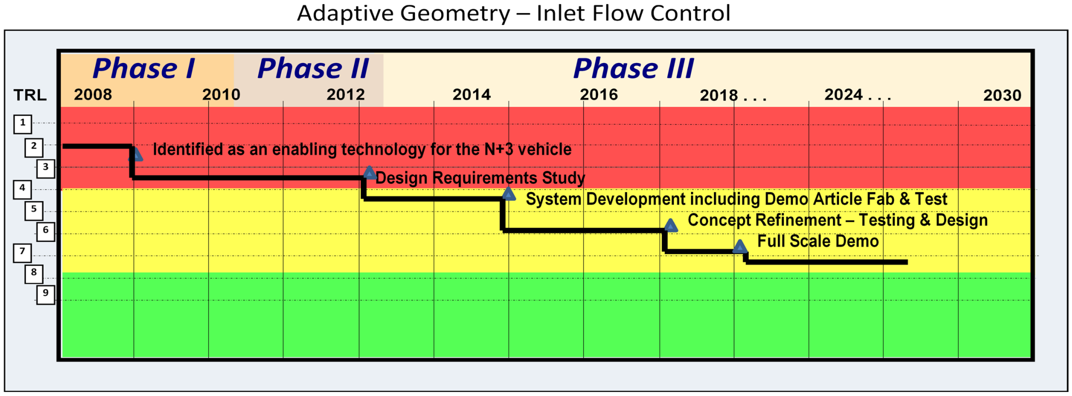


Figure 99.—Roadmap for adaptive geometry—inlet flow control.

8.9 Adaptive Geometry—Inlet Flow Control (Choking)

8.9.1 Addressed N+3 Goals

- Noise
- Efficiency

8.9.1.1 Description

Inlet Flow Choking uses variable geometry to choke the inlet at low speed. This technology reduces and prevents the fan noise from propagating out of the inlet. Development within LM has been conducted, but the technology has not been demonstrated. Research has also shown 10 to 20 percent increases in take-off and transonic thrust as well as 10 percent improvements in subsonic SFC. Additional research is required to mature and verify the technology.

8.9.2 Roadmap

Figure 99 illustrates a high-level maturation plan for the technology. First, a design requirements study guides the fabrication and testing of a demo. Next, concept refinement is done with additional design and testing. Ultimately, a full-scale demo brings the TRL to 6 in approximately 2018.

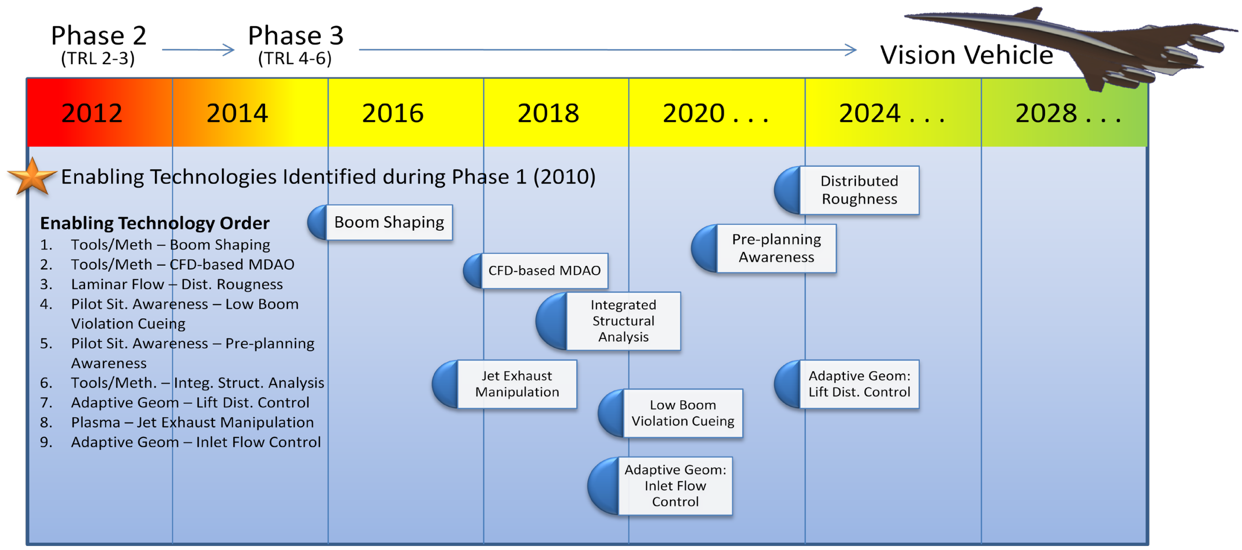


Figure 100.—Airframe technology roadmap for enabling supersonic technologies.

8.10 Technology Roadmap Overview

Figure 100 highlights the general timeline that each prioritized, enabling technology will reach a TRL 6. Assuming sufficient funding, all technologies are within an acceptable timeframe to apply to an N+3 demonstrator.

9.0 New Technology—Propulsion

Based on the initial technologies prioritized in Table 15, the process of designing the variable cycle propulsion system, and the assessment of how the propulsion system does relative to meeting the environmental goals, several technologies need to be developed for the proposed propulsion system. Technology development roadmaps are provided for the VCE, low noise/high performance nozzle, advanced low NOx combustor, ATMS, Transonic Thrust Augmentation device, and constant volume combustion. All of these technologies are included in GE's baseline propulsion system except for the constant volume combustion system. CVC was included in the roadmaps because the trade study, although relatively simple, does show significant SFC benefits and the current study didn't get into the system weight and installation portion, there is thought to be benefit to continuing to look at this technology.

9.1 VCE

9.1.1 Goals and Objectives

1. Develop advanced VCE for supersonic commercial application
2. Develop ATMS
3. The engine will meet the NASA emissions, efficiencies, and noise goals allowing the aircraft to meet sonic boom goals
4. The engine should be designed to achieve low SFC for supersonic while providing lightweight, high reliability and long life.

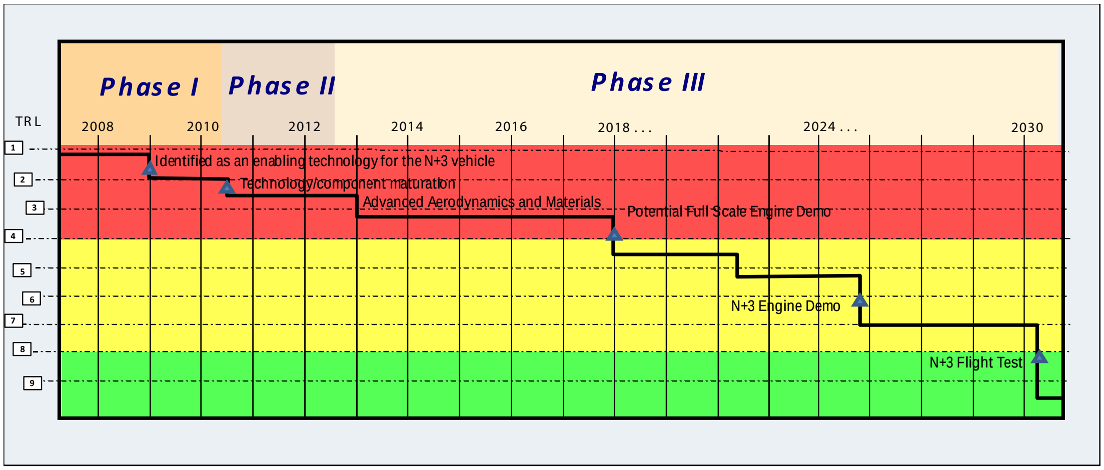


Figure 101.—Roadmap for VCE propulsion system.

9.1.2 Technical Description

The required elements to mature this propulsion system are outlined in Figure 101; the primary elements include technology and component maturation, continued advances and developments in advanced aerodynamics and materials.

An N+3 engine demo program could potentially start around 2019 depending on funding availability. It is anticipated that many of the required technologies may already be at TRL 6 before that, but some most likely will not. This N+3 engine demo program would provide the opportunity to mature the remaining technologies and verify the capability to proceed to the full system development program for the N+3 Supersonic program. The initial engine demo program is currently unfunded. The demo engine is the potential test bed for technology maturation to TRL 6. If this demo test bed does not occur then all the technologies will have to be matured to TRL 6 in the later N+3 engine demo.

9.2 Low Noise/High Performance Nozzle Exhaust

9.2.1 Goals and Objectives

1. Exhaust system that meets operability, performance, and noise goals, utilizing the cycle based on the VCE.
2. Exhaust system to meet NASA N+3 Airport Noise Goal—Stage 3—20 to 30 EPNdB
3. High nozzle performance throughout flight envelope.
4. Light weight, high reliability, variable geometry

9.2.2 Technical Description

Propulsion system studies have shown that an advanced VCE with an exhaust system comprised of an Axi-Plug nozzle with jet noise reduction features can meet the N+3 supersonic airport noise goals. The basic Axi-Plug nozzle provides high performance with variable geometry. The VCE enables the jet noise reduction features in the nozzle.

9.2.3 Roadmap

Figure 102 shows the roadmap for the low noise/high performance exhaust system.

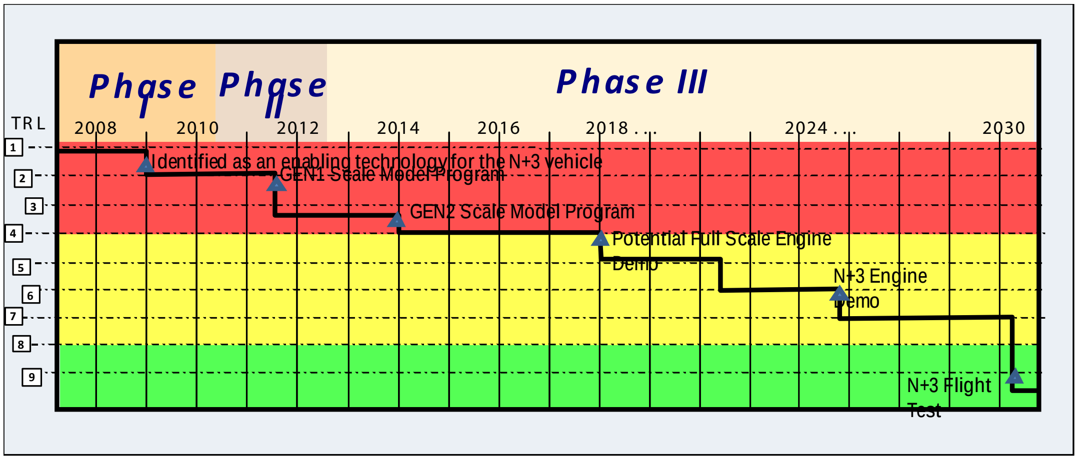


Figure 102.—Low noise/high performance exhaust system roadmap.

The next step in the roadmap is to design, fabricate, and test an exhaust system consisting of the Axi-Plug nozzle jet noise reduction technologies. This will verify how these technologies work together. After that an exhaust system could potentially be matured in the potential engine demo or an N+3 engine demo.

9.3 Advanced Low NOx Combustor

9.3.1 Goals and Objectives

1. Develop advanced combustor with enhanced premixing capable of achieving EINOx = 5 at supersonic cruise conditions.
2. Develop advanced materials and cooling technologies to reduce cooling flow requirements.
3. Evaluate and develop advanced piloting systems to approach entitlement emissions, and improve combustion dynamics/stability.

9.3.2 Technical Description

Various system level approaches need to be examined to achieve the aggressive N+3 emission goal of EINOx = 5 at cruise conditions. If a variant of the single-stage Twin Annular Premixed Swirler (TAPS) combustor will be used, substantial improvements in mixing effectiveness will be required to create a lean-burn premixed combustion system capable of achieving these low NOx levels. If a TAPS variant is not feasible, other advanced mixing concepts such as Lean Direct Injection (LDI) or Accelerating Swirler Passage (ASP) may be employed to achieve a near-perfectly premixed condition.

Advanced cooling technology must be developed, which will reduce the amount of cooling flow needed and direct more air to the mixer. New materials such as Ceramic Matrix Composites (CMC) can be used to construct the combustor to reduce cooling requirements as well.

Advanced piloting systems will be evaluated and developed, which will eliminate the high NOx production from the traditional pilot diffusion flame, and improve combustion dynamics/stability.

9.3.3 Roadmap

The combustor roadmap is shown in Figure 103. At the start of the supersonic N+3 program, the combustor was identified as the key enabling technology to achieve the N+3 cruise NOx goal. A NASA-funded combustor program is already underway aimed at supersonic vehicles and will be able to provide important information towards achieving this goal. The supersonic N+1 program plans on delivering hardware by mid-2010.

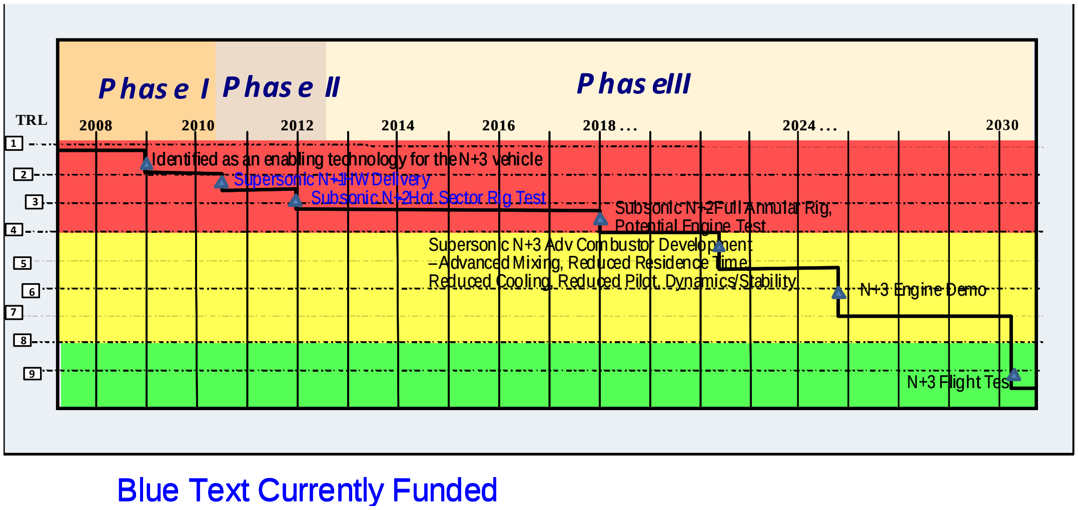


Figure 103.—Low emission combustor roadmap.

Based on information obtained from these programs, the supersonic N+3 combustor program should develop advanced concepts in rapid mixing, reduced residence time, reduced cooling, reduced pilot contribution, and increased flame stability, by approximately 2022. To be in service by the 2035 timeframe, an engine demo (TRL–6) would be required by about 2025, followed by a flight test by about 2031.

9.4 ATMS

9.4.1 Goals and Objectives

1. Develop ATMS that permits high OPR operation at supersonic cruise conditions
2. Minimal impacts on duct losses or overall engine performance.
3. Light weight, high reliability, long life

9.4.2 Technical Description

The propulsion system gets a significant SFC improvement by running very high OPRs, but in doing so the T3 gets very high. Analysis has shown the ATMS system to contribute a significant improvement in SFC.

9.4.3 Roadmap

Figure 104 shows the roadmap for the development and maturation for the ATMS system for the N+3 Supersonics application. The first step is a core engine demonstration. After this a heat exchanger appropriate for the N+3 supersonic application could be developed in preparation for an engine demonstration.

9.5 Transonic Thrust Augmentation Device

9.5.1 Goals and Objectives

1. Develop advanced augmenter capable of moderate ΔT augmentation for thrust boost at critical thrust pinched flight points
2. Minimal impacts on exhaust or overall engine performance.
3. Requires no flame holders or spray bars
4. Light weight, high reliability, long life

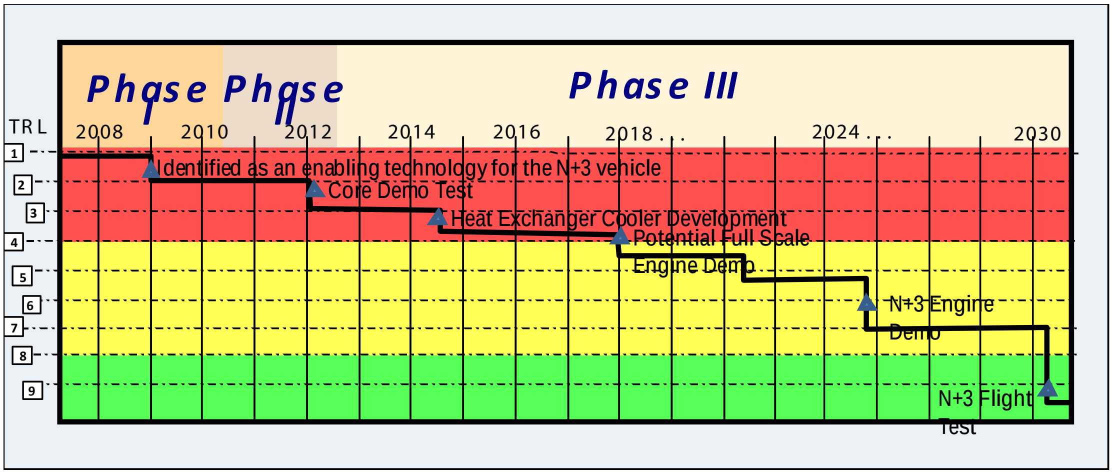


Figure 104.—Cooled cooling air roadmap.

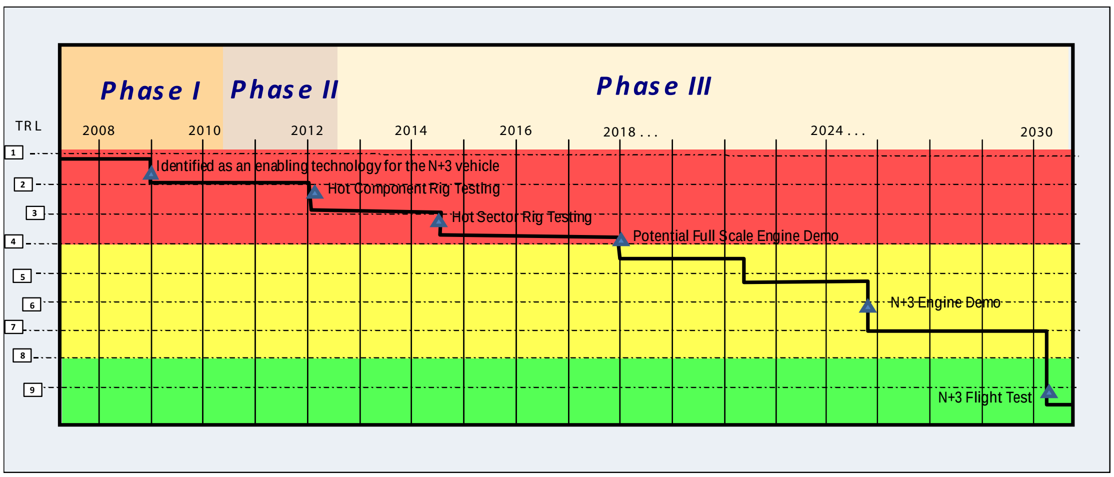


Figure 105.—Transonic thrust augmentation device roadmap.

9.5.2 Technical Description

Previous internal work has evolved a Transonic Thrust Augmentation device. This lightweight simple system is capable of producing a large localized temperature augmentation, which mixes out quickly with minimal hot streak footprints that increases the overall temperature of the exhaust gases by a moderate amount while producing almost negligible losses.

9.5.3 Roadmap

Figure 105 shows the roadmap for the Transonic Thrust Augmentation device. The next steps are hot component then hot sector tests leading to an engine test.

9.6 CVC Roadmap

9.6.1 Goals and Objectives

1. Develop CVC for VCE to improve SFC.
2. Minimal impact to system.
3. Light weight, high reliability and long life.

9.6.2 Technical Description

Due to the current low TRL and complexity the initial development of incorporating CVC in a gas turbine is expected to occur for a nonaviation application and then leveraged for aviation applications.

9.6.3 Roadmap

Figure 106 shows the roadmap for the development of CVC.

9.7 Technology Roadmap Overview

Figure 107 highlights the general timeline that each prioritized, enabling technology will reach a TRL 6. Assuming sufficient funding, all technologies are within an acceptable timeframe to apply to a N+3 demonstrator.

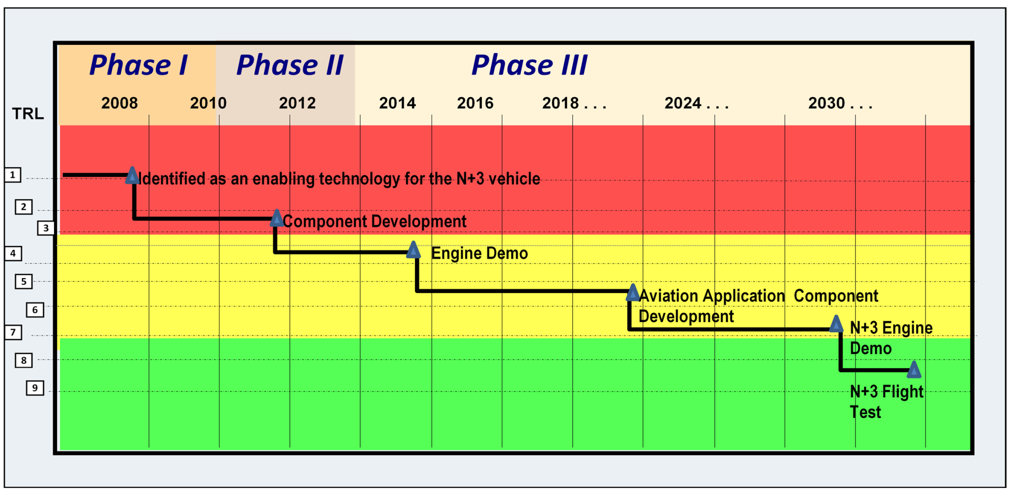


Figure 106.—CVC roadmap.

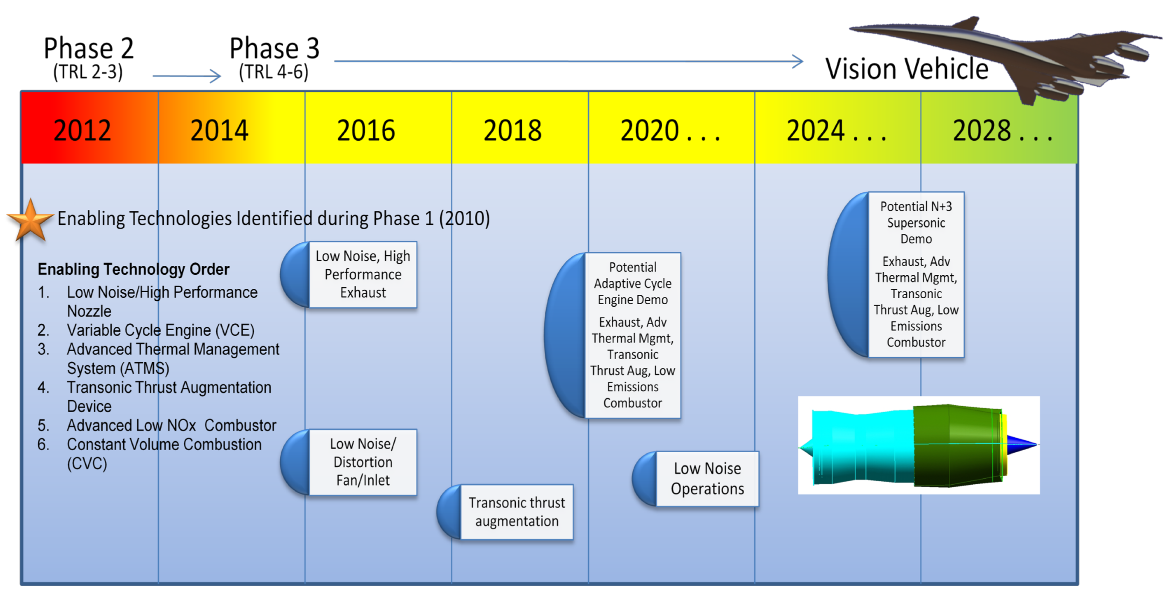


Figure 107.—Technology roadmap overview for propulsion technologies.

10.0 Conclusions

10.1 Tasks and Trade Studies—Airframe

10.1.1 Advanced Concept Vehicle Definition

An initial concept with an inverted V-tail and under the wing engine placements was drawn as a reference to compare alternative configurations. After exploring the configuration design trade space it was concluded that the inverted V-tail configuration with under the wing engine placements provided the best platform to achieve the N+3 goals. Figure 108 highlights the final configuration that was ultimately sized to have a gross takeoff weight was 285,000 lb, with a thrust to weight ratio of 0.34 and a wing loading of 92 psf.

The final wing, canard and tails were optimized to reduce the sonic boom with minimal aerodynamic efficiency reduction. This optimization resulted in a reduction of the 1.38 psf max shock to 0.29 psf, and a reduction in L/D from 10.1 to 8.0. Distributed roughness and plasma technologies are outlined in the technology roadmaps as solutions to increase the L/D and achieve the 4000 to 5500 nmi range and 3.5 to 4.5 pax-nmi/lb-fuel fuel efficiency goals.

10.1.2 Rapid Conceptual Design Low-Boom Design Process or Design Space Trade Studies

LM’s Rapid Conceptual Design (RCD) framework was instrumental in demonstrating that a low-boom aircraft, with adequate technologies, is able to meet the N+3 noise and mission performance goals. RCD was used to generate the target signature corresponding to an average loudness of 70 PLdB, shape lifting surfaces to meet that signature, size the N+3 configuration, and investigate the benefits of key technologies.

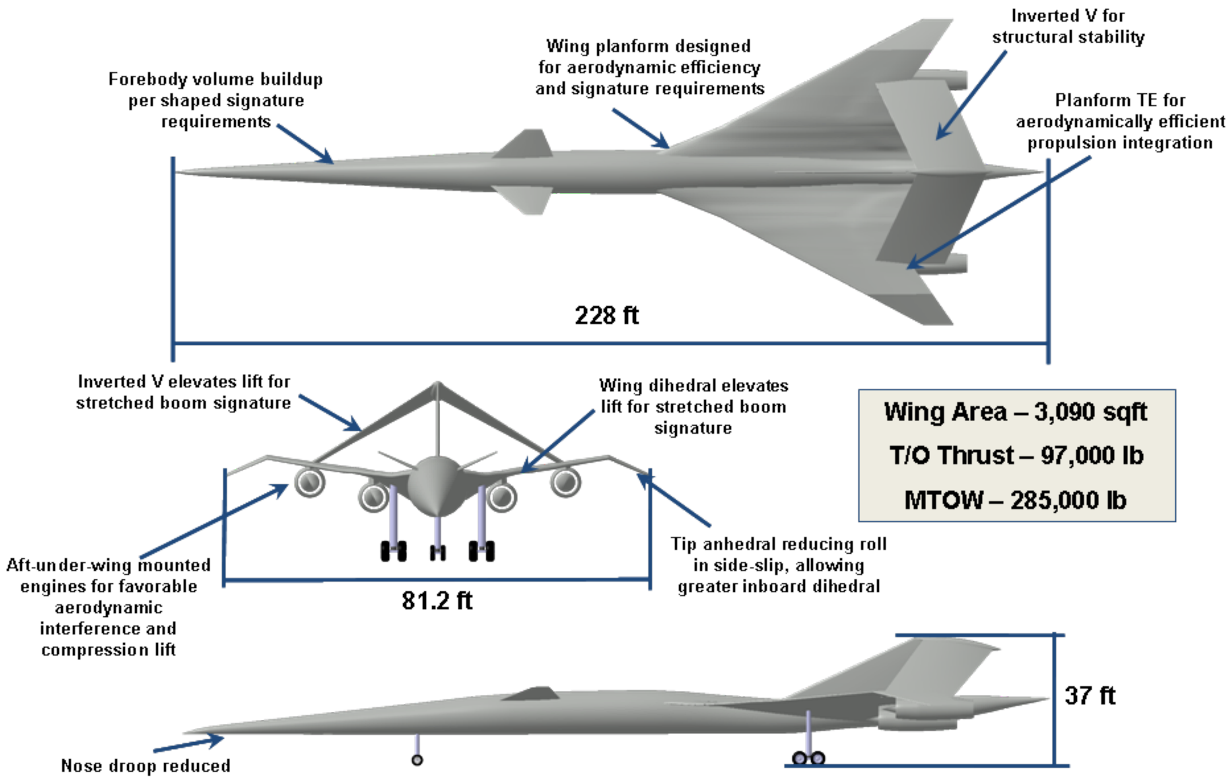


Figure 108.—Final configuration three-view.

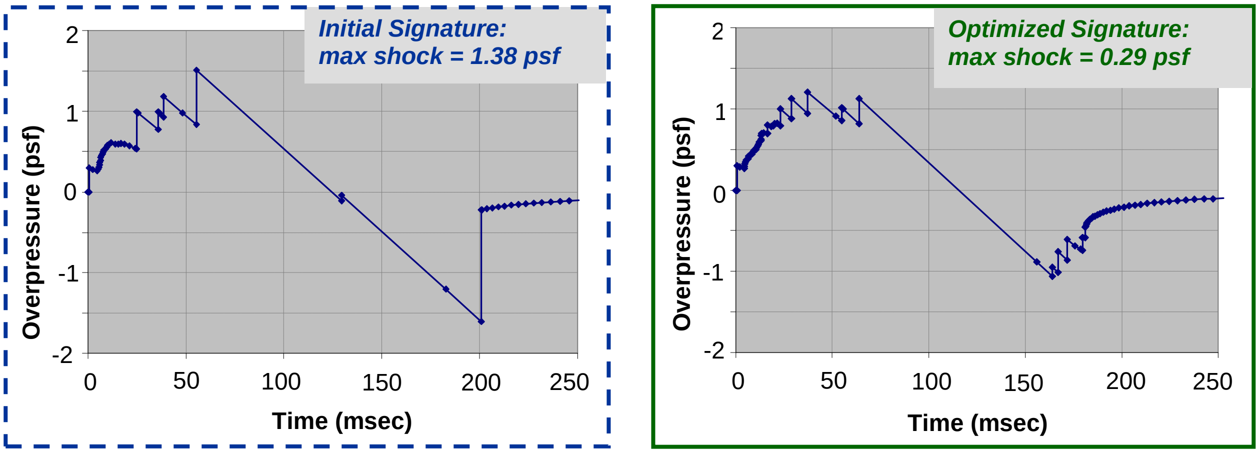


Figure 109.—Ground signature before and after aero/boom shape optimization

RCD-based aerodynamic/boom shape optimization was used to shape the surfaces of the wing, inverted V-tail, and canard to ensure that the aircraft's ground signature conformed to the established, 70-PLdB target. This markedly improved the aircraft's ground signature as shown in Figure 109, and was accomplished by adjusting the camber slope at 20 specific locations to redistribute the configuration's equivalent area distribution. Although the boom-optimized shape exhibited a lift-to-drag ratio approximately 21 percent lower than that of a purely minimum-drag shape, aerodynamic technologies such as NLF can counteract this effect and enable the N+3 vehicle to maintain mission performance that complies with its payload, range, speed, and efficiency goals.

RCD was subsequently used to size the configuration for maximum range at 285,000 lb MTOW. This resulted in a thrust-to-weight ratio and wing loading of 0.34 and 92 psf, respectively. Sizing was based on the VCE with thrust augmentation technology, which enabled the aircraft to achieve a balanced field length of 9970 ft. This engine also enabled the N+3 aircraft to reach 40,000 ft in 22 min, permitting it to climb above existing subsonic traffic prior to accelerating to Mach 1.6. The sized configuration's range was limited by available fuel volume; morphing structure technology could relieve this constraint and increase range.

10.2 Tasks and Trade Studies—Propulsion

Preliminary designs for a VCE and two nonvariable mixed flow turbofans (MFTF) were developed using the Numerical Propulsion System Simulation (NPSS) code as part of the NASA N+3 supersonic program. This program studied advanced airframe and propulsion concepts for a supersonic commercial passenger airplane in the 2035 timeframe. In particular, the program set challenging noise, emissions, and efficiency requirements for an environmentally friendly aircraft. The proposed engine concept incorporated advanced technologies such as ATMS permitting high OPR and thermal efficiency, an Axi-Plug exhaust with Noise Reduction Technologies, and a Transonic Thrust Augmentation device. The two MFTF engines did not use the Noise Reduction Technologies in the exhaust. The studies showed that noise and performance goals could be met by the VCE and the first MFTF within the context of continuing development of advanced technologies. The emission goal is projected to be met with the VCE and first MFTF propulsion systems through a combination of a more advanced TAPS type combustor and a small decrease in the peak temperature in the engine. To take advantage of the full thermal capability of these propulsion systems would require even more advanced technologies not previously considered, and alternate combustor or combustion approaches. The final engine was an “Optimized” cruise engine, which ignored the airport noise and emissions goals and focused solely on fuel efficiency in the smallest lightest propulsion system.

GE developed preliminary designs for a VCE and a MFTF propulsion system to meet the thrust requirements and program metrics, provided by LM. The overall efficiency figure of merit for both is projected to be better than the goal. Airport noise and assessments were performed for these propulsion systems and both are projected to meet the goal. The third "Optimized" cruise MFTF engine designed at a higher FPR provides the best FOM but would not meet the acoustic and emissions goals. An NPSS customer deck was developed for the VCE Propulsion System.

Cruise emission assessments were performed and the maximum T4 of the engine must be reduced to meet the cruise NOx goal. This results in a relatively small impact to SFC and propulsion weight for the VCE propulsion system. Other combustor concepts may be developed to regain the maximum thermal capability of this VCE in the future. The cruise "optimized" engine was not designed to meet the emissions goal.

10.3 System of Systems Analysis

The N+3 vehicle's impact on the civil air transport system (ATS) was analyzed by Purdue University in terms of productivity (passenger * knots), environmental impacts (carbon dioxide and NOx emissions), and fleet direct operating costs (DOC). Optimal allocations of N+3 supersonic transports- defined as that which maximizes either productivity or passenger time saved- were determined for various future scenarios, which were established by projecting different rates of N+3 availability and passenger demand growth. Maximum fleet-wide productivity was calculated for different limits on fleet CO2, establishing the trade space between ATS productivity and emissions in the presence of N+3 SST's. More importantly, SST's were consistently allocated to routes of 3000 to 5000 nmi, which is consistent with the N+3 range goal of at least 4000 nmi.

The impact of N+3 operations on the demand for airports and airspace, assessed by LM Transportation and Security Solutions, will require some additional airport capacity during peak hour operations. However, most operations are likely to be scheduled during the periods of nonpeak conventional operations and will therefore take advantage of currently unused airport capacity. Furthermore, N+3 route networks between various airports are fairly well separated (assuming they are able to fly great circle routings) even for busy air corridors. Departure climbs to 10,000 ft at low speed are contained within 21 current National Air Traffic System (NAS) departure sectors; higher subsonic climbs to 23,000 ft involve nine additional, current sectors. A marginal increase in air traffic complexity and controller workload is predicted during these phases. The most significant increases in air traffic complexity and controller workload are incurred by the N+3's transonic acceleration and supersonic climb, which lead to potential conflicts with existing subsonic traffic. These conflicts are most likely to occur between 34,000 and 39,000 ft; therefore, they can likely be alleviated by using the VCE to move transonic acceleration to 40,000 ft.

10.4 Technology Roadmaps—Airframe

Technology prioritization was done by calculating value in terms of the overall benefit of the technology to the air vehicle, probability of success, and the cost to develop that technology to a TRL 6. Each technology was then prioritized and put into the following roadmap format, Table 15, to illustrate the enabling airframe technologies required to realize an environmentally friendly vision vehicle. Risk analysis and maturation plans demonstrated that each technology addressed an N+3 goal and was capable of maturation within the 2030 to 2035 timeframe. It was also determined that different technologies were applicable to N+1 and N+2 air vehicles. These technologies, including low boom violation cueing and preplanning awareness (highlighted in the table), were added to the final technology list, but it assumed that they will be developed under other N+2 program efforts.

TABLE 15.—PRIORITIZED AIRFRAME TECHNOLOGY ROADMAP

Priority no.	Category	Prioritized, enabling N+3 technology	Addressed N+3 goal	Vehicle benefit	Current TRL level	Vehicle application	Availability timeframe (TRL = 6)
1	Tools/ methods	Low boom shaping	Boom mitigation	Optimized boom configuration capable of achieving 70 PLdB	1-2	N+2 and N+3 supersonic application	~2015
2	Tools/ methods	CFD-based MDAO	Boom mitigation	Optimized boom configuration capable of achieving 70 PLdB	2-3	N+3	~2016
3	Laminar flow	Distributed roughness	Fuel efficiency, range	L/D +1 to 1.5, Increased efficiency at higher Machs, less friction/drag, reduction in aircraft wt.	3	N+2 and N+3 supersonic application	~2022
4	Pilot situational awareness	Low boom violation cueing	Boom mitigation	In-flight boom intelligence, reduced sonic boom, operation within FAA limits	1-2	N+2	~2018
5	Pilot situational awareness	Boom/noise preplanning awareness	Boom mitigation	Intelligent/Boom conscience route finding, operation within FAA limits	1-2	N+2	~2020
6	Tools/ methods	Integrated structural analysis	Efficiency	Optimized empty weight design	1-2	N+3	~2017
7	Adaptive geometry	Lift distribution control	Efficiency, noise	Adaptive airfoils to optimize range	2-3	N+3	~2018
8	Plasma	Jet Exhaust Manipulation	Noise	Reduced nozzle PLdB noise by 6 to 8 dB	2-3	N+3	~2016
11	Adaptive geometry	Inlet flow control	Noise, efficiency	Reduced inlet fan noise with improved efficiency (+10% inc in take-off thrust and transonic thrust. Plus 10% subsonic SFC improvement)	2-3	N+3	~2018

Recommended future technology development efforts for airframe technologies include:

- Concentration on supersonic specific technologies for the N+3 vehicle to ensure serviceability in the 2030 to 2035 timeframe
  - Tools/methods
  - Laminar flow
  - Adaptive geometry
- First, develop low cost, high impact tools and methodologies such as Multi-Fidelity Low Boom Shaping and CFD-based MDAO to achieve low boom levels with minimum aerodynamic efficiency impacts and the most overall, multi-disciplinary optimum design.
- Second, advance distributed roughness with plasma augmentation to achieve the maximum laminar flow possible by the N+3 timeframe
- Third, promote adaptive geometry technologies and mature adaptive geometry applications to maximize N+3 fuel efficiency.

10.5 Technology Roadmaps—Propulsion

GE and Lockheed jointly assessed the most beneficial technology elements of the propulsion system. These are highlighted in Table 16. Technology roadmaps were developed for these items, leading to appropriate technology readiness level progression for the N+3 timeframe.

A list of key items for future work is listed below:

- Currently funded DOD programs are continuing the development of many of the VCE technologies.
- The Transonic Thrust Augmentation device is a critical technology to continue developing.

- The currently funded NASA Supersonics Low Emissions combustor program will provide key validation data for high temperature NOx levels, and the maturation of some enabling technologies. Alternate combustor/combustion concepts need to be explored, as these propulsion systems are developed to take advantage of the full thermal capability of the system.
- Predictive and design tool development in many areas need to be continued to be developed. Aero-acoustics, both fan and jet noise tools are not at a stage to provide direct quantitative design inputs. Combustion and Emissions is another area where continued tool development is critical

TABLE 16.—PRIORITIZED PROPULSION TECHNOLOGY ROADMAP

Priority no.	Prioritized, enabling N+3 technology	Addressed N+3 goal	Vehicle benefit	Current TRL level	Vehicle application	Availability timeframe (TRL = 6)
1	Low noise/high performance nozzle	Airport noise, fuel efficiency	Meet noise and efficiency goal	3	N+3	~2015
2	VCE	Airport noise, fuel efficiency, sonic boom	Smaller, lighter propulsion system that meets airport noise goals	3	N+3	~2016
3	ATMS	Fuel efficiency, sonic boom	Higher temperature capability, higher OPR for smaller, lighter, more efficient propulsion system	3	N+3	~2022
4	Transonic thrust augmentation device	Airport noise, fuel efficiency, sonic boom	Smaller, lighter engine, potential airport noise benefit	2	N+3	~2018
5	Advanced low NOx combustor	Cruise emissions	Meet cruise emissions	3	N+3	~2020
6	CVC	Fuel efficiency	Fuel efficiency	2	N+3	~2017

10.6 Meeting NASA N+3 Goals

Our integrated airframe and propulsion system, along with identified technologies, is projected to meet or exceed all N+3 targets. Results of the environmental and performance characteristics of our advanced vehicle concept with technology inputs are summarized in Table 17.

TABLE 17.—LM'S PREFERRED CONCEPT WITH CRITICAL TECHNOLOGY MEETS OR SURPASSES ALL N+3 GOALS

	NASA N+3 Efficient MultiMach Aircraft (Beyond 2030)	N+3 Goal Status
Environmental Goals		
Sonic Boom	65 to 70 PLdB low boom flight 75 to 80 PLdB unrestricted flight	70 to 76 PLdB KEY GOAL
Airport Noise	20 to 30 EPNdB (cumulative below stage 3)	18.4 (32.2 jet only) KEY GOAL
Cruise Emissions (g/kg fuel)	<5 EINOx Plus particular and water vapor mitigation	5 EINOx
Performance Goals		
Cruise Speed	Mach 1.3 to 2.0 low boom flight Mach 1.3 to 2.0 unrestricted	Mach 1.6
Range	4000 to 5500 nmi	4850 nmi
Payload	100 to 200 pax	100 pax
Fuel Efficiency	3.5 to 4.5 (pax-nmi/lb-fuel)	3.64 (pax-nmi/lb-fuel) KEY GOAL

Appendix A.—Acronym List

AFRL	Air Force Research Laboratory
ANSI	American National Standards Institute
ASA	Absorption of Sound by the Atmosphere
ASDI	Aircraft Situation Display to Industry
ASE	Aero-Servo Elasticity
ASP	Accelerating Swirler Passage
AST	Advanced Supersonic Transport
ATC	Air Traffic Control
ATM	Air Traffic Management
ATMS	Advanced Thermal Management System
ATS	Air Transportation System
BFL	Balanced Field Length
BIMS	Biologically Inspired Morphing Structures
BPR	Bypass Ratio
CAD	Computer Aided Design
CAEP	Committee on Aviation Environmental Protection
CDP	Compressor Discharge Pressure
CFD	Computational Fluid Dynamics
CFG	Gross Thrust Coefficient
CG	Center of Gravity
CMC	Ceramic Matrix Composite
CPR	Core Pressure Ratio
CVC	Constant Volume Combustion
DBD	Dielectric Barrier Discharge
DDT	Deflagration-to-Detonation Transition
DFM	Departure Flow Manager
DOC	Direct Operating Costs
DOD	Department of Defense
DRE	Distributed Roughness Elements
EBC	Environmental Barrier Coatings
EINOx	Emission Index for NOx
EIS	Entry Into Service
EPNL	Effective Perceived Noise Level
ETMS	Enhanced Traffic Management System
FAA	Federal Aviation Administration
FAR	Fuel/Air Ratio
FHV	Fuel Heating Value
FOM	Figure of Merit
FPR	Fan Pressure Ratio
GE	General Electric

GRC	Global Research Center
GTOW	Gross Takeoff Weight
HPT	High Pressure Turbine
HTEX	Heat Exchanger
HX	Heat Exchanger
IML	Inner Mold Line
IR&D	Internal Research & Development
IRP	Intermediate Rated Power
ISA	International Standard Atmosphere
KCAS	Knots Calibrated Airspeed
KEAS	Knots Equivalent Airspeed
LCTR	Large Civil Tiltrotor
LDI	Lean Direct Injection
LLI	Late Lean Injection
LM	Lockheed Martin
LMCO	Lockheed Martin Corporation
LPT	Low Pressure Turbine
LTO	Landing and Takeoff
MDAO	Multi-Disciplinary Analysis and Optimization
MFR	Mass Flow Ratio
MFTF	Mixed Flow Turbofan
MN	Mach Number
MTOW	Maximum Takeoff Weight
NAS	National Air Transportation System
NLF	Natural Laminar Flow
NOx	Nitrogen Oxides
NPR	Nozzle Pressure Ratio
NPSS	Numerical Propulsion System Simulation
NRA	NASA Research Announcement
OD	Outer Diameter
OEI	One Engine Inoperative
OEW	Operational Empty Weight
OML	Outer Mold Line
OPR	Overall pressure ratio
OTA	Open Travel Alliance
PAI	Propulsion/Airframe Integration
PAX	Passenger
PC	Power Code
PDC	Pulse Detonation Combustor
PDE	Pulse Detonation Engine
PLdB	Perceived Loudness Decibels

PLR	Programmed Lapse Rate
PR	Pressure Ratio
P-RNAV	Precision Route Navigation
QSST	Quiet Supersonic Transport
RCD	Rapid Conceptual Design
RH	Relative Humidity
RNAV	Route Navigation
RNP	Required Navigation Performance
ROC	Rate of Climb
RQL	Rich Quench Lean
RVSM	Reduce Vertical Separation Minimum
SERN	Single Expansion Ramp Nozzle
SF	Scale Factor
SFC	Specific Fuel Consumption
SLS	Sea Level Static
SOA	State of the Art
SST	Supersonic Transport
TAPS	Twin Annular Premixed Swirler
TOC	Top of Climb
TOFL	Takeoff Field Length
TOGW	Takeoff Gross Weight
TRL	Technology Readiness Level
TSS	Transportation and Security Solutions
UAS	Unmanned Aircraft System
UPWT	Unitary Plan Wind Tunnel
VCE	Variable Cycle Engine
VLJ	Very Light Jets
WBS	Work Breakdown Structure

Appendix B.—Enabling Technologies

Table B.1 through Table B.4 show enabling technologies.

TABLE B.1.—N+3 SUPERSONIC TECHNOLOGY LIST—BOLT-ON TECHNOLOGIES

Technology	Source	Category	Description	Benefits	Drawbacks	N+3 goals addressed	Readiness	Comments
Engine: GE Global Research Center: Propulsion, Noise, Emissions, Fuel								
Adaptive cycle engine	GE	Propulsion	Advanced turbofan engine with adaptive cycle features	Fuel burn, noise	Complexity	Efficiency, noise, emissions	TRL 3	
Contrail elimination through microwaves	Literature	Propulsion	Emit microwaves into jet plume to heat water vapor and delay formation of ice crystals	Can reduce or eliminate contrails	Weight, 0.1% engine power (claimed)	Emissions	Researched by Cranfield University, Rolls Royce filing patent for technology	Sounds a lot better than flying at 25,000 ft. If the claims of minimal engine power are true, this could be a very effective way to address contrail formation
High aspect ratio nozzle	N+3 kickoff meeting brainstorm	Propulsion	Increase frequency of jet noise to levels where it would be better attenuated in the atmosphere	Reduces noise	Adds weight and volume for nozzle duct, thrust penalties	Noise	High-TRL, can be done	Not the most effective means of reducing noise, you need to get to about AR 10 before seeing much of any benefit and that requires a large duct
Embedded engine accessories	LM configuration brainstorming session	Propulsion	Engine accessories better packaged in engine architecture	Reduces nacelle size by eliminating accessory box		Efficiency, boom	Engine architecture design	May be packaging issues, may not get the distribution desired
Fluid shield	GE	Noise	Asymmetric outer layer in jet plume, use lower surface bypass air to shield noise from core	Reduces noise without much penalty	Weight and efficiency penalties of ducting the flow	Noise	Research phase, might have been lab tested	Some benefit to jet noise.
Actuated core exhaust chevrons	Peter Coen's tech list (NASA internal, Ron Noebe)	Noise	Chevrons are actuated using shape memory alloys, retracted after takeoff to eliminate thrust penalties	Reduce noise with no cruise efficiency penalty	Complexity, maybe weight	Efficiency, noise	Being researched with NASA NRAs	Small benefit to efficiency
Scarfed nozzles	Penn State (McLaughlin & Morris)	Noise	Nozzles are "beveled" or "scarfed" on the bottom to direct noise upward	Reduces jet noise from sources close to the nozzle exit		Noise	Lab tested	Low cost way to reduce jet noise. Would work well with inverted velocity profile since more prominent sources are close to nozzle exit
Tunable resonators	Penn State (McLaughlin & Morris)	Noise	Precisely positioned arrays of resonators that generate an anti-phase secondary sound field at the tip of the rotor-stator interaction in axial flow high pressure fans.	Reduces fan noise by cancelling tones at the blade passage frequency and higher harmonics	Weight and complexity	Noise	Lab tested	Resonators are passive which makes concept less complex. Noise cancellation results sound encouraging. Doesn't address fan broadband noise however, just rotor-stator tones

TABLE B.1.—N+3 SUPERSONIC TECHNOLOGY LIST—BOLT-ON TECHNOLOGIES

Technology	Source	Category	Description	Benefits	Drawbacks	N+3 goals addressed	Readiness	Comments
Internally mixed nozzles	Penn State (McLaughlin & Morris)	Noise	Efficient mixing of the fan flow with the core flow can produce a jet that will produce less noise without sacrificing thrust.	The estimated benefits are of the order of 2 dB should the conditions be ideal.	Weight from mixer shroud, slight performance penalty	Noise	Has been demonstrated in the laboratory and in small scale engines in some engine conditions.	
Non-round nozzles (rectangular or elliptical)	Penn State (McLaughlin & Morris)	Noise	Nozzles are rectangular or elliptical shaped and are of moderate aspect ratio (<15)	Reduces noise in the major axis plane	Slightly increases noise in the minor axis plane, weight and volume issues, small performance penalties	Noise	Lab tested, F117, other military airplanes	Not much noise benefit until you get to high aspect ratios, minor axis noise is increased, and weight and performance penalties usually are incurred depending on nozzle design. Usually the higher the aspect ratio, the larger the nozzle
Low-emissions alternative fuels	LM proposal brainstorming session	Fuel	Alternative fuels that produce low emissions	Reduce emissions, possibly cost in the long run	Possibly increase cost since infrastructure might be more expensive, may hurt efficiency too	Efficiency (maybe), emissions	Depends on fuel, many research efforts, we would have to pick a specific one (algae?)	Likely addition. Algae and other plant-based fuels are being studied by Boeing and NASA for commercial aircraft.
Active combustion control	Peter Coen's tech list (Penn State (Santavicca))	Emissions	Active Combustion Control for Supersonic Low Emission Combustion	Lowers emissions	Complexity, possibly performance penalties	Emissions	Being researched with NASA NRAs	
Configuration								
High notch ratio planform with flow control	N+3 proposal	Aero	Wing with high notch ratio (high TE sweep)	Low induced and wing wave drag	Heavy, low speed higher vortex drag and pitch-up w/o attached flow control	Efficiency	Idea. Would need to develop and test specific design	Dependant on effective flow control
Synthetic cockpit vision	LM proposal brainstorming session	Avionics	Use TV camera system to give pilot better visibility where nose is in the way	Eliminates need for folding nose or any other design compromises necessary for the pilot to see the runway	None	Efficiency	Needs development but research activities are ongoing	Synthetic vision has been eyed for a long time as a solution to the runway visibility problem, more than likely this will be implemented on any new supersonic transport or bizjet
Swing canard	LM configuration brainstorming session	Configuration	Deploy canard only at low speeds to control trim and stability	Lower drag, better boom	Weight and complexity of retraction mechanism	Efficiency, boom	Would have to be designed in	Not sure if it buys its way on, would have to make sure aero benefits outweigh retraction weight penalties. Might take weight penalty if there was a very large boom benefit
Wing tip tanks	LM configuration brainstorming session	Configuration	Strategically shaped wing tip tanks	Structural stability, span load alleviation, area ruling	Weight	Efficiency, boom	TRL-9, airplanes have employed them before	

TABLE B.1.—N+3 SUPERSONIC TECHNOLOGY LIST—BOLT-ON TECHNOLOGIES

Technology	Source	Category	Description	Benefits	Drawbacks	N+3 goals addressed	Readiness	Comments
Configuration								
Configuration shaping	LM proposal brainstorming session	Configuration	Shape configuration to close fore and aft shock to acceptable levels using advanced MDO techniques	Constrain sonic boom while maintaining efficiency and trim	Efficiency is compromised if it has to be balanced against boom requirements	Boom, efficiency	Has been done for QSST, more research to be done	Best solution so far for constraining boom. Advanced technology like plasma and lasers have some potential but the vehicle shape is the most available technology
Variable sweep outboard wing panels	N+3 kickoff meeting brainstorm	Configuration	Vary sweep of wing using pivots or other mechanical system	Easier to balance low speed takeoff requirements with high speed drag and boom goals, less weight than full variable sweep wings since it's just outboard panels	Large weight penalties in pivots and mechanical systems	Efficiency, noise, boom	TRL-9, done before on F14, F111, and B1	Swing wings have fallen out of style for many years. There would need to be a new and substantially more effective concept or mechanical system for the technology to buy its way on. May consider variable sweep for outer panels.
Quiet spike	N+3 kickoff meeting brainstorm	Configuration	Extending and retracting spike, extends for cruise to increase effective length of airplane, retracts for better landing	Reduces boom	Weight and complexity of retraction mechanism	Boom, efficiency	Tested on F-15 for mechanical reliability	Questionable if spike buys you anything over a boom shaped vehicle. Retraction mechanism would weigh as much if not more than a long nose
Knight's lance nose	N+3 proposal	Configuration	Similar to quiet spike but would be non-retractable	Reduces boom	Weight, landing slap-down considerations	Boom, efficiency	idea	An extra long nose could play a similar role to the quiet spike and push the signature out farther. It doesn't have to be as long as the quiet spike since there is no telescoping mechanism with discrete steps, advanced materials could mitigate landing slap-down concerns.
Windowless cabin	LM proposal brainstorming session	Passenger cabin	Eliminate windows and replace with TV flat-screens showing the outside	Huge weight savings from eliminating holes in structure, manufacturability benefits, cabin noise benefits	Passenger acceptance	Efficiency	Could easily be implemented, passenger acceptance needs to be thoroughly assessed	A significant number of passengers would not be enthused with the idea of no windows, TV screens would not suffice because they're not "the real thing", some might suffer claustrophobia, it's possible this could be done but passenger acceptance (however irrational) must be taken very seriously
Deployable prop	LM proposal brainstorming session	Propulsion	Prop deploys out of turbofan engine to use for takeoff, allows less compromise in engine cycle	Increase engine cruise efficiency and decrease takeoff noise	Increased weight and complexity	Efficiency, noise	Low TRL, just an idea but not too far-fetched	Hard to say if engine efficiency would outweigh weight penalties. Also need to determine prop size and how mechanical deployment system would work
Thrust vectoring	LM proposal brainstorming session	Propulsion	Vector engine exhaust slightly downward during cruise to improve boom	Reduce aft shock without having to heavily constrain configuration	Thrust (only get cosine), trim, weight if thrust vector is variable	Boom, efficiency	Could easily be done	Slight benefit but trim would be an issue

TABLE B.1.—N+3 SUPERSONIC TECHNOLOGY LIST—BOLT-ON TECHNOLOGIES

Technology	Source	Category	Description	Benefits	Drawbacks	N+3 goals addressed	Readiness	Comments
Configuration								
Acoustic cancelling of engine noise	LM proposal brainstorming session	Noise	Speakers around engine that broadcast out-of-phase tones to cancel engine noise sources	Decrease fan tones	Weight, complexity, power, little overall noise benefit since jet dominates	Noise	Systems in various stages of research	Would only be effective for tonal noise sources such as fans. For a supersonic engine, jet noise dominates which is broadband. Might help on approach since inlet fan noise is a big player.
Faired landing gear	N+3 proposal	noise	Fairing over landing gear	Reduces gear noise	Weight penalties, possible integration issues	Noise	Faired gear concepts in research and testing	Main way to cut down on landing gear noise
Adaptive geometry								
Inlet choking	N+3 proposal	Noise	Vary inlet geometry so you get choked flow in the inlet at low speeds	Reduces inlet fan noise since noise can't propagate upstream through the choked region	Weight and complexity of variable geometry mechanism, could possibly use advanced morphing materials	Noise	Researched before but never demonstrated	Read about this concept for subsonic engines, the degree of area reduction necessary to choke the flow requires a complex mechanism to do it. Potentially we could use some sort of morphing technology to do it and maintain better flow at cruise
Independent throat and exit area nozzle control	Penn State (McLaughlin & Morris)	Propulsion, noise	Can independently control throat and exit areas	Reduces broadband shock noise in the jet plume and optimizes performance for a wide variety of operating conditions	Weight penalties for mechanical systems actuators, may investigate morphing materials	Noise, efficiency	Linked control deployed on military engines	Sounds good as long as weight and complexity can be kept to a minimum. Investigate morphing materials. This should be easy for the throat area but more difficult for the exit area
Morphable control surfaces (seamless gaps)	N+3 kickoff meeting brainstorm	Controls	Use a technology like shape-memory alloys or piezoelectric actuators and flexible material to bend surfaces without gaps	Lowers drag slightly, potential lower weight depending on system used, reduces airframe noise	Would make it more difficult to generate drag at low speeds on approach	Efficiency, noise	Low to mid-TRL, some shape memory alloy and piezoelectrics employed for other technologies like helicopter blades	Noise benefits would be more effective for subsonic aircraft, some drag benefit by elimination of gaps.
Inflatable wing elements	LM configuration brainstorming session	Configuration	Could inflate outboard wing sections for takeoff and stow them for cruise, could also have inflatable leading edges to control separation at high alpha	Lower drag, better low speed control	Weight and complexity of retraction mechanism	Efficiency	Would have to be designed in	Some possibilities, would have to buy its way on. Also perhaps inlet increase radius for LS flow
Plasma technology								
DBD plasma flow control	LM RTP	Aero	Use DBD plasma actuators to clean up separation regions and reduce drag, maybe also achieve spanwise laminar flow	Drag reduction	Weight, complexity, power	Efficiency	DBD actuators are mid-TRL, how to deploy them needs to be studied	Potential technology for controlling separation, improving high-lift, or laminar flow

TABLE B.1.—N+3 SUPERSONIC TECHNOLOGY LIST—BOLT-ON TECHNOLOGIES

Technology	Source	Category	Description	Benefits	Drawbacks	N+3 goals addressed	Readiness	Comments
Plasma technology								
Plasma boom optimization	LM proposal brainstorming session	Systems	Use plasma generators to change airflow at key locations on aircraft and dissipate shocks.	Reduce boom without having to heavily constrain the configuration	Power requirements	Boom, efficiency	DBD actuators are mid-TRL, how to deploy them and whether or not they would be effective for boom needs to be studied	May work for boom but power requirements may preclude them
Plasma virtual length	LM proposal brainstorming session	Configuration	Use plasma generators to manipulate the airflow in front of and behind the vehicle, boom is reduced since vehicle's apparent length changes	Reduce sonic boom	Power consumption to generate plasma	Boom	Low TRL, some analytical studies done	Previous studies in QSP found that power requirements were too high, increasing length would improve boom but not dramatically
Jet exhaust manipulation with plasma	Tech Fair - Ohio State (Samimy)	Noise	Use plasma actuators on nozzle lip to play with jet characteristics to reduce noise	Jet noise reduced about 2-3 dB	Power required for plasma	Noise	Research phase	Could potentially be combined with chevrons to provide a good overall jet noise reduction
Piezoelectric synthetic jet actuators for flow control	N+3 proposal	Aero	Control separation in critical regions, especially low speed high lift	Enables higher alphas with less pitch-up concerns, smaller wing	Power, weight, complexity	Efficiency	Synthetic jets are well studied and have been deployed, how to deploy them in these applications needs study	Similar to plasma actuators
Laminar flow								
Distributed roughness	Saric and Reed	Aero	Distributed bumps on aircraft surfaces. Creates acoustic disturbances out of phase with cross-flow disturbances and maintains laminar flow on swept wings	Lower drag at supersonic speeds	Manufacturing complexity	Efficiency	Wind tunnel tested	Great potential for supersonic laminar flow. Most viable technology for swept wings.
Fuselage riblets	N+3 kickoff meeting brainstorm	Aero	Use micro-riblets in skin to achieve drag reduction	Lower drag	Manufacturing complexity, possibly extra weight	Efficiency	Some research done at lab-scale	Looks like good passive drag device
Active LE suction for laminar flow	N+3 kickoff meeting brainstorm	Aero	Use engine bleed to achieve laminar flow by suction	Lower drag at supersonic speeds, active system effective	Requires significant engine bleed, hurts efficiency, trade needs to be done if drag benefits outweigh propulsion efficiency penalties	Efficiency	Easy to employ, some development needed to get it right	Cost/benefit questionable. Distributed roughness is probably a better solution.

TABLE B.1.—N+3 SUPERSONIC TECHNOLOGY LIST—BOLT-ON TECHNOLOGIES

Technology	Source	Category	Description	Benefits	Drawbacks	N+3 goals addressed	Readiness	Comments
Laminar flow								
Supersonic micro-array flow control	Peter Coen's tech list (NASA internal)	Propulsion		Improves boundary layer health downstream of oblique shock	Complexity, engine bleed	Efficiency	Being researched with NASA NRAs	Not sure how it fits with external compression but an application could probably be found
Materials								
Supersonic turbine blades made with SiC fibers in efficient weaving or braiding process	Peter Coen's tech list (Teledyne)	Propulsion	SiC turbine blades	Lighter, possibly cheaper to make than Nickel alloy, better temperature threshold, more creep resistant.	Maybe more expensive to manufacture	Efficiency	Being researched with NASA NRAs	Better applied in the near-term as a weight saver. Could enable a higher turbine inlet temperature but that still needs to be researched.
Aluminum-Lithium	N+3 proposal	Materials				Efficiency		
GLass-REinforced aluminum (GLARE)	N+3 proposal	Materials				Efficiency		
Titanium-5553 alloy	N+3 proposal	Materials				Efficiency		
Fiber-reinforced polymer composites (FRPC)	N+3 proposal	Materials				Efficiency		
Aircraft operations								
Takeoff overspeed	LM	Ops	Take advantage of low-speed aerodynamics of supersonic configurations. Set takeoff speed higher than required to lower climb CL, improve climb L/D, increase climb rate, and be able to cut back deeper over the cutback certification point	Reduces community noise on takeoff by providing more flexibility on the climb flight path.	Safety	Noise	Can be done	Likely allowable under current FARs
Lower cruise altitude	LM proposal brainstorming session	Ops	Cruise at lower altitude (<30 kft) to avoid contrails and lower NOx emissions	Lower emissions, no radiation concerns	Less propulsion efficiency (supersonic transports generally like to cruise at 50 kft and above), weather, ride quality	Emissions	Just design configuration to cruise below 30 kft	Helps with CO_2 and NOx emissions and also avoids the radiation issues with cruising at 50,000+ ft. Penalties in engine efficiency, and sonic boom will be substantially louder requiring more effort to constrain it. Ride quality will be compromised since you can't fly above the weather. Emissions could be better addressed by engine technology
Helical takeoff profile	N+3 kickoff meeting brainstorm	Ops	Use corkscrew takeoff profile	Reduces community noise by containing footprint in the airport boundary	Possible passenger discomfort, ATC issues, not a certifiable noise profile	Noise	Can be done	Would require an FAA rules change for certification and there may be ATC issues. Aircraft can do it but existing infrastructure would have to change to accommodate it.

TABLE B.1.—N+3 SUPERSONIC TECHNOLOGY LIST—BOLT-ON TECHNOLOGIES

Technology	Source	Category	Description	Benefits	Drawbacks	N+3 goals addressed	Readiness	Comments
Aircraft operations								
Structural health monitoring	LM	Systems	Sensor devices that monitor integrity of key structural members	Allows structures to be designed with less margin and for maintenance checks to be reduced	Complicates design	Efficiency	Research and lab stages	This is a promising technology and will eventually make its way onto all aircraft. Supersonic configurations will benefit from it more however since their structures demand less margin
Automatic low-speed pitch-up control	LM configuration brainstorming session	Systems	Use automatic control system to mitigate pitch-up tendencies, this enables greater trailing edge sweep which is more efficient	Greater trailing edge sweep since margin doesn't have to be designed in to account for pilot response time, lower drag	Redundancy, weight of system	Efficiency, boom	Low-TRL	Good idea, wing shouldn't have to be designed to make up for lack of pilot response time in pitch-up tendencies

TABLE B.2.—N+3 SUPERSONIC ALTERNATIVE CONFIGURATION OPTIONS

Configuration	Source	Category	Description	Benefits—baseline	Drawbacks—baseline	N+3 goals addressed	Comments
Joined and braced structure	LM	Airframe	Joined structure (wing-tail), blended structure and bracing structure to reduce weight, alleviate dynamic structural criticality and/or enable thinner and higher fineness designs (reducing wave drag).	Reduce weight, reduce flutter, reduce wave drag		Efficiency, boom	
Mother/ Daughter configuration	LM	Airframe	Subsonic “mother” configuration attached to supersonic “daughter” configuration. Daughter configuration would be optimized for supersonic cruise and would incur none of the airframe and propulsion penalties of low speed. Mother configuration would use its engines to takeoff and carry Daughter configuration through takeoff to higher Q climb, releasing for transonic climb to supersonic cruise. Mother may or may not be required for landing. Mother configuration could also be more of a low sweep/high BPR wing pack that could attach and detach and fly to and from airports independently. There could be a system of system advantage as one Mother could potentially serve several Daughters. They would be piloted when together but Mother might return autonomously.	Easier to balance noise with efficiency and boom by not having to compromise these design considerations in one design. Benefit would come from a fleet depending on how many daughters could be served by one mother	Safety issues, extra pilots adding to cost (unless mother was autonomous or flown remotely by daughter pilots when joined), total system heavier than single airplane	Efficiency, boom, emissions, noise	Aggregate benefit can only be realized in a fleet if one mother can serve multiple daughters since the total stack will weigh far more than a single airplane. Can be a viable option though if N+3 goals absolutely cannot be met by a single platform.
Low-speed autonomous pack	LM	Airframe	Similar to Mother/Daughter, only subsonic airplane is smaller and autonomous. Supersonic A/C would be designed for cruise and subsonic A/C would be a minimalist configuration with unswept wings, high-bypass turbofans, landing gear, and minimal structure. It would takeoff and land mated to the supersonic passenger A/C.	Same considerations as Mother/Daughter.	Same considerations as Mother/Daughter. The subsonic "pack" is smaller though so less expensive.	Efficiency, boom, emissions, noise	Same comments

TABLE B.2.—N+3 SUPERSONIC ALTERNATIVE CONFIGURATION OPTIONS

Configuration	Source	Category	Description	Benefits—baseline	Drawbacks—baseline	N+3 goals addressed	Comments
Takeoff assistor	LM	Airframe	Similar to subsonic "pack" only now it is an autonomous takeoff "assistor" which would be a minimalist configuration with quiet turbofans which would tow the supersonic passenger aircraft on a cable through takeoff and to launch altitude. The supersonic A/C could have its engines at partial throttle during takeoff to stay within noise limits and still be controllable. Supersonic A/C would land on its own	Same considerations as Mother/Daughter only now supersonic A/C has to land on its own.	Substantially less drawbacks than Mother/Daughter. Safety issue is much less since no in-air mating is required. The subsonic or "extra" configuration is also as small as possible to minimize the extra expense.	Efficiency, boom, emissions, noise	Probably the most feasible 2 A/C solution. Safety issue of in-air mating is removed, and although supersonic A/C has to land on its own, the jet noise problem is still addressed. As with the other two 2 A/C solutions, this would only begin to make sense if the jet noise problem could not be solved for a reasonable cruise efficiency, and one subsonic A/C could serve multiple supersonic A/C and the benefit would be realized in the overall system of systems
Oblique Flying Wing	LM	Airframe	Similar to the elliptical design produced by NASA Ames. Takes off horizontally, and then turns to an oblique angle for transonic and supersonic speeds.	Better adapts to low speed and high speed optimum sweep.	Packaging, windows, weight, complexity from rotation mechanisms for engines, stability and balance	Efficiency, boom	Benefits are only realized at lower supersonic Mach nos. (~1.3) since required sweep angles are too high at higher Mach nos.
Oblique wing with fuselage	LM	Airframe	Similar to the AD-1. Oblique angle of wing could be adjusted in flight about a single pivot.	Better adapts to low speed and high speed optimum sweep. Less of a weight penalty than a standard swing wing	Weight from pivot, stability and balance, mechanism complexity, more difficult to design for low-boom since lift starts early and has to be symmetric on both sides of the wing	Efficiency, boom	Would have to trade to see if weight penalty and trim penalties are paid for by variable sweep benefits
Swing wing	LM	Airframe	Similar to F-14, B-1, F-111, and Boeing SST. Potentially newer materials and technologies could enable the benefits of a swing wing for less weight penalty. Swing could just be employed on the outer portions of the wing as well or be employed on the canard.	Better adapts to low speed and high speed optimum sweep. Boom shaping benefits	Weight from pivots, mechanism complexity	Efficiency, boom	It's difficult for variable sweep to buy its way on. More advanced pivoting mechanisms with newer materials would have to substantially reduce the weight penalty
Twin fuselage	LM	Airframe	Two fuselages sharing a common wing. Has some drag benefits from favorable interference effects between the fuselages.	Busemann biplane effects between the fuselages, shocks from adjoining fuselages also can create high pressure air on aft facing surfaces fineness ratio of fuselages can be decreased by halving diameter for the same length, engines can be mounted in center wing eliminating need for inverted v tail	Length is good for boom and this configuration compromises that, aeroelastic effects from torqueing of the fuselages, doesn't work well for low passenger volumes	Efficiency	Boom is the main thing that will have to be assessed with this concept to see if it's worth considering the possible aero and structural benefits. Also, given the current passenger seating configuration, length would have to be reduced since less than 2 by 2 seating for a long-haul flight creates space issues (i.e., claustrophobia, families not being able to sit together

TABLE B.2.—N+3 SUPERSONIC ALTERNATIVE CONFIGURATION OPTIONS

Configuration	Source	Category	Description	Benefits—baseline	Drawbacks—baseline	N+3 goals addressed	Comments
Aft fuselage mounted engines	GE	Propulsion	GE engine architecture for variable cycle	Allows efficient variable bypass in one engine	Complexity, possibly weight	Efficiency, noise, boom	Probably the best option for an engine architecture to balance efficiency and noise goals
Distributed engines	LM	Propulsion	Thrust is provided by many small engines distributed about the airframe	Potential benefits include, greater overall reliability, lower cost, aero benefits, less integration issues, lower noise	Potential penalties include the same things	Efficiency, noise, emissions	Looked at this before and the problem is complex and has no firm answers. Many aspects are configuration dependent.
Embedded engines	LM, GE	Propulsion	Engines are embedded in the airframe instead of hanging by pylons	Drag benefits, boom benefits	Not a lot of volume to store engines, weight increases and prop losses from ducting, possible cabin noise penalties and rotor burst considerations, harder to integrate new engines	Efficiency	Podded or ramp engines would have to be real show-stoppers in aero and boom to move to this arrangement. Embedded would be considerably easier if distributed engines were used
Auxiliary turbofans	LM, GE	Propulsion	Turbofans deployed for takeoff and stowed for cruise.	Use turbofans for low speeds to meet noise constraints, allows cruise engines to be optimized for cruise and not have to deal with noise issues. Also eliminates the need for aux inlets	Weight and complexity of retraction, turbofans dead weight during cruise unless they are utilized in an efficient way (i.e., embedded with a duct)	Efficiency, noise	Turbofan(s) could be embedded in the fuselage and either deploy outward or receive air through a retractable inlet. Stowing the engine would be very difficult. Also, takeoff and cruise thrusts are very similar so there's no benefit from sizing down the cruise engines, otherwise this might make more sense to do.
Over-wing mounted engines	LM, GE	Propulsion	Engines mounted over the wing instead of under	Shield inlet radiated fan noise on approach and eliminate nacelle shock contribution to boom signature	Aero penalty, wing would have to be shaped or some sort of flow control device employed to give the engine good airflow, possible propulsion penalties from expanded air coming from wing upper surface	Noise, boom	Trade should be done to assess this configuration. Current thinking is that boom issues with an under-wing mounted configuration can be designed out through wing camber reflex.
Cross-shafted auxiliary fans	NASA	Propulsion	Bleedless mixed compression inlet	Zero bleed inlet with supersonic mixed compression	Improves propulsion efficiency, zero-bleed allows for near-perfect performance		Mutually exclusive with LM external compression inlet scheme, trade should be done to see which architecture would be preferable. Both concepts incorporate zero-bleed technology

TABLE B.3.—N+3 SUPERSONIC TOOLS AND METHODS LIST

Tool and method	Source	Category	Description	Benefits	N+3 goals addressed	Readiness	Comments
CFD mesh adaption for mid-field pressure signature	NASA	Aero, boom	Uses mesh adaption schemes to resolve the grid around shocks and provide an accurate mid-field pressure signal for boom propagation	Enables coupling of CFD near-field analysis and far-field boom propagation	Efficiency, boom	In development, NASA internal, NRA funded	
CFD mesh adaption and error quantification	NASA	Aero, boom	Uses adjoint methods to quantify error in CFD computations and adjust the mesh accordingly	Enables user to specify a spatial discretization error tolerance. Useful for resolving mid-field pressure signals for boom propagation and aero analysis	Efficiency, boom	In development, NASA internal, NRA funded	This will be useful for specifying accuracy of a mid-field pressure signature and having the grid adapt to it
CFD-based adjoint shape optimization	LM	Airframe shaping	Use adjoint methods with CFD-based aero and boom analysis to optimize OML for low-boom and efficient cruise	Balances aero and boom demands	Efficiency, boom	Employed on QSST for aero optimization. Boom implementation still needs work. Somewhat still in the research phases	This method is key for high fidelity OML refinement that can shape complex configurations to meet stringent aero and boom requirements
System of System Fleet Allocation Tools	Purdue	Airspace, ops	Performs SoS optimization of an aircraft fleet operating over a route structure	Assesses impacts on cost, environment, and mobility of injecting a supersonic aircraft into a standard fleet mix		Research and application	Good tool for looking at the overall benefit of supersonic travel. Important trades will be mobility versus fuel costs and environmental considerations
Integrated engine, exhaust plume, airframe prediction capability	NASA	Boom				In development, NASA internal, NRA funded	
Lift and Nozzle Change Effects on Tail Shocks (LaNCETS)	NASA	Boom				In development, NASA internal, NRA funded, flight test validation	
Low-Boom Tools for plume/aft shaping	Wyle (Plotkin)	Boom	Develop interactive design tool based on a Generalization of the George-Seebass theory. New extended theory design tool will be coupled to PCBoom. Develops an engine exhaust plume model for inclusion in the generalized George-Seebass method			In development, Wyle (Plotkin), NRA funded	
Atmospheric Sonic Boom Prediction Model for PCBOOM	Wyle (Page)	Boom			Boom	In development, Wyle, NRA funded	
Prediction of boom signatures around buildings	Penn State (Sparrow)	Boom	Tool that predicts interaction of boom signatures and building structures	Enables refined outdoor boom predictions in urban environments, helps with acceptability studies and policy	Boom	In development, Penn State, NRA funded	

TABLE B.3.—N+3 SUPERSONIC TOOLS AND METHODS LIST

Tool and method	Source	Category	Description	Benefits	N+3 goals addressed	Readiness	Comments
Modeling of boom in buildings	VPI (Burdisso), Wyle (Sizov)	Boom	Models that predict sonic boom transmission through building structures	Enables predictions of boom effects on people inside buildings, helps with acceptability studies and policy	Boom	In development, VPI and Wyle, NRA funded	
Modeling of rattle from sonic booms	Wyle (Sizov)	Boom	Models induced noise (rattle) from sonic booms on objects	Enables predictions of secondary noise effects from sonic booms, helps with acceptability studies and policy	Boom	In development, Wyle, NRA funded	
Improved Nozzle Force Measurements	NASA	Boom testing	The one-component force balance in the Nozzle Acoustic Test Rig (NATR) was refurbished and upgraded to improve force measurement accuracy and repeatability			In development, NASA internal, NRA funded	
Multifidelity design methods for supersonic aircraft	Stanford (Kroo)	Design				In development, Stanford (Kroo), NRA funded	
Detection and Control of Instabilities	Georgia Tech (Seitzman)	Emissions	Detection and control of instabilities and blowoff for low emissions		Emissions	In development, Georgia Tech, NRA funded	
Emissions by Modeling Combustion	Stanford (Pitsch)	Emissions	Emissions prediction and modeling of supersonic vehicle combustion systems		Emissions	In development, Stanford (Pitsch), NRA funded	
Compu. Tools for Superheated Fuels	UTRC, UMass	Emissions	Validated computational tools for low emissions injector design using superheated/supercritical fuels		Emissions	In development, UTRC and UMass, NRA funded	
Control of Boundary Representation Topology in MDAO	MIT (Haimes)	Geometry	Develop geometry management tools and techniques to address the remaining obstacles to hands-off operation of interdisciplinary coupling in MDAO with CAPRI				
Hi-Fi MDO: Software Infrastructure	M4 Engineering (Baker)	MDAO	Develop physics-based multidisciplinary analysis and optimization capabilities in the form of reusable modules in an object-oriented environment			In development, Stanford (Kroo), NRA funded	
Comprehensive Model for the Prediction of Supersonic Jet Noise	Penn State (Morris), Boeing	Noise		Enables better understanding of supersonic jet noise so that designs can be accurately evaluated	Noise	In development, Penn State (Morris) and Boeing, NRA funded	Jet noise is king on these engines so this model will be useful for developing source predictions for community noise studies. If the model gives locations of prominent sources, it can also be useful for noise/airframe interaction studies

TABLE B.3.—N+3 SUPERSONIC TOOLS AND METHODS LIST

Tool and method	Source	Category	Description	Benefits	N+3 goals addressed	Readiness	Comments
Prediction and modeling of supersonic jet noise using large-eddy simulation	Stanford, Illinois (Lele)	Noise		Enables better understanding of supersonic jet noise so that designs can be accurately evaluated	Noise	In development, Stanford and Illinois, NRA funded	
Exhaust plume reshaping techniques	UC Irvine (Papamoschou)	Noise	Reduces supersonic jet noise by using external and internal vanes to redirect and concentrate cold fan flow beneath the hot core flow	Reduces jet noise	Noise	In development, UC Irvine (Papamoschou), NRA funded	
High Speed Temperature Analysis Software and Support for Temporally-Resolved Laser Raman Temperature Measurements in a Supersonic Jet	Aerodyne Research (Anan)	Noise			Noise	In development, Aerodyne, NRA funded	
Computational bleed model for supersonic inlets	Boeing (Mace)	Propulsion	Computes bleed losses for supersonic inlets			In development, Boeing (Mace), NRA funded	
High Fidelity Supersonic Exhaust System Design and Validation	Rolls Royce Liberty Works (Jimerson)	Propulsion, noise			Efficiency, noise	In development, RRLW, NRA funded	
Aero-Propulso-Servo-Elastic design	LM, NASA	Structures, flutter control	Design methods and approaches that use flexibility of the vehicle for control	Lighter structure, simplified controls	Efficiency		Very generalized philosophy at the moment. Specific applications should be formulated and researched
Aeroelastic tailoring		Structures, flutter control	Tailoring composite skin design to provide directional stiffness for particular loads	Lighter structure, more unconventional wing designs	Efficiency	Used on the X-29 and other programs	Will have a lot of applications depending on use of composites
Reduced-Order Modeling for APSE design	LM, NASA	Structures, flutter control	Mathematical techniques for efficient structural dynamics calculations	Enables efficient design and analysis of vehicle structural dynamics with sufficient fidelity	Efficiency	Research stage	Enables faster and more robust aeroelastic analysis at good fidelity levels. Sounds good for design

TABLE B.4.—N+3 SUPERSONIC LIST OF MATERIALS AND GENERIC TECHNOLOGIES

Technology	Source	Description	Potential applications	Areas to research	Readiness	Comments
Ceramic matrix composite nozzles	N+3 proposal	Nozzles are made of CMC materials rather than metallic ones and can stand the high temperatures	Hot nozzle materials	Manufacturing techniques, cost reduction	GE working on it. Proposal claims that LM "demonstrated" them	Great idea for weight reduction. Not sure what readiness they are and if there are any drawbacks
Aluminum-Lithium	N+3 proposal					
GLass-REinforced aluminum (GLARE)	N+3 proposal					
Titanium-5553 alloy	N+3 proposal					

TABLE B.4.—N+3 SUPERSONIC LIST OF MATERIALS AND GENERIC TECHNOLOGIES

Technology	Source	Description	Potential applications	Areas to research	Readiness	Comments
Fiber-reinforced polymer composites (FRPC)	N+3 proposal					
Integrated structure and subsystems	LM proposal brainstorming session	Subsystems made from structural components and "manufactured/ integrated" in rather than "bolted on"	A number of subsystems could be manufactured this way, applications will emerge in detail design and subsystem studies	Applications, manufacturing processes, cost savings over conventional subsystems integration	Initial idea	Integral manufacturing has been a growing trend in general. I think the idea of "integrated subsystems" will generally make their way onto the airplane naturally and will only do so when it makes sense. Applications are very detail design oriented
Carbon nanotube composites	LM proposal brainstorming session	Composites constructed primarily from carbon nanotube fibers	Primary and secondary structure is possible. A number of detail design applications would probably come first	Research investment in this area is considerable, mechanical, electrical, and thermal properties. Manufacturing, especially on a large scale, is a big area of research.	Largely in research stage (TRL <2), could be ready by 2030	A lot of potential for weight savings in theory but much work remains to be done on research and implementation. These materials would be most useful when stiffness is a primary concern and they could provide some more design liberties with wing thickness, nose length, etc.
Highly Tailored Composite Structures (hits)	N+3 proposal	Use directional composite ply layups to tailor structures, particularly for stiffness and buckling	A number of structural members where buckling is a concern, specific areas of the wing skins	Layup procedures, manufacturing techniques, cost reduction		
Plasma boom optimization	LM proposal brainstorming session	Use plasma generators to change airflow at key locations on aircraft and dissipate shocks.	Reduce boom without having to heavily constrain the configuration	Configuration dependent. How could plasma help dissipate shocks? What power requirements are needed? How would the system work?	DBD actuators are mid-TRL, how to deploy them and whether or not they would be effective for boom needs to be studied	
Structural health monitoring	LM	Sensor devices that monitor integrity of key structural members, Allows structures to be designed with less margin and for maintenance checks to be reduced	Main application would be key members of primary and secondary structure that are subject to frequent maintenance checks.	Effectiveness of monitoring, application techniques	Research and lab stages	This is a promising technology and will eventually make its way onto all aircraft. Supersonic configurations will benefit from it more however since their structures demand less margin

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14. ABSTRACT
The N+3 Final Report documents the work and progress made by Lockheed Martin Aeronautics in response to the NASA sponsored program "N+3 NRA Advanced Concept Studies for Supersonic Commercial Transports Entering Service in the 2030 to 2035 Period." The key technical objective of this effort was to generate promising supersonic concepts for the 2030 to 2035 timeframe and to develop plans for maturing the technologies required to make those concepts a reality. The N+3 program is aligned with NASA's Supersonic Project and is focused on providing alternative system-level solutions capable of overcoming the efficiency, environmental, and performance barriers to practical supersonic flight.

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