N+3 Phase I Final Review

Contract NNC08CA86C
NASA Glenn Research Center
21 April 2010

Dr. Sam Bruner
Principal Investigator
Northrop Grumman Corporation
Outline

• Introduction
• Scenario Development
• Requirements Definition
• Design Tools and Processes
• Candidate Configurations and Technologies
• Air Vehicle Design Studies
• Technology Maturation Plans
• Summary and Conclusions

• Closed session with NASA partners
N+3 Phase I Final Review: Introduction

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Dr. Sam Bruner
Manager, Advanced Configurations
Northrop Grumman Corporation
Northrop Grumman Team

• **Northrop Grumman**
  – Scott Collins – Program Manager
  – Dr. Sam Bruner - Principal Investigator
  – Chris Harris - Systems Analysis IPT Lead
  – Nicholas Caldwell - Propulsion Integration
  – Peter Keding - Technology Modeling and Vehicle Trades/Optimization
  – Scott Baber - Configuration Design
  – Luck Pho - Aerodynamic Design and Performance
  – Kyle Rahrig – Acoustic Modeling and Analysis

• **Rolls-Royce Liberty Works**
  – David Eames

• **Sensis**
  – Dave Miller – Traffic Forecasting and Simulation

• **Tufts University**
  – Dr. Rich Wlezien - Future Scenario Research and Technology Maturation Planning Effort

• **Spirit Aerosystems**
  – Dr. Judy Gallman - Advanced Acoustic Inlet Liner
Objectives for Past Eighteen Months

- NASA seeks to “stimulate innovation and foster the pursuit of revolutionary conceptual designs for aircraft that could enter into service in the 2030-35 period”
- In response, Northrop Grumman:
  - Developed a credible future scenario to establish a context for the proposed advanced vehicle concept.
  - Executed advanced concepts systems study that methodically identified and evaluated integrated aircraft configurations
  - Developed an advanced concept whose mission capabilities would enable it to fill a broad, primary need within the future scenario
  - Proposed an prioritized suite of enabling technologies and corresponding technology development roadmaps required to realize the preferred vehicle concept by the 2030-35 timeframe

Northrop Grumman’s preferred concept is revolutionary in its performance, if not in its appearance
Scenario Analysis

- Develop a future scenario that describes the challenges that may be facing commercial aircraft operators in the 2030-35 and beyond timeframe.
  - Provide a context within which the proposer’s advanced vehicle concept(s) may meet a market need and enter into service.
- Northrop Grumman provides four scenarios that cover the range of possibilities
  - King Carbon
  - Not In My Backyard
  - Bright Bold Tomorrow
  - Doom and Gloom
- Scenarios used to develop weighting factors for use in design trade studies
Traffic and Passenger Forecast

- Scenario studies supplemented by rigorous
  - Analysis of current traffic movements
  - Forecasts of future traffic and passenger demands
- Simulations provide sensitivities to key design parameters
- Final design requirements validated through simulation
## Requirements for Conceptual Design

### Scenario Analysis

### Traffic and Passenger Forecasts

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<tr>
<td>Performance: Aircraft Fuel Burn</td>
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<td>Performance: Field Length</td>
<td>Exploit Metroplex Concepts</td>
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<table>
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<tr>
<th>Mission Requirements Derived from Traffic Study</th>
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<tr>
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Solid TRL 6 by 2025 to manage commercial risk
Reference Vehicle vs Preferred Vehicle

- **Reference Vehicle**
  - Vehicle used as baseline for establishing current-year capability
  - Perturbation on a 737-500, assuming constant technology
  - Resized to meet same mission requirements as the preferred vehicle
  - “Rubber Engine”, “photographically scaled” wing

- **Preferred vehicle**
  - Final design concept that meets the mission requirements and best meets the N+3 objectives
  - Embodies prioritized set of enabling technologies
  - Chosen via a rational downselect from a wide choice of architectures
  - Only indirect consideration of cost
Preferred Vehicle Overview

Dimensions in ft

Phase 1 Preferred Configuration Summary

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N+3 Phase 1 Technologies

- Three-Shaft Turbofan Engine
  - Ultrahigh Bypass Ratio of ~18
  - Compressor Intercooling
  - Lean-Burn Ceramic Matrix Composite (CMC) Combustor
  - CMC Turbine Blades
  - Cooled Cooling Air Turbine
  - Shape Memory Alloy Nozzle
  - Porous Ceramic Nozzle Material
  - Endothermic Fuel System
  - Ultrahigh-Performance Fiber
  - Advanced Metallics
  - Aeroservoelastic Structures
  - Swept-Wing Laminar Flow
  - Large Integrated Structures
  - Landing Gear Fairings
  - Pt Preform Joints
  - Carbon Nanotube Electrical Cables
  - Advanced Inlet Acoustic Liner

Technology Suite

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F=Fuel Burn, E=Emissions, N=Noise, L=Field Length

Large Benefit | Small Benefit | No Benefit

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• Northrop Grumman meets all design intents.
  – All goals met except fuel burn
  – Fuel burn still represents outstanding improvement
  – Achievable with technology possible by 2025

| N+3 (2030-2035 Service Entry) Advanced Aircraft Concepts Goals (Relative to User-Defined Reference) | Noise (Cum below Stage 4) | -71 EPNdB | -70 EPNdB | ✓ |
| LTO NOx Emmissions (below CAEP/6) | -75% | -75% | ✓ |
| Performance: Aircraft Fuel Burn | better than 70% | 64% | ✓ |
| Performance: Field Length | Exploit Metroplex Concepts | Exploit Metroplex Concepts | ✓ |
| Range | 1600nm | 1600nm | ✓ |
| Passengers | 120 | 120 | ✓ |
| Field Length, TO and Ldg (SL, Std Day) | 5,000 feet | 5,000 feet | ✓ |
| Cruise Mach | 0.75 | 0.75 | ✓ |
| Cruise Altitude | < FL450 | < FL450 | ✓ |
• Seventeen high priority technologies identified
• Appendix to written report discusses disposition of 72 technologies considered but dismissed
Today’s Objectives

• Describe the Northrop Grumman experience in detail
• Demonstrate:
  – Our approach meets the broad needs for the years 2030-2035
  – Our design achieves the environmental intent of the NASA N+3 challenges
  – We have identified the technologies that enable revolutionary improvements in vehicle performance
Outline

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- Scenario Development
- Requirements Definition
- Design Tools and Processes
- Candidate Configurations and Technologies
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- Summary and Conclusions

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N+3 Phase I Final Review: Scenario Study

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NASA Glenn Research Center
21 April 2010

Dr. Rich Wlezien
Tufts University
N+3 Scenario Objective

Scenario Task Objective: develop a future scenario within which to describe the challenges that may be facing commercial aircraft operators in the 2030-35 and beyond timeframe
Scenario Process

- NASA guidance – scenario may be developed using relevant existing studies or as a part of this study
- Team conducted research on existing studies, literature search on issues, and held interchange meetings
- Observed three primary scenarios across research findings
- Developed weighting factors to discern value with respect to goals of concepts and technologies in context of scenarios
- Identify those that provide greatest value across scenarios
Future Energy Scenarios

- Increasing Supply
- Balancing Resources
- Reducing Demand
- Collapse

Energy and Resource Use vs. Time (Today)
Global “growth” scenario (Increasing Supply)
ExxonMobil projects that global oil production will continue to grow well beyond 100 million barrels a day. In its latest reference scenario, for example, the US Department of Energy (Energy Information Administration), expects global production to be 112 million barrels a day in 2030.

Global “plateau” scenario (Balancing Resources)
Shell “Blueprints Scenario”, argues that global production will flatten around 2015 and remain on a plateau into the 2020s propped up by expanding volumes of unconventional oil production because of the decline of conventional oil production.

Global “descent” scenario (Reducing Demand)
Shell “Scramble Scenario” predicts a fall off of global production as oilfield flows from the newer projects fail to replace capacity declines from depletion in older existing fields.

Global “collapse” scenario
There is another, very worrying, scenario, wherein the steady fall of the descent scenario is steepened appreciably by a serial collapse of production in some - possibly many – of the aged supergiant and giant fields that provide so much global production today.

The Industry Taskforce on Peak Oil and Energy Security (Arup, FirstGroup, Foster and Partners, Scottish and Southern Energy, Solarcentury, Stagecoach Group, Virgin Group, Yahoo!) considers that the “descent” scenario is a highly probable global outcome, but they also fear that a “collapse” scenario is possible, albeit less likely.
Aircraft Efficiency Data

NLR-CR-2005-669
Fuel efficiency of commercial aircraft, An overview of historical and future trends
Peeters P.M., Middel J., Hoolhorst A.
Sources: 15 scenarios from 4 studies

- Shell Energy Scenarios to 2050 (Shell – 2 scenarios)
- JPDO Futures Working Group (JPDO – 5 scenarios)
- Maintaining U.S. Leadership in Aeronautics: Scenario-Based Strategic Planning for NASA's Aeronautics Enterprise, National Research Council (NRC – 5 scenarios)
Scenario Overview

King Carbon

NIMBY

Bright, Bold Tomorrow

Doom and Gloom

D-1  C-1  A-1  B-5

D-2  C-3  A-2  B-3

C-2  A-3  B-1

A-3  A-5  B-4  B-2
### Scenarios breakdown

<table>
<thead>
<tr>
<th>Organization</th>
<th>Report/Scenario Title</th>
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<tbody>
<tr>
<td><strong>A) JPDO Futures Working Group</strong></td>
<td>“Futures Working Group Final Report (Draft)”, 2004</td>
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<tr>
<td></td>
<td>1. <em>Is it hot in here or what?</em></td>
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<tr>
<td></td>
<td>2. <em>Storm Clouds</em></td>
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<td></td>
<td>3. <em>Markets Rule</em></td>
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<td>4. <em>Asia’s Century</em></td>
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<td></td>
<td>5. <em>Terror Uncontained</em></td>
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<tr>
<td><strong>B) National Research Council (NRC)</strong></td>
<td>“Maintaining U.S. Leadership in Aeronautics: Scenario-Based Strategic Planning for NASA’s Aeronautics Enterprise”, 1997</td>
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<td></td>
<td>1. <em>Pushing the Envelope</em></td>
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<td>3. <em>Regional Tensions</em></td>
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<td>4. <em>Trading Places</em></td>
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<td>5. <em>Environmentally Challenged</em></td>
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<td>1. <em>FROG! First Raise Our Growth</em></td>
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<td></td>
<td>2. <em>Jazz – Dynamic Reciprocity</em></td>
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<td></td>
<td>3. <em>GEOpolity – Sustainable Guidance to Market</em></td>
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<td><strong>D) Shell</strong></td>
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Reducing Demand
“King Carbon”

The confluence of peak oil and global warming concerns results in the imposition of strict “carbon taxes” to limit the burning of fossil fuels. Years of complacency and a business as usual approach has led to the realization that something must be done quickly. Insufficient investment in alternative fuels and sequestration technologies leaves little time to invest in alternative fuel infrastructure. Ground transport and electricity generation at least have some alternatives – air transport must address skyrocketing fuel costs with new approaches to conservation and efficiency. Global alliances cutting across the developed and undeveloped countries set global standards for carbon consumption.
Global Oil vs. Projected Demand

Source: Peak Oil Consulting
A combination of new energy sources and new approaches to energy conservation have brought supply and demand into a long-term balance. Air transportation is growing slowly, but remains a strong component of the overall transportation mix. The push to greater efficiency and energy conservation has reinvigorated the cities, leading to much higher population densities. Land for airports is at a premium, and the luxury of large buffer zones is not viable. Local populations are becoming increasingly intolerant to noise and airport emissions such as NOx, soot, particulates, and hydrocarbon emissions. Strict local rules evolve first in the EU and California, and the bar for noise and local emissions is set very high.
Increasing Supply
“Bright, Bold Tomorrow

New approaches to energy initiated in the early 21st century now pervade the transportation system, and reasonably-priced carbon-based biofuels from algae farms are now widely available. The world economy has more than recovered from the downturn of the first decade, and renewed prosperity places high demand on global travel. New investment in airport infrastructure has saturated the hub-and-spoke system, and widespread point-to-point transportation is now available. Smaller, single-pilot aircraft dominate the transportation system, and the only realistic alternative is smaller local airports, and closer spacing for aircraft going into the larger airports.
Focus on sequestration for global warming amelioration
Three Scenarios that Cover the Spectrum of Future States

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<td>Fuel Burn</td>
<td>Bright, Bold Tomorrow</td>
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### Summary

<table>
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<tr>
<th>Scenario</th>
<th>Challenges</th>
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</table>
| **NIMBY**         | • NIMBY foresees modest (2%/yr) world-wide growth in air transport  
• U.S. and Europe call for stricter emission and noise requirements similar to N+3 goals  
• Replacement of aircraft, in particular single-aisle class will occur  
• Aircraft must offer improved efficiency and greater locale (local emissions requirements may vary between airports) and passenger acceptance to enable market growth  
• NextGen, through ops improvements, will enable smaller aircraft and better local acceptance |
| **King Carbon**   | • King Carbon foresees decreasing (-2%) demand for air transport due to increasingly higher cost of fuel and shortages from lack of national planning  
• Taxes instituted to support entire transportation sector fuel efficiency initiatives  
• Alternative forms of moderate range transportation take hold  
• Slower growth in developing countries and retraction in U.S. and Europe  
• Fleet recapitalization will slow unless national technology investments reduce acquisition costs  
• Development of efficient aircraft w/equally attractive cost and time to market is critical  
• Systems capable of performing on different fuels depending on availability in areas of operation |
| **Bright, Bold Tomorrow** | • Bright, Bold Tomorrow occurs under strong national and global economies with correspondingly robust (4%) increase in air transportation  
• Multi-national investment strategies occur as countries partner to develop techs and systems  
• Economic expansion results in need and opportunity for timely travel to a wide range of locales  
• Effective management of air travel industry growth to prevent emission issues occurring beyond what technology can resolve will be critical  
• Technical challenges will include bringing fleets of safe, cruise efficient STOL aircraft online and the corresponding management of increasingly complex airspace |
Mapping Goals to Scenarios

Individual Scenario Weighting Factors

Combined Scenario Weighting Factors

Application of Weighting Factor discussed in Analysis Process
Summary

- Future likely dominated by national strategies and objectives in energy, environment, economy, and defense
- Team presented summary of existing studies, literature search on issues, and internal observations
- Identified three primary scenarios covering research findings
- Used weighting factors to discern value of concepts and technologies in context of scenarios and related to goals
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Dave Miller
Sensis Corporation
Chris Harris
Northrop Grumman Corporation
Agenda

• Simulation and Modeling Process
• N+3 Impact Assessment Approach
• Airspace Concept Evaluation System (ACES)
• Future Demand Generation
• NextGen Assumptions for N+3 Simulations
• Summary of Assumptions of N+3
Simulation and Modeling Process

- System-wide simulations using the Airspace Concept Evaluation System (ACES)
- AvDemand was used to create future schedules with N+3 vehicle
- Tail-tracking algorithm was used to create airframe-based itineraries
- Simplified N+3 performance model used in ACES 4-D trajectory simulator
- Airport and airspace capacities reflect JPDO-provided NextGen assumptions

Primary goal was NAS assessment of passenger throughput and delay
N+3 Impact Assessment Approach

- A surrogate vehicle was used for the initial analysis of N+3 vehicle performance to develop sensitivities for requirements.
- Targeted markets consisted of origination and destination (O/D) pairs serviced by the Boeing 737 and other similar aircraft.
- Separate future schedules were created and simulated for the reference vehicle, similar vehicles, and the advanced N+3 vehicle and the results compared.
  - Differences were used to assess the impact of the advanced vehicle configurations on NextGen.
  - Performance metrics investigated included fuel efficiency, thrust, cruise speed, and cruise altitude.
  - System-wide comparisons included passenger throughput and delay.
- Assessed N+3 field length by using a bypass alternative that shifts demand to regional, underutilized facilities.
Airspace Concept Evaluation System (ACES)

- Distributed, fast-time, computer simulation of gate-to-gate flight operations in the NAS
- Developed in support of the NASA Virtual Airspace Modeling and Simulation (VAMS) project to assess future Air Traffic Management (ATM) concepts
- Utilizes an agent-based software architecture to model the behavior and interactions of Traffic Flow Management (TFM), Air Traffic Control (ATC), Flight Deck, and Airline Operational Control (AOC) entities
- Models terminal, and en route operations
- Utilizes a high fidelity, physics-based, four-degrees of freedom trajectory generator
- Used to assess new vehicle concepts in current and future air traffic environments
ACES Software Architecture

**ACES Inputs**

- **Airport Capacities**
  - Airport States
    - VFR
    - IFR
  - Origin/Destination
  - Aircraft Type
  - Trajectory
  - Cruise Alt & Speed
  - Departure Time

- **Flight Data Set**
  - Departure Time
  - Airport Capacities
  - Airport States
  - VFR
  - IFR

- **Static Data**
  - Airport Adaptation Data
  - Center/Sector Adaptation Data
  - Sector Capacities

**ACES Simulation**

- **Center A**
  - TRACON
  - Airport
  - TFM
  - ATC

- **Center B**
  - TRACON
  - Airport
  - TFM
  - ATC

**ACES Functionality**

- Generic/Enhanced Airport Model
- Winds On/Off
- Delay Maneuvers
- Departure Meter Fix Separation
- Airline Operations Control
- Rerouting
- Surface Traffic Limitations
- Conflict Detection & Resolution

**ACES Outputs**

- Aircraft State Message
- Flight Time Data Message
- Airport Acceptance Rate Message
- Center Handoff Message

**Local Data Collection**
Future Demand Generation

- AvDemand was used to create future demand schedules from a representative “seed” day
  - Seed day was Thursday, July 13th 2006
  - Same seed day used by JPDO for NextGen research

- N+3 vehicle was substituted into future demand schedules
  - Assumed a production rate of 400/year for N+3 vehicle with production starting in 2030 and 4000 vehicles in service by 2040
  - Took into account present day fleet mix and aircraft types
  - Assumed retirement of present-day aircraft types e.g. MD-80, DC-9, B737, etc.
Airframes-based Itineraries

- A tail-tracking algorithm was used to link together the flights in the AvDemand generated future schedules
  - Required to honor turnaround times and account for propagated delay
  - Propagated delay accounts for 30% of all delay according to the Bureau of Transportation and Statistics
- Future schedules generated had a median of 5 flights per day per airframe
NextGen Assumptions for N+3 Simulation

• NextGen to be fully implemented by 2025

• Modeled NextGen improvements:
  – All known new and planned runway construction and JPDO operational improvements
  – Airport capacities were increased on average for the top 35 airports by approximately 45%
  – En route sector capacities were increased by a factor of 1.7
    • Monitor Alert Parameter (MAP) is used to determine sector capacity
    • MAP values were multiplied by the improvement factor to increase the sector capacity for the N+3 simulations
How Flights Were Shifted for Metroplex Operations

- Traffic was offloaded to auxiliary airports within 70 nm of hub airport to ensure that capacity/demand ratio was less than 90% at hub
- Assumes JPDO NextGen airport capacities for 2025
Summary of Assumptions for N+3 NAS Simulations

- NextGen implementation by 2025
  - En route sector capacity increases due to operational improvements
  - Airport capacity due to new runway construction and operational improvements
  - Availability of Virtual Towers for regional airports to enhance Metroplex operations

- Production rate of 400/year for 10 years starting in 2030

- Turnaround time of 36 min

- Metroplex defined by 70 nmi radius from hub airport, 40 flights/hour capacity each satellite airport
Requirements Definition Process

Scenario Inputs:
1.8X – 3.0X Traffic Levels

NextGen Assumptions

ACES N+3 NAS Simulations

ITERATIVE

N+3 Surrogate

N+3 Preferred Configuration

OVERALL
NIMBY
King Carbon
Bright, Bold Tomorrow

Metroplex (Field Length)
Cruise Speed
Range
Passenger Load

Flight Demand
Capacity
Time
Major Airport
Auxiliary Airport

Flight Demand
Capacity
Time

Delay Maneuvers
ACES Functionality
Departure Meter Fix
Separation
Airline Operations
Control
Rerouting
Surface Traffic
Limitations
Conflict Detection &
Resoluation
Generic/Enhanced
Airport Model
Winds On/Off

Aircraft State
Message
Center Handoff
Message
Flight Time Data
Message
Airport Acceptance Rate Message
Local Data Collection

ACES Outputs

Airport Acceptance Rate Message
Local Data Collection
ACES Outputs
Primary Mission is to Serve Traffic Volumes Predicted by BBT Scenario

High traffic growth rates for an extended period can be sustained if infrastructure & macroeconomics are supporting.
Is Metroplex Needed?

• Sensitivity to even small increases in traffic levels, well below predicted 1.8X-3X range is high

• NextGen and current infrastructure alone are not enough for even moderate traffic increases

Metroplex Resources are Required to Enable the Challenging Future Traffic Levels
Metroplex Airfields are Available to Add Large Infrastructure Set to NAS

35 Major Airports

Goal is to leverage existing Metroplex runways to exploit underutilized resources.

Population Distribution

NextGen Enabled Fields
Identification of Metroplex Assets

- Metroplex offloading was used to assess the N+3 field length capability
  - Support traffic projections by shifting flights to nearby underutilized runways
  - Utilization of existing Metroplex assets was assumed (no new construction)

- Selection of Metroplex Airports
  - Located within 70nm of the associated primary airport
  - Public-use airport
  - At least 150ft width
  - History of commercial service
Creating a scheme to offload traffic from major hubs, utilizing NextGen-enabled airfields, is a crucial component of the 2035 simulations...

Determining field length capability depends greatly upon NextGen resources in ~2035, combined with future traffic projections.
Using metroplex airports with 5000’ or longer runways...

1. Critical ~3X traffic levels were successfully met. High delay levels were still observed.

2. Reduces significant levels of hub traffic volume...

3. By offloading to metroplex fields at critical capacity ratio.

- % Increase in Airports Relative to Current Towered Airports
  - 1: 674%, 2: 673%, 3: 637%, 4: 493%, 5: 329%

- % Increase in Flight Counts
  - Time of Day
    - 5: 186%, 6: 118%, 7: 75%, 8: 52%, 9: 37%, 10: 23%, 11: 15%, 12: 6%

- Decrease in 3X Traffic due to Offloading to Reliever Airports

- Flight Counts
  - Length of Longest Runway (Thousands of Feet)
What is the Right Cruise Speed?

To minimize adverse impact on NAS traffic delay and throughput, a minimum cruise speed of Mach 0.75 was adopted.

More airframes are required since flights/day decreases.
• The current most prevalent vehicle size class in use in terms of number of flights is also aptly suited to the metroplex mission:

Trip Distance (nm) by Airframe for Most Commonly Flown Airframes

Top 20 airframes show mainly 120-150 PAX aircraft cruising <1600nm almost exclusively
Further Refining the Range Requirement

- The range requirement was determined from projected 2025 levels from FAA estimated city-pair growth rates, using a Pareto type approach...

**Current & Future Stage Length Distributions**

Distributions show low sensitivity of overall character to growth levels.

**Cumulative Projection 2025**

To best meet the broadest possible need for future metroplex missions, a “conservative” 1600 nm range was selected.
Best Passenger Count for 1600nm Metroplex Operations Mission

- Correlation with the top 20 most often flown airframes show that 120-150 PAX is primary need
- Metroplex operations will likely be more readily accepted with smaller, lighter, cleaner, and quieter aircraft
- Smaller aircraft assure higher loading rates, and reduce propagated system delays

The primary vehicle need in the future NAS is the 120-150 PAX class. 120 was chosen for best Metroplex adoption potential.
Summary of Derived N+3 Requirements

- NextGen alone is not sufficient
- By engaging Metroplex fields with 5000’ runways (or greater), a huge addition in capacity and attendant reduction in delay is achieved
- Substantial future delays will be seen (or attendant price increases, congestion, frustration) if not implemented soon
- For the broadest capability, a range of 1600 nm is sufficient
- Passenger count of 120 will serve primary Metroplex mission
- Cruising at Mach 0.75 or greater will best utilize N+3 airframes

<table>
<thead>
<tr>
<th>Mission Requirements</th>
</tr>
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<tbody>
<tr>
<td>Range (with reserves):</td>
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<td>Passengers:</td>
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<td>Landing Distance (Sea Level/Standard Day):</td>
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<td>Minimum Cruise Mach:</td>
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Outline

• Introduction
• Scenario Development
• Requirements Definition
• Design Tools and Processes
• Candidate Configurations and Technologies
• Air Vehicle Design Studies
• Technology Maturation Plans
• Summary and Conclusions

• Closed session with NASA partners
N+3 Phase I Final Review:
Design Tools and Processes

Contract NNC08CA86C
NASA Glenn Research Center
21 April 2010

Peter Keding
Configuration Design and Integration
Northrop Grumman Corporation
**Tools and Processes Overview**

**Tools**
- Flight Optimization System (FLOPS)
- Airspace Concepts Evaluation System (ACES)
- Conceptual Mass Properties (CONMAP)
- Model for Investigating the Detectability of Acoustic Signatures (MIDAS)

**Processes**
- Calibration
- Optimization
- System Effectiveness Ratings (SER)
Vehicle Design Tools

**FLOPS**
- Developed by NASA Langley
- Used for preliminary design and analysis of flight vehicles
- Uses nine separate modules that allow for multidisciplinary vehicle design, including:
  - Weights
  - Aerodynamics
  - Takeoff/landing
  - Engine data scaling and interpolation
  - Mission performance
  - Program control

**CONMAP**
- Developed by Northrop Grumman
- Provides high-level weight and longitudinal center of gravity estimates based on vehicle geometry, system definitions, and vehicle functions

---

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<thead>
<tr>
<th>CONMAP</th>
<th>FLOPS</th>
<th>Delta</th>
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</table>
**MIDAS**

- Developed by Northrop Grumman
- Allows for calculation of noise sources
- Some modules based on NASA’s ANOPP
- Includes models to predict shielding and refraction, acoustic radiation and duct propagation, and acoustic attenuation and reflection
- Flight profile and individual noise sources used to compute EPNL

**ACES**

- Simulates nationwide air traffic management, flight, and airspace operations center functions
- Allows system-wide impacts of new aviation concepts to be analyzed
- Visualization of how the NAS will handle future flight demands
FLOPS Calibration Process

- Tool calibration and validation required before beginning design process

- B737-800 with the CFM56-7B27 used to calibrate FLOPS

- Used publically released geometry to generate vehicle in CATIA and FLOPS

- Must calibrate weights before aerodynamics
• 737-800 CATIA model used to generate weight statement in CONMAP, geometric input used to create FLOPS weight statement

• Publicly released weight information used to validate CONMAP

• FLOPS/CONMAP weight comparison used for FLOPS calibration, reconciled differences in FLOPS using calibration factors

• Iterated until weights were within an acceptable tolerance

<table>
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<tr>
<th></th>
<th>CONMAP Weight (lb)</th>
<th>FLOPS Weight (lb)</th>
<th>Delta (lbs)</th>
<th>Delta [%]</th>
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\[ \Delta \text{TOGW} = 0.26\% \]
• Takeoff and landing max $C_L$ and low-speed drag polars determined through historical trends

• High-speed drag polars calculated internally in FLOPS
  • Calibrated to match publically released performance characteristics

• Validated against historical trends for tube-and-wing aircraft of similar gross weight and passenger count

A similar process was used to calibrate these tools for hybrid wing-body vehicles using a Northrop Grumman internal database of all-wing aircraft.
Fuel Optimization

- FLOPS parametric mode to generate an array of vehicles within the trade space (aspect ratio, wing area, thrust)
- Use parser to filter configurations based on mission requirements and geometric constraints
- Sort candidate configurations by objective function
- Repeat process, refining trade space each iteration until objective function is minimized within an acceptable tolerance
- Subsequent analysis of emissions and acoustics
Fuel Burn Objective Function

- Optimizing solely on mission fuel drives aspect ratio higher with little regard for vehicle empty weight
- New objective function weighted combination of both mission fuel and gross weight
  - Yielded lower empty weight vehicles while still allowing for higher aspect ratios
  - Empty weight serves as a surrogate for vehicle cost
• Effective at examining and refining a large trade space

• Resulted in optimum performance of trade space while satisfying performance and geometric constraints
System Effectiveness Ratings (SER)

- SER metrics defined in order to quantify configuration performance relative to the 2030-2035 future scenario and the N+3 goals

- Take into account the benefits and penalties of technologies at the system level

- No extra credit is given for configurations that exceed individual N+3 goals

- Penalties
  - Noise, fuel burn, and emissions SER < 0 for negative system impacts
  - Field length SER = 0 for configurations which do not meet the requirement

\[
SER = \sum_{i=1}^{4} \omega_i SER_i
\]

where SER\(_i\) are the goal-specific system effectiveness ratings, and \(\omega_i\) are scenario-based weighting factors
System Effectiveness Ratings (SER)

Fuel

- **Goal:** 70% reduction in fuel burn from reference vehicle and mission

\[
SER_{fuel} = \frac{MF_{ref} - MF}{0.70MF_{ref}}
\]

- \(MF_{ref}\) = Reference vehicle mission fuel
- \(MF\) = Current configuration mission fuel

Emissions (\(NO_x\))

- **Goal:** 75% reduction in \(NO_x\) emissions from CAEP/6 requirement

\[
SER_{NOx} = \frac{NO_{x\_CAEP/6} - NOx}{0.75NO_{x\_CAEP/6}}
\]

- \(NO_{x\_CAEP/6}\) = Max permissible \(NO_x\) production based on OPR and SLS thrust
- \(NOx\) = Current configuration \(NO_x\) production

Noise

- **Goal:** 71 EPNdB reduction in EPNL from Stage 4 requirement

\[
SER_{EPNL} = \frac{EPNL_{Stage4} - EPNL}{71}
\]

- \(EPNL_{Stage4}\) = Stage 4 FAR noise limit for vehicle based on its gross weight
- \(EPNL\) = Current configuration cumulative noise

Field Length

- **Goal:** Enable metroplex operations, field length \(\leq 5,000\) ft

\[
SER_{FL} = \text{floor}\left(\frac{5000 + \epsilon}{FL}\right)
\]

- \(\epsilon\) = Arbitrarily small positive number
- \(FL\) = Current configuration field length

Scenario Weighting Factors
Tools and Processes Review

- Advanced tools capable of analyzing N+3 vehicles for performance, acoustics, and NAS simulations

- Calibration and validation of tools leads to robustness and higher fidelity

- Optimization process effective at examining large trade space and converging on optimized configuration

- Metrics and process established for quantifying configuration and technology effectiveness relative to N+3 goals

Tools and processes in place to support trade studies for a wide range of configurations and technology suites
Outline

• Introduction
• Scenario Development
• Requirements Definition
• Design Tools and Processes
• Candidate Configurations and Technologies
• Air Vehicle Design Studies
• Technology Maturation Plans
• Summary and Conclusions

• Closed session with NASA partners
N+3 Phase I Final Review: Candidate Configurations and Technologies

Contract NNC08CA86C
NASA Glenn Research Center
21 April 2010

Nicholas Caldwell, Peter Keding, Chris Harris
Northrop Grumman Corporation
Reference Vehicle

- Vehicle used as baseline for establishing current-year capability
- Perturbation on a 737-500, assuming constant technology
- Resized to meet mission requirements
- “Rubber Engine”, “photographically scaled” wing

<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>737-500</th>
<th>Reference Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td># Passengers</td>
<td>[]</td>
<td>123</td>
<td>120</td>
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<tr>
<td>Range</td>
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<td>2,400</td>
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<tr>
<td>Ramp Gross Weight</td>
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<td>Fuel Weight</td>
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<td>Wing Reference Area</td>
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<tr>
<td>Wing Sweep</td>
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<td>Wing Span</td>
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<td>T/W Ratio</td>
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<td>Max Wing Loading</td>
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<tr>
<td>Balanced Field Length</td>
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<tr>
<td>Landing Field Length</td>
<td>[ft]</td>
<td>4,450</td>
<td>4,996</td>
</tr>
</tbody>
</table>
Candidate Configurations and Technologies

- Engine Architecture Concepts
- Airframe Concepts
- Advanced Technologies

Technologies

Airframes

Engine Architectures
Engine Architecture Concepts
Reference Engine

Specifications:
- Maximum Thrust: 20,000 lbf
- Cruise SFC: 0.67 pph/lbf
- Overall Pressure Ratio: 22.4 (sea level)
- Fan diameter: 60”
- Bypass ratio: 6.0 (sea level)

CFM56-3B1 (Scalable Reference Engine)

CFM56-3B1 chosen due to its use on the Boeing 737-500

Scalable reference engine was carried through the study to serve as a baseline against which to derive fuel burn improvements
Advanced Engine Architectures

All engines modeled with constant $C_v$ (velocity coefficient) of 0.995, base $C_d$ (discharge coefficient) of 0.995, no bleed, and constant inlet pressure recovery

**Open Rotor**
- Low fuel consumption
- High noise potential
- Weight of gearbox and rotors

**Three-Shaft Turbofan**
- High BPR (~18) = propulsive efficiency
- High OPR (~50) = thermal efficiency
  - Low noise
  - Low weight

**Geared Turbofan**
- High BPR = propulsive efficiency
- High OPR = thermal efficiency
  - Low noise
  - Low weight
• The geared and three-shaft turbofans exhibit nearly identical fuel performance for a constant level of technology.

• Three-shaft turbofan and open rotor show 44% and 60% reduced fuel burn, respectively, at max takeoff thrust compared to the reference engine.
Engine Down-Selection

• Scalable reference engine is maintained throughout the study to serve as a baseline

• Geared turbofan set aside due to its similarities to the three-shaft turbofan

• Open rotor showed the best sea level static fuel consumption

• Open rotor maintained for further investigation regardless of its potential noise penalties
<table>
<thead>
<tr>
<th><strong>Initial Design Space</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advanced Tube-and-Wing</strong> (ATW)</td>
</tr>
<tr>
<td>• Higher recovery propulsion installation</td>
</tr>
<tr>
<td>• Low fuselage drag</td>
</tr>
<tr>
<td>• Compatible with high aspect ratio wings</td>
</tr>
<tr>
<td>• Drag and wetted area of external nacelle</td>
</tr>
<tr>
<td><strong>ATW with Embedded Propulsion</strong></td>
</tr>
<tr>
<td>• Noise shielding benefits</td>
</tr>
<tr>
<td>• Potential reduction in nacelle drag and wetted area due to removal of engine pods</td>
</tr>
<tr>
<td>• Propulsive efficiency penalties</td>
</tr>
<tr>
<td>• Possible ingestion of fuselage boundary layer</td>
</tr>
<tr>
<td>• Physical integration challenges</td>
</tr>
<tr>
<td><strong>Hybrid-Wing-Body</strong> (HWB)</td>
</tr>
<tr>
<td>• Higher recovery propulsion installation</td>
</tr>
<tr>
<td>• Noise shielding benefits</td>
</tr>
<tr>
<td>• Centerbody sized by passenger count</td>
</tr>
<tr>
<td>• Drag and wetted area of external nacelle</td>
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<tr>
<td>• Possible ingestion of fuselage boundary layer</td>
</tr>
<tr>
<td>• Physical integration challenges</td>
</tr>
</tbody>
</table>
Hybrid Wing-Body Sizing Constraint

- Minimum centerbody height determined by passenger height
- Centerbody volume sized by number of passengers
- Wing spar location and propulsion integration dictates length of centerbody and thickness-to-chord ratio

Minimum centerbody size determined by passenger count, regardless of mission
**Initial Design Space**

**ATW with Canard**
- Unconventional stability and control
- Higher induced drag due to additional lifting surface
- Higher recovery propulsion installation
- Low fuselage drag

**Channel Wing**
- Reduced field length
- Increased wing wetted area and weight
- Channel sized by rotor diameter
- Incompatible with turbofan engines
- Physical integration challenges

**Joined Wing**
- Lower structural weight
- Low fuselage drag
- Good transonic aerodynamic properties
- Excess wetted area and interference drag
- Minimal engine noise shielding due to engine placement and wing size

**Low Aspect Ratio Span Loader (LARS)**
- Induced drag is a balance of aircraft weight and aspect ratio
- More efficient passenger loading/unloading
- Platform for distributed propulsion systems
Qualitative Down-selection

- Wide range of configurations considered in initial design space

- Considerations:
  - Propulsive efficiency
  - Predicted aerodynamic performance
  - Packaging issues

- Smaller subset of candidate configurations selected based on this qualitative assessment
Qualitative Down-selection

- Based on a quantitative analysis that looked at factors relevant to the N+3 goals, three configurations were eliminated.

- A smaller subset of configurations was considered further.
Quantitative Down-selection

• All vehicles designed to meet 5,000 ft field length requirement
  - Conventional high-lift systems proved sufficient

• Remaining requirements used for downselection
Advanced Technologies
Technology Assessment Overview

- Initial technology database identified over 100 candidate technologies for the N+3 timeframe
- QFD process sorted technologies based on scenario weighting factors
- Candidate technologies selected from QFD results and modeled in FLOPS and MIDAS
Quality Function Deployment (QFD) Process

- Input from SMEs used to rate technologies with respect to each N+3 metric
- Scenario weighting factors used to produce Technology Effectiveness Rating (TER)
- Further assessed based on TRL and interaction with other technologies
- Sorted technologies downselected to a manageable number for more detailed investigation
Candidate Technologies

All-inclusive technology QFD

- **Noise**
  - Inverted Flow Nozzle
  - Landing Gear Fairings
  - Landing Gear Assembly Component Integration
  - Deployable Vortex Generators

- **Aerodynamics**
  - Distributed Exhaust Nozzle & Flap
  - Steady Circulation Control
  - Swept-Wing Laminar Flow
  - Modeling for Inlet Optimization

- **Airframe**
  - 3D Woven Pi Preform Joints
  - Advanced Metallic Structural and Subsystem Alloys
  - Ultrahigh Performance Fiber
  - Carbon Nanotube Electrical Cables
  - Affordable Large Integrated Structures
  - Integrated Aeroservoelastic Structures

- **Propulsion**
  - Intercooled Compressor Stages
  - Lean-Burn CMC Combustor
  - CMC Turbine Blades
  - Compressor Flow Control
  - Active Compressor Clearance Control
  - Lightweight Fan/Fan Cowl
  - Fan Blade Sweep Design
  - Swept Fan Outlet Guide Vanes
  - Variable Geometry Nozzle

Filtered by projected technology readiness inside N+3 time window

For use on subsequent charts:

- Used on Final Configuration
- Not Used on Final Configuration
Inverted Flow Nozzle

- **Discipline**: Noise
- **TRL Level**: 4
- **Primary Metric Addressed**: EPNL
- **Consequences of Failure**: Severe

Inverts high-temperature core flow and the low-speed cooler fan flow to generate two mixing interfaces for the core stream

Increased mixing capacity of the primary stream leads to reduced noise generation

- **Benefits**: Reduced jet noise
- **Penalties**: Increased weight, decreased thrust, increased engine complexity

- Modeled in MIDAS as a conservative broadband jet source noise reduction
- Modeled in FLOPS as weight and propulsive penalties

Baseline Flow

Inverted Flow

Inverter/20-lobe mixer configuration (w/ acoustic shield) at NASA ARC
Landing Gear Fairings

- **Discipline**: Noise
- **TRL Level**: 8
- **Primary Metric Addressed**: EPNL
- **Consequences of Failure**: Minimal

Passive method to streamline the landing gear assembly during low altitude operations
Reduces vortex shedding due to bluff-body nature of nose and main landing gear

- **Benefits**: Reduced landing gear drag, noise
- **Penalties**: Increased weight
- Modeled in MIDAS as a conservative broadband source noise reduction
- Modeled in FLOPS as a drag reduction and weight penalty on each of the landing gear assemblies
Landing Gear Component Integration

- **Discipline**: Noise
- **TRL Level**: 8
- **Primary Metric Addressed**: EPNL
- **Consequences of Failure**: Minimal

Integration of smaller landing gear assembly components into larger, more concise parts leads to reduced noise and landing gear drag. Minimizes exposed small parts reduces flow turbulence and small-scale vortex shedding.

- **Benefits**: Reduced landing gear drag, noise
- **Penalties**: Increased complexity, more difficult maintenance
- Modeled in MIDAS as a conservative broadband source noise reduction
- Modeled in FLOPS as a drag reduction on each of the landing gear assemblies

Fully Dressed B737-300 NLG
Deployable Slat Vortex Generators

- **Discipline:** Noise
- **TRL Level:** 4
- **Primary Metric Addressed:** EPNL
- **Consequences of Failure:** Minimal

VGs are small vanes on the scale of the boundary layer used to delay the onset of flow separation by generating vortices which promote mixing and re-energize the boundary layer. This forces the flow to remain attached, leading to a decrease in noise in a narrow low-frequency range, but increases noise in the high-frequency range due to the development of small scale turbulence.

- **Benefits:** Reduced narrowband noise
- **Penalties:** Increased weight
- Deployable VGs have been modeled into the wing slat and weight penalty
- Modeled in MIDAS as a frequency-dependent noise attenuation
- Modeled in FLOPS as weight penalty
Distributed Exhaust Nozzle (DEN) and Flap

- **Discipline**: Aerodynamics/Acoustics
- **TRL Level**: 2
- **Primary Metric Addressed**: $C_D$, $C_{L,\text{max}}$, EPNL, Weight, Thrust
- **Consequences of Failure**: Moderate

Engine exhaust is ducted through small ports in the wing flap. The blowing is used for circulation control as well as preventing flow separation over flaps. Exhaust flow is converted to small jets whose noise signature is characterized by higher frequencies which are more readily damped by the atmosphere.

- **Benefits**: Increased max lift coefficient with reduced noise footprint
- **Penalties**: Increased weight and complexity, decrease in thrust, increase in drag
- **Modeled in MIDAS**: as frequency-dependent noise attenuation
- **Modeled in FLOPS**: as weight, propulsive, and parasite drag penalties in addition to a max $C_L$ increase
Steady Circulation Control

- **Discipline**: Aerodynamics
- **TRL Level**: 3
- **Primary Metric Addressed**: $C_{L,max}$, $C_D$, Weight, Thrust
- **Consequences of Failure**: Moderate

Extracts engine bleed for jet blowing over round trailing edge surface to increase lift. Blown sheet of air remains attached to round circulation control (CC) surface which acts as a BL control at low blowing flow rates. At higher blowing rates, blown flow stays attached to CC TE which moves the airfoils stagnation point and streamline to the lower surface of the airfoil.

- **Benefits**: Increased max lift coefficient
- **Penalties**: Increased weight and complexity, decreased thrust
- Modeled in FLOPS as weight, propulsive, and parasite drag penalties in addition to a max $C_L$ increase
Swept-Wing Laminar Flow

- **Discipline:** Aerodynamics
- **TRL Level:** 4
- **Primary Metric Addressed:** $C_D$
- **Consequences of Failure:** Moderate

Delaying the onset of turbulent flow on the wing leads to cruise drag reduction.

Natural swept-wing laminar flow is achieved through optimal selection of airfoil and wing shapes and advanced manufacturing techniques.

Foreign-object debris can lead to premature turbulent transition which will penalize the drag-reducing effectiveness of the wing.

- **Benefits:** Reduced skin friction drag on the wing
- **Penalties:** Susceptibility to failure, lower $C_{L_{max}}$, constrained $M_{DD}$
- **Required slat removal modeled in MIDAS**
- **Modeled in FLOPS as percentage of surface(s) in laminar flow region**
Modeling for Inlet Optimization

- **Discipline:** Propulsion
- **TRL Level:** N/A
- **Primary Metric Addressed:** TSFC
- **Consequences of Failure:** N/A

**Benefits:** Increased pressure recovery, improved fuel burn, decrease in drag, increased range

**Penalties:** Little benefit with pitot-static engine configurations

- Modeled in FLOPS as an increase in pressure recovery and decrease in drag

Propulsion flow-path and integration effects modeling tool for complex inlet geometries

MDO tools and analysis allow for optimum engine configuration and propulsive efficiency, while reducing drag in certain body configurations

More applicable with embedded propulsion configurations
3-D Woven Pi-Preform Joints

- **Discipline:** Airframe
- **TRL Level:** 4
- **Primary Metric Addressed:** Weight
- **Consequences of Failure:** Varies per application

Enables creation of large integrated composite structures and sub-structures through composite pi-joints

Design allows for exploitation of orthotropic properties of carbon fiber and limits out of plane failure modes

Allows for failure arrest in design

Dry assembly materials remove manufacturing size limitations found on pre-preg systems

- **Benefits:** Reduction in joint and fastener weight, reduction in part count and assembly processes, enables larger integrated structures
- **Penalties:** Increase in cost
- **Modeled in FLOPS as weight reduction**
Advanced Metallic Structural and Sub-System Alloys

- **Discipline:** Airframe
- **TRL Level:** 5
- **Primary Metric Addressed:** Weight
- **Consequences of Failure:** Vary per application

Aluminum and titanium alloys meet high demand for materials with increased structural properties and withstand elevated temperatures.

Materials exhibit improved strength to weight ratios and fatigue/crack growth properties.

- **Benefits:** Reduced structural and subsystem weights
- **Penalties:** Increase in manufacturing cost
- **Modeled in FLOPS as weight reduction**
Ultrahigh Performance Fiber

- **Discipline**: Airframe
- **TRL Level**: 2
- **Primary Metric Addressed**: Weight
- **Consequences of Failure**: Vary per application

A high strength low density polymer fiber in which the monomers are aligned and fused through chemical bonding along the length of the fiber.

Hydrogen bonding between fibers and carbon nanotubes have been absent in previous composites.

Results in increase in strength and positive thermal and flame resistance properties.

- **Benefits**: Reduced structural weight, reduced part count, larger integrated structures.
- **Penalties**: Increase in manufacturing cost.
- Modeled in FLOPS as weight reduction.
Carbon nanotubes are manufactured by injecting fuel and reaction gas into a floating catalyst suspended in a furnace. Can produce CNT threads which can be woven into a braid and CNT sheets. CNT sheets are extremely lightweight, strong, with good electrical properties. CNT braids are extremely lightweight, strong, and have slightly reduced electrical properties.

- **Benefits:** Reduced electrical system weight
- **Penalties:** Increase in electrical system cost
- **Modeled in FLOPS as weight reduction**
Affordable Large Integrated Structures

- **Discipline:** Airframe
- **TRL Level:** 4
- **Primary Metric Addressed:** Weight
- **Consequences of Failure:** Vary per application

Advancements in alloy, composite, and composite joint technology allow more design flexibility toward unitized structures. Developments in materials reduce weight while new methodology further reduces weight. Eliminates structural discontinuities and fastened assemblies, increasing structural efficiency. Reduction in part count.

- **Benefits:** Reduction in structural weight, lower manufacturing time and cost.
- **Penalties:** Possible limits on vehicle life, structure must be more robust to avoid repair, increased part complexity, constrained design volume.
- Modelled in FLOPS as weight reduction.
Integrated Aeroservoelastic (ASE) Structures

- **Discipline:** Airframe/Aerodynamics
- **TRL Level:** 5
- **Primary Metric Addressed:** Weight
- **Consequences of Failure:** Catastrophic

Utilization of directional stiffness into aircraft structural design to control aeroelastic deformation which benefits aerodynamics, control, and structure in a positive way. Structural weight no longer primary factor in wing design, but should include other disciplines.

MDO improves design efficiency by designing a wing to meet specific loads, flight conditions, and performance.

- **Benefits:** Reduced structural and control system weight
- **Penalties:** Increase in manufacturing cost and time
- **Modeled in FLOPS as weight reduction**
Intercooled Compressor Stages

- **Discipline:** Propulsion
- **TRL Level:** 3
- **Primary Metric Addressed:** TSFC
- **Consequences of Failure:** Minimal

Reducing the temperature of the compressed flow between compressor stages increases the thermal efficiency of the engine because less work is required to compress lower temperature gas.

Intercooler can not completely drop the intermediate flow to ambient temperature, as there will always be an efficiency associated with its heat exchange capacity.

- **Benefits:** Reduced fuel consumption, increased thrust, reduced emissions
- **Penalties:** Added engine weight due to the presence of the intercooler
- **Modeled by RR-LW**
Lean-Burn CMC Combustors

- **Discipline:** Propulsion
- **TRL Level:** 6
- **Primary Metric Addressed:** NOx
- **Consequences of Failure:** Moderate

Staged combustors incorporate multiple (typically two) distinct combustion zones serviced by independent fuel injection systems.

Depending on the engine power setting, different combinations of combustor stages may be used, and the burner can then be optimized for multiple flight conditions.

This level of control allows for emissions to be more tightly monitored and controlled.

**Benefits:** Reduced emissions, reduced sensitivity to fuel composition, leaner combustion

**Penalties:** Increased engine weight, increased fuel system complexity

**Modeled by RR-LW**
CMC Turbine Blades

- **Discipline:** Propulsion
- **TRL Level:** 3
- **Primary Metric Addressed:** TSFC
- **Consequences of Failure:** Severe

Ceramic matrix composite turbine blades and turbine materials are attractive due to their high temperature tolerance. Without the need to cool the turbine blades, compressor bleed is no longer required, and higher temperatures can be achieved with the combustor. CMC blades will also weigh less than those constructed from current metallic alloys.

- **Benefits:** Reduced engine weight, reduced fuel consumption, decreased takeoff and landing distances
- **Penalties:** Increased emissions due to higher combustor temperatures
- **Modeled by RR-LW**
Compressor Flow Control

- **Discipline:** Propulsion
- **TRL Level:** 4
- **Primary Metric Addressed:** TSFC
- **Consequences of Failure:** Minimal

Extracting or diffuser bleed flow and injecting it into the compressor face in order to tailor the compressor flow to minimize the likelihood of stall or surge

Can be used to control flow distortion or to dampen flow instabilities that are associated with stall or rotating surge

Requires sensors and control system to detect and control the instabilities or flow characteristics that need to be dampened

- **Benefits:** Reduced likelihood of compressor surge or stall, increased engine performance
- **Penalties:** Engine bleed must be compensated by increased performance, increased engine weight
- **Modeled by RR-LW**
Active Compressor Clearance Control

- **Discipline:** Propulsion
- **TRL Level:** 4
- **Primary Metric Addressed:** TSFC
- **Consequences of Failure:** Minimal

Tip clearances can vary depending on flight conditions, engine power settings, etc. Active compressor clearance control provides higher compressor efficiencies by minimizing blade tip losses by maintaining tip clearances through active means. Generally takes the form of variable, flexible clearance control maintained by electromagnetic actuators.

- **Benefits:** Higher component efficiencies, improved TSFC
- **Penalties:** Added engine weight
- **Modeled by RR-LW**
Lightweight Fan/Fan Cowl

- **Discipline:** Propulsion
- **TRL Level:** 3
- **Primary Metric Addressed:** TSFC, Field Length
- **Consequences of Failure:** Moderate

Through optimization of the engine front-end structure using light weight material, a shorter (lower wetted area) nacelle is achievable. This technology also allows for mounting of AGB closer to the engine core, reducing nacelle diameter and hence drag.

- **Benefits:** Weight, reduced nacelle drag
- **Penalties:** Lighter engine requires more structural weight in the wing
- **Modeled by RR-LW**
Introducing sweep into the fan blades minimizes the occurrence of shocks on the fan blade tips. This increases fan efficiency by minimizing pressure losses. Fan efficiency also increased by allowing for the formation of a more favorable boundary layer.

- **Benefits:** Reduced noise, increased fan efficiency
- **Penalties:** Blade complexity, axial length
- Modeled by RR-LW
**Swept Fan Outlet Guide Vanes**

- **Discipline:** Propulsion
- **TRL Level:** 5
- **Primary Metric Addressed:** TSFC
- **Consequences of Failure:** Minimal

Introducing sweep into the fan outlet guide vanes has the potential to reduce pressure losses. By delaying the impact of turbulent rotor wake on OGV, noise reduction is achievable through this design strategy.

- **Benefits:** Reduced noise, increased fan efficiency
- **Penalties:** Blade complexity, axial length
- Modeled by RR-LW
Shape Memory Alloy Nozzles

- **Discipline:** Propulsion/Noise
- **TRL Level:** 5
- **Primary Metric Addressed:** EPNL, TSFC
- **Consequences of Failure:** Moderate

Variable geometry nozzles utilize a SMA actuated hinge that is able to be varied and controlled as seen on many modern military aircraft.

- **Benefits:** Reduced Noise
- **Penalties:** Decrease in fuel efficiency, increase in nozzle weight
- **Modeled by RR-LW**

Variable-area exhaust nozzle: fully open

Variable-area exhaust nozzle: reduced area

Allows for optimization of engine for given power setting and flight condition.

Noise generated from engine is proportional to diameter of the nozzle exit squared and to the exit velocity to the eighth power.
Double Degree-of-Freedom Inlet Liner

- **Discipline:** Noise
- **TRL Level:** 8
- **Primary Metric Addressed:** EPNL
- **Consequences of Failure:** Moderate

Contains two layers of absorbing material and perforated sheets separating the layers

Absorbing sections divided up into smaller cells designed to target specific tonal frequencies

Trade between absorption capacity and drag from the porous face sheet

- **Benefits:** Reduced Noise
- **Penalties:** Decrease in fuel efficiency, increase in weight
- Modeled in MIDAS as frequency-dependent noise attenuation
Candidate Configurations and Technologies Review

- Two advanced and one reference engine architectures selected
- Planform down-selection led to the HWB and ATW as the two preferred airframes
- Candidate technologies selected from QFD results and modeled in FLOPS and MIDAS
Outline

- Introduction
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  - Air Vehicle Design Studies
- Technology Maturation Plans
- Summary and Conclusions

- Closed session with NASA partners
N+3 Phase I Final Review: Air Vehicle Design Studies

Contract NNC08CA86C
NASA Glenn Research Center
21 April 2010

Peter Keding, Nicholas Caldwell, Dr. Sam Bruner
Northrop Grumman Corporation
Air Vehicle Design Studies Overview

- Sizing and Performance
- Aircraft Acoustics
- Aircraft Emissions
- System Effectiveness Rating Results
- Preferred Configuration
Air Vehicle Design Studies Overview

- Sizing and Performance
- Aircraft Acoustics
- Aircraft Emissions
- System Effectiveness Rating Results
- Preferred Configuration
Sizing and Performance Analysis
Advanced Liner Design

- Design of advanced inlet and fan duct liners to aid in the reduction of noise towards the N+3 goal levels.

- Advanced materials exhibit better absorptive properties and are capable of increased integration.

- Advanced two degree-of-freedom liner reduces overall sound pressure level (OASPL) over larger frequency range than baseline.

- Reduction in OASPL has been shown to be largely insensitive to power setting.
Analysis of Engine Mounting Configurations

- Wing- and fuselage-mounted three-shaft turbofan and open rotor configurations used a tube-and-wing baseline airframe.

- T-tail design selected for fuselage-mounted engine configurations
  - Places horizontal tail out of the engine exhaust
  - Increases structural weight

- Quantified the performance and weight change associated with each configuration.

- Both mounting configurations were analyzed with the addition of laminar flow.

Laminar flow regions for: a) clean wing, fuselage-mounted b) wing-mounted turbofan engine.
Analysis of Engine Mounting Configurations

- Wing-mounting resulted in the lowest fuel burn between configurations
  - With laminar flow
  - Without laminar flow

- Open rotor wing-mounting dismissed due to configuration problems
  - Tip clearance

- Engines were fuselage-mounted for all HWB configurations
  - Shielding benefits
  - No vertical tails to re-size
  - Available space
Laminar Flow Integration

- Conventional leading edge devices will trip the boundary layer.
- Removal of leading edge devices penalizes maximum lift coefficient.
- Wing size and thrust must increase to meet field performance constraints.
- Wetted area increase on HWB outweighs fuel savings due to reduced skin friction.
- Reconciling laminar flow and high-lift devices would result in improved fuel burn potential.

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<thead>
<tr>
<th></th>
<th>Tube and Wing</th>
<th>Hybrid Wing Body</th>
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<tbody>
<tr>
<td><strong>Takeoff</strong></td>
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</tr>
<tr>
<td>Initial Max CL</td>
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<tr>
<td>Final Max CL</td>
<td>2.232</td>
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<tr>
<td>% CL Reduction</td>
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<td>28.00%</td>
</tr>
<tr>
<td><strong>Landing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial Max CL</td>
<td>3.24</td>
<td>1</td>
</tr>
<tr>
<td>Final Max CL</td>
<td>2.736</td>
<td>0.72</td>
</tr>
<tr>
<td>% CL Reduction</td>
<td>15.56%</td>
<td>28.00%</td>
</tr>
</tbody>
</table>
$M_{DD}$ and Sweep Analysis

- Drag divergence Mach number studies were performed for initial sizing for a range of wing sweeps, thickness-to-chord ratios, and wing technology.

- Enables a cruise Mach number up to 0.8
  - Meets minimum cruise Mach number of 0.75 defined in mission requirements.
Landing and Takeoff Operations

- Detailed trajectories were developed for each configuration below 10,000 ft

- **Takeoff/Climb:** Federal Aviation Regulation (FAR) Part 36 rules permit engine cutback

- **Landing/Descent:** Used three degree glide slope for approach, landing configuration set at outer marker
• The FAR Part 36 limits the effective perceived noise level (EPNL) allowable by aircraft

• Restrictions placed on cumulative EPNL divided into three categories: takeoff, sideline, and approach

• Stage 4 requirements are a function of vehicle gross weight and number of engines
Modeled Noise Source Components

- OASPL directivities were computed for each noise source at multiple altitudes

- Identified targets for noise reduction
  - Landing gear
  - Slats and flaps
  - Jet and fan

Example Noise Source Calculation and Directivity
• The ATW was found to have the lowest cumulative EPNL between airframes.

<table>
<thead>
<tr>
<th>Effective Perceived Noise Level, EPNdB</th>
<th>Reference Vehicle</th>
<th>ATW</th>
<th>HWB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takeoff</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sideline</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Approach</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cumulative</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Aircraft Emissions
Reference LTO Cycle Definition

- Defined by ICAO Annex 16, Volume II, Aircraft Engine Emissions for all aircraft engines rated above 6,000 lbf

- Conducted at sea level static conditions by varying the engine throttle to simulate the different portions of the LTO cycle

<table>
<thead>
<tr>
<th>Power Setting</th>
<th>Time, min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takeoff 100%</td>
<td>0.7</td>
</tr>
<tr>
<td>Climb 85%</td>
<td>2.2</td>
</tr>
<tr>
<td>Approach 30%</td>
<td>4.0</td>
</tr>
<tr>
<td>Idle 7%</td>
<td>26.0</td>
</tr>
</tbody>
</table>

2.1% of cycle time
79.0% of cycle time

Low NOX combustor must be effective across operating range
CAEP/6 NOx Emissions Metric

- Mass of emissions computed as the sum of the fuel flows, NOx production (g/kg fuel), and operational time for each stage of the simulated LTO cycle:

\[ D_p = \sum t_i NOx_i \dot{W}_f,i \]

- This value is divided by the SLS thrust of the engine to compare to the CAEP/6 requirement:

\[ \frac{D_p}{F_\infty} \]

Historical emissions performance trends (\( F_\infty > 20,000 \text{ lbf} \))

<table>
<thead>
<tr>
<th>OPR, ( F_\infty )</th>
<th>Thrust &lt; 20,000 lbf</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPR</td>
<td>Thrust ≥ 20,000 lbf</td>
</tr>
</tbody>
</table>
System Effectiveness Rating (SER) Results
Technology Packaging

- Technology suites were developed based on the technology SER assessments
- Noise and performance packages were developed
- Technologies with highest SER were retained

<table>
<thead>
<tr>
<th>Technology</th>
<th>ATW No Tech</th>
<th>ATW Noise Tech</th>
<th>ATW Performance Tech</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scaled CFM56-3B1</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open Rotor</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Three-Shaft Turbofan</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aeroservoelastic Structures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MS Ultra-High Performance Fiber</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Affordable Large Integrated Structures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-D Woven and Stitched Composites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced Metallics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swept-Wing Laminar Flow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon Nanotube Electrical Cables</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landing Gear Fairings</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landing Gear Integration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerothermal Concepts</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boundary Layer Ingestion</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steady Circulation Control</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet Optimization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distributed Exhaust Nozzle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vortex Generators</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Major Technology Suites for ATW Configurations**
Final Configuration SER Comparisons

• The ATW exhibits better system-level performance than the HWB

• The ATW open rotor configuration performs slightly better than the ATW three-shaft turbofan
  - Assuming the two engines have the same noise output

The ATW is the preferred configuration
Final Engine Down-Selection

- No reliable method currently available to compute open-rotor acoustic levels
- Trade study was performed to quantify the SER sensitivity between engines
- Acoustics experts agree that this is highly unlikely with current understanding of this noise source

The open-rotor becomes the preferred engine if no more than ~3 EPNdB louder than the three-shaft turbofan

The three-shaft turbofan was selected as the preferred vehicle engine
Preferred Configuration
### Phase 1 Preferred Configuration Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range (With Reserves):</td>
<td>1,600 nm</td>
</tr>
<tr>
<td>Passengers:</td>
<td>120</td>
</tr>
<tr>
<td>Field Length Capability:</td>
<td>5,000 ft</td>
</tr>
<tr>
<td>Cruise Altitude:</td>
<td>45,000 ft</td>
</tr>
<tr>
<td>Design Mach Number:</td>
<td>0.75</td>
</tr>
<tr>
<td>Ramp Gross Weight:</td>
<td>80478 lb</td>
</tr>
<tr>
<td>Zero Fuel Weight:</td>
<td>71,333 lb</td>
</tr>
<tr>
<td>Operating Empty Weight:</td>
<td>46,133 lb</td>
</tr>
<tr>
<td>Empty Weight:</td>
<td>43,666 lb</td>
</tr>
<tr>
<td>Wing Aspect Ratio:</td>
<td>12.7</td>
</tr>
<tr>
<td>Cruise Specific Fuel Consumption:</td>
<td>0.451 pph/lb</td>
</tr>
</tbody>
</table>

### Technology Suite

- **Three-Shaft Turbofan Engine**
  - Ultra-High Bypass Ratio ~18
  - CMC Turbine Blades
  - Lean-Burn CMC Combustor
  - Intercooled Compressor Stages
  - Swept Fan Outlet Guide Vanes
  - Fan Blade Sweep Design
  - Lightweight Fan/Fan Cowl
  - Compressor Flow Control
  - Active Compressor Clearance Control
  - Shape Memory Alloy Nozzle
  - Swept Wing Laminar Flow
  - Large Integrated Structures
  - Aeroservoelastic Structures
  - Ultrahigh Performance Fibers
  - Carbon Nanotube Electrical Cables
  - 3-D Woven Pi Preform Joints
  - Advanced Metallics
  - Landing Gear Fairings
  - Advanced Acoustic Inlet Liner
Dramatic improvements in empty weight and fuel have been enabled by advanced technologies.

<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>737-500</th>
<th>Reference Vehicle</th>
<th>Preferred Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td># Passengers</td>
<td>[]</td>
<td>123</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Range</td>
<td>[nm]</td>
<td>2,400</td>
<td>1,600</td>
<td>1,600</td>
</tr>
<tr>
<td>Ramp Gross Weight</td>
<td>[lb]</td>
<td>133,500</td>
<td>120,170</td>
<td>80,478</td>
</tr>
<tr>
<td>Empty Weight</td>
<td>[lb]</td>
<td>68,860</td>
<td>67,350</td>
<td>43,660</td>
</tr>
<tr>
<td>Fuel Weight</td>
<td>[lb]</td>
<td>42,186</td>
<td>25,048</td>
<td>9,144</td>
</tr>
<tr>
<td>Wing Reference Area</td>
<td>[ft^2]</td>
<td>1,135</td>
<td>1,280</td>
<td>967.5</td>
</tr>
<tr>
<td>Wing Sweep</td>
<td>[deg]</td>
<td>25</td>
<td>25</td>
<td>26</td>
</tr>
<tr>
<td>Wing Span</td>
<td>[ft]</td>
<td>94.9</td>
<td>100.4</td>
<td>111.0</td>
</tr>
<tr>
<td>Wing AR</td>
<td>[]</td>
<td>7.9</td>
<td>7.9</td>
<td>12.7</td>
</tr>
<tr>
<td>T/W Ratio</td>
<td>[]</td>
<td>0.30</td>
<td>0.34</td>
<td>0.36</td>
</tr>
<tr>
<td>Max Wing Loading</td>
<td>[psf]</td>
<td>117</td>
<td>94</td>
<td>83.2</td>
</tr>
<tr>
<td>Balanced Field Length</td>
<td>[ft]</td>
<td>8,630</td>
<td>4,497</td>
<td>4,999</td>
</tr>
<tr>
<td>Landing Field Length</td>
<td>[ft]</td>
<td>4,450</td>
<td>4,996</td>
<td>4,906</td>
</tr>
</tbody>
</table>
Airframe / Engine Matching

Flight Envelope

Wing loading for field performance synergistic with cruise performance

Aerodynamic Efficiency

Thrust-to-Weight ratio enables 5000 ft BFL as well as efficient cruise at FL 450
Weight Fraction Comparison and Weight Statement

System/Components | % TOGW | Weight, lbf
--- | --- | ---
**Structural** | 23.9% | 19264
- Wing | 7.9% | 6365
- Horizontal Tail | 0.9% | 691
- Vertical Tail | 0.4% | 356
- Fuselage | 7.9% | 6324
- Landing Gear | 4.4% | 3552
- Nacelle | 2.5% | 1976

**Propulsion** | 6.3% | 5058
- Engines | 5.5% | 4453
- Fuel Tanks & Plumbing | 0.8% | 605

**Systems & Equipment** | 24.0% | 19341
- Surface Controls | 1.7% | 1377
- Auxiliary Power | 0.8% | 626
- Instruments | 0.7% | 587
- Hydraulics | 4.4% | 3581
- Electrical | 1.1% | 865
- Avionics | 1.5% | 1232
- Furnishings & Equipment | 11.8% | 9518
- Air Conditioning | 1.7% | 1357
- Anti-icing | 0.2% | 198

**Empty Weight** | 54.3% | 43663

**Operating Weight** | 57.3% | 46133
- Fuel | 11.4% | 9145
  - Mission Fuel | 11.4% | 9145

**Passengers & Cargo** | 31.3% | 25200
- Passengers | 26.8% | 21600
- Passenger Baggage | 4.5% | 3600

**Zero Fuel Weight** | 88.6% | 71333
- Fuel | 11.4% | 9145
  - Mission Fuel | 11.4% | 9145

**Max Ramp Weight** | 100.0% | 80478

Largest contributors to gross weight identify future weight reduction targets.
## Preferred Performance

<table>
<thead>
<tr>
<th>Performance Criteria</th>
<th>N+3 Goal (2030-2035 EIS)</th>
<th>Phase I Achievement</th>
<th>Absolute % of Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise (Cum Below Stage 4)</td>
<td>-71 dB</td>
<td>-70 dB</td>
<td>98%</td>
</tr>
<tr>
<td>LTO NOx Emissions (Below CAEP/6)</td>
<td>Better than -75%</td>
<td>-91%</td>
<td>121%</td>
</tr>
<tr>
<td>Fuel Burn</td>
<td>Better than -70%</td>
<td>-64%</td>
<td>91%</td>
</tr>
<tr>
<td>Field Length</td>
<td>Exploit Metroplex</td>
<td>Exploited Metroplex</td>
<td></td>
</tr>
</tbody>
</table>

### Performance Criteria

- **Noise (Cum Below Stage 4)**: -71 dB, -70 dB, 98%
- **LTO NOx Emissions (Below CAEP/6)**: Better than -75%, -91%, 121%
- **Fuel Burn**: Better than -70%, -64%, 91%
- **Field Length**: Exploit Metroplex, Exploited Metroplex

### Graphs

- **Payload, lb vs. Range, nm**
  - Max Payload: (71,333 lb)
  - Fuel Capacity: 65,000 lb
  - 70,000 lb
  - 75,000 lb
  - 80,000 lb
  - 85,000 lb
  - 90,000 lb

- **Range, nm vs. Mach Number**
  - 120 Passengers
  - 200 nm Reserves
  - Mach 0.75 Cruise
  - 200 nm Reserves

- **Mach 0.75 Cruise**
  - 200 nm Reserves

---

*Maximum Payload (71,333 lb)*

*Fuel Capacity (90,000 lb)*

*Mach 0.75 Cruise 200 nm Reserves*
Preferred Vehicle Fuel Burn Reduction

- Overall fuel reduction represents technology set applied as a group
- Propulsion system resulted in largest overall fuel burn reduction
- Aerodynamics, structures, and propulsion disciplines all important towards achieving fuel burn reduction

Graph showing fuel burn reduction for various technologies and disciplines, with a goal of -63.5% fuel burn reduction.
Preferred Vehicle Noise Reduction

- Ultra-high bypass ratio engine (~18) directly reduces jet noise
- Slat removal and landing gear fairings greatly reduced landing/approach noise
- Jet noise further reduced by shape memory alloy nozzle
- Fan noise limited by the addition of advanced liner technology
Preferred Configuration Emissions Results

- The three-shaft and open rotor engine architectures generate significantly less NO\textsubscript{x} emissions than enforced by CAEP/6

- N+3 emissions goal is achieved through the use of staged combustion enabled by CMC liners

<table>
<thead>
<tr>
<th>CAEP/6 Requirement</th>
<th>Achievement</th>
<th>Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>48.3</td>
<td>40.3</td>
</tr>
<tr>
<td>Open Rotor, Fn = 16760 lbf</td>
<td>73.72</td>
<td>10.63</td>
</tr>
<tr>
<td>Three-Shaft, Fn = 14393 lbf</td>
<td>102.9</td>
<td>9.69</td>
</tr>
</tbody>
</table>

NASA N+3 Goal
75% reduction from CAEP/6
Outline

- Introduction
- Scenario Development
- Requirements Definition
- Design Tools and Processes
- Candidate Configurations and Technologies
- Air Vehicle Design Studies
- Technology Maturation Plans
- Summary and Conclusions

- Closed session with NASA partners
N+3 Phase I Final Review:
Technology Maturation Planning

Contract NNC08CA86C
NASA Glenn Research Center
21 April 2010

Chris Harris
Northrop Grumman Corporation
Set of Technology Maturation Plans

- All technologies that were included on the final preferred configuration were included in the maturation planning.
- Internal R&D and relevant external sources were used to compile initial “trajectory” for near-term planning and expectations.
- Future planning considered potentials for scheduled risk, as well as technical risk, so some activities show longer duration than typical.
- We are presenting a limited set of the most beneficial technologies.

As an example of technology maturation, mixing devices for jet noise reduction were studied in the 50’s (G.M. Lilley) and just recently were adopted on commercial transport. Approximately 10 years passed from ~TRL 4 to certification.
• Plasma actuators are viewed as a prime candidate for implementation since although they offer relatively low momentum addition compared to other active flow actuators, they may greatly affect the coherent structure of the shed vorticity.
• However, at this low TRL, it is viewed as a prime candidate in a series of actuator trials, so that the most effective control scheme can be developed.
• Elimination of the slat by integrating virtual or seamless leading edge concepts is estimated at a current TRL of 2.
• This technology item spawned from a more detailed consideration of the laminar flow requirements, not initially assumed in the technology QFD study.
• Continued development of new approaches through experimental and computational approaches is envisioned, working towards approaches that are both effective at increasing CL on a laminar flow wing, and have a tolerable failure mode that prohibits immediate stall.
Plasma actuators are viewed as a prime candidate for implementation since although they offer relatively low momentum addition compared to other active flow actuators, they may greatly affect the coherent structure of the shed vorticity. However, at this low TRL, it is viewed as a prime candidate in a series of actuator trials, so that the most effective control scheme can be developed.
Variable geometry nozzles utilizing SMA materials to actuate a high-bypass ratio fan nozzle are estimated to be at a TRL of 4. SMA characterizations should be performed to reliably (minimizing hysteresis) actuate at least a 2-position nozzle practical for takeoff and cruise operations. Investigating the tradeoff between continuously varying nozzle area, and two or multi-position fixed positions should be performed by exploring multiple configurations.
• At a current TRL of approximately 4 (depending on which material class of several), optimizations of alloy chemistries for structural and subsystem components should continue to investigate good candidates for limited sample production throughout the next several years.
• Near-term goals should focus on higher toughness and strength in compressive as well as tensile modes, as well as at elevated temperatures and room temperatures. High-pressure, dynamic, hydraulic applications should be targeted as well.
Ultra-High Performance Composite Fiber

- Further work to verify performance for aircraft panel applications should focus on using the status fibers, which have known fabrication quality limitations, to develop layup processes with appropriate resins.
  - Fiber manufacturing development must occur in parallel to improve fiber performance and manufacturability to reinforce the TRL 3 level risk.
  - Coupon testing to examine basic composite properties through break tests and surface examination, along with basic stress/strain testing should occur at this stage.

- For moving to TRL 4, improved fibers must be available starting in several years following coupon testing to advance a simple composite panel structure through compression and break testing, as well as verifying layup procedures and the expected resin-fiber interface properties.
Carbon nanotube cables are currently estimated at a TRL of 3, and must be pursued in terms of both core wire performance, and outer mesh conductor performance (coaxial arrangement).

- To reach TRL 4 for both of these components, at least two years (potentially several) of development is forseen to assess feasibility of optimized designs for combined prototypes.
- Separate development will occur on each to adequately lower risk levels initially, and identify and isolate technical hurdles.
- For acquiring a TRL of 5, performance of a subsystem prototype installation for a moderately complex electrical system should be evaluated.
Researchers have demonstrated some components of low- and moderate-fidelity transport of fan-face distortion through to the bypass duct and core compressor, but this has not been in concert with other activities required to bring this capability to TRL 4.

This would also require adding additional multi-fidelity models of inlet losses and integration effects to estimate performance quickly for MDO applications.

Handling of complex geometry requirements (to handle BLI, podded, embedded configurations) passed automatically through an API that must be devolved into a set of modeling constraints should be a cornerstone component.
• Continued development to further reduce risk at this level should include prototype development activities including Reliability Based Design (RBD) methods for joint designs.  
• Advanced structural models should be developed to predict performance at joint component and integrated structure levels. Weight models should be updated for system level evaluations.  
• A follow-on task for advancement to TRL 5 is the implementation of previous design and prediction tools to design/fab/test a large substructure in the NASA COLTS facility.
Aeroservoelastic Structures

- Previous development of advanced state-space simulations, analysis methods, and flutter control law development should be leveraged to develop a simplified high aspect ratio wing design to be evaluated by testing of a cantilevered semi-span wind tunnel model.
- A static aeroelastic scaling of this subscale model should be sufficient for this activity. Moderate drag reduction and load control goals should be pursued.
- Parallel refinement of requirements for an integrated system should be performed and incorporated into future model designs to a practical extent.
Intercooled Compressor Stage

- Evaluation of subscale concepts to investigate pressure loss and cooling performance should be performed in the next several years utilizing DOE and other methods to optimize subsystem-level integration into the engine.
- This should occur in simulated design flow (flowrates, pressure) conditions downstream of HPC installation to bring to TRL 4.
- CFD simulations should be carried out to understand pressure loss mechanisms and improve heat transfer rates.
- System concept studies should continue to use updated models for top-level mission benefits.
- Development of the CMC liner technology should occur in parallel with this activity so that the design for staged combustion, which will allow huge NOx reductions across the power setting range, can assume CMC availability.
- Design and test of injector concepts for use in staged combustion on a flamed tube to validate the design and also investigate the compatibility with alternative fuels.
- Diagnostics data from the previous study will feed aid in evaluating performance on a two-cup sector test at high OPR, focusing on integration, ignition, lean blowout, and subidle efficiency, as well as the primary emissions metrics.
Cooled Cooling Air and Endothermic Fuel Cooling

- To advance to a TRL of 6, demonstration on an integrated, ground-based engine should be performed. Assessment of flow levels and heat exchanger pressure losses, with surrogate cooling fluids representative of cracked fuels (if none are available) should be performed. A low-loss, lightweight heat exchanger design should be validated as a key outcome.
- Developing an array of potential candidates of jet fuels in bench-test burners measuring heat sink capability and exothermic properties would elevate this technology to a TRL of 4. Simultaneous efforts to de-oxidize the fuel & pursue other coke-mitigation strategies, although not detailed here, should be made to sufficiently reduce coke deposition due to the oxidation mechanism across the temperature range relevant to an inline turbofan fuel heat exchanger for cooled cooling air.
Outline

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- Closed session with NASA partners
SELECT Final Review: Summary and Conclusions

Contract NNC08CA86C
NASA Glenn Research Center
21 April 2010

Dr. Sam Bruner
Manager, Advanced Configurations
Northrop Grumman Corporation
Rational Design Process

- Future Scenarios
- Requirements Definition
- Optimization and Trade Studies
- Methodical Technology Downselect
- Candidate Technologies
- NASA N+3 Goals
- Engine and Airframe Architectures

Preferred Concept Vehicle

Relevant Technologies for N+3 EIS
Future Scenarios Drive Design

- Broad future need identified for
  - Efficient 1600 nautical mile capability
  - 120 passenger load

- Prioritized objectives
  - Reduced fuel burn
  - Reduced emissions
  - Reduced noise

- Future traffic growth sustainable by
  - Utilizing existing 5000 foot runways in Metroplex operations
  - Contingent upon NextGen enabling technology
Key Enabling Technologies

- Propulsion system
  - Low SFC
  - Low jet velocity
  - Low NO_x
- Aerodynamics
  - Swept wing laminar flow
- Materials
  - Light-weight materials
  - Advanced structural concepts
- Subsystems
  - Advanced nozzles and inlets
  - Landing gear fairings and integration
- Airframe / Engine integration
  - Proper matching of T/W and W/S
**Summary Accomplishments**

- Northrop Grumman meets all design intents.
  - All goals met except fuel burn
  - Fuel burn still represents outstanding improvement
  - Achievable with technology possible by 2025

<table>
<thead>
<tr>
<th>N+3 (2030-2035 Service Entry)</th>
<th>Advanced Aircraft Concepts Goals (Relative to User-Defined Reference)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise (Cum below Stage 4)</td>
<td>-71 EPNdB</td>
</tr>
<tr>
<td></td>
<td>-70 EPNdB</td>
</tr>
<tr>
<td>LTO NOx Emissions (below CAEP/6)</td>
<td>-75%</td>
</tr>
<tr>
<td></td>
<td>-75%</td>
</tr>
<tr>
<td>Performance: Aircraft Fuel Burn</td>
<td>better than 70%</td>
</tr>
<tr>
<td></td>
<td>64%</td>
</tr>
<tr>
<td>Performance: Field Length</td>
<td>Exploit Metroplex Concepts</td>
</tr>
<tr>
<td></td>
<td>Exploit Metroplex Concepts</td>
</tr>
<tr>
<td>Range</td>
<td>1600nm</td>
</tr>
<tr>
<td></td>
<td>1600nm</td>
</tr>
<tr>
<td>Passengers</td>
<td>120</td>
</tr>
<tr>
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<td>120</td>
</tr>
<tr>
<td>Field Length, TO and Ldg (SL, Std Day)</td>
<td>5,000 feet</td>
</tr>
<tr>
<td></td>
<td>5,000 feet</td>
</tr>
<tr>
<td>Cruise Mach</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td>Cruise Altitude</td>
<td>&lt; FL450</td>
</tr>
<tr>
<td></td>
<td>&lt; FL450</td>
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</table>

**Solid TRL 6 by 2025 to manage commercial risk**
Conclusions

• Northrop Grumman’s preferred concept is revolutionary in its performance, if not in its appearance

• Breakthrough performance is obtainable via cascading benefits in a variety of areas

• Several topics deserve further study in Phase II
NORTHROP GRUMMAN

Defining the future

To outer space

From undersea

To cyberspace