N+3 Small Commercial Efficient & Quiet Air Transportation for Year 2030-2035

NASA Contract NNC08CA85C

GE/Cessna/Georgia Tech Team

Final Report April 22, 2010
## Agenda  GE/CA/GT April 22, 2010 N+3 Final Report

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
<th>Speaker(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:00</td>
<td>Introduction. Study Objectives and Metrics</td>
<td>GE</td>
</tr>
<tr>
<td>8:15</td>
<td>Future Scenario Vision. Air Transport Network Studies</td>
<td>GT</td>
</tr>
<tr>
<td>8:25</td>
<td>- Notional Trip vs. ALN, Impact on Infrastructure and Community</td>
<td></td>
</tr>
<tr>
<td>9:00</td>
<td>Baseline Aircraft Definition</td>
<td>CA</td>
</tr>
<tr>
<td>9:15</td>
<td>Baseline Propulsion System. Baseline A/C vs. Metrics</td>
<td>GE</td>
</tr>
<tr>
<td>9:25</td>
<td>Advanced Airliner Technologies and Trade Studies</td>
<td>GE</td>
</tr>
<tr>
<td>9:30</td>
<td>- Advanced Propulsion Trade Studies. Concept Selection</td>
<td></td>
</tr>
<tr>
<td>10:00</td>
<td>- Break</td>
<td></td>
</tr>
<tr>
<td>10:15</td>
<td>- Advanced Airliner Studies, Methods Assessment</td>
<td>CA</td>
</tr>
<tr>
<td>10:45</td>
<td>- Concept Selection</td>
<td>GT</td>
</tr>
<tr>
<td>11:00</td>
<td>Year 2035 Advanced Airliner Concept</td>
<td>CA</td>
</tr>
<tr>
<td>11:20</td>
<td>- Ultra-Quiet and Efficient Airliner Concept</td>
<td>GE</td>
</tr>
<tr>
<td>11:40</td>
<td>- Ultra-Quiet and Efficient Turboprop Concept</td>
<td>GE</td>
</tr>
<tr>
<td>12:00</td>
<td>- Advanced Airliner vs. Baseline and Metrics. Key Technologies</td>
<td>GE</td>
</tr>
<tr>
<td>12:30</td>
<td>Technology Roadmaps</td>
<td>CA/GE</td>
</tr>
<tr>
<td></td>
<td>Summary</td>
<td>GE</td>
</tr>
</tbody>
</table>
GE, Cessna, and the Georgia Institute of Technology are studying a vision of aviation in the 2030-2035 time frame to change the paradigm of air travel and have a positive economic impact on suburban communities.

Focus:
> Address future growth in air travel demand that is projected to overwhelm the current hub-and-spoke air transport system.
> Develop ultra-efficient, low emission, quiet ~20 passenger aircraft to utilize the existing community airport infrastructure for direct point-to-point travel.
> Phase I Study Goal: Identify key enabling technologies for small airliners

Benefits
> Reduced congestion at major airports, freeing them to serve large aircraft.
> Reduced total travel time, fuel consumption, noise, emissions, travel stress.
> Positive economic impact on communities surrounding small airports.
> Utilize US taxpayers $15B+ investment in community airports

Plan
> Identify Future Network Vision, metrics for evaluation.
> Evaluate aircraft size and missions to best achieve goals.
> Develop a scalable current technology air vehicle to be used as study baseline.
> Identify advanced aircraft and propulsion concepts aimed at improving study metrics and the future transport system. Trade studies to assess technology impact on goals.
> Select best technologies & configuration. Develop advanced airliner. Evaluate vs. goals.
> Identify key technologies, roadmaps, risks, recommendations for further study.
Air Transportation Network

Demand & Airport Capacity

Current Demand Assessment

> Where do people travel?

> How do people travel?
  – Air, Auto

Point-to-Point Travel for 2008

- 50+ pass regional jet
- Departure Hub
- 150+ pass airliner
- Arrival Hub
- Drive
- Trip Distance
Air Transportation Network

Demand & Airport Capacity

Current Demand Assessment

> Where do people travel?
> How do people travel?
  - Air, Auto

Future Demand

> Project based on GDP and travel growth

Point-to-Point Travel for 2035

- 150+ pass airliner
- 50+ pass regional jet
- Drive
- Departure Airport
- Departure Hub
- Trip Distance
- Arrival Hub
- Drive
Air Transportation Network

Demand & Airport Capacity

Current Demand Assessment
- Where do people travel?
- How do people travel?

Future Demand
- Project based on GDP & travel growth.

Adjust transportation network
- Capture regional air & road travel
- Increased Flexibility
  - Semi-scheduled operations
  - Rapid update of schedule based on loads
- Maximize use of land and airside capacity and $15B Taxpayer Investment in GA Airports.
- Minimize travel time, noise and emissions, and overall carbon footprint

Point-to-Point Travel for 2035

- 150+ pass airliner
- 50+ pass regional jet
- 10 to 30 passenger airliner

- Less Travel Distance
- Less Travel Time
- Less Fuel/Pax/Trip Dist.

Trip Distance

Departure
- Airport
- Hub
- Drive

Arrival
- Hub
- Drive

Current Demand Assessment

Future Demand

Adjust transportation network

Current Demand Assessment

Future Demand

Adjust transportation network

Current Demand Assessment

Future Demand

Adjust transportation network
2030-2035 Vision & Metrics: Small Commercial Aviation Utilizing Community Airports

Distributed point-to-point operation vs. hub-and-spoke

- Direct flights closer to O-D without need to go through overloaded hubs
- Avoid capacity limitations and increasing delays, missed connections
- Minimize traffic, parking, terminal navigation delays of major airports

~20 Pax Aircraft, Mission Range < 1000 nm, Flight speed < 0.7 M₀
- Network Demand Study determines optimum size, mission, speed

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise (cum. below Stage 4)</td>
<td>-32 dB</td>
<td>-42 dB</td>
<td>-71 dB or 55 LDN at average airport boundary</td>
</tr>
<tr>
<td>LTO NOx Emissions (below CAEP 6)</td>
<td>-60%</td>
<td>-75%</td>
<td>better than -75%</td>
</tr>
<tr>
<td>Performance: Fuel Burn</td>
<td>-33%</td>
<td>-40%</td>
<td>better than -70%</td>
</tr>
<tr>
<td>Performance: Field Length</td>
<td>-33%</td>
<td>-50%</td>
<td>exploit community airports</td>
</tr>
</tbody>
</table>
N+3 Small Commercial Subsonic Metrics and Baselines

Field Length (and width)
> Sufficient to utilize community airports and capture vast majority of population.

Noise: 55 LDN at Airport Boundary or 71 dB Cum Margin Below Stage 4
> Develop a notional Community airport. Establish Current Noise Level.
> Quantify N+3 Air Vehicle impact on noise w/ projected frequency of flights.
> Meet 71 EPNdB Cum Below Stage 4. Impact LDN at Airport Boundary << 1 dB.

-70% Fuel Burn
> Quantify improvement of Advanced Airliner vs. Baseline Airliner
> Notional comparison of Baseline 2008 N+3 Aircraft/Network vs. Hub & Spoke

-75% NOx LTO below CAEP/6 (g/kN FN)
> NOx unregulated below 6000 lb FN.
  – Use 6000 lb FN Standard as Baseline.
> NOx unregulated for Turboprops/Open Rotor Systems.
  – Treat Propulsion System Net Thrust as if Turbofan for Takeoff, Approach, and Climb
  – Rational Substitute for Turbofan Idle. (4% Shaft Power, 80% Prop Speed)
> Advanced Air Vehicle LTO and Cruise NOx vs. Baseline
> Baseline Air Vehicle & N+3 Network vs. Current Network (LTO NOx g/Pax/trip)
Study Work Plan

Task 1: Develop Reference Baseline
> Define the vision of the future point-to-point air transport system
> Establish current and predicted future air travel demand, and the appropriate aircraft size, range, speed, TOFL to offload hubs by utilizing community airports.
> Develop a current technology ~20 passenger baseline airliner & engine to:
  – Establish a baseline to quantify the improvements of the Advanced Air Vehicle
  – Calibrate and validate the aircraft modeling tools used in advanced evaluating concepts using production CJ2+ aircraft and Cessna’s design tools and expertise.
> Look at N+3 travel impact on local economy, environment, and airport infrastructure

Task 2: Advanced Concept Development
> Identify Advanced Aircraft & Propulsion technologies and configurations. Screen by estimated benefits, risks, and feasibility in 2030-2035 timeframe
> Define 2030-2035 Advanced Reference Air Vehicle as baseline for evaluating unconventional Aircraft/Propulsion concepts
> Evaluate the benefit of advanced technologies and unconventional aircraft/engine configurations to the air transport system and study metrics
> Define best 2035 Aircraft/Propulsion Concept to enhance the study metrics
> Identify Key, Enabling Technologies, Roadmaps, Recommendations for Further Study

Task 3: Program Management, Reporting, and Communications
N+3 Service Study Roadmap


Configuration Workshops → Potential Technologies → Advanced Technologies of Interest
Introduction. Study Objectives and Metrics

Future Scenario Vision. Air Transport Network Studies

Baseline Aircraft Definition

Baseline Propulsion System. Baseline A/C vs. Metrics

Advanced Airliner Technologies and Trade Studies

Advanced Airliner vs. Baseline and Metrics. Key Technologies

Technology Roadmaps

Summary
Air Transportation Network

*Demand & Airport Capacity*

Current Demand Assessment

- Where do people travel?
- How do people travel?

Future Demand

- Project based on GDP & travel growth.

Adjust transportation network

- Capture regional air & road travel
- Increased Flexibility
  - Semi-scheduled operations
  - Rapid update of schedule based on loads
- Maximize use of land and airside capacity and $15B Taxpayer Investment in GA Airports.
- Minimize travel time, noise and emissions, and overall carbon footprint

**Point-to-Point Travel for 2035**

- Less Travel Distance
- Less Travel Time
- Less Fuel/Pax Trip Dist.

*Imagination at work*
Capability Needs for Small Airliners

Hub-Satellite to Hub-Satellite Trips (Hub Capacity Augmentation)
> Use satellite airports and high-speed ground connection (Hub to Satellite)
> Enables use of satellite airports without runway infrastructure investments
> Enables flexible capacity increases (don’t need to fill up large aircraft)

Small Community to Hub-Satellite (Service, Hub Connection Trip)
> Fuel costs drive need for new technology replacements of current day turboprops and regional jets
> As current 50 pass routes require 100 pass service, new 20-80 passenger routes (different communities) will require service

Small Community to Small Community Service (Hub Skipping)
> New service connections will be required, as Hub airports & Hub satellites become choked
> Point-to-Point routes enables traffic increase without burden to Hub

Small Airliners are Required for Future Trans. System
Network Inefficiencies

Empty Seats (Load Factor)
> Airlines focus on flying seats full & cancel flights with low load factors
> Airlines change aircraft type to RJ, 737, etc. to align with demand

Hub-n-spoke connection (Increased Travel Distance)
> Funneling people into Hubs enables high load factor flights between Hubs
> Hub feeder routes increase market size and provide service to small communities

Aircraft Re-Positioning (Move Empty Plane to Demand)
> Maintenance, weather, & other system scheduling disturbances cause airlines to re-schedule and or re-locate aircraft with low load factors or empty seats
> Fractional business jet fleets frequently operate with 30-45% of flights empty with customer-first, never-reject-demand business model
> Air-Taxi & Charter Operations reduce empty flights by rejecting demand and charging a premium for re-locating aircraft
> Breakthrough’s in scheduling software suggest the re-positioning problem can be solved with carefully selection of city pairs and daily or weekly changes to route structure (align supply with demand

Can we create a future network with 100% load factors and point-to-point trips that reduce travel distance?
Air Transport Network Demand & Capacity Study

**Objective:** Estimate current and 2030-2035 air travel demands, the capacity of network, and best aircraft size to meet demands.

**Deliverables:**

- **Current vs. Future Small Airport Travel Demand**
  - Current/future short range (<1000 mi) demand for point-to-point travel
  - Identify city pairs and candidate small airports
  - Estimated trips/day and appropriate aircraft size to meet future demands

- **Network Comparison: Point-to Point vs. Hub-and-Spoke**
  - Improvement in distance traveled and fuel savings vs. hub-and-spoke

- **Future Small Airport Capacity: Impact on Infrastructure**
  - Appropriate aircraft size for future ground infrastructure
  - Estimate of airside/landside capacities and infrastructure improvements needed

- **Future Network and Air Vehicle**
  - Estimate of demand satisfied by future network/air vehicle vs. current baseline

**Future Research:**

- Provide a Foundation for Scheduling (Operations Research) that will enable point-to-point service with near 100% load factors
Demand Model Ground Rules

Based on CONUS data found in 1995 ATS.

Two types of transportation consumer

- Households generate leisure, personal business trip parties.
- Enterprises to generate business trip parties.

Three transportation modes

- Auto: ground vehicle
- ALN: commercial air transportation
- N+3: transportation service provider using N+3 aircraft

The agents formulate disutility to make a choice based on time and money spent

Demand calculated is raw demand, not necessarily captured demand

- It may not be feasible to serve those demand levels with scheduled service

Sensitivity Study Parameters and Ranges

- Price multiplier (with respect to airline ticket price)
  - $X = [0, 8]$, baseline $X=3$
- Vehicle speed
  - $V = [275, 480]$ knots, baseline $V=344$ knots
- Vehicle range
  - $R = [400, 1200]$ nmi, baseline $R=800$ nmi
- Airport accessibility
  - $d = [5, 15]$ miles, baseline $d=10$ miles
**Price Multiplier Sensitivity**

### Modal Split (or Market Share)

<table>
<thead>
<tr>
<th>Price Multiplier (X)</th>
<th>ALN</th>
<th>Auto</th>
<th>N+3</th>
</tr>
</thead>
<tbody>
<tr>
<td>X = 0.0</td>
<td>0.4%</td>
<td>20.7%</td>
<td>78.86%</td>
</tr>
<tr>
<td>X = 1.0</td>
<td>4.9%</td>
<td>64.4%</td>
<td>30.66%</td>
</tr>
<tr>
<td>X = 2.0</td>
<td>17.7%</td>
<td>73.1%</td>
<td>9.25%</td>
</tr>
<tr>
<td>X = 3.0</td>
<td>22.0%</td>
<td>74.3%</td>
<td>3.68%</td>
</tr>
<tr>
<td>X = 4.0</td>
<td>23.7%</td>
<td>74.6%</td>
<td>1.74%</td>
</tr>
<tr>
<td>X = 5.0</td>
<td>24.4%</td>
<td>74.6%</td>
<td>0.96%</td>
</tr>
<tr>
<td>X = 6.0</td>
<td>25.2%</td>
<td>74.2%</td>
<td>0.60%</td>
</tr>
<tr>
<td>X = 7.0</td>
<td>25.0%</td>
<td>74.6%</td>
<td>0.38%</td>
</tr>
<tr>
<td>X = 8.0</td>
<td>25.3%</td>
<td>74.4%</td>
<td>0.26%</td>
</tr>
</tbody>
</table>

For X=3 N+3 captures 3.68% of all trips, or approx 14% of air travel.
## 2030 Scenarios

All other things constant consider impact of:

- Income growth (annual increase of 1.5% in real GDP per capita)
- Population growth (361 millions, ~1.4X to Y1995)

### Y2030

<table>
<thead>
<tr>
<th>Trips per day</th>
<th>ALN</th>
<th>Auto</th>
<th>N+3</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/ X=2</td>
<td>561,874</td>
<td>1,834,833</td>
<td>502,876</td>
<td>2,899,583</td>
</tr>
<tr>
<td>w/ X=3</td>
<td>772,295</td>
<td>1,918,985</td>
<td>244,685</td>
<td>2,935,966</td>
</tr>
<tr>
<td>w/ X=4</td>
<td>870,315</td>
<td>1,957,635</td>
<td>132,891</td>
<td>2,960,841</td>
</tr>
</tbody>
</table>

### Vs.

- ~2X
- ~1.5X
- ~4X
- ~1.7X

### Y1995

<table>
<thead>
<tr>
<th>Trips per day</th>
<th>ALN</th>
<th>Auto</th>
<th>N+3</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/ X=2</td>
<td>294,212</td>
<td>1,217,528</td>
<td>154,157</td>
<td>1,665,896</td>
</tr>
<tr>
<td>w/ X=3</td>
<td>372,746</td>
<td>1,258,087</td>
<td>62,328</td>
<td>1,693,161</td>
</tr>
<tr>
<td>w/ X=4</td>
<td>404,236</td>
<td>1,272,836</td>
<td>29,645</td>
<td>1,706,717</td>
</tr>
</tbody>
</table>
Demand elasticities with respect to changes in aircraft characteristics
Ticket price multiplier (x) is dominant factor
Vehicle Size Study (3 Phases)

**Tradeoff Input**
- Sizing and Ticket price estimation
- FLOPS/ALCCA
- LEAF Tool
- Demand estimation

**Mi Plus**
- 204 X 204 O-D Matrices
- Filtering Process
- Phase A result

**MSA granularity**
- Expansion Process with Clustering Algorithm
- ~500 X ~500 O-D Matrices
- Filtering Process
- Phase B result

**Expansion Process with Clustering Algorithm**
- Phase C result
Phase A Result

Used basic trend of ticket price as a function of aircraft size

- Based on student tool derived from FLOPS/ALCCA

Number of N+3 passengers increases continuously with increasing vehicle capacity (due to resulting lower ticket price)

Number of operations, however, levels off

- Optimum at ~23 PAX
Filtering Process

Analysis is performed on total produced and attracted demand for each O-D locale

*Mi* Plus produces numbers for raw demand

> Captured demand is not necessarily proportional to raw demand!
> 1000 consumers in Jersey City vs. 1000 consumers in rural Texas

Utilize demand density to provide insights into captured demand

> Assume all trips will be round-trips
> Find area of each MSA via aggregation of county level data
> Calculate demand density, Total Demand / Area, for each MSA and non-MSA

Use a transfer function to translate demand density into percent captured demand

> Different parameters chosen for 10 to 30 PAX aircraft
Phase B Filtering Results

As expected, the filtering process reduces expected N+3 passengers the most for 30 PAX vs. 10 PAX. Filtering scales the number of operations down, but doesn’t significantly affect the overall trend.
Phase C

Phases A & B involve an aggregation process, not dealing with a specific O/D market and its utilization, etc.

Unlike Phases A and B, Phase C involves complicated and iterative tasks in nature.

Creation of:
- Population layer
- Airport layer
- MSA layer

Clustering 3000+ counties into 500+ population clusters in conjunction with 1995 ATS MSA definitions.

Mi plus run w/ large number of agents to get sufficient definition for each OD pair

OD expansion to consider more detailed geographical information

Airport mapping to obtain airport specific OD distribution

Filtering process to capture viable market pairs
Population Layer

Explored dividing population cluster parameters sets by region (west vs. NE)

> Fidelity gain did not justify additional computational load

Four Parameters:
1) Minimum Population to qualify as a center $\rightarrow$ 75,000
2) Capture circle radius $\rightarrow$ 15 mi
3) Minimum Population to qualify as a cluster $\rightarrow$ 75,000
4) Minimum # of counties $\rightarrow$ 1

Percent of CONUS Population Captured: 81.8%
Number of Clusters: 577
Airport Layer:  
Number of Airports vs. Runway Length

5000 ft marks initial explosion in number of airports available  
3000 ft mask the point at which additional airports captured taper off

4000 ft chosen as initial target  
Over 95% of the population within 20 mi of an airport with a 4000ft runway
Airport Layer

Database of 3920 airports must be filtered to eligible airports for an N+3 service

Main criteria

- Large and medium hubs eliminated
- Military base air fields eliminated
- Runway of > 4000 ft effective* length
- Runway of > 75 ft width
- Surface Type
  - Concrete or Asphalt AND
  - Excellent or Good Condition

1356 eligible airports for N+3
Phase C Result

Before applying LF>60% condition

After applying LF>60% condition

This volume still represents over 3% of all true demand and 15% of air travel demand
Demand Driven Desirements for AC

Price goal
- Below 2x market share capture increases dramatically
- We will need to consider operations costs

Speed
- Sensitivity to speed is larger for longer ranges
- For a given price this aircraft parameter has the largest impact
- At Mach 0.55 still capturing similar percent of market share, price reduction potential of lower speed will benefit market share

Range
- Maximum range does not significantly influence market capture
  - Market for this aircraft is typically in the shorter ranges

Accessibility
- Distance to portal influences mode choice – more airports
- This led to runway study and a desired field length of 4000ft

Seats
- Phases A, B & C agree on a 20+ passenger aircraft
- Approximately 22 seats seems to be optimal for balancing demand captured vs. load factors required for profitability
Noise Impact of N+3 Service

Must use notional airport due to community sensitivities

- Non-hub airport near a population center
- No current commercial service
- 4000ft runway
- Access to services such as baggage claim, rental cars and parking

Original set of operations at notional airport provided by Sensis includes

- 14 distinct aircraft
  - Smallest: PA-28
  - Largest: ERJ-135
- 24 origin or destination airports
  - Closest: 39 nmi
  - Farthest: 945 nmi

Original operations set expanded to capture year 2006 daily operations

- Same mix between arrivals and departures
- Same equipment usage desired
- Similar schedule desired
- Same origin or destination assumed
- Scaled to 152 total operations based on airport master plan
Baseline Noise at Notional Airport

Baseline uses 2006 traffic levels at the notional airport on a given day.

All traffic assumed to arrive/depart out of a single runway:

- Insufficient information on arrival/departure trajectories – using straight in/straight out
- Overestimates noise along that runway
- Underestimates noise in other runway directions

Noise at airport boundary above 55 dB DNL for current traffic.
Notional Door-to-Door Trip

Select a trip with approximately half the maximum range of the aircraft (400nmi)

Assume Hub & Spoke trip involves a longer overall trip as well as two LTO cycles
  > 200 nmi in an RJ
  > 400 nmi in a 737

Assume shorter driving distance for N+3 network based on travel habits survey
  > 25 mi to major airport
  > 12 mi to N+3 airport
  > Use an average of 20 mpg for car

Load Factors for RJ and 737 based on historical tends
  > 70% for RJ, 80% for 737
  > 87% (23pax – 3 empty seats) for N+3 aircraft

Travel time assumptions
  > Only 1hr layover for hub & spoke
  > No security/parking wait time at portals
  > 30mph driving speed for urban Hub airport and suburban community
  > Optimistic look at Hub & Spoke
Mobility and Fuel Burn Impact of N+3 service

- Similar fuel burn
- Reduced LTO NOx
- Reduced distance
- Reduced travel time

<table>
<thead>
<tr>
<th>Fuel/Passenger (lbs)</th>
<th>LTO NOX (g/trip/Pax)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N+3 Hub Diff</td>
<td>N+3 Hub Diff</td>
</tr>
<tr>
<td>123.1 119.4 3.1%</td>
<td>47.7 64.1 -26%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Door to Door Dist (nmi)</th>
<th>Door to Door Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N+3 Hub Diff</td>
<td>N+3 Hub Diff</td>
</tr>
<tr>
<td>421 643 -35%</td>
<td>143 241 -41%</td>
</tr>
</tbody>
</table>
Ground Infrastructure

Airport ground infrastructure consists of airside and landside facilities and is a function of the amount and type of passengers and aircraft utilizing the airport.

The passenger terminal system is the major connection between the ground access system and the aircraft and generally consist of three components:

- **Access interface**
  - Passengers transfer from arrival mode to processing
  - Circulation and curbside parking and loading/unloading

- **Processing**
  - Passengers are prepared for an air transportation trip
  - Primary activities are ticketing, baggage handling, and security

- **Flight Interface**
  - Passenger transfers from processing on to the aircraft
  - Primary activity is aircraft loading and unloading
Ground Infrastructure Impact of N+3 Service

FAA Advisory Circulars (AC) 150/5360-9 and 150/5360-13 provide guidance on estimating the size of airport facilities.

- **N+3 Daily/Annual Enplanements from Mi**
  - Greater than 250,000?
    - Use AC 150/5360-13
  - Less than 250,000?
    - Use AC 150/5360-9

- **Parking Spaces**
- **Gross Terminal Area per Gate**
- **Convert to Peak Hour (AC 150/5360-13)**
- **Queuing Area in Front of Ticket Counters**
- **Lobby Waiting Area**
- **Baggage Claim Public Space**
- **Airline Office, Outbound Baggage and Operational Space**
- **Food, Beverage and Miscellaneous Concessions**
Ground Infrastructure Impact of N+3 Service

- Results will be heavily influenced by N+3 scheduling and existing facilities.
- If small airports currently had NO terminal buildings, N+3 traffic would require $2 to $4 billion investment (assuming $200 to $300 per sq ft). However, much of this infrastructure currently exists.
- Need to be evaluated on a case by case basis (3 examples shown).
- Other possible investments required:
  > Emergency response equipment required when commercial service is introduced
  > Reliable satellite to hub transportation

<table>
<thead>
<tr>
<th>Airport Code</th>
<th>Location</th>
<th>N+3 rank</th>
<th>N+3 Annual Enplanements</th>
<th>Parking Spaces</th>
<th>Number of Gates</th>
<th>Total Terminal Building Area (ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HHR</td>
<td>Hawthorne, CA</td>
<td>10</td>
<td>1,887,399</td>
<td>2,814</td>
<td>17</td>
<td>191,000</td>
</tr>
<tr>
<td>LZU</td>
<td>Lawrenceville, GA</td>
<td>101</td>
<td>419,021</td>
<td>726</td>
<td>5</td>
<td>40,500</td>
</tr>
<tr>
<td>CBF</td>
<td>Council Bluffs, IA</td>
<td>204</td>
<td>126,994</td>
<td>226</td>
<td>1</td>
<td>5,500</td>
</tr>
</tbody>
</table>
Economic Impact of N+3 Service

A complex relationship exists between an airport and the local economy

- De-coupling the interaction results in an inaccurate representation

Economic activity can develop a need for transportation, but an investment in transportation can lead to economic activity

Input-Output Method

- Most common form of assessment in the United States
- Measures direct, indirect, and induced effects
- Total economic impact is the sum of these three measures
- Direct Impacts
  - Spending in the local area by visitors as well as airport employees
- Indirect Impacts
  - Estimated flow of dollars generated from the supply of materials, goods, or services attributable to airport by off-airport businesses
- Induced Impacts
  - Multiplier effect of respending the dollars generated through direct and indirect activities
Airport Economic Impact

Regional Input-Output Modeling System (RIMS II)

- Based on accounting framework input-output (I-O) tables
- Frequently used to estimate the regional impact of a new or expanded airport
- Requires extensive airport specific data not publicly available for all airports

Attempting to correlate historical airport economic impact data vs. enplanements

- Texas state airport economic impact analyses vs. FAA enplanements for 2005
- Texas studies were compared to 2009 Iowa studies
- Slopes vary widely from one region to another and cannot be

Studies suggest that a 10% increase in enplanements will result in a 1% increase in service related employment

A general rule of thumb is that for every direct employee of the airport, there are six indirect jobs related to that employee

Further study with in depth tools such a RIMS and extensive data collection for representative airports necessary to identify full impact
Agenda  GE/CA/GT April 22, 2010  N+3 Final Report

Introduction. Study Objectives and Metrics

Future Scenario Vision. Air Transport Network Studies
  > Notional Trip vs. ALN, Impact on Infrastructure and Community

Baseline Aircraft Definition

Baseline Propulsion System. Baseline A/C vs. Metrics

Advanced Airliner Technologies and Trade Studies
  > Advanced Propulsion Trade Studies. Concept Selection
  > Break
  > Advanced Airliner Studies, Methods Assessment
  > Concept Selection

Year 2035 Advanced Airliner Concept
  > Ultra-Quiet and Efficient Airliner Concept
  > Ultra-Quiet and Efficient Turboprop Concept
  > Advanced Airliner vs. Baseline and Metrics. Key Technologies

Technology Roadmaps

Summary
20-Passenger Baseline Airliner
Design Mission – Baseline Airliner

<table>
<thead>
<tr>
<th>Philosophy</th>
<th>Baseline-20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Range (nm)</td>
<td>500-1000</td>
</tr>
<tr>
<td>Cruise Mach No.</td>
<td>0.6 – 0.7</td>
</tr>
<tr>
<td>Takeoff Field (ft.)</td>
<td>3,000-5,000</td>
</tr>
<tr>
<td>Landing Field (ft.)</td>
<td>2,500-4,500</td>
</tr>
<tr>
<td>Ceiling Altitude (ft.)</td>
<td>25,000-45,000</td>
</tr>
<tr>
<td>Seating Capacity</td>
<td>10-40</td>
</tr>
<tr>
<td>Cabin Comfort</td>
<td>near 737</td>
</tr>
<tr>
<td>Certification Basis</td>
<td>4CFR Part 25</td>
</tr>
<tr>
<td></td>
<td>Part 21 Ops</td>
</tr>
<tr>
<td></td>
<td>2 Pilots, 1 Attendant</td>
</tr>
</tbody>
</table>

Size for near 100% load factor and 800 nm
Speed is a customer desire & aircraft utilization issue
- Current day operators fly at \( M \geq 0.75 \) (RJ, 737)
- High fuel cost drives choice for subcritical Mach No.
- Should we have a \( M=0.75 \) baseline for NASA’s 70% goal?
# 20 Passenger Payload

## Payload

<table>
<thead>
<tr>
<th>Item</th>
<th>Formula</th>
<th>Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passengers</td>
<td>$195 \times 20$</td>
<td>3900</td>
</tr>
<tr>
<td>Checked Bags</td>
<td>$30 \times 20$</td>
<td>600</td>
</tr>
<tr>
<td>Carry-on Bags</td>
<td>$16 \times 20$</td>
<td>320</td>
</tr>
<tr>
<td>Air Freight</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td><strong>Total Payload</strong></td>
<td></td>
<td><strong>4845</strong></td>
</tr>
</tbody>
</table>

## Crew Weight (including bags)

<table>
<thead>
<tr>
<th>Item</th>
<th>Formula</th>
<th>Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilots</td>
<td>$2 \times 240$</td>
<td>480</td>
</tr>
<tr>
<td>Attendant</td>
<td>210</td>
<td>210</td>
</tr>
<tr>
<td><strong>Total Crew</strong></td>
<td></td>
<td><strong>690</strong></td>
</tr>
</tbody>
</table>

## Included in Interior Weight

<table>
<thead>
<tr>
<th>Item</th>
<th>Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magazines</td>
<td>7</td>
</tr>
<tr>
<td>Drinks and Ice</td>
<td>16</td>
</tr>
</tbody>
</table>
20 Passenger Cabin (100 in, 3 abreast)

Goal = 737 Comfort
Baseline Aircraft Configuration Concept

Low Wing, Aft Engine, T-Tail, Turbofan

- Lifting surface geometry from CJ2+
  - Long range cruise Mach = 0.59 for CJ2+
  - Balance field length = 3360 ft for CJ2+

- Tricycle landing gear with dual tire trailing link main gear

Two moderate BPR, mixed flow turbofans

Advanced aluminum metal bond structure

- Standard approach for all Cessna jets

- Steel, composites, & other materials used as appropriate (landing gear, control surfaces, fairings, etc.,)

Flight control system from Citation Sovereign

- Manual ailerons, elevators, and rudder
- Hydraulically assisted ailerons and roll spoilers
- Single slotted Fowler flaps (electric)
Baseline Aircraft Systems Concept

Hydraulic System

- 3000 psi closed center system, engine driven pumps

Environmental Control & Auxiliary Power Unit

- Air cycle system for heat, cooling, & pressurization
- Turbine APU & main engine provide system bleed air

Avionics & Electrical

- 115 VAC, engine driven alternator for windshield anti-ice
- 28 VDC power from main engine starter generators
- Modern, low work load, glass cockpit

Ice Protection

- Bleed air anti-ice for wing and horizontal tail
- Electric heat for windshield, air data system, etc.

Interior

- 737 seated comfort
- 3 abreast seating, 1 isle, 100 inch diameter fuse.
B-20 Full Payload Mission Profile

- Climb to 41K’
- Cruise at M=0.6, 41K’
- Design Mission
- Climb to 41K’
- Cruise at M=0.6, 41K’
- 800 nm
- 200 nm
- Descend to SL
- 25K’
- Reserve

- Cruise at M=0.6, 41K’
- 800 nm
- Climb to 41K’
- Cruise at M=0.6, 41K’
## B-20 Performance

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFR Range (200 nm alternate)</td>
<td>800 nm</td>
</tr>
<tr>
<td>Cruise Speed</td>
<td>Mach = 0.60</td>
</tr>
<tr>
<td>Maximum Operating Altitude</td>
<td>41,000 ft</td>
</tr>
<tr>
<td>Flight Crew</td>
<td>690 lbs</td>
</tr>
<tr>
<td>Flight Crew Details</td>
<td></td>
</tr>
<tr>
<td>2 Pilots (240 lbs each)</td>
<td></td>
</tr>
<tr>
<td>1 Flight Attendant (210 lbs)</td>
<td></td>
</tr>
<tr>
<td>Payload</td>
<td>4845 lbs</td>
</tr>
<tr>
<td>Payload Details</td>
<td></td>
</tr>
<tr>
<td>20 Passengers (195 pounds + 30 lbs checked baggage + 16 lbs carry on)</td>
<td></td>
</tr>
<tr>
<td>20 Passengers</td>
<td></td>
</tr>
<tr>
<td>Air Freight (25 lbs)</td>
<td></td>
</tr>
<tr>
<td>Balanced Field Length, Part 25</td>
<td>4,000 ft</td>
</tr>
<tr>
<td>Balanced Field Length, Part 25 Details</td>
<td></td>
</tr>
<tr>
<td>Certificated Noise Levels</td>
<td></td>
</tr>
<tr>
<td>Takeoff</td>
<td>78.9 EPNdB</td>
</tr>
<tr>
<td>Sideline</td>
<td>85.3 EPNdB</td>
</tr>
<tr>
<td>Landing</td>
<td>86.9 EPNdB</td>
</tr>
<tr>
<td>Cumulative</td>
<td>251.1 EPNdB</td>
</tr>
<tr>
<td>Margin to Stage 4</td>
<td>19.9 EPNdB</td>
</tr>
<tr>
<td>Margin to Stage 4 Details</td>
<td></td>
</tr>
<tr>
<td>Landing &amp; Take off NOx Emissions</td>
<td></td>
</tr>
<tr>
<td>Margin to 6000 FN CAEF 6 Standard</td>
<td>25%</td>
</tr>
</tbody>
</table>
Methods Comparisons

Used CJ-2 to calibrate methods between FLOPS and Cessna data
Followed CJ-2 process for B-20 with baseline information generated by Cessna methods
Some differences in mission modeling capabilities
  > Climb/descent profiles
  > Reserve fuel
Generally excellent overall agreement
  > Reasonable agreement between MAPS and FLOPS on total mission fuel even though there are small differences in individual mission segments (caused by climb/descent)
  > 20% difference in reserve fuel – simplified modeling later improved
  > 3% difference in mission and total fuel quantities - excellent

<table>
<thead>
<tr>
<th>Mission Phase</th>
<th>FLOPS Fuel, lbs</th>
<th>MAPS Fuel, lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxi/Takeoff</td>
<td>205</td>
<td>200</td>
</tr>
<tr>
<td>Climb</td>
<td>912</td>
<td>795</td>
</tr>
<tr>
<td>Cruise</td>
<td>2,060</td>
<td>2,198</td>
</tr>
<tr>
<td>Descent/Landing</td>
<td>339</td>
<td>209</td>
</tr>
<tr>
<td><strong>Mission Fuel</strong></td>
<td><strong>3,516</strong></td>
<td><strong>3,402</strong></td>
</tr>
<tr>
<td>Reserves</td>
<td>1,311</td>
<td>1,584</td>
</tr>
<tr>
<td><strong>Total Fuel</strong></td>
<td><strong>4,827</strong></td>
<td><strong>4,986</strong></td>
</tr>
</tbody>
</table>
## Baseline Aircraft

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FLOPS</th>
<th>MAPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing Area, sq ft</td>
<td>407.9</td>
<td>383.4</td>
</tr>
<tr>
<td>Thrust per Engine, lb</td>
<td>4,558</td>
<td>5,165</td>
</tr>
<tr>
<td>Total Fuel</td>
<td>4,827</td>
<td>4,986</td>
</tr>
<tr>
<td>Fuel Fraction</td>
<td>0.19</td>
<td>0.20</td>
</tr>
<tr>
<td>Balanced Field Length</td>
<td>4,000</td>
<td>3,749</td>
</tr>
<tr>
<td>Range, nm</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>Empty Weight, lb</td>
<td>14,611</td>
<td>14,643</td>
</tr>
<tr>
<td>Basic Operating Weight, lb</td>
<td>15,301</td>
<td>15,333</td>
</tr>
<tr>
<td>Ramp (Gross) Weight, lb</td>
<td>24,973</td>
<td>25,164</td>
</tr>
</tbody>
</table>
Baseline & Other Current Day Jets

- Citation CJ2+
  - 12,500 lbs

- 20 Passenger Baseline
  - 24,973 lbs

- Citation Sovereign
  - 30,300 lbs
Summary of 20 Passenger Baseline

24,973 lb aircraft with two engines, two pilots, & 1 attendant
(Larger than CJ2+, Smaller than Sovereign)

Payload approx $\frac{1}{2}$ fuel Citation Sovereign
  > Payload = 4845 lb (pass. + bags), Crew + Attendant = 690 lbs

3 Abreast 737 comfort with 100 inch diam. Fuse.

Mission = 800 nm range, Mcr = 0.60, Alt = 41,000 ft
  > High altitude cruise is important for fuel burn
  > Higher cruise speed would increase utilization (need low fuel cost)

Aircraft & systems technology similar to current day business jets

Single-slotted fowler flaps are sufficient for 4,000 ft field length requirement

Profile drag, wing weight, fuselage weight, engine weight, and fuel burn are key areas to apply 2035 technology.
Agenda  GE/CA/GT April 22, 2010 N+3 Final Report

Introduction. Study Objectives and Metrics  GE  8:00

Future Scenario Vision. Air Transport Network Studies  GT  8:15
  > Notional Trip vs. ALN, Impact on Infrastructure and Community

Baseline Aircraft Definition  CA  9:00

Baseline Propulsion System. Baseline A/C vs. Metrics  GE  9:15

Advanced Airliner Technologies and Trade Studies  GE  9:25
  > Advanced Propulsion Trade Studies. Concept Selection
  > Break  10:00
  > Advanced Airliner Studies, Methods Assessment  CA  10:15
  > Concept Selection  GT  10.45

Year 2035 Advanced Airliner Concept  CA  11:00
  > Ultra-Quiet and Efficient Airliner Concept
  > Ultra-Quiet and Efficient Turboprop Concept  GE  11:20
  > Advanced Airliner vs. Baseline and Metrics. Key Technologies  GE  11:40

Technology Roadmaps  CA/GE  12:00

Summary  GE  12:30
Definition of Baseline Propulsion System

Objective: Develop current technology propulsion system as a baseline engine for evaluating the advanced air vehicle and air transport system

Deliverable: Scalable propulsion system characteristics representative of 2008 fielded commercial turbofans

Approach:

> Survey current commercial turbofans in the ~2,000 to 9,000 lb FN range
> Identify anticipated nominal requirement for Baseline 20 Pax Aircraft
> Develop trends of Weight, SFC, Dimensions vs. nominal thrust size
> Model characteristics of a typical 2008 Commercial Turbofan
  – Thrust & Fuel Burn throughout flight envelope
  – Propulsion System Weight & Installation Envelope
  – Emissions and Noise
> Develop scalable models of engine characteristics vs. nominal thrust size
Establishing Current Baseline Propulsion Characteristics

- **SFC**
- **Weight (Lb)**
- **Fan Diameter (in)**
- **Bypass Ratio**

Graphs showing relationships between Max Thrust (Lbf) and other variables.
Nominal B20 Baseline Airliner Propulsion Requirements

Takeoff Thrust = 4400 lb, **Flat-rated to 80F**
- Installed, with Offtakes.
- 4600 lb FN, Uninstalled, w/o Offtakes
- Scalable 3000 to 6000 lb FN

### Installation/Offtakes:

<table>
<thead>
<tr>
<th></th>
<th>Normal Losses</th>
<th>Icing Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP Bleed (lb/min)</td>
<td>---</td>
<td>11.5</td>
</tr>
<tr>
<td><strong>Bleed (lb/min)</strong></td>
<td>24.1</td>
<td>24.1</td>
</tr>
<tr>
<td>HP Bleed (lb/min)</td>
<td>---</td>
<td>47.1</td>
</tr>
<tr>
<td>Accessory horsepower</td>
<td>34.0</td>
<td>34.0</td>
</tr>
<tr>
<td>Inlet recovery</td>
<td>0.995</td>
<td>0.995</td>
</tr>
</tbody>
</table>

**Offtakes have significant impact on engine size, fuel burn**
Nominal Current Technology Baseline Engine
GE4400B Mixed-Flow Commercial Turbofan

Length = 64.7”

Df = 30”

4600 lb FN (Flat-rated to 80F, Uninstalled)
30” Diameter Fan, 1.65 P/P_{tip}, 3.8 BPR
22 OPR @ Cruise. 18 OPR, 915F T3 @ 80F T/O
2300F T41 R/L, 1460F T45 R/L
Weight = 1030 lbs (w/o nacelle or tailpipe)
# Baseline Engine Cycle Parameters: GE4600B

<table>
<thead>
<tr>
<th></th>
<th>Cruise 41K/0.6/ISA</th>
<th>Max Climb 41K/0.6/ISA</th>
<th>T/O SLS/80F</th>
<th>Uninstalled SLS/80F</th>
</tr>
</thead>
<tbody>
<tr>
<td>FN (lb)</td>
<td>850</td>
<td>930</td>
<td>4400</td>
<td>4600</td>
</tr>
<tr>
<td>SFCq</td>
<td>.705</td>
<td>.707</td>
<td>.463</td>
<td>.453</td>
</tr>
<tr>
<td>WrFan (lb/s)</td>
<td>179</td>
<td>182</td>
<td>154</td>
<td>156</td>
</tr>
<tr>
<td>WrCore (lb/s)</td>
<td>27.4</td>
<td>27.9</td>
<td>24.5</td>
<td>24.6</td>
</tr>
<tr>
<td>BPR</td>
<td>3.7</td>
<td>3.5</td>
<td>3.8</td>
<td>3.8</td>
</tr>
<tr>
<td>FPR</td>
<td>1.65</td>
<td>1.7</td>
<td>1.47</td>
<td>1.49</td>
</tr>
<tr>
<td>OPR</td>
<td>22</td>
<td>23.5</td>
<td>17.3</td>
<td>17.7</td>
</tr>
<tr>
<td>T3F avg</td>
<td>705</td>
<td>730</td>
<td>903</td>
<td>915</td>
</tr>
<tr>
<td>T41F avg</td>
<td>2020</td>
<td>2090</td>
<td>2200</td>
<td>2200</td>
</tr>
<tr>
<td>T45F avg</td>
<td>1245</td>
<td>1295</td>
<td>1382</td>
<td>1383</td>
</tr>
</tbody>
</table>
2008 Baseline Engine Characteristics vs. Market

GE4600B Cruise SFC vs. Market

GE4600B Bypass Ratio vs. Market

GE4600B Fan Diameter vs. Market

GE4600B Engine Weight vs. Market

GE Imagination at work
**Bypass Ratio Sensitivity Study: 4600 lb FN Class Baseline**

- **Max Cruise Thrust**
  - Normalized Thrust (%)
  - Bypass Ratio: 2.5, 3, 3.5, 4, 4.5, 5, 5.5

- **Max Cruise SFC**
  - Normalized SFC (%)
  - Bypass Ratio: 2.5, 3, 3.5, 4, 4.5, 5, 5.5

- **Fan Diameter**
  - Normalized Fan Diameter (%)
  - Bypass Ratio: 2.5, 3, 3.5, 4, 4.5, 5, 5.5

- **Weight**
  - Normalized Weight (%)
  - Bypass Ratio: 2.5, 3, 3.5, 4, 4.5, 5, 5.5

- Tailpipe and Nacelle will have larger penalty on higher bypass ratio configurations.
GE4400B Baseline Engine Summary

> Good representation of fielded 2008 Commercial Turbofan engine characteristics. (SFC, Diameter, BPR, Weight, etc.)
> Moderate Bypass Ratio (~4) is representative of the market in this thrust class.
> Scaling factors surprisingly linear over range of interest (3000-6000 lb FN)
> Bypass ratio sensitivity study gives options for optimizing cruise speed and altitude.
> Mixed Flow for low community and cabin noise.
> Modern RQL Combustor technology has 25% margin to CAEP 6 LTO NOx requirements.
Baseline Aircraft & N+3 Network Metrics

• Impact of Current N+3 Traffic on Community Noise

• Impact of Future N+3 Traffic on Community Noise

• N+3 Network vs. Hub & Spoke
Community noise prediction for B20

- Noise predictions calculated by ANOPP
  - Inputs from parametric cycle deck and WATE
  - Trajectories were calculated in FLOPS, according to FAR36 specifications
  - Geometry inputs were derived from the aircraft and engine dimensions
  - Jet, fan, and airframe noise were included
    - “Small engine” methods selected for engine modules
    - Other sources (core, turbine) were assumed to be negligible

<table>
<thead>
<tr>
<th>Baseline Aircraft Noise Levels</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Takeoff</td>
<td>78.89 EPNdB</td>
</tr>
<tr>
<td>Sideline</td>
<td>85.27 EPNdB</td>
</tr>
<tr>
<td>Approach</td>
<td>86.92 EPNdB</td>
</tr>
<tr>
<td>Cumulative</td>
<td>251.08 EPNdB</td>
</tr>
<tr>
<td>Cum Below Stage 4</td>
<td>19.92 EPNdB</td>
</tr>
</tbody>
</table>
Airport Noise Contour

6 flights in current flight schedule for notional airport identified as similar to B20 aircraft
Those 6 flights repeated in schedule with the equipment replaced by the new aircraft
A sensitivity study carried out introducing 6 - 24 flights into the schedule respectively
24 flights operated with a B20 aircraft added to the schedule show relatively little impact
Based on demand study for current day on average across the US approximately 6 operations per airport

Increase in 55dB contour area due to 24 B20 ops is minimal (0.5 nmi$^2$)
**Agenda GE/CA/GT April 22, 2010 N+3 Final Report**

**Introduction. Study Objectives and Metrics**  
GE  8:00

**Future Scenario Vision. Air Transport Network Studies**  
GT  8:15
- Notional Trip vs. ALN, Impact on Infrastructure and Community

**Baseline Aircraft Definition**  
CA  9:00

**Baseline Propulsion System. Baseline A/C vs. Metrics**  
GE  9:15

**Advanced Airliner Technologies and Trade Studies**  
GE  9:25
- Advanced Propulsion Trade Studies. Concept Selection
- Break  
  10:00
- Advanced Airliner Studies, Methods Assessment  
  CA  10:15
- Concept Selection  
  GT  10.45

**Year 2035 Advanced Airliner Concept**  
CA  11:00
- Ultra-Quiet and Efficient Airliner Concept
- Ultra-Quiet and Efficient Turboprop Concept  
  GE  11:20
- Advanced Airliner vs. Baseline and Metrics. Key Technologies  
  GE  11:40

**Technology Roadmaps**  
CA/GE  12:00

**Summary**  
GE  12:30
Impact of Advanced Propulsion Technologies & Configurations

**Objective:** Assess impact of identified advanced propulsion technologies and unique components/configurations

**Approach:**
- Develop a Year 2035 Advanced Reference Engine (high bypass ratio, direct-drive, ducted turbofan) to study Year 2025 TRL 4-6 technologies
  - Advanced materials, cooling, aerodynamics, high pressure ratio/temp, etc
  - Scalable. Nominal cruise thrust ~30 less than Baseline Engine.

- Model/estimate impact of advanced and unconventional engine configurations and subsystems on fuel burn, noise, emissions, weight
  - Single/counter rotating rotors (ducted and unducted, direct/electrical/gear-driven), multiple fans, fuel cells, hydrogen, constant volume combustion

- Define the best advanced propulsion concept(s) identified in the transport systems evaluation and the critical technology development needs
Advanced Reference Turbofan Technologies

**Advanced materials/cooling**
Higher temp/strength Next Generation CMC airfoils and combustor/flowpath liners
Next Generation environmental barrier coatings
Higher temp/strength disk/shaft materials
Dual Alloy Turbine Disk and Dual alloy Hi-Temp Ti Impeller
Next Gen High temp shafts
Advanced Composite Fan, OGV, Nacelle, Front frame, Core Cowl, AGB

**Advanced mechanical systems**
Advanced seals and improved rotor/stator flow discouragers
Advanced air bearings and Hybrid ceramic bearings
Advanced active clearance control including impeller shroud.

**Advanced aero/operability/manufacturing**
Improved airfoil & end wall contour, min thickness for high efficiencies with small components
Active stall/surge prediction/detection/control
Variable A18 for operability and performance optimization for low FPR designs
NASA N+3 – Advanced Reference Engine Mechanical Systems Technologies Summary

- Hybrid Ceramic-Metal Bearings
- Advanced Seals
- Air Bearing
- Active Flow Control Duct
- Low-Emissions Radial TAPS Combustor
- Active Impeller Clearance Control
- Active HPT Clearance Control
- Active LPT Clearance Control
NASA N+3 – Advanced Reference Engine Materials Summary

Stator Materials
- Carbon-Fiber Fan Case
- 1-Piece Carbon-Fiber OGV/Front Frame
- Composite AGB

Rotor Materials
- Next Gen Carbon Fiber Composite Fan Blade
- Dual-Alloy Blisks
- Dual-Alloy High-Temp Ti Impeller
- Next Gen CMC HPT Blades
- Hi-Temp Ti Compressor Casings
- Next Gen CMC Combustor Shells
- Next Gen CMC HPT Vanes
- CMC HPT Shrouds & Duct Fairings
- Shrouded Next Gen CMC Fwd LPT Blades
- TiAl Aft LPT Blades
NASA N+3 – Advanced Reference Engine Cycle Summary

Installed Performance

41K/0.6/ISA Max Cruise:  \( FN = 630 \text{ lb}, \ SFC = 0.508 \text{ lb/hr/lb} \)

SLS/80F Takeoff:  \( FN = 3800 \text{ lb}, \ SFC = 0.29 \text{ lb/hr/lb} \)

Weight = 721 lb (uninstalled)
Advanced Propulsion Design Space Exploration

Assume Advanced Air Vehicle Cruise Thrust Req’t ~30% less than Baseline

Develop Advanced Reference 2035 Turbofan
- Advanced Technologies but Conventional Configuration
- Separate Flow, Hi-BPR Turbofan. Ducted, Front-Drive Fan.
- Use Aircraft Fn/Weight vs. SFC sensitivities to size FPR.
- Size Highest BPR Alternative as Reduced Noise Option
- Use as baseline for evaluating unconventional technologies

Explore impact of FPR, BPR, OPR, T41 on Size, Weight, SFC, NOx, Noise
- Account for impact of component size on efficiencies
- Account for impact of T3 and T41 on Cooling flows and NOx

Explore impact of Thrust Class on SFC, FN/Weight

Explore impact of Customer Offtakes on SFC, FN/Weight
Impact of T41 and OPR on SFC and BPR

Size/cooling effects limit benefit of higher OPR, T41

Cruise SFC vs Bypass Ratio

Base T41
+200F
+400F
+600F
+800F

OPR Base
+5 atm
+10 atm
+15 atm
+20 atm
Impact of T41 and Pressure Ratio on Turbomachinery Size

High T41, High OPR, High BPR Reduce Airfoil Sizes & Increase Losses

Compressor HPC/HPT flow functions significantly smaller than other high performance turbomachinery

NASA N+3 Advanced TF Engine Sized 41k/0.6 using Sizing Effects 8.25.09
FPR 1.6 Parametric on OPR and T41
Impact of Fan PR on SFC and Specific Thrust

Sized at 630 lb FN @ 41K/0.6/ISA

-1% SFC ~ +4% Weight, Drag

Baseline Aircraft Trade Factor = -1% SFC ~ 2.3% Weight

FPR < 1.6 Reduces Noise, but not necessarily Mission Fuel Burn
## Propulsive Efficiency Study

### Impact of Fan PR at Constant T41, Min Airfoil Size

<table>
<thead>
<tr>
<th></th>
<th>Baseline 2008 Turbofan</th>
<th>Advanced Turbofan</th>
<th>Advanced Turbofan</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fan tip PR</strong></td>
<td>1.69</td>
<td>1.6</td>
<td>1.45</td>
</tr>
<tr>
<td><strong>41K/0.6/ISA Mx Cr</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thrust</td>
<td>920</td>
<td>630 (-32%)</td>
<td>630</td>
</tr>
<tr>
<td>SFC</td>
<td>0.705</td>
<td>0.508 (-28%)</td>
<td>0.494 (-30%)</td>
</tr>
<tr>
<td>Dfan</td>
<td>30&quot;</td>
<td>28.9&quot;</td>
<td>32.1&quot;</td>
</tr>
<tr>
<td>BPR</td>
<td>3.5</td>
<td>10.2</td>
<td>13.1</td>
</tr>
<tr>
<td><strong>SLS/80F Take Off</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thrust</td>
<td>4400</td>
<td>3800</td>
<td>4050</td>
</tr>
<tr>
<td>TSFC</td>
<td>0.47</td>
<td>0.29</td>
<td>0.26</td>
</tr>
<tr>
<td>Weight</td>
<td>1030</td>
<td>721</td>
<td>820</td>
</tr>
<tr>
<td><strong>Thrust/Wt</strong></td>
<td>4.3</td>
<td>5.3 (+23%)</td>
<td>4.9 (+16%)</td>
</tr>
<tr>
<td><strong>Cum Noise EPNdB</strong></td>
<td>251</td>
<td>238.4</td>
<td>231.7</td>
</tr>
</tbody>
</table>

(w/o technology or trajectory benefits)

**13:1 BPR Turbofan has similar fuel burn to 10:1, ~7EPNdB cum quieter**
Turboprops already meet Stage 4 Limit in this size class
B20 Baseline Cert Level Noise vs. Current A/C

Aircraft Cert Noise Levels vs. MTOGW

Stage 4 Limit

Cum EPNdB Cert Level

Baseline Aircraft/Engine ~ 20+ dB Cum below Stage 4 Req’t

Aircraft MTOGW (x 1000 lb)

2008 Baseline Aircraft w/ ~4 BPR, Mixed Flow TF is relatively quiet
Community noise for advanced engines

- Turbofan noise predictions calculated by ANOPP
  - Inputs from parametric cycle deck and WATE
  - Trajectories were calculated in FLOPS, according to FAR36 specifications
  - Jet and fan noise modules were included (Stone Jet 2 and Heidmann)
    - “Small engine” methods selected where possible
    - Other sources (core, turbine) were assumed to be negligible

- Turboprop noise predictions calculated using SAE AIR-1407 empirical method
  - Basic inputs included diameter, number of blades, tip speed, power input, and flight speed
  - SAE method used to predict full power (sideline) noise only
  - Turboprop NPD curves in the AEDT database were used to estimate off-design noise levels (NPD curves include airframe noise)
    - ANOPP airframe noise predictions matched the NPD levels at low power
Impact of FPR, BPR on Noise

Aircraft Cert Noise Levels vs. MTOGW

Ultra-High BPR reduces Noise to ~ N+2 levels, Adv Tech needed for N+3
# Advanced Noise Reduction Technologies

<table>
<thead>
<tr>
<th>Jet Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D Integrated Propulsion Systems (Installation effects)</td>
</tr>
<tr>
<td>Shape Memory Alloy / Variable shape Chevrons (Fan &amp; Core)</td>
</tr>
<tr>
<td>Non-axisymmetric / Beveled Nozzles</td>
</tr>
<tr>
<td>Offset High Speed Stream</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fan Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAA based Low Noise Blade / OGV Design</td>
</tr>
<tr>
<td>Soft / Active OGV</td>
</tr>
<tr>
<td>Zero splice lip, inlet &amp; fan case liners</td>
</tr>
<tr>
<td>Optimized Zone Nacelle Liners</td>
</tr>
<tr>
<td>Scarfed Inlet</td>
</tr>
<tr>
<td>Inlet Blowing</td>
</tr>
<tr>
<td>Active Rotor Wake Control</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Propeller Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAA based Low Noise Prop</td>
</tr>
<tr>
<td>Active Pitch Control</td>
</tr>
<tr>
<td>Active Flow Control</td>
</tr>
<tr>
<td>Non-uniform Blade Arrangements</td>
</tr>
<tr>
<td>Tip Speed Optimization</td>
</tr>
</tbody>
</table>
NASA N+3 – Advanced Reference Engine
Acoustics Technologies Summary

<table>
<thead>
<tr>
<th>Noise Level</th>
<th>Value (EPNdB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takeoff</td>
<td>59.62</td>
</tr>
<tr>
<td>Sideline</td>
<td>73.21</td>
</tr>
<tr>
<td>Approach</td>
<td>78.39</td>
</tr>
<tr>
<td>Cumulative</td>
<td>211.22</td>
</tr>
<tr>
<td>Cum Below Stage 4</td>
<td>59.78</td>
</tr>
</tbody>
</table>

Advanced Turbofan Aircraft Noise Levels

Cert Noise for 13 BPR Adv TF

Acoustic Panels
In Fan Case

Soft
OGVs

Variable
Fan Nozzle

Full Composite
Integrated Nacelle-
Core Cowl

Chevron
Core Nozzle

CAA-based
Low Noise
Blade and
OGV

Leaned
& Swept
OGVs

Acoustic Foam
Core Nozzle
Aircraft Cert Noise Levels vs. MTOGW

Advanced Aircraft, Propulsion, Noise technologies bring TF within ~10 EPNdB of N+3 Goal
Propulsor key to achieving N+3 Goal
Emissions Goal: -75% LTO NOx vs. CAEP/6

LTO NOx is a Function of SFC, OPR, and T41

> Reducing fuel burn via improved propulsive efficiency helps
> Reducing fuel burn via reducing losses/cooling (thermal efficiency) helps
> Reducing fuel burn via increased OPR (T3) and T41 increases NOx

Advanced Engine LTO NOx with RQL Technology

<table>
<thead>
<tr>
<th></th>
<th>2008 Baseline</th>
<th>Advanced TF Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Rated Thrust (lb)</td>
<td>4400</td>
<td>3801 (-14%)</td>
</tr>
<tr>
<td>BPR</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>OPR</td>
<td>22</td>
<td>Higher</td>
</tr>
<tr>
<td>T41 R/L</td>
<td>2300F</td>
<td>Higher</td>
</tr>
<tr>
<td>LTO NOx vs. CAEP/6 (g/kN FN)</td>
<td>-25%</td>
<td>-60%</td>
</tr>
<tr>
<td>(relative to 6000 lb FN req’t)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LTO NOx (g/cycle)</td>
<td>825</td>
<td>352 (-57%)</td>
</tr>
</tbody>
</table>

Improved Prop & Thermal Efficiency and Reduced Thrust Req’t

Additional Technologies Needed to Achieve –75% LTO NOx
Advanced Reference TF Design Space Study

Findings

Conventional Turbomachinery limits Benefits of OPR, T41

> Size impact on efficiencies and cooling result in diminishing returns
> Limiting Temp, OPR allows uncooled CMC HPT Blade and reduced NOx, Cost, Weight
> Offset Core, Rear-drive or Remote Fan, CVC, Single Engine req’d for Higher OPR’s, T41

Core Turbomachinery much smaller than today’s high performance products or advanced technology demonstrators.

> High T41 & efficiencies, low losses & cooling, dramatically reduces core size.

Low radius ratio of small, high performance axi-centrif core limits BPR to ~13

> Core bore limits Direct-Drive shaft Torque or Geared Fan Dynamic operating range
> Offset core, Rear- or Electric-Drive Fan, or Topping cycle needed for higher BPR’s
> Weight/Drag Penalties of Higher BPR’s likely to hurt mission Fuel Burn
  – Small aircraft boundary layer (~ 1 inch) of N+3 Vehicle limits Dist. Prop. benefits
> 13 BPR + Advanced A/C, Propulsion, Noise Tech’s still 10 EPNdB short of Noise Goal

For M = 0.6, Single Rotation Fans, Rotors Best Cost/Noise/Weight/Perf Trade

> Interaction losses at low PR’s outweigh benefits of reduced loading and exit swirl

Customer Offtakes have big impact on small core (> +10 SFC, +25% Core weight)

> Significant operability bleed required for low-altitude ops
> Evaluate using operability bleed at T/O for active noise suppression
Remaining Propulsion Challenges to Goals

LTO NOx 75% Below CAEP 6:
- ~60% Below CAEP 6 due to Thermal/Propulsive efficiency improvements
- Scale GE TAPS Technology to meet remaining ~40% reduction to goal

Field Length:
- Improved T/O thrust of high BPR/Prop concepts helps goal
- Manage increase in propulsion system weight

Community Noise:
- Advanced technologies (-20 EPNdB) mitigate impact of Future N+3 growth traffic
- 13 BPR + Advanced A/C, Propulsion, Noise Tech’s ~ 60 EPNdB below Stage 4
- Assess prop/propfan noise impact

Fuel Burn:
- Greatest challenge. Advanced Reference Aircraft studies indicate we may be 15+ points (40%) away from goals.
- Need to explore concepts to address thermal and propulsive efficiency
  - Topping cycles
  - Fuel cells/Hybrid Prop
  - Open Rotor
Approaches to meeting N+3 Goals

- **Super-High BPR (>13) Geared Fan** (Noise, Fuel Burn, TOFL)
- **Distributed Propulsion** (Fuel Burn, Noise, TOFL)
- **Pulsed Detonation Combustion Topping Cycle** (Fuel Burn)
- **Open Rotor** (Fuel Burn, Noise, Emissions, TOFL)
  > Single or Counter rotating prop or Propfan
- **Fuel Cell** (Fuel Burn, Noise, Emissions)
  > PEM Fuel Cell Propulsion – LH2
  > SOFC/Gas Turbine Hybrid propulsion – LH2
  > SOFC/Gas Turbine Hybrid propulsion – Jet Fuel
Imagination at work

Ultra-High BPR Geared Fan (Noise, Fuel Burn, TOFL)

Concept: Drive Fan with High Speed LP Turbine and Gearbox.

Intent: Higher BPR to reduce noise.

Issues:
> Direct drive limited to ~13 by core bore and resulting fan shaft torque.
> High Speed LP Turbine would reduce shaft torque, stage count
> At 13 BPR, large diameter is required to keep LP shaft sub-critical over entire dynamic operating range.
  – High speed subcritical shaft diameter LARGER than direct drive shaft
  – High perf axi-centrif core results in smaller radius ratio, bore than axial config

Conclusion: Geared Fan does not allow much higher BPR in small, high perf axi-centrif configs
Distributed Propulsion (Fuel Burn, Noise, TOFL)

Concept: Multiple Propulsors per powerplant.

Intent: High effective propulsive efficiency by re-energizing aircraft boundary layer or shape drag with many low PR fans.

Issues:
> Very low fan PR and potential for airframe shielding could result in extremely quiet aircraft
> Concept works best with at aft end of HWB or Delta-wing config
  - These concepts result in high drag for small, low-speed aircraft
> Advanced aircraft boundary layer is very small
  - Short, laminar flow fuselage and high AR wing
  - ~1” or 2” on fuselage.
  - << 1” on wing

Conclusion: Distributed propulsion would reduce noise, but increase fuel burn, complexity, cost
Pulsed Detonation Engine (PDE) (Fuel Burn)

**Concept:** PD Combustor as topping cycle for Gas Turbine Cycle.

**Intent:** Detonation combustion raises effective overall pressure ratio and temperature for higher thermal efficiency

**Issues:**
- Conventional gas turbine OPR and T41 limited by airfoil size for this low thrust size application.
- Pulsed Detonation Combustion (PDC) increases time-averaged OPR, temperature
- Concept works best with large energy addition across combustor

**Conclusion:** Pulsed Detonation Combustion topping improves SFC at the expense of weight and complexity. Net benefits are application dependent.
What is Detonation Combustion?

- Detonation is one of several possible modes of combustion
- Key feature: pressure-rise combustion

Source: Frank Lu, University of Texas at Arlington
PDC cyclic process

**Tube PDC**
1 Fuel fill
2 Initiation
3 Detonation
4 Blowdown
5 Purge Air

**IC Engine Analogy**
1 Intake Stroke
2 Compression and Power Stroke
3 Exhaust Stroke

[Diagram showing the cyclic process with steps labeled as 1, 2, 3, 4, and 5, and corresponding steps for the IC engine as Intake Stroke, Compression and Power Stroke, and Exhaust Stroke.]

**IC Engine Analogy**

- [1] - Fill
- [2] - Initiation
- [3] - Detonation
- [4] - Blowdown/Expansion
- [5] - Purge Air

**GE** Imagination at work
Pulsed Detonation Engine Study Findings

- Pulsed Detonation Combustor pressure rise (and benefit) is larger for low OPR/high T41 engines. (Greater energy addition = Stronger pressure rise)
- Intercooling could allow further SFC Improvement at higher OPR’s
- Substantial SFC Improvement vs. Advanced Reference Engine
- Weight increase vs. SFC improvement result in poor mission fuel burn trade for this short range aircraft
  > Intercooling weight also outweighs SFC improvement for this application
- High Peak Pressures and Temperatures add challenge to NOx goal
  > May require exhaust treatment. (Added weight.)
- Weight, Peak Pressure/Temp issues similar for other constant volume topping concepts (internal combustion engines, etc.)
  > Gas turbines minimize peak temps, pressures, and weight
- PDC topping cycles best suited for longer range or ground applications at assumed level of technology
Open Rotor Propulsor (Fuel Burn, Emissions, Noise, TOFL)

**Concept:** Single or Counter-rotating Prop or Propfan

**Intent:** Increase propulsive $\eta$ & Takeoff FN, reduce noise

**Issues:**

- Open rotors move large amounts of air at low delta-V
  - High propulsive efficiency without the weight and losses of UHBPR fan duct
- Counter-rotating rotors reduce residual swirl for higher efficiency
  - Benefit small at low speeds ($M<0.6$), but interaction noise high
- Takeoff trajectory and low delta-V $\Rightarrow$ Reduce Noise
  - Limited noise shielding and low airfoil count hurt noise.

**Conclusion:**

- Single-rotation variable pitch prop has good potential for $M = 0.6$ airliner
- Dramatically lower SFC, but higher weight, than Turbofan
  - Aircraft trade studies to assess mission fuel burn
- Potential for $> 12$ EPNdB reduction vs. TF
# Propulsive Efficiency Study

## Impact of Fan PR at Constant T41, Min Airfoil Size

<table>
<thead>
<tr>
<th></th>
<th>Baseline 2008 Turbofan</th>
<th>Advanced Turbofan</th>
<th>Advanced Turbofan</th>
<th>Advanced Turbopop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan tip PR</td>
<td>1.69</td>
<td>1.6</td>
<td>1.45</td>
<td>1.67</td>
</tr>
<tr>
<td><strong>41K/0.6/ISA Mx Cr</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thrust</td>
<td>920</td>
<td>630 (-32%)</td>
<td>630</td>
<td>630</td>
</tr>
<tr>
<td>SFC</td>
<td>0.705</td>
<td>0.508 (-28%)</td>
<td>0.494 (-30%)</td>
<td>0.391 (-45%)</td>
</tr>
<tr>
<td>Dfan</td>
<td>30&quot;</td>
<td>28.9&quot;</td>
<td>32.1&quot;</td>
<td>12.4 ft</td>
</tr>
<tr>
<td>BPR</td>
<td>3.5</td>
<td>10.2</td>
<td>13.1</td>
<td></td>
</tr>
<tr>
<td><strong>SLS/80F Take Off</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thrust</td>
<td>4400</td>
<td>3800</td>
<td>4050</td>
<td>5500</td>
</tr>
<tr>
<td>TSFC</td>
<td>0.47</td>
<td>0.29</td>
<td>0.26</td>
<td>0.17</td>
</tr>
<tr>
<td>Weight</td>
<td>1030</td>
<td>721</td>
<td>820</td>
<td>1290</td>
</tr>
<tr>
<td>Thrust/Wt</td>
<td>4.3</td>
<td>5.3 (+23%)</td>
<td>4.9 (+16%)</td>
<td>4.3</td>
</tr>
<tr>
<td>Cum Noise EPNdB</td>
<td>251</td>
<td>238.4</td>
<td>231.7</td>
<td>~220</td>
</tr>
</tbody>
</table>

(w/o technology or trajectory benefits)

Turboprop’s superior SFC, Emissions, Noise vs. Weight Penalty
Fuel Cell Propulsion (Fuel Burn, Emissions)

Concept: PEM Fuel Cell or SOFC/Gas Turbine Hybrid supply power to Propulsor motor. Liquid Hydrogen (LH2) or Jet Fuel.

Intent: Dramatically higher thermal efficiency. Low Emissions.

Issues:
> Fuel cells have extremely high thermal efficiency (up to 70% stack efficiency) and low scaling effects in this size class.
  – High efficiency at low power (cruise)/Low efficiency at high power (T/O)
> Power density predicted to more than double by N+3 timeframe.
  – Weight/volume still much greater than gas turbine
  – Reformer (to utilize HC fuels) dramatically adds to aircraft weight/ volume
> Very Low Emissions, especially with LH2 fuel. No NOx

Conclusion:
> Great potential, but need to evaluate on aircraft to understand trades.
Fuel Cell Propulsion

• Types of Fuel Cells

• Projection of Year 2030 performance
  • PEM Fuel Cell Turbofan. Comparison to ARTF.
  • PEM and SOFC/Gas Turbine Hybrid Turboprops
  • Liquid Hydrogen (LH2) and jet Fuel

• Aircraft Assessment of Fuel Cell propulsion vs. Advanced Gas Turbine
Fuel Cells

Electrochemical device to directly convert chemical energy to electrical energy

<table>
<thead>
<tr>
<th>Cathode</th>
<th>Anode</th>
<th>Electrolyte</th>
<th>Air</th>
<th>Load</th>
<th>Fuel</th>
<th>Solid Oxide Fuel Cell (SOFC)</th>
<th>Proton Exchange Membrane (PEM - FC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perovskite</td>
<td>Nickel</td>
<td>Zirconia</td>
<td>Platinum</td>
<td>Polymer</td>
<td>Platinum</td>
<td>$\text{O}_2 + 4\text{e}^- \rightarrow 2\text{O}^2^-$</td>
<td>$\text{O}_2 + 4\text{e}^- + 4\text{H}^+ \rightarrow 2\text{H}_2\text{O}$</td>
</tr>
</tbody>
</table>

500-1000°C Op Temp
Hybrid/GT Propulsion APU

~100°C Op Temp
Main Propulsion

Fuel Cells: Gas Turbine (GT) Propulsion

Solid Oxide Fuel Cell (SOFC)

Proton Exchange Membrane (PEM - FC)
Projected Power Density of PEM FC For In-Flight Operation at Altitude

Power vs. Current Density

- Red – 2030
- Magenta – 2015
- Blue - 2008
Projected Efficiency of PEM FC
For In-Flight Operation at Altitude

Fuel Cell Efficiency

Blue - 2008
Magenta – 2015
Red – 2030

Stack Cruise Effic ~71%
Stack T/O Effic ~59%

3x Power for 12 pt Stack Efficiency Loss
# PEM Fuel Cell vs Advanced Reference Turbofan

Sized to Produce the Same Cruise Thrust

## Cruise Performance

<table>
<thead>
<tr>
<th></th>
<th>Adv Turbofan</th>
<th>PEM FC TF</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPR</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>FN ((lb)@ 41K/0.6 \text{ Mx Cr})</td>
<td>630</td>
<td>630</td>
</tr>
<tr>
<td>SFC @ Mx Cr ((\text{lbm/hr/lbFN}))</td>
<td>0.509</td>
<td>- 75%</td>
</tr>
<tr>
<td>SFC @ Mx Cr ((\text{BTU equiv}))</td>
<td>- 55%</td>
<td></td>
</tr>
<tr>
<td>Fuel Weight + Tank ((lb))</td>
<td>~2800</td>
<td>~750</td>
</tr>
<tr>
<td>Power Plant Weight ((lb))</td>
<td>721 x 2</td>
<td>~4300 x 2</td>
</tr>
<tr>
<td>Total Weight ((lb))</td>
<td>~4250</td>
<td>~9350</td>
</tr>
<tr>
<td>PP + Fuel Volume</td>
<td>80 cu ft</td>
<td>375 cu ft</td>
</tr>
<tr>
<td>LTO NOx</td>
<td>325g</td>
<td>0 g</td>
</tr>
</tbody>
</table>

- Fuel Cell SFC improvement smaller at higher powers (Climb, Takeoff)
- Fuel Cell Propulsion system weight/volume >> Adv Reference Turbofan
  - Would result in much higher thrust requirement and Aircraft size/weight
  - Increased aircraft size would increase cost and reduce fuel savings
Turboprop Fuel Cell Concepts vs. Advanced GT Powerplants Sized to Produce 4200 lb of Takeoff Propeller Thrust

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced Gas Turbine Turboprop</td>
<td>1</td>
<td>1045 lb</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>LH2 PEM Fuel Cell</td>
<td>0.3</td>
<td>3458 lb</td>
<td>42 cu ft</td>
<td>67 cu ft</td>
<td>+7.7 ft</td>
</tr>
<tr>
<td>LH2 SOFC/GT Hybrid</td>
<td>0.25</td>
<td>3774 lb</td>
<td>81 cu ft</td>
<td>55 cu ft</td>
<td>+9.6 ft</td>
</tr>
<tr>
<td>Jet A SOFC/GT Hybrid w/ Reformer</td>
<td>0.55</td>
<td>3774 lb + 3857 lbr Reformer</td>
<td>81 (PP) + 97 (reformer) cu ft</td>
<td>0</td>
<td>+12.7 ft</td>
</tr>
</tbody>
</table>

Dramatic SFC reduction must be traded against high weight/volume
System Analysis for Fuel Cell Technology

- Due to the nature of vehicle sizing and synthesis, it is necessary to resize the vehicle until a closed solution is found.
- ModelCenter® environment created to find converged solutions.
- Vehicle scales up with additional propulsive system weights and wetted areas (from fuselage length increases).
- Vehicle scales down with reduced fuel flow factor to represent use hydrogen as a fuel if in isolation.
- As vehicle scales, the propulsive system weights and volumes will also change.

<table>
<thead>
<tr>
<th></th>
<th>Fuel Factor</th>
<th>Propulsion System Weight</th>
<th>Power Plant Volume</th>
<th>Fuel Volume</th>
<th>Fuselage Length Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH2 PEM Fuel Cell</td>
<td>0.3</td>
<td>3458 lbm</td>
<td>42 cu ft</td>
<td>67 cu ft</td>
<td>7.7 ft</td>
</tr>
<tr>
<td>LHS SOFC/GT Hybrid</td>
<td>0.25</td>
<td>3774 lbm</td>
<td>81 cu ft</td>
<td>55 cu ft</td>
<td>9.6 ft</td>
</tr>
<tr>
<td>Jet A SOFC/GT Hybrid</td>
<td>0.55</td>
<td>3774 (+3857 for reformer) lbm</td>
<td>(81 PP + 97 reformer) cu ft</td>
<td>0</td>
<td>12.7 ft</td>
</tr>
</tbody>
</table>
## Mission Evaluation of Fuel Cell Turboprop Concepts

<table>
<thead>
<tr>
<th></th>
<th>Aircraft TOGW</th>
<th>Aircraft Empty Weight</th>
<th>Takeoff Thrust per Engine</th>
<th>Mission Fuel Burn (lbs)</th>
<th>Mission Energy Usage (Btu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced Gas Turbine Turboprop</td>
<td>14550 lb</td>
<td>7636 lb</td>
<td>3353 lb</td>
<td>1088 lb</td>
<td>Base</td>
</tr>
<tr>
<td>LH2 PEM Fuel Cell</td>
<td>+41%</td>
<td>+86%</td>
<td>+21%</td>
<td>-55%</td>
<td>-19%</td>
</tr>
<tr>
<td>LH2 SOFC/GT Hybrid</td>
<td>+41%</td>
<td>+87%</td>
<td>+21%</td>
<td>-60%</td>
<td>-28%</td>
</tr>
<tr>
<td>Jet A SOFC/GT Hybrid w/ Reformer</td>
<td>+136%</td>
<td>+250%</td>
<td>+114%</td>
<td>+21%</td>
<td>+21%</td>
</tr>
</tbody>
</table>

- At projected technology level, LH2 Fuel Cells have the potential to reduce energy usage 20% to 30%, and eliminate harmful emissions.
  - Must be weighed against the cost, noise of larger aircraft
  - Assumed jet fuel Reformer weight/volume negates benefits for short range aircraft

- LH2 economy or further improvements in fuel cell/reformer technology needed for our community airport-based short-range N+3 aircraft
Advanced Propulsion Configuration Selection

> TOPSIS used as an aide in selecting best N+3 Advanced Propulsion Concept

> Advanced Concepts evaluated vs. Advanced Reference Turbofan Concepts
  - 1,3,5,7,9 ranking system used
  - Advanced Reference Turbofan ranked 5 on all metrics

> Fuel Burn and Noise weighted 50% higher than LTO NOx and Field Length Metrics
  - Operating Cost, Environmental Impact, and Community Acceptance most important to viability of this new form of air travel
  - Technical Feasibility and Impact on Cost also Viability metrics
## Propulsion System Configuration Selection TOPSIS

<table>
<thead>
<tr>
<th>Weighting</th>
<th>Fuel Burn</th>
<th>LTO NOx</th>
<th>Noise</th>
<th>Small Airport Compatibility/TOFL</th>
<th>Feasibility for 2030 EIS</th>
<th>Aircraft Acquisition Cost/Ticket Price</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

- **Adv Noise Optimized TF**
  - Fuel Burn: 5
  - LTO NOx: 5
  - Noise: 5
  - Small Airport Compatibility/TOFL: 5
  - Feasibility for 2030 EIS: 5
  - Aircraft Acquisition Cost/Ticket Price: 5
  - Ranking: 4

- **Adv Noise Optimized TP**
  - Fuel Burn: 7
  - LTO NOx: 7
  - Noise: 9
  - Small Airport Compatibility/TOFL: 7
  - Feasibility for 2030 EIS: 7
  - Aircraft Acquisition Cost/Ticket Price: 5
  - Ranking: 1

- **Open Rotor**
  - Fuel Burn: 7
  - LTO NOx: 7
  - Noise: 1
  - Small Airport Compatibility/TOFL: 7
  - Feasibility for 2030 EIS: 5
  - Aircraft Acquisition Cost/Ticket Price: 5
  - Ranking: 6

- **Geared Fan > 13 BPR**
  - Fuel Burn: 3
  - LTO NOx: 3
  - Noise: 7
  - Small Airport Compatibility/TOFL: 5
  - Feasibility for 2030 EIS: 1
  - Aircraft Acquisition Cost/Ticket Price: 5
  - Ranking: 6

- **Distributed Propulsion**
  - Fuel Burn: 3
  - LTO NOx: 3
  - Noise: 9
  - Small Airport Compatibility/TOFL: 5
  - Feasibility for 2030 EIS: 5
  - Aircraft Acquisition Cost/Ticket Price: 3
  - Ranking: 5

- **Pulse Detonation**
  - Fuel Burn: 3
  - LTO NOx: 1
  - Noise: 3
  - Small Airport Compatibility/TOFL: 5
  - Feasibility for 2030 EIS: 3
  - Aircraft Acquisition Cost/Ticket Price: 3
  - Ranking: 8

- **Battery Propulsion**
  - Fuel Burn: 5
  - LTO NOx: 9
  - Noise: 3
  - Small Airport Compatibility/TOFL: 1
  - Feasibility for 2030 EIS: 1
  - Aircraft Acquisition Cost/Ticket Price: 1
  - Ranking: 9

- **PEM Fuel Cell TP (LH2)**
  - Fuel Burn: 9
  - LTO NOx: 9
  - Noise: 7
  - Small Airport Compatibility/TOFL: 3
  - Feasibility for 2030 EIS: 3
  - Aircraft Acquisition Cost/Ticket Price: 3
  - Ranking: 2

- **SOFC/Hybrid TP GT (LH2)**
  - Fuel Burn: 9
  - LTO NOx: 9
  - Noise: 7
  - Small Airport Compatibility/TOFL: 3
  - Feasibility for 2030 EIS: 3
  - Aircraft Acquisition Cost/Ticket Price: 3
  - Ranking: 3

- **SOFC/Hybrid TP GT (JP Fuel)**
  - Fuel Burn: 5
  - LTO NOx: 7
  - Noise: 5
  - Small Airport Compatibility/TOFL: 3
  - Feasibility for 2030 EIS: 3
  - Aircraft Acquisition Cost/Ticket Price: 1
  - Ranking: 7

### Notes
- **Noise Optimized Turboprop ranked highest due to high overall scores**
- **Fuel Cells have excellent potential to minimize environmental impact**
  - High weight, volume impact aircraft cost, noise, and small airport compatibility
  - Weight vs. SFC trade makes Fuel Cells better suited to longer range aircraft
  - Concept merits further study for other applications/more advanced technology
<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:00</td>
<td><strong>Introduction. Study Objectives and Metrics</strong></td>
</tr>
<tr>
<td>8:15</td>
<td><strong>Future Scenario Vision. Air Transport Network Studies</strong></td>
</tr>
<tr>
<td></td>
<td>- Notional Trip vs. ALN, Impact on Infrastructure and Community</td>
</tr>
<tr>
<td>9:00</td>
<td><strong>Baseline Aircraft Definition</strong></td>
</tr>
<tr>
<td>9:15</td>
<td><strong>Baseline Propulsion System. Baseline A/C vs. Metrics</strong></td>
</tr>
<tr>
<td>9:25</td>
<td><strong>Advanced Airliner Technologies and Trade Studies</strong></td>
</tr>
<tr>
<td></td>
<td>- Advanced Propulsion Trade Studies. Concept Selection</td>
</tr>
<tr>
<td>10:00</td>
<td><strong>Break</strong></td>
</tr>
<tr>
<td>10:15</td>
<td><strong>Advanced Airliner Studies, Methods Assessment</strong></td>
</tr>
<tr>
<td></td>
<td>- Concept Selection</td>
</tr>
<tr>
<td>11:00</td>
<td><strong>Year 2035 Advanced Airliner Concept</strong></td>
</tr>
<tr>
<td></td>
<td>- Ultra-Quiet and Efficient Airliner Concept</td>
</tr>
<tr>
<td></td>
<td>- Ultra-Quiet and Efficient Turboprop Concept</td>
</tr>
<tr>
<td></td>
<td>- Advanced Airliner vs. Baseline and Metrics. Key Technologies</td>
</tr>
<tr>
<td>12:00</td>
<td><strong>Technology Roadmaps</strong></td>
</tr>
<tr>
<td>12:30</td>
<td><strong>Summary</strong></td>
</tr>
</tbody>
</table>
Single Engine, Single Pilot Regulations

Regulatory History

> Prior to 1995 Commuter Operations with less than 30 pax fell under FAA Part 135 operational regulations
> High accident rates led to regulatory call for “one level of safety for all airline operations.” Fed. Reg., Vol. 60, No. 244, Dec. 20, 1995
> Currently all scheduled operations with more than 9 passengers fall under FAA Part 121 operational regulations

Operations at or below 25,000 ft

> Small benefits for reduced requirements for
  – fuselage & window pressure loads
  – oxygen system
> Capability Need > 25K ft for near all weather capability

At 20 passengers we are a Part 121 Airline

> 2 Engines, 2 Pilots, & 1 Flight Attendant
## Interactive Reconfigurable Matrix of Alternatives

### Alternatives (First)

<table>
<thead>
<tr>
<th>Alternatives #1</th>
<th>Score A</th>
<th>Score B</th>
<th>Score C</th>
<th>Score D</th>
<th>Score E</th>
<th>Score F</th>
<th>Score G</th>
<th>Score H</th>
<th>Score I</th>
<th>Score J</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing Body Blend</td>
<td>Fairing</td>
<td>Moderate Blend</td>
<td>Extreme Blend</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Number of Wings</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wing Location</td>
<td>Low</td>
<td>Mid</td>
<td>High</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>High Lift System Type</td>
<td>None</td>
<td>Tracked</td>
<td>Slanted</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wing Bracing</td>
<td>None</td>
<td>Strut</td>
<td>Truss</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Joined Wing</td>
<td>None</td>
<td>Tip</td>
<td>Mid</td>
<td>Bus</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Morphing Wing</td>
<td>None</td>
<td>Variable Twist</td>
<td>Variable Camber</td>
<td>Trailing Edge Control</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wing Tip Devices</td>
<td>None</td>
<td>Winglet</td>
<td>Raked</td>
<td>Morphing</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tail Effectors</td>
<td>Canard, Horizontally Tailed</td>
<td>Canard, Vertically Tailed</td>
<td>V-Tail</td>
<td>Wing Tip</td>
<td>Elevator, Winglet</td>
<td>Drag Rudder</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Roll Effectors</td>
<td>Aileron, Spoiler</td>
<td>Wing Trailing Edge</td>
<td>Wing Trailing Edge</td>
<td>Wing Tip</td>
<td>Elevator, Winglet</td>
<td>Drag Rudder</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Propulsion Location</td>
<td>Below Wing</td>
<td>Mid Wing</td>
<td>Over-Wing</td>
<td>Aft Fuselage</td>
<td>Tip Mounted</td>
<td>Near Mounted</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Propulsion Type</td>
<td>Propeller</td>
<td>Counter-Rotating Open Rotor</td>
<td>Dual Fan</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Propulsion per Core</td>
<td>Distributed</td>
<td>Distributed</td>
<td>Distributed</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Engine Conversion</td>
<td>Brayton</td>
<td>Constant Volume</td>
<td>Turbofan</td>
<td>Fuel Cell</td>
<td>Piston</td>
<td>Electric Motor</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Augmentation</td>
<td>None</td>
<td>Battered</td>
<td>Battered</td>
<td>Fuel Cell</td>
<td>Battered</td>
<td>Solar Cell</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Primary Fuel</td>
<td>Liquid Hydrocarbon</td>
<td>Gasoline, Hydrocarbon</td>
<td>Hydrogen (gaseous)</td>
<td>Hydrogen (Liquid)</td>
<td>Batteries</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Number of Propulsors*</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>Tail Integration</td>
<td>Padded</td>
<td>Semi-Submerged</td>
<td>Submerged</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wing Sweep</td>
<td>None</td>
<td>Forward</td>
<td>Aft</td>
<td>Compound</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gust Alliteration*</td>
<td>None</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Leading Edge Shocks</td>
<td>None</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Leading Edge Device</td>
<td>None</td>
<td>Slant</td>
<td>Kruger</td>
<td>Droop</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Powered Lift</td>
<td>Externally Blown</td>
<td>Internally Blown</td>
<td>Circulation Control</td>
<td>None</td>
<td>Upper Surface Blowing</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Propulsion Drive (Remote)</td>
<td>Direct Shaft</td>
<td>Variable Geometry</td>
<td>Fluid Gestures</td>
<td>Electric</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Propulsion Airframe Shield</td>
<td>None</td>
<td>Yes</td>
<td>Yes</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Langmuir Stability</td>
<td>Stable</td>
<td>Neutral</td>
<td>Unstable</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Engine Fire Control</td>
<td>None</td>
<td>Passive</td>
<td>Active</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ALF Location</td>
<td>Fuselage</td>
<td>Wing</td>
<td>Nacelle</td>
<td>Tail</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### Vehicle Configuration

![Vehicle Configuration Chart](https://via.placeholder.com/150)

**Vehicle Configuration**

- **Primary Fuel**
- **Energy Conversion**
- **Propulsion Type**
- **Augmentation**
- **Propulsion per Core**
- **Engine Integration**
- **High Lift System Type**
- **Propulsion Drive (Remote)**
- **Propulsion Airframe Shield**
- **Langmuir Stability**
- **Engine Fire Control**
- **ALF Location**

**Score**

![Score Chart](https://via.placeholder.com/150)
IRMA Concepts & Technologies

- Advanced propulsion systems (fuel burn)
- Laminar flow boundary layers (drag, fuel burn)
- Tailless and or reduced stability configurations (drag, fuel burn)
- Low wing loading for high altitude cruise (drag, fuel burn)
- Mission optimization through 4D trajectories (fuel burn)
- Active gust load alleviation (weight & ride control)
- Advanced composite airframe structures (weight)
- Multi-function structures (weight)
- More electric aircraft subsystems (weight, fuel burn, maintenance cost)
- Single engine airliner operation (weight, maintenance cost)
- Single pilot airliner operation (weight, direct operating cost)
Can we eliminate some previous ideas?

- **Noise**: Does not appear to be an issue.
  - Increase in Noise at N+3 Airports is not a concern.
  - Field length is achievable with DC-9-30 High-Lift Tech.

- **Fuel Burn, Field Length**: Single engine operations are not likely to be allowed.

- **Fuel Burn, Cost**: Regulations not likely to allow single engine operations.
New Configuration & Technology Ideas
New ideas may lead to weight or drag reduction

Zero wing sweep & subsonic cruise speeds supports laminar flow technologies

Fly-by-wire systems enable small tail surfaces, gust load alleviation, & span efficiency control

Aft-fuselage engines or pusher propellers support laminar flow on wing & forward fuse.

Piaggio Avanti has some desirable features

Adv. structures concepts enable low cost, light weight, laminar flow shapes

Integrate ice protection, antennas, & boundary layer suction in structure

Aft-Engine Propeller/Open Rotor

Advanced APU provides electric power for
- Ground ECS
- Ice Protection
- Hybrid Lam. Flow
- Emergency Power
Sizing & Mission Sensitivities

Number of Passengers
Impact of High Lift Technology
Impact of Cruise Speed & Altitude
Impact of Technologies that Reduce
  > Drag
  > Weight
  > SFC
Passenger, Vehicle Size Sensitivity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>From 20 to 29 passenger</th>
<th>From 29 to 38 passenger</th>
<th>From 20 to 38 passenger</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTOGW, lb/pass</td>
<td>688</td>
<td>703</td>
<td>696</td>
</tr>
<tr>
<td>Total Fuel, lb/pass</td>
<td>94</td>
<td>100</td>
<td>97</td>
</tr>
<tr>
<td>Thrust, lb/pass</td>
<td>116</td>
<td>116</td>
<td>116</td>
</tr>
<tr>
<td>Wing Area, sq ft/pass</td>
<td>12</td>
<td>13</td>
<td>13</td>
</tr>
</tbody>
</table>

Linear increase in MTOGW and total fuel per passenger
Constant Thrust and Wing Area per passenger

29 Passenger Floor Plan

38 Passenger Floor Plan

GE Imagination at work
Baseline Cruise Altitude & Profile Drag

- Engine TSFC tends to be constant with altitude
- Altitude influence on dynamic pressure reduces profile drag

- CJ2+ burns 25% less fuel at 45K ft vs. 35K ft on 500 nm mission
- CJ2+ burns 17% less fuel at 45K ft vs. 35K ft on 250 nm mission
Baseline & High-Lift Technology

Advanced High-Lift Technology isn’t Necessary for 2035 Configuration
Baseline Component Weights & Drag

Weight Opportunities in Fuel, Fuse, Eng., & Wing

Laminar Flow, Wing Span, Winglets, Morphing for Drag

Drag Opportunities in Profile & Induced
### Summary

<table>
<thead>
<tr>
<th></th>
<th>B-20, M=0.6</th>
<th>All New Tech Turbofan, M 0.60</th>
<th>Advanced Turbofan Only M=0.6, 41K’</th>
<th>Laminar Flow Only M=0.6, 41K’</th>
<th>Weight Reduction Only M=0.6, 41K’</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTOGW, lbs</td>
<td>25119</td>
<td>16939</td>
<td>22154</td>
<td>23208</td>
<td>20589</td>
</tr>
<tr>
<td>BOW</td>
<td>15488</td>
<td>10239</td>
<td>14387</td>
<td>15026</td>
<td>11737</td>
</tr>
<tr>
<td>Mission Fuel, lbs</td>
<td>3402</td>
<td>1480</td>
<td>2248</td>
<td>2547</td>
<td>3029</td>
</tr>
<tr>
<td>Reserve Fuel, lbs</td>
<td>1584</td>
<td>575</td>
<td>874</td>
<td>990</td>
<td>1178</td>
</tr>
<tr>
<td>Thrust, lbs</td>
<td>5165</td>
<td>3798</td>
<td>5318</td>
<td>3935</td>
<td>4903</td>
</tr>
<tr>
<td>Wing Area, sq ft</td>
<td>383.4</td>
<td>377.5</td>
<td>361.3</td>
<td>464.8</td>
<td>344.2</td>
</tr>
<tr>
<td>BFL, ft</td>
<td>2569</td>
<td>1596</td>
<td>2020</td>
<td>2447</td>
<td>1988</td>
</tr>
<tr>
<td>Max Fuel, lbs</td>
<td>4986</td>
<td>2055</td>
<td>3122.00</td>
<td>3537</td>
<td>4207</td>
</tr>
<tr>
<td>Wing Loading</td>
<td>65.52</td>
<td>44.87</td>
<td>61.32</td>
<td>49.93</td>
<td>59.82</td>
</tr>
<tr>
<td>Thrust to Weight</td>
<td>0.41</td>
<td>0.45</td>
<td>0.5</td>
<td>0.34</td>
<td>0.48</td>
</tr>
<tr>
<td>% Fuel Reduction from Baseline</td>
<td>0.0</td>
<td>56.5</td>
<td>33.9</td>
<td>25.1</td>
<td>11.0</td>
</tr>
</tbody>
</table>

BFL does not size the wing – Engine & Wing for Top-of-Climb!  
Adv. Turbofan engine reduces fuel burn 34%  
60% Laminar flow reduces fuel burn 25%  
-24% Wempty reduces fuel burn 11%  
As Lifting Surfaces Shrink, Fuselage Wetted Area Starts to Dominate  
Less Weight, Better Engines, & Less Drag Req. for -70% Goal
Approaches to Drag Reduction

Profile Drag – (Cruise Altitude, & Laminar Flow)
> Design for natural laminar flow – Explore active technologies
> Eliminate cross-flow instability by eliminating wing sweep
> Eliminate shock induced instabilities by slowing down

Induce Drag (Wing Span, & Flight Controls)
> Increase Wing Span & Efficiency Throughout Mission
  – Mostly a wing span issue (strut-braced wings???)
  – Little benefit for cruise flaps or morphing un-swept wings
> Reduce loads through active gust load alleviation (wing weight)
> Reduce tail size & trim loads by flying at reduced static stability
  – A small part of induced drag

Compressibility Drag (Slow Down)
> Fly at speeds less than or equal to the critical Mach number
Tails & GoldSchmied Propulsion

A sailplane type configuration might be best.
Laminar Flow Fuselage Studies
(2-A abreast)

Max Diam. at 50%

55% of Swet fwd. of Max Diam.

Slightly Oval for Height

Max Diam. at 37%

43% of Swet fwd. of Max Diam.

Nearly Round (3-A abreast)

Max Diam. at 37%

46% of Swet fwd. of Max Diam.

Slightly Oval for Width

(4-A abreast)

Swet-Total = 92% of 2-A abreast

Swet-Total = 91% of 2-A abreast

GE

ASDL
Laminar Flow Fuselage - Comparisons
2-abreast, 3-abreast, & 4-abreast configurations studied

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Wetted Area</th>
<th>Cross Section</th>
<th>% fuse length where max width occurs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-abreast</td>
<td>100%</td>
<td>Oval</td>
<td>50%</td>
</tr>
<tr>
<td>3-abreast</td>
<td>92%</td>
<td>Round</td>
<td>37%</td>
</tr>
<tr>
<td>4-abreast</td>
<td>91%</td>
<td>Oval</td>
<td>37%</td>
</tr>
</tbody>
</table>

All configurations have equal tail lengths (control authority)
4-abreast configuration considered best

- Less total wetted area
- 37% of length contains 46% of Total Fuselage Swet
- Oval cross section simplifies integration of wing and gear
  - Small penalty for oval cross section offset by adv. materials
Fuselage Studies – Constant Payload
(Doors, Bags, Emergency Exits, etc)

Round X-Section
Typical Taper Fwd & aft

Swet-Total
989 sq. ft.
15% < B20

Modified Oval X-Section
Conic Taper Fwd. & Aft

Constant X-Section
Rapid Taper Fwd. & Aft

Swet-Total
965 sq. ft.
17% < B20

Loft Optimization = 15-17% Reduction in Fuselage Swet
Fuselage Study – Conclusions

15-20% Savings in Wetted Area Relative to B20 Configuration

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Swet %</th>
<th>% Fuse Length to Max Width</th>
<th>% Swet Fwd</th>
</tr>
</thead>
<tbody>
<tr>
<td>B20</td>
<td>100%</td>
<td>17%</td>
<td>25%</td>
</tr>
<tr>
<td>4-Abreast Conic</td>
<td>85%</td>
<td>37%</td>
<td>46%</td>
</tr>
<tr>
<td>4-Abreast Const. X-Section</td>
<td>83%</td>
<td>19%</td>
<td>21%</td>
</tr>
</tbody>
</table>

Potential for up to 46% of Swet in favorable pressure gradient & 15% less total wetted area

46% of Swet in Laminar Flow & 15% less wetted area is equivalent to having 56% of B20 fuselage in Laminar Flow
Technical Approach - Airframe

Advanced Composites
> Reduce weight through superior material strength properties

Protective, Health-Monitoring, Outer Skin
> Integrate Acoustic, Thermal, EMI, Lightning, Aesthetic (paint) functions in one light weight skin
> Enable new approach to health monitoring, inspection, & repair

Gust Load Alleviation & Envelope Protection
> Reduce weight by reducing loads on primary structure

Integrated antennas, systems, and active flow control
> Support laminar flow
> Eliminate surface protuberances
Advanced Composite Structures

- Carbon/Epoxy Fuselage
- Fiber Metal Laminate and, or Carbon/Epoxy Wing
- Integral Structural Fairing
- Carbon/Epoxy Control Surfaces, Nacelle
- Carbon/Epoxy Vertical Integral to Tail Cone
Current Tech. Composite Structures

40-50% weight savings from material strength
Design for Environmental & Operational Risk eliminates most of weight savings
  – Impact Damage
  – Hot and/or Wet exposure
  – Tg (High operating temperatures)
  – Lightning strike & EMI protection

A new approach to environmental protection, & damage detection would enable breakthrough weight savings
### Structures & Systems Weight Savings

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing</td>
<td>15.60%</td>
<td>30.00%</td>
<td>35.00%</td>
<td>39.20%</td>
<td>New conductive skin reduces risk &amp; supports acoustic, thermal, and some ice protection functions</td>
</tr>
<tr>
<td>Tail</td>
<td>5.16%</td>
<td>30.00%</td>
<td>35.00%</td>
<td>44.00%</td>
<td>Systems, landing gear, &amp; nacelles benefit from transition to electric systems, application of new materials, and optimized integration &amp; installation concepts</td>
</tr>
<tr>
<td>Fuselage</td>
<td>24.16%</td>
<td>25.00%</td>
<td>30.00%</td>
<td>34.00%</td>
<td>Avionics &amp; instruments benefit from panel mount integration &amp; continued breakthroughs in commercial electronics</td>
</tr>
<tr>
<td>Propulsion</td>
<td>18.98%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>29.67%</td>
<td>Some functions for acoustic damping, thermal insululation, ice protection, &amp; paint moved to wing, tail, and fuselage weight groups (New Conductive Skin)</td>
</tr>
<tr>
<td>Landing Gear</td>
<td>5.49%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>15.00%</td>
<td></td>
</tr>
<tr>
<td>Nacelle &amp; Air Induction</td>
<td>2.71%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>20.00%</td>
<td></td>
</tr>
<tr>
<td>Surface Controls</td>
<td>1.88%</td>
<td>-15.00%</td>
<td>0.00%</td>
<td>15.00%</td>
<td></td>
</tr>
<tr>
<td>Hydraulics</td>
<td>1.28%</td>
<td>-15.00%</td>
<td>0.00%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Electrical</td>
<td>5.41%</td>
<td>-35.00%</td>
<td>0.00%</td>
<td>15.00%</td>
<td></td>
</tr>
<tr>
<td>Avionics and Instruments</td>
<td>3.95%</td>
<td>-35.00%</td>
<td>30.00%</td>
<td>60.00%</td>
<td></td>
</tr>
<tr>
<td>Furnishings &amp; Equip</td>
<td>10.48%</td>
<td>-60.00%</td>
<td>0.00%</td>
<td>29.19%</td>
<td></td>
</tr>
<tr>
<td>Air-conditioning &amp; Anti-Ice</td>
<td>4.06%</td>
<td>-15.00%</td>
<td>0.00%</td>
<td>26.34%</td>
<td></td>
</tr>
<tr>
<td>Paint</td>
<td>1.12%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td><strong>Total % Savings</strong></td>
<td><strong>0</strong></td>
<td><strong>1.60%</strong></td>
<td><strong>15.47%</strong></td>
<td><strong>33.11%</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Risk**
- Application of aluminum structure & system integration technology
- Application of current composite & system integration technology
- Improved Materials, EMI, Lightning, & Sys. Integration
- Conductive, Protective, & Health Monitoring Skin
Protective Outer Skin
Smoothing, Thermal, Absorbing, Reflective, Conductive, Cosmetic: STAR – C²

Primary Structure for Loads, Environment and Damage
- Prime/Paint
- Lightning Strike
- Fill/Fair
- Skin
- Acoustic Foam w/aluminum foil

Current Technology

Protective Outer Skin over Primary Structure
- Frame
- Stringer
- Protective Outer Skin
  - Conductive skin
    - (Lightning, EMI, Paint, smoothness for laminar flow)
- New Concept
  - Energy Absorbing Foam
    - (Impact, Sound, Thermal, Space for wires, antenna’s, etc.)
  - Frame
Energy Absorbing Foam
(Light Weight, Easy to Install)

Conductive/Impact skin or film
(Polymer / Fabric - Fast Installation - Covers Fasteners & Joints)
Introduction. Study Objectives and Metrics

Future Scenario Vision. Air Transport Network Studies
- Notional Trip vs. ALN, Impact on Infrastructure and Community

Baseline Aircraft Definition

Baseline Propulsion System. Baseline A/C vs. Metrics

Advanced Airliner Technologies and Trade Studies
- Advanced Propulsion Trade Studies. Concept Selection
- Break
- Advanced Airliner Studies, Methods Assessment
- Concept Selection

Year 2035 Advanced Airliner Concept
- Ultra-Quiet and Efficient Airliner Concept
- Ultra-Quiet and Efficient Turboprop Concept
- Advanced Airliner vs. Baseline and Metrics. Key Technologies

Technology Roadmaps

Summary
2035 Configuration Selection & Optimization

Configurations/IRMA

Potential Technologies (Aero, Structures)

Adv. Ref. Trades

Configurations Workshops

Final Vehicle

Technologies of Interest

2035 Optimization Studies
### Metrics for Multi-Attribute Decision-Making, TOPSIS

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Noise</strong></td>
<td>Noisier concepts get lower scores. Assess noise at airport boundaries.</td>
</tr>
<tr>
<td><strong>Simplicity</strong></td>
<td>Complex concepts get lower scores.</td>
</tr>
<tr>
<td><strong>Cost/Ticket Price</strong></td>
<td>Higher ticket prices get lower scores. Assess any part of configuration that would translate into ultimately higher ticket prices for passengers</td>
</tr>
<tr>
<td><strong>Environmental Impact</strong></td>
<td>Lower impact gets higher scores. Includes all environmental impact except noise and NOx (such as water vapor, etc)</td>
</tr>
<tr>
<td><strong>Fuel Burn/Energy Consumed</strong></td>
<td>Better fuel burn gets higher scores. Assess primarily drag, somewhat propulsion (since we have different propulsor options for many concepts)</td>
</tr>
<tr>
<td><strong>LTO NOx Emissions</strong></td>
<td>Higher emissions get lower scores.</td>
</tr>
<tr>
<td><strong>Passenger Acceptance</strong></td>
<td>A more readily accepted configuration gets higher scores.</td>
</tr>
<tr>
<td><strong>Safety</strong></td>
<td>A safer configuration gets higher scores.</td>
</tr>
<tr>
<td><strong>TOFL &amp; Metroplex Compatibility</strong></td>
<td>If concept appears able to meet 4000 foot runway constraint, and/or helps enable the metroplex concept, it gets higher scores</td>
</tr>
</tbody>
</table>
TOPSIS - Configurations
# TOPSIS Rankings

## Average Results Prior to Workshop

<table>
<thead>
<tr>
<th>Config. # / Weightings</th>
<th>Noise</th>
<th>Simplicity</th>
<th>Cost/Ticket</th>
<th>Environmental Impact</th>
<th>Fuel Burn and/or Energy Consumed</th>
<th>LTO NOx Emissions</th>
<th>Passenger Acceptance</th>
<th>Safety</th>
<th>TOFL &amp; Metroplex Compatibility</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strut Braced Wing</td>
<td>7</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>9</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Blended Wing Body</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Twin Boom</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>5</td>
<td>7</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Laminar Fuselage</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Adv Tube/Wing</td>
<td>5</td>
<td>8</td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>8</td>
<td>7</td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

## Consensus Results at Work No. 2

<table>
<thead>
<tr>
<th>Config. #/Weighting</th>
<th>Noise</th>
<th>Simplicity</th>
<th>Cost/Ticket</th>
<th>Environmental Impact</th>
<th>Fuel Burn and/or Energy Consumed</th>
<th>LTO NOx Emissions</th>
<th>Passenger Acceptance</th>
<th>Safety</th>
<th>TOFL &amp; Metroplex Compatibility</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Adv Tube and Wing</td>
<td>6</td>
<td>9</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>9</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>2. Hi AR Pusher</td>
<td>3</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>7</td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>3. Laminar Fuselage</td>
<td>5</td>
<td>7</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>4. Twin Boom Laminar Fuse</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>2a. Hi AR Tractor</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>8</td>
<td>1</td>
</tr>
</tbody>
</table>
Tractor vs. Pusher Turboprop Optimization

Create dynamic, parametric environment around the 2035 advanced reference vehicle

> 2035 advanced reference vehicle includes techs on weight reduction, laminar flow, and advanced turbofan engine

Use dynamic, parametric environment to find minimal fuel weight

> “Dial-in” optimal combination of vehicle thrust-to-weight ratio, wing loading, cruise Mach number, and cruise altitude
> Does not account for top-of-climb rate of climb (TOC ROC) constraint of 200 fpm
> Solutions found were checked by FLOPS to see if TOC ROC constraint is satisfied
> Iterate to obtain minimum fuel weight solution that satisfies the TOC ROC constraint

Process is very tedious and time consuming
Turbofan, Tractor, Puller Modeling Assumptions

<table>
<thead>
<tr>
<th>Engine Deck</th>
<th>Turbofan</th>
<th>Turboprop Puller</th>
<th>Turboprop Pusher</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE3800AR</td>
<td>GE3800AR Scaling</td>
<td>GE5000ATP Scaling</td>
<td>5% Penalty Relative to GE5000ATP Scaling</td>
</tr>
<tr>
<td>SFC Impact</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GE3800AR Scaling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drag Delta due to Propeller</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Fuselage Laminar Flow (%)</td>
<td>60%</td>
<td>60%</td>
<td>60%</td>
</tr>
<tr>
<td>Wing Laminar Flow (%)</td>
<td>60%</td>
<td>10%</td>
<td>50%</td>
</tr>
<tr>
<td>Horizontal Tail Laminar Flow (%)</td>
<td>60%</td>
<td>60%</td>
<td>60%</td>
</tr>
<tr>
<td>Vertical Tail Laminar Flow (%)</td>
<td>60%</td>
<td>60%</td>
<td>60%</td>
</tr>
<tr>
<td>Nacelle Laminar Flow (%)</td>
<td>60%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

SFC Impact = SFC scaling, weight, diameter, and length scaling programmed into FLOPS for each engine type

- GE’s Propulsion Scaling Models
- Implemented via user defined control flags
Tractor vs. Pusher Dynamic Environment

- **Turbofan**
  - Fuel Weight: 12250 lbs
  - Wing Loading: 40.26
  - Thrust to Weight: 0.4492
  - Lfus: 49.500348
  - AR: 10.998661
  - ClmaxLnd: 1.975
  - Drag Factor: 1
  - Cruise Altitude: 0.5956
  - Cruise Mach: 1

- **Tractor**
  - Fuel Weight: 3000 lbs
  - WSR: 52.47
  - TWR: 0.3524
  - Lfus: 49.50035
  - AR: 10.99989
  - Ctomax: 1.94452
  - fodsub: 1
  - CrnAlt: 39000
  - CrnMach: 0.4809
  - k_OEW: 1.01144

- **Pusher**
  - Fuel Weight: 5000 lbs
  - WSR: 40.29
  - TWR: 0.4476
  - Lfus: 55.111
  - AR: 10.998661
  - cl_ind_max: 1.95677
  - fodsub: 1.0001
  - CrnAlt: 39000
  - CrnMach: 0.55
  - k_OEW: 1.0087
Imagination at work

Created using ModelCenter®

Objective:
Minimize mission fuel weight

Constraint:
TOC ROC > 200 fpm

Design Variables:
- Thrust to weight ratio
- Wing loading
- Wing aspect ratio
- Cruise Mach number
- Cruise Altitude
Wing Loading Impact

Minimum fuel weight solutions are relatively insensitive to wing loading
Mission fuel weight varies only by 34 lbs
Wing loading varies from 55 to 80 psf
Allows for wing design freedom for laminar flow control and for noise considerations
Cleaner wing design with no flaps for noise reduction
## Optimal Configuration Selection

<table>
<thead>
<tr>
<th></th>
<th>Turbofan</th>
<th>Tractor</th>
<th>Pusher</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Engine Deck</strong></td>
<td>GE3800AR</td>
<td>GE4200ATP</td>
<td>GE5000ATP</td>
</tr>
<tr>
<td><strong>MTOGW, lbs</strong></td>
<td>17625</td>
<td>14664</td>
<td>17186</td>
</tr>
<tr>
<td><strong>Mission Fuel, lbs</strong></td>
<td>1348</td>
<td>1095</td>
<td>1249</td>
</tr>
<tr>
<td><strong>ESF</strong></td>
<td>0.9273</td>
<td>0.7996</td>
<td>0.7221</td>
</tr>
<tr>
<td><strong>Wing Area, sq ft</strong></td>
<td>391.7</td>
<td>203.6</td>
<td>429.6</td>
</tr>
<tr>
<td><strong>BFL, ft</strong></td>
<td>1822</td>
<td>2505</td>
<td>1619</td>
</tr>
<tr>
<td><strong>TOC ROC, ft/min</strong></td>
<td>212.8</td>
<td>202.9</td>
<td>297.9</td>
</tr>
<tr>
<td><strong>Aspect Ratio</strong></td>
<td>11</td>
<td>14.0</td>
<td>11.0</td>
</tr>
<tr>
<td><strong>Cruise Mach</strong></td>
<td>0.65</td>
<td>0.55</td>
<td>0.46</td>
</tr>
<tr>
<td><strong>Cruise Altitude, ft (ending)</strong></td>
<td>44152</td>
<td>39000</td>
<td>40123</td>
</tr>
<tr>
<td><strong>W/S</strong></td>
<td>45</td>
<td>72.03</td>
<td>40.00</td>
</tr>
<tr>
<td><strong>T/W</strong></td>
<td>0.4</td>
<td>0.457</td>
<td>0.400</td>
</tr>
</tbody>
</table>

 많은 엔진을 사용하는 pusher 모델이 선택되었습니다. 이 모델은 연료 소비량, 배출량, 비행기 크기를 최소화하기 위해 선택되었습니다.

---

GE Imagination at work

[GE Logo]

[Imagination at work]

[GE Logo]

[Imagination at work]
<table>
<thead>
<tr>
<th>Agenda GE/CA/GT April 22, 2010 N+3 Final Report</th>
</tr>
</thead>
</table>

### Introduction. Study Objectives and Metrics

- **GE** 8:00

### Future Scenario Vision. Air Transport Network Studies

- **GT** 8:15
  - Notional Trip vs. ALN, Impact on Infrastructure and Community

### Baseline Aircraft Definition

- **CA** 9:00

### Baseline Propulsion System. Baseline A/C vs. Metrics

- **GE** 9:15

### Advanced Airliner Technologies and Trade Studies

- **GE** 9:25
  - Advanced Propulsion Trade Studies. Concept Selection

- **Break** 10:00

- **CA** 10:15
  - Advanced Airliner Studies, Methods Assessment

- **GT** 10:45
  - Concept Selection

### Year 2035 Advanced Airliner Concept

- **CA** 11:00
  - Ultra-Quiet and Efficient Airliner Concept

- **GE** 11:20
  - Ultra-Quiet and Efficient Turboprop Concept

- **GE** 11:40
  - Advanced Airliner vs. Baseline and Metrics. Key Technologies

### Technology Roadmaps

- **CA/GE** 12:00

### Summary

- **GE** 12:30
2035 Selected Configuration
Design Mission – 2035 Final Configuration

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFR Range (200 nm alternate)</td>
<td>800 nm</td>
</tr>
<tr>
<td>Maximum Takeoff Weight, Full Fuel, Optimal Climb and Descent, Maximum Cruise Thrust at 39,000 ft</td>
<td></td>
</tr>
<tr>
<td>Cruise Speed</td>
<td>Mach = 0.50 to 0.60</td>
</tr>
<tr>
<td>Top of Climb, 39,000 ft, ISA (Optimized for Fuel Burn)</td>
<td></td>
</tr>
<tr>
<td>Maximum Operating Altitude</td>
<td>41,000 ft</td>
</tr>
<tr>
<td>Cruise Altitude &amp; Aircraft Optimized for Fuel Burn</td>
<td></td>
</tr>
<tr>
<td>Takeoff Runway Length</td>
<td>3,650 ft</td>
</tr>
<tr>
<td>Maximum Takeoff Weight, Sea Level, ISA, Balanced Field Length per Part 25</td>
<td></td>
</tr>
<tr>
<td>Climb Performance</td>
<td>30 min. to 39,000 ft</td>
</tr>
<tr>
<td>Maximum Takeoff Weight, Sea Level, ISA</td>
<td></td>
</tr>
<tr>
<td>Landing Runway Length</td>
<td>2,750 ft</td>
</tr>
<tr>
<td>Maximum Landing Weight, Seal Level, ISA, per Part 25</td>
<td></td>
</tr>
<tr>
<td>Certificated Noise Levels</td>
<td></td>
</tr>
<tr>
<td>Takeoff</td>
<td>56 EPNdB</td>
</tr>
<tr>
<td>Sideline</td>
<td>70 EPNdB</td>
</tr>
<tr>
<td>Landing</td>
<td>70 EPNdB</td>
</tr>
<tr>
<td>Cumulative</td>
<td>196 EPNdB</td>
</tr>
<tr>
<td>Margin to Stage 4 Requirement</td>
<td>75 EPNdB</td>
</tr>
<tr>
<td>LTO NOx vs. CAEP/6 Standard for 6000 lb FN (Modified Idle)</td>
<td>77% Margin</td>
</tr>
</tbody>
</table>
Advanced Air Vehicle Mission/Fuel
69% less fuel compared to Baseline Airliner

- Outstanding overall agreement in mission and total fuel burned
- Main differences in climb, descent/landing and reserves – attributed to code modeling differences

<table>
<thead>
<tr>
<th>Mission Phase</th>
<th>FLOPS Fuel, lbs</th>
<th>MAPS Fuel, lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxi/Takeoff</td>
<td>82</td>
<td>95</td>
</tr>
<tr>
<td>Climb</td>
<td>214</td>
<td>230</td>
</tr>
<tr>
<td>Cruise</td>
<td>608</td>
<td>633</td>
</tr>
<tr>
<td>Descent/Landing</td>
<td>191</td>
<td>116</td>
</tr>
<tr>
<td><strong>Mission Fuel</strong></td>
<td><strong>1,095</strong></td>
<td><strong>1,074</strong></td>
</tr>
<tr>
<td><strong>Reserves</strong></td>
<td><strong>399</strong></td>
<td><strong>418</strong></td>
</tr>
<tr>
<td><strong>Total Fuel</strong></td>
<td><strong>1,494</strong></td>
<td><strong>1,492</strong></td>
</tr>
</tbody>
</table>
2035 Selected Configuration

### Metrics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FLOPS</th>
<th>MAPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing Area, sq ft</td>
<td>203.6</td>
<td>203.6</td>
</tr>
<tr>
<td>Thrust per Engine, lbs</td>
<td>3,353</td>
<td>3,353</td>
</tr>
<tr>
<td>Total Fuel, lbs</td>
<td>1,494</td>
<td>1,492</td>
</tr>
<tr>
<td>Fuel Fraction</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>BLF, ft for Clmax=1.685</td>
<td>3,642</td>
<td>3,756</td>
</tr>
<tr>
<td>Empty Weight, lbs</td>
<td>7,636</td>
<td>7,821</td>
</tr>
<tr>
<td>Basic Operating Weight, lbs</td>
<td>8,325</td>
<td>8,510</td>
</tr>
<tr>
<td>Ramp (Gross) Weight, lbs</td>
<td>14,664</td>
<td>14,849</td>
</tr>
</tbody>
</table>

### Fuel reduction compared to baseline B-20, %

68.9

### Cert Noise:

- Cum Margin Below Stage 4: 75 EPNdB

### LTO NOx:

- Margin to CAEP/6 6000 lb FN Req’t: 77% margin

### Field Length:

- Margin N+3 Airport Req’t, ft: 358.0
2035 Comparison to Current Baseline and Existing Aircraft

Citation CJ2+
12,500 lbs

Citation Sovereign
30,300 lbs

20 Passenger Baseline
24,973 lbs

20 Passenger 2035 Configuration
14,664 lbs
Enabling Technologies

Advanced Turboprop Engine (-45% in SFC)
  > 45% Reduction in SFC

Aerodynamics (46% Laminar Flow)
  > Natural Laminar Flow
  > Hybrid Laminar Flow
  > Self-Cleaning Surfaces

Structure, Systems, & Prop. (-33% in Empty Weight)
  > Advanced Composite Structures
  > Protective Skin
  > Health Monitoring
  > Electric Systems
  > Systems Integrated in to Protective Skin
  > Adv. Engine
2035 Selected Configuration

- Electric Generators, High Volt. Dist.
- Cruise Flaps: Fuse $\alpha$
- Aft cabin door in turbulent flow region
- "Sealed" escape hatches
- Virtual reality or "sealed" windows
- Adv. Composites STAR – C$^2$
- Protective skin
- Adv. & Electric Systems
- Advanced turboprop
- Prone pilots/integral windscreen
- Self-Cleaning Surf./with Ice Prot
- Gust Load Alleviation & Ride Control
- HLFC

imagination at work
Fuselage Shaped for Natural Laminar Flow
Natural Laminar Flow Regions

- Natural laminar flow should occur in the light blue regions
- If NLF does not occur:
  - During climb and descent – 800 nm range reduces to 753 nm
  - During entire mission – 800 nm range reduces to 663 nm
  - Hybrid laminar flow might be necessary for nose gear door and windscreen
Hybrid Laminar Flow

Possible to provide suction to either preserve (low power) or re-establish (high power) laminar flow.

Adding system (weight) and extra fuel burned to support hybrid laminar flow reduces benefit of natural laminar flow but may solve targeted problem areas.

<table>
<thead>
<tr>
<th>Aircraft Component</th>
<th>Preserve Laminar Flow (Hp)</th>
<th>Re-Establish Laminar Flow (Hp)</th>
<th>Length Around Component (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose Gear Door</td>
<td>0.25</td>
<td>2.33</td>
<td>162</td>
</tr>
<tr>
<td>Windshield</td>
<td>0.48</td>
<td>4.48</td>
<td>312</td>
</tr>
<tr>
<td>Aircraft Total (4 inch strip)</td>
<td>1.45</td>
<td>13.62</td>
<td>474</td>
</tr>
</tbody>
</table>

![Graph showing MTOGW (lbs) vs HP with lines indicating AC Sized w/No LF, Increasing HP for LF, and Final Configuration. Points indicating Preserve LF and Reestablish LF.]

- 46 lbs weight of plumbing (99 lbs MTOGW)

---

**Imagination at work**

**GE**

**ASDL**
Advanced Composite Structure

Skin, Stringer, Frame
(Cost, Repair, Weight, Sys. Integration)

Primary Structure for Loads, Environment and Damage

Protective Outer Skin over Primary Structure

Current Technology

New Concept

Protective, Multifunction Skin
(Smoothing, EMI, Lightning, Thermal, Acoustic, Reflective)

Adv. Fibers, Resin Systems
(-30% to -35% in Structural Weight)
UQETP Airliner Features Impacting Noise

- Innovative Aero and Structural Features Significantly Reduce Aircraft Noise
  - Reduced Drag and Weight:
    - Reduces engine size/propulsor power
    - Reduces size and complexity of control surfaces
  - Clean aero design (partial laminar flow) reduces the generation of airframe noise

- Light wing loading and high TP T/O thrust enables short field length without airframe noise.
Summary of 2035 Final Configuration

14,664 lb aircraft with two engines, two pilots, & 1 attendant (Larger than CJ2+ but nearly same weight; significantly lighter than Sovereign)

Mission = 800 nm range, Mcr = 0.55, Alt = 39,000 ft
> High altitude cruise is important for fuel burn
> Cruise speed eliminates compressibility drag
> Zero wing sweep supports natural laminar flow

4 Abreast 737 comfort with oval fuselage shaped to promote natural laminar flow
> Losing all laminar flow reduces range from 800 to 663 nm
> Losing laminar flow during climb/descent reduces to 753 nm

Advanced turboprop, innovative protective conductive skin/energy absorbing foam, and systems technologies advances all contribute to satisfying all of NASA goals.
Agenda GE/CA/GT April 22, 2010 N+3 Final Report

Introduction. Study Objectives and Metrics GE 8:00

Future Scenario Vision. Air Transport Network Studies GT 8:15
  > Notional Trip vs. ALN, Impact on Infrastructure and Community

Baseline Aircraft Definition CA 9:00

Baseline Propulsion System. Baseline A/C vs. Metrics GE 9:15

Advanced Airliner Technologies and Trade Studies GE 9:25
  > Advanced Propulsion Trade Studies. Concept Selection
  > Break 10:00
  > Advanced Airliner Studies, Methods Assessment CA 10:15
  > Concept Selection GT 10.45

Year 2035 Advanced Airliner Concept CA 11:00
  > Ultra-Quiet and Efficient Airliner Concept
  > Ultra-Quiet and Efficient Turboprop Concept GE 11:20
  > Advanced Airliner vs. Baseline and Metrics. Key Technologies GE 11:40

Technology Roadmaps CA/GE 12:00

Summary GE 12:30
Advanced Ultra Quiet and Efficient Turboprop (UQETP)

Noise Optimized Propeller w/ Excellent T/O and Cruise Performance

Efficient, Light Weight, Low Emissions Advanced TP Engine

Innovative Concept to Minimize Environmental Impact and Maximize Community Acceptance and Network Viability
Imagination at work

Efficient, Noise Optimized Propeller

- 3200 lb Hot Day T/O Thrust, 9.8’ Prop
- 8 bladed, moderate AF and loading, ultra-low tip speed design (U_{tip} = 600 fps T/O, 590 fps Cruise) yields excellent T/O Noise and thrust w/ high cruise efficiency
- Thin, durable airfoils (adv mat’ls, manufacturing) manage weight
- Proplets reduce tip speed, noise
- CAA and innovative Non-Uniform geometry reduce noise, not perf.
- Noise sensing propulsion control adjusts power, pitch, speed to avoid stall and minimize noise during T/O
Advanced Turboprop can meet N+3 Goal with Innovative Technologies
**N+3 Noise Goal Exceeded with Advanced Aircraft and Propulsion Technologies**

<table>
<thead>
<tr>
<th>Advanced Turboprop Aircraft Noise Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takeoff</td>
</tr>
<tr>
<td>Sideline</td>
</tr>
<tr>
<td>Approach</td>
</tr>
<tr>
<td>Cumulative</td>
</tr>
<tr>
<td>Cum Below Stage 4</td>
</tr>
</tbody>
</table>
Noise Into the Future

• Base operations at notional airport increased by 1.2% in Year 2030 according to master plan
• 6 current day baseline aircraft flights added to schedule operated
• Based on demand study for 2030 assume a 4x growth in N+3 trips, 24 flights added

Small growth in base ops. 4x growth in quiet N+3 ops results in only 0.02 nmi² growth in 55dB area, or 0.015 LDN increase @ Airport Boundary. Added N+3 traffic transparent to Community
Advanced TAPS flow staging dramatically reduces NOx at cruise power and above

Advanced TAPS Pilot needed to improve Taxi & Approach Performance
Advanced Radial TAPS (Twin Annular PreSwirl)
Lean burn, staged, compact combustor

- Staged combustion within swirler
- Twin annular flames
- Central pilot for good operability and low CO and HC at low power
- Lean-premixed fuel/air mixture in main swirler for reduced NOx at high power and cruise
  - Lean mix enabled by Advanced Materials/Cooling
- Some TAPS features difficult to scale to this size

Radial TAPS for small engines:
- Larger centerbody for a larger pilot zone.
- Increased injector size/reduced number
- Reduced engine length
- Ease of assembly/maintenance
- Airblast atomization to further improve premixing
- Ease of assembly/maintenance
LTO NOx IMPROVEMENT vs. BASELINE

Advanced UQETP Turboprop LTO NOx vs. Baseline Engine

<table>
<thead>
<tr>
<th></th>
<th>w/ RQL</th>
<th>w/ Adv Radial TAPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takeoff</td>
<td>- 66%</td>
<td>- 89%</td>
</tr>
<tr>
<td>Climb</td>
<td>- 64%</td>
<td>- 90%</td>
</tr>
<tr>
<td>Approach</td>
<td>- 52%</td>
<td>- 59%</td>
</tr>
<tr>
<td>Idle</td>
<td>- 40%</td>
<td>- 55%</td>
</tr>
<tr>
<td><strong>Total LTO NOx (g/cycle)</strong></td>
<td>- 56%</td>
<td>- 74%</td>
</tr>
</tbody>
</table>

LTO NOx vs. CAEP/6
(vs. 6000 lb FN Requirement. Turboprop Idle = 4%SHP, 80% prop speed)

|                      | - 59%  | - 77%               |

- **NOx Goals Achievable w/ Improved Cycle + Mat’ls + Advanced Radial TAPS**
  - Scaling TAPS technology to this size, however, is a significant challenge

- **Low Power Emissions are biggest opportunity**
  - Focus on Pilot for further improvement

- **Reduced N+3 ground operation time is additional real world benefit**

Exceeds N+3 LTO NOx Goal.
LTO & Cruise NOx > 70% better than Baseline.
NASA N+3 – UQETP Advanced Turboprop Concept
Component and Systems Technologies

- Active Axial Stall Detection/Suppression
- Active Impeller Clearance Control
- Low-Emissions Radial TAPS Combustor
- Active HPT Clearance Control
- Innovative Advanced Impeller
- Optical Wireless Sensor Technology
- Hybrid Ceramic-Metal Bearings
- Advanced Seals
- Advanced Air Bearing
- Lightweight GGT/PT Rotor Structure
- Low-Loss Non-Contacting Seals
## UQETP Propulsion System Performance

<table>
<thead>
<tr>
<th>Units</th>
<th>SLS TAKEOFF (flat rated)</th>
<th>ROLLING TAKEOFF (flat rated)</th>
<th>TOP OF CLIMB (run to FN)</th>
<th>INITIAL CRUISE (run to FN)</th>
<th>DESIGN POINT Max Cr 100% N2r</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALT (ft)</td>
<td>0</td>
<td>0</td>
<td>39000</td>
<td>39000</td>
<td>39000</td>
</tr>
<tr>
<td>Mach</td>
<td>0</td>
<td>0.25</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>TAMB (deg R)</td>
<td>518.7</td>
<td>518.7</td>
<td>390.0</td>
<td>390.0</td>
<td>390.0</td>
</tr>
<tr>
<td>Cust Bleed (lb/sec)</td>
<td>0.402</td>
<td>0.402</td>
<td>0.402</td>
<td>0.402</td>
<td>0.402</td>
</tr>
<tr>
<td>Cust Power (hp)</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>FNTOT (lbf)</td>
<td><strong>3353</strong></td>
<td>2548</td>
<td><strong>515</strong></td>
<td>412</td>
<td>474</td>
</tr>
<tr>
<td>TSFC (lb/h/lbf)</td>
<td>0.189</td>
<td>0.247</td>
<td>0.408</td>
<td>0.418</td>
<td><strong>0.406</strong></td>
</tr>
<tr>
<td>FN engine (lbf)</td>
<td>171</td>
<td>103</td>
<td>25</td>
<td>13</td>
<td>20</td>
</tr>
<tr>
<td>FN prop (lbf)</td>
<td>3182</td>
<td>2445</td>
<td>490</td>
<td>399</td>
<td>454</td>
</tr>
<tr>
<td>SHP (hp)</td>
<td><strong>1591</strong></td>
<td><strong>1591</strong></td>
<td>532</td>
<td>429</td>
<td>489</td>
</tr>
<tr>
<td>Corr Core Speed (%)</td>
<td>96.1</td>
<td>95.4</td>
<td>102.4</td>
<td>98.3</td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

> 40% better SFC than Baseline despite small size
Year 2035 Ultra Quiet and Efficient Turboprop (UQETP)

Ultra-Efficient, Low NOx Turboprop Engine

Composite Case Propeller Gearbox

Composite Engine Mount Tube

Full Composite Nacelle

Composite Inlet

Composite Spinner

Ultra-Quiet 8-Bladed Composite Propeller

Proplet Tips

$\text{FN}_{\text{total}} = 3353 \text{ lb}$

Installed, Hot Day Thrust

Weight $= 882 \text{ lb}$

Total System (Engine, Prop, Gearbox, Shaft)
## Advanced Propulsion System Uninstalled Weights

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propeller</td>
<td>292</td>
</tr>
<tr>
<td>Propeller Gearbox</td>
<td>215</td>
</tr>
<tr>
<td>PGB Mounting</td>
<td>28</td>
</tr>
<tr>
<td>Engine</td>
<td>347</td>
</tr>
<tr>
<td>Total</td>
<td>882 lb</td>
</tr>
</tbody>
</table>

## GE UQETP – Advanced Turboprop Engine Weight

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Frame - Compressor Module</td>
<td>76</td>
</tr>
<tr>
<td>Midframe - Combustor Module</td>
<td>46</td>
</tr>
<tr>
<td>High Pressure Turbine Module</td>
<td>25</td>
</tr>
<tr>
<td>Low Pressure Turbine Module/Exhaust Frame</td>
<td>67</td>
</tr>
<tr>
<td>Controls, Lube System, Accessory Gearbox, Configuration Hardware</td>
<td>133</td>
</tr>
<tr>
<td>Total Weight</td>
<td>347 lb</td>
</tr>
</tbody>
</table>

*Imagination at work*
UQETP Summary

• Innovative, Low Noise Propeller is key to minimizing noise and gaining community acceptance.
  > Excellent Takeoff thrust also eliminates need for lift technology and associated airframe cost and noise
  > Prop is the right choice for M < 0.6 regardless of engine technologies
      – Minimizes size of the powerplant

• Advanced Materials, Manufacturing, Systems technologies dramatically reduces Environmental Impact (SFC, Emissions)

• Advanced Radial TAPS Combustor brings large engine emissions technology down to a small, maintainable configuration
Agenda GE/CA/GT April 22, 2010 N+3 Final Report

Introduction. Study Objectives and Metrics GE 8:00

Future Scenario Vision. Air Transport Network Studies GT 8:15
  > Notional Trip vs. ALN, Impact on Infrastructure and Community

Baseline Aircraft Definition CA 9:00
Baseline Propulsion System. Baseline A/C vs. Metrics GE 9:15

Advanced Airliner Technologies and Trade Studies GE 9:25
  > Advanced Propulsion Trade Studies. Concept Selection
  > Break 10:00
  > Advanced Airliner Studies, Methods Assessment CA 10:15
  > Concept Selection GT 10:45

Year 2035 Advanced Airliner Concept CA 11:00
  > Ultra-Quiet and Efficient Airliner Concept
  > Ultra-Quiet and Efficient Turboprop Concept GE 11:20
  > Advanced Airliner vs. Baseline and Metrics. Key Technologies GE 11:40

Technology Roadmaps CA/GE 12:00

Summary GE 12:30
Advanced Airliner Concept vs. Baseline & Metrics

Field Length: 4000 ft to Satisfy Small Airports in N+3 Network

- Light weight aircraft and high propulsor thrust result in a takeoff BFL of only 3650 ft

-70% Fuel Burn Metric vs. Current Technology Baseline Aircraft

- Weight, aero, propulsion technologies result in a 69% improvement vs. Baseline

Further opportunities for improvement:
- Optimization of cruise altitude/mission profile/trajectory
- Re-regulation to allow electronic co-pilot
- Technologies beyond TRL 6 in Year 2025

-75% LTO NOx vs. CAEP/6 Requirement

- Efficient Aircraft and Propulsion System, Innovative Radial TAPS Combustor yield 77% Margin vs. CAEP/6 LTO NOx 6000 lb thrust requirement.
- 74% Lower LTO NOx, 71% Lower Cruise NOx than Baseline on a grams/Trip basis
- N+3 Point-to-Point travel inherently lower LTO emissions than Hub & Spoke (Single LTO)
- Reduced idle/taxi at small airports also reduces LTO NOx

71 dB Cum Margin to Stage 4 Noise Limit, 55 LDN at Airport Boundary

- Small, Clean Aircraft & Innovative Propulsor potentially enable 75 dB Margin to Stage 4
- Noise increase of only 0.015 dB LDN at the airport boundary due to added N+3 traffic.
- N+3 traffic increase should be virtually unnoticeable to local community.

Potential to Meet N+3 Goals & Achieve Economic Viability
## Impact of Advanced Aircraft & Propulsion System

<table>
<thead>
<tr>
<th></th>
<th>TOGW (lb)</th>
<th>Thrust (lbf)</th>
<th>Fuel Burn (lb/mission)</th>
<th>LTO NOx (g/LTO/Pax)</th>
<th>LTO Noise EPNdB Cum</th>
<th>Field Length (Landing, T/O)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline Airliner</strong></td>
<td><strong>24973</strong></td>
<td><strong>4557.5</strong></td>
<td><strong>3516</strong></td>
<td><strong>43</strong></td>
<td>-20</td>
<td><strong>4000</strong></td>
</tr>
<tr>
<td><strong>B20 w/ 2008 TF</strong></td>
<td><strong>BASE</strong></td>
<td><strong>BASE</strong></td>
<td><strong>BASE</strong></td>
<td><strong>BASE</strong></td>
<td><strong>BASE</strong></td>
<td><strong>BASE</strong></td>
</tr>
<tr>
<td><strong>Advanced Airliner</strong></td>
<td><strong>14550</strong></td>
<td><strong>3203.8</strong></td>
<td><strong>1088</strong></td>
<td><strong>10.5</strong></td>
<td><strong>-75</strong></td>
<td><strong>-9%</strong></td>
</tr>
<tr>
<td><strong>A20 w/ 2030 ATP</strong></td>
<td><strong>-42%</strong></td>
<td><strong>-30%</strong></td>
<td><strong>-69%</strong></td>
<td><strong>-75%</strong></td>
<td><strong>-55</strong></td>
<td><strong>-8%</strong></td>
</tr>
<tr>
<td><strong>Adv Reference Airliner</strong></td>
<td><strong>17511.1</strong></td>
<td><strong>4090.4</strong></td>
<td><strong>1669</strong></td>
<td><strong>17.3</strong></td>
<td><strong>-41</strong></td>
<td><strong>-8%</strong></td>
</tr>
<tr>
<td><strong>AR20 w/ 2030 ARTF</strong></td>
<td><strong>-30%</strong></td>
<td><strong>-10%</strong></td>
<td><strong>-53%</strong></td>
<td><strong>-59%</strong></td>
<td><strong>-21</strong></td>
<td><strong>-8%</strong></td>
</tr>
<tr>
<td><strong>Advanced Propulsion Only</strong></td>
<td><strong>22267</strong></td>
<td><strong>5197</strong></td>
<td><strong>1800</strong></td>
<td><strong>20.6</strong></td>
<td><strong>-62</strong></td>
<td><strong>+23%</strong></td>
</tr>
<tr>
<td><strong>B20 w/ 2030 ATP</strong></td>
<td><strong>-11%</strong></td>
<td><strong>+14%</strong></td>
<td><strong>-49%</strong></td>
<td><strong>-52%</strong></td>
<td><strong>-42</strong></td>
<td><strong>+23%</strong></td>
</tr>
<tr>
<td><strong>Advanced Airframe Only</strong></td>
<td><strong>16437.6</strong></td>
<td><strong>3287.8</strong></td>
<td><strong>2135</strong></td>
<td><strong>31.9</strong></td>
<td><strong>-32</strong></td>
<td><strong>+6%</strong></td>
</tr>
<tr>
<td><strong>A20 w/ 2008 TF</strong></td>
<td><strong>-34%</strong></td>
<td><strong>-28%</strong></td>
<td><strong>-39%</strong></td>
<td><strong>-25%</strong></td>
<td><strong>-12</strong></td>
<td><strong>+6%</strong></td>
</tr>
</tbody>
</table>

- Assess Impact of Advanced Conventional Technologies vs. Innovative Propulsion and Aircraft Technologies

- Advanced Reference Aircraft (AR20, w/o Innovative TAPS, Noise Tech’s, or Natural Laminar Flow design) achieves > 50% improvement in Fuel Burn, Emissions, but is 30 EPNdB short of Noise Goal

- Innovative and Advanced Propulsion further improve noise 21 EPNdB, nearly match AR20 Fuel & NOx, but is heavier, costlier than AR20

- Innovative and Advanced Airframe technologies alone provide less noise, emissions, fuel burn improvement, but result in smaller aircraft and engine (Cost)
One-Off Technology Assessment Methodology

Start with the 2035 Advanced Airliner Concept

- Advanced turboprop puller configuration

Remove each technology one at a time

- Airframe advanced structures
- Airframe advanced systems
- Airframe novel protective skin
- Airframe advanced aerodynamics (HLC)
- Propulsion advanced mechanical systems
- Propulsion advanced component aerodynamics
- Propulsion advanced material and manufacturing

Reoptimize T/W and W/S to minimize fuel burn

- Satisfy 200 ft/min TOC requirement. Let TOFL constraint to assess impact

Record delta in the metrics relative to the 2035 Advanced Airliner Concept
# Impact of Advanced and Innovative Technologies

## One-off Assessment: Impact of Technology Removal

<table>
<thead>
<tr>
<th>Technology</th>
<th>TOGW</th>
<th>Engine Size</th>
<th>Fuel Burn</th>
<th>LTO NOx (g/PAX)</th>
<th>LTO Noise (EPNdB cum)</th>
<th>Field legth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced A20ATP</td>
<td>BASE</td>
<td>BASE</td>
<td>BASE</td>
<td>BASE</td>
<td>BASE</td>
<td>BASE</td>
</tr>
<tr>
<td>Advanced Propulsion Mech Systems</td>
<td>1%</td>
<td>2%</td>
<td>7%</td>
<td>10%</td>
<td>~ same</td>
<td>2%</td>
</tr>
<tr>
<td>Advanced Propulsions Aero</td>
<td>1%</td>
<td>-5%</td>
<td>14%</td>
<td>10%</td>
<td>~ same</td>
<td>11%</td>
</tr>
<tr>
<td>Adv Propulsion Mat’ls/Manufacture</td>
<td>4%</td>
<td>~ same</td>
<td>13%</td>
<td>40%</td>
<td>~ same</td>
<td>4%</td>
</tr>
<tr>
<td>Advanced Radial TAPS</td>
<td>~same</td>
<td>~same</td>
<td>~same</td>
<td>75%</td>
<td>~same</td>
<td>~same</td>
</tr>
<tr>
<td>Noise Optimized Turboprop</td>
<td>~same</td>
<td>~same</td>
<td>~same</td>
<td>~same</td>
<td>~same</td>
<td>+29 dB</td>
</tr>
<tr>
<td>AF Structural Technologies</td>
<td>20%</td>
<td>9%</td>
<td>10%</td>
<td>15%</td>
<td>+3dB</td>
<td>4%</td>
</tr>
<tr>
<td>Advanced Airframe Systems</td>
<td>5%</td>
<td>-1%</td>
<td>2%</td>
<td>~same</td>
<td>+1dB</td>
<td>~same</td>
</tr>
<tr>
<td>Multifunction AF Structure</td>
<td>1%</td>
<td>0%</td>
<td>~same</td>
<td>~same</td>
<td>~same</td>
<td>~same</td>
</tr>
<tr>
<td>Novel Protective AF Skin</td>
<td>7%</td>
<td>1%</td>
<td>3%</td>
<td>2%</td>
<td>+1dB</td>
<td>7%</td>
</tr>
<tr>
<td>Novel Laminar Flow Technologies</td>
<td>7%</td>
<td>43%</td>
<td>20%</td>
<td>65%</td>
<td>+9dB</td>
<td>4%</td>
</tr>
</tbody>
</table>
## Impact of Advanced and Innovative Technologies

### One-off Assessment: Impact of Technology Removal

<table>
<thead>
<tr>
<th></th>
<th>TOGW</th>
<th>Engine Size</th>
<th>Fuel Burn</th>
<th>LTO NOx (g/PAX)</th>
<th>LTO Noise (EPNdB cum)</th>
<th>Field Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced A20ATP</td>
<td>BASE</td>
<td>BASE</td>
<td>BASE</td>
<td>BASE</td>
<td>BASE</td>
<td>BASE</td>
</tr>
<tr>
<td>Advanced Propulsion Mech Systems</td>
<td>1%</td>
<td>2%</td>
<td>7%</td>
<td>10%</td>
<td>~ same</td>
<td>2%</td>
</tr>
<tr>
<td>Advanced Propulsion Aero</td>
<td>1%</td>
<td>-5%</td>
<td>14%</td>
<td>10%</td>
<td>~ same</td>
<td>11%</td>
</tr>
<tr>
<td>Adv Propulsion Mat'ls/Manufacture</td>
<td>4%</td>
<td>~ same</td>
<td>13%</td>
<td>40%</td>
<td>~ same</td>
<td>4%</td>
</tr>
<tr>
<td>Advanced Radial TAPS</td>
<td>~ same</td>
<td>~ same</td>
<td>~ same</td>
<td>75%</td>
<td>~ same</td>
<td>~ same</td>
</tr>
<tr>
<td>Noise Optimized Turboprop</td>
<td>~ same</td>
<td>~ same</td>
<td>~ same</td>
<td>~ same</td>
<td>+29 dB</td>
<td>15%</td>
</tr>
<tr>
<td>AF Structural Technologies</td>
<td>20%</td>
<td>9%</td>
<td>10%</td>
<td>15%</td>
<td>+3 dB</td>
<td>4%</td>
</tr>
<tr>
<td>Advanced Airframe Systems</td>
<td>5%</td>
<td>-1%</td>
<td>2%</td>
<td>~same</td>
<td>+1 dB</td>
<td>~ same</td>
</tr>
<tr>
<td>Multifunction AF Structure</td>
<td>1%</td>
<td>0%</td>
<td>~ same</td>
<td>~ same</td>
<td>~ same</td>
<td>~ same</td>
</tr>
<tr>
<td>Novel Protective AF Skin</td>
<td>7%</td>
<td>1%</td>
<td>3%</td>
<td>2%</td>
<td>+1 dB</td>
<td>7%</td>
</tr>
<tr>
<td>Novel Laminar Flow Technologies</td>
<td>7%</td>
<td>43%</td>
<td>20%</td>
<td>65%</td>
<td>+9 dB</td>
<td>4%</td>
</tr>
</tbody>
</table>

### A/C Aero, Propulsion Tech’s Critical. Prop Noise and A/C Structures Key.

<table>
<thead>
<tr>
<th></th>
<th>Weighting</th>
<th>Fuel Burn</th>
<th>LTO NOx</th>
<th>LTO Noise</th>
<th>Field Length</th>
<th>A/C Cost/ Ticket Price</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weighting</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Propulsion Techs (Mat'ls, Aero, Systems)</td>
<td>9</td>
<td>7</td>
<td>0</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Advanced Radial TAPS</td>
<td>0</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Efficient, Noise Optimized Propeller</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>7</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>A/C Materials/Structure/Systems</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>A/C Laminar Flow Technologies</td>
<td>5</td>
<td>7</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
# Agenda GE/CA/GT April 22, 2010 N+3 Final Report

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:00</td>
<td>Introduction. Study Objectives and Metrics</td>
</tr>
<tr>
<td>8:15</td>
<td>Future Scenario Vision. Air Transport Network Studies</td>
</tr>
<tr>
<td></td>
<td>Notional Trip vs. ALN, Impact on Infrastructure and Community</td>
</tr>
<tr>
<td>9:00</td>
<td>Baseline Aircraft Definition</td>
</tr>
<tr>
<td>9:15</td>
<td>Baseline Propulsion System. Baseline A/C vs. Metrics</td>
</tr>
<tr>
<td>9:25</td>
<td>Advanced Airliner Technologies and Trade Studies</td>
</tr>
<tr>
<td></td>
<td>Advanced Propulsion Trade Studies. Concept Selection</td>
</tr>
<tr>
<td>10:00</td>
<td>Break</td>
</tr>
<tr>
<td>10:15</td>
<td>Advanced Airliner Studies, Methods Assessment</td>
</tr>
<tr>
<td>10:45</td>
<td>Concept Selection</td>
</tr>
<tr>
<td>11:00</td>
<td>Year 2035 Advanced Airliner Concept</td>
</tr>
<tr>
<td></td>
<td>Ultra-Quiet and Efficient Airliner Concept</td>
</tr>
<tr>
<td></td>
<td>Ultra-Quiet and Efficient Turboprop Concept</td>
</tr>
<tr>
<td></td>
<td>Advanced Airliner vs. Baseline and Metrics. Key Technologies</td>
</tr>
<tr>
<td>12:00</td>
<td>Technology Roadmaps</td>
</tr>
<tr>
<td>12:30</td>
<td>Summary</td>
</tr>
</tbody>
</table>
Laminar Flow – Tech. Dev. Roadmaps

Aero 1.1: Steps & Gaps in Favorable Pressure Gradients
  > Literature Survey (flat plates, special cases)
  > BL-Transition, Stability (favorable pressure gradient)
  > Wind Tunnel, & Flight Test

Aero 1.2: Suction Requirements for Active Flow Control
  > Explore limited application of suction in strips
  > Quantify suction for stabilizing, & re-establishing BL

Aero 2.0: Hydrophobic, Hydrophilic, & Self Cleaning Surfaces
  > Study impact of coating properties on bug adhesion
  > Consider addition of surface water or cleaning solution
  > Quantify time, effort to clean aircraft surface

3-5 years for Phase I, 5-15 years transition to widespread application
# Structures & Systems Tech. Roadmaps

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 Aluminum Aircraft</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010 Composite Aircraft (-2% Empty Weight)</td>
<td>Test Data for 2010 Materials</td>
<td>Airplane Design, Test, &amp; Certification</td>
<td>2020 Composite Aircraft (-14% Empty Weight)</td>
<td></td>
</tr>
<tr>
<td>Multi-Function Structure / Multi-Function Protective Skin</td>
<td>Material, &amp; Design Data</td>
<td>Airplane Design, Test, &amp; Cert.</td>
<td>Composite Aircraft (-20.5% Empty Weight)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Composite Aircraft (-33% Empty Weight)</td>
<td></td>
</tr>
</tbody>
</table>
Composites – Material Prop. & Design Data

Concurrent Material Prop. & Aircraft Design = RISK
Can we shrink the time and $ for Design Data Dev.?
Structures – Tech. Dev. Roadmaps

STC 1.1: Material Standards
> Standard formulations for composite materials
> Standard material production processes
> Statistically verified performance properties for coupons & elements

STC 1.2, 1.3: Methods for Base Material Properties & Design Data
> Semi-empirical/Analytical tools reduce time and $ for coupon and element material data
> Analytical tools to reduce time and $ for design data with damage, repair, and extreme environments

STC 2.1: Star-C$^2$ Protective Skins
> Identify candidate materials
> Test for Impact, EMI, Lightning, & Acoustic damping
> Develop installation, repair, & replacement procedures

STC 2.2: Structural Health Monitoring
> Architecture trades for compatibility with Star-C$^2$ skin
> Requirements for reliable system that replaces inspections
> Operational scenarios for known structural health

3-5 years for Phase I, 5-15 years transition to widespread application
Systems – Tech. Dev. Roadmaps

Sys 1.0: Ice Protection for Laminar Flow Surface
- Compatibility with Star-C² skin
- Compatibility with self-cleaning surfaces
- Ice protection function in smooth surface

Sys 2.0: Multi-Function Structure
- Stiffeners for air ducts, wires, & acoustic vibration
- Optimize structure for load and systems function

Sys 3.0: Suction Systems for HLFC
- Compatibility with Star-C² skin
- Compatibility with self-cleaning surfaces
- Light weight, low power systems

3-5 years for Phase I, 5-15 years transition to widespread application
Invest in (STC2) Star-C^2 skin, (Aero2) Self-Cleaning Surface, & (Sys3.0) Suction for HLFC
Future Low Noise/High Performance Propeller

- Propeller designed and controlled to minimize T/O noise
- Increased airfoil count, large diameter, moderate AF allow low power loading and reduced tip speed
- Proplets increase efficiency and reduce tip speed and noise
- Advanced airfoil shape (CAA, mat’ls, manu) and innovative features
- Noise sensing propulsion control adjusts power, pitch, rpm to minimize noise and avoid stall during T/O

Emerging CAA Tools Show Great Promise
Future Low Noise/High Performance Propeller

Goals and Objectives
1. Propeller with high cruise efficiency
2. Propeller with low noise
3. Light weight, high reliability

Milestones
1. GEN1 Scale Model Test
2. Non-Uniform Spacing, Tip Features, Fluidics assessment
3. GEN2 Scale Model Test
4. Engine Test

Deliverables
1. GEN1 Prop Design
2. Scale Model Hardware
3. GEN2 Prop Design
4. Scale Model Hardware
5. Engine Hardware
Advanced, Low NOx Radial TAPS Combustor

- Enhance TAPS emissions reduction technologies and broaden the range of scalability.
- Improve TAPS main stage mixing to meet 75% below CAEP/6 LTO NOx.
- Improve materials and cooling technology for leaner combustion.
- Develop innovative pilot to reduce approach and idle emission with good stability and ignition capability.
- Develop concepts to scale TAPS across a wide range of thrust, OPR, T41.

Enhanced Low Emissions Technology for any Thrust Class
## Advanced Radial TAPS Roadmap

### Goals and Objectives

1. Develop small premixing combustor w/ 30% to 50% lower LTO NOx w/ good performance & stability
2. Develop advanced materials & technologies to minimize cooling and enable leaner combustion
3. Develop advanced pilot systems to reduce low power emissions, with good ignition and stability

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline TAPS N+1 (&gt;50% below CAEP/6 NOx)</td>
<td>♦</td>
<td>♠</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAPS entry into widebody service (GE9x)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAPS N+1 applications (&gt;60% below CAEP/6 NOx) - CLEEN</td>
<td>♦</td>
<td>♠</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAPS entry into narrow body service</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAPS entry into regional jet service</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAPS N+2 Civil Engine Technology Development (&gt;70% below CAEP/6 NOx)</td>
<td>♦</td>
<td>♠</td>
<td>♦</td>
<td>♠</td>
<td>♠</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N+2 Advanced Low Nox Combustor Technology for Subsonic Civil Aircraft</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---NEED MF INPUT ON FUTURE NASA PLANS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAPS N+3 High T4 Engine Technology Development</td>
<td>♦</td>
<td></td>
<td>♠</td>
<td>♠</td>
<td>♠</td>
<td>♠</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NASA Low Emissions Combustion Concepts: SSBJ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>USAF HEETE Mixer Studies</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>USAF HEETE Combustion System Development / Core Test</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>USAF HEETE Engine Demo</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAPS N+3 Small Engine Technology Development</td>
<td>♦</td>
<td>♠</td>
<td>♠</td>
<td>♠</td>
<td></td>
<td>♠</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main stage mixing studies and flame tube tests</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical and thermal design and analysis - minimum cooling flow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small diameter pilot stage CFD studies, flame tube and sector tests</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full annular test rig design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full annular rig test</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology readiness analysis and final report (TRL 5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Milestones

- **2016**: Systems analysis, conceptual design
- **2017**: Main stage mixing studies, flame tube test.
- **Min cooling combustor mech design & analysis**
- **Small diameter pilot stage CFD, flame tube, sector test**

### Deliverables

- Combustor conceptual design/analysis
- Combustor mechanical design
- Flame tube rig hardware, test, analysis
Advanced Propulsion Materials, Manufacturing, Mechanical Systems

- Enhanced disk, shaft, airfoil materials and manufacturing processes to allow more complex shapes, lower weight, higher temps, speeds
- Hi-temp flowpath, combustor, structural materials to reduce weight, cooling
- Lightweight composites for AGB’s, PGB, Low temp structures
- Advanced bearings, seals, clearance control to improve performance and durability and reduce weight and emissions

Propulsion technologies improve SFC, Weight, Durability, Emissions
Future SOFC/GT Hybrid Electric Aircraft Propulsion

- SOFC is still an immature technology
- Few large-scale (> 100 kW) systems have been developed
  - relatively low power density “non-planar” configurations
  - low “entitlement” (ultimate capability) for the reduced weight & volume needed for aircraft/airship propulsion applications
- Minimization of weight & volume for airship propulsion entails an additional suite of development needs

---

Little Work Focused on Aviation CTQs
# Future SOFC/GT Hybrid Electric Aircraft Propulsion

## Goals and Objectives

1. Hybrid propulsion system to meet fuel efficiency and emissions goals.
2. Identify optimized system design and configuration for SOFC/GT hybrid propulsion aircraft, including specific power requirements for SOFC.
3. Develop advanced SOFC stack technology to meet specific power requirements dictated by system optimization results.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System Design &amp; Modeling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conceptual System Design &amp; Modeling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>🟠</td>
<td>🟠</td>
<td>🟠</td>
</tr>
<tr>
<td>Define major components and the process flow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Define basic requirements for components / subsystems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component / Subsystem / Balance of Plant Design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start communication with airframers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>🟠</td>
<td>🟠</td>
<td>🟠</td>
</tr>
<tr>
<td>Detailed component designs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>🟠</td>
<td>🟠</td>
<td>🟠</td>
</tr>
<tr>
<td>Component level prototypes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>🟠</td>
<td>🟠</td>
<td>🟠</td>
</tr>
<tr>
<td>Component validation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>🟠</td>
<td>🟠</td>
<td>🟠</td>
</tr>
<tr>
<td>System level validation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>🟠</td>
<td>🟠</td>
<td>🟠</td>
</tr>
<tr>
<td>Subsystem test validations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System level test validations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Solid Oxide Fuel Cell Design and Development</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Development of Materials for High Specific Power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>🟠</td>
<td>🟠</td>
<td>🟠</td>
</tr>
<tr>
<td>Double power density to 2 W/cm² on button cells</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Develop lightweight interconnect and packaging for 50% mass reduction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced Fabrication to Enable High Specific Power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>🟠</td>
<td>🟠</td>
<td>🟠</td>
</tr>
<tr>
<td>Scale advanced fabrication technique to 100 cm² cells</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Develop cell architecture to deliver 1.5W/cm² at 80% fuel utilization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demonstrate 3-cell lab short stack (0.5 kW) with required specific power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demonstrate 3 kW, 3-cell lab short stack with required specific power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stack and System Demonstrations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>🟠</td>
<td>🟠</td>
<td>🟠</td>
</tr>
<tr>
<td>Demonstrate 25 kW SOFC system w/ required specific power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demonstrate 200 kW SOFC system w/ required specific power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demonstrate integrated 200 kW SOFC / GT system</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Agenda GE/CA/GT April 22, 2010 N+3 Final Report

Introduction. Study Objectives and Metrics GE 8:00

Future Scenario Vision. Air Transport Network Studies GT 8:15
  > Notional Trip vs. ALN, Impact on Infrastructure and Community

Baseline Aircraft Definition CA 9:00
Baseline Propulsion System. Baseline A/C vs. Metrics GE 9:15

Advanced Airliner Technologies and Trade Studies GE 9:25
  > Advanced Propulsion Trade Studies. Concept Selection
  > Break 10:00
    > Advanced Airliner Studies, Methods Assessment CA 10:15
    > Concept Selection GT 10:45

Year 2035 Advanced Airliner Concept CA 11:00
  > Ultra-Quiet and Efficient Airliner Concept
  > Ultra-Quiet and Efficient Turboprop Concept GE 11:20
  > Advanced Airliner vs. Baseline and Metrics. Key Technologies GE 11:40

Technology Roadmaps CA/GE 12:00

Summary GE 12:30
Summary

N+3 Network enables Increased Future Mobility and Travel Convenience utilizing Community Airports, without Negative Environmental Impact

> Total trip fuel burn, emissions comparable to hub and spoke at current tech
> Advanced technologies dramatically reduce fuel burn, emissions
> Focus on cost will make this convenient travel affordable to majority of public

Light, Clean Airliner and Ultra-Quiet Turboprop could add >1000 airports to Airline Network due to short TOFL and good Community Acceptance

N+3 Goals Achievable with Advanced and Innovative Technologies
> Further optimization of Trajectory/Technologies could yield added improvement

Recommendations for Further Studies
> Develop Key Technology Roadmaps
> Further investigate viability, mechanics, impact of new N+3 Transport Network
> Investigate Fuel Cell Propulsion for larger aircraft, later timeframes
> Investigate impact of lower TRL technologies
Fuel Cell Environment Elements

PreConverger – Used to adjust FLOPS initial GW estimate in response to increases fuselage length and propulsion system weight.

Flops_DesignSpace_Run – Runs FLOPS to size the vehicle with the given fuselage length and propulsion system weight.

PEM_Sizing – Uses the values contained in Table 9 along with newly sized vehicle to estimate the fuel volume, power plant volume, and the power plant weight. Power plant weight is estimated by applying the engine scale factor from the sized vehicle to the corresponding base Propulsion system weight in Table 9. The power plant volume is determined in the same manner. The fuel volume is calculated by multiplying the appropriate baseline fuel volume in Table 9 by the ratio of fuel usage between the baseline vehicle and the sized vehicle containing a fuel cell technology.

Propulsion Weight – This module takes the weight estimated by the PEM_Sizing module and determines the additional weight that must be added to the sized vehicle in order to arrive at a closed solution.

Fuel_Volume_Calcs – This module uses the power plant and fuel volume calculations from the PEM_Sizing module to estimate the increase in fuselage length that is needed to accommodate the fuel cell power plant and fuel.

Fuel_Volume_Converger and Propulsion_Weight_Converger – These feedback the estimated propulsion system weights and corresponding volumes into the FLOPS analysis and resize the vehicle until they arrive at a closed solution. The result is a vehicle with a consistent fuselage length to accommodate the power plants and fuel that has also been sized large enough to accommodate the additional weight associated with the fuel cells.