NASA AERONAUTICS BOOK SERIES

Green Light for Green Flight

NASA's Contributions to Environmentally Responsible Aviation

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The Active Flow Control system was tested on a full-sized tail in the National Full-Scale Aerodynamics Complex (NFAC). (NASA)

CHAPTER 1

Birthing the Environmentally Responsible Aviation Initiative

For over a century, NASA and its predecessor, the National Advisory Committee for Aeronautics (NACA), have undertaken research and technology development that directly contributed to establishing air transportation as a cornerstone of our way of life. These efforts led to advances across the spectrum of study, from a basic understanding of the science of flight to practical engineering achievements that transformed concepts into reality. Although the shape and speed of commercial airliners have not changed significantly since the late-1950s, many aspects of performance—such as range and fuel efficiency, and environmental impacts including noise and emissions—have improved tremendously. By the beginning of the 21st century, however, it became clear that more work was necessary. Heightened sensitivity to, and understanding of, the impact of aviation on the environment and the reduced availability of low-cost energy placed the spotlight directly on aircraft efficiency and reducing environmental impacts. This realization spawned one of NASA's most ambitious aviation projects to date.

NASA researchers believe that in the second quarter of this century, commercial airline companies could save as much as $250 billion thanks to so-called "green" aviation technology pioneered by the Agency and industry partners under NASA's Environmentally Responsible Aviation (ERA) project. This 6-year effort, which concluded in 2015, focused on development of technologies that will help aircraft manufacturers to reduce fuel consumption, exhaust emissions, and aircraft noise by increasing engine efficiency and improving overall aircraft design. The Agency initiated the ERA project to explore, mature, and document the feasibility, benefits, and technical risks of vehicle concepts and enabling airframe and propulsion technologies originally identified in the Agency's Fundamental Aeronautics Program (FAP) and, in particular, the Subsonic Fixed Wing (SFW) project in order to mitigate the impact of aviation on the environment. NASA ultimately contributed more than $400 million to the project, which also received approximately $250 million from industry partners including Boeing and Pratt & Whitney.

The ERA project began in 2009 as part of the NASA Aeronautics Research Mission Directorate's Integrated Systems Research Program. Current-generation aircraft already benefit from NASA investments in aeronautical research of past decades. The development of digital fly-by-wire flight controls, supercritical airfoils, and winglets during the early 1970s and 1980s improved flying safety, controllability, and fuel efficiency, but most important, they became standard features of many modern aircraft. Once fully matured, technologies developed through the ERA project promise to become standard features of future generations of commercial air transports.

Forecasts call for the Nation's air transportation system to undergo significant expansion up to 2035. Unless new technologies are introduced, adverse environmental impacts from increased air operations could curtail the ability of the Next Generation Air Transportation System (NextGen) to accommodate projected growth in demand for air transportation. To offset these impacts, NASA implemented the ERA project to pioneer technologies that might be sufficiently mature to meet mid-term goals—within the first 5 to 10 years—for reducing community noise footprints, fuel burn, and nitrogen oxide (NOx) emissions. Researchers would also attempt to determine the potential benefits of various advanced aircraft configurations beyond the conventional tube-and-wing design that has been standard since the earliest days of commercial air transportation. If successful, NASA scientists believe, such new technologies and configurations could cut airline fuel consumption in half, reduce pollution by as much as 75 percent, and drop noise pollution to nearly one-eighth of current levels.[1]

Simultaneously, the Federal Aviation Administration (FAA) is working to implement significant improvements to the National Airspace System between 2012 and 2025. The advent of NextGen is transforming America's air traffic control system from a land-based radar network to one using Global Positioning System (GPS) satellite technology and replacing radio communications with digital data transfer. FAA officials expect this approach to shorten routes, save time and fuel, reduce traffic delays, increase airport

1. Pia Bergqvist, "NASA's ERA Project Could Save Airlines Billions," *Flying*, January 13, 2016. at *https://www.flyingmag.com/nasas-era-project-could-save-airlines-billions/* (accessed August 21, 2019).

capacity, and permit controllers to monitor and manage aircraft with greater safety margins.[2]

Project Goals and Relevance

For planning purposes, ERA project managers defined first-generation technology (i.e., circa 2015) as N+1, second-generation (that is, circa 2020) as N+2, and third generation (the target date of about 2035) as N+3. Researchers were challenged to mature a variety of promising new technologies and to study vehicle concepts that together might simultaneously meet NASA Subsonic Transport System Level Metrics for noise, emissions, and fuel burn within the N+2 timeframe. To that end, the ERA project challenged researchers to focus on technologies in four research areas. These included innovative aerodynamic flow-control concepts for drag reduction, improvements in composite materials for reducing aircraft structural weight, advanced ultra-high-bypass (UHB) engine designs for improving fuel efficiency and noise reduction, and advanced combustor designs for reducing NOx emissions. Airframe and propulsion technologies sufficiently mature for full-scale development by 2020 could enter into service by 2025.

The Aeronautics Research Mission Directorate's (ARMD) focus on long-term, cutting-edge research that expands the boundaries of aeronautical knowledge for the benefit of the broad aeronautics community directly supported NASA's mission to pioneer scientific discovery, aeronautics research, and space exploration. At the time, both the Agency's aeronautics and space research and technology activities were focused on lightweight integrated structures and environmentally friendly, high-performance propulsion systems. Additionally, such factors as continuing growth in air traffic volume, the vital role of air transportation on the global economy, and concerns about the overall environmental impacts of aviation added focus to the National Aeronautics Research and Development Policy that was established by President George W. Bush in 2006.

To address such concerns in the context of that policy, NASA set aggressive goals for noise reduction, emissions, and energy consumption. Originally developed under the SFW project, these goals were updated jointly with the ERA project to be consistent with the goals of the National Plan for Aeronautics Research and Development, which had also been approved by President Bush in 2007. As a result, ERA project research would have far-reaching effects on

2. U.S. House of Representatives Comm. on Science, Space, and Technology, 112th Cong. (2011) (statement of Peter H. Appel, Administrator, Research and Innovative Technology Administration, U.S. Dept. of Transportation). *https://www.hq.nasa.gov/legislative/hearings/2011%20hearings/9-8-11_APPEL.pdf* (accessed August 21, 2019).

ERA Goals, Objectives and System Level Metrics

	ERA Goal		
	N+1 = 2015** Technology Benefits Relative to a Single Aisle Reference Configuration	**N+2 = 2020**** Technology Benefits Relative to a Large Twin Aisle Reference Configuration	**N+3 = 2025**** Technology Benefits
Noise below Stage 4	–32 dB	–42 dB	–71 dB
LTO NOx Emissions below CAEP 6	–60%	–75%	better than –75%
Performance: Aircraft Fuel Burn	–33%	–50%	better than –70%
Performance: Field Length	–33%	–50%	exploit metro-plex* concepts

** Technology Readiness Level for key technologies = 4–6. ERA undertook a time phased approach, TRL 6 by 2015 for "long-pole" technologies

* Concepts that enable optimal use of runways at multiple airports within the metropolitan area

Goals for the ERA project focused primarily on maturing technologies that could enter service by the year 2020. (NASA)

civil and military aviation with a focus on energy efficiency, national security, aviation safety, and enhanced mobility.[3]

The ERA project and its partners, including the Air Force Research Laboratory and the FAA, commercial aircraft industry, and academia were united in a common goal of reducing the environmental impact of aviation. In large part, this was due to similarities in military and civil transport capability requirements that offered significant opportunities for leveraging and, where possible, cost sharing technology development. In fact, the Department of Defense (DOD), FAA, and the airframe and engine companies were already aggressively pursuing energy efficient, environmentally friendly technologies. The FAA Continuous Lower Energy Emissions and Noise (CLEEN) program, for example, focused on integrated technology demonstrations to facilitate N+1 technology transition into the commercial air fleet. The DOD identified energy efficiency as a near-term strategic initiative to enable effective mobility.

3. Fayette Collier and Gaudy Bezos-O'Connor, "Technology Development Project Plan: Environmentally Responsible Aviation Project," ERA-01-0001, Rev. B, NASA Aeronautics Research Mission Directorate, September 30, 2013, 9–14.

Though industry generally looks to near-, mid-, and far-term horizons like the ERA project, the emphasis is more typically geared toward producing and marketing the next generation of aircraft. The ERA project's focus provided a technology pull well beyond the next generation of vehicle systems.[4]

Management by Technical Challenges

At its formulation, planners organized and managed the ERA Phase 1 portfolio around four major subprojects. The Airframe Technology subproject focused on research into lightweight structures, flight dynamics and control, drag reduction, and noise reduction. The Propulsion Technology subproject included research into improving jet engine combustors, propulsor concepts, and the gas generator core (engine section containing the compressor, combustor, and turbine). The Vehicle Systems Integration (VSI) subproject focused on research into systems analysis, airframe-propulsion integration, propulsion-airframe aero-acoustics, and advanced vehicle concepts. A fourth subproject concerned overall management of the ERA project.

The ERA project defined metrics for measuring technical progress at the technology, airframe and propulsion systems, vehicle, and fleet levels as aligned with the ARMD's framework of managing the NASA aeronautics portfolio by technical challenges and their corresponding progress indicators or key performance parameters. Use of this concept of Management by Technical Challenges enabled ERA managers to provide context and a compelling case for why the project's technical content was needed, what they were trying to achieve, and how they intended to execute the technical plan. Managers defined specific technical challenges and identified key performance parameters for each to quantify progress in technology maturation by establishing performance targets, and by tracking progress as major testing campaigns were completed and system-level assessments conducted. In preparation for Phase 2, the ERA Project mapped airframe, propulsion, and vehicle system integration research activities to five technical focus areas and evaluated the projected individual technology contribution of each.[5]

The Phase 2 Integrated Technology Demonstration (ITD) Portfolio was consistent with ARMD's principles of Management by Technical Challenges.[6] Phase 2 technical focus areas and corresponding technical challenges are:

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4. Ibid.
5. Ibid.
6. Ibid.; Pamela A. Davis, Steven B. Harris, Dawn C. Jegley, and Thomas K. Rigney, "Environmentally Responsible Aviation Project Status of Airframe Technology Subproject Integrated Technology Demonstrations," presented at the AIAA SciTech Conference, Kissimmee, FL, January 5, 2015.

- **TFA1: Innovative Flow Control Concepts for Drag Reduction**
  - **TC1:** Demonstrate drag reduction of 8 percent, contributing to the 50 percent fuel burn reduction goal at the aircraft system level, without significant penalties in weight, noise, or operational complexity.
- **TFA2: Advanced Composites for Weight Reduction**
  - **TC2:** Demonstrate weight reduction of 10 percent compared to composites, contributing to the 50 percent fuel burn reduction goal at the aircraft system level, while enabling lower drag airframes and maintaining safety margins at the aircraft system level.
- **TFA3: Advanced UHB Engine Designs for Specific Fuel Consumption and Noise Reduction**
  - **TC3:** Demonstrate UHB efficiency improvements to achieve 15 percent Thrust Specific Fuel Consumption (TSFC) reduction, contributing to the 50 percent fuel burn reduction goal at the aircraft system level, while reducing engine system noise and minimizing weight, drag, NOx, and integration penalties at the aircraft system level.
- **TFA4: Advanced Combustor Designs for Oxides of Nitrogen Reduction**
  - **TC4:** Demonstrate reductions of landing and takeoff NOx emissions by 75 percent relative to the stringent standards established at the International Civil Aviation Organization's (ICAO) Committee on Aviation Environmental Protection, Sixth Meeting (CAEP6), held in Montreal, Canada, in 2004, and reduce cruise NOx by 70 percent while minimizing the impact on fuel burn at the aircraft system level, without penalties in stability and durability of the engine system.
- **TFA5: Airframe and Engine Integration Concepts for Community Noise and Fuel Burn Reduction**
  - **TC5:** Demonstrate reduced component noise signatures leading to an Effective Perceived Noise in decibels (EPNdB) decrease by 42 EPNdB to Stage 4 noise margin for the aircraft system while minimizing weight and integration penalties to enable 50 percent fuel burn reduction at the aircraft system level.[7]

7. Collier and Bezos-O'Connor, "Technology Development Project Plan," 14–17.

ERA Project — Key Technical Focus Areas and Technical Challenges

1. ***Innovative Flow Control Concepts*** for Drag Reduction

   TC: Reduce fuel burn by 6 percent while minimizing maintenance issues

2. ***Advanced Composites*** for Weight Reduction

   TC: Reduce aircraft weight by 10 percent over SOA composites while maintaining safety margins at the aircraft system level

3. ***Advanced UHB Engine Designs*** for Specific Fuel Consumption and Noise Reduction

   TC: Reduce fuel burn by 20 percent while reducing engine system noise and while minimizing weight, drag and integration penalties at AC system level

4. ***Advanced Combustor Designs*** for Landing Takeoff Oxides of Nitrogen Reduction

   TC: Reduce L TO NOX by –75 percent while reducing fuel burn by 50 percent at the aircraft system level

5. ***Airframe and Engine Integration Concepts*** for Community Noise Reduction

   TC: Reduce component noise signatures while minimizing weight and integration penalties at aircraft system level to achieve 42 EPNdB margin to Stage 4

After selecting five key technical focus areas, ERA planners designated specific technical challenges to drive progress forward. (NASA)

ERA Formulation and Planning

In the Formulation Phase of the project (dubbed Phase 0), a planning team used prior research results and inputs from stakeholders across the aviation community, to develop an overarching plan along with an effective approach to achieve the project's goals. To begin, researchers considered how to best exploit some of the concepts and technologies already under investigation through NASA's SFW project. Each of these technologies was evaluated to determine its respective Technology Readiness Level (TRL), a measurement used to assess maturity.

NASA uses nine Technology Readiness Level rating levels. The lowest is TRL-1, designated when scientific research is just beginning, and results are being translated into future research and development. This represents a transition from basic science to applied research and explores the essential characteristics of systems and architectures. A rating of TRL-2 is assessed once the basic principles have been studied and it is clear that initial findings have practical applications. Technology at the TRL-2 level is still considered very speculative, as there is as yet little or no experimental proof of concept for the technology. Once active research and design efforts begin, a technology may be elevated to TRL-3. This generally requires both analytical and laboratory studies to determine whether a technology is viable and ready to be advanced further through the development process. During TRL-3, researchers typically demonstrate technical feasibility using a simple proof-of-concept model. Next, the new technology is advanced to TRL-4. During this phase, multiple components or subsystems are integrated and tested in a laboratory environment. Research under TRL-5 involves more rigorous testing and thorough validation under environmental conditions that are as realistic as possible. Once this has been completed, the technology is ready to advance to TRL-6 in the form of a fully functional prototype or representational model. Engineering feasibility is demonstrated in a suitably relevant end-to-end environment (ground, air, or space). By the time the technology reaches TRL-7, it is ready for a system prototyping demonstration in an operational environment. At this point, a working model or prototype should be at or near the scale of the proposed operational system, with most functions available for demonstration and testing. TRL-8 technology has been tested and "flight qualified," and is ready for implementation. Finally, once a technology has been "flight proven" through successful operational experience, it can be elevated to TRL-9.[8]

NASA's Aeronautics Research Mission Directorate (ARMD) is tasked with advancing U.S. technological leadership in aeronautics through partnership with industry, academia, and other Government agencies that conduct aeronautics-related research. This includes addressing the fundamental research needs of NextGen in partnership with member agencies of the NASA Joint Planning and Development Office. In 2008, members of the NASA Advisory Committee (NAC) called for ARMD to plan and develop candidate systems-level research projects consistent with the Agency's National Policy and Plan and to leverage NASA's unique expertise and competencies, to advance

8. NASA, "Definition of Technology Readiness levels," undated fact sheet *https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html* (accessed August 21, 2019); John C. Mankins, Advanced Concepts Office, Office of Space Access and Technology, NASA, "Technology Readiness Levels, a White Paper," April 6, 1995. *http://www.artemisinnovation.com/images/TRL_White_Paper_2004-Edited.pdf* (accessed August 21, 2019).

Definition of Technological Readiness Levels

TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or flight)
TRL 7	System prototype demonstration in a ground or flight environment
TRL 8	Actual system completed and "flight qualified" through text and demonstration (ground or flight)
TRL 9	Actual system "flight proven" through successful mission operations

Technology readiness was rated on a scale of nine levels, from lowest (TRL-1) to highest (TRL-9). (R.P. Hallion)

state-of-the-art capabilities in key disciplines and facilitate transition of results to the aviation community.[9]

In support of this goal, NASA created the Integrated Systems Research Program (ISRP) to conduct research at an integrated system level on promising concepts and technologies and to explore, assess, and demonstrate the benefits in a relevant environment. All research in this program was coordinated with ongoing long-term, foundational research, as well as with efforts being undertaken by other Government agencies such as the FAA. In order to meet the projected growth in demand for air transportation, the ISRP was designed to focus primarily on maturing and integrating major vehicle system and subsystem technologies for accelerated transition to practical application. However, the greatest foreseeable obstacles to increasing the number of flight operations at many of the Nation's largest airports were environmental concerns over noise and emissions that would necessarily limit the growth capacity of those airports, and therefore limit the capacity of the entire air transportation system. Based on these parameters, the U.S. National Research Council (NRC); Congress; the Executive Office of the President; and the NAC issued several mandates, directives, and recommendations to NASA. Some of these

9. Dr. Jaiwon Shin, "Aeronautics Research Mission Directorate System-Level Research," presented at the Meeting of Experts, Aeronautics and Space Engineering Board Meeting of the National Research Council, Washington, DC, May 14, 2009.

cited the need for NASA to develop a "green aircraft initiative" and to advance the development of technologies and operational procedures to decrease the significant environmental impacts from aviation.[10] This set the stage for creating the ERA project.

Langley Research Center Project Scientist Dr. Richard A. Wahls. (NASA)

About 2 weeks after the 2008 presidential election, ARMD associate administrator Dr. Jaiwon Shin called SFW project scientist Dr. Richard A. Wahls at Langley Research Center (LaRC) to discuss preliminary plans for a two-pronged project to advance an environmentally responsible approach to aircraft design and operations. One team would focus on a segment, dubbed ERA-Vehicle (ERA-V), that would explore and assess new aircraft design concepts and enabling technologies through system-level experimentation to simultaneously reduce total fuel burn, carbon emissions, and airport area noise. The other, ERA-Operations (ERA-O), would investigate air traffic control system technologies that could significantly improve safety, capacity, and efficiency on runways and in the Nation's skies, as envisioned under NextGen, while simultaneously providing environmentally friendly procedures for reducing fuel burn, emissions, and noise.[11] Ultimately, the ERA-V planning activity became the first and only project in the new ISRP, while selected activities from the ERA-O planning team were integrated into a revamped Airspace Systems Program.[12]

Wahls was assigned to serve as activity planning lead for the FAP, reporting directly to the FAP director, Dr. Ajay Misra. He pulled together approximately 30 people in multiple disciplines from all four of the NASA Aeronautics Centers to formulate the overall ERA concept. With a new administration coming into the White House, this challenge was particularly daunting. "At that time," he recalled, "NASA was dealing with the presidential transition

10. Aeronautics Research Mission Directorate, program overviews and descriptions, *https://www.nasa.gov/pdf/428150main_Aeronautics_Research.pdf*, circa 2008 (accessed August 3, 2016).
11. Dr. Richard A. Wahls interview with the author, August 4, 2016.
12. Thomas B. Irvine, "Research and Technology Project Formulation Authorization Document: Environmentally Responsible Aviation (ERA) Project," Integrated Systems Research Program, NASA Aeronautics Research Mission Directorate, June 9, 2009, 2.

team and trying to figure out what the budget would be, and whether [ERA] would even make it into the [new NASA] budget."[13]

Only a handful of people within NASA were initially aware of what was being planned. Information regarding the fledgling ERA project was otherwise embargoed from being disclosed to industry or media representatives. "We weren't allowed to talk about it because it was still in the budgeting process," said Wahls. "Basically, from November 2008 through May 2009, there were people inside NASA that knew that there was planning going on, but nobody outside knew what was going on."[14]

Eventually, the effort grew to the point where so many people were involved that others began to suspect what was afoot. "We were using all the knowledge of all the partnerships we already had, and of all the technologies that were available at the time, to formulate a construct that we were pretty sure people would buy into, and they did," Wahls remembered, "It was a pretty interesting time."[15]

Planning Guidance

According to official planning guidance, as of November 2008, ARMD leadership still envisioned two distinct system-level activities, the ERA-V and ERA-O efforts, which would be distinct yet coupled. From a technical approach perspective, development of a multifunctional testbed vehicle would serve as a centralized airborne test facility for systems integration research. The proposed experimental vehicle testbed, or XVT, was expected to provide significant collaborative opportunities between the ERA-V and ERA-O activities. It soon became apparent, however, that the anticipated ERA budget would not support acquisition of an XVT. Nevertheless, the idea endured. Early ERA-related studies included analysis to inform project leaders as to the potential scope, cost, and benefits to be derived from such an asset, thereby providing a basis for future decisions.[16]

Throughout the initial formulation, the technical scope of ERA remained focused primarily on N+2 concepts at technologies at the airframe, propulsion, and vehicle systems level. From a schedule perspective, planners held to a nominal 6-year timeframe with definitive start and end points. The ERA project notionally had two 3-year phases, with Phase 1 setting the stage for Phase 2. Originally, the second phase emphasized construction and utilization

13. Wahls interview.
14. Ibid.
15. Ibid.
16. Irvine, "Research and Technology Project Formulation Authorization Document: Environmentally Responsible Aviation (ERA) Project," 2.

of the multifunctional airborne testbed for research and development. Without the XVT, the two-phase approach remained but with some necessary adjustments and overlap.[17]

From a budget perspective, the original ERA planning guidance covered 6 years beginning in FY 2009 and totaling $451.2 million. This included $215.6 million for design and fabrication of the XVT and associated ERA experiments. Original estimates were based on an annual budget ranging from $35 million in FY 2009 to a peak of $133 million in FY 2013. However, based on the President's FY 2010 budget, the ERA project had a much flatter level in the $60 to $65 million range, and totaling at about $318.8 over 5 years.[18]

According to Richard Wahls, the overall shape and structure of ERA depended entirely on the availability of funding. "To put it in context," he explained, "back in the 1990s with the Advanced Subsonic Technology and High Speed Research programs, the NASA aeronautics budget was up in the low billion-dollar range, and when those projects ended, the budget started a steady decrease through the late 1990s until it was only at the $450 million level."[19]

Wahls noted that prior to 2007, there had not been a sustained increase in the NASA aeronautics budget in roughly 10 years. Around that time, Congress added about $30 to $40 million, but the additional money was of the sort that had to be spent within the fiscal year for which it was allocated, making it nearly impossible to develop a long-range plan. "So, when President Obama's 5-year budget was announced, aeronautics was increased to something like $510 million, and that was the first sustained increase in NASA aeronautics in over a decade."[20]

Meeting of Experts

After the president's new budget became public, ERA planners arranged for a meeting of experts from the Aeronautics and Space Engineering Board (ASEB), National Research Council (NRC) to gather feedback on the project's technical feasibility. Ilan Kroo, a distinguished professor of aeronautics and astronautics at Stanford University and a member of the NAC Aeronautics Committee, chaired the 2-day meeting, which began on May 14, 2009, in National Harbor, Maryland. This event was open to the general public.

Dr. Jaiwon Shin led off with an overview of ARMD plans and goals for system-level research in environmental impact mitigation. John A. Cavolowsky, acting director of the Airspace Systems Program (ASP), and NextGen

17. Ibid.
18. Ibid.
19. Wahls interview.
20. Ibid.

integration manager Barry Sullivan gave presentations on technologies for NextGen systems analysis, integration, and evaluation. Anthony Strazisar, acting director of FAP, presented a broad overview of the proposed ERA project followed by a much more in-depth technical description by Wahls. The ERA Planning Team Lead later described the pressure he felt as he prepared to make his presentation. "The night before, I remember cramming for my 2-hour presentation like it was my Ph.D. dissertation," he recalled. "There was so much riding on it, and if those experts had said, 'You're way off base, this is garbage,' ERA would probably not have happened."[21] Wahls' presentation, entitled "Environmentally Responsible Aviation Technical Overview," represented not only his own viewpoint, but the contributions of a multicenter ERA planning team including Dr. Fayette S. "Fay" Collier Jr., Dr. Rubén Del Rosario, Dennis Huff, Laurence "Larry" Leavitt, Patrick "Pat" Stoliker, and Anthony "Tony" Strazisar. So incisive was this survey, and so positive was its reception, that it served as the foundational document underpinning the entire ERA effort and, for that reason, is included as Appendix 1 of this work.

Dr. Jaiwon Shin, NASA Associate Administrator for the Aeronautics Research Mission Directorate. (NASA)

The following morning was devoted to breakout sessions, discussions between presenters and experts, and comments from general public attendees. According to Wahls, there was a great deal of useful feedback that coupled with budgetary allocations helped drive the final planning stages. Early on, there had been some discussion of building a large-scale experimental demonstrator aircraft, or X-plane. Such an endeavor would have added to the complexity, and therefore the overall cost, of the ERA project. Unfortunately, funding on that scale was not available, so planners opted to focus on a number of critical technologies in the first phase of the project, and then select the most promising ones for more detailed study in the second phase. As Wahls put it, "We were looking into whether we could do an X-plane, and then the projected budget went down and ERA ended up becoming a Phase 1 portfolio

21. Ibid.

of a number of activities, and then a down-select to a Phase 2 that focused on certain technologies."[22]

Phase 1 focused on studies involving:

- Stitched composite technology for weight reduction and damage tolerance,
- Laminar flow technology for drag reduction,
- Flight dynamics and control technology for enabling alternate aircraft configurations,
- Engine combustor technology for low emissions,
- Propulsion technology and integration for improved specific fuel consumption (SFC) and noise reduction, and
- Propulsion shielding for noise reduction.

These concepts and technologies would be explored and assessed with respect to feasibility, potential benefits, interdependencies, and risks. Researchers were tasked to refine existing concepts and develop new ideas, and to uncover unexpected multidisciplinary interactions. Based on the results, they would then prioritize the various technologies for further study. Phase 1 results, system studies, and stakeholder input would determine which technologies were most promising, or best suited to meeting ERA project goals. Eight of these were eventually selected for more detailed exploration as Phase 2 integrated technology demonstrations, which began in FY 2013 and continued throughout the remainder of the ERA project.[23]

Having secured validation of the basic ERA concept, it was time to formalize the project's organization and structure. Management personnel were drawn from the SFW project through which a variety of advanced aircraft concepts including a hybrid wing-body, truss-braced wings, and others was already being investigated. Dr. Fay Collier was SFW principal investigator and Dr. Rubén Del Rosario served as project manager. As project scientist, Wahls primarily acted as a senior technical advisor. "I'm pretty sure that Fay kind of endorsed me to peel away from SFW to lead the planning for ERA," he said.[24]

Collier assumed leadership of the ERA effort immediately following completion of the meeting of experts. His team formulated detailed project life cycle events to be executed over the remainder of FY 2009 and Collier conducted

22. Ibid.
23. Dr. Richard A. Wahls, "Environmentally Responsible Aviation Technical Overview," presented at National Research Council Aeronautics and Space Engineering Board meeting, National Harbor, MD, May 14, 2009, *https://www.hq.nasa.gov/office/aero/pdf/2009_05_14_nrc_rich_wahls_508.pdf* (accessed August 3, 2016).
24. Wahls interview.

Dr. Fayette S. "Fay" Collier. (NASA)

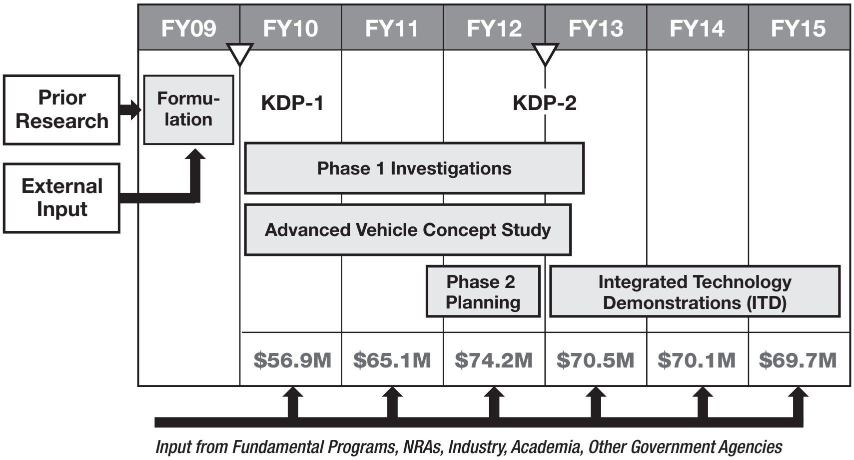
major planning reviews with NASA senior leadership. These included an acquisition strategy meeting with associate administrator Christopher J. Scolese in August 2009 and a baseline review the following month, during which Dr. Shin granted the authority to proceed with Phase 1 starting October 1.

After ERA went public and Collier moved over from SFW to become the ERA project manager, Del Rosario was placed in charge of SFW. It was also a busy time for Wahls. "For the next 6 months, I served as technical advisor to both of them. We then worked through the rest of the summer to formalize the ERA program so that we could start in October [the beginning of FY 2010]. Around November or December, they had mercy on me and let me choose which project I would work with, to do one or the other."[25]

At that point, Anthony E. "Tony" Washburn became chief technologist for ERA and Wahls went back to serving full time as chief technical advisor and strategist for SFW. "It was a real hard decision for me because in my heart and soul I had been in all the ERA planning, but I was equally invested in SFW," said Wahls. "I decided to go the SFW route because I felt that I could better complement Rubén."[26]

As the structure of the new project also began to come into focus, budget realities affected plans to include air traffic management operations research as part of ERA along with the vehicle-related efforts. According to Wahls, "Their budget was always going to be a little bit lower than ours, and around about the middle of April 2009 we were told that we didn't have enough money to do both of those things." So, while ERA went on to focus on vehicle technologies, the ASP effort spun off on its own using SFW funds. "So, there was this dynamic of one project that was kind of losing money, but the money for subsonic vehicles was going up because ERA was bigger than what was being pulled out of the Subsonic Fixed Wing project, so it was a win all the way around," Wahls explained. Around that time, Congress passed the American

25. Wahls interview.
26. Ibid.



ERA Project Flow with key decision points at the beginning of Phase 1 and Phase 2. (R.P. Hallion)

Recovery and Reinvestment Act of 2009. "It was a stimulus package that came right in the middle of February when we were planning everything, and we were looking into how that might feed into [ERA]," said Wahls. "It was a different color of money, and there were certain amounts that could be applied to get things started."[27]

Wahls noted that of all the many challenges the ERA faced at its onset, the most significant—and ultimately the most significant early accomplishment—was securing funds for the project in the President's budget submission and winning the approval of the panel of experts. Additionally, the unusually rigid two-phase project structure with set starting and ending points was a real test for NASA. As Wahls explained, "From the beginning, Jaiwon had said that this was not going to be an enduring project; we were going to start it and… stop it, and… show that we can complete a project and hold a schedule." Normally, he added, the project managers would designate a specific set of milestones spanning 5 or 6 years, and that would constitute the project plan. "But we made the case that we wanted to have this decision point [at the end of Phase 1] and then down-select technologies for Phase 2," he said. "That was a whole programmatic challenge in itself that kind of set the stage for some of the other projects that followed. From there, a lot of what happened in Phase 1 was involved with technologies that were ready to graduate to higher technology readiness levels. So we picked a suite of things that we thought were ready, and that's how the first phase of ERA started."[28]

27. Ibid.
28. Ibid.

ERA Phase 1 (FY 2010–FY 2012)

Phase 1 spanned the first 3 years of implementation and served two primary purposes. First, during this phase a significant NASA Research Announcement (NRA) was defined with the primary purpose to conduct N+2 vehicle system studies, develop enabling technology roadmaps, and scope key enabling system-level experiments, ranging from those focused on integrated airframe systems and integrated propulsion systems to the development of appropriate experimental vehicle testbed, or X-plane, concepts. The scope of Phase 1 included trades on technology suites, scale, cost and schedule. This NRA also enabled solicitation of ready-to go, system-level experiments that could be initiated in short order.

Second, several promising technology solutions were matured from ARMD foundational projects. In general, these larger-scale experiments were selected from the existing ARMD technology portfolio because they provided both a significant system benefit and were already at a TRL level that warranted conducting a large-scale demonstration to validate the technology.[29]

One of the most promising concepts for simultaneously meeting all of the subsonic transport system level metrics was the hybrid wing-body (HWB) configuration, also known as the blended wing body (BWB). Proving the viability of the HWB concept was at the forefront of the ERA project and was dependent on two "long pole" items. First was the requirement to demonstrate low-speed flight controls and handling characteristics. Second was successful demonstration of an advanced composite manufacturing technique called Pultruded Rod Stitched Unitized Structure (PRSEUS). Additionally, researchers hypothesized that the HWB would be the best configuration for achieving the very difficult goal of simultaneously meeting fuel burn and noise goals. The emergence of advanced open rotor propulsion systems promised increased propulsive efficiency and reduced noise. Research ultimately demonstrated that combining the HWB airframe with open rotor propulsion came very close to meeting all ERA goals.

During Phase 1, engineers and scientists assessed dozens of environmentally friendly aircraft technologies. These included:

- Advanced vehicle design studies,
- Open rotor technology for reduced engine noise,
- Non-stick coatings for low-drag wing designs intended to achieve drag reduction via laminar flow,

29. Fayette S. Collier, "Technology Development Project Plan: Environmentally Responsible Aviation Project," NASA Integrated Systems Research Program, October 21, 2009, 11.

- Testing advanced fabric composite manufacturing techniques,
- Reducing mission fuel burn and community noise (including airframe noise and propulsion noise from the fan, core, and jet of gas turbine engines, and minimizing propulsion-airframe aeroacoustics via tailored airframe-propulsion integrated design and shielding),
- Integration of advanced engines, cowlings, nacelles, and pylons for zero installation drag,
- Advanced engine combustor development,
- Ultra-quiet HWB wind tunnel demonstrations and systems analysis, and
- Test flights of a subscale remotely piloted HWB research vehicle.

Many of these concepts showed great potential for reducing aircraft noise and carbon footprints. By the end of Phase 1, ERA project teams were ready to take the valuable lessons learned over the first 3 years and begin implementing the most promising technologies during Phase 2.

Key enablers for beginning Phase 1 included stable funding coupled with a number of promising concepts and technologies that had strong potential for further system-level maturation. With the endorsement of the panel of experts, the NAC called upon ARMD leadership to plan and develop a number of candidate research projects consistent with the National Aeronautics Policy and Plan and leverage NASA's unique expertise and competencies. The primary goal was to advance state-of-the-art capabilities in several key disciplines and facilitate transition of results to the aerospace community. At the time when ERA was formulated, there was strong support from industry for new system-level research for improving aircraft efficiency.[30]

Advancing the State of the Art

The ERA Phase 1 research portfolio focused on exploring, assessing, and demonstrating the benefits of promising concepts and technologies, and expanding upon previous work. Phase 1 efforts took full advantage of previous groundwork laid at the foundational research level and moved it from a TRL of at least 4 or 5 (component and/or breadboard validation in a laboratory or relevant environment, respectively) to a desired TRL of at least 6 (system prototype demonstration in an operational environment). The ERA planning team began by identifying technologies already investigated in ARMD programs that had

30. Craig L. Nickol and William J. Haller, "Assessment of the Performance Potential of Advanced Subsonic Transport Concepts for NASA's Environmentally Responsible Aviation Project," AIAA-2016-1030, presented at American Institute of Aeronautics and Astronautics SciTech, 54th AIAA Aerospace Sciences Meeting, San Diego, CA, January 6, 2016, 1.

the potential to reduce subsonic transport emissions, fuel burn and noise, yet met the minimum TRL requirements.[31]

Technologies under consideration had to meet several criteria in order to be selected for research. First, a candidate technology had to have attained sufficient maturity in the foundational research program that it merited more in-depth evaluation at an integrated system level. Second, systems analysis had to indicate that the technology in question had the maximum potential for contributing to the simultaneous attainment of all ERA technical goals. Finally, any research had to be appropriate for NASA to conduct and could not duplicate that being done by other Government agencies.[32]

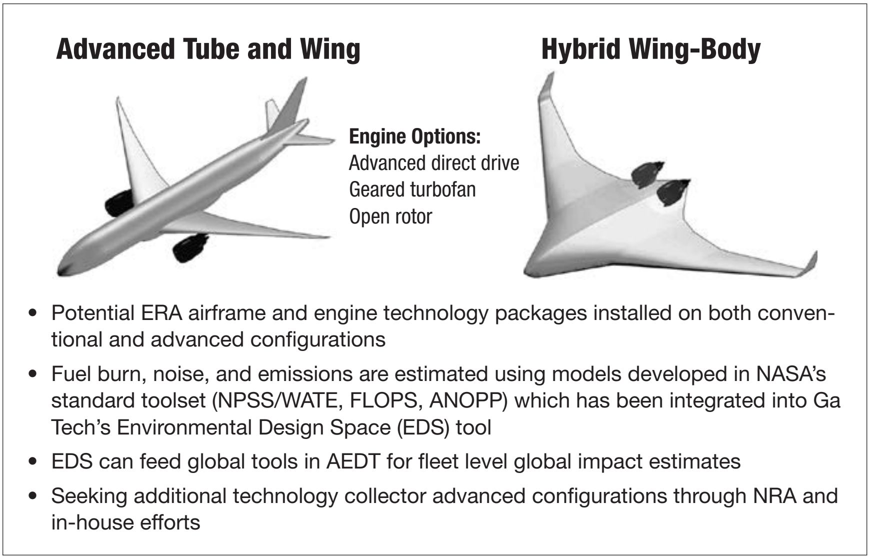
For the most part, ERA efforts focused on the N+2 technologies that had the potential to mature to a TRL level of 4–6 by 2020. By August 2010, researchers had assembled an ERA N+2 technology database analysis examining the interaction of 65 different technologies, including 19 related to airframe design and manufacturing processes, and 46 related to engine performance. According to Craig Nickol, ERA vehicle systems integration element lead, researchers took into account current and projected TRLs and studied the interactions of various technologies using a compatibility matrix. Analysts then estimated projected benefits and impacts on fuel burn, noise, and emissions using models developed with NASA's Aircraft Noise Prediction Program (ANOPP), Flight Optimization and Performance Sizing (FLOPS) tool, and Numerical Propulsion Simulation System/Weight Analysis of Turbine Engines (NPSS/WATE) modeling programs. Under contract to NASA, researchers at Georgia Institute of Technology integrated this software toolset into their own computer-based Environmental Design Space (EDS) tool to make deterministic and probabilistic assessments of the ERA technology package most likely to result in the best overall performance.[33]

For baseline purposes, researchers used the Boeing 777 as an ideal example of an advanced, long-range, large twin-aisle (LTA) tube-and-wing (TAW) airliner configuration. The optimal technology package for this class of aircraft included a combination of 14 new airframe technologies and 25 engine technologies. Many of these came directly from the Phase 1 portfolio. Among the new airframe advances were stitched composite materials, laminar flow control (LFC) airfoils and nacelles, active flow control rudder, continuous mold-line

31. Collier and Bezos-O'Connor, "Technology Development Project Plan," 11.

32. Nickol and Haller, "Assessment of the Performance Potential of Advanced Subsonic Transport Concepts," 1–2.

33. Nickol and Haller, "Environmentally Responsible Aviation (ERA) Project: Assessing Progress toward Simultaneous Reductions in Noise, Fuel Burn and NOx," presented at the 49th AIAA Aerospace Sciences Meeting, Orlando, FL, January 4, 2011, passim.



NASA planners employed Notional Advanced Tube-and-Wing and HWB concepts as initial technology baseline "collectors" for evaluating ERA engine and airframe combinations, and for modeling emissions, noise, and fuel burn. (NASA)

(CML) link flaps, and aerodynamic landing gear fairings. New engine technologies included active compressor/turbine flow control, active film cooling, highly loaded compressor/turbine systems, ceramic matrix composites (CMC), metal-foam liners and engine vanes, and advanced combustors. Analysts also studied noise and fuel-burn tradeoffs and compared optimized performance points to goals established in the ERA project plan.[34]

Individually, each of these goals presented a significant challenge. Because ARMD leadership had decreed that all goals be met simultaneously, it was much more difficult to make tradeoffs or compromises with regard to each parameter. The bar had been set intentionally high because NASA analysts determined that without major improvements, environmental and related cost concerns would significantly impede the growth of future civil and military air transport operations. Rising oil prices alone dictated a necessity for improving fuel economy. In 2008, when aviation fuel cost approximately $3 per gallon, U.S. commercial carriers alone spent $59 billion. At the same time, there was an increasing focus on the environmental effects of aircraft exhaust emissions. Annual fuel consumption for Defense Department purposes was roughly 4.6 billion gallons, pumping as much as 250 million tons of carbon dioxide (CO_2) into the atmosphere. Additionally, population growth in areas surrounding

34. Ibid.

existing airports and increased demand for air transportation heralded the need to reduce aircraft noise, which would also act as a restraining factor on growth of the National Airspace System (NAS).[35]

The ERA initiative was well timed to leverage these environmental and economic concerns and accelerate new commercial engine and airframe developments. Project researchers anticipated that new technologies would yield a high payoff for a multitude of commonly used commercial platforms such as the Boeing 737 and 777 series, Airbus A320, and the Canadair Regional Jet (CRJ) family of aircraft. Moreover, the ERA technology portfolio would have a significant impact on the wide-body replacement market regardless of whether new aircraft were designed using conventional tube-and-wing or more advanced configurations. A year into Phase 1, project manager Fay Collier expressed confidence in meeting the expected challenges. "People are asking how we are going to do this," he said. "We've done some experiments that lead us to believe that although this is difficult, we think it is achievable."[36]

Phase 1 Research Portfolio

The ERA project's Phase 1 technology investigations were approved for implementation at the first key decision point, known as the KDP-1 Formulation Review. At this time, the Phase 1 research portfolio was organized and managed around the three major technical subprojects: Airframe Technology, Propulsion Technology, and Vehicle Systems Integration. The technology portfolio within each subproject was divided into the following research elements:

- Airframe Technology Subproject
  - Lightweight Integrated Structures Element
  - Flight Dynamics and Control Element
  - Drag Reduction Element
  - Noise Reduction Element
- Propulsion Technology Subproject
  - Combustor Technology Element
  - Propulsor Technology Element
  - Core Technology Element
- Vehicle Systems Integration Subproject
  - Systems Analysis Element

35. Guy Norris, "'Green' Airliner Targets Achievable by 2025, Says NASA," *Aviation Week & Space Technology*, *http://aviationweek.com/awin/green-airliner-targets-achievable-2025-says-nasa*, April 18, 2011 (accessed July 21, 2016).
36. Ibid.

Concept Modeling Summary

	Regional Jet	Single Aisle	Small Twin Aisle	Large Twin Aisle	Very Large
Baseline Vehicle	**CRJ900**	**737-800**	**767-300ER**	**777-200ER**	**747-400**
Engine	CF34-8	CFM56-7B27	CF6-80	GE90-94B	PW4056
Passengers	86	174	210	301	416
2025 Tube+Wing					
Fuel Burn	–42.0%	–40.8%	–47.3%	–44.3%	–41.0%
Noise (dB cum below Stage 4)	30.5	24.0	27.1	27.3	22.6
Emissions	–75.0%	–75.0%	–75.0%	–75.0%	–75.0%
2025 HWB					
Fuel Burn	N/A	N/A	TBD	–50.2%	TBD
Noise (dB cum below Stage 4)	N/A	N/A	TBD	43.6	TBD
Emissions	N/A	N/A	TBD	–75.0%	TBD

This ERA concept modeling summary compares late 1990s baseline commercial transport aircraft to proposed future concepts. (NASA)

- Propulsion Airframe Integration Element
- Propulsion Airframe Aero-Acoustics Element
- Advanced Vehicle Concepts Element

Airframe Technology Subproject

The Airframe Technology subproject was designed to conduct system level experiments on airframe technologies, particularly with a view toward addressing the fuel burn and noise reduction goals. The Phase 1 airframe technology portfolio was built upon technologies that would take full advantage of previous groundwork laid at the foundational research level, and in Phase 1 move from a TRL of 3, in most cases, to at least a TRL of 4 (component and/or breadboard validation in a laboratory).[37]

Planners selected numerous key airframe technologies for Phase 1 investigations based on projected vehicle-level benefits. The following technologies were of paramount interest:

37. Collier and Bezos-O'Connor, "Technology Development Project Plan," 10–17.

- Lightweight Integrated Structures
  - PRSEUS composite technology system that includes
    - Stitching
    - Resin infusion
    - Unitized structures
    - Damage tolerant structures
    - Post-buckled structures
- Flight Dynamics and Control
  - Stability and control characteristics of low-noise HWB vehicle configurations
- Drag Reduction
  - Active flow control rudder
  - Natural laminar flow ground test capability
  - Hybrid laminar flow control via discrete roughness elements
  - Adaptive Compliant Trailing Edge (ACTE) flaps
- Noise Reduction
  - Flap edge and landing gear fairings noise reduction concepts

Lightweight Integrated Structures Element

The Lightweight Integrated Structures investigation focused on a new structural concept called PRSEUS. This lightweight, damage-tolerant, stitched composite system offered benefits with regard to manufacturing a wide variety of aircraft components from wings to cargo doors, but primarily served as an enabling technology for non-circular pressurized fuselage assemblies. Aircraft designers considered the ability to build a non-circular pressurized fuselage as key to enable vehicle concepts with a reduced overall wetted area (surface area in direct contact with external airflow). Reductions in wetted area directly addressed the fuel-burn goal through reduced overall skin friction drag.

The PRSEUS concept introduced both new materials and manufacturing processing methods in a structural concept with high potential for both weight reduction (10.3 percent compared to advanced composite sandwich structures analytically applied to a non-circular center body shell) and manufacturing cost savings (based on experience with a similar but non-primary structural application). However, to be a viable approach, these new materials and processes needed to be validated.

In Phase 1, researchers adopted a building block approach to analysis and testing, from coupons to structural elements and subcomponents. These efforts culminated during Phase 2 in full-scale PRSEUS testing involving a full test matrix of specimens with large cutouts, impact damage, and discrete-source damage subjected to representative loadings. Data requirements included information on repair methodology, material durability, combined load conditions, and long-term structural performance, as well as safety margins, design methodology, inspection techniques, and understanding of load paths. Additionally in Phase 1, researchers investigated PRSEUS acoustic transmission characteristics to determine cabin noise impacts. Investigators also identified structural design strategies for minimizing the coupling of cabin and engine noise.[38]

Flight Dynamics and Control Element

During Phase 1, NASA, Boeing and the Air Force Research Laboratory (AFRL) collaborated on flight-testing an 8.5-percent-scale, remotely piloted aircraft of a potential, full-scale HWB-type aircraft called the X-48. The plane was equipped with a computerized "fly-by-wire" system and flown remotely from a ground control station. Flight-testing consisted of a multi-step research program aimed at ascertaining the low-speed handling and flying qualities of this type of aircraft. Researchers experimented with two leading-edge configurations, with wing slats either extended or retracted. Flying with the slats extended allowed the plane to fly slower with greater lift, representative of takeoff and landing conditions. The high-speed, slats-retracted, configuration represented the aircraft in cruise mode. Additionally, two different stabilizer and engine arrangements were evaluated.[39]

Designed by Boeing and built by Cranfield Aerospace, the initial X-48B configuration was flown in partnership with NASA at Armstrong Flight Research Center (AFRC) beginning in July 2007. The aircraft weighed about 500 pounds and spanned just over 20 feet. Initially powered by three 52-pound-thrust JetCat P200 turbojets, the demonstrator was capable of a top speed of 140 miles per hour and a maximum altitude of around 10,000 feet. Flight-testing through the summer of 2010 focused on defining the low-speed, low-altitude flight characteristics of the HWB configuration, including engine-out control, stall characteristics, and handling qualities.

Following its 92nd flight, the aircraft underwent extensive modification to the X-48C configuration. External changes entailed relocating wingtip winglets inboard next to the engines, effectively turning them into a widely spaced twin V-tail. The three noisy turbojets were replaced with two quieter 89-pound-thrust JetCat SPT15 ducted fan engines. The center-body's aft deck was extended approximately 2 feet and the engines positioned between the tails to provide further sound baffling.

38. Ibid.

39. Ibid.

The X-48C configuration, more highly refined than the B configuration, repeated many of the same test points as the previous X-48B. The major differences between the two configurations were optimized to reduce the predicted noise footprint at full scale. Flight data were obtained on both configurations at the same flight conditions to determine which one provided better low-speed, high angle-of-attack handling characteristics.[40]

Drag Reduction Element

For conventional commercial aircraft, the two main contributors to overall drag are skin friction drag and lift-induced drag. In ERA Phase 1, researchers focused on technologies related to the reduction of the overall viscous drag, specifically to reductions in wetted area or skin friction. Viscous drag contributes on the order of 50 percent of the total drag for a typical transonic transport vehicle and is highly dependent on the wetted area of the aircraft, the boundary layer state, and flight conditions. In particular, for a given wetted area, a turbulent boundary layer causes significantly more skin friction drag than does a laminar boundary layer. Laminar flow is one of the key aerodynamic technologies with the potential to provide large reductions in fuel burn (roughly 5 to 15 percent, depending on configuration). To achieve significant total projected fuel burn reductions on the order of 40 percent required by the N+2 goals, researchers' projections indicated that laminar flow needed to be obtained over 60 percent of the chord on the upper wing surface, simultaneously with 50 percent of the chord on the lower wing surface.[41]

From an aerodynamic perspective, multiple approaches to achieve laminar flow are available. In Phase 1, the ERA project focused, in part, on validating the NASA LaRC National Transonic Facility (NTF) as a viable ground-test facility for natural laminar flow (NLF) testing. Researchers also investigated the possibility of achieving hybrid laminar flow control by applying discrete roughness elements (DREs), small micro-bumps spaced at specific intervals along a swept leading edge of an airfoil. The DRE investigation in Phase 1 enabled a better understanding of the application of DREs at moderate Reynolds numbers (the ratio of inertial forces to viscous forces within a fluid which is subjected to relative internal movement due to different fluid velocities) and assessed their feasibility at higher-chord Reynolds numbers typical of large subsonic transports.

Some Phase 1 research was devoted to the study of engineered airfoil surfaces. For example, because resistance to insect impacts is important to establishing and maintaining laminar flow, researchers identified and tested

40. Ibid.

41. Collier and Bezos-O'Connor, "Technology Development Project Plan," 14–15.

low-energy surface coatings for composite wings that might make manufacturing tolerances considerably lower in the leading-edge area. Another approach to reduce viscous cruise drag was to reduce the wetted area due to improved aerodynamic efficiency through the use of active flow control. This technique enables more aggressive surface performance though the use of low-energy interactions in the boundary layer for the purpose of gust load alleviation, buffet control, and high-lift enhancement. At the time, the concept of using active separation control to increase rudder/aileron effectiveness for the purpose of reducing the size of control surfaces was ready to be pursued at the system level for technology integration. Phase 1 wind-tunnel investigations applied active separation control to the rudder and vertical tail for the purpose of reducing the tail surface area required during a hypothetical engine-out contingency landing. Preliminary system analysis indicated a cruise drag reduction benefit of 1 to 2 percent through the application of this technology on the vertical tail alone. Additionally, at the start of Phase 1, NASA and the AFRL formed a partnership to conduct a "bolt-on" ACTE flight experiment using a modified Gulfstream G-3 aircraft. Both the DRE and ACTE flight experiments were classified as potential ITD candidates for Phase 2.[42]

Noise Reduction Element

During landing, propulsion noise is typically reduced because engine power is cut back significantly. As a result, the airframe contribution to community (airport environment) noise from conventional aircraft systems and configurations is approximately equal to that of the engines. ERA researchers expected N+2 vehicle configurations would employ engine noise shielding to further reduce community noise, along with quieter high-bypass-ratio engines. Therefore, the primary source of noise during future landings would result from airframe-related elements, specifically the landing gear and flap edges. Researchers considered using both aerodynamic fairings to mitigate landing gear noise, and CML technology to eliminate gaps between flaps, ailerons, and wings.

Testing of CML concepts revealed some structural weaknesses requiring further study of new structural concepts. This pushed Phase 1 research to focus on the development of noise reduction fairings for airframe-related elements. This included wind tunnel testing of a semi-span scale model of a G550 business jet baseline configuration without noise reduction fairings. Resulting data were used to validate aerodynamic performance models and baseline flight test data to determine scaling effects for Phase 2 test results. As part of Phase 2, researchers planned to use aero-acoustic wind tunnel data to determine the most promising noise reduction concepts to be integrated onto the main

42. Ibid.

landing gear and flap edges of a full-scale Gulfstream G550 and conduct a series of flight tests.[43]

Propulsion Technology Subproject

All three of ERA's N+2 goals were addressed in Phase 1 investigations within the Propulsion Technology subproject. Advanced combustor designs focused on NOx reduction and required a different approach than what was used to meet NASA subsonic transport system level metrics for N+1. The ERA noise reduction goal required new propulsor configurations, including engine noise shielding in an advanced propulsor. Fuel-burn reduction goals required a higher bypass-ratio propulsion system to improve propulsive efficiency. Investigations also addressed highly loaded front block compressor designs to enable higher thermal efficiency.[44]

In Phase 1, the Propulsion Technology Subproject addressed the following propulsion technologies:

- Combustor technology element
  - Advanced combustor concepts
  - Active combustion control
  - Lightweight CMC liners
- Propulsor technology element
  - Open rotor
  - UHB turbofan with noise reduction technologies including:
    - Lip liner
    - Over the rotor metal foam liner
    - Soft vane
    - Zero splice inlet
  - Shape memory alloy variable area nozzle
- Core Technology Element
  - High temperature erosion coatings for CMC vanes and exhaust nozzles
  - High operating pressure ratio (OPR) compressor/turbine

Combustor Technology Element

As part of Phase 1, researchers sought to achieve landing and takeoff NOx reduction goals by maturing several new combustor concepts in partnership with engine manufacturers and fuel injector companies. Their strategy

43. Ibid.
44. Ibid.

aimed toward improving injector designs and developing innovative concepts to improve fuel/air mixing into the combustor. This was accomplished in combination with higher temperature materials that required less cooling air, namely coated CMC, along with fuel flexibility and improved fuel injector timed-modulation control.

Researchers considered designs for conventional and alternative fuels. Alternative fuels with higher thermal stability allowed for improved injector designs without choking concerns. As part of Phase 1, advanced combustor concepts were developed and screened through flame tube tests (matured to TRL 4) and sector tests (matured to TRL 5). Industry cost-shared the flame tube and sector tests with NASA. Advanced combustor testing was conducted using the Advanced Subsonic Combustion Rig (ASCR) facility and advanced fuel flexible injectors were tested at the CE-5 Facility, both located at the NASA Glenn Research Center (GRC). Additional testing took place in industry test facilities. A promising advanced combustor concept was selected for further engine development as part of Phase 2.[45]

Propulsor Technology Element

Propulsive efficiency has a significant impact on an aircraft's SFC, and increasing the bypass ratio of a turbofan engine provides benefits for both fuel-burn reduction and noise reduction. The ability to increase bypass ratio is limited by engine size, weight, aerodynamic drag and installation issues. ERA researchers considered several advanced propulsion systems for future aircraft having higher bypass ratios, including open-rotor systems and UHB geared turbofans. For N+2 vehicle concepts, the integration of these propulsion systems was a key technical issue addressed by the ERA project.

Researchers investigated near-term and far-term advanced propulsor configurations in Phase 1. Near-term investigations focused on wind tunnel testing of the best available propulsor systems, both open rotor and UHB turbofans, that offered the desired performance and acoustic characteristics. Through high-fidelity model-scale experiments, Phase 1 propulsor technology investigations assessed system level performance and acoustics. The results were critical for anchoring system studies and identifying appropriate propulsion/airframe configurations that warranted further study in Phase 2.[46]

Testing of a low-noise, open-rotor system, initiated under the SFW Project, was completed during FY 2010 in the 9-by-15-foot and 8-by-6-foot wind tunnels at GRC for acoustic and aerodynamic performance. The open rotor propulsor was tested both in isolation and with simulated installed effects

45. Ibid.
46. Ibid.

for candidate N+2 vehicle concepts. Candidate technologies tested for lower noise included increased rotor spacing, lower blade count, lower tip-speed rotors with larger diameters, clipped aft rotors, and optimized spanwise rotor loading. Researchers used particle-image velocimetry, pressure-sensitive paint, and phased-array data to develop a complete validation dataset for open-rotor aerodynamic and acoustic code assessment and development. This investigation explored the design space for lower noise while maintaining the high propulsive efficiency provided by a counter-rotating open-rotor system.

As with the open-rotor configuration, subscale UHB turbofan models were tested in the GRC wind tunnels in both isolation and with simulated installed effects in late FY 2011 and early FY 2012. These tests provided the opportunity to investigate the impact of increasing the bypass ratio to approximately 15 to 18. Additionally, a test for a distortion-tolerant, integrated-inlet fan investigated cruise performance impacts and helped establish a database for code development. Researchers studied installation effects such as pylon, fuselage, and wing integration along with features that minimized interaction noise sources. Technologies investigated included shape memory alloy variable-area nozzles, acoustically treated ("soft") stator vanes, over-the-rotor acoustic treatment, low-distortion short inlets, active stall control integrated with the variable area nozzle, and a distortion-tolerant fan design.[47]

Core Technology Element

The thermal efficiency of the engine core that provides power to the propulsor is an important parameter for fuel consumption. Researchers found that although there is a perception that the optimum thermal efficiency has almost been reached for gas turbine engine core components, there are still opportunities for optimizing the system for fuel burn reduction by increasing the turbine inlet temperatures and increasing the overall pressure ratio of the compression system. In Phase 1, several advanced technologies were selected for maturation that promised benefits in the near term to virtually any core engine system. ERA researchers performed low-level exploratory work with CMC materials and structures and investigated an advanced highly loaded front block compressor concept. They concluded that CMC materials are ready for application in the N+2 timeframe for engine components such as turbine vanes and core exhaust nozzles.

The greatest advantage of CMCs over existing materials is that their lightweight structures can withstand very high temperatures. For the ERA project, researchers investigated the properties of both turbine vanes and panels for core nozzles made from CMC capable of withstanding 2,400 ˚F. Testing proved

47. Ibid.

these materials highly effective as a practical cooling strategy for ceramic turbine vanes. Studies involving turbine vane design, fabrication, and testing explored materials and structures, coatings, ceramics durability, and heat-transfer characterization at realistic engine temperatures. Two different fabrication techniques were pursued by the end of FY 2010 that led to a verification of the manufacturability of CMC turbine vanes and coatings. CMC nozzles were developed and demonstrated using lightweight/high temperature static structures to reduce weight of the nacelle/exhaust stream. Researchers concluded that high-temperature ceramic composites with integral acoustic treatments could save considerable weight while reducing noise simultaneously. During Phase 1, a CMC exhaust nozzle was designed, and representative panels were fabricated for coupon durability assessments in FY 2010. In FY 2011, key subcomponents were built to verify fabrication methods. Additionally, NASA established a partnership with industry to test key nozzle subcomponents in FY 2012.[48]

Generally, an engine with a high number of low-pressure turbine stages tends to be long and heavy. For an N+2 powerplant, it was considered desirable to keep the engine as short and light as possible. In Phase 1, NASA researchers and designers from General Electric (GE) worked together to develop a highly loaded, high aerodynamic efficiency design that used steady blowing in the exit guide vanes to enable more rear-stage loading and fewer stages for the same work. Designers employed three-dimensional optimization in the design for the first time, which resulted in improved non-axisymmetric contouring of the hub end wall, ultimately contributing to higher efficiency. The advanced compressor was fabricated at GE and the first stage configuration of the compressor was tested in the GRC W7 facility to verify the design. Phase 1 investigations validated this design approach and were subsequently implemented in testing of an advanced compressor during Phase 2.[49]

Vehicle Systems Integration Subproject

The Vehicle Systems Integration subproject combined airframe technologies and propulsion technologies into larger subsystems, multicomponent, and vehicle experiments to address progress towards the simultaneous achievement of N+2 subsonic transport system level metrics with regard to emissions, fuel burn, and noise reductions. For Phase 1, this subproject also included multidisciplinary systems analysis activities.

In Phase 1, the focus of the four elements of the VSI Subproject included:

48. Ibid.
49. Ibid.

- Systems Analysis Element
  - Individual technology maturation assessment against ERA N+2 metrics
  - Vehicle-level assessment of the ERA technology suite against ERA N+2 metrics
  - Fleet-level assessment on the technology insertion timeframe for all vehicle classes across N+1, N+2, and N+3 aircraft and propulsion system generations
  - Airframe and propulsion system integration studies on the most promising technologies based on predicted performance against ERA N+2 metrics
- Propulsion-Airframe Integration (PAI) Element
  - Subscale, high-speed UHB turbine powered simulator PAI test on an advanced tube-and-wing vehicle concept in cruise configuration
- Propulsion-Airframe Aeroacoustic (PAA) Element
  - Subscale, low-speed, open rotor PAA testing of HWB vehicle configuration
  - Subscale, low-speed, UHB turbine powered simulator PAA testing of HWB vehicle configuration
- Advanced Vehicle Concepts Element
  - Over-the-wing nacelle vehicle configuration study
  - N+2 Advanced Vehicle Concepts study

Systems Analysis Element

At formulation, a suite of potential ERA project technologies and concepts were identified and assessed utilizing an "analysis of alternatives" approach. Researchers conducted a broad survey of technologies with the goal of identifying technologies with a potential to reach TRL 4–6 in the 2015 timeframe. Additionally, these technologies provided positive system-level benefits toward simultaneously meeting the N+2 noise, emissions, and fuel burn goals. Unconventional air vehicle concepts and configurations were also included as part of the technology survey. Subsystem technologies were then integrated onto advanced vehicle configurations to assess system-level benefits. This initial assessment informed the development of the ERA Phase 1 investigations.[50]

Phase 1 airframe and propulsion technology performance results from subsystem and component testing were extrapolated, when feasible, to estimate full-scale, integrated performance at the airframe system, propulsion system, vehicle, and fleet level against N+2 subsonic transport system metrics for emissions, fuel

50. Ibid.

burn and noise reduction. At the end of Phase 1, a common set of metrics was established and validated across the airframe, propulsion, and vehicle integration research areas of the ERA project. Academic, industry, and NASA results were used to validate the analysis of alternatives approach. Research teams also conducted sensitivity analysis for critical technology elements.

Researchers produced semiannual updates and annual reports to communicate the assessment status and findings to ERA project leaders, the ISRP program, and ARMD. These technology and concept integration assessments supported the formulation of the Phase 2 investigation presented at the KDP-2 Review at the end of FY 2012. The systems analysis/integration function continued into Phase 2. Results were reported directly to the ERA Project Management Leadership Team, a multi-center NASA, academic, and industry team that served as an "honest broker" whenever it became necessary to set priorities.[51]

Propulsion-Airframe Integration Element

Aircraft engines are the single most significant contributor to aircraft community noise. Prior to the ERA project, virtually all large-scale installed engine/airframe performance information came from conventional tube-and-wing configurations with engine pods hanging below the wings. Alternate configurations, such as the HWB with top-mounted engines, high-wing tube-and-wing concepts with conventional nacelle installations (as on military transports, for example), and low-wing tube-and-wing concepts having over-wing-mounted nacelles, provide shielding benefits that offer tremendous potential to reduce community noise.

Phase 1 research focused on understanding PAI challenges associated with integration of a UHB engine on a transonic transport configuration with some form of acoustic shielding installed. This investigation involved the optimization of multiple concepts with a candidate UHB engine design, and included the simultaneous design of wing airfoil shapes, pylons, and nacelle configurations. A semi-span high-speed wind-tunnel model was designed from outer mold line shapes developed during the design process. Researchers then modified an existing turbine power simulation with an advanced fan-and-stator design simulating an engine-bypass ratio on the order of 15-20. A transonic performance test was conducted in the Ames Research Center (ARC) 11-Foot Unitary Tunnel in FY 2011. The resulting data validated the design methodology and provided insights on the impact of large turbofan shapes on

51. Ibid.

other aerodynamic considerations, such as control surfaces and variable-area fan nozzles.[52]

Propulsion-Airframe Aeroacoustic Element

Phase 1 investigations for the PAA Element provided valuable insight in both performance and noise characteristics of key propulsion concepts integrated with the HWB advanced airframe concept. This configuration provided built-in acoustic shielding by making efficient use of the large vehicle surface below the engine to prevent much of the engine noise from radiating to the ground, especially when coupled with improved designs of nacelles, nozzles, and novel engine/airframe installation effects. At the time, based on limited laboratory experiments and analytical predictions, it appeared that there was significant noise-reduction potential due to shielding of both fan and jet noise if optimum engine placement could be determined and methods of enhancing shielding with nozzle, pylon, and airframe edge treatments and devices studied.[53]

Two complex scale-model aeroacoustic wind-tunnel tests were completed in Phase 1. Both experiments provided high-fidelity acoustic data in a wind-tunnel environment to validate improved predictive capabilities. In addition, these tests provided direct quantitative evidence that the HWB configuration, specifically designed for significant noise shielding, did provide cumulative noise reductions on the order of 17 dB as predicted. These highly complex tests required hot-jet-propulsion simulation capability (to mimic the effects of aeroacoustic noise) that most low-speed wind-tunnel facilities lacked. Coupled with a new phased-array microphone technology, tests were undertaken in the LaRC 14-by-22-foot subsonic tunnel and the Boeing Low-Speed Aero Acoustic Facility (LSAF). The results quantified key installation parameters such as jet-airframe spacing, jet-flap interaction, pylon effects, sideline noise shielding from canted vertical tails, and other noise reduction concepts on the aeroacoustic signatures at low speeds. High-fidelity acoustic data acquired with microphone array technology developed for the HWB 14-by-22-foot wind-tunnel tests was incorporated into noise prediction tools to provide more accurate assessments on the acoustic characteristics of any low-noise vehicle or component technology during flight.[54]

Advanced Vehicle Concepts Element

Although elements of the Phase 1 research portfolio offered significant improvements in both aircraft noise and fuel burn, it soon became abundantly clear

52. Ibid.
53. Ibid.
54. Ibid.

that even applying all of the N+2 technologies then under consideration to an advanced tube-and-wing configuration would not meet all ERA goals. Doing so would require exploring radically new and innovative aircraft configurations.[55]

The Phase 1 investigations in this element focused on identifying and characterizing advanced vehicle concepts with the potential of meeting the ERA Subsonic Transport System Level N+2 goals. The investigations were conducted via the N+2 Advanced Vehicle Concept NRA, with some in-house modeling support initially focused on the over-wing-nacelle concept in FY 2010 and an alternative advanced concept in FY 2011. Various propulsion technologies (open-rotor, UHB, geared-turbofan [GTF], etc.) and vehicle configuration (HWB, high-wing, over-the-wing-nacelle, truss-braced-wing, etc.) concepts were evaluated under this NRA. The advanced vehicle concepts identified through the NRA process identified the critical technologies that needed to be matured to TRL 6 by 2015 to enable entry into service (EIS) by 2025. These advanced vehicle concepts and their respective technology suites were incorporated into the Analysis of Alternative assessment and validation that informed the ERA Phase 2 Portfolio formulation.[56]

ERA Phase 2 Planning

The ERA project's Phase 2 ITD portfolio was defined to begin after completion of Phase 1 investigations (scheduled for October 1, 2012) and conclude on September 30, 2015. Development of the portfolio required input from a broad range of sources, including the ERA Phase 1 project system assessment, Phase 1 technology maturation, the Phase 1 N+2 Advanced Vehicle Concepts NRA, ongoing ARMD project foundational research developments, and other national interests.

Phase 2 planning began in October 2011 with the formation of the Phase 2 Tiger Team led by the ERA project chief technologist Tony Washburn and chief engineer Mark Mangelsdorf. Their team included subject matter experts leading major efforts in the airframe technology, propulsion technology, and vehicle systems integration subprojects. The Tiger Team identified ITD opportunities that were feasible in the FY 2013–FY 2015 timeframe through dialogue with existing partners from Phase 1 and dialogue with governmental partners (FAA CLEEN, AFRL, and Air Mobility Command) as well as from the N+2 AVC

55. Nickol and Haller, "Environmentally Responsible Aviation (ERA) Project: Assessing Progress," passim.
56. Collier and Bezos-O'Connor, "Technology Development Project Plan," 25–31.

NRA results, specifically the FY 2013–FY 2015 critical technologies and TRL Maturation Roadmaps.[57]

Evaluating Candidate ITD Opportunities

Selected ITD opportunities were vetted both within NASA and with industry. The Tiger Team held a technology review in February 2012 with technical representatives from ARMD, ISRP, and the implementing NASA Centers. Another meeting of experts was held in March 2012, with representatives from the aviation industry, including aircraft and engine manufacturers, technology suppliers, academia, and other Federal laboratories to vet candidate technologies under consideration and the candidate ITD demonstrations being considered. Additionally, NASA released a Request for Information (RFI) in January 2012 requesting inputs from the aviation community regarding areas of interest in the conduct of collaborative, 50-50 cost share integrated technology demonstrations.

A rigorous technical and programmatic review and assessment process commenced at the completion of the internal and external technical reviews, and the RFI submission period closed. The candidate ITD Opportunities were evaluated based on the following criteria:

1. Assess the Candidate ITD Technical Benefit
   - Contribution to the NASA Subsonic Transport System Level Metrics
   - Scalability of the ITD Technologies, including level of broad applicability to the fleet classes
   - Ending TRL
   - Industry interest, i.e., partner cost share and Independent Research and Development (IRAD)
2. Assess ITD Execution Risk
   - Technical Risks included:
     - ITD complexity with respect to technology integration challenges and number of interfaces
     - Intellectual property difficulty with respect to ease of negotiation of Government use and public data rights
   - Cost and Schedule Risks included:
     - Partner contributions/cost share
     - Facility and workforce availability
     - Acquisition method

57. Ibid.

Project managers conducted a benefit, risk, and cost analysis of all candidate ITDs, considering the following factors:

- Technical Focus Area (TFA) balance
- Individual system benefits contributions
  - Best fuel burn, emissions, and noise
- Industry-Government partnerships
- Center balance

Other considerations included inputs from the ERA project subproject managers, Phase 2 Technical Tiger Team, the Phase 2 Technical Review Panel members, and the ISRP and ARMD Leadership. The project manager's ITD portfolio recommendation was presented to ARMD leadership at the ERA Project Phase 2 Technology Tollgate meeting held on June 25, 2012. At this review, ARMD authorized the development of detailed implementation plans for the recommended ITD portfolio. The ERA deputy project manager led an ITD Detail Planning Process that resulted in development of ITD-driving technical requirements, a risk-informed budget and schedule with 80 percent confidence level, risk registries, and an ITD cost and schedule margin reserve.[58]

The Phase 2 portfolio achieved a significant and quantifiable measure of progress towards the National Research and Development Plan and ERA/ISRP integrated systems research goals. It encompassed a selection of ITDs that ERA planners believed would enable:

- Technology maturation in the N+2 timeframe;
- Clear technology/product transition paths via industry and Other Government Agency (OGA) partnership cost share indicating high national interest, industry, and U.S. Government commitment to mature the technology suite over the 3 years of ERA Phase 2;
- Broad applicability across vehicle configurations; and
- High probability of transition into the fleet no later than 2025.

The Phase 2 key decision point (KDP-2) review was held at NASA Headquarters on September 26, 2012, following nearly 12 months of preparation. Satisfied with the results, Dr. Jaiwon Shin authorized the ERA project to proceed with the selected ITDs.

Each Phase 2 ITD was assigned an alphanumerical designation that identified the associated technical focus area and the technology demonstration concept proposed as shown in the two examples below. Note that the first

58. Ibid.

digit represented the primary TFA and ITD impacts, and the second digit represented the secondary TFA and ITD impacts.[59]

- **21A:**
  - Technical Focus Area 2: Advanced Composites for Weight Reduction
  - Technical Focus Area 1: Innovative Flow Control Concepts for Drag Reduction
  - Technology Demonstration Concept A: The first concept formulated to address TFA 2 and 1
- **21C:**
  - Technical Focus Area: 2: Advanced Composites for Weight Reduction
  - Technical Focus Area: 1: Innovative Flow Control Concepts for Drag Reduction
  - Technology Demonstration Concept C: The third concept formulated to address TFA 2 and 1

The Phase 2 ITDs were managed under the same subproject structure as in Phase 1:

- **AT Subproject:**
  - **12A+:** AFC Enhanced Vertical Tail (Lead) and Advanced Wing Flight Experiment. *Key partner:* Boeing Commercial
  - **21A:** Damage Arresting Composite Demonstration. *Key partner:* Boeing Commercial
  - **21C:** ACTE Flight Experiment. *Key partners:* FlexSys, Inc. and AFRL
- **PT Subproject:**
  - **30A:** Highly Loaded Front Block Compressor. *Key partner:* General Electric
  - **35A:** Second Gen UHB Propulsor Integration. *Key partner:* Pratt & Whitney
  - **40A:** Low NOx Fuel Flexible Combustor Integration. *Key partner:* Pratt & Whitney
- **Vehicle Systems Integration Subproject:**
  - **50A:** Flap Edge and Landing Gear. *Key partner:* Gulfstream
  - **51A:** UHB Integration for HWB aircraft. *Key partner:* Boeing Commercial

59. Ibid.

The ERA project manager was accountable to the ISRP director with overall technical and programmatic management responsibility, including strategic and tactical direction. The deputy project manager was responsible for execution of the Project Plan and providing oversight of day-to-day operations. In Phase 2, the position of chief technologist from Phase 1 was replaced with a Systems Engineering and Integration lead. The inclusion of a strong systems engineering leadership team was deemed critical to execution of Phase 2.[60]

Risk Management

The ERA project developed and approved a Continuous Risk Management/Risk Informed Decision Making plan that tracked schedule, cost, and technical risks. The ERA risk management process tracked risks by milestone, annual performance goals, key performance parameters, technical maturation, and technical challenges. The ERA Risk Management Working Group served as the official forum for risk identification, assessment, and mitigation plan development. The ERA Risk Management Board was the project forum for risk evaluation, deliberation, classification, and control of project risks.

The Phase 1 ERA technology portfolio was focused on validating the performance of technologies at the system level to TRL 4. The design of experiments and system level assessments validated technical performance to "buy down" the inherent risks of these advanced technologies. In Phase 2, the ERA Project conducted ITDs that tested technologies at the system level, further maturing each new technology and validating technical performance at the airframe/engine system level, which further reduced performance uncertainty as system complexity and scale increased. This further reduced overall risk.

The ITD structure of the project required more specialization for Phase 2. The realization that each ITD was a project unto itself meant that risk had to be tracked and managed at the project level, ITD level, and subproject level simultaneously. For this reason, ERA managers introduced the Risk Management Panel (RMPn) concept for Phase 2, and additional risk managers were added to the organizational structure to assist in the control of risk at multiple levels of the project.[61]

Technology Transfer

A coherent plan for technology transition approach was essential to the success of the ERA project. Technology transfer was the primary means by which project team members shared their research with stakeholders and with the aeronautics community at large. The ERA project pursued an overarching strategy

60. Ibid.
61. Ibid.

of collaboration with industry, universities, and other Government agencies to advance the TRL of the Phase 2 technology portfolio and achieve measurable progress towards NASA's N+2 Subsonic Transport System Level metrics.

Project results were appropriately disseminated and validated through a peer-review process. NASA transferred data and/or hardware to end-user customers for use throughout the life of the project. Data transfer took place via technology interchange meetings and membership on key technical working groups in industry, academia, and other Government agencies, in addition to specific requirements in agreements with partners.[62]

62. Ibid.

Boeing's elegant Subsonic Ultra Green Aircraft Research (SUGAR) Volt concept was among the many early designs examined by the NASA Aeronautics Research Mission Directorate in April 2010 for its NRA-funded studies into advanced aircraft that could enter service in the 2030–2035 timeframe. (NASA)

CHAPTER 2

The ERA Advanced Vehicle Concepts Study

Despite obvious advances in aircraft design and manufacturing techniques, the basic configuration for a commercial air transport has changed very little over the past six decades. One need only compare the similarities that the Boeing 707, first introduced in December 1957, shares with the Boeing 787 that debuted some 50 years later. Most other modern airliners share this configuration as well. The wings, invariably swept, are usually mounted low on the fuselage. Pylon-mounted gas turbine engines are typically attached to the wings or flank the aft end of the tubular, constant-diameter cylindrical fuselage. This elegantly simple configuration is attractive to manufacturers because it can be easily assembled using conventional techniques and materials. It may not, however, necessarily yield maximum aerodynamic efficiency or minimize fuel consumption. In fact, most airframes tend to be over-engineered for structural strength or to provide airfoil stiffness as a hedge against wing flutter. This design technique may result in excess structural weight as well as incorporate features that add drag, both of which reduce aerodynamic and fuel efficiency.

Commercial airliners typically have a cylindrical fuselage that is joined to either straight or swept-back wings; the wings can be placed either high or low on the fuselage; and the tail section can have its horizontal tail surfaces project either from the fuselage or be perched on the top of the vertical fin. During the ERA project, NASA and industry teams considered a wide variety of alternatives ranging from modified tube-and-wing designs featuring nonstandard engine placement to mitigate jet noise, un-ducted turbofans, V-tails, joined or box wings, high-aspect-ratio braced wings, and even tailless configurations. Engineers evaluated the potential effects of alternate fuselage shapes, wing and body integration, engine installation, and controls integration. Reduction of the wetted area of some configurations offered huge potential for viscous drag reduction.

Three areas in which commercial aircraft design has seen a great deal of improvement are materials, propulsion, and aerodynamic efficiency. Strong, lightweight composites offer opportunities to reduce overall gross weight. This is crucial to improving fuel consumption, as are any technologies that reduce airframe drag. By far the greatest progress has been made in propulsion technology. Advanced high-bypass turbofan engines are much more efficient and more reliable than older turbojets and quieter as well. The incorporation of supercritical airfoils and winglets has also provided performance benefits. The resulting dramatic improvements in fuel economy have imparted better performance in terms of passenger miles flown per gallon of fuel expended (P-mpg).[1]

The 707-320 Intercontinental variant, powered by four turbofan engines, could carry a maximum of 189 passengers. This yielded approximately 45 P-mpg. (By comparison, the 787 with two turbofans and 240 to 330 seats, performs at 120 P-mpg, mostly resulting due to improved engine efficiency.)[2] These numbers may be further improved through advanced aerodynamic designs, engines, and manufacturing techniques.

New technologies developed during the ERA project can be used to significantly enhance future tube-and-wing designs as well as to help introduce radically different configurations. Though the traditional tube-and-wing configuration offers numerous advantages, such as decoupled bending and pressure loads, as well as circumferential or hoop stress to maintain the integrity of the pressure vessel, there are also attendant disadvantages. Foremost among these is the large amount of wetted area contributing to overall aerodynamic drag. The non-lifting tubular fuselage results in a large drop-off of lift at the center of the airframe, and cantilevered wings require a heavy wing box assembly to counteract bending loads.

Alternative configurations require many trade-offs as well, some of which can be minimized through the use of new technologies. The truss-braced wing concept, for example, may incorporate a lighter, thinner, airfoil with a longer span. But while this may reduce both structural weight and wave drag, it also increases parasitic drag and wetted area, and introduces interference drag from truss attachment points as well as compressive loading on the truss assemblies. A multiple-fuselage approach may provide shielding for engine noise, but suffers from interference drag and, potentially, from non-linear elastic effects. Flying wing and blended wing body (BWB) designs have a greatly reduced wetted area and increased inherent lift. Greater wing thickness results in lower bending stress, and powerplant placement can significantly reduce engine noise. The elimination of a conventional tail assembly requires special attention to flight controls and, because pressure loads are not carried in hoop stress, the pressure

1. P-mpg = (payload weight/total gross weight) × (lift/drag) × engine efficiency.
2. Mark Drela, "Making an Extraordinary Machine Better," presented at TEDxNewEngland, Boston, MA, October 24, 2012, *56* (accessed September 3, 2019).

NASA LaRC engineers used this 15-percent-scale semi-span model designed by Boeing to assess the aeroelastic qualities of an unusual truss-braced wing configuration in the Transonic Dynamics Tunnel. (NASA)

vessel needs to be assembled using unconventional means.[3] NASA and industry teams had an opportunity to explore these problems through the ERA N+2 Advanced Vehicle Concepts study.

Developing the ERA's Preferred System Concept (PSC)

NASA invited proposals from throughout the aircraft industry to perform a study to determine aircraft systems (configuration, technologies, and airspace requirements) and a time-phased technology development plan that would meet NASA's N+2 subsonic system-level metrics, based on entry into service (EIS) circa 2025. NASA project managers would use the results to guide technology investments during ERA Phase 2.

Objectives of the study as defined by a NASA Research Announcement (NRA) included development of a preferred system concept (PSC), with several variants, designed to meet or exceed N+2 metrics. Those companies offering proposals were encouraged to describe their view on potential 2025 NextGen National

3. Eric M. Boekeloo, Anthony Favaloro, Timothy Harris, Luke Humphrey, Brandon Johnson, Troy Lake, Collin McAtee, Kimberly Scheider, Yukiko Shimizu, and Barrett Tirey, "Integrated Systems Design of a Cargo Aircraft with Environmentally Responsible Goals," AIAA-2012-1759, presented at 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, HI, April 24, 2012, 4.

NAS environmental challenges and constraints. NASA requested that proposers evaluate how their PSC would operate within the NextGen NAS with regard to noise profiles, landing and takeoff (LTO) and cruise NOx output, carbon emissions, and operational trajectories. Additional objectives included development of time-phased technology maturation plans to quantify beginning and ending TRLs, and to prioritize which technologies would have to be developed within the FY 2013–2015 timeframe in order to enable each PSC. The NRA specified that approximately $9 million would be split among two to three awards. Results of the 18-month effort would do much to determine the outcome of the FY 2012 decision point for Phase 2. One of the most important goals, according to Mark Mangelsdorf, was "to foster strategic partnerships between NASA and the awardees for collaborative research and development of innovative concepts and ideas."[4]

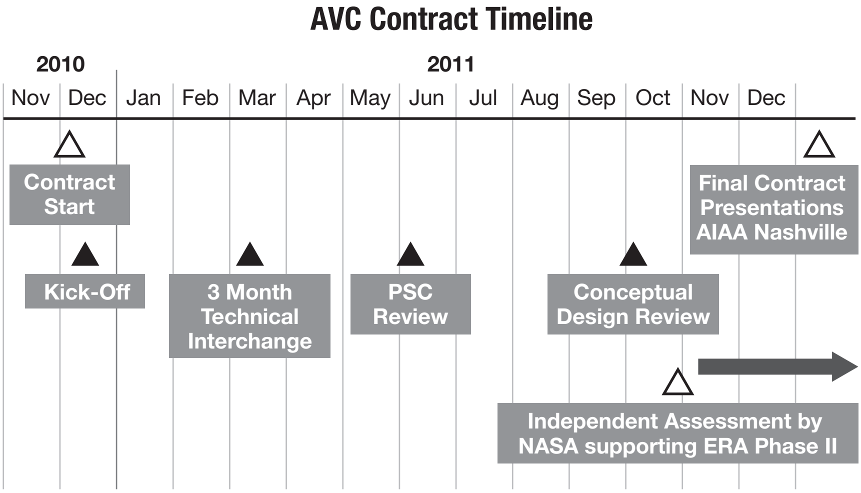
Proposals included relevant qualifications, capabilities, and experience of each lead organization and team members, as well as work plans that outlined schedules with milestones and measurable metrics. Because NASA wanted to maximize public access to the results, intellectual property rights were negotiated on a case-by-case basis. In order to minimize paperwork, the science and technology management section of each proposal was limited to 50 pages. Proposals were evaluated on the basis of the following four criteria:

- Relevance to ERA objectives (20 percent),
- Technical merit (35 percent),
- Effectiveness of the proposed work plan (20 percent), and
- Team qualifications (25 percent).

The final NRA was posted on March 1, 2010, with proposals due by April 15. Final selections were complete by May 1, and the awardees were on contract by June 30.[5]

Winners were Boeing, Lockheed Martin, and Northrop Grumman. From December 2010 through December 2011, these three industry teams derived and then evaluated new aircraft configurations designed to burn as much as 50 percent less fuel than comparable aircraft that entered service in 1998, emit 75 percent fewer harmful pollutants, and reduce the size of areas affected by objectionable airport noise by as much as 83 percent. The Boeing 777-200LR, with a 291-seat capacity, cruising speed of 550 miles per hour, and a 10,000-mile range, served as a baseline reference. The Advanced Vehicle Concepts (AVC)

4. Mark F. Mangelsdorf, "Overview of ERA's Advanced Vehicle Concepts NRA," presented at the N+2 Advanced Vehicle Concepts and Quick Starts NRA Pre-Proposal Meeting, February 19, 2010, *https://www.hq.nasa.gov/office/aero/pdf/era_preproposal_overview2010.pdf* (accessed September 3, 2019).
5. Ibid.



NASA held the various contractor teams to a strict schedule to ensure that the Advanced Vehicle Concept study produced the desired results within the ERA timeframe. (NASA)

study was broken down into five tasks, the first four relating to a planned full-sized concept and the fifth specifically related to proposals for a subscale test vehicle (STV) that would serve as a technology demonstrator.[6]

Task 1 was to develop a future scenario beginning with evaluating how each of the contenders would best fit into the FAA's NextGen airspace plan. Task 2 focused on meeting PSC performance requirements. Specifications for notional commercial transports called for a maximum speed of between 0.70 and 0.85 Mach, a range of 8,000 nautical miles, and a 50,000-pound passenger/baggage payload. Industry teams were also encouraged to develop a freighter variant capable of transporting a 100,000-pound payload over a range of 6,500 nautical miles. Task 3 detailed a 15-year technology maturation road map for each of the critical technologies, specifying research, analysis, tool and method development as well as necessary ground or flight tests. Each technology maturation plan accounted for cost, schedule, and technical outcome, and was expected to be useful for advocacy beyond the ERA project timeline. Task 4 would focus on the "long poles," or the critical enabling technology demonstrations to be used for the second half of the ERA program in FY 2013–FY 2015. Researchers had to consider the scalability of these technologies for use in the proposed STV, and the potential ramifications of cost, complexity, schedule, and technical risk. Task 5 entailed conceptual design of the STV that, if built, would

6. Mark F. Mangelsdorf, "Environmentally Responsible Aviation N+2 Advanced Vehicle Concepts NRA Status," presented at the ASME Turbo Expo conference, Vancouver, BC, June 6–10, 2011, 1–20.

have to be large enough to simultaneously demonstrate ERA noise, emissions and fuel-burn goals. The half-scale-or-larger STV was to have the same overall configuration as the full-scale PSC, the same cruising speed, retractable landing gear, and be adaptable for use in additional future demonstration efforts. The size of the vehicle was necessary to provide realistic aero-acoustic data. Planners projected that the STV would have a 20-year service life.[7]

NASA managers were eager to take advantage of improvements in airframe and powerplant designs as quickly as possible and sought ways to apply technology to existing airframes that were then in service or expected to be introduced within the next decade. As Mangelsdorf noted, "We're also interested in technologies that apply to N+1—[these are] nearer term single-aisle concepts or ones that can be retrofitted to current 737/CRJ-class [Boeing 737 and Bombardier CRJ] models."[8]

Key factors in both the N+1 and N+2 studies were benefit gains versus a specific class of aircraft. While N+1 focused on smaller technology gains applicable to short-range, domestic flights in 737/CRJ-class aircraft, N+2 focused on long-range, international flights in 777-class transports. "There's a difference in range and seating capacity, and also in Mach number," said Mangelsdorf. "The 777 cruises between approximately 0.82 to 0.85 Mach, while the 737 cruises at around 0.78 to 0.80 Mach." Some ERA researchers were considering slower aircraft concepts because they burned less fuel, but there was point at which this benefit began to decrease. "You burn less fuel per minute, the slower you go," Mangelsdorf pointed out, "but if you slow down too much, you burn more fuel per mile because the number of minutes is stacking up, so your total fuel burn ultimately increases."[9]

While ERA managers were trying to decide how best to focus their efforts, the SFW program was looking at several revolutionary concepts that were more attuned to N+1 or even N+3. In 2010, a team led by Boeing proposed the Subsonic Ultra Green Aircraft Research (SUGAR) Volt, a twin-engine concept with a hybrid propulsion system combining gas turbine and battery technology, a tube-shaped body, and a truss-braced wing mounted to the top of the aircraft. It was designed to fly at Mach 0.79 while carrying 154 passengers 3,500 nautical miles.

Researchers at the Massachusetts Institute of Technology submitted a design called the D8 "Double Bubble" based on a modified tube and wing with a very

7. Guy Norris, "'Green' Airliner Targets Achievable by 2025, Says NASA," *Aviation Week & Space Technology*, *http://aviationweek.com/awin/green-airliner-targets-achievable-2025-says-nasa*, April 18, 2011 (accessed July 21, 2016).
8. Ibid.
9. Mark F. Mangelsdorf, interview with the author, October 19, 2016.

Boeing's elegant Subsonic Ultra Green Aircraft Research (SUGAR) Volt concept was among the many early designs examined by the NASA Aeronautics Research Mission Directorate in April 2010 for its NRA-funded studies into advanced aircraft that could enter service in the 2030–2035 timeframe. (NASA)

wide fuselage to provide extra lift, with narrow-chord low-sweep wing offering reduced drag and weight. Optimized for domestic service, the D8 series aircraft could fly at Mach 0.74 while carrying 180 passengers 3,000 nautical miles in a coach cabin roomier than that of a Boeing 737-800. Another team, from California Polytechnic State University, submitted the Advanced Model for Extreme Lift and Improved Aeroacoustics (AMELIA), a possible future subsonic HWB vehicle with short takeoff and landing capabilities. Of the three, only the AMELIA was suited to N+2, but according to Rich Wahls, "The powers that be didn't want ERA to become driven strictly by an HWB configuration."[10]

10. Wahls interview.

Alternative Lockheed-Martin (left bottom), Northrop-Grumman (left top), and Boeing (right) consortium approaches to meet NASA's goals for making future aircraft burn 50 percent less fuel than aircraft that entered service in 1998, emit 75 percent fewer harmful emissions, and shrink the size of geographic areas affected by objectionable airport noise by 83 percent.

Low-speed designs like the SUGAR Volt and D8 introduced a number of economic variables extraneous to ERA management's interest at the time, which remained firmly fixed on technical issues. "We decided to reduce those variables and go for a Mach number of 0.85," said Mangelsdorf, "because we know that 0.85 Mach is a speed that works well for long-distance flights."[11] Configurations like the truss-braced wing and Double Bubble were far better suited to the domestic 737-class market than was the HWB. Moreover, he noted, "Our studies showed that the HWB does not scale well at or below a 737-class airframe. "As you shrink it, your packaging challenge gets tougher and by the time you fit the people and the landing gear in, your wetted area per passenger gets too high and you begin to lose the benefit over a tube-and-wing configuration."[12]

As all of these different ideas evolved, Dr. Jaiwon Shin and others were examining possibilities for NASA to fund new X-plane projects, leading to the AVC study contract awards. "We had the NASA subsonic metrics chart

11. Mangelsdorf interview.
12. Mangelsdorf interview.

that outlined N+1, N+2, N+3 fuel-burn versus noise-reduction goals for those timeframes," said Mangelsdorf, "and that provided guidance as to what it would take to get a 777-class vehicle to meet those requirements, both in terms of passenger count and range." Those targets for simultaneous achievement of a 50-percent fuel burn reduction and 75-percent NOx reduction, as well as a –40 db noise reduction, drove the size the vehicle proposed in each AVC study.[13]

Three Teams = Three Very Different Approaches

Design studies by each of the industry teams yielded three very different configurations, and one of these—the Northrop Grumman entry—was ultimately discarded in favor of a different design altogether. ERA managers planned to down-select the best two in December 2011, and eventually choose one for the STV.

Lockheed Martin: Looking Toward the Joined Wing

The Lockheed Martin Skunk Works (LMSW) team, which included Rolls-Royce and the Georgia Institute of Technology, offered an unconventional "joined wing" concept for improved structural and aerodynamic efficiency. It incorporated advanced technologies in the areas of propulsion for significant fuel burn and noise reduction, new lightweight composite materials, laminar wing aerodynamics, and other efficiency technologies. Designers envisioned that the concept would be integrated into existing airport infrastructure without significant changes and provide a passenger experience consistent with the best contemporary airliners.[14]

Starting with a standard tubular fuselage, designers abandoned traditional wings and tails for the joined wing configuration. In place of wingtips, swept wings turned upward to join with a second set of airfoils that met at the vertical stabilizer. The result looked like a futuristic biplane, except that the continuous surface of the non-planar airfoil would act to eliminate wingtip vortices that are a major component of wake turbulence and induced drag. By having what amounted to two sets of wings, it was possible to use airfoils with a narrower chord than on conventional wings. To further reduce drag, the joined wing was also to be designed for laminar flow control. According to Bruce McKay, LMSW ERA project chief engineer and propulsion lead, "[The joined wing] uses two [sets of] very long, skinny wings which are aerodynamically more

13. Ibid.
14. Mangelsdorf, "Environmentally Responsible Aviation N+2 Advanced Vehicle Concepts NRA Status," 1–20.

efficient than traditional wings, and the aft wing is actually mounted high on the airplane, which allows me to put much larger, more efficient engines on it."[15]

For propulsion, the airplane was to be equipped with two Rolls Royce LibertyWorks UltraFan engines, each with a bypass ratio (flow of air around engine compared to through the engine) nearly five times greater than then-current engines. The unusual configuration called for suspending the power plants from beneath the upper aft set of airfoils. According to McKay, Rolls Royce designed the ultra-high-bypass engines to push the limits of turbofan technology to maximize efficiency. "We get about 20 percent to 25 percent better fuel efficiency with those," he noted.[16]

Advances in strong, lightweight composite materials were crucial to enabling construction of a joined wing airliner. LMSW leveraged its experience with the Lockheed-Martin X-55 Advanced Composite Cargo Aircraft (ACCA) that demonstrated the feasibility of designing and manufacturing large, bonded unitized structures featuring low-temperature, out-of-autoclave curing. First flown in 2009, the X-55 employed the cockpit, wings, engines, and horizontal tail of a Dornier 328J airliner. The LMSW team then constructed the advanced composite fuselage in two large half-section subassemblies (upper and lower) using honeycomb-sandwich construction with carbon composite skins and Nomex core. Instead of the numerous frames, stiffeners, and metal fasteners commonly used in traditional aircraft, the composite components were bonded together with adhesive and ply overlays along the longitudinal seam. Compared to the basic Dornier 328J airframe, the ACCA structure used only around 300 structural parts versus the original 3,000 metallic parts and approximately 4,000 mechanical fasteners compared to 40,000. A new vertical tail was designed using tailored stiffness technology.[17] As applied to advanced aircraft concepts, these technological leaps would allow manufacturers to save time during both the design and construction phases, reduce aircraft structural weight, and reduce corrosion and metal fatigue problems.

The joined wing design is optimized for low drag and reduced fuel burn. LMSW program manager Kenneth Martin noted that a full-scale airframe based on the team's PSC would be 181 feet long with a 171-foot wingspan. A lightweight composite airframe would allow for a maximum takeoff weight

15. Bruce McKay interview with Johnny Alonso, NASA 360, S03E22, NASA podcast, December 5, 2011, transcript at *http://www.nasa.gov/multimedia/podcasting/nasa360/nasa360-0322.html*, (accessed September 3, 2016).
16. Ibid.
17. Lockheed Martin, "The Carbon Comet: X-55 Advanced Composite Cargo Aircraft," *http://www.lockheedmartin.com/us/100years/stories/acca.html*, date unknown (accessed September 3, 2016).

The Lockheed-Martin X-55 ACCA taking off from Air Force Plant 42 at Palmdale, CA, on its first flight, June 2, 2009. The X-55 marked an important step forward in understanding and realizing the potential of advanced composites. (NASA)

(MTOW) of around 365,900 pounds versus the 550,400 pound maximum gross weight of an equivalent 1998 technology-standard aircraft. Designers anticipated a similar reduction in fuel weight to less than half that of the 250,000 pounds required by the baseline design. Advanced composite construction also made possible a high-aspect-ratio wing configuration that would allow steep landing approaches to help contain noise within airport boundaries. This contributed to a noise reduction of –35 decibels. Martin noted that, with potential military roles in mind, the LMSW joined wing configuration also offers "scalability from tactical to strategic, as well as reduced span for compatibility with the existing infrastructure."[18]

ERA managers were suitably impressed with the 63,600-pound-thrust Rolls-Royce UltraFan engine. This revolutionary powerplant is a hybrid between current advanced turbofans and open-rotor engines. With a diameter of approximately 140 inches, the geared fan assembly is extremely large compared to conventional turbofans. Rolls-Royce encased the UltraFan in a slender, natural laminar-flow nacelle without a thrust reverser. Additionally,

18. Guy Norris, "Future-Airliner Concept Contenders Reveal Design Surprises," *Aviation Week & Space Technology*, *http://aviationweek.com/awin/future-airliner-concept-contenders-reveal-design-surprises*, January 16, 2012 (accessed September 3, 2016).

data indicated that engine emissions beat the target by coming in at –89 percent relative to CAEP6 standards. Fay Collier noted enthusiastically that, "We thought we knew where things were going with the engine companies, but the UltraFan concept came out of the blue."[19]

For the flight demonstration program, LMSW proposed building a 50-percent-scale STV measuring 125 feet in length and spanning 99 feet, with a maximum takeoff weight of 162,500 pounds. Powered by unspecified 45,000-pound-thrust engines, the demonstrator was to have a cockpit configuration based on that of the Lockheed Martin C-130J transport with open-architecture mission systems to support avionics and system upgrades. Design flexibility allowed for further optimizations including such airframe noise-reduction technology as continuous-mold line flaps, aerodynamic landing-gear fairings, slat fillers, and shape-memory alloy serrations on the engine bypass-duct exit.[20]

Northrop Grumman: Extending its Heritage of Pure Flying Wings

Northrop Grumman initially proposed a notional double-fuselage configuration, but expected a final—and probably very different—concept to evolve over the course of the study. The unusual twin-hulled aircraft sported two identical bodies, each with its own V-tail. A crew cabin and cockpit were centrally located at the apex of gently swept wings bridging the top of the double fuselage. Placement of two pylon-mounted high-bypass turbofan engines on either side of the crew compartment and beneath the wing provided some measure of acoustic shielding. As with the LMSW effort, the Northrop Grumman team sought reductions in weight and drag coupled with improvements in engine efficiency. Eventually, the Northrop Grumman team, which also included Rolls-Royce, Wyle Laboratories, and Iowa State University, abandoned the radical twin-fuselage configuration in favor of a flying wing based directly on the Northrop Grumman B-2A bomber design heritage.[21]

Northrop Grumman had a long history with flying-wing designs dating to aviation pioneer John K. "Jack" Northrop. By 1947, his company was flying a prototype eight-engine, jet-powered flying wing bomber, the YB-49A, with a span of 172 feet, a top speed of more than 400 miles per hour, and a range of nearly 3,000 miles with a 10,000-pound payload. Northrop also explored the possibility of producing an 80-passenger commercial transport variant, though it was never built. Northrop Grumman's entry for the ERA design

19. Ibid.
20. Ibid.
21. Mangelsdorf, "Environmentally Responsible Aviation N+2 Advanced Vehicle Concepts NRA Status," 1–20.

Northrop developed a notable and frontier-breaking family of small and large flying wings. Here is the largest, the jet-powered eight-engine YB-49A, shown during a 1948 test flight over the Muroc bombing range. While visually impressive, the YB-49A—like all early flying wings—was impractical, with serious stability and control deficiencies. Modern digital electronic flight control technology, coupled with advances in composite structural materials, makes such aircraft practical. (USAF)

competition echoed this "Flying Wing airliner of tomorrow" concept but with all the advantages of modern technology.[22]

As Northrop Grumman ERA program manager Aaron Drake noted, this approach came very naturally to the company's design team. "The airplanes of today look very similar to how they've looked for 50 or 60 years, and because of that, there has been a lot of time to optimize those airplanes," he said, explaining that the tube-and-wing configuration has undergone continual improvement to maximize efficiency. "What we're looking at [now] is taking advantage of configurations that are different than the conventional transport airplanes,

22. For Northrop's extensive studies of flying wings, see Tony Chong's book *Flying Wings and Radical Things: Northrop's Secret Aerospace Projects and Concepts 1939–1994* (Forest Lake, MN: Specialty Press, Inc., 2016), 10–16, 25–34, 39–42, 49–50, 55–63, 69–70. Chong is the recipient of the History Manuscript Award of the American Institute of Aeronautics and Astronautics.

ones that maybe draw on sort of unique military heritage—airplanes that were designed for other missions—and then take what's been learned from that."[23]

In particular, Drake noted the low-drag aerodynamic advantages of the flying wing configuration. "Flying wings offer a lot of inherent efficiency advantages, largely because every part of the aircraft actually is performing the function of flying," he said. "You're not carrying extra structure, fuselage, whatever, just to carry passengers; it's all working toward the goal of flying efficiently." He added that his team had identified a number of technologies in various levels of maturity that might, with additional work over the next few years, be incorporated into the design of a flying-wing transport to improve its efficiency. "One of the technologies that we're looking at is swept-wing laminar flow control, basically technology to make the aerodynamics better and reduce drag," he said. "Essentially what it means is designing the wing so that the air that passes over the wing does so more smoothly [so that] you get less drag." This technique has already been applied to airplanes with long, thin, straight wings, such as the Northrop Grumman RQ-4 Global Hawk. "Applying it to a transport like the ERA aircraft is more difficult than our past applications because of the wing sweep, and because of the size of the airplane."[24]

Northrop Grumman's PSC called for building the airframe using a combination of conventional materials and advanced composites. "Our concept makes extensive use of composites, but not in a way that is particularly risky," said Drake. "These are sort of conventional approaches to composites that have been well proven in military applications, [the benefits of which can now] be extended into transport aircraft."[25]

When designing a flying wing configuration, the passenger/cargo compartment layout "drives the center-body, and the propulsion system is integrated with the flow path and side clearances," Drake explained. The 224-seat passenger version of the company's PSC had a 260-foot span and a wide center-body cabin that was 119 feet in length. The Northrop Grumman team also proposed a freighter variant, spanning 230 feet, with a slenderer center-body and a 100,000-pound cargo capacity. "We're focusing a lot also on the cargo applications of it, because that's just as important for transport efficiency," Drake said. He emphasized that despite the airplane's size and unusual configuration, the large flying wing could be easily integrated into existing airport environments. "It still fits on conventional taxiways because we haven't pushed

23. Aaron Drake interview with Johnny Alonso, NASA 360, S03E22, NASA podcast, December 5, 2011, transcript at *http://www.nasa.gov/multimedia/podcasting/nasa360/nasa360-0322.html*, (accessed September 3, 2016).
24. Ibid.
25. Ibid.

beyond what some of the very largest airplanes flying today have in terms of the sort of space that they take up at the airport." In fact, taking advantage of such advanced technologies as laminar flow control that promote reduced fuel consumption means that the airplane can be made smaller that it might be otherwise since less airframe space for fuel tanks is required.[26]

The flying-wing configuration also offered opportunities for jet noise reduction. Unlike most conventional transport aircraft, where the engines are located beneath the wings or on either side of the fuselage, the powerplants would be buried inside the wing itself. As on the B-2A, exhaust gases would vent across wide, flat channels on the aft upper surface, allowing the aircraft structure to block some of the noise generated by the engines. The inherent size of the airfoil itself would also allow for good performance at low speeds, such as during takeoff and landing, without the need for the kinds of high-lift devices typically found on the leading and trailing edges of conventional wings. Airflow around these devices is a leading source of airframe-generated noise. "By not having those, we make our airplane a lot quieter," said Drake. He added that the team's concept was built around manufacturers' descriptions of expected future powerplants to be developed over the next decade or so that will have improved efficiency and reduced noise levels. "So, this is an airplane that in operational service would have something like 40 percent less fuel consumption than the current airplanes that are out there today, and it would be much, much quieter." So much so, he insisted, that, "If you were outside the airport boundaries, you probably wouldn't hear it during takeoff."[27]

By the end of the Advanced Vehicle Concepts study, the Northrop Grumman PSC had a predicted noise reduction of around –74.7 decibels, emissions 88 percent below current levels, and fuel burn 41.5 percent below the 1998 baseline. Among the team's key design concepts were composite wing structures, integrated high-bypass engines, advanced inlets, maneuver-load alleviation, and carbon-nanotube data cables. Northrop Grumman proposed to build a 55 percent scale STV spanning 143 feet and powered by four General Electric Passport (formerly called TechX) high-bypass turbofans. "The biggest benefit is in the advanced propulsion," Drake stated, "which provides 20 percent of overall improvement; second is swept-wing laminar flow, which contributes around 8.3 percent."[28]

26. Ibid.

27. Ibid.

28. Norris, "Future-Airliner Concept Contenders Reveal Design Surprises."

Boeing Consortium: Advancing the Hybrid Wing-Body

Boeing led a consortium composed of Pratt & Whitney, Rolls-Royce, the Massachusetts Institute of Technology, and Cranfield Aerospace (the latter a British partner). Despite Boeing's long history with tube-and-wing airliners, the company chose to pursue a cutting-edge HWB reflecting the work of noted aerodynamicist Robert Liebeck, powered by either two GTF engines or three UHB open-rotor propfans (turbine engines featuring contra-rotating fan stages not enclosed within a casing). The design incorporated a variety of technologies to reduce noise and drag, and long-span wings to improve fuel efficiency.

At first glance, the HWB looks much like a flying wing in that there is no clear dividing line between the wings and the main body of the aircraft. But upon closer examination it becomes clear that though the wings are smoothly blended into the body, the airframe is composed of distinct wing and body structures. Unlike a flying wing, which has no distinct fuselage, the HWB features a central crew/passenger/cargo section that is clearly more body than airfoil. With a relatively wide center-body chord and a narrow wing chord, the HWB has been described as resembling a manta ray.

The Boeing team realized that the HWB planform offered significant improvements in lift-to-drag (L/D) ratio versus a tubular fuselage—because lift is distributed over a broader area—as well as opportunities to take advantage of such enabling technologies as lightweight, damage-arresting composite structures, laminar-flow-control techniques, acoustic shielding, low-speed flight controls, and high-efficiency engines.

The Boeing team's advanced vehicle concept PSC featured pylon-mounted engines positioned between the tails and forward of the trailing edge. Boeing ERA program manager John Bonet explained that this decision was based solely on a desire to minimize the airplane's acoustic footprint. Earlier design iterations featured engines embedded within the trailing edge, which reduced drag but not noise because there was nothing to shield the exhaust. "If it were only [a matter of] aerodynamic efficiency, we would have them hanging off the back, but you wouldn't have any shielding of the engines and the [HWB] would be just as loud as a tube-and-wing airplane," Bonet said.[29]

Boeing engineers assumed a 14 percent fuel-burn benefit based on detailed analysis of operating in NextGen airspace. Choice of engine was also important, which is why the team considered two powerplant options for the HWB. The first configuration, featuring twin high-bypass-ratio GTF engines, was projected to achieve a 52 percent reduction in fuel burn, beating the nominal

29. John Bonet interview with Juan Alonso, NASA 360, S03E22, NASA podcast, December 5, 2011, transcript available at *http://www.nasa.gov/multimedia/podcasting/nasa360/nasa360-0322.html*, (accessed September 3, 2016).

target, but it fell short of NASA's noise goal by realizing only a 34-decibel reduction. The second and more unconventional configuration was powered by three General Electric/CFM Leap-X-based propfans. This arrangement afforded even lower fuel consumption through better engine performance and reduced emissions, but the open-rotor was 8 decibels noisier than the GTF-powered version.[30]

Minimizing engine noise revealed a host of other acoustic sources that would have to be dealt with, but also afforded the opportunity to meet the –42-decibel goal through reduction of airframe noise. "We noticed that jet noise is so low on the HWB that other sources become dominant," said Bonet, noting that advanced landing gear and slat-noise reduction could make up the difference. "Airframe noise reductions are the only ones that will allow us to meet the noise goals."[31]

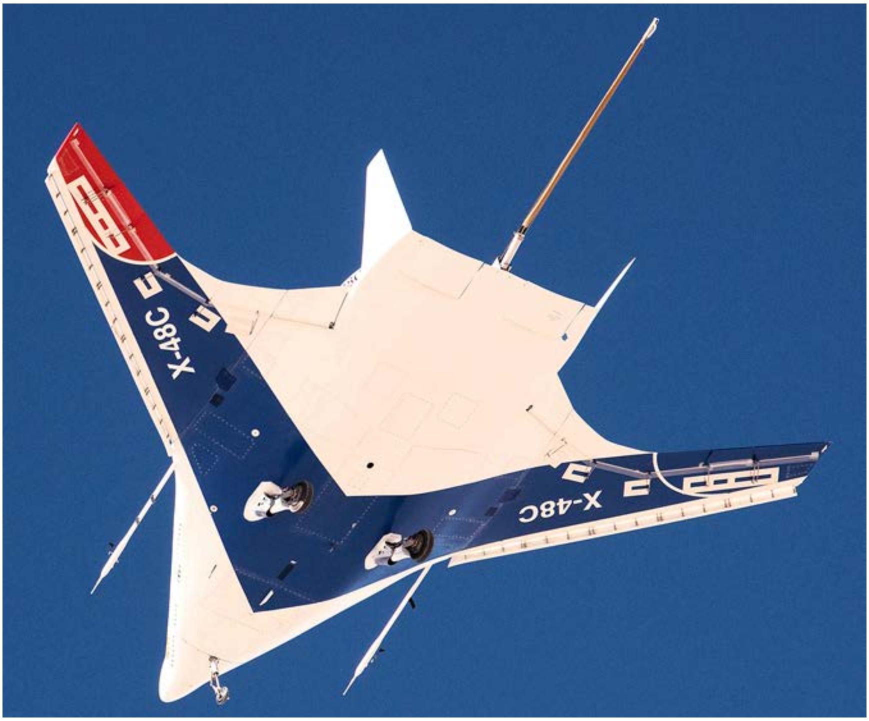
Boeing proposed building a 65-percent-scale version of the team's preferred concept. The 83-foot-long, 149-foot-span STV was to be powered by twin 24,000-pound-thrust Pratt & Whitney PW1000G GTF engines. The HWB airframe configuration necessitated a modular, stitched resin-infused composite structure, but cost reduction could be realized through the use of commercial off-the-shelf (COTS) landing gear and a modified business-jet flight deck with modular electronics. The wings would not initially be equipped for drag-reducing laminar flow, though it would be possible to introduce the feature later on.[32]

Subscale HWB Testbed

Although not part of the AVC study, the Boeing/Cranfield team leveraged lessons learned from their HWB design efforts by flight-testing the subscale remotely piloted X-48B/C research vehicle. The demonstrator performed 92 flights in the X-48B configuration during Phase 1 and an additional 30 flights between August 2012 and April 2013, after being modified to the X-48C configuration.

This second phase of testing directly supported the ERA project by demonstrating a noise-shielding configuration. "We have accomplished our goal of establishing a ground to flight database and proving the low speed controllability of the concept throughout the flight envelope," Collier proclaimed at the conclusion of X-48C flight-testing, adding, "The hybrid wing body

30. Norris, "Future-Airliner Concept Contenders Reveal Design Surprises."
31. Ibid.
32. Ibid.



Flight-testing at NASA AFRC of the subscale Boeing-Cranfield X-48C Remotely Piloted Aircraft demonstrated the low-speed handling characteristics of a proposed HWB transport. (NASA)

has shown promise for meeting all of NASA's environmental goals for future aircraft designs."[33]

The Study Teams' Final Reports

When Lockheed Martin, Boeing, and Northrop Grumman submitted their final reports in early January 2012, each team offered a preferred system concept that either met or closely matched NASA's stringent noise, emissions, and fuel-burn targets for airliners entering service in the late 2020s. Each team was also asked to sketch out a 15-year technology maturation road map and propose critical technology demonstrations for the second half of the ERA program. NASA officials had expected each concept to score high marks, but the teams presented a surprisingly wide array of unanticipated technologies and innovations. In addition to the unconventional flying-wing and HWB designs from Northrop Grumman and Boeing, and an innovative Rolls-Royce engine

33. Gray Creech, "X-48 Research: All good things must come to an end," *http://www.nasa.gov/topics/aeronautics/features/X-48_research_ends.html*, April 17, 2013, (accessed September 5, 2016).

powering Lockheed Martin's joined wing concept, the AVC studies unexpectedly highlighted significant benefits that would result from flying advanced airliners within the FAA's NextGen airspace system. Fay Collier noted, "There were a number of things I hadn't anticipated, and one was the benefit of [NextGen improvements to the] national airspace system; that's a low-hanging fruit, maybe, and confirms a number that came out of our colleagues in the SFW program."[34]

To maximize the STV's value as a research platform, NASA asked the AVC study teams for designs with a 10,000-hour, 20-year service life. Additionally, following the ERA program, the optionally manned STV was to be flown autonomously as part of a research effort to integrate unmanned aircraft systems into the national airspace system in 2020–2025. The STV might then finish its career as a testbed for ERA's sister effort, the SFW fundamental research program, from 2025–2030.[35]

By the time the AVC studies were completed, however, according to Mangelsdorf and Rich Wahls, NASA was facing a looming budget squeeze that forced the Agency to reconsider its ambitions for funding a flying, full-scale STV demonstrator in the near term.[36] "It quickly became apparent that ERA was not going to have a budget profile to do a half-scale X-plane," Wahls said.[37]

Ultimately, the AVC study only represented about 5 percent of the total ERA Phase 1 investment, but successes during this phase provided ARMD decision makers with the necessary confidence to proceed through the next key decision point and gain authority to undertake Phase 2. Results of the AVC contracts were then used as a foundation upon which to build the case for an eventual X-plane program sometime after the conclusion of the ERA project. In fact, the project management tools and rigor established in ERA and subsequent projects, along with information first generated in the AVC studies, were crucial to building ARMD confidence in such X-Plane programs as the low sonic boom flight demonstrator.

NASA Reaches Key Decision Point

Toward the end of ERA Phase 1, as the key decision point approached, NASA established a Tiger Team for down-selecting key technologies to be explored in greater detail during the second phase. Substantial progress on the broader aspects of Phase 1 informed the development of technology road maps and

34. Norris, "Future-Airliner Concept Contenders Reveal Design Surprises."
35. Norris, "Future-Airliner Concept Contenders Reveal Design Surprises."
36. Mangelsdorf interview.
37. Wahls interview.

priority targets for Phase 2, which were shaped, in part, by the results of the vehicle concept studies.[38] The resulting plan for the remainder of the program focused on eight integrated technology demonstrations (ITDs) that were completed by NASA researchers and industry partners overseen by project managers (named in parentheses) at LaRC, AFRC, and GRC. These ITDs included:

- ***Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS):*** Assessment of a low-weight, damage-tolerant, stitched composite structural concept for stitching together large sections of lightweight composite materials that could be used in uniquely shaped future aircraft that weighed up to 20 percent less than a similar all-metal aircraft. (LaRC: Dawn Jegley)
- ***Adaptive Compliant Trailing Edge (ACTE):*** A radical new morphing wing technology that allows an aircraft to seamlessly extend its flaps, leaving no drag-inducing, noise-enhancing gaps for air to flow through. (AFRC: Tom Rigney)
- ***Flap and Landing Gear Noise Reduction Flight Experiment:*** Analysis, wind-tunnel and flight tests to design quieter flaps and landing gear without performance or weight penalties and develop new design tools to aid engineers in reducing noise from deployed wing flaps and landing gear during takeoff and landing. (LaRC: Mehdi Khorrami)
- ***Highly Loaded Front Block Compressor Demonstration:*** Tests to show ultra-high-bypass (UHB) or advanced turbofan efficiency improvements of a two-stage, transonic high-pressure engine compressor, and refine the design of a General Electric open rotor compressor stage of a turbine engine to improve its aerodynamic efficiency. (GRC: Ken Suder)
- ***2nd Generation UHB-Ratio Propulsor Integration:*** Collaboration with Pratt & Whitney on the company's geared turbofan jet engine to improve propulsion efficiency and reduce noise. (GRC: Ken Suder)
- ***Low NOx Fuel Flexible Engine Combustor Integration:*** Testing an improved design for a jet engine combustor to reduce NOx emissions. (GRC: Ken Suder)
- ***UHB Engine Integration for a Hybrid Wing-Body:*** Computer modeling and wind-tunnel verification of HWB airframe/powerplant integration concepts to reduce noise and fuel consumption. (LaRC: Greg Gatlin)

38. Norris, "Future-Airliner Concept Contenders Reveal Design Surprises."

Environmentally Responsible Aviation

Integrated Technology Demonstrators	Partner
AFC Enabled Vertical Tail and Advanced Wing Flight Experiment	Boeing
Damage Arresting Composites Demonstration	Boeing
Adaptive Compliant Trailing Edge Flight Test	AFRL/FlexSys
Highly Loaded Front Block Compressor Demonstration	General Electric
2nd Generation UHB Propulsor Integration	Pratt & Whitney
Fuel Flexible, Low NOx Combustor Integration	Pratt & Whitney
Landing Gear and Flap Edge Noise Reduction Flight Test	Gulfstream
UHB Integration on Hybrid Wing-Body Aircraft	Boeing

Work during ERA Phase 2 focused on eight integrated technology demonstrations undertaken with several industry partners, and with the Air Force Research Laboratory (AFRL).

- ***Boeing ecoDemonstrator 757:*** Use of a full-scale flying laboratory to demonstrate an active flow control (AFC) enhanced vertical tail flight experiment that could enable future aircraft to fly with smaller tails, thus reducing weight and drag, and an Insect Accretion Mitigation (IAM) to test wing surface coatings designed to minimize drag caused by bug residue building up on the leading edge. (LaRC: Mike Alexander)

The challenge the ERA faced with these eight ITDs was simple but formidable: winnow down the number of possible ITDs and then build manageable work efforts to achieve them within the remaining 3 years. Such schedule consciousness may have shocked those accustomed to working on programs with flexible end dates, but was, in fact, a rediscovery of the time-and-schedule consciousness the Agency had earlier displayed, in the heyday of the Space Race in the 1960s.

Researchers intentionally damaged a critical portion of a PRSEUS composite panel to observe whether the damage progressed under stress. Only after being subjected to stresses well beyond those expected during flight did it finally fail, resulting in the tear seen here. (NASA)

CHAPTER 3

Pursuing Damage-Tolerant Composite Structures

The Phase 2 ITDs aggressively pushed the technological state of the art. Thus, although innovative airframe concepts like the HWB offered characteristics that might dramatically reduce fuel consumption, they also presented significant design challenges. For example, constructing a non-circular pressure vessel capable of meeting the necessary reduced structural-weight requirements required a novel approach. Researchers at NASA and Boeing teamed up to advance a new structural concept called Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) for stitching together large sections of damage-tolerant, lightweight composite materials that could be used to build uniquely shaped future aircraft weighing as much as 20 percent less than similarly sized all-metal airframes. During ERA Phase 2, researchers assessed structural test articles assembled from integrally stiffened PRSEUS panels designed to maintain residual load-carrying capabilities under a variety of damage scenarios.[1]

NASA-led research and development of advanced composite structures began during the 1970s in response to rising fuel costs and perceived requirements for more energy-efficient commercial transports. Launched at LaRC in 1976, the Aircraft Energy Efficiency (ACEE) program sought to dramatically reduce airline fuel consumption through improved aerodynamic efficiency and lighter structures as well as development of improved engines. Composites research became a centerpiece of the ACEE program, with the primary goal of accelerating the application of composite primary structures in future civil air transport aircraft designs. Although this goal was never achieved by the time ACEE ended in 1985, contracts with Boeing, McDonnell Douglas, and Lockheed provided the aircraft industry with important new technology. Without the impetus of a NASA technology program, industry players lacked confidence to proceed with such a high-risk investment as using composites

1. Dawn C. Jegley and Alexander Velicki, “Development of the PRSEUS Multi-Bay Pressure Box for a Hybrid Wig Body Vehicle,” AIAA-2015-1871, presented at 56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Kissimmee, FL, January 8, 2015, 1.

for primary structural components. There was not yet sufficient evidence that composite structures could be produced more economically than aluminum assemblies, or that conventional laminated composites could withstand the rigors of routine flight operations with minimal damage.[2]

New manufacturing techniques were necessary to overcome these hurdles, and so researchers turned to methods similar to those used by the textiles industry. Advanced composite assemblies would need to be made using woven, knitted, braided, or stitched bundles of carbon filaments (called tows) to make dry preforms. These would then be subjected to resin transfer molding, or resin film infusion (RFI), to produce a composite with through-the-thickness reinforcement. As with conventional composites, the epoxy resin was cured using heat and pressure inside an autoclave. The process could be facilitated by using sheets of material that have been pre-impregnated ("pre-preg") with epoxy resin that could be stored in bulk in a cool area until use. Additionally, in order to reduce labor-intensive operations, production methods would need to be automated to the greatest extent practical. After examining several potential methods for manufacturing preforms, NASA researchers settled on a method involving stitching. Compared to other processes (such as weaves, knits, and braids), stitching offered the greatest potential for cost-effective manufacturing of damage-tolerant structures. In fact, several military programs already employed stitched carbon/epoxy pre-preg with Kevlar thread to enhance the structural integrity and damage tolerance of thin composite panels. Unfortunately, in the mid-1980s, these methods were of limited use for stitching the thick pre-pregs that would be required for use in large wing structures.[3]

NASA researchers at LaRC explored the potential of several textile processes for use in cost-effective production of damage-tolerant structures. Despite known deficiencies in shear stiffness (resistance to deformation in response to lateral strain), biaxial woven and knitted fabrics were considered simply because they were readily available from commercial sources. A tri-axial weave would have been better, but at the time, such a thing was not commercially available. In fact, the textile industry did not see a sufficient market for woven carbon fabrics to make production a worthwhile investment. Instead, researchers began looking at a process to manufacture tri-axial warp-knit fabric. This technique combined warp knitting with stitching for through-the-thickness reinforcement to create useful preforms. Testing at LaRC provided data for identifying

2. Marvin B. Dow and H. Benson Dexter, "Development of Stitched, Braided and Woven Composite Structures in the ACT Program and at Langley Research Center (1985 to 1997)," NASA TP-97-206234, November 1997, 1, 1–8.
3. Ibid., 1–2.

knitted preforms with the best combination of strength and damage tolerance. McDonnell Douglas later used these data in selecting a warp-knit fabric that could be used in the fabrication of a composite wing structure. NASA researchers also looked at braiding carbon tows to create a multi-axial preform that would be useful for producing damage-tolerant composite laminates. They discovered, however, that the same reinforcement feature of the braids that contributed to low damage-tolerance also reduced the laminate's in-plane strength. Moreover, existing commercial braiding machines could not economically produce large-area preforms. Lockheed Martin and Northrop Grumman conducted in-house research demonstrating the usefulness of braided composites for smaller structures including window belts, curved fuselage frames, and wing stiffeners, where flexibility and damage tolerance are essential. Similarly, McDonnell Douglas adopted braided preforms for blade-section stiffeners on wing covers.[4] The greatest promise, however, lay in stitching.

Advanced Composite Technology

In 1987, NASA issued an NRA seeking proposals for innovative approaches to cost-effective composite fabrication, enhanced damage tolerance, and improved analysis methods. The response from industry and academia included 48 proposals, of which 15 were accepted for contract awards. The following year, these contracts became the basis for the Advanced Composite Technology (ACT) program, which focused on developing composite primary structure for fuselage and wing assemblies, and provided impetus for a rapid transition of this technology to industry. ACT program managers specified a goal of reducing the structural weight of a future commercial transport aircraft by 30 to 50 percent while also reducing manufacturing costs by as much as 25 percent. The resulting primary wing and fuselage structures had to behave (structurally) in a predictable manner, meet FAA requirements for certification (including with regard to damage tolerance), and be repairable in a manner acceptable to the airlines. Another important objective of the ACT program was development of an integrated, affordable composites technology database to foster a rapid and timely transition of this technology into production airframes. Administrative management for the ACT program was assigned to the Structures Technology Program Office at LaRC, and each company that received a contract had its own focus. Boeing concentrated on low-cost, automated fabrication techniques. Several other contractors investigated new RTM materials and processes. Lockheed Martin, Northrop Grumman,

4. Ibid., 2–3.

and McDonnell Douglas worked on design and fabrication of composite aircraft structures.[5]

McDonnell Douglas had been investigating a revolutionary process that involved stitched dry carbon fabric preforms and reinforced composite laminates. Best of all, the resulting assemblies demonstrated outstanding damage tolerance, acceptable fatigue performance, and good strength properties. The company employed an integrated approach that balanced compromises between design and manufacturing in order to simplify fabrication tools, lessen thermal distortion, improve accuracy during assembly, and prevent separation due to out-of-plane loads.[6]

To showcase the process, McDonnell Douglas demonstrated a building-block approach to assembling a wing stub box with a 12-foot span and 8-foot chord. The stub box featured stitched upper and lower covers including skin, blade-stiffeners, spar caps, and intercostals (the supporting structures between load-bearing members) as integral structures. Technicians at the McDonnell Douglas plant in Long Beach, California, fabricated large tension and compression panels, which later underwent testing at LaRC. Evaluation of various epoxy resins led to the conclusion that a formula called Hercules 3501-6 had the best properties and cost advantages. Fabrication of the stub box successfully demonstrated a full-scale stitched/RFI process for assembling an integral wing cover incorporating heavy spar caps, intercostals, and stiffeners with runouts. The build team also took advantage of lessons learned during process development. Replacing uni-weave fabric, for example, with multi-axial warp-knit fabric preforms eliminated many handling and lay up problems.[7]

In July 1995, the fully assembled wing stub box arrived at LaRC, where it was bolted to a massive steel backstop in the Materials Laboratory for a series of static loading tests. These included tests building up to the design limit load (DLL), the maximum load factor authorized during operational service. Researchers also gauged the results against the calculated design ultimate load (DUL), the point at which catastrophic failure was expected to occur. Objectives included demonstrating that stitched panels could meet stringent FAA damage and repair criteria, and particularly that damaged composite panels could be restored to design ultimate strength. Prior to the DLL test, technicians purposely inflicted visible damage at a critical location. To promote realism, all repairs were made by aircraft maintenance technicians from American Airlines using mechanically fastened plates. This work was completed before subjecting the test article to the DUL test, during which the stub

5. Ibid., 4.
6. Ibid., 6.
7. Ibid., 6.

The McDonnell Douglass-fabricated composite wing stub box undergoing loads testing at LaRC in 1995. McDonnell Douglas subsequently merged with Boeing in August 1997. (NASA)

box failed at a load equivalent to 143 percent DLL. Notably, failure occurred close to the test-fixture mounting point, a metal assembly located some distance from the repair site.[8]

By this time, work was already under way to design, build, and test a 42-foot semi-span composite wing. Researchers from both NASA and McDonnell Douglas considered this a necessary step in the building-block approach to fabricating and testing a full span stitched composite wing-and-center-box assembly of the type that could be used on a 220-seat, single-aisle aircraft. In terms of size and complexity, the semi-span wing test article represented a major step forward. Whereas the stub box was a simple structure with flat cover panels, the wing would require aerodynamically contoured covers, as well as simulated control surfaces, engine pylon attachment, and landing gear fairings. Meeting the challenge of these requirements called for advanced tooling concepts and new computer modeling techniques.[9] Boeing assumed responsibility for these efforts following the company's merger with McDonnell Douglas in August 1997.

One objective of the semi-span wing development was to demonstrate technology readiness through processing, scale-up, and structural testing. Researchers

8. Ibid., 6.
9. Ibid., 6.

used the results to develop and verify techniques to be used in the design, manufacture, and testing of a follow-on full-scale aircraft wing. First, designers established specifications for a representative composite wing box structure as part of efforts to develop detail design features along with the associated analytical and manufacturing techniques. This wing box was derived from an aircraft concept representative of a next-generation twin-engine, 220-passenger commercial aircraft equipped with a supercritical airfoil wing with an aspect ratio of 12:1 that was optimized using composite material properties.[10]

For test purposes, the semi-span box represented only the first 42 feet of the wing starting from the aircraft side-of-body splice outward toward the wingtip. It consisted of an upper and lower stitched/RFI cover, two spars, and 18 ribs spaced approximately 30 inches apart. Composite stringers were spaced 7.6 inches apart, compared to 6.5-inch spacing for stringers used on typical aluminum wing panels. Taking advantage of the stitching technology, many components were integrated into the cover panels. This reduced the assembly part count and eliminated thousands of fasteners and their associated costs and weight penalties. Each cover panel consisted of multiple stacks of uni-axial warp-knit carbon fiber material stitched together to form the wing skin. Additional structural details stitched into the skin panel included blade stiffeners to give added structural stability and interleaved spar caps and intercostal clips for attaching various substructural components. This substructure consisted of ribs and bulkheads made of conventional tape lay up carbon composite pre-preg and spar webs of stitched/RFI multi-axial warp knit material. Stiffening elements were fabricated by bonding pre-cured stiffeners to pre-cured flat webs. To complete the box assembly, mechanical fasteners were used to attach the cover panels to the substructure. Once completed, the dry preform assembly was placed into rigid tooling and infused with resin in an autoclave.[11]

Boeing shipped the completed McDonnell Douglas–legacy wing box to LaRC, where engineers mounted it to a laboratory wall for testing. Researchers introduced loads using hydraulic jacks to simulate representative aircraft design requirements. Although the semi-span test article did not fully represent an optimized wing box design, it included many important design features that emerged as potential solutions to issues that needed addressing in the design of a stitched/RFI composite wing box for commercial aircraft applications.[12]

Following these tests, Boeing continued efforts to develop cost-effective composite manufacturing processes in support of the NASA Airframe

10. Ibid., 24.
11. Ibid., 25–26.
12. Ibid., 25–26.

McDonnell Douglas researchers focused their early composite wing structure research toward application to future derivatives of the firm's MD-90 series of commercial transports; here is a Delta Airlines Boeing 717 (N978AT) originally ordered by Air Tran as an MD-95. (R. P. Hallion)

Materials and Structures element of the Advanced Subsonic Technology (AST) program. Earlier ACT research results showed great promise for reducing both manufacturing-cost and damage-tolerance barriers to the application of stitched/RFI materials in primary structures for commercial transports. Replacing thousands of mechanical fasteners with a highly automated stitching process had the potential to significantly reduce manufacturing costs of composite structures while simultaneously reducing stress-induced damage and airframe weight. Such advances in composite structure fabrication represented a significant advantage over metallic designs. Toughened-resin systems used during ACT efforts in the 1980s showed promise for improving the damage tolerance of carbon fiber composites, but high costs offset the benefits. Development of through-the-thickness stitching of dry preforms provided a more affordable alternative.[13]

Goals of the AST program included making composite wing structures 25 percent lighter than current aluminum wing designs, reducing fabrication costs by 20 percent, and reducing airline operating costs by approximately 4 percent. Preliminary design studies by Boeing under LaRC contract NAS1-20546 showed that these goals were achievable. Using a wing-torque-box design

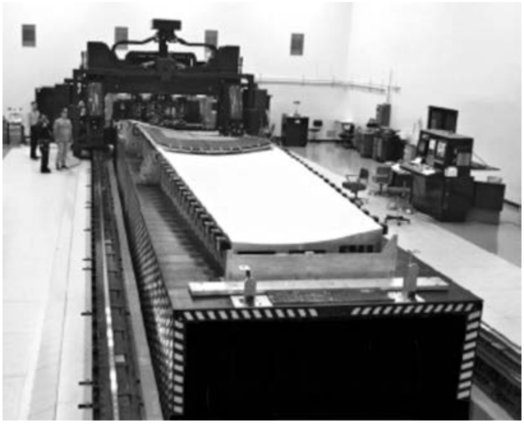
13. Ibid., 1.

applicable to an MD-90-40X commercial passenger transport, the company conducted a weight-trade study that verified the weight savings a stitched/RFI structure would offer compared to an identical wing box design built from aluminum alloys. Under the AST Composite Wing program, Boeing planned to build and test a full-scale, full-span, wing-box/fuselage section to demonstrate the maturity of stitched/RFI technology, but due to program scope reductions the full-scale structural test article was never built.[14]

Among the most significant results of the ACT program were development of automated stitching equipment for fabricating an integral wing skin and stiffener concept and improved understanding of the structural mechanics of stitched composites, damage containment, and failure effects. NASA awarded Boeing a contract to develop a high-speed, multi-needle Advanced Stitching Machine (ASM) capable of stitching entire wing covers for large commercial transport aircraft. The Ingersoll Milling Machine Company of Rockford, Illinois, was selected to design and build the ASM under subcontract to Boeing. Pathe Technologies, Inc., of Irvington, New Jersey, designed and built the ASM's advanced stitching heads. In a cost-sharing effort, NASA spent $10 million on development of the ASM and Boeing paid for renovations at the company's Marvin B. Dow Stitched Composites Center in Huntington Beach, California, which underwent extensive modification to accommodate the ASM.[15]

Equipped with four stitching heads, the ASM combined high speed with advanced automation, allowing manufacturers to assemble large complex wing structures without manual intervention. The ASM was capable of stitching single-piece aircraft wing cover panels 40 feet long, 8 feet wide, and 1.5-inches thick, at a rate of 3,200 stitches per minute. The stitching heads were capable of making eight stitches per inch with precision row spacing of just 0.2 inches. Achieving this rate required development of an automated thread gripper and cutting mechanism and a pivoting needle mechanism, as well as a cooling system to prevent excessive needle temperature buildup and bending. Prior to stitching a wing panel, a laser projection system precisely located the dry fabric wing skin preforms and any secondary materials, such as stiffeners. Computer controls directed and confirmed the stitching pattern and allowed for 38 axes of motion. Automated controls then synchronized the movements of the stitching heads with each of 50 lift tables necessary to control stitching over the contoured shapes of the airfoil. Researchers demonstrated that the ASM was

14. Ibid. 1–2.
15. Darryl R. Tenney, John G. Davis Jr., R. Byrin Pipes, and Norman Johnson, "NASA Composite Materials Development: Lessons Learned and Future Challenges," presented at NATO RTO AVT-164 Workshop on Support of Composite Systems, Bonn, Germany, October 19, 2009, 19.



The automated NASA-Boeing-Ingersoll Advanced Stitching Machine made it possible to assemble large complex wing structures quickly and without manual intervention. (NASA)

capable of stitching wing cover panels in a single two-shift operation that saved days over conventional composite manufacturing processes. Moreover, subsequent cost analyses indicated that a reduction of 20 percent could be achieved over equivalent wings built from aluminum alloys, and the desired weight savings goal was achieved as well.[16]

In order to support future FAA certification of composite wing structures for commercial transports, ACT researchers had to develop new test procedures and analyses databases. Numerous material samples, sub-elements, and elements underwent extensive testing prior to trials involving larger test articles. Researchers performed pre- and post-test analyses on each item and test article in order to understand failure modes and validate analytical methods. These efforts culminated in testing of the 41-foot-long stitched/RFI composite semi-span wing assembly in 2000. Over the course of eight trials in the LaRC Structures and Materials Laboratory, this structural test article was subjected to multiple specified load conditions under simulated positive and negative g-loading to incrementally build up to and exceed the DLL.[17]

Researchers installed a total of 466 strain gages on the edge of critical access holes at the midplane, but not on the cover panel surface. Additional gages were placed on the skin and stringer-blade surfaces. Resulting data indicated that local nonlinear deformations occurred in the upper cover panel in an unsupported region behind the rear spar. High strain levels were also detected at access holes on the lower cover panel. One surprise was that larger local displacements and strains occurred during the test than had been predicted by nonlinear finite element model (FEM) analysis. Post-test analyses suggested that further refinements to the FEM might provide a better agreement between analytical results and test data. Otherwise, experimental and analytical results

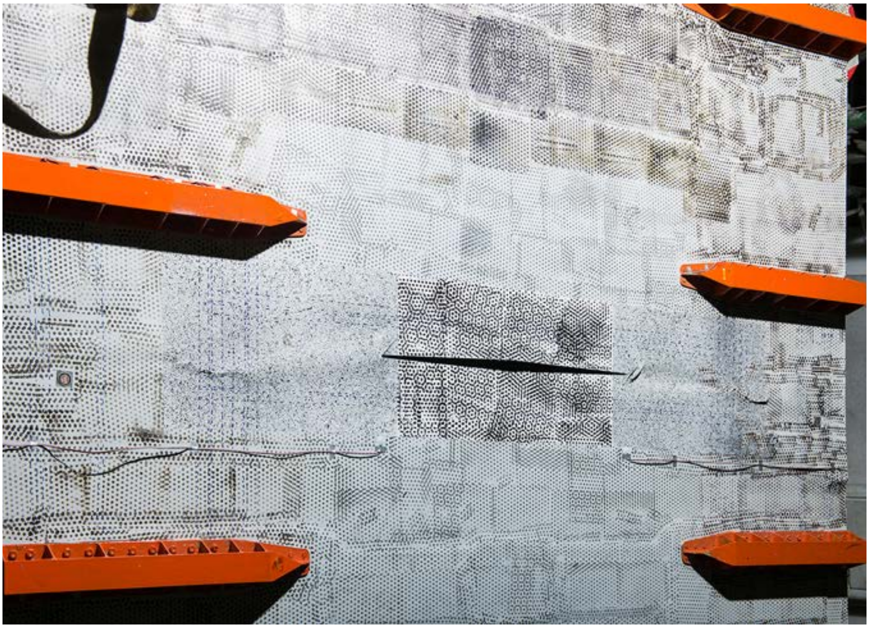
16. Ibid., 19–20.
17. Ibid., 20.

were in generally good agreement. This further validated the importance of a building-block approach to developing and understanding the behavior and failure modes of composite structures.[18]

After successfully completing the first six tests, researchers inflicted discrete source damage on the upper and lower cover panels of the wing by making 7-inch-long saw cuts to both the upper and lower cover panels. Each cut ran through two stinger bays and cut through a stringer. The airfoil was then loaded to 70-percent DLL in a 2.5g up-bending condition and unloaded (relaxed). Once the airfoil was relaxed, technicians repaired the damaged area to restore the wing to full load-carrying capability. Repairs consisted of a metal plate that conformed to the wing contours on the outer surface of the cover panels, and internally spliced stringers. All parts of the repair assembly were attached to the wing using conventional mechanical fasteners. Researchers then inflicted six impacts on the test article. First, a 25-pound, 1.0-inch-diameter falling weight was dropped three times from a height of 4 feet, resulting in barely visible damage to the upper cover panel. The depth of the resulting damage ranged from 0.01 to 0.05 inches. Next, an air-propelled steel projectile was used to inflict three impacts to the lower cover panel with an energy level of 83–84 foot-pounds. The 0.5-inch-diameter steel sphere was accelerated to a speed of approximately 545 feet per second, resulting in clearly visible damage with indent depths up to 0.135 inches. The wing was then loaded to failure in a 2.5g up-bending load condition. Ultimately, the test article withstood 97 percent of the DUL prior to failing through a lower-cover access hole, which resulted in the loss of the entire lower cover panel.[19]

These results were quite good, and the research team came away with many valuable lessons. Among these was that the building-block approach based on tests and analyses of materials and components that make up the structure imparted significant risk reduction, as well as providing important data and analyses to support the FAA certification process. Researchers noted that composite structures tended to fail in quasi-brittle mode, and that out-of-plane loads (often ignored when manufacturing metal structures) must be considered. Applying loads to areas with perforations such as fastener holes and access openings, stiffener run-out, and sites of discrete damage (even when barely visible) have potential for delamination and failure. The ACT program identified issues in design, analyses, fabrication, and testing of built-up structure that formed the basis for identifying important thrusts for composite

18. Ibid., 21.
19. Ibid., 20–21.



Researchers intentionally damaged a critical portion of a PRSEUS composite panel to observe whether the damage progressed under stress. Only after being subjected to stresses well beyond those expected during flight did it finally fail, resulting in the tear seen here. (NASA)

fabrication techniques and provided insight into the potential payoff of new technology development.[20]

Perhaps surprisingly, many years passed following completion of the ACT program before the first stitched-composite production part flew on an airplane. In 2003, Boeing added a composite fairing to the aft fuselage of its C-17 Globemaster III cargo transport, but it experienced only light loading, and did little to demonstrate the structural advantages of stitching. It was, however, an important step in establishing the manufacturing benefits of stitched/RFI technology. It was not until 2007 that more innovative one-piece multi–rib-stiffened box structures were produced in the form of new landing gear doors for the C-17. The complex preforms were stitched together, infused with resin, and cured at atmospheric pressures in an oven. To suppress out-of-plane de-laminations that were common to the bonded production doors they replaced, all the rib caps and perimeter lands on the new door assemblies were reinforced with through-the-thickness stitching. This allowed operation

20. Ibid., 21–22.

of the doors further into the post-buckled regime than was possible with the earlier bonded design.[21]

PRSEUS

Following the end of the ACT program, Boeing continued to work with stitched composites in conjunction with the Air Force Research Laboratory (AFRL) in Dayton, Ohio. The most promising result was a highly integrated stitched concept in which an arrangement of dry, warp-knit fabric preforms, pultruded rods, and foam core materials are assembled and then stitched together to create an optimal structural geometry for fuselage loading.[22] The PRSEUS concept eventually became a major component of ERA Phase 2 research.

Invented in the 1950s by W. Brandt Goldsworthy, a plastics engineer at Douglas often credited as the "father of composites," pultrusion (for "pull" and "extrusion") is a process whereby dry, continuous fibers are pulled through a resin bath and then through a heated die that cures the resin to set the fiber bundle into its final shape. "Goldsworthy's invention of the pultrusion process in the 1950s," historian Stephen Trimble has written, "would make durable and high-strength composites affordable for a range of applications, from cars to aircraft parts to fishing rods."[23]

For their part, Boeing researchers discovered that adding pultruded rods to the top of each stiffener in a stitched composite assembly allowed the components to be stronger in bending and more structurally efficient, enabling use of lighter-weight structures than would normally be required.[24] This was of great interest to NASA because it would help achieve ERA project goals with regard to reducing overall aircraft structural weight.

Early testing began with small samples (called "coupons" in materials-testing parlance) that were developed to a point where researchers were confident about moving on to larger scale test articles. By the time NASA got involved with PRSEUS, Boeing and AFRL had significantly advanced the art of composite fabrication. Previously, resin-infused materials had to be cured using hard metal tooling and the high pressures and temperatures that could be achieved only with an autoclave. According to Dawn C. Jegley, a senior aerospace engineer in the LaRC Structural Mechanics and Concepts Branch,

21. Ibid., 22.
22. Ibid., 23.
23. Stephen Trimble, "Evolving the Modern Composite Airplane," in Richard P. Hallion (ed.), *NASA's Contributions to Aeronautics, v.2: Flight Environment, Operations, Flight Testing and Research*, NASA SP-2010-570-Vol 2 (Washington, DC: NASA, 2010), 379.
24. Dawn C. Jegley, interview with the author, July 28, 2016.

Boeing devised a method that eliminated the need for an autoclave altogether; composite lay ups could be cured with just an oven and vacuum pressure. “That was really helpful as we began making larger and larger parts,” she said, “because we no longer needed to worry about whether we had an autoclave available and we were no longer limited based on the size of the autoclave.” It also helped reduce some of the uncertainties inherent in the process. When ready for use, pre-preg sheets were removed from the freezer and thawed. At that point, there was only a limited amount of time—usually no more than 30 days—before the lay-up had to go into the autoclave before the epoxy resin set up. “If something goes wrong during that phase where you’re laying up all the pieces, you risk having [the process] go past that 30 days,” Jegley said. “If your autoclave breaks down when you’re partway through laying up the part, then you’re going to have parts backing up on the production line and your pre-preg is going to go bad before you have a chance to cure it.”[25]

Dawn C. Jegley, senior aerospace engineer in the LaRC Structural Mechanics and Concepts Branch. (NASA)

Another advantage of PRSEUS was the elimination of conventional fasteners (rivets, screws, bolts, etc.) and a reduction in the number of parts needed for each assembly. “Instead of using fasteners,” Jegley said, “you just stitch the whole thing together and then you don’t have to drill holes; you don’t have to keep track of all those fasteners.” In traditional metal aircraft assemblies, drilled holes and fastener-stress can cause imperfections that later result in cracking or other damage. All drill holes have to be inspected repeatedly throughout the airplane’s service life, a time-consuming and costly process. A reduction in the required number of metal fasteners promotes structural integrity while reducing inspection costs and, not incidentally, aircraft weight. It does, however, have an impact on disassembly and access to internal spaces. “It becomes much more difficult to disassemble the parts,” Jegley noted. “That’s where there is a tradeoff and why you wouldn’t want to stitch the whole airplane together because you do need to be able to

25. Ibid.

get inside [for maintenance], but at the same time it allows you to build some very large assemblies using a smaller total number of parts."[26]

A stitched composite wing assembly, for example could be fabricated from root to tip using single-piece cover panels with integral stiffeners. Similarly, a fuselage or HWB center-body could be constructed from just behind the cockpit to just forward of the tail in one piece with all stiffeners in both directions built in. Instead of being assembled in cylindrical barrel sections, the lower half could be fabricated first and packed with all of the necessary hydraulics, electrical systems, and other equipment, and then the floor stitched in place while the top is still open. Eventually, the upper half would be installed. Systems designers see this as an advantage because not only does this eliminate all the joints from one barrel to the next, but it also eliminates the need for joints between the different hydraulic components and electrical components from one barrel section to the next. "So you have integrated all of it, and you have easy access [to equipment spaces] before you put the floor in," Jegley said. It also allows for larger single-piece subassemblies. "That way, when you get to final assembly, you're now bringing together very few pieces; when you put them all together, you still have real joints and metal fittings and fasteners, but you're bringing together a much smaller number of parts."[27]

PRSEUS technology also made it possible to get away from pre-preg by instead using dry warp-knit fabric stitched together with Kevlar or Vectran, and then curing it later in an oven. The greatest advantage of using dry fabric materials was being able to store them almost indefinitely at room temperature. Then, according to Jegley, "You can just push everything off to the side and wait to put it into the oven." This technique came in handy while making some of the parts for a large test article. "Because of timing, we were making up panels and then stacking them off to the side in the lab at Boeing while we waited for the oven to become available so we could do all the curing," said Jegley. "With pre-preg, you could never do that; [the new method] helped us get some of the panels laid up and ready to go and move forward with the schedule without being affected by a short period of time when we didn't have the oven available to us."[28]

ERA researchers recognized PRSEUS technology as a key enabler for manufacturing future HWB airframes. It was clear that requirements for ensuring pressure integrity of a passenger cabin with a non-circular cross section would result in significant weight penalties if the aircraft were assembled using conventional methods. In fact, this would have been equally true using what were

26. Ibid.

27. Ibid.

28. Ibid.

then state-of-the-art methods for fabricating composite materials. Certain regions of the pressure vessel are subject to out-of-plane loading conditions, in which traditional layered-material composite techniques would require thousands of mechanical attachments to suppress de-laminations and to join structural elements, ultimately leading to fastener pull-through problems in the thin-gauge skins. Such fasteners and attachments would necessarily contribute to airframe weight. Another argument against conventional composite fabrication involved high manufacturing costs associated with a highly contoured airframe. Building the HWB using traditional means would require complex outer-mold-line (OML) tooling as well as individual toolsets for all of the interior stringers and frame members, which would further drive up costs. PRSEUS technology provided the means to fabricate complex aircraft structures that were both effective in out-of-plane loading scenarios and affordable to produce.[29]

Not only is the flattened geometry of the HWB subject to secondary bending stresses during pressurization, but the shell also experiences a unique biaxial load pattern during maneuver loading conditions. Researchers discovered that these load magnitudes are more nearly equal in each in-plane direction than is typically found in conventional tube-and-wing fuselage arrangements where the cantilevered fuselage is more highly loaded in the N_x (streamwise, or fuselage-bending) direction, along the stringers, than in the N_y (spanwise, or wing-bending) direction, along the frames. This characteristic dictates a structural concept in which the optimum surface panel geometry must provide continuous load paths in both directions in addition to efficiently transmitting internal pressure loads (N_z). Additionally, a conventional panel built up in a skin-stringer-frame arrangement would typically include discontinuous frame-shear-clip members to allow stringers to pass through uninterrupted in the primary longitudinal loading direction.[30]

Such an arrangement in an HWB would be less effective in bending and axial loading than a continuous frame design attached directly to the skin. In contrast, the PRSEUS approach replaces conventional laminated and bonded assembly techniques with a single piece, co-cured panel design with seamless transitions and damage-arresting interfaces.[31] The highly integrated nature of the PRSEUS stiffened-panel design promotes unprecedented potential for structural optimization through fiber tailoring and load-path continuity

29. Dawn C. Jegley and Alex Velicki, "Status of Advanced Stitched Unitized Composite Aircraft Structures," AIAA-2013-0410, presented at the 51st AIAA Aerospace Sciences Meeting, Grapevine, TX, January 7–10, 2013, 1–2.
30. Ibid., 2.
31. Ibid., 2.

between individual structural elements. The PRSEUS structural concept was made possible through advances in fabric manufacturing, out-of-autoclave resin infusion processing, through-thickness stitching technology, and single-sided stitching.[32]

In PRSEUS panel geometry, load-path continuity at the stringer-frame intersection is maintained in both directions by passing the rod through a small keyhole aperture in the frame web. The presence of the rod increases the local strength and stability of the stringer section while simultaneously enhancing the panel's overall bending capability. Frame elements, placed directly on the inner mold line skin surface, are designed to take advantage of carbon fiber tailoring by placing bending and shear-conducive lay-ups where they will be most effective. The stitching is used to suppress out-of-plane failure modes, enabling a higher degree of tailoring than would be possible using conventional laminated materials. This configuration results in a bi-directionally stiffened panel that is highly efficient in all three loading directions. Although this design is ideal for the HWB pressure cabin, it is also applicable to cylindrical fuselage sections with thin skins as well as composite wing structures. The stitching approach would allow thin fuselage skins to safely buckle while causing minimal disruption of transverse stiffener elements, allowing the stringer to pass through a frame or wing rib cap.[33]

A Crucial Milestone: Fabricating and Proof-Testing a Multi-Bay Box

The key to maturing stitched composite manufacturing technology for possible use in constructing a future HWB aircraft involved a building-block approach to development and validation of the PRSEUS concept. Over a roughly 4-year period, from late 2009 through 2013, researchers took their work from TRL-3 to TRL-5, demonstrating construction of tension and compression panels, a pressure panel and pressure cube, and then a multi-bay box, the latter demonstrating over a 10 percent benefit in weight reduction relative to sandwich composites.

The first step in designing an effective pressure vessel was to evaluate the effect of pressure on a test article called the Internal Pressure Box (IPB). This TRL-4 activity demonstrated the capability of a minimum-gauge PRSEUS panel to carry limit loads of 1P (equal to a normal operating pressure of 9.2 psi) and 2P, which represents the 18.4 psi maximum overpressure condition. Next, the team built a single pressurized cube as a risk-reduction test

32. Jegley and Velicki, "Development of the PRSEUS Multi-Bay Pressure Box," 3.
33. Ibid., 3.

article to examine a new integral cap joint concept. Finally, lessons learned from these tests led to fabrication of a large-scale test article representing a section of an HWB fuselage that could be tested under combined axial and pressure loading.[34]

As tested on the IPB, the 108-by-48-inch PRSEUS panel had 20-inch frame spacing, 6-inch stringer spacing, and a 0.052-inch skin thickness. Prior to testing, engineers conducted both linear and nonlinear static analyses using a model with a combination of shell and beam finite elements. The test panel was then bolted to a metallic pressure vessel and subjected to pressure loads while a combination of instruments and sensors monitored displacements and strains. Results showed that the pristine pressure panel was capable of withstanding the required 2P internal overpressure loading condition with no evidence of damage. Researchers then inflicted barely visible impact damage (BVID) to a primary load-carrying member, the rod region of a stringer, and ran the tests again. Even with slight damage, the panel withstood the 2P load condition as well as higher pressures up to 28.44 psi before suffering initial failure through the center stiffener. Technicians arrested the damage before it could reach the skin by stitching the stiffener, and the panel was then loaded to 30 psi without sustaining additional damage or loss of pressure integrity. Because initial failure occurred at a load significantly higher than that required for commercial transport aircraft, researchers concluded that pressure loading is not a critical load condition for a minimum gauge PRSEUS panel. Therefore, the minimum gauge panel geometry of the pressure panel was also applied to the panels used for constructing the pressure cube test article.[35]

The IPB consisted of six composite PRSEUS panels assembled using aluminum fittings and an untested stitched integral-cap-joint concept. The cube assembly was designed to represent a portion of a pressurized HWB fuselage section incorporating the upper cover skin (crown) panel, two side ribs, two side bulkheads, and a pressurized floor section. Because the crown panel was representative of the upper surface of the baseline aircraft, there were few fasteners protruding through the OML, where they would be exposed to the airstream. Two pairs of opposing panels, arranged symmetrically to represent rib and bulkhead panel regions, formed the sides of the pressure cube. These were representative of the outer cabin pressure-carrying ribs and the rear pressure bulkhead of the baseline aircraft.[36]

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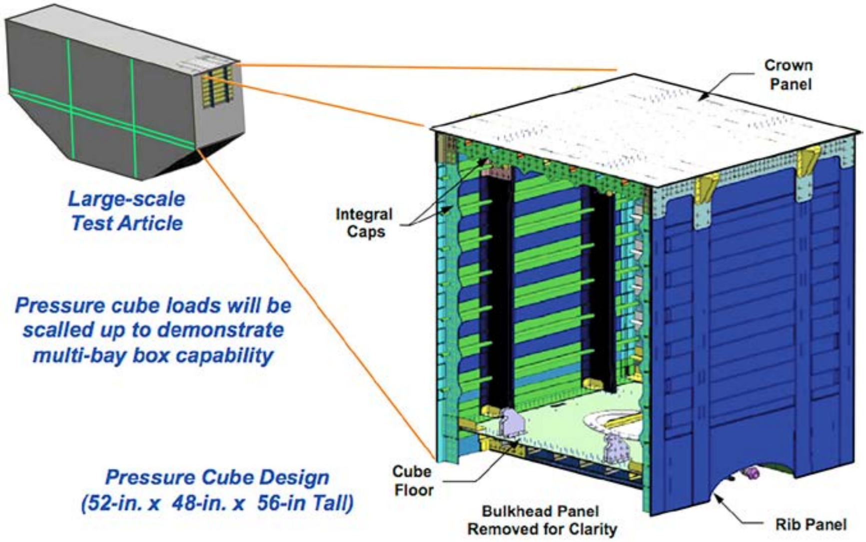
34. Nicolette Yovanov, Andrew E. Lovejoy, Jaime Baraja, and Kevin Gould, "Design, Analysis and Testing of a PRSEUS Pressure Cube to Investigate Assembly Joints," presented at the 2012 Aircraft Airworthiness and Sustainment Conference, Baltimore, MD, April 2, 2012, 1–2.
35. Ibid., 3.
36. Ibid., 4.

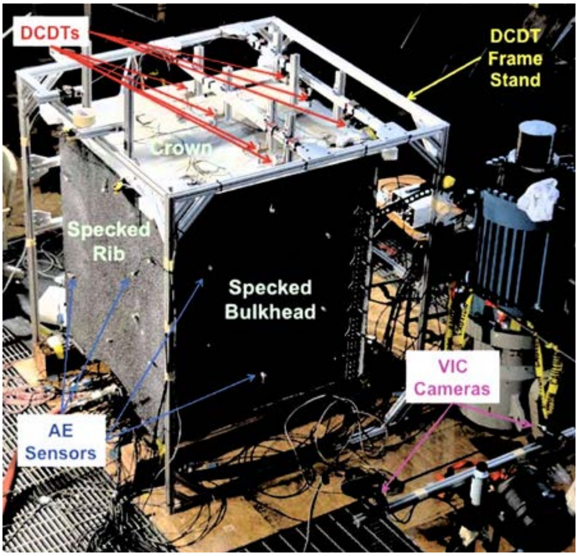


The PRSEUS pressure cube was a representative section of the eventual HWB large-scale test article. (NASA)

In order to accommodate an access door and instrumentation pass-through, the floor panel was not strictly representative of the baseline aircraft, but was designed using available panel tooling. Where necessary, components were secured using aluminum fittings and titanium bolts. Stitched T-shaped integral caps were manufactured into the panels to reduce the complexity and number of metallic fittings required to assemble the panels. This integral cap joint design, incorporated around all four edges of the crown panel to provide a means of attaching the side panels, was the main focus of the pressure cube risk-reduction test. The pressure cube was also the first test specimen in which PRSEUS panels were joined together to create a 90-degree corner. Researchers needed to verify that the joint concept could hold an adjusted 2P load case scaled up to account for the subscale dimensions of the cube. Prior to shipping the cube assembly to LaRC, technicians applied a coat of flat white paint to the interior surfaces and the crown panel OML, and gray paint with a speckled pattern to the rib and bulkhead panel exterior surfaces to help engineers visualize the path of panel delamination and cracks during pressure testing.[37]

Once again, researchers began by making a detailed FEM to obtain linear analysis predictions and nonlinear analysis verification. They created detailed local FEMs for joint analysis, and, when necessary, employed additional

37. Ibid., 4.

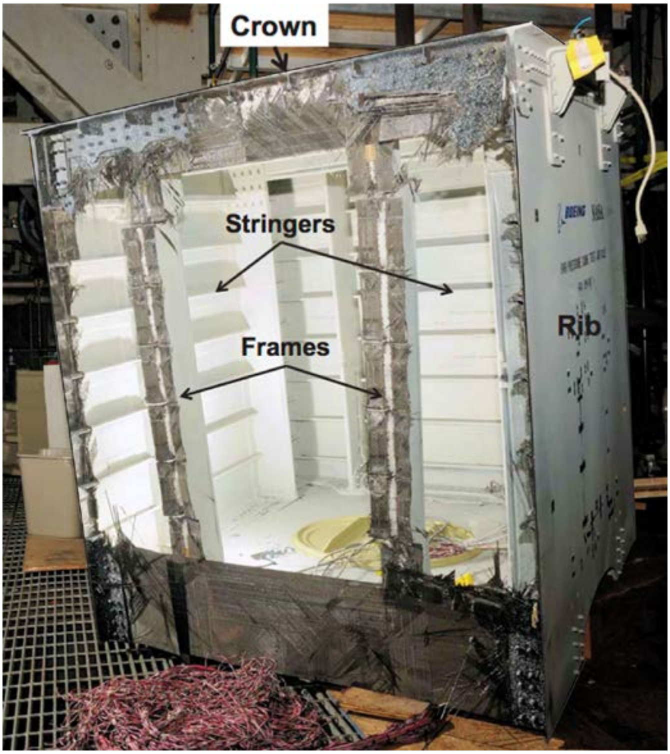


The PRSEUS pressure cube test setup at LaRC. Loads were measured with direct-current differential transformers and acoustic emission sensors. High-speed video cameras recorded the results. (NASA)

analysis to predict the response of specific local regions of the cube. This detailed analysis was required to predict failure loads and to verify the analytical methods that would later be used for design and analysis of the large-scale test article. The research team completed linear analysis prior to pressure testing in order to determine panel strains and displacements for correlation during the test (to predict critical panel locations and failure modes), and to demonstrate that the overall specimen strength would meet the 2P load requirements.[38]

As with the earlier pressure panel test, the design pressure limits for the cube were 1P, with a 2P maximum overpressure condition. After testing began, the cube was subjected to several pressure loads at various levels while still in pristine condition, and was later pressure loaded to failure with BVID imparted to the exterior of the cube at one of the rib integral cap web locations. Initially, researchers conducted two checkout tests at 4.6 psi (0.5P) to verify proper operation of all data acquisition systems and the pressure control system. The pristine cube was cycled up to 1P pressure and then completely unpressurized. Additionally, the pristine cube was cycled up to 20.15 psi (2.2P) prior to being unpressurized to ensure that no failure would occur for the overpressure condition, but with an additional margin of 10 percent included for safety. Following these pressure cycles, inspectors examined the cube using ultrasonic non-destructive inspection (NDI) techniques. Researchers then turned the cube on its side and, using a 1-inch spherical drop weight with an impact-energy of 100 foot-pounds, imparted BVID to an integral cap where it attached a rib and bulkhead. After inspectors performed additional NDI in the vicinity of the BVID, the cube was rotated back to the test position and then pressurized until catastrophic failure

38. Ibid., 4.

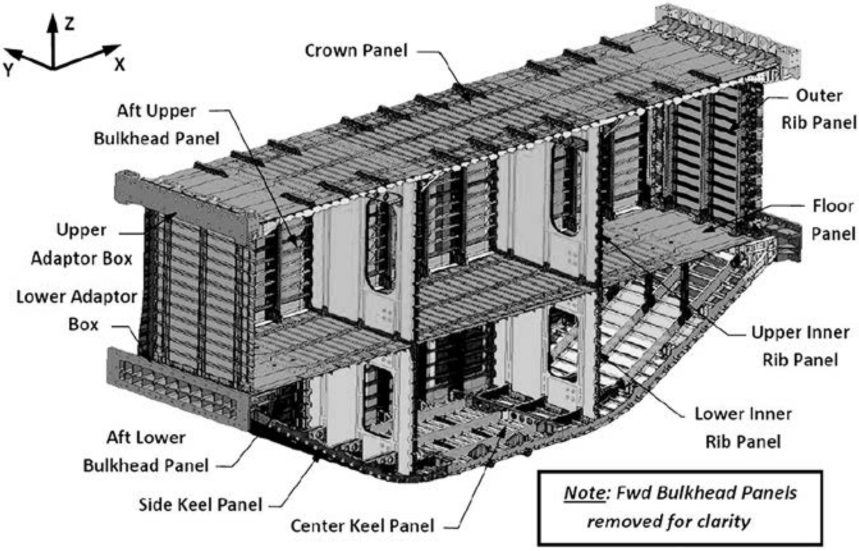


The PRSEUS pressure cube is seen here after being tested to failure. One panel has been completely blown off, some rib frames were fractured, and a metal fitting failed due to local buckling of the composite structure. (NASA)

occurred. Afterward, they performed a final NDI on what remained of the cube.[39]

Upon completion of the pressure cube tests, researchers determined that the combined pretest and post-test analytical methods used correlated well with actual test results. Assessment of strain gauge, video image correlation, and NDI data demonstrated that key failure modes and locations had been accurately predicted. In order to effectively serve as a risk-reduction specimen, loads in the joints of the pressure cube had to be accurately scalable to demonstrate the higher loads expected in the large-scale test article when subjected to the 2P overpressure condition. Researchers, therefore, conducted additional post-test correlation to relate the bending moments of the pressure cube to those of the planned Multi-Bay Box (MBB) large-scale test article.

39. Ibid., 6–7.



At 80-percent-scale, the PRSEUS Multi-Bay Box represented a significant portion of the HWB center-body assembly. This schematic shows the internal structural arrangement of the MBB. (NASA)

This comparison yielded a factor of 2.35 difference in the bending moments due to geometric considerations. This meant that to scale up to the required bending moment, the pressure cube needed to meet a loading condition of 4.7P, or approximately 43 psi. This demonstrated that a pressure cube failure at 48 psi (5.2P) correlated to an MBB test article failure at 20 psi (2.2P), which met the overpressure requirement.[40]

The final step in the PRSEUS technology building block series involved extensive testing of an 80-percent-scale MBB representing a portion of the center section of an HWB transport aircraft capable of withstanding bending and internal pressure loadings representative of operational conditions. NASA partnered with Boeing to evaluate the MBB test article using the LaRC Combined Loads Test System (COLTS) facility. Boeing fabricated the test article primarily using PRSEUS cover panels, pressure bulkheads, and floor structures assembled into a double-deck test article measuring approximately 30 feet wide, 14 feet high, and 7 feet deep.[41]

40. Ibid., 8–9.

41. Dawn C. Jegley, Marshall Rouse, Adam Przekop, and Andrew E. Lovejoy, “The Behavior of a Large-Scale, Stitched Composite Multi-Bay Pressure Box,” NASA TM-2016-218972, April 2016, 1–2.

Following completion at Boeing's Long Beach facility, the PRSEUS MBB is prepared for shipment to LaRC. (NASA)

The MBB test article was assembled at the Boeing C-17 manufacturing plant in Long Beach. It was sized to represent an 80-percent-scale section of the most heavily loaded portion of the HWB center-body. This made the MBB large enough to be representative of a full-scale structure while still allowing the largest composite panels to fit inside the available oven for curing, and also permitting the assembled structure to fit within the COLTS test chamber. The MBB structural arrangement consisted of 11 PRSEUS panels forming the exterior shell and floor members, along with four interior ribs. Boeing first fabricated the crown panel, which was the first 30-foot-long PRSEUS panel ever made. As such, there was necessarily somewhat of a learning curve to the manufacturing process. Increasing the scale of the panel resulted in imperfections caused by motion of metal plates used to transmit normal pressure and temperature, and provided a smooth surface for the finished laminate during the lay up process. During resin infusion and curing, these plates shifted in such a way as to create dents in the OML surface. Because the panel skin was only 0.052 inches thick in some places, manufacturers were concerned that these dents might harm the load-carrying capability of the crown panel in compression. It became necessary to add bonded patches over the dents to ensure that the crown panel would not fail prematurely.[42]

After the MBB arrived at LaRC, researchers subjected it to a series of loadings in the COLTS facility. As with the IPB experiments, testing was first conducted with the structure in pristine condition, then with intentional minor damage, and then finally pressurized to failure. Data were monitored and recorded using several types of instrumentation including 262 linear and 36 rosette strain gauges, 15 linear variable displacement transducers, 4 pressure transducers, 4 fiber optic wires, 4 video digital image correlation systems, 26 acoustic emission sensors, and 9 video cameras used to record the behavior of the test article and the COLTS system. Researchers initially installed strain gauges on all panels and on most load-introduction elements. They added more strain gauges following application of BVID to track the progression of damage emanating from the impact site. Video cameras inside each of the MBB's six bays recorded cracks and deformations of the bulkheads, crown, and keel. Researchers monitored additional video cameras outside the test article to obtain a global view of the structure.[43]

Once the MBB had been installed inside the COLTS, researchers applied mechanical loads to simulate critical flight conditions and internal pressure loads to represent normal cabin pressure. Four actuators provided mechanical loads while internal pressure was introduced through a valve in an upper bulkhead panel access door. Holes in the floor ensured that the pressure remained constant in both the upper and lower sections of the test article. The test series included runs during which mechanical loads were applied alone, pressure was applied alone, and combinations of internal pressure and mechanical loads were applied simultaneously. In each case, loading was quasi-static and was applied slowly enough to ensure that mechanical actuators were synchronized with one another and with the pressure load.[44]

Once again, researchers conducted DLL and DUL loadings of the pristine structure before running the same tests with intentional damage. In all cases where the load factor was less than or equal to DUL and pressure loading was applied simultaneously with the mechanical load, the pressure and actuator systems were programmed to ramp together from zero to maximum loading. When the programmed mechanical loading exceeded predicted DUL, the pressurization system was programmed to not exceed the DUL condition for pressure. During each test run, researchers ramped loads from zero to maximum with short pauses at intervals to compare test data with predictions. Once the

42. Ibid., 6.
43. Ibid., 7–8.
44. Ibid., 9.

maximum load value was attained, it was held briefly to allow for data collection and then the structure was unloaded at a steady but relatively rapid rate.[45]

For the next series of test runs, the COLTS proved to be a valuable tool for ERA researchers in evaluating the MBB's damage-tolerance characteristics. Several experiments were devised to examine the PRSEUS structure's ability to withstand the types of minor damage that might be incurred during routine flight line operations. "Some of the things that could impact the plane are rocks or debris on the runway when it's taking off or landing," said NASA research aerospace engineer Andrew Lovejoy, "or you can have a mechanic hit it with a tool, or a vehicle driving by could hit it."[46]

Any of those events—extremely common occurrences at airports—could cause damage that might be barely visible only to crewmembers doing a walk-around inspection. One of the goals of designing damage-arresting composites was so that an aircraft would be capable of sustaining operational loads even with that damage in place. Once again, it was necessary to conduct impact tests to intentionally cause BVID, but with such a large test article inside the COLTS facility this proved especially challenging.[47]

To solve this problem, NASA technicians designed and built a unique test rig. "If you are going to impact the top of something, you would just have a free-falling weight that would come down and hit," said Lovejoy. "You have a mass and a height, so that's a fairly straightforward calculation of the energy; if you wanted to hit on the side, you have a spring-loaded impactor." But researchers needed to strike upward at the keel, or underside, of the MBB. "There is very limited space in COLTS," Lovejoy explained. "You can have an air-driven projectile, or a spring-loaded one, but those are less controllable, so we came up with the 'roller-coaster' impactor." In order to produce a controlled impact, it was necessary to propel a weight down a track that curved upward until the impactor was oriented in a vertical direction. "We didn't have any device to do that," he added, "so we built from scratch an impactor and a track to make it go where we wanted it to go; two pieces of track encapsulated it just before impact to guarantee that we're getting that vertical impact on the bottom of the keel."[48]

Damage testing consisted of three impacts to the interior of the structure on the stiffened side of the upper bulkhead, and three impacts to the exterior of the structure on the unstiffened side of center keel. Researchers used a

45. Ibid., 9–10.

46. Andrew Lovejoy interview, *NASA X*, "End of an ERA—Part 1," NASA TV, November 24, 2015. Subsequent Lovejoy quotes are from this interview unless otherwise noted.

47. Ibid.

48. Ibid.

The COLTS control room team gathers data during a test run. (NASA/David C. Bowman)

spring-loaded impactor at locations at the top of a stringer along the upper edge of a frame, and at a mid-bay location between stiffeners to inflict BVID to the MBB interior. These impacts represented a range of locations and the type of damage possible due to service events such as tool drops. Exterior damage was inflicted using the gravity-fed "roller-coaster" apparatus to strike locations at the flange edge of a stringer, at the flange edge of a frame, and at a mid-bay skin location between stiffeners. These strikes were imparted to an area of the structure that would likely buckle during loading so as to evaluate whether typical exterior impacts would degrade the performance of buckled structure. In each case, researchers employed a weight with a 1-inch-diameter hemispherical tup.[49]

Researchers noted that BVID results for the interior sites corresponded to 20 foot-pounds for the top of the stiffeners, which caused little damage but is the maximum energy allowed for internal impacts to commercial aircraft, and 15 foot-pounds for the skin mid-bay location, where visible damage was clearly evident. BVID for the exterior sites corresponded to energy levels of 60 foot-pounds, 50 foot-pounds, and 15 foot-pounds for the frame flange, stringer flange, and the mid-bay locations, respectively. On one of the exterior tests, the tup slightly missed the planned impact site, striking the thin-skin region instead of directly at the adjacent flange. As a result, the damage was more severe than intended. The tup created a through-hole that was clearly visible from both the exterior and interior. Engineers evaluated the damage at

49. Jegley, et al., "The Behavior of a Large-Scale, Stitched Composite Multi-Bay Pressure Box," 10.

this location and indicated that it would not reduce the ability of the structure to sustain mechanical load but might reduce the structure's ability to support internal pressure loads. Technicians effected repairs by taping a non-structural patch over the hole on the inner, stiffened side of the center keel. Inspectors conducted ultrasonic scans immediately before and after each impact so the extent of the damage could be quantified. These scans indicated that although delamination occurred at the keel skin and flange impact sites, it was successfully arrested at the stitch line closest to the impact site. Scans of the bulkhead stiffener impacts found no damage, but inspection of the interior skin impact revealed delamination running from the point of impact to the nearest stitch line, located at the edge of the adjacent flange.[50]

COLTS engineers repeated the DLL and DUL loadings with the final BVID test to a load greater than DUL in both the up-bending and up-bending-plus-pressure conditions. Loads were applied using the same methodology as in the earlier tests, but the pressure was held constant while the mechanical load was increased by 10 percent. Next, the mechanical load was decreased to DUL and held constant while the pressure load was decreased to zero, leaving the test article at DUL in the up-bending condition without pressure. Finally, the mechanical load was increased to 10 percent greater than DUL and held briefly before being removed.[51] Researchers calculated that the ultimate load factor was 1.5 times the DLL. With testing and data acquisition complete, they concluded that the PRSEUS large-scale test article had performed beautifully under conditions of multiple and extreme stresses. "In fact," said Lovejoy, "the MBB exceeded expectations, performing well beyond the predicted DUL." From these results, researchers concluded that PRSEUS technology offered an opportunity to lighten the HWB structure even more, potentially making future aircraft even more efficient.[52]

PRSEUS Results

Testing of PRSEUS technology during the ERA project was the culmination of more than two decades of effort to develop technology that would improve damage tolerance and reduce the weight of composite structures for commercial transport aircraft applications through the use of through-the-thickness stitching. The partnership between NASA and Boeing under the ERA project further advanced this technology in an attempt to encourage and enable next-generation aircraft configurations such as the HWB.

50. Ibid., 10–11.
51. Ibid., 11.
52. Lovejoy interview.

Analytical modeling and engineering experiments conclusively demonstrated that PRSEUS technology effectively suppressed delamination, arrested damage, and reduced or eliminated the need for fasteners in the acreage of composite panels. A traditional layered assembly would require thousands of mechanical fasteners to join structural elements and suppress delamination. Disadvantages of using metal bolts and rivets to join layers of thin-gauge composite skins include added weight, localized stress fractures, and fastener pull-through (a critical failure mode). Reducing the number of fasteners eliminates the need to drill large numbers of holes, reduces the necessity to add doubler plates to mitigate stress concentrations around those holes, and minimizes the time required to inspect fastener holes throughout the service life of the aircraft.[53]

The PRSEUS panel architecture constituted a significant step beyond current state-of-the-art conventional layered composite systems. The addition of a pultruded rod to the stringer, and a tall foam-filled frame perpendicular to the stringer, improved bending stiffness in both directions compared to traditional construction, a characteristic critical to the HWB configuration. PRSEUS also provided efficient load paths because all panel elements are integrated into a single one prior to curing, eliminating the need for shear clips and other elements that add weight to the structure. The pultruded rod increased local strength and stability of the stringer section while shifting the neutral axis away from the skin to further enhance overall panel buckling characteristics. Frame elements were stitched directly onto the skin surface to take advantage of carbon fiber tailoring by placing bending and shear-conducive lay-ups where they are most effective. The integral panel design exploited the orthotropic nature of carbon fibers and suppressed out-of-plane failure modes with through-the-thickness stitching. These two features enable applying PRSEUS technology as an effective damage-arresting design approach for composite structures.[54]

Another advantage expected of the PRSEUS lightweight composite concept is a dramatic overall reduction in airframe weight. This feature was particularly significant when designing the HWB pressure cabin, where the design was largely driven by out-of-plane loading considerations. In addition to secondary bending stresses experienced during pressurization, another key difference between the highly contoured HWB shell and the traditional cylindrical fuselage is a unique bi-axial loading pattern that occurs during maneuver loading

53. Jegley, et al., "The Behavior of a Large-Scale, Stitched Composite Multi-Bay Pressure Box," 25–26.
54. Tenney, et al., "NASA Composite Materials Development: Lessons Learned and Future Challenges," 23.

conditions. Load magnitudes for the HWB are nearly equal in each in-plane direction (N_x and N_y), in contrast to the type of loading typically found in conventional tube-and-wing fuselage configurations, where the cantilevered fuselage is more highly loaded in the N_x direction, along the stringer, than in the N_y direction, along the frame. This dictates that the optimum structural panel geometry for the HWB should have continuous load paths in both directions (N_x and N_y), in addition to efficiently transmitting internal pressure loads (N_z).[55]

For a conventional panel built up in a skin-stringer-frame arrangement, the frame shear clip is typically discontinuous to allow the stringer to pass through the frame. If such an arrangement were used to assemble the HWB center-body, the frame would be less effective in bending and axial loading than a continuous frame attached directly to the skin. Additionally, the resulting panel assembly would necessarily be heavier to provide structural strength. To overcome the inherent weight penalties of the non-circular pressure cabin, aircraft manufacturers could instead use PRSEUS technology to design a lightweight bi-directionally stiffened panel, where the wing bending loads are carried by the frame members and the fuselage bending loads are carried by the stringers. Such a panel arrangement could be optimized to include continuous load paths in both directions, highly tailored stringer and frame laminates, thin skins designed to operate well into the post-buckled regime, and crack-arresting features designed to minimize damage propagation.[56] Research results indicate that the PRSEUS concept would be approximately 10.3 percent lighter than a conventional aluminum honeycomb sandwich assembly in the pressure cabin of a large BWB aircraft.[57]

Beginning with tests of small sample coupons and ending with a 30-foot-long large-scale pressure box, the PRSEUS ITD successfully demonstrated the viability of both the technology itself and the use of PRSEUS construction techniques to build the center-body for a proposed HWB transport aircraft. This building-block approach showed that designs could be refined and the risk of premature failure reduced as more complex assemblies were introduced. The final test series involving the MBB validated flight-maneuver load conditions and internal pressurization loads to demonstrate that the technology was capable of meeting the structural weight goals established for the HWB airframe. The test article demonstrated anticipated post-buckling behavior, and preliminary evaluations showed no damage growth from impact sites.

55. Jegley, et al., "The Behavior of a Large-Scale, Stitched Composite Multi-Bay Pressure Box," 2–3.
56. Ibid., 3.
57. Tenney, et al., "NASA Composite Materials Development: Lessons Learned and Future Challenges," 23.

While this ITD was primarily aimed at demonstrating PRSEUS viability for the HWB, the benefits demonstrated could also be applied to traditional tube-and-wing aircraft, other advanced configurations, spacecraft, and any structures where weight and through-the-thickness strength are significant design considerations.[58] From a production standpoint, PRSEUS is also attractive because no autoclave is required, and therefore larger composite parts can be fabricated. "PRSEUS is broadly applicable to fuselages and wings of any shape; it is lightweight, damage-tolerant and built with fewer parts," said Fay Collier, adding "It could be a game changer."[59]

58. Jegley, et al., "The Behavior of a Large-Scale, Stitched Composite Multi-Bay Pressure Box," 25–26.
59. Guy Norris, "'Green' Airliner Targets Achievable by 2025, Says NASA," *Aviation Week & Space Technology*, *http://aviationweek.com/awin/green-airliner-targets-achievable-2025-says-nasa*, April 18, 2011 (accessed July 21, 2016).

NASA-Armstrong/Air Force Research Laboratory tests of ACTE flaps installed on a NASA Gulfstream Aerospace G-III validated that the seamless design with its advanced lightweight materials could reduce wing structural weight, improve fuel economy and efficiency, thereby reducing environmental impacts. (NASA)

CHAPTER 4

The Adaptive Compliant Trailing Edge Investigation

Another important element of NASA's green aviation research involved developing a wing surface capable of changing shape in flight, which would make airplanes quieter and more fuel-efficient. This played strongly to NASA's traditional excellence in aerodynamic research, which dated to the earliest days of its predecessor, the National Advisory Committee for Aeronautics. The Adaptive Compliant Trailing Edge (ACTE) is an imaginative morphing wing technology that allows an aircraft to seamlessly extend its flaps, leaving no drag-inducing, noise-enhancing gaps for air to flow through, creating energy-robbing (hence fuel-robbing) turbulence and vortices. Compliant structures are used to change the wing trailing edge shape to maintain smoothly curved surfaces along the flow direction, thereby avoiding abrupt discontinuities, particularly those created by conventional hinged control surfaces such as roll-controlling ailerons, lift-enhancing flaps and slats. Compliant structures allowed smooth variation of the trailing edge shape in the spanwise direction, making it possible to seal any gaps at the edges of deflected control surfaces. These characteristics can improve control surface effectiveness and also provided the ability to tailor spanwise aircraft load distribution to enhance aerodynamic efficiency, reduce structural loads, and generate control forces.[1]

A compliant structure is a monolithic joint-less mechanism that exploits the elasticity of material to produce a desired functionality such as force or motion transmission, motion guidance, shape changing, and/or energy storage and release. As applied to a device such as an aircraft flap, compliant structures are optimized to distribute localized strain to change the shape of the control surface as needed during flight. Instead of using a series of mechanical actuators, a compliant structure deforms as a whole, thus avoiding high-stress concentrations in localized regions. Known as distributed compliance, this

1. Sean Wakayama and Edward V. White, "Evaluation of Adaptive Compliant Trailing Edge Technology," AIAA 2015-3289, presented at the 33rd AIAA Applied Aerodynamics Conference, AIAA Aviation Forum, Dallas, TX, June 25, 2015, 1.

NASA-Armstrong/Air Force Research Laboratory tests of ACTE flaps installed on a NASA Gulfstream Aerospace G-III validated that the seamless design with its advanced lightweight materials could reduce wing structural weight, improve fuel economy and efficiency, thereby reducing environmental impacts. (NASA)

design concept offers additional benefits because the entire adaptive structure can reshape itself into complex predetermined positions with minimal force and can be locked in place at any desired configuration. Although such structures are generally described as flexible, they are actually optimized to resist deflection under significant external aerodynamic loading and provide the same stiffness and structural strength as a conventional flap.[2]

Compliant trailing-edge flaps are configured to have a seamless surface contiguous with the primary wing surface. Elimination of surface discontinuities results in both lower drag and higher control authority than provided by conventional hinged flaps because a compliant flap increases camber under load, generating more lift, and is more effective in roll and gust-load-alleviation per degree of deflection. Additional benefits of seamless surfaces include making the flaps less susceptible to icing and fouling from debris, and the seamless transition between the fixed and movable portions of the wing reduces noise

2. Sridhar Kota, Russell Osborn, Gregory Ervin, Dragan Maric, Peter Flick, and Donald Paul, “Mission Adaptive Compliant Wing – Design, Fabrication and Flight Test,” RTO-MP-AVT-168, NATO Research and Technology Organization, 2009, 2–5.

The Air Force-NASA AFTI F-111A (SN 63-9778) Mission Adaptive Wing (MAW) testbed on one of its test flights. (NASA)

associated with the turbulent airflow generated by discontinuous surfaces at the flap ends when the high-lift devices are deployed for landing.[3]

There was historical precedent for NASA's work on compliant trailing edge flaps. In 1978, as part of the joint Air Force-NASA Advanced Fighter Technology Integration (AFTI) program, the Air Force Flight Dynamics Laboratory (AFFDL, now enfolded within the Air Force Research Laboratory) launched a joint Air Force-NASA program to build and test a so-called "mission adaptive wing" (MAW). The MAW, an outgrowth of aerodynamicist Richard T. Whitcomb's brilliant conceptualization of the so-called "supercritical wing" (SCW) earlier tested on a modified Vought TF-8A Crusader, was a smooth variable-camber relatively low-aspect-ratio wing which, via series of internal actuators and linkages, could be adjusted for optimum transonic and supersonic flight performance. Following tests of competing industry designs in the Langley 8-ft Transonic Pressure Tunnel, Boeing received a 1979 contract to fabricate the new wing, which was subsequently installed on a modified General Dynamics F-111A airplane (SN 63-9778) already flying with an experimental NASA-developed SCW as part of the Air Force-NASA Transonic Aircraft Technology Program. Over 59 flights totaling 145 flight-test hours from 1985

3. Ibid., 5–7.

through 1988, the AFTI F-111A MAW demonstrated that such a wing could afford significant aerodynamic and performance advantages—cruise performance showed an approximately 7 percent reduction in drag, supersonic range at low altitude increased by 25 percent, and the plane had 30 percent greater range at high altitude than a conventional F-111A—though weight and complexity of the mechanical actuation system hindered its further development at that time, and some promised modes of camber control remained unexplored.[4]

From the mid-1980s through the early 1990s, a succession of wind tunnel test programs had shown that an aeroelastic wing—one thin- and flexible-enough to have reduced torsional stiffness, in contrast to a conventional wing, which deliberately has a robust structure to minimize loads-induced deformation—would also have greatly enhanced control power: the ability to be flexed as an entire surface for enhanced roll control and also for loads alleviation. Additionally, gross weight could be reduced significantly, perhaps by as much as 20 percent. As a consequence, in 1996, NASA, in conjunction with the Air Force and Boeing (to whom Lockheed-Martin, British Aerospace, and Moog, Inc., were subcontractors), began the Active Aeroelastic Wing (AAW) development and flight validation program, a major step forward towards creating a bird-like "morphing" wing, one where the aeroelastic response of the wing itself could be exploited to "deform" the wing's shape into one furnishing optimum aerodynamic performance and flight loads distribution across the range of an aircraft's flight envelope.[5]

As they had earlier with the AFTI F-111A MAW, Boeing engineers, in conjunction with their military and NASA counterparts, took key structural and other components from the wings of a retired NASA F/A-18A: the former

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4. Eric J. Miller, Josue Cruz, Shun-Fat Lung, Sridhar Kota, Gregory Ervin, Kerr-Jia Lu, and Pete Flick, "Evaluation of the Hinge Moment and Normal Force Aerodynamic Loads from a Seamless Adaptive Compliant Trailing Edge Flap in Flight," AFRC-E-DAA-TN28829 (January 21, 2016), 5; Richard P. Hallion and Michael H. Gorn, *On the Frontier: Experimental Flight at Dryden* (Washington, DC: Smithsonian Books, 2001), 271–273; Joseph R. Chambers, *Partners in Freedom: Contributions of the NASA Langley Research Center to U.S. Military Aircraft of the 1990s*, NASA SP-2000-4519 (Washington, DC: NASA, 2000), 81; Sheryll Goecke Powers, Lannie D. Webb, Edward L. Friend, and William A. Lokos, "Flight Test Results from a Supercritical Mission Adaptive Wing with Smooth Variable Camber," NASA TM-4415 (November 1992), 2–3.
5. Ed Pendleton, Pete Flick, Donald Paul, Dave Voracek, Eric Reichenbach, and Kenneth Griffin, "The X-53: A Summary of the Active Aeroelastic Wing Flight Research Program," AIAA 2007-1855, presented at the 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, April 23–26, 2007, 1–2.

The NASA-AFRL-Boeing F/A-18 Active Aeroelastic Wing testbed (later designated X-53) employed "wing-warping" reminiscent of that employed by the Wright brothers at the dawn of powered, winged flight. Here it is demonstrating its ability to undertake a full-stick-deflection 360-degree roll. (NASA)

High-Alpha Research Vehicle (HARV), NASA 840.[6] They added a drive system for cycling independent outboard and inboard leading edge flaps, and replaced the plane's thick wing panels with thinner panels fabricated from aluminum and titanium with solid composite skins, reducing the wing's torsional stiffness by approximately 17 percent over the baseline F/A-18A. (In effect, they were "restoring" the F/A-18 wing to the original very elastic "thin" structural design that had characterized early production models). The modified wing incorporated new high-rate actuators that, driven by a new flight control system, could deflect the wing surface similar to the "wing warping" the Wright brothers had employed on their 1903 Kitty Hawk Flyer. The new wings were then joined to a Navy-furnished airframe, the resulting "new" F/A-18 AAW becoming the

6. Alpha (which often appears as its Greek letter α) means "angle of attack" in aerospace engineering shorthand.

NASA 853. (In 2006, the F/A-18 AAW was designated the X-53, though it is best-remembered by its original name).[7]

Extensive ground tests, including tests of a scale F/A-18 AAW model in the NASA Langley Transonic Dynamics Tunnel in July and August 2004, preceded Phase I flight testing, which included functional check flights, aeroservoelastic clearance flights, aerodynamic and loads model development, and envelope expansion. Phase I commenced in November 2002, and concluded in April 2003 after 50 test missions, during which the F/A-18 AAW flew to Mach 1.32, approximately 914 miles per hour, at 24,800 feet. Following extensive preparations including exploiting Phase I-acquired data to update aerodynamic and loads databases, and others necessitated by the complex nature of the closed-loop control laws testing to come, Phase II commenced in mid-December 2004 and continued through the end of March 2005. Testing went smoothly, including full-deflection 360-degree rolls validating full-scale AAW performance, and concluded in less than 4 months, after a total of 34 Phase II flights. Overall, the F/A-18 AAW was a great success, proving the practicality and benefits of active aeroelastic control.[8]

Though undertaken for very different purposes, the F-111A MAW and F/A-18A AAW thus constituted important predecessor steps before the onset of the ACTE investigation. It began in the summer of 2014, when researchers at AFRC replaced the conventional aluminum flaps, speed-brakes, and spoilers of the Armstrong Flight Research Center's Gulfstream Aerospace G III (NASA 804) with advanced, shape-changing assemblies that formed seamless bendable and twistable surfaces. A series of flight tests from November 2014 through April 2015 explored the feasibility of using such flexible trailing-edge wing flaps to improve aerodynamic efficiency and reduce noise generated during takeoffs and landings. Employment of ACTE technology would also result in size and weight reductions for aircraft wings, leading to reductions in fuel burn and greenhouse gas emissions. Other potential aerodynamic benefits of ACTE include increased control effectiveness and alleviation of structural loads. ERA researchers concluded that the results of flight-testing successfully increased the ACTE technology TRL to 6.[9]

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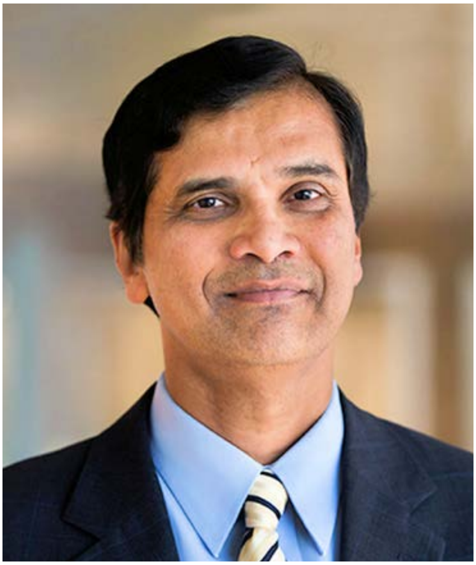
7. Ibid., 4–9.
8. Ibid., 10–20. See also Robert Clarke, Michael J. Allen, Ryan Dibley, Joseph Gera, and John Hodgkinson, "Flight Test of the F/A 18 Active Aeroelastic Wing Airplane," NASA TM-2005-213664 (August 2005), 3–35.
9. Craig L. Nickol and William J. Haller, "Assessment of the Performance Potential of Advanced Subsonic Transport Concepts for NASA's Environmentally Responsible Aviation Project," AIAA-2016-1030, presented at American Institute of Aeronautics and Astronautics SciTech, 54th AIAA Aerospace Sciences Meeting, San Diego, CA, January 6, 2016, 4.



Dr. Sridhar Kota, founder and CEO of FlexSys, and the former Assistant Director for Advanced Manufacturing at the White House Office of Science and Technology Policy, from 2009–2012. (NASA/FlexSys)

The ACTE ITD was a joint effort between NASA and AFRL, using flaps designed and built by FlexSys, Inc., of Ann Arbor, Michigan. With AFRL funding available through the Air Force's Small Business Innovation Research (SBIR) program, FlexSys developed a variable geometry airfoil system called FlexFoil that could be retrofitted to existing airplane wings or integrated into new airframes. During test efforts at Armstrong, FlexSys founder and chief executive officer Dr. Sridhar Kota (an engineering professor at the University of Michigan and former Assistant Director for Advanced Manufacturing at the White House Office of Science and Technology Policy) expressed the hope that testing with a modified Gulfstream G-III would confirm his design's flightworthiness and open doors to future applications and commercialization.

According to Kota, "The aerospace community has known for a long time that if you have a seamless wing that can be morphed in flight to maximize performance, then you can get significant fuel efficiency." In the earliest days of aviation, various designers—the Wrights, Louis Blériot, Louis Béchéreau, Robert and Léon Morane, Igo Etrich, Tony Fokker, Geoffrey de Havilland, and Igor Sikorsky, among many others—used wing warping for controlling their wood-and-fabric aircraft. Later use of metal alloys for structural strength precluded designing aircraft with morphing wings, but the advent of strong, lightweight flexible materials made it possible to revisit the concept. While looking at this problem in the early 1990s, Kota came up with an idea he called "compliant design" that used techniques borrowed more from nature than from traditional mechanical design.[10]

In conventional aircraft construction, everything that is strong is also very rigid. Mechanical functionality requires multiple parts and complex

10. Sridhar Kota interview, *NASA X*, "End of an ERA – Part 1," NASA TV, November 24, 2015.

mechanisms. "Designs in nature are different," he explained. "They are strong, but they are compliant, they're flexible; you can see countless examples in nature of intricate mechanical motion without conventional joints." In Kota's FlexFoil system, every part of the structure shares a small portion of the total load; stresses are evenly distributed. "You have large deflections and small strains, so you can do this multiple times [throughout the life of the aircraft], you can do millions of cycles and still not fail." Although the exact technique remains a trade secret, Kota explained that a proprietary algorithm minimizes the force it takes to morph the wing into a prescribed shape. This technique also has inherent mechanical advantages in that it remains very rigid toward external loads and although the design is incredibly strong, it does not require large, heavy motors to actuate the control surface.[11]

Specific details regarding the design configuration and materials that make up the ACTE control surfaces remain proprietary, but the potential benefits are known. A morphing surface has the potential to cut cruise drag by around 3 percent on retrofitted aircraft and up to 12 percent on all-new designs. The shape-changing mechanism exploits the inherent elasticity of the composite material from which it is made, and by using evenly distributed devices rather than flexural hinges, the ACTE flap requires less power to actuate than conventional flaps. The seamless transition region with the wing eliminates a major source of airframe noise, which is most noticeable during takeoff and landing. Additionally, the ACTE flap provides larger system-level weight benefits for all-new designs (as opposed to retrofits) because it could be used to twist a specially designed wing spanwise to reduce loading as well as wing-bending moment.[12]

In the mid-1990s, Kota unveiled his unique concept to Air Force engineers at the AFRL at Wright-Patterson AFB, Ohio, eventually securing SBIR funding through AFRL. According to Pete Flick, ACTE project manager at AFRL, the laboratory's investment from 1998 to 2015 totaled around $20 million. NASA ACTE project manager Thomas Rigney said that his Agency contributed about $25 million starting in 2009. The NASA portion primarily supported flight-testing and modifications to the G-III testbed that included fitting it with special instrumentation and a new power system.[13]

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11. Ibid.
12. Guy Norris, "NASA-led Team Completes Morphing Flap Tests," *Aerospace Daily & Defense Report*, May 5, 2015, *http://aviationweek.com/technology/nasa-led-team-completes-morphing-flap-tests* (accessed October 1, 2016).
13. Jerome Greer Chandler, "Flexible Flap Test Program Looks to Take 'Next Step,'" *Aviation Pros*, July 16, 2016, *http://www.aviationpros.com/article/12079146/flexible-flap-test-program-looks-to-take-next-step* (accessed November 1, 2016).

Project manager Tom Rigney, right, briefs NASA Administrator Charlie Bolden on the progress of ACTE in 2012. (NASA)

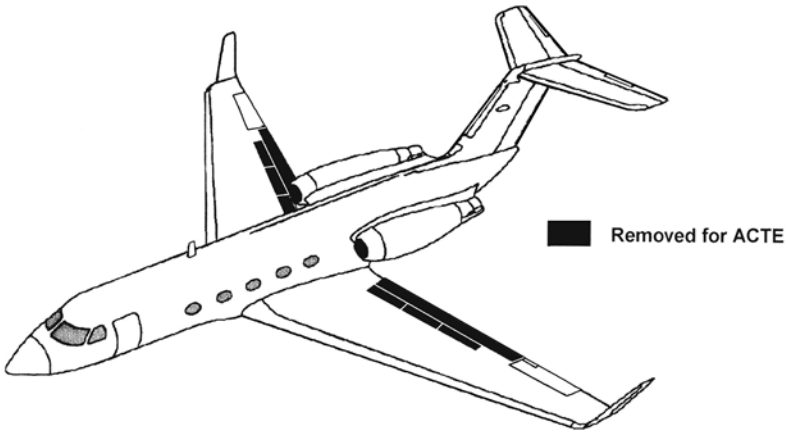
According to Rigney, "The reason we needed to do this on a full-scale aircraft was to take the readiness level from TRL-5 to TRL-6 in a relevant flight environment; for that you need a full-scale aircraft." This was important because Government and industry team members were convinced that ACTE technology had the potential to be a real game changer for the aeronautics community, particularly with regard to its impact on fuel savings. "The amount of potential fuel savings is significant," said Rigney, "not just for the economy, but for the environment."[14]

Researchers selected the AFRC-based Gulfstream G-III Subsonic Research Aircraft (SCRAT) as the ACTE testbed because the airplane's baseline flight characteristics were well understood, and the modification process would be relatively uncomplicated. Additionally, the aircraft was already equipped with data acquisition and telemetry systems for transmitting data to the AFRC control room, where researchers and engineers monitor experiments and safety-related information. Necessary modifications included removal of both the left and right aluminum Fowler flaps, each 19 feet long. Technicians replaced these with flexible ACTE flaps, which were mated to the same attach points on the wing as the original flaps. The main portion of each ACTE assembly was blended seamlessly into the wing structure on both ends via flexible transition sections. These had to be both strong and flexible enough to withstand aerodynamic loads and maintain the integrity of the outer mold-line while being exercised through large deformations.[15]

14. Tom Rigney interview, *NASA X*, "Revolutionary Evolution – ERA," NASA TV, February 17, 2014.
15. Claudia Y. Herrera and Shun-Fat Lung, "Aeroelastic Response of the Adaptive Compliant Trailing Edge Transition Section," presented at 54th AIAA Aerospace Sciences Meeting, San Diego, CA, January 4, 2016, 4.

ACTE Flight Experiment Flap Replacement

- Compliant flap replacing both aircraft flaps in their entirety
- Ground spoilers, flight spoilers/speed-brakes and flaps removed to make room for ACTE
- Target flap geometry approximately 19-ft in-span for each surface



The ACTE trailing edge flaps replaced the G-III's conventional flaps, spoilers, and speed-brakes. (NASA)

ACTE Ground Tests

Ground testing was an essential element of the ACTE project development approach, which incorporated conventional design practices and a build-up test and model-validation approach. Throughout the project, researchers conducted a wide variety of ground-based tests to ensure airworthiness of the structure and to mitigate potential risks to schedule and mission success. These experiments included material characterization testing, structural proof testing, structural qualification testing, fatigue testing, and ground vibration testing (GVT). Project engineers employed a methodical building-block approach to ground testing so that any design and fabrication flaws could be detected and corrected early in order to minimize schedule delays and cost increases. According to AFRC aerostructures engineer Claudia Herrera, this method also "provided opportunities for the project team to gain early fundamental insight into the compliant structure technology." Before any hardware was subject to evaluation, engineers first used a computational tool called FEM analysis to build confidence in the validity of their mathematical models. FlexSys then manufactured two prototype test articles representative of the ACTE flap design and fabrication process. Ground testing of these articles provided the data necessary to support an accurate airworthiness assessment of the flight article. This was crucial to the success of the project. Not only did these tests

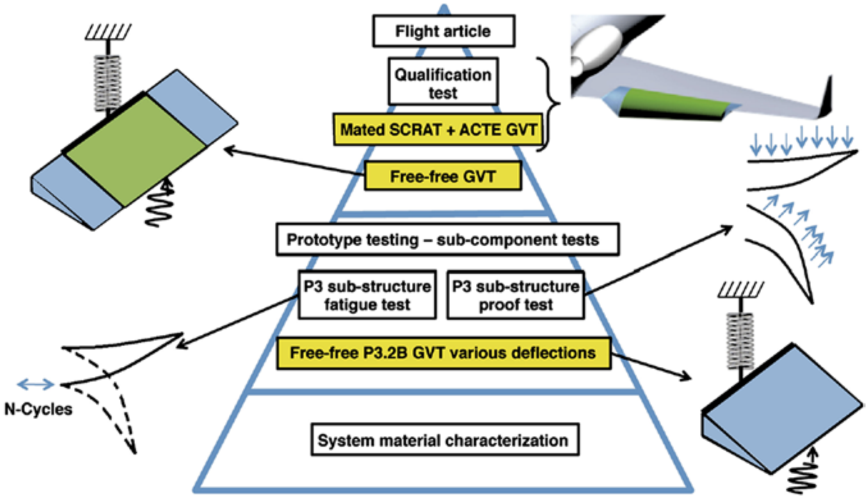


Diagram of the ACTE building-block testing approach. (NASA)

provide confidence in the aeroelastic analyses, they also helped determine best practices for testing the flight article.[16]

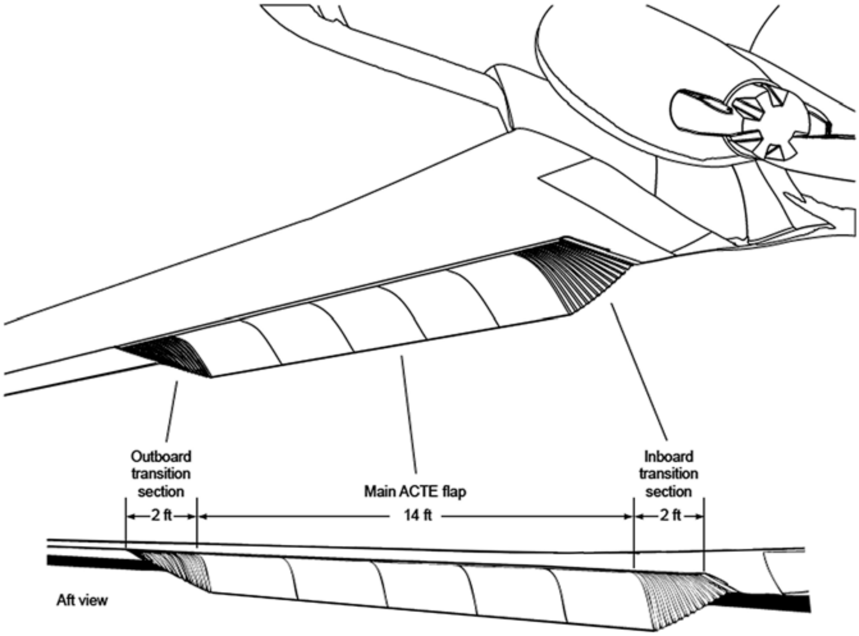
Ground testing included analyses of aeroelastic response through the transition sections used to integrate the ACTE flap to the G-III wing in a continuous mold-line. Researchers evaluated the results to ensure that the combined SCRAT/ACTE system was safe to fly within the desired flight envelope. Per AFRC aeroelastic guidelines, the testbed with its integrated ACTE flaps was required to demonstrate a 20 percent flutter margin to satisfy project requirements for airworthiness. To satisfy this requirement, engineers performed vibration testing and used the resulting data to develop a detailed FEM. In order to minimize impacts to the flight schedule while accurately modeling the flight article, FlexSys built two sets of prototype test articles, designated Prototype 2 (P2) and Prototype 3 (P3) prior to fabricating the ACTE flight-test articles. The differences between P2 and P3 were essentially minor design, fabrication, and manufacturing process changes that allowed P3 to minimize strain levels when subjected to large deflections. The P3 design possessed the full chord-wise size of the flight-test article but represented only a section of the spanwise size. Prototypes containing components designated as "A" were representative of a portion of the main flap section, while those with components designated "B" were full-scale chord-wise transition sections.[17]

16. Ibid., 4.
17. Ibid., 4–5.

The engineering team performed GVTs on test articles P2.2B and P3.2B as a proof-of-concept for testing the compliant structure. NASA personnel conducted both tests at the FlexSys facility in Ann Arbor. The results provided confidence in test procedures as well as data for understanding the modal characteristics of the transition sections needed for validation of the FEM. Both test articles represented the right-hand inboard transition section with only slight variations. Conducted in September 2012, the P2.2B GVT was the first opportunity to experimentally evaluate the structural dynamic response of the FlexSys compliant flap structure. Goals included measurement of vibration frequencies and mode shapes at several deflections and two different boundary conditions. The engineers wished to consider any apparent change in structural stiffness due to changing the flap deflection. They also needed to evaluate several factors including the use of accelerometers as instrumentation on flexible structures, various types of excitation methods and instrumentation mass-loading effects, and a variety of analytical FEM techniques. The results provided a comprehensive set of lessons learned on how best to model the ACTE flap and how to test compliant structures, and also helped identify possible design variables for updating the FEM. For the P3.2B GVT in April 2013, the test article was a reproduction of the right inboard transition section of the ACTE flight article. It included a 3-inch section simulating the main flap portion of the ACTE flight article, a 5.75-inch section to simulate the fixed wing structure, and a truncated section of the ACTE flap spar with an attachment simulating how the flap would connect to the SCRAT airframe.[18]

Engineers analyzed the ACTE structure's modal response by deflecting the ACTE FEM analytically using the ANSYS and NASTRAN software packages to match the planned physical deflections of the structure. To do this, FlexSys first developed a mathematical relation between the amount of input applied at the flap actuation points and the amount of control-surface deflection relative to the airplane's fixed wing section outer mold-line. These same inputs were applied at the actuation locations in the FEM. The engineering team then analyzed the deflected structure for natural mode shapes and frequencies using a non-linear analysis method. During the P2.2B test, researchers noticed that the resulting deflected FEMs did not match the test results as well as expected, and it was necessary to validate each of the deflected shapes against the measured deflected structure to determine which software performed best for creating the deflected FEM of the ACTE structure. As a result, validation of the analytical deflected shapes against the measured deflected shapes became an important objective to be satisfied during the P3.2B GVT. Other test objectives for the P3.2B GVT included quantifying changes in frequencies and mode shapes as a

18. Ibid., 5–6.



The various ACTE flap components, as seen from aft of the wing. (NASA)

function of flap deflection, evaluating various types of excitation methods, and determining what design variables to use in potential future FEM updates.[19]

Results of the P3.2B GVT indicated that ANSYS consistently produced more accurate analytical deflection frequencies and mode shapes that better matched the GVT data. Because they took a conservative approach with the FEM in the flutter analysis, the analytical results were lower than GVT results for critical modes. Although a post-test FEM update was not required, the team performed one in order to more accurately determine material properties for the flexible structure. After being validated, these properties were inserted into the full-flap FEM, which was also validated and updated using the full-flap GVT results. While conducting these tests, engineers noted that a geometry change caused by applying different flap deflections significantly altered the internal loading of the structure. This created an apparent change in stiffness that was manifested in the test frequencies and mode shapes. It became necessary to apply multiple types of excitation to locations on the simulated wing and main flap sections to verify that the modes of interest identified through earlier analysis were adequately measured. The resulting

19. Ibid., 7.

GVT data were used to ensure correlation with analytical models. Testing also produced some unexpected results. Unexpectedly high damping values had to be empirically estimated due to some unique characteristics of the flexible structure, and researchers discovered an unpredicted mode at 30 degrees deflection. Engineers concluded that the truncated main flap section of the P3.2B test article probably engendered a lack of stiffness in the spanwise direction for the highly deflected flap.[20]

The team performed flutter analyses using ZAERO, a powerful engineering tool developed by Zona Technologies Inc., in Scottsdale, Arizona, that integrates essential disciplines required for advanced aeroelastic design and analysis. In order to facilitate this, researchers at AFRC first developed a baseline SCRAT aerodynamic model based on a half-model supplied by Gulfstream Aerospace and updating it to reflect the full aircraft configuration complete with ACTE flaps. Using a finished model that contained 3,021 flat-panel elements, researchers analyzed two fuel conditions (full and empty) and three flap settings from –2 to 30 degrees. Flutter frequency response was calculated for speeds ranging from 0.6 to 0.8 Mach.[21]

According to Tom Rigney, the greatest challenge was integrating the ACTE flap with the SCRAT testbed. "It was a major modification," he said, "and it was absolutely critical to get the new flap to fit exactly right; it had to be very closely coupled with the wing." There was little room for error because if either flap was just one degree out of alignment, it could make the airplane difficult to control. "When the ACTE flaps first arrived at Armstrong, they didn't fit just right and we had to work very closely with the people in the machine shop to adjust the flaps and compensate for gaps, and things like that," said Rigney. "We were eventually able to meet the requirements, but it wasn't easy."[22]

Testing of the complete SCRAT aircraft with flaps installed took place in the AFRC Loads Laboratory. Having access to a comprehensive set of data and accurate loads equations resulted in more precise flight-test data and enhanced safety of flight because researchers were able to expand the flight-test envelope without exceeding the aircraft's structural limits. Before flying the airplane in the ACTE configuration, however, technicians first had to conduct specialized tests that involved applying loads to the aircraft via hydraulic jacks. Scientifically calibrated strain gages provided researchers with highly accurate measurements of the applied stresses, enabling them to predict the structural performance of the aircraft in flight. According to chief test engineer Larry Hudson, "Doing a test of this nature enables us to understand on the ground,

20. Ibid., 8.
21. Ibid., 14.
22. Thomas K. Rigney, interview with the author, January 17, 2017.

Aeronautical engineer William Lokos monitors a wing loading test of the NASA Gulfstream G-III SCRAT at the NASA Armstrong Flight Research Center's Loads Laboratory. (NASA)

by applying certain loads into the airplane, what loads will be experienced in flight under similar conditions."[23]

Lifting the airplane off the loads lab floor with the three inflatable airbags isolated the airframe from any potential influence the landing gear might exert upon strain-gage data. According to principal investigator Bill Lokos, the center's loads lab had never previously employed this method. Technicians positioned the airbags beneath the wings and aft fuselage to keep the main gear tires off the floor thus ensuring that loading across the aircraft's center wing box structure remained constant. This was necessary, Lokos explained, because increased loading on the wings typically resulted in decreased loads on the gear, which affected the strain-gage measurements and skewed the results of the preliminary equations. Supporting the G-III with standard aircraft jacks was not an option, he noted, because the effects were even more pronounced than those produced by the gear alone. Alternatively, using a cradle system would have been costly and time-consuming. Airbags of the type used to lift

23. Peter W. Merlin, "Pumping It Up: Airbags Take the Weight in ACTE G-III Loads Tests," June 16, 2014, *http://www.nasa.gov/centers/armstrong/Features/ACTE_G-III_loads_test.html* (accessed September 18, 2016).

aircraft in the field following gear-up landings were already available as proven, off-the-shelf hardware.[24]

Once the G-III was properly positioned, lab technicians applied loads with hydraulic jacks positioned underneath the wings. Structures lead Eric Miller explained that combining known loads values with strain-gage responses in the lab helped researchers develop a database for validating or correcting existing load equations. "We correlate these data so that we can drive our own load equations and be able to monitor flight loads in real time during ACTE flight tests," he said.[25]

Flight-Testing ACTE

Now, the team was ready to begin collecting flight-test data to validate preflight modeling. Based on these analyses, both ACTE flap assemblies had been fully instrumented to capture the in-flight aeroelastic response for comparison to a set of predictions for each deflection test point. Engineers in the AFRC mission control room monitored the instrumentation suite via telemetry throughout every flight. Flight-test points that could be compared directly to analytical predictions were considered anchor points, but the ACTE flaps were also deflected to positions that were not analyzed. The results of these spot checks could be used only to verify trends between anchor points.[26]

Prior to takeoff, an aircraft crewmember manually excited the transition sections with a few sharp taps, and the response was measured through the onboard data collection system. While flying, engineers used response data provided during various maneuvers to estimate vibration frequency and damping. While airborne, excitation was provided primarily by light turbulence encountered during flight over the Edwards Air Force Base test ranges. After each test mission, the engineers evaluated mode symmetry by comparing recordings of accelerometer signal data.[27]

For the sake of simplicity and safety, the actuation system was not exercised during flight. Instead, the ACTE research team developed a build-up approach to flight-testing that entailed clearing the ACTE flight envelope through a series of specific test points in such a manner as to strategically increase dynamic pressure and Mach number throughout the performance envelope. Initial flights took place at low altitudes and speeds, followed by

24. Ibid.
25. Ibid.
26. Herrera and Lung, "Aeroelastic Response of the Adaptive Compliant Trailing Edge Transition Section," 16–17.
27. Ibid., 17.

Gulfstream G-III SCRT ACTE testbed N804NA takes off on an early test flight, accompanied by a NASA AFRC F/A-18 chase airplane. (NASA)

tests at high-altitude and low speeds. The next step included high-altitude and high-speed tests and concluded with low-altitude and high-speed tests. "It was a build-up approach," Rigney explained. "Each time, we increased the flap angle and airspeed parameters, and we expanded the [performance] envelope on every flight."[28]

During each flight, the AFRC mission control center was staffed to monitor mission-critical, safety-of-test, and safety-of-flight parameters. The SCRAT crew included two pilots and one engineer, and each mission was required to be accompanied by a safety chase aircraft. Each test mission consisted of a set of specific flight-test maneuvers to validate stability and control predictions, aerodynamics models, structural analyses, and aeroelastic predictions. The high-speed/high-altitude envelope provided flight limits for small flap deflections, and the low-speed/low-altitude envelope provided flight limits for large flap deflections.[29]

During the inaugural ACTE flight, the experimental control surfaces were locked at a 0-degree setting. Although the flaps were not actuated during flight,

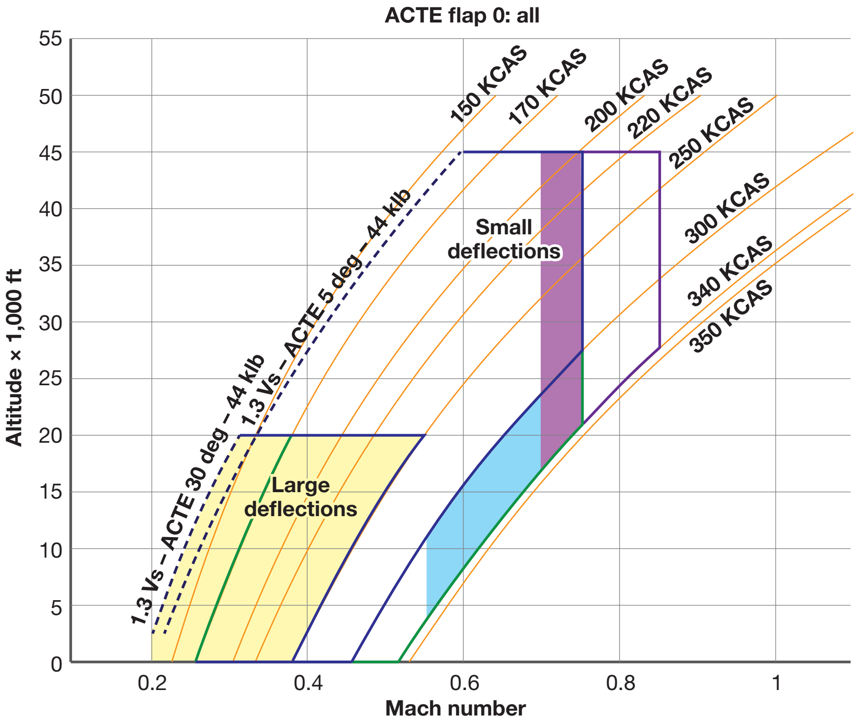
28. Rigney interview with author.

29. Herrera and Lung, "Aeroelastic Response of the Adaptive Compliant Trailing Edge Transition Section," 16.

NASA's SCRAT testbed in flight. Note ACTE flap deflection. (NASA)

Flight research engineers monitor an ACTE test flight from the AFRC mission control room. (NASA)

a set of incremental fixed-flap settings were later employed on subsequent test missions to collect a variety of data demonstrating the capability of the flexible surfaces to withstand a real flight environment. Data from each of these test points were combined to extrapolate the behavior of the flap while extending and retracting throughout the flight envelope. "We have progressed from an



G-III flight envelope with ACTE flaps installed. (NASA)

innovative idea and matured the concept through multiple designs and wind-tunnel tests, to a final demonstration that should prove to the aerospace industry that this technology is ready to dramatically improve aircraft efficiency," said AFRL program manager Pete Flick following the initial test.[30]

"The first flight went as planned; we validated many key elements of the experimental trailing edges," said Tom Rigney, noting that now the team faced a variety of challenges including a tight schedule. "We had to minimize the downtime between flights, and the airplane had not been flown for a long time prior to the ACTE project, which created a lot of maintenance problems up front," he recalled. The NASA maintenance crew thoroughly inspected the aircraft and made necessary repairs. Problems had to be addressed rapidly, and there were some surprises during the first few flights. "Once those were overcome," Rigney noted, "we had to deal with new schedule pressures because we had less time to complete all of our flights." He said that between flights, the team focused on the

30. Peter W. Merlin, "ACTE Takes Flight," *The Armstrong X-Press*, Vol. 56, Issue 7, November 2014, 1–2.

time it took to reduce the data, and made every effort to optimize the amount of work done between flights. "Normally, you have milestones that you monitor to make sure everything is on track," he explained, "but I created what I called 'inch-stones,' where everything is monitored very tightly to make sure we were on schedule and doing all the flights that we needed to." He also kept AFRC managers apprised of potential conflicts, so they could resolve them as early as possible. "Overall, we hit our mark in terms how many flights we wanted and the amount of time we wanted them done in," he said. "It's hard to convey the amount of effort it took when there were so many people working hard at what they do, because when you're successful, you make it look easy."[31]

Every aspect of the flight-test process was designed to prove the radical new technology with a minimum of risk. Each incremental test point expanded the flight envelope enough to move on to the next step. The decision, made early in the project, to use fixed flap positions instead of actuating the flaps in flight was based on risk reduction and also allowed the team to move forward at an accelerated pace. "Actuators for ACTE will be developed using existing technology," said Rigney. "We didn't need to test that." Backup instrumentation systems made it possible to continue flying even if one or more sensors failed during a flight. "The ERA project was really good at making sure we had enough emphasis on risk management," he said. "It was a key factor in our success."[32]

The ACTE project achieved a major milestone at AFRC on February 18, 2015, when the modified G-III completed a flight with 15 degrees flap deflection, thus successfully meeting all of the project's primary requirements. Throughout the flight test series, data were taken at points ranging from –2 degrees (up) to 30 degrees (down). Although the flexible ACTE flaps are designed to morph throughout the entire range of motion, each test was conducted at a single fixed setting in order to collect incremental data with a minimum of risk. Following the milestone flight, NASA ARMD Integrated Aviation Systems program director Ed Waggoner declared, "Reaching our minimum success criteria for the ACTE Integrated Technology Demonstration is a testament to the exceptional cooperation and collaboration toward the success of this flight campaign" between NASA, AFRL and FlexSys. "Every milestone we achieve helps us to better understand how these enabling technologies reduce aviation's impact on the environment."[33]

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31. Rigney interview with author.
32. Ibid.
33. Peter W. Merlin, "Shape-Changing Flap Project Meets First Milestone," NASA Armstrong News Features, March 11, 2015, *http://www.nasa.gov/centers/armstrong/Features/acte_milestone.html* (accessed September 18, 2016).

Flight test of ACTE flap at 25 degrees deflection. (NASA)

By the end of April 2015, the team had successfully completed 23 ACTE test flights aimed at proving the airworthiness of the flexible structure and its ability to withstand high dynamic pressures at speeds up to 0.8 Mach and aerodynamic loads up to 11,500 pounds per flap segment at high deflection angles. Despite the complexity of the task, all primary and secondary objectives for the test series were successfully completed on schedule and within budget. "It was a very successful demonstration in that we accomplished all of our primary and secondary goals," said Rigney, "we didn't miss any requirements at all."[34]

Moreover, he explained, ACTE technology is expected to have far-reaching effects on future aviation. Advanced lightweight materials will reduce wing structural weight and give engineers the ability to aerodynamically tailor the wings to promote improved fuel economy and more efficient operations, while reducing environmental impacts. "It also has the potential to save hundreds of millions of dollars annually in fuel costs," he said.[35]

Researchers incorporated the results of the ACTE flight tests in subsequent LaRC design trade studies for future large transport aircraft. "Armstrong's work with ACTE is a great example of how NASA works with our Government and industry partners to develop innovative technologies that make big leaps

34. Rigney interview with author.

35. Ibid.

Overview of ACTE Flights Conducted by NASA

Flap Setting	Cleared Alt. (ft)	Max Q (psf)	Max Accel (Gs)
20	High Speed Taxi	NA	NA
0	10,000	206	1.7
0	20,000	206	1.7
0	40,000	310	1.85
0	40,000	384	1.8
2	20,000	215	1.74
2	40,000	213	1.91
2	40,000	370	1.8
5	30,000	210	1.7
10	20,000	210	1.8
12.5	20,000	210	1.96
15	20,000	206	1.8
17.5	20,000	100	1.7
20	20,000	100	1.7
25	20,000	100	1.7
5	40,000	200	1.8
5	40,000	304	1.97
–2	20,000	206	1.7
–2	40,000	206	1.7
–2	40,000	245	1.7
–2	40,000	300	1.7
30	20,000	101	1.7
15	20,000	200	1.7

in efficiency and environmental performance," said Jaiwon Shin. "This is consistent with the Agency's goal to support the nation's leadership in the aviation sector."[36]

36. J. D. Harrington and Leslie Williams, "NASA Successfully Tests Shape-Changing Wing for Next Generation Aviation," NASA News Release 15-072, April 28, 2015.

Evaluating Future ACTE Applications

Every now and then, NASA research leads to innovations that become industry standards. Two excellent examples include winglets and supercritical wings. Both represent simple, yet elegant, solutions to the problem of making airplanes more aerodynamically efficient. When first introduced in the early 1970s these technologies seemed revolutionary, yet today they are commonplace, having been integrated into a wide range of civil and military aircraft. Based upon its success in testing and its relatively high TRL, it is likely that ACTE technology will be similarly received by the aviation industry.

Several analyses of ACTE and similar technologies reported aerodynamic advantages derived from adaptive trailing edges. Sridhar Kota and others at FlexSys and AFRL projected a 3.3 percent improvement in cruise lift-to-drag ratio for a conventional medium-range transonic transport retrofitted with ACTE flaps.[37] NASA researchers at LaRC conducted a study using the center's Airborne Subscale Transport Aircraft Research (AirSTAR) testbed, a 5.5 percent dynamically scaled, remotely piloted, twin-turbine, swept-wing, generic transport model designed to provide an experimental flight-test capability for research experiments pertaining to dynamics modeling and control beyond the normal flight envelope. In this case, the AirSTAR was used to demonstrate flap camber shapes optimized with a vortex lattice code at multiple cruise conditions. The results showed induced drag improvements ranging from 1.2 percent to 9.9 percent depending on flight condition and the rate at which camber was allowed to change in the spanwise direction.[38] A study at the University of Michigan examined the application of morphing trailing edges to a conventional long-range, twin-aisle transport configuration. Using a Navier-Stokes based aerodynamic optimization of a variable camber trailing edge flap on a 777-size aircraft, researchers projected drag reductions from one percent at on-design conditions to five percent at off-design conditions.[39]

In May 2013, NASA sponsored a Boeing study evaluating the comprehensive effects of ACTE technology on a variety of commercial transport aircraft applications. Study goals included quantifying changes in weight, drag, and

37. Kota, et al., "Mission Adaptive Compliant Wing - Design, Fabrication and Flight Test," 18–19.
38. James Urnes, Nhan Nguyen, Corey Ippolito, Joseph Totah, Khanh Trinh, and Eric Ting, "A Mission-Adaptive Variable Camber Flap Control System to Optimize High Lift and Cruise Lift-to-Drag Ratios of Future N+3 Transport Aircraft," AIAA 2013-0214, presented at the 51st AIAA Aerospace Sciences Meeting, Grapevine, TX, January 7–10, 2013, 1–6.
39. Zhoujie Lyu and Joaquim Martins, "Aerodynamic Shape Optimization of an Adaptive Morphing Trailing Edge Wing," AIAA 2014-3275, 52nd AIAA Aerospace Sciences Meeting, January 13–17, 2014, 1–14.

NASA's AirSTAR subscale flight research vehicle was used to demonstrate optimized flap camber shapes at multiple cruise conditions. (NASA)

fuel burn caused by the introduction of ACTE technology to three aircraft configurations: a 224-seat HWB, a 222-seat conventional wide-body transport, and a 154-seat conventional narrow-body transport. Both the HWB and wide-body transport were designed for 8,000 nautical mile range at 0.85 Mach cruise speeds. The narrow-body transport was designed for 3,500 nautical mile range at an average cruising speed of 0.785 Mach. For the purpose of the study, conventional elevon and aileron controls on the outboard wing of the HWB were replaced with ACTE surfaces. Researchers converted the aft portions of the flaps on the tube-and-wing wide-body and narrow-body configurations to ACTE surfaces, allowing the flaps to be extended as single-slotted Fowler flaps in low-speed conditions to preserve high-lift characteristics.[40]

With flaps retracted for high-speed flight conditions, ACTE allowed the flap trailing edges to both control roll and alleviate aerodynamic loads. The latter thus made possible tailoring span-loading over a wide range of flight conditions and thus achieving more structurally efficient span-loadings in critical structural design conditions, as well as achieving more aerodynamically efficient span-loads in cruise. Having the capability to reduce bending moments through load alleviation made it possible to incorporate wings with lower structural weight than is typical, and improvements in cruise span-loads

40. Wakayama and White, "Evaluation of Adaptive Compliant Trailing Edge Technology," 2.

resulted in lower drag. Both of these characteristics contributed to reductions in fuel consumption. The study also revealed some penalties derived from using ACTE technology. These included higher weights for control surface structures, control surface actuators, and hydraulic systems needed to power the larger actuators. These weight estimates were based partially on results from the ACTE G-III flight demonstration at AFRL and might be offset by future improvements to the technology.[41]

Each configuration in the Boeing study was evaluated with and without application of ACTE technology. Because each model had a fixed wing area and engine thrust, the results demonstrated only the direct effects of ACTE, but not the augmentation of effects that would result from changing these variables. The benefits derived from the use of ACTE varied among the different aircraft, and were largely driven by the effectiveness of control surface arrangements and the importance of wing-weight reduction for each aircraft configuration. Researchers planned to use these results in subsequent studies to model the integrated effects of ACTE in combination with other technologies, as well as in scaling effects.[42]

Results of the initial study showed that the 224-seat HWB configuration derived the least amount of benefit from ACTE. Researchers found that the benefits of ACTE on span loading and load alleviation could have been accomplished just as easily with less weight penalty using the original control surfaces. Although some additional aerodynamic benefits might have been achieved by closing control-surface gaps, these effects were beyond the analysis methods used in this study. The most significant benefit demonstrated was a mere 0.7 percent fuel burn reduction.[43]

ACTE surfaces were added to the aft portion of the flaps on the 154-seat narrow-body transport model. These flaps were configured with typical single slotted Fowler motion to provide high-lift capability, but the ACTE surfaces could be actuated even with the flaps stowed for high-speed flight conditions. In this case, the ACTE surfaces were used primarily for load alleviation and roll control. Researchers discovered that when taking some responsibility for roll control away from the ailerons, the ACTE surfaces freed the ailerons to be partially used for load alleviation. Additionally, use of the ACTE surfaces to transfer loads for roll control inboard effectively reduced bending moments during critical rolling maneuvers. In this configuration, ACTE technology

41. Ibid., 2.
42. Ibid., 2.
43. Ibid., 11.

Researchers found that ACTE provided smaller benefits to HWB configurations than to conventional tube-and-wing aircraft. (NASA)

provided a net benefit of 0.9 percent reduction in fuel burn, which was somewhat better than in the HWB configuration.[44]

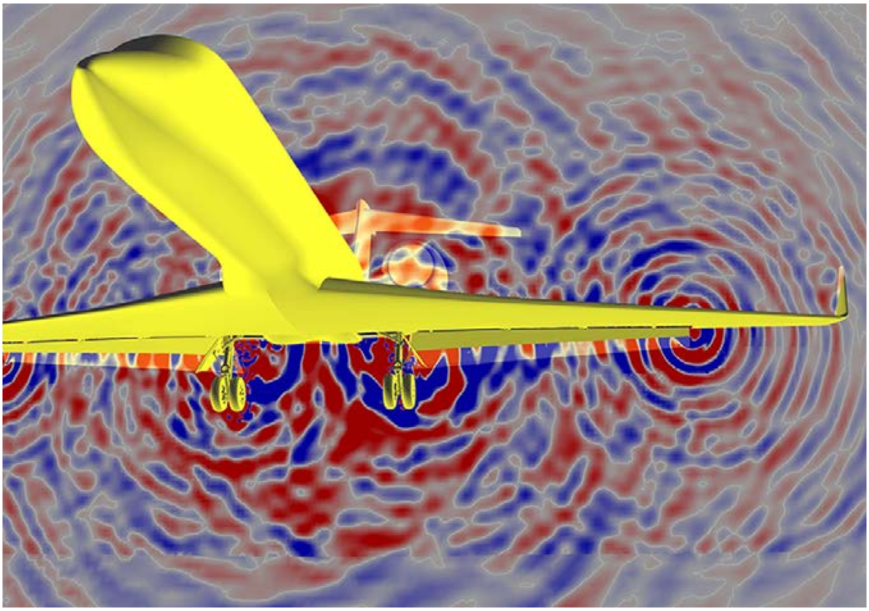
The greatest benefits resulted from the 222-seat wide-body transport with ACTE surfaces added to the aft portion of the flaps. These modified surfaces worked with the outboard ailerons to provide load alleviation while the inboard ailerons were responsible for roll control. Although the original control surfaces could have provided effective load alleviation by themselves, the application of ACTE technology demonstrated larger benefits because the control surface arrangement was favorable for load alleviation, and because wing weight reduction had greater vehicle-level effects. Altogether, this configuration resulted in a 2.6 percent reduction in empty weight, 2.4 percent reduction in takeoff weight, and a 3.0 percent reduction in fuel burn.[45]

The Boeing researchers concluded that the arrangement of control surfaces may have a strong influence on the benefits of ACTE, and that optimization of the sizing and placement of control surfaces would better define the limits of this technology. They also noted that trading load alleviation benefits against penalties for control surface structure and actuator weight could also allow

44. Ibid., 11.
45. Ibid.,12.

aircraft designers to size control surfaces in such a way as to provide greater load alleviation benefits. Most important, they felt that with further work ACTE technology could contribute significantly to fuel-burn reduction.[46]

46. Ibid., 12.



NASA researchers simulated the radiated sound field produced by a full-scale Gulfstream G-III aircraft during landing. (NASA)

CHAPTER 5

Reducing Airframe Noise

NASA's major ERA goals included reducing and mitigating aircraft noise in communities adjacent to airports, a quest rendered more significant still because analysts predicted an average growth in U.S. carrier passenger flights of 2.2 percent per year between 2013 and 2033, with slightly higher-than-average growth in the first 5 years. An increase in takeoff and landing cycles could be expected to trigger an increase in noise complaints in communities surrounding affected airports.

For decades—well over a half-century—reducing and mitigating aircraft noise had been a NASA (and NACA before it) area of interest. Traditionally, the

The NASA Boeing 747 SOFIA (Stratospheric Observatory for Infrared Astronomy) flying low over the NASA Ames Research Center. Aircraft noise during takeoffs, climb-outs, approaches, and landings has a significant impact on quality of life in communities adjacent to airports and has been a long-standing research interest of NASA scientists, engineers, and technologists. (NASA) greatest source of aircraft noise has been propulsion systems, particularly as the growl of piston-and-propeller systems gave way to the roar of turbojets. Over the past 50 years, air traffic increased dramatically and communities rapidly encroached on airport boundaries. Noise complaints soon became the number-one issue reported to FAA public liaison offices around the country. Solutions ranging from restricting the number of flights allowed per day to nighttime curfews for commercial air carriers had an adverse economic impact. Noise-abatement approaches and departure trajectories have mitigated the problem to some degree, but the most significant improvement was the advent of quieter turbofan engines. Advances in quiet engine technologies have resulted in such significant reductions in engine noise during takeoff and landing operations that, for current state-of-the-art aircraft, engine and airframe noise are nearly comparable. NASA researchers, therefore, sought to decrease airframe noise in order to minimize community exposure to aircraft acoustics. Primary sources of airframe noise include the wing high-lift system (slats and flaps) and the undercarriage (nose and main landing gear). Secondary sources include slat brackets, flap actuators, and gaps between airframe and control surfaces.[1]

According to Mehdi Khorrami, lead project investigator at LaRC and ERA noise-reduction element lead, a complete understanding of the problem requires full consideration of both engine noise and airframe noise contributions to an airplane's acoustic signature. "You have to look at the problem from a system level," he said, "because if you can reduce overall noise by 3 or 4 decibels, you have effectively cut it in half." ERA goals for N+2 civil transports called for a reduction of 32 decibels below current FAA Stage 4 standards, and a reduction of -42 decibels for aircraft entering service in the N+3 timeframe. "Our dream is to see Stage 4 minus 71 decibels," said Khorrami, "because by then you have essentially confined aircraft noise to within airport boundaries."[2]

To begin making these goals a reality, ERA managers established the Flap Edge and Landing Gear Noise Reduction ITD. Objectives for this effort included development of advanced modeling tools and capabilities that would enable aerodynamic and acoustic design considerations to be integrated concurrently early in the airframe design process, and innovations in effective noise-reduction concepts. One such concept consisted of modifications to the side edges (tips) of the flaps to mitigate noise source regions by altering local steady and fluctuating flow fields. For landing gear, the addition of

1. Craig L. Nickol and William J. Haller, "Assessment of the Performance Potential of Advanced Subsonic Transport Concepts for NASA's Environmentally Responsible Aviation Project," AIAA-2016-1030, presented at American Institute of Aeronautics and Astronautics SciTech, 54th AIAA Aerospace Sciences Meeting, San Diego, CA, January 6, 2016, 4.
2. Mehdi R. Khorrami, interview with the author, August 17, 2016.

Airflow over spoilers, flaps, slats, and associated actuator hardware is an important source of aerodynamic noise. (Peter Merlin)

aerodynamic fairings altered the flow fields impinging on various gear components in a way that minimized pressure fluctuations on the gear surfaces.[3]

During approach and landing, when engines are throttled back to reduce thrust, the noise generated by various parts of the airframe may be louder than that produced by the propulsion system. In order to effectively mitigate this problem, it is necessary to lessen the combined acoustic signatures from all major contributors concurrently. "As you reduce noise from one source," Khorrami explained, "another one becomes more prominent." The task is especially complicated because aircraft of different sizes and configurations offer different challenges. "Any protuberance in an area where it creates turbulent flows will generate airframe noise," Khorrami said. "Turbulent vortex filaments interacting with the flaps and landing gear merge together and become stronger, creating pressure fluctuations on the aircraft surface that we hear as noise."[4]

Initially, Khorrami led studies of the acoustic effects of specific structures such as the nose gear and flaps. "I was working with Fay Collier under the Subsonic Fixed Wing program and we made some measurements with a

3. Nickol and Haller, "Assessment of the Performance Potential of Advanced Subsonic Transport Concepts for NASA's Environmentally Responsible Aviation Project," 4.
4. Khorrami interview.

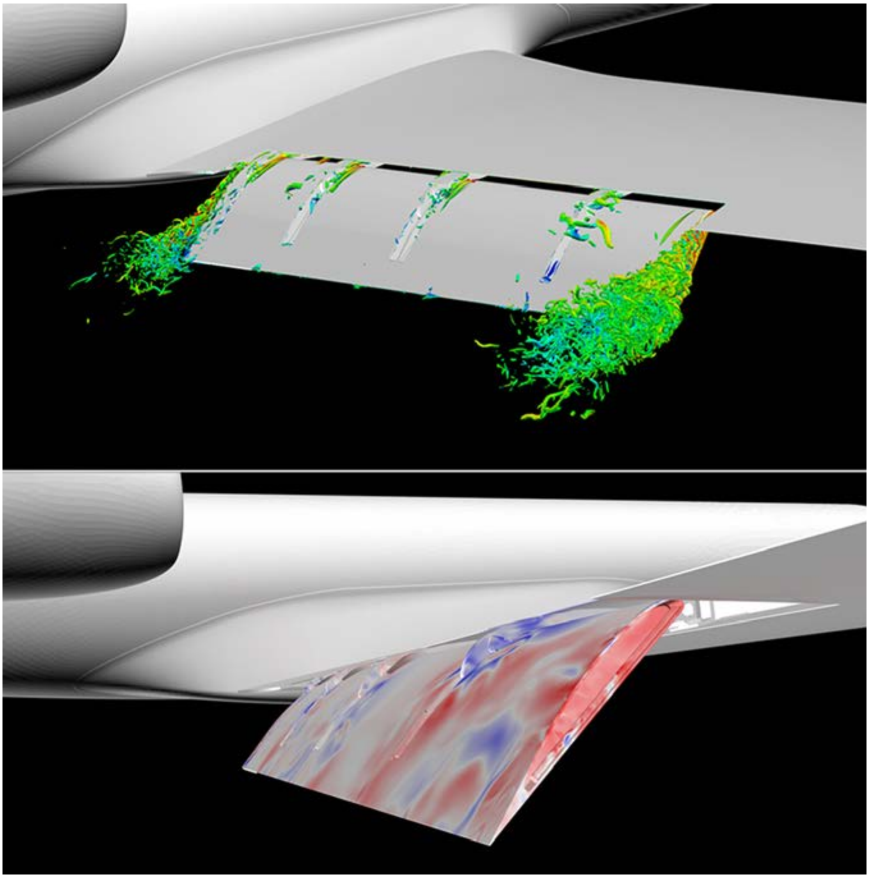
NASA Langley research scientist Mehdi Khorrami. (NASA)

G550 aircraft in 2006," he recalled. Researchers at LaRC then conducted further investigations with a small-scale, semi-span model of a G550 to look at several aircraft components and try to understand their effect on airframe noise characteristics. In 2009, the team decided to expand the research from just looking at individual components to visualizing the entire airplane as an integrated system. "When the ERA project was created, we fully migrated [our research] to ERA because it was a technology development project," Khorrami said, "and we wanted to develop new technologies to reduce airframe noise." He added that, "During Phase 1 of ERA, our major focus was trying to see how much data we could get from scale models and with the same [G550] testbed we used in 2006, and in Phase 2 we made a full-blown effort to push our computational models."[5]

The first step toward designing viable noise-reduction technologies was to accelerate the development of high-fidelity simulation tools with accurate predictive capabilities. To this end, NASA partnered with Gulfstream Aviation for a comprehensive computational effort designed to advance the state of the art in airframe noise prediction from scale models to system-level, full-size aircraft configurations. "First, we simulated airflow over a semi-span scale model of a G550 in landing configuration to accurately capture the prominent noise sources at both flap tips for the baseline configuration," Khorrami said. "We then evaluated the effectiveness of noise-reduction technologies applied to the flap tips."[6]

Advanced computing software was key to success. Researchers used both the NASA LaRC FUN3D unstructured Navier-Stokes flow solver and Exa Corporation's PowerFLOW Lattice-Boltzmann flow solver to perform time-accurate simulations. As efforts continued, the subscale half-span model was replaced with a full-span, full-scale baseline aircraft in landing configuration

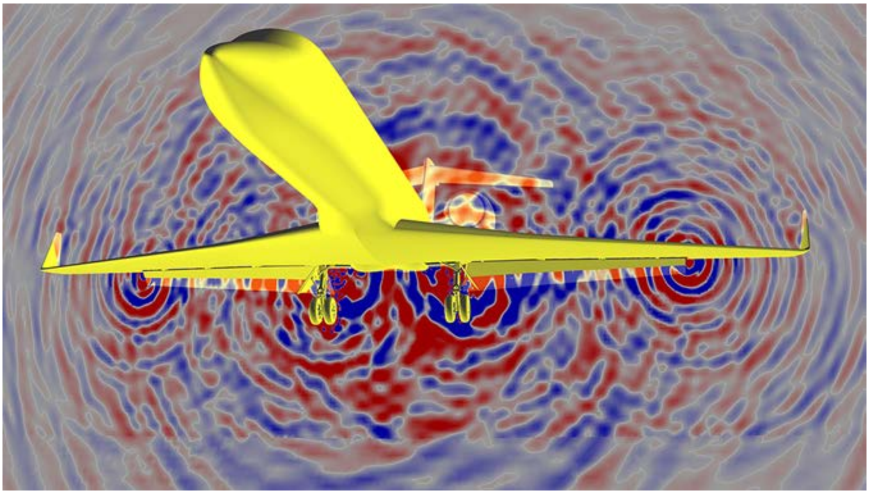
5. Ibid.
6. Ibid.



Two visualizations of the simulated flow-field for a Gulfstream aircraft high-lift configuration depict complex, unsteady flow features at both flap tips. The upper image shows the formation of vortex filaments and their roll-up into a single, prominent vortex at each tip. The lower image shows the corresponding surface pressure fluctuation field (noise sources), corroborating wind-tunnel measurements obtained at NASA LaRC. (NASA)

with wing flaps deflected 39 degrees and the main landing gear deployed. Once again, simulated airflow over the model's virtual surface revealed the primary airframe noise sources associated with the G550. Khorrami explained, "We focused our efforts on accurately resolving the local flow fields at three locations: the flap tips, the regions near the main landing gear, and the interaction zones between these two areas."[7]

7. Ibid.



NASA researchers simulated the radiated sound field produced by a full-scale Gulfstream G-III aircraft during landing. (NASA)

High-fidelity simulations enabled researchers to probe into the underlying noise-generating mechanisms associated with airflow over the flaps and landing gear, and to develop potential solutions. Because these simulations presented numerous challenges due to geometric complexities and requirements for a wide range of spatial and temporal resolution, all computations had to be performed on Pleiades, one of the world's most powerful supercomputers. This vital resource was located at ARC, where the NASA Advanced Supercomputing Division's visualization team created renderings from the resulting datasets. According to Khorrami, even medium-resolution simulations required as many as 4,000 processors and 1.5 million processor hours and generated 40 to 50 terabytes of data. "The knowledge gained from these computations allowed us to develop and improve several concepts that reduce the noise generated by these components," he said.[8]

Wind-Tunnel Test Setup

Several methods for mitigating airframe noise underwent aeroacoustic testing in the NASA LaRC 14-by-22-foot subsonic wind tunnel during three test series, each lasting 4 to 5 weeks. The test article was an all-metal 18-percent scale, semi-span, high-fidelity model of a Gulfstream G550 aircraft. It was designed, fabricated, instrumented, and integrated at NASA LaRC based on a

8. Ibid.

set of airframe geometry files provided by Gulfstream. Model details included a 185.4-inch-long half-span fuselage, a wing measuring 104.5 inches from the tunnel floor to the tip, a flow-through engine nacelle, engine pylon, and high-fidelity scale replicas of the flap and main landing gear.[9]

The initial test series, completed in November 2010, documented the model's basic aerodynamic characteristics. At this time, researchers acquired measurements of such global forces as lift and drag, along with steady and unsteady surface pressure measurements. The second series of tests took place in February and March 2013. These experiments were dedicated to conducting comprehensive aeroacoustic testing of the model in a landing configuration, with and without flap/gear noise-reduction devices installed. The third and final test series was completed in April 2013. These tests were devoted to collecting off-surface flow measurements from the model in baseline landing configuration with emphasis on gear-flap flow interactions.[10]

Acquisition of acoustic measurements and determination of flyover sound directivity patterns for flap/gear noise sources necessitated that the wind-tunnel facility be operated in an open-wall mode in which the ceiling and the sidewalls of the tunnel test section were raised. This had been determined during the 2010 series, when tests demonstrated that the model's overall aerodynamic characteristics were largely unaffected regardless of whether the measurements were conducted with the test section in a closed-wall or open-wall mode. In order to reduce the adverse impact of background noise and improve the quality of the collected acoustic data, the tunnel had to be modified to operate in a semi-anechoic acoustic mode. In this configuration, the test-section floor, raised ceiling, and control room blast wall were all treated with sound-absorbing foam wedges and the sidewalls were covered with perforated mesh skins backed by foam. Even the floor area outside of the test section was covered with soft foam slabs to absorb sound.[11]

Acoustic measurements were obtained using a traversing microphone array constructed specifically for use in the LaRC wind tunnel. The phased array consisted of 97 individual Bruel and Kjaer (B&K) Model 4938 quarter-inch pressure-field microphones that were flush-mounted within an 8-foot-diameter flat fiberglass honeycomb plate. An operational frequency range of approximately 1.5 to 80 kHz was achieved by placing the microphones in an irregular

9. Mehdi R. Khorrami, William M. Humphreys Jr., David P. Lockard, and Patricio A. Ravetta, "Aeroacoustic Evaluation of Flap and Landing Gear Noise Reduction Concepts," AIAA Paper 2014-2478, presented at the 20th AIAA/CEAS Aeroacoustics Conference, Atlanta, GA, June 16–20, 2014, 2.
10. Ibid., 1–2.
11. Ibid., 9.

Test setup in the LaRC 14-by-22-foot wind tunnel with the 18-percent-scale semi-span G550 model and microphone array. (NASA)

circular pattern comprised of 16 "arms" with six microphones in each, and a single microphone positioned at the center of the array. The array panel, positioned at a lateral distance of 17.5 feet from the tunnel center line, was mounted on a rigid frame attached to two sets of 44-foot-long linear traversing rails. These rails were positioned in such a way as to allow the array to face the pressure side of the G550 model and permit smooth movement of the array panel in the streamwise direction along the full length of the test section. An additional set of six microphones was positioned around the phased-array panel for use in characterization of noise directivity for various model configurations. Given that airframe noise during landing operations was of primary interest, a 39-degree flap setting with the main landing gear alternately installed and removed were the most heavily tested configurations.[12]

Flap Noise Mitigation

In 2013, the research team experimented with several types of flap modifications to reduce noise. Because the model flap had been designed in a modular fashion, with removable inboard and outboard tips, it was possible to evaluate

12. Ibid., 9–11.

more than 30 permutations of five different design concepts. These included a porous skin treatment, a variety of bulk and locally reactive acoustic liners, Flap Edge Noise Reduction Fins (FENoRFins) with both circular and non-circular cross sections, FLEXible Side-Edge Link (FLEXSEL), and Reactive Orthotropic Lattice Diffuser (ROLD). For all concepts tested, the extent of the tip area receiving treatment was carefully tailored to remain very small relative to the total flap surface area and the spanwise extent of treated area scaled with local maximum flap thickness. To maintain the flap's overall aerodynamic efficiency, the first 10 percent of the flap chord at the leading edge remained unaltered.[13]

The porous tip concept involved substituting the upper, lower, and side surfaces of the flap with a wire mesh skin having a specific acoustic resistance. Treated surfaces produced a cavity at each tip that allowed interaction between the external flow and the internal cavity fluid (air). Computational models and earlier studies guided the design of the porous surface treatment, which was tailored to minimize aerodynamic performance penalties while achieving substantial noise reduction. To achieve these goals, technicians fabricated cage-like structures at each tip to accommodate a wire-mesh skin that was carefully spot-welded to the cage to avoid creating surface imperfections. This resulted in a treated area that was continuous with the remaining flap surfaces. Researchers produced four sets of treated inboard and outboard tips with respective skin surface resistances of 150, 270, 450, and 570 Rayl (a unit of acoustic impedance). To determine whether the concept performed differently depending on the size of the treated area, they also tested an additional set of 270-Rayl tips where the spanwise extent of the treatment had been reduced by 33 percent on both upper and lower flap surfaces.[14]

Researchers experimented with bulk and locally reactive acoustic liners, also applied to the flap tips. In one configuration, they fabricated a sixth set of porous tips with an extremely low resistive skin (20 Rayl mesh) and then filled the interior volume of the cage with bulk absorbent materials. Tests were conducted using such fill materials as Nomex Felt Model 4485R and FeCrAlY (iron-chromium-aluminum-yttrium) metal foam of varying densities. Experts at LaRC also designed and tested a locally reactive acoustic liner that featured a series of serpentine channels of various lengths terminating within the interior volume adjacent to the flap tips. These channels were designed to achieve optimal absorption over a wide range of acoustic frequencies. Due to the small scale of the test model, it was impossible to obtain the most efficient design

13. Ibid., 3.
14. Ibid., 3.

for maximizing sound absorption, but these tests served as useful proof-of-concept demonstrations.[15]

FENoRFins are modifications consisting of an array of densely packed comb-like structures (fins) in a three-dimensional arrangement extending inward in the spanwise direction from the flap side edge to reduce airframe noise generated by the interaction between unsteady airflow and the flap edge surface. Limiting control action to the steady and fluctuating fields within a very small region near the edges leaves the gross aerodynamic characteristics of the flap unaltered, minimizing aerodynamic penalties. The aeroacoustic environment created by the FENoRFins alters the effective boundary condition at the surface of the flap, significantly reducing the steady-pressure differential experienced by the flap edge. As a result, the vortex formation process at the edge may be delayed or substantially weakened.[16] For subscale testing, the spanwise extent of the fin region (that is, the length of each FENoRFins element) followed a slanted pattern with the shortest fins applied near the leading edge and the longest toward the trailing edge of the flap. Researchers evaluated several FENoRFins concepts and discovered that circular cross-section fins with the smallest diameter tested produced the best noise reduction.[17]

Researchers also experimented with a continuous-mold-line flap configuration. They conducted extensive testing of FLEXSEL, a structural-link design in which the flap side edge is connected to the wing edge adjacent to the flap with stretchable hyper-elastic materials. In order to effectively evaluate its noise reduction capability, the team tested both rigid polycarbonate and soft elastomeric versions of the FLEXSEL concept. An additional set of rigid FLEXSEL flap tips with a 40 percent larger transition section was fabricated to determine the effects of more extensive spanwise treatment on aerodynamic and acoustic performance.[18]

The final flap modification, known as ROLD, consisted of a honeycomb-like, interconnected structure added to the region of the flap that experiences the highest degree of sound-generating airflow instability. ROLD combined several attributes of the porous skin treatment and liner concepts. All three surfaces in the flap tip region were porous, and the internal structure was comprised of passages or perforations orthogonally aligned in all three directions. The intersection of passages from each direction created a three-dimensional lattice structure that was orthotropic in nature (that is, having elastic properties

15. Ibid., 4.
16. Khorrami interview.
17. Khorrami et al., "Aeroacoustic Evaluation of Flap and Landing Gear Noise Reduction Concepts," 5.
18. Ibid., 5–6.

in two or three planes perpendicular to each other).[19] Researchers tested three sets of ROLD flap tips with different-sized holes, spaced evenly. Acoustic performance of the ROLD concept improved as the size of the holes decreased, with the smallest diameters producing the highest noise reduction.[20]

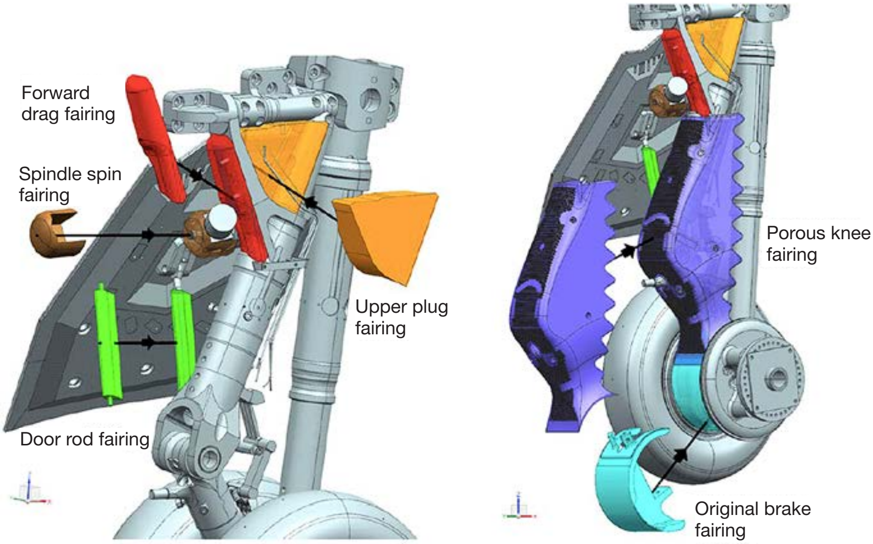
Each of the flap modifications tested could be easily retrofitted to existing aircraft structures, and several designs demonstrated significant noise reduction without adversely affecting aerodynamics. The porous characteristics of ROLD and the gaps between FENoRFins fin elements changed the boundary condition at the surface of the flap, reducing the steady pressure differential experienced along the flap edge. This reduced turbulent flow and delayed the type of vortex formation that causes noise during landing approach. Aerodynamic penalties were minimized by limiting the control action to the steady and fluctuating fields within a very small region near the flap edge. Testing of the 18 percent scale model thoroughly validated earlier computational modeling. According to Mehdi Khorrami, "Comparisons of fluctuating surface pressures between untreated and treated flaps showed an order of magnitude reduction of pressure fluctuation amplitude by three to 5 decibels."[21]

Main Landing Gear Noise Mitigation

Mitigating noise from the main landing gear posed a greater challenge because an aircraft undercarriage comprises a complex system of subcomponents of various shapes and sizes. Whereas all flaps are generally similar in shape, landing gear configurations vary widely from aircraft to aircraft depending on size and mission requirements. Consequently, researchers realized, no single concept could be expected to produce the desired noise-reduction levels. It quickly became apparent that they would have to approach the problem of gear noise reduction using multiple, complementary concepts tailored to specific noise sources associated with individual subcomponents.[22]

Installation of aerodynamic and acoustically absorbent fairings over various gear components offered a relatively simple and effective solution. NASA researchers pursued initial design studies under a collaborative effort with industry partners Goodrich Landing Gear Services, Exa Corporation, and Gulfstream. During the subsequent developmental phase, Goodrich employed

19. Ibid., 6.
20. Mehdi R. Khorrami, William M. Humphreys Jr., and David P. Lockard, "An Assessment of Flap and Main Landing Gear Noise Abatement Concepts," AIAA Paper 2015-2987, presented at the 21st AIAA/CEAS Aeroacoustics Conference, Dallas, TX, June 22–26, 2015, 3.
21. Khorrami interview.
22. Khorrami, et al., "Aeroacoustic Evaluation of Flap and Landing Gear Noise Reduction Concepts," 7.



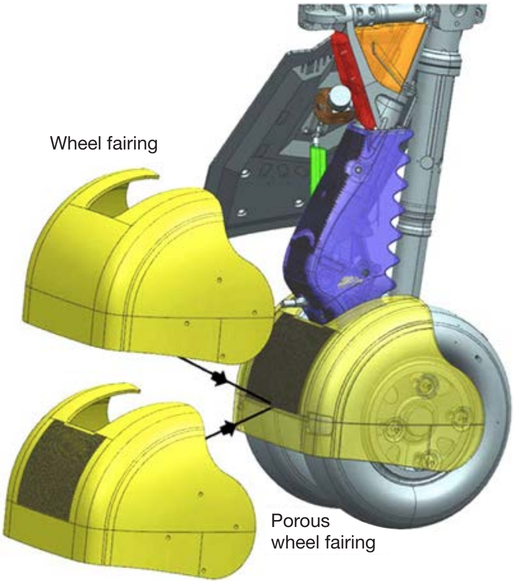
Main landing gear noise-reduction concepts employed a variety of aerodynamic and acoustically absorbent fairings over multiple components. (NASA)

high-fidelity computer simulations to obtain a set of viable fairing concepts. Designers then used these same computational models to further refine the most promising concepts to achieve designs that provided at least the minimum desired noise-reduction goals for each gear component.[23]

To accurately evaluate the acoustic performance of the landing gear noise-reduction concepts using the 18 percent scale model, technicians replaced the baseline Gulfstream landing gear with a modified set fabricated by Goodrich. Prior to installation, however, researchers placed the Goodrich gear into the Virginia Tech Stability Tunnel as a stand-alone test article. From September 2011 until July 2012, they tested the effectiveness of numerous permutations of seven independent noise-reduction concepts. The results guided researchers in identifying the most effective technologies to be further evaluated on the half-span model in the 14-by-22-foot wind tunnel at LaRC in 2013.[24]

These technologies were simple but effective. First, technicians installed streamlined housings (collectively called "upper fairings") over several existing components to mitigate turbulent-flow fluctuations across the gear strut. A plug filled the void between the forward drag brace and the strut, and the

23. Ibid., 7.
24. Ibid., 7.



Solid and porous aerodynamic fairings designed were installed over the main wheels. (NASA)

landing gear door connecting rod was covered with an aerodynamic cover. Next, a more complex structure called a porous knee fairing covered the upstream main post, and a streamlined, tight-fitting fairing covered brake components located between the two wheels. Researchers were pleased to find that the knee fairing significantly diminished the noise-producing flow interaction between the front and rear struts.[25]

An early brake fairing design performed well acoustically but was deemed impractical for application in a realistic environment at full scale due to brake cooling and maintenance issues. Instead, it was replaced with a larger aerodynamic fairing that partially covered the front portion of the two main wheels. Testing of both solid and partially porous wheel fairings proved very effective in reducing aerodynamic noise, while avoiding the pitfalls of the earlier brake fairing concept. The only challenge left was to reduce the low frequency noise associated with the wheel well cavity. The solution involved installing a stretchable mesh to cover the cavity opening. During tests on the isolated Goodrich gear in the Virginia Tech tunnel, mesh cover reduced low-frequency gear noise by more than 2 to 3 decibels.[26]

Researchers also strove to understand the complex phenomenology of noise produced by interactions between airflow and two or more closely aligned airframe components. The test model was representative of many types of aircraft in use today, wherein the deployed main landing gear is located underneath the wing and aligned with the inboard tip of the deflected flap. In this configuration, the turbulent wake of the main gear typically impinges on the flap edge at the inboard tip. The research campaign provided an excellent opportunity for a detailed examination of gear-flap interactions in a realistic setting and

25. Ibid., 7.
26. Ibid., 7.

their effects on the airplane's acoustic signature. Using various combinations of low-noise gear modifications and flap, researchers demonstrated that flap noise was largely unaffected by the deployed gear. The reduction in aerodynamic noise produced by the main landing gear was primarily attributed to a slowing of the flow impinging on the gear caused by flap down wash. As Khorrami noted, "We showed that installation effects have a pronounced impact on gear noise, which was substantially reduced when the flap was deflected downward [as on landing approach]."[27]

Developing Predictive Tools

Testing new noise-reduction technologies and hardware was only one aspect of the Flap and Landing Gear Noise Reduction ITD. The other involved development of new design tools to aid engineers in modifying existing wing flaps and landing gear—or designing new ones—that would produce significantly reduced acoustic signatures during takeoff and landing. In the latter, ERA researchers pushed the state of the art in airframe noise-prediction modeling that could be applied to everything from subscale test articles to a full-scale aircraft with all its complex geometries. "That was, I think, the most important thing to come out of our ITD," Khorrami said. "By the end, we had developed a number of technologies that resulted in four or five patents, but I am most proud of the computational simulation. It was truly world class."[28]

The complexity of the problem created a serious challenge for engineers and programmers. Among the most daunting tasks was the development of a virtual full–scale geometry model from very old airframe design data provided by Gulfstream. "These were data that had to be converted so we could use it in CAD [computer-aided design] models for both the wind-tunnel and computer simulation," Khorrami explained, "and that took a lot of detailed effort." But the resulting computational modeling software exceeded the team's wildest expectations. "It was something most of us only dreamed of," he said, "because we always thought it would happen perhaps 20 or 30 years from now. We put a lot of resources into it and a can-do mentality that we were going to push it until it couldn't be pushed anymore."[29]

Researchers compared preliminary computations to test results from the LaRC wind tunnel, which had originally been built in the 1970s as an aerodynamic testing facility. It was later modified to allow aeroacoustic testing of rotary wing configurations and, under the auspices of the ERA project,

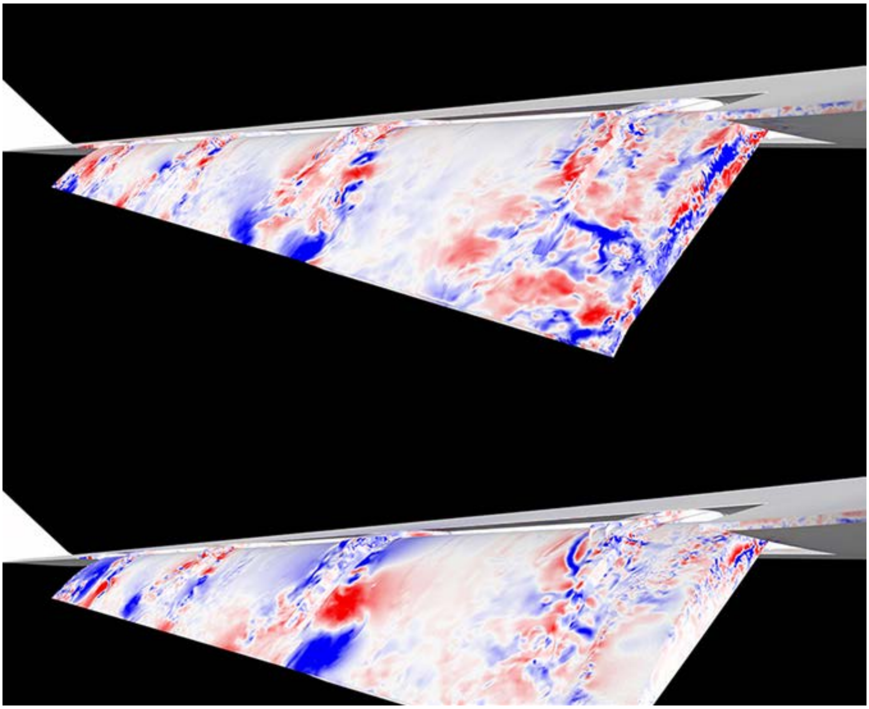
27. Khorrami, et al., "An Assessment of Flap and Main Landing Gear Noise Abatement Concepts," 24.
28. Khorrami interview.
29. Ibid.

underwent significant improvements to facilitate airframe noise testing of both conventional and unconventional aircraft configurations. In advance of tests with the G550 model, researchers measured tunnel background noise inside an empty test section, with and without airflow, employing an array of microphones positioned at specified flyover directivity angles that would later be used to acquire the model's acoustic signature. Additionally, a series of pyrotechnic charges was detonated along the center line of the empty tunnel in front of the microphone array to identify significant unwanted sound reflections that might cause spurious returns. With careful planning and extensive acoustic treatments applied to the test-section floor, sidewalls, and ceiling, such interference was effectively eliminated.[30]

There were, however, still obstacles to overcome. When acoustic engineers compared integrated sound pressure levels from the microphone array (computed over the entire measurement grid) with the spectrum obtained from the individual microphone mounted at the center of the array, they discovered elevated tunnel background noise at both low and high frequencies. Jet shear-layer interaction with the flow collector lip, which was not acoustically treated, seemed the most likely cause of the higher background noise at low frequencies. Elevated background noise at high frequencies was mostly due to roughness of the tunnel floor, which was formed from wire cages containing sound-absorbing foam wedges. This background noise rendered measurements with individual microphones unreliable for determining absolute noise levels for the model and had to be accounted for when processing the final test data.[31]

Through direct comparison of computer-based models with wind-tunnel test data and acoustic measurements obtained during the 2006 flight test, Khorrami's team successfully demonstrated that high-fidelity computer simulations could accurately predict the very complex fluid dynamic processes that generate airframe noise. "It was like a puzzle," he said. "We used all the pieces to shed some light on the problem, and to benchmark our computational tools; to find out how we were doing, we looked at how the computer modeling compared to the wind-tunnel results and validated the results with flight-testing. It was a step-by-step, or building-block, approach." The ultimate goal was to develop technologies that could be applied to most current and future aircraft, but, more important, to have the ability to predict the noise both in terms of a baseline aircraft as well as for whatever future configurations emerged, and to see how much improvement had been made.[32]

30. Khorrami, et al., "An Assessment of Flap and Main Landing Gear Noise Abatement Concepts," 12.
31. Ibid., 12.
32. Khorrami interview.



Gulfstream aircraft during landing (flaps deployed), showing significant reduction in fluctuation amplitudes with the application of noise reduction technology. Top image: untreated inboard flap tip; bottom image: tip with porous surface treatment. (NASA)

Modeling the acoustic signatures of flaps and slats was relatively easy because these aerodynamic devices have a high degree of universality. Whether installed on a regional jet, a 767, or something else, the basic configuration is very similar. "Obviously," said Khorrami, "the noise-prediction tools that we have developed can be applied regardless of aircraft geometry, whether it is a tube-and-wing or a hybrid wing-body, and once you have the prediction tool, you can apply it to any concept, any configuration, and you can develop [noise reduction] technology for that particular configuration."[33]

The problem of landing-gear noise is much more complex because each type of aircraft has a different undercarriage geometry. Depending on the size and weight of the aircraft, the nose gear may have one or two wheels and the main gear may have as many as three on each gear truck. The more complex the gear arrangement, the more auxiliary components are necessary. "All those little details can have an impact on how much noise is generated and how that

33. Ibid.

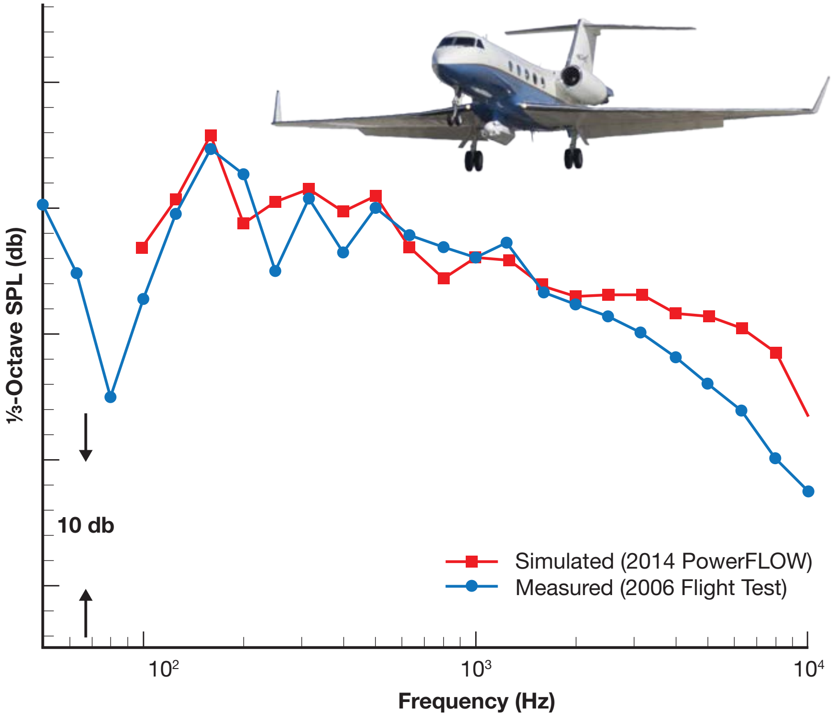
noise propagates," Khorrami explained. "With a good prediction tool, you can see how the noise gets generated and figure out what other areas you have to go after, and then you can tailor your design as necessary."[34]

Computational software for the project was adapted from an existing program developed by Exa Corporation for automotive applications. At the time that ERA began, Exa was seeking to expand the company's business from automotive to aerospace. "It was a convergence of the right people at the right time," said Khorrami. "We also used some of our own in-house code as a benchmark to make sure their software worked for what we wanted to do." The Exa software proved well suited to highly complex geometries that challenged other codes. "During our project, [the Exa code] was greatly expanded and improved because we pushed the state of the art," he added.[35]

Simulations performed for the ERA study constituted the first attempt to predict airframe noise radiating from a full-scale aircraft in landing configuration with most of the geometrical details included. NASA research results subsequently stimulated such aerospace industry giants as Boeing, Airbus, Gulfstream, Bombardier, Embraer, and others to consider applying these new predictive tools to current and future aircraft designs. Engine manufacturers also expressed interest. According to Khorrami, "Our study will help NASA mature existing technologies and eventually produce new ones that will confine aircraft noise footprints within airport boundaries."[36]

ERA planners originally intended to follow up modeling and wind-tunnel testing with further flight tests of the G550 at NASA's Wallops Flight Facility, Virginia, to gather steady-state surface pressures on the wing and flaps, as well as unsteady pressures on the flap edges, nose, and main landing gear. To accomplish this, researchers developed a ground-based microphone array to measure the sound footprint of an airplane in flight. Dubbed an "acoustic camera," it was designed to provide detailed information on the location and intensity of various noise sources as the airplane passed overhead. "My only regret is that the flight tests for Phase 2 were not accomplished due to funding constraints at Gulfstream," Khorrami lamented. "We were going to fly in 2014, but after the Critical Design Review something happened and the flights got cancelled." After that happened, NASA Headquarters continued to express interest in conducting a full-scale demonstration at some point in the future. "So in 2016, after ERA, we moved the array to Armstrong Flight Research Center, where NASA has a Gulfstream G-III testbed aircraft," said Khorrami. "It's quite a

34. Ibid.
35. Ibid.
36. Ibid.



This comparison between measured and simulated far-field noise spectra for a full-scale Gulfstream aircraft during landing shows that high-fidelity computer simulations can accurately predict the very complex fluid dynamic processes that generate airframe noise. (NASA)

capable system," he added, "so we are now trying to transfer that technology we developed under ERA to a flight demonstration at Armstrong."[37]

This setback forced Khorrami's research team to push the computational simulation to its fullest capability. Fortunately, the structure of the ERA project provided the necessary resources to do this. "ERA was an unusual program because we knew exactly when it would start and when it would finish," he said. "Headquarters was fully behind it throughout the 6-year span, and one of the reasons that ERA was so successful was that we had stable funding throughout."[38]

37. Ibid.

38. Ibid.

Sound Advice

Stephen Rizzi, a senior researcher for aeroacoustics at LaRC, led another team whose mission was to create technological tools capable of predicting and simulating sounds of flying machines still in the conceptual phase. Using computer models, flight measurements, and wind-tunnel data, they developed methods for predicting the sonic characteristics that would be produced by aircraft of any given configuration. These data were then turned into a set of synthesized sounds that were played for people who volunteered to be subjects in what were dubbed psychoacoustic tests—measurements of how humans react to different levels of aircraft noise. Rizzi's system produced scientifically valid simulations of whirring rotors, roaring jet engines, and even the sounds of wind rushing over flaps and landing gear. Programmers had to consider such elements as distance, motion, the Doppler effect, and atmospheric influences on sound.[39]

This process of studying a test subject's reaction, called "auralization," is intended to help aircraft designers take noise into consideration when imagining new shapes and configurations. According to Rizzi, the automotive industry has been conducting similar tests for many years, but until recently there has not been a similar capability for aircraft designers. "By putting these pieces of prediction and auralization together," he explained, "we have [created] a new capability."[40]

The new noise-predicting software tool is called the NASA Auralization Framework (NAF). It incorporates a set of computer codes to transform noise predictions from numerical data into actual sounds. This is especially important if future aircraft are to be designed so as to cut noise to nearly one-eighth of what is currently allowed, and to confine the most annoying noise levels to within an airport's outer fence line. Until now, NASA researchers have relied on a number of older computer-based tools including the ANOPP, which was first developed during the mid-1970s. This program allowed acoustic engineers to calculate how much noise would be made by aircraft components such as engines, flaps, slats, landing gear, and any other protuberances sticking out into the slipstream and causing localized, noise-making turbulence. The advent of unconventional aircraft configurations such as the HWB necessitated

39. Sam McDonald, "New Acoustics Techniques Clear Path for Quieter Aviation," October 14, 2014, *http://www.nasa.gov/larc/new-acoustics-techniques-clear-path-for-quieter-aviation* (accessed August 7, 2016).

40. Ibid.

development of a new, more versatile version called ANOPP2 to analyze noise produced by aircraft that don't follow the conventional tube-and-wing design.[41]

By 2013, it was abundantly clear that numerical predictions alone were insufficient. The NAF, therefore, was developed by NASA and its partners as a complementary tool to ANOPP. Rizzi explained that with the NAF, researchers input all the ANOPP/ANOPP2 aircraft noise prediction calculations, process the information and, within minutes, produce an electronic audio file that can be played on any compatible sound system.

"The vision is that an engineer working on the aeroacoustics of a new airplane would be able to readily generate an auralization output in the form of a calibrated [sound] file," he said.[42]

Having a realistic sound file available provides several major benefits. The first concerns how hearing the sound helps verify and validate the engineering processes used to make the prediction in the first place. "If my prediction method is producing something that I know doesn't sound realistic—for example, if I am trying to auralize an aircraft already flying today to use as a reference and the file sounds nothing like the real thing—then that tells me something is wrong or missing in the process," Rizzi explained.[43]

Sound files can also be used to evaluate how people respond to aircraft noise from various configurations. Using a concept called "perception-influenced design," aircraft manufacturers can use these data to make an airplane quieter and less of an annoyance to communities surrounding affected airports. For example, a listener may hear two different sounds at the same decibel level but perceive them very differently. According to Rizzi, it doesn't matter how loud or quiet the sound is if it is perceived as annoying.

With airplanes, two different engines may be equally loud in terms of decibels but may sound differently because of the way they are designed, making one more annoying than the other. As Rizzi noted, "What we're trying to do is not only lower the decibel level to meet future noise regulations, but we also want to make sure that the resulting sound isn't objectionable to the public."[44]

Rizzi believes the third major benefit is the capability to use sound files as a communication or public relations tool aimed at anyone who has a vested interest in how much noise an airplane makes near or at an airport. Interested parties include airport or airline officials, Federal regulators, state and local

41. Jim Banke, "NASA Researchers Turn Noise Predictions into Sound—and Video," June 13, 2016, *https://www.nasa.gov/aero/nasa-researchers-turn-noise-predictions-into-sound-and-video* (accessed August 7, 2016).
42. Ibid.
43. Ibid.
44. Ibid.

lawmakers, and most especially members of the general public living in close proximity to an airport. "With this tool we can share these sound files with a community so they can hear first-hand what a new jet engine or airplane design might sound like," said Rizzi. "We can tell people we've made a reduction of 42 decibels in noise levels, but what does that sound like? How does that compare with current levels? Now we can demonstrate that with realistic sound."[45]

In May 2016, during an international aeroacoustics conference in France, NASA used the NAF to demonstrate how several noise-reducing technologies evaluated during the ERA project would deliver on the promise of cutting noise to nearly one-eighth of today's standards. Prior to the conference, NASA researchers partnered with AMA Studios in London to combine the noise prediction sound files with flight-simulator-quality, computer-generated imagery representing two of the proposed future aircraft configurations studied for ERA. The result was a startlingly lifelike depiction that enabled designers to see as well as hear their work in action. Rizzi noted that the combined audiovisual presentation could also serve as a valuable tool to showcase to the public the dramatic reductions in perceived noise levels achieved by new aircraft designs.[46]

In the initial set of videos, the two different aircraft were shown from the perspective of someone standing near a runway as the airplane was taking off, as well as near the end of the runway directly under the final-approach path of the airplanes. One aircraft represented a typical twin-engine tube-and-wing configuration similar to a wide-body Boeing 777. The second aircraft was an HWB configuration with twin engines mounted on top of the airplane near the tail. "If you watch the videos and compare the sound of the two aircraft, both in terms of the overall decibel level and the annoyance factor, there's no debate that the hybrid wing-body represents a huge reduction in perceived noise," Rizzi said, adding that "The videos were well received by those attending the conference, with many [in the audience] noting how helpful it was to be able to compare the sounds of the two different aircraft shown."[47]

Auralization studies have continuing at a steady pace since 2001, with support from a number of the Agency's ARMD programs, including the Rotary Wing and Aeronautical Sciences projects of the Fundamental Aeronautics Program and ERA. Researchers at LaRC recruit test subjects as often as four times per year and pay them a modest amount to listen to sound simulations and register their reactions. Subjects sit in a small, theater-like room outfitted with 27 speakers and 4 subwoofers and answer questions on an electronic tablet while listening to simulated aircraft sounds. "We conduct a test, we analyze the

45. Ibid.
46. Ibid.
47. Ibid.

Dr. Stephen Rizzi, NASA Langley Research Center's Senior Researcher for Aeroacoustics, monitoring aircraft noise simulations played for test subjects. Much of the software used to simulate and test aircraft flight noise has been developed in-house at NASA's Langley Research Center. (NASA)

data, and we report on it," Rizzi said. Research results will become increasingly valuable in years ahead due to predicted growth in commercial air traffic and the advent of new technologies such as drones for delivering consumer goods. "We're in a leadership position on this," Rizzi noted, describing his team's forward-thinking acoustics research. "There is no organization I know of that has the capabilities that we do; it's a one-stop-shop for this type of work."[48]

He noted that his team had come a long way from initially focusing on making recordings of aircraft and reproducing those sounds in a controlled lab setting for test subjects. "That works well if the aircraft you're interested in is a real aircraft," he said, "but we work for NASA, so we're more interested in the future and there are no recordings of paper planes; that led us down the path

48. McDonald, "New Acoustics Techniques Clear Path for Quieter Aviation."

of having to synthesize the sound." Rizzi knows what he's talking about. He is a musician in his spare time and he sees a clear relationship between the science of noise and the art of melody. "There's a lot of overlap in the techniques used to generate the musical kinds of sounds and those used with aircraft noise synthesis," he said. It's why he enjoys his work so much. "It's new and there aren't a lot of other people doing it."[49]

In the spring of 2016, Rizzi's team demonstrated an NAF simulation of a proposed open-rotor engine for a group of engineers from General Electric. They were evidently excited to hear the sound of the latest power plant, even before it actually flew. "They really started thinking, 'Wow, what can we do [to change the character of the sound and make it more acceptable]?'" Rizzi said. "When you get a reaction like that based on your work, that's a pretty gratifying experience."[50]

49. Ibid.
50. Ibid.

National Full-Scale Aerodynamics Complex (NFAC) 40-by-80-foot test section with a Boeing HWB model. The size of the NASA personnel gives a sense of the immense size of this 70-year-old facility. (NASA)

CHAPTER 6

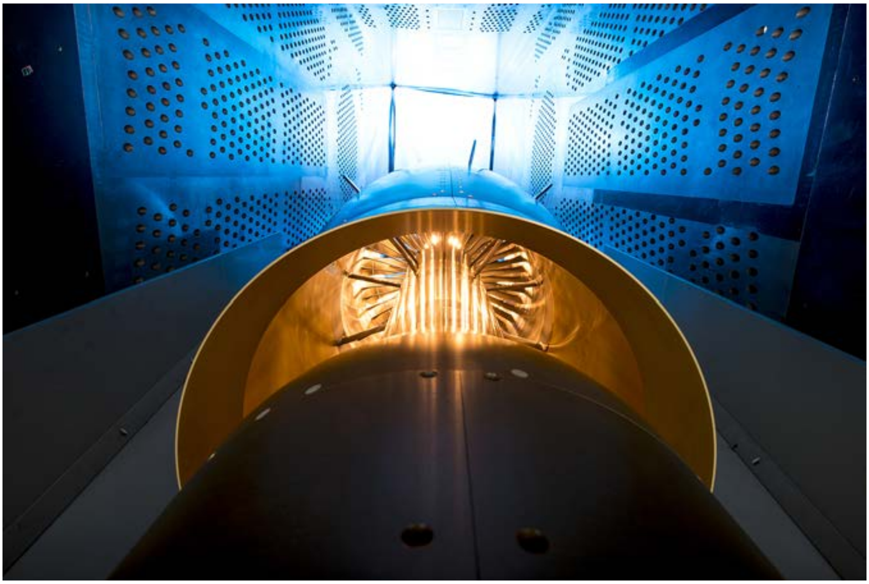
Integrated Propulsion System Technologies

ERA researchers pursued several technologies for improving aircraft jet engine performance in ways that would simultaneously reduce fuel-burn, noise, and emissions to meet national objectives. Project goals for fuel burn called for an immediate reduction of 33 percent relative to optimum performance standards as of 2005, and of at least 50 percent by the year 2020. Within these same timeframes, researchers hoped to reduce NOx emissions by 60 percent and 75 percent, respectively, relative to CAEP 6 standards. Goals for noise reduction were based on effective perceived noise levels measured in decibels (EPNdB), a measure of the relative loudness on an individual aircraft during a 10-second duration pass-by event. In the immediate, researchers strove to reduce aircraft noise footprints by 32 EPNdB relative to FAA Stage 4 requirements, and by 42 EPNdB by 2020.[1]

Working in collaboration with Pratt & Whitney, General Electric, and the FAA, GRC completed three engine-related integrated technology demonstrations. Promising technologies selected for maturation included:

- An improved two-stage transonic high-pressure engine compressor for an advanced UHB turbofan,
- Integration of a second-generation ultra-high-bypass-ratio propulsor (mechanism consisting of fan, stators, and nacelle) to improve propulsion efficiency and reduce the noise of a geared turbofan engine,
- An improved design for a jet engine combustor to reduce NOx emissions, and
- Verification of HWB power plant and airframe integration concepts that would allow fuel consumption reductions in excess of 50 percent while simultaneously reducing noise on the ground.

1. Dale E. Van Zante and Kenneth L. Suder, "Environmentally Responsible Aviation: Propulsion Research to Enable Fuel Burn, Noise, and Emissions Reduction," ISABE 2015-20209, presented at the 22nd International Symposium of Air Breathing Engines, Phoenix, AZ, October 25, 2015, 13.



Inside the 8-by-6-foot wind tunnel at NASA GRC, engineers tested a fan and inlet design, commonly called a propulsor, which uses 4 to 8 percent less fuel than today's advanced aircraft. Designed to be embedded in the aircraft's body, it would ingest the slower flowing boundary-layer air that normally develops along an aircraft's surface and use it to help propel the aircraft more efficiently. (NASA)

These demonstrations successfully advanced the maturation of compressor, propulsor, and combustor technologies for the next generation of jet engines.[2]

Turbine Engine Design and Performance

Gas turbine engines have been a fundamental part of aviation since the beginning of the Jet Age in the early 1940s. The two most common variants are the turbojet, which produces thrust from the direct impulse of exhaust gases, and the turbofan, in which a set of ducted fan blades produces additional thrust. Turbofans tend to be inherently less noisy than turbojets and are thus better suited to requirements for quieter aircraft.

In a jet engine, the compression system feeds high-pressure air into the combustion chamber (combustor), where it is heated before passing through a set of nozzle guide vanes to the turbine. Most modern designs are swirl-stabilized, creating a low-pressure zone and generating turbulence in the flow to rapidly mix fuel with air. However, the higher the turbulence, the higher the pressure

2. Ibid., 13.

loss for the combustor, so the swirler must be carefully designed so as not to generate more turbulence than necessary to sufficiently facilitate combustion.[3]

The combustor converts chemical energy bound in the fuel into thermal energy to drive the compressor. The amount of thrust produced by a turbofan engine is the product of the mass of air per unit time and the change in velocity imparted to that mass. It is more efficient to impart a smaller velocity change on a large volume of air than to make a large velocity change to a smaller volume of air; the more efficient the engine, the less fuel is consumed. For these reasons, designers of turbofan technology have been developing engines with higher bypass ratios (BPR) and lower fan pressure ratios (FPR) in order to produce more efficient power plants with a high operating pressure ratio (OPR). One significant obstacle is the necessity to increase fan diameter to maintain consistent thrust. Increasing fan size adds weight and produces requirements for larger engine nacelles that add drag at higher airspeeds. More thrust is needed to overcome the additional drag.[4]

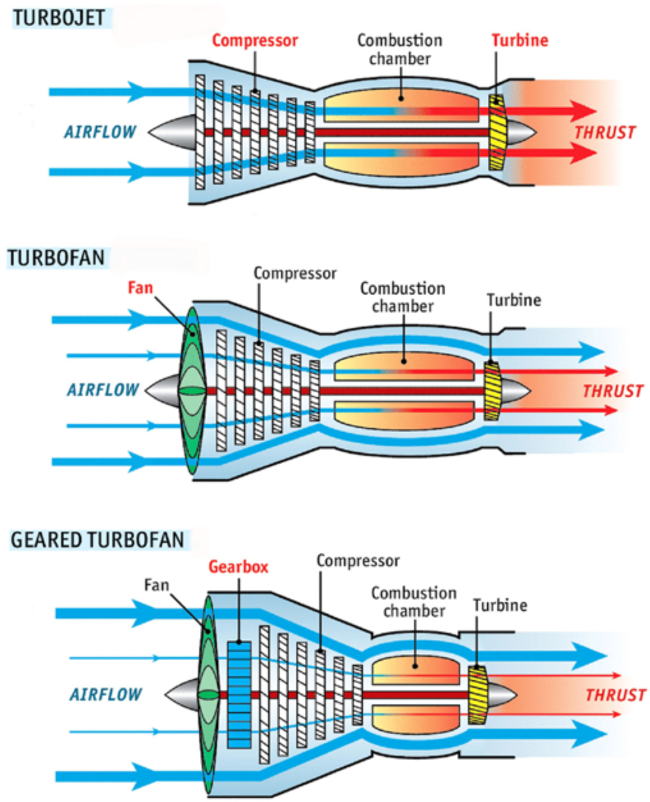
Engine core size is another important factor because fan speed must be kept as low as possible to reduce its noise signature. However, since a common drive shaft connects the core components and the fan, lower fan speeds necessitate lower compressor and turbine component speeds in the engine core as well. A specific amount of power is required to drive the fan for a given amount of thrust. Therefore, as the fan speed drops, the core components must increase in size, both in number of stages and in stage diameter, to provide the necessary power since the core component speeds cannot increase. Larger components, or increased numbers of stages, add more weight to the engine, thus requiring increased fuel burn to carry that weight around. At some point, fan size increases to a point where the added weight of the fan and nacelle, the additional nacelle drag, and the increase in core weight overcomes the fuel advantage of the higher BPR and lower FPR design.[5]

The fuel-burn trend line for a given engine cycle eventually drops to a minimum where increasing engine BPR beyond a certain point yields negative results, with higher fuel burn as increases in engine weight and size overcome the benefits of a high-BPR engine cycle. With the technology available at the start of the ERA project, this phenomenon resulted from the conventional high-bypass engine cycle known as direct drive, in which both fan and core

3. Christopher E. Hughes, Dale E. Van Zante, and James D. Heidmann, "Aircraft Engine Technology for Green Aviation to Reduce Fuel Burn," NASA TM-2013-217690, June 2011, 3.
Van Zante and Suder, "Environmentally Responsible Aviation: Propulsion Research to Enable Fuel Burn, Noise, and Emissions Reduction," 3.

4. Ibid., 3.

5. Ibid., 3–4.



Basic operation of turbojet, turbofan, and geared turbofan engines. (NASA)

components are rotating on the same shaft. Because the fan, compressor, and turbine all rotate at the same speed, system operation is constrained by the lowest-speed component, which is the fan in the propulsor. A low-speed fan design forces the core to run at slower, less-efficient speeds. As a result, more compressor and turbine stages are required to produce the necessary power to drive the fan and provide sufficient thrust at a given operating speed. Adding more stages increases engine weight.[6]

Pratt & Whitney designers sought to solve this problem by introducing a paradigm-shifting advanced technology, the geared turbofan (GTF). In the GTF, the fan and the core components are separated by a gear system that allows the fan and the core to operate at different speeds. This allows the core to operate more efficiently and produce desired thrust levels at the fan stage

6. Ibid., 4.

using fewer compressor and turbine stages compared to a direct-drive engine. The net result is reduced engine weight and, therefore, greater fuel economy.[7]

Pratt & Whitney developed the first-generation GTF in partnership with NASA. Work began in 2006 with testing of a scale model in the 9-by-15-foot low-speed wind tunnel at GRC. These tests validated the predicted aerodynamic, acoustic, and aeroelastic design characteristics of the GTF. Pratt & Whitney conducted the first full-scale GTF engine demonstration in 2008, followed shortly thereafter by the first flight-test demonstration using the company's modified Boeing 747SP flying testbed. The first-generation GTF first entered service in January 2016 as the PW1100G-JM. During development, NASA and Pratt & Whitney collaboratively investigated a low-speed/low-pressure-ratio fan, fan gear system, low-emissions combustor, and a compact high-speed low-pressure spool. These technologies enabled higher fan efficiencies by pushing engine BPR into the UHB ratio range of 12 or greater while allowing for FPR reduction of between 1.3 and 1.4.[8]

The PW1100G represented N+1 technology. At this level, researchers expected the GTF to once again reach a maximum benefit point as the design BPR continued to increase while FPR decreased. In order to achieve ERA N+2 system-level environmental goals, this necessitated a second technological paradigm shift to significantly extend the beneficial fuel-burn trend line. To this end, NASA and Pratt & Whitney again partnered to investigate second-generation GTF propulsor technologies to enable a BPR up to 18 and an FPR of between 1.25 and 1.3. Researchers projected the second-generation GTF would provide a 25- to 30-percent reduction compared to an Airbus A320 powered by two Pratt & Whitney V2500 engines.[9]

Another unconventional propulsion technology considered during ERA was the prop-fan, or "open rotor," engine. NASA had previously explored this concept, also known as an "un-ducted fan" (UDF), as early as the mid-1980s but it was never adopted by the aircraft industry. Superficially, the front end of the UDF resembled that of a turbojet or turbofan, featuring a conventional circular air inlet. At the back end of the nacelle, however, it sported an unshrouded, contra-rotating propeller consisting of a large number of short, twisted fan blades.[10]

After initial flight testing, the UDF was largely shunned due to the excessive cabin noise it generated compared with turbofan engines. ERA researchers chose to revisit this technology because it offered the potential for large

7. Ibid., 4.
8. Ibid., 4.
9. Ibid., 6.
10. Ibid., 7.

increases in propulsion efficiency and, therefore, significant reduction in fuel burn compared with then-current high-BPR turbofans. Open rotor engines represent the ultimate in high-BPR propulsion, typically providing BPRs between 40 and 80 as well as very low FPRs (below 1.1) compared with other types of aircraft power plants, and thus offering very high propulsive efficiency overall. Designers at General Electric Aviation predicted that their open rotor concept had the potential to reduce fuel burn by as much as 25 to 30 percent compared to such modern turbofan engines as the company's own GE CFM56-5B.[11]

With renewed emphasis on reducing the environmental impact of commercial aircraft, NASA partnered with General Electric to investigate open rotor propulsion for ERA N+2 generation aircraft systems. As a starting point, the company built upon its experience with the GE36 proof-of-concept UDF demonstrator that had been successfully flight-tested in 1986 and 1987, winning the prestigious Collier Trophy. By 2009, designers of a new generation of open rotor engines had access to tremendous increases in aerodynamic design capability in computational fluid dynamics, advanced high-speed computers, and strong lightweight-materials technology that had been developed over the preceding two decades. General Electric designers could now take advantage of advanced tailored-construction techniques to optimize fan blade shapes for maximum performance and minimum noise. In 2010, this effort spawned an extensive series of tests at GRC of a new generation of advanced fan blade technology, sponsored through both the SFW and ERA projects.[12] This led to three ERA propulsion ITDs that were focused on increased thermal efficiency, increased propulsive efficiency and noise reduction, and low-NOx combustor designs for high pressure ratio engines.[13]

Highly Loaded Front Block Compressor Demonstration

The first demonstration, ITD30A, sought to improve overall aircraft engine efficiency with a view toward reducing TSFC and total fuel burn, as well as those enabling technologies needed for developing high-OPR core engines. TSFC quantifies the fuel efficiency of an engine design with respect to thrust output. Researchers hoped to increase both efficiency and core pressure by 30 percent relative to ERA baseline engine specifications in order to achieve a 2.5 percent TSFC reduction. To this end, the Highly Loaded Front Block Compressor

11. Ibid., 7.
12. Ibid., 8.
13. Van Zante and Suder, "Environmentally Responsible Aviation: Propulsion Research to Enable Fuel Burn, Noise, and Emissions Reduction," 3.

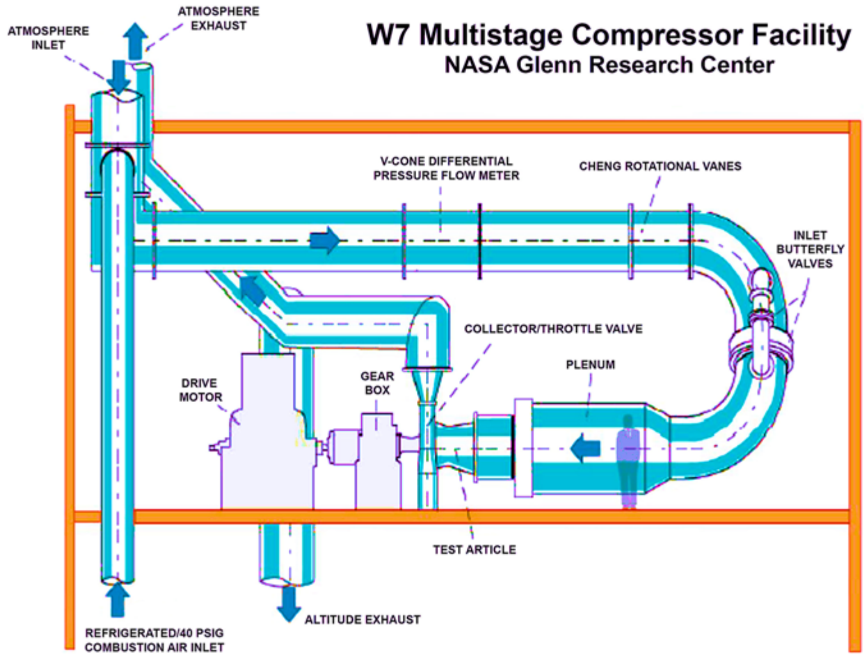
Demonstration included two test and analysis campaigns to improve both propulsive efficiency and engine core thermal efficiency. In order to meet ERA goals, designers had to increase engine OPR and efficiency without adversely affecting system weight, length, diameter, or operability. In the first campaign, which took place during ERA Phase 1, researchers investigated the performance of the two front stages of a legacy high-OPR six-stage core compressor. ERA Phase 2 focused on two major variants of a new compressor design.[14]

For ITD30A, NASA researchers partnered with designers at General Electric to refine the design of the open rotor compressor stage of a UHB turbofan engine. This work mainly focused on increasing engine core thermal efficiency by boosting the engine's OPR via a pressure ratio increase in the high-pressure compressor (HPC). Boosting OPR by adding more compressor stages would also increase the engine's weight and complexity, so the team chose a novel approach. They opted to enhance the capability of the HPC's "front block" (comprising the first three stages) through increased stage loading while simultaneously maintaining compressor efficiency comparable to that of state-of-the-art HPCs. For the purposes of the ERA demonstration, technology development and maturation activities focused on improving the pressure rise across the first three stages of a 30:1 class HPC. According to James D. Heidmann, project engineer for the ERA Propulsion Technology subproject, the primary objective was to validate innovative engineering concepts and models for higher OPR in an advanced technology development compressor (ATDC) testbed to achieve NASA fuel burn and NOx emissions goals.[15]

Phase 1 Demonstration

In preparation for ERA Phase 1 testing, NASA collaborated and developed cost-sharing protocols with industry partners, academia, and other Government agencies to create and operate the ATDC testbed in the W7 Multi-Stage Compressor Test Facility at NASA Glenn Research Center. During FY 2010–2011, this necessitated refurbishing the test rig's straddle-mounted driveline, balancing a 640-pound five-stage checkout rotor, and installing a new high-temperature throttle valve. The facility's 15,000-hp synchronous-drive motor was capable of operation between 300 and 3,600 rpm and was equipped with a 5.21:1-ratio gearbox enabling a maximum compressor shaft speed of nearly 20,000 rpm. NASA researchers worked with Pratt & Whitney, General Electric, and Rolls-Royce to define the basic operating envelope for the W7 compressor rig while also designing and fabricating the ATDC Phase A

14. Ibid., 3–4.
15. James Heidmann, "NASA's Current Plans for ERA Propulsion Technology," presented at the 48th AIAA Aerospace Sciences Meeting, Orlando, FL, January 4–7, 2010, 1–8.



Schematic rendering of the W7 Test Facility at GRC. (NASA)

test article.[16] Ultimately, NASA was responsible for refurbishing the W7 facility and conducting the ATDC tests. General Electric received a contract to provide an advanced two-stage compressor test article and additional test support. Research goals focused on making steady and unsteady flow measurements, initially for the first stage by itself and then subsequently after adding the second stage. This would enable detailed evaluation of the performance and losses in each stage.[17]

Baseline and developmental testing of the state-of-the-art transonic high-pressure compressor began in FY 2012. Researchers primarily sought to understand the flow physics that typically limit stage loading, characterize interactions between the various rows of compressor blades, and validate the design methodology and capability of predictive tools through comparison with experimental results. Initial checkout of the W7 facility driveline was conducted in June 2012. When technicians operated the driveline motor up

16. Ibid.
17. Kenneth L. Suder, "Overview of the NASA Environmentally Responsible Aviation Project's Propulsion Technology Portfolio," AIAA-2012-4038, presented at 48th AIAA/ASME/SAE/ASEE, Joint Propulsion Conference, Atlanta, GA, July 33–August 1, 2012, 16.

to 9,000 rpm, they detected a vibration in the gearbox that was later diagnosed as an issue with the coupling between the gearbox and compressor shaft. Modifications to the coupling installation eliminated the problem.[18]

In September, General Electric delivered the compressor test rig to GRC, where it was installed in the W7 facility for testing. Researchers then validated the bi-directional capability of the W7 motor drive, and worked to increase flow quality and reduce measurement uncertainty within the multistage compressor facility. The results of pretest computational fluid dynamics (CFD) simulations were compared to experiment data to determine the breakout of the Stage 1 and Stage 2 blade-row interaction effects that limit stage loading and high-OPR capability. General Electric performed system studies that indicated the highly loaded front block compressor would provide a 25 percent increase in OPR relative to that of the GE90, then the world's most powerful turbofan engine. Notably, this would result in a 2.0 to 2.5 percent reduction in TSFC.[19]

When these tests concluded in 2015, the results indicated that highly loaded core compressor technology developed under the ERA project had successfully realized fuel-burn reduction goals by increasing compressor OPR to increase the engine's thermal efficiency. Contemporary turbofan engines then in service operated at an OPR of 30 to 45. The new research results potentially paved the way for engines with an OPR between 60 and 70, nearly doubling the compressor pressure ratio performance while retaining a high level of efficiency. Because previous General Electric test experience of a similar two-stage compressor had failed to meet high-speed efficiency goals due to unpredicted pressure losses, the new test article was designed to run in both one-stage and two-stage configurations in separate tests to assess whether interaction between the bow shock of the second rotor and the upstream stage contributed to the anomaly, or if the anomaly was due to interaction between the first-stage rotor and stator sections. Losses encountered in the earlier tests were not fully understood and had not been predicted by sophisticated CFD simulations, including multi-blade-row unsteady modeling of the inlet guide vane through Rotor 2.[20]

The primary research goal of the next set of tests was enabling engineers to fully understand first-stage performance under isolated and multistage conditions. Secondary goals included developing a detailed set of aerodynamic data

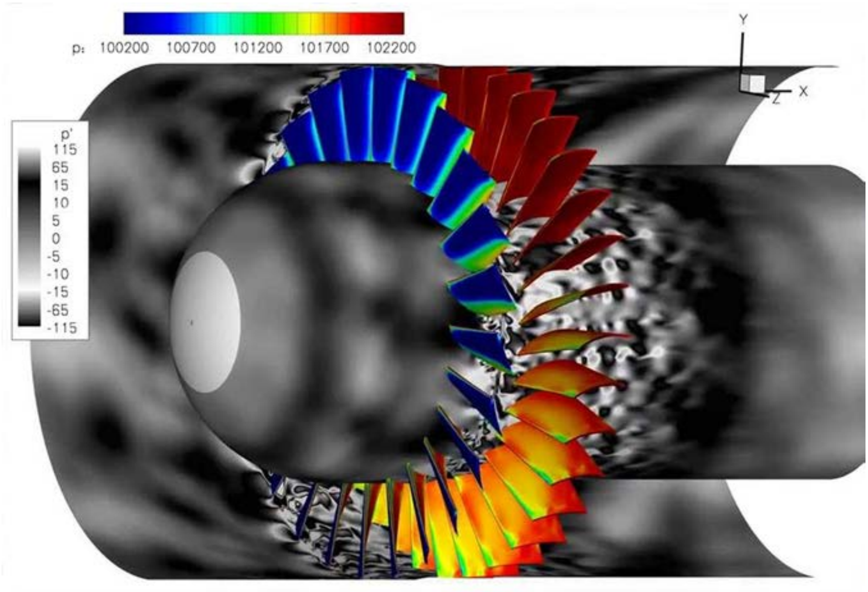
18. Ibid., 16.
19. Ibid., 16–17.
20. Patricia S. Prahst, Sameer Kulkarni, and Ki H. Sohn, "Experimental Results of the First Two Stages of an Advanced Transonic Core Compressor Under Isolated and Multi-Stage Conditions," GT2015-42727, presented at the ASME Turbine Technical Conference and Exposition, Montreal, Canada, June 2015, 1–2.

for CFD model validation. Researchers initially ran the compressor in a one-stage configuration to fully characterize and understand Stage 1 in isolation, and then subsequently ran both stages together. This allowed them to isolate the effect of the Rotor 2 bow shock as it impinged on the upstream blade rows. Advanced diagnostic instrumentation provided data that allowed the team to fully understand the loss mechanisms, thus permitting designers to develop highly loaded front stages that mitigate the identified losses and permit the core compressor to reach target efficiency levels.[21]

General Electric provided a test article that included an air inlet and the first two stages of a highly loaded axial compressor. The first test assembly consisted of an inlet, fan frame struts, guide vanes, Rotor 1, and Stator 1, with a downstream de-swirl vane to maintain axial flow. The configuration for the second test consisted of all of these components plus a transition duct from the low-pressure compressor to the high-pressure compressor, a second rotor and stator, and no de-swirl vane. The inlet guide vanes and both stators were of a variable geometry configuration and were designed to follow a vane schedule corresponding to the rotation speed. Researchers acquired data at various off-schedule vane angles in order to assess performance at different rotor-loading values.[22]

Technicians installed a variety of instrumentation to obtain performance maps during the single-stage compressor test. Most of these data were acquired at 97 percent and 100 percent Nc (that is, corrected speed, the speed at which a component would rotate if the inlet temperature corresponded to ambient conditions at sea level, on a standard day). Pressure rakes mounted at mid-pitch of the struts in five circumferential locations allowed researchers to establish inlet total pressure and temperature profiles. Steady-state static pressure ports located above the rotor tips identified rotor start and unstart conditions and captured rotor shock and tip vortex data. Two rows of high-response pressure transducers measured the unsteady pressure over the rotor to provide a detailed perspective of the rotor static-pressure field. Two stator vanes were instrumented with total pressure probes along five radial locations on the leading edges to obtain rotor performance data, and two others were similarly instrumented with temperature sensors. Five circumferentially spaced rakes situated downstream of Stator 1 at the leading edge of the de-swirl vane measured stator exit flow. Additional data were provided by sensors that captured casing and hub static pressures along the entire flow path from the inlet through the diffuser section. Researchers determined overall performance of the one-stage configuration by measuring the difference between readings taken at the

21. Ibid., 2.
22. Ibid., 2.

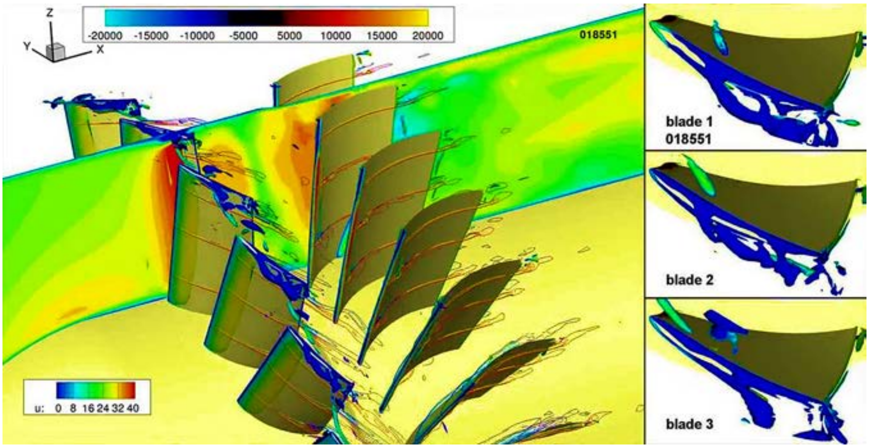


CFD model of the flow through an inlet and through rotor and stator blades. (NASA)

inlet and exit rakes. Detailed measurements with a traversing probe averaging data taken at four points across the diameter of the exit duct provided finer data definitions.[23]

The research team then installed the second stage on the test article and repeated the data runs. This design configuration pushed the design to higher blade loading levels (pressure rise per stage) but failed to meet efficiency goals. Test results indicated that Stage 2 was choking at a mass-flow rate that prevented Stage 1 from reaching peak efficiency. Upon reviewing the data from both configurations to determine the most likely cause of this stage mismatch, researchers found that Stator 1 performed equally well with or without the presence of the second stage. They concluded that the performance deficit was likely from a first-stage loss not predicted by available design tools. Phase 1 testing yielded a vast amount of high quality data, but much work remained. Most important, the resulting data set could be used to validate CFD models and help determine how to redesign the compressor system while accounting for loss mechanisms.[24]

23. Ibid., 2–4.
24. Ibid., 10–11.



CFD visualization illustrating rotor tip leakage. (NASA)

Phase 2 Demonstration

Flow across the span of the front two compressor stages was transonic. As a result, stage performance was very sensitive to changes in the effective flow area. Such changes can affect flow separation, as well as cause low momentum and loss due to passage shock and/or blade row interactions. During Phase 1 testing, researchers sought to understand the flow physics that resulted in high losses, characterize blade row interactions and their impact on loss, and validate the design methodology and capability of the prediction tools through comparisons with experimental results. Phase 2 testing involved a completely new core compressor design strategy that leveraged lessons learned from the Phase 1 compressor design. This new compressor was designed for increased efficiency and higher blade loading.[25]

The primary goals of Phase 2 were to realize higher efficiency levels than those of Phase 1 and increase blade-loading levels relative to those of the best design then available, but not to the higher levels of blade loading attempted in the Phase 1 design. The Phase 2 compressor test program was undertaken in the third and fourth quarters of FY 2015. It consisted of two tests designated Build 1 and Build 2, where the primary difference was that Build 2 was designed to achieve higher compressor blade loading at the same efficiency levels as Build 1. The higher blade loading of Build 2 provided an overall system benefit because

25. Van Zante and Suder, “Environmentally Responsible Aviation: Propulsion Research to Enable Fuel Burn, Noise and Emissions Reduction,” 4.

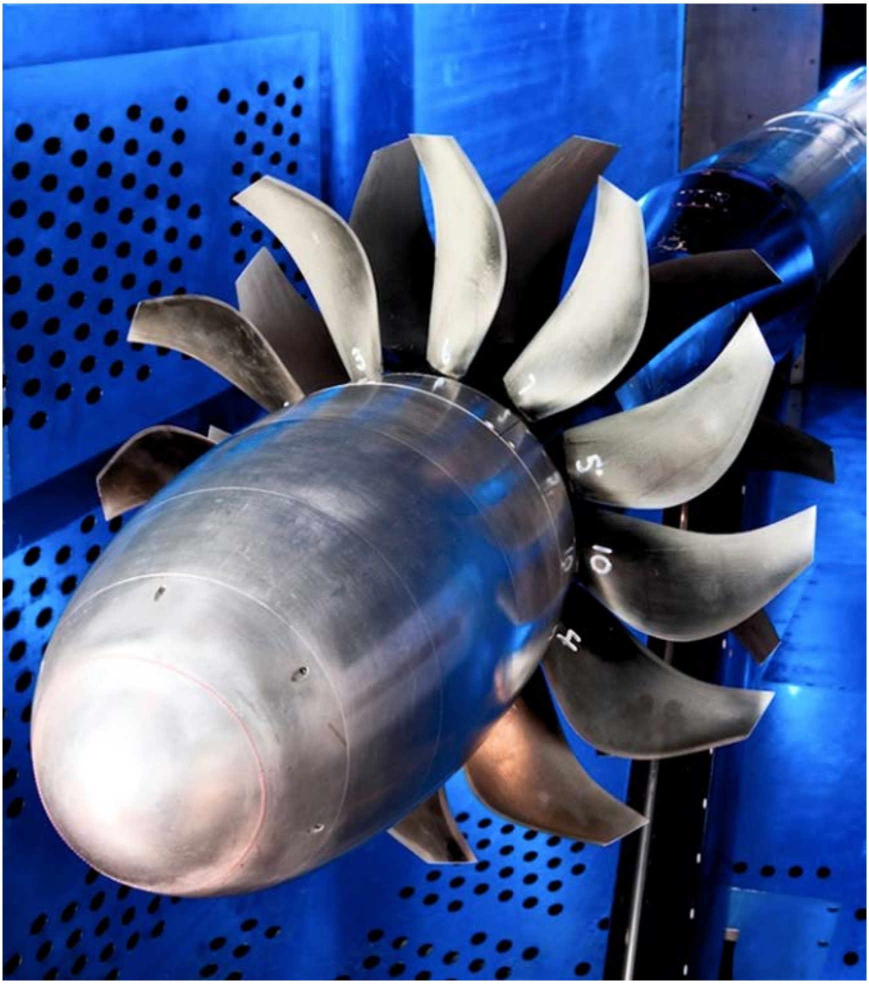
A Pratt & Whitney next-generation ultra-high-bypass-ratio turbofan model undergoing testing in the NASA Glenn Research Center's 9-by-15-foot Low Speed Wind Tunnel. (NASA)

compressor bleed locations could be moved further upstream, reducing the compressor work required to provide the bleed flow.[26]

Second-Generation Ultra-High-Bypass Propulsor Integration

During another demonstration (ITD35A) in late 2011, NASA researchers worked with Pratt & Whitney to mature several low-FPR, UHB propulsor technologies through a series of collaborative tests of a scale model second-generation GTF in the NASA GRC 9-by-15-foot low-speed wind tunnel. Prior to ERA, first-generation GTF testing demonstrated the potential efficiency gains that could be achieved with low-FPR, geared-fan propulsor systems. Designers developed a fan architecture that served as a basis for the PW1500G engine, but the success of the demonstration at GRC motivated the company to evolve the technology for use in larger thrust-class engines. One of the most important improvements involved the addition of a gear to the fan drive

26. Ibid., 6.



An open-rotor engine model undergoes testing in the GRC 8-by-6-foot high-speed tunnel. (NASA)

system to allow the low-tip speed, low-FPR fan to be coupled to a smaller, more efficient high-speed core. This lowered the minimum fuel burn FPR but resulted in a necessarily larger fan diameter so as to produce an equivalent amount of thrust. This was significant because increased fan size could result in prohibitively large high-drag nacelles. Shortening the length of the nacelle would increase the acoustic signature, so designers also had to explore noise-reduction technologies.[27]

27. Van Zante and Suder, "Environmentally Responsible Aviation: Propulsion Research to Enable Fuel Burn, Noise and Emissions Reduction," 6–7.

Acoustic liners offered one possible solution, but engines with large-diameter fans and short nacelles provide limited internal surface area for acoustic liners, and the effectiveness of these liners is also decreased due to the less optimal lift-to-drag ratio of the bypass duct. NASA ERA researchers increased the acoustic treatment area in the propulsor through development of two advanced liner concepts that came to be known as over-the-rotor (OTR) and soft vanes (SV). The OTR concept featured an acoustically designed casing treatment installed above the rotor tip region. The proprietary design absorbed pressure fluctuations at the source before the sound could propagate for any appreciable distance. The SV concept employed cylindrical folded passages inside the fan exit guide vanes to absorb pressure fluctuations at their source.[28]

Results were mixed. Researchers conducted separate tests of the OTR and SV concepts employing a legacy fan with a 1.5 FPR, both in a rotor-only configuration to analyze any performance impact as well as inside a production-type nacelle configuration to measure the resulting acoustic characteristics. Noise measurements taken of the rotor alone demonstrated minimal and acceptable efficiency losses resulting from the OTR treatment. Acoustic results from SV tests with the nacelle installed achieved a noise reduction of 1.5 dB, but there was no comparable noise reduction using the OTR concept in the same configuration. Test data suggested that OTR deficiencies likely resulted from manufacturing difficulties as well as from acoustic design limitations for the rotor tip flow-field conditions.

Bypass duct pressure losses have a greater influence on engine TSFC for low-FPR engines cycles than relative to legacy engines. Pratt & Whitney and NASA researchers explored this phenomenon while testing concepts for low-loss fan exit guide vanes (FEGVs) and methods for optimizing duct end-wall contouring in combination with axial spacing changes to limit total nacelle length. These tests validated a design concept resulting in lower duct/FEGV pressure losses for advanced propulsor configurations. A final series of tests in 2014 and 2015 focused on a scale model of the FAA-sponsored CLEEN engine, an open-rotor UHB power plant designed by Pratt & Whitney for increased performance and reduced noise comparable to existing turbofan levels. The wind-tunnel model used for the integrated systems test featured a drooped inlet, bifurcated bypass duct, exit guide vanes, and a non-axisymmetric bypass duct. One of the primary objectives of the experiment, which concluded in June 2015, was to compare model-scale acoustic results to those acquired from later full-scale engine static testing. ERA performance goals for ITD35A called for a nine percent reduction in TSFC and a 15 EPNdB cumulative noise reduction relative to the baseline engine. NASA and Pratt & Whitney team members

28. Ibid., 7.

were pleased to conclude that the test results validated both the aerodynamic and acoustic performance of the new propulsor section technologies.[29]

Low NOx Fuel Flexible Combustor Integration

A series of increasingly stringent Government NOx emission standards imposed by the ICAO CAEP over the years has limited aviation emissions below 3,000-foot altitudes. CAEP standards cover the landing, takeoff, descent, and taxiing phases of engine operation in a prorated fashion. Goals set for ERA included a demonstration of a low-NOx, fuel-flexible combustor designed to provide a 75 percent reduction in emissions below CAEP6 standards without increasing particulate matter, and with minimal impact on fuel-burn and noise targets. ERA researchers recognized that the primary technical challenge centered on the fact that to meet fuel-burn reduction targets, advanced engines must operate at higher pressures and temperatures that encourage NOx production. New, advanced injector designs and air/fuel-mixing concepts, such as lean direct injection (LDI), were required to meet emissions targets and provide fuel flexibility. Leaner-burn concepts, however, tend to provide less stability margin and require fuel-staging and combustion control. ERA planners, therefore, established the Low NOx Fuel Flexible Combustor Integration Demonstration, ITD40A, to reduce technical risks and mature a new fuel-flexible combustor concept from Pratt & Whitney that would maintain low-NOx emissions at the higher cycle conditions expected of future engines.[30]

"Emissions during landing and takeoff affect local air quality, and above 3,000 feet they account for 92 percent of total ozone," said ERA combustor task lead Chi-Ming Lee. But, he added, "The problem is that the NOx emissions increase as overall pressure ratio increases, particularly above 50:1, so it is a tremendous challenge for us." The answer lay in balancing an advanced combustor design with an improved fuel-air mixer and a lean direct-injection combustion system. Lee observed: "Every time we improve fuel mixing, the NOx drops."[31]

For the ERA Phase 1 demonstration in 2012, Lee's team began by testing a single-injector flame tube before progressing to multi-injector sector

29. Ibid., 6–8.
30. Joanne C. Walton, Clarence T. Chang, Chi-Ming Lee, and Stephen Kramer, "Low NOx Fuel Flexible Combustor Integration Project Overview," NASA TM-2015-218886, NASA Glenn Research Center, Cleveland, OH, October 2015, 2.
31. Guy Norris, "'Green' Airliner Targets Achievable by 2025, Says NASA," *Aviation Week & Space Technology*, *http://aviationweek.com/awin/green-airliner-targets-achievable-2025-says-nasa*, April 18, 2011 (accessed July 21, 2016).

combustor trials using arc-shaped partial combustor rings and, ultimately, a full annular (ring-shaped) combustor test aimed at substantial NOx reductions of up to 80 percent by 2015. Researchers focused on maturing injector design, active combustion, and advanced liner technologies from TRL3 to at least TRL5. Among the active combustor concepts studied were devices designed to carefully control combustion instability and incorporate an intelligent fuel/air management system. They also studied advanced liners made from fiber-reinforced silicon carbide matrix ceramic composites (known as SiC/SiC CMCs) capable of reducing combustor cooling-air requirements. "We need 80 percent of the air in front of the combustor to get fuel/air mixing going and that's going to come from the combustor liner," said Lee. His team also sought to further refine existing fuel injectors to accommodate alternative jet fuels such as those produced through the Fischer-Tropsch process, in which fuel is synthesized from nonpetroleum sources such as coal, natural gas, and renewable biomass. According to Lee, "This provides more opportunities for emissions reductions because [Fischer-Tropsch fuel] has no aromatics, no sulfur and its distillation profile is different; it can vaporize quicker than jet fuel, and the viscosity is less. This, in turn, means droplet size is 10 to 20 percent smaller."[32]

Pratt & Whitney's experimental axial stage combustor (ASC) was designed to operate on the lean-lean concept, in which the engine burns fuel with an excess of air as compared with conventional engines. This would enable increased fuel combustion while simultaneously decreasing hydrocarbon emissions. Two types of fuel injectors were employed during different thrust conditions. When operating at low-power conditions, the ASC concept used a pilot injector at the front of the combustor, while additional main injectors were used in addition to the pilot injector for high-power conditions. The key to maintaining low NOx production at N+2 cycle conditions was to keep the fuel-air mixture as lean as practical throughout the entire axial length of the combustor.[33]

During ERA Phase 1, researchers from NASA, General Electric, and Pratt & Whitney validated lean-burn combustor performance through a series of flame tube, sector, and full annular tests in the GRC ASCR facility. Prior to testing, the ASCR was upgraded to provide entrance conditions of 900 pounds per square inch absolute (psia) and temperatures up to 1,300 degrees Fahrenheit. To meet ERA goals researchers pursued multiple concepts including a lean partial-mixed combustor and lean direct multi-injection system. The results of flame tube tests were used to select the most promising candidates for additional sector rig and annular combustor testing. An integrated CMC and

32. Ibid.

33. Van Zante and Suder, "Environmentally Responsible Aviation: Propulsion Research to Enable Fuel Burn, Noise and Emissions Reduction," 9.

NASA researchers conduct an experiment in the Advanced Subsonic Combustor Rig test facility at GRC. (NASA)

environmental barrier coating (EBC) liner system made it possible to supply more air for fuel/air mixing because less cooling air was required than for an engine with a conventional metallic liner.[34]

Under the ERA project, engine designers sought to develop combustor concepts having a high-OPR engine cycle that met specified N+2 noise, fuel burn, and emissions goals as part of an overall aircraft system. Advanced lean-burn concepts offered by General Electric were based on previous efforts tested under the NASA-sponsored Ultra-Efficient Engine Technology (UEET) program of the 1990s. This led to development of the twin annular premixing swirler (TAPS) combustor, most recently included in the GEnx-1B and GEnx-2B engines that power the Boeing 787 and 747-8 wide-body aircraft, respectively. Features of the TAPS design included independently controlled, swirl stabilized, annular flames for low-power (pilot) and high-power (main) operation.

34. Kenneth L. Suder, John Delaat, Chris Hughes, Dave Arend, and Mark Celestina, "NASA Environmentally Responsible Aviation Project's Propulsion Technology Phase I Overview and Highlights of Accomplishments," AIAA 2013-0414, presented at the AIAA 51st Aerospace Sciences Meeting, Grapevine, TX, January 7–10, 2013, 4.

In this configuration, a concentric main flame holder surrounded the central pilot flame. By itself, the pilot flame not only provided good low-power operability, but also resulted in reduced carbon monoxide and hydrocarbon emissions. The main burner was optimized to produce low NOx emissions during high-power operation. Incorporating advanced liner materials benefitted the combustion system in terms of both durability and emissions by decreasing cooling air requirements and enabling a higher fraction of combustion air in the main mixer for lower NOx emissions.[35]

In a jet engine, the flame tube is designed to allow a percentage of the air that enters the combustion chamber to mix with the fuel inside the combustion chamber. It also controls the ignition process, so the flame never actually touches the walls of the chamber or extends back into the turbine section. Researchers tested several advanced TAPS injector concepts in a flame tube configuration to evaluate emissions, combustion dynamics, and auto-ignition margins up to full operating conditions. The results demonstrated acceptable operability margins at takeoff conditions and indicated that landing and takeoff emissions would likely exceed ERA targets. Based on analysis of test results, the research team selected the most effective injector design for incorporation into an advanced five-cup sector rig in the ASCR. Data obtained during the latter half of 2012 over the entire flight envelope including high-power operation met the conditions required for calculating the ICAO landing and takeoff NOx emissions levels for engines with an overall pressure ratio of 50:1. Preliminary results indicated that the General Electric combustor concept has the potential to meet ERA goals.[36]

Engineers at Pratt & Whitney and United Technologies Research Center (UTRC), in East Hartford, Connecticut, employed modern tools to improve fuel/air mixing at individual injection points in order to reduce the number of injection points by a factor of two compared to previous designs, and to investigate a variety of advanced concepts. This effort resulted in several configurations that featured lean-staged multipoint designs, radially staged swirlers, rich quench lean (RQL) combustors, and axially staged combustors. These concepts offered simplicity, operability, durability, and emissions levels that ultimately made the RQL family of combustors a staple in Pratt & Whitney engines. The company's TALON X combustor was developed with support from NASA under the UEET program and was selected for use in a GTF engine slated for several future Airbus, Bombardier, and Mitsubishi aircraft.[37]

35. Ibid., 5.
36. Ibid., 5–6.
37. Ibid., 6.

Initial testing at UTRC used an idealized single-nozzle rig at 7 and 30 percent power settings for a variety of injector configurations and fuel/air ratios. The results demonstrated that all of these concepts could produce emissions results below the ERA goals set by NASA. A few of the concepts not only performed very well with regard to NOx emissions but also demonstrated excellent efficiency. Following additional testing and analysis, one injector concept was selected for evaluation in an advanced three-cup sector rig in the ASCR facility in 2012. As with the General Electric combustor design, results were extremely encouraging.[38]

For lean combustion cycles, up to 70 percent of the total combustor airflow has to be pre-mixed with fuel before entering the combustion chamber. Cooling flow must therefore be reduced accordingly to provide sufficient air for mixing. An optimized fuel/air mixture is key to lowering flame temperatures and reducing thermal NOx formation. At the beginning of ERA Phase 1, researchers considered a 75 percent reduction goal for landing and takeoff NOx emissions to be a significant challenge for partial pre-mix combustor configurations such as those being pursued by both Pratt & Whitney and General Electric. As an additional hedge, in case the partial pre-mix systems demonstrated unresolvable auto-ignition issues at the higher inlet pressure and temperature conditions, ERA researchers also pursued lean direct injection concepts from industry partners Goodrich, Woodward FST, and Parker Hannifin.[39]

Although limited in scope, these efforts aggressively explored radical new ideas such as burning blends of up to 80 percent alternative fuel to 20 percent ordinary jet fuel. These designs pushed multipoint LDI concepts that NASA had been working on for more than 2 decades to new levels of maturity. LDI is ideal for ultrahigh pressure engine operation in which the flame front moves closer to the injectors than it does in conventional power plants. Some of these concepts also incorporated fuel-flow control features to prevent instability. After evaluating several designs, Goodrich engineers down-selected their best concept and began lean blow-off testing in the NASA high-pressure flame tube facility at GRC. Unfortunately, testing had to be temporarily suspended due to a fuel leak and was scheduled for completion at a later date. Woodward FST researchers completed light-off and lean blow-off testing of their injector concept using their own facilities as well as NASA's. Parker Hannifin tested the

38. Ibid., 7.
39. Van Zante and Suder, "Environmentally Responsible Aviation: Propulsion Research to Enable Fuel Burn, Noise and Emissions Reduction," 9–10.

fuel-spray and lean blow-off characteristics of a new miniaturized fuel valve actuator designed for fast response time for combustion control.[40]

The ERA combustor technology maturation plan involved parallel research activities at different TRL levels. For example, low-TRL flame tube tests of several swirler concepts were ongoing throughout much of Phase 2, with the most promising concepts being down-selected for further demonstration in sector tests. Even before all these latter tests were completed, engineers had to freeze the swirler design that was to be tested using the full annular rig. This technique kept things moving along and allowed researchers to demonstrate the best available technology to the highest possible TRL allowed by the design/test schedule.[41]

Test results from ERA Phase 1 in 2012 indicated that partial pre-mix concepts from both Pratt & Whitney and General Electric had the potential to meet NASA NOx goals without LDI, active combustion control, or alternative fuels. Researchers conducted tests involving conventional and blended alternative fuels in all three test rigs (flame tube, arc sector, and full annular) to build a state-of-the-art emissions, performance, and fuel flexibility database that would eventually enable development of combustors that might be integrated into commercial fleets by 2025. At the end of Phase 1, the Pratt & Whitney ASC concept was selected for continued technology maturation from TRL4 to TRL5 during Phase 2. Plans for these tests called for using a sector combustor rig to demonstrate improved operability over Phase 1 results for a full range of operational conditions including ambient inlet temperatures as high as 1,300 degrees Fahrenheit, compressor pressures up to 50 atmospheres, and a maximum flame temperature of 3,000 degrees.[42]

UTRC and GRC arc sector testing performed during the first year of Phase 2 focused on system integration and fuel flexibility. Initial testing with the UTRC sector rig validated performance of second-generation concepts previously explored in a single-nozzle rig by researchers from NASA, UTRC, Georgia Institute of Technology, and the University of Connecticut. Here, researchers sought to obtain low-power emissions points and determine how to best operate and stage the combustor configuration. Experiments included designs featuring combustor liners, cooling techniques, and a variety of different fuel nozzles. In order to substantiate and refine the design, researchers assessed system integration aspects across a range of operational temperatures

40. Suder, et al., "NASA Environmentally Responsible Aviation Project's Propulsion Technology Phase I Overview and Highlights of Accomplishments," 7.
41. Van Zante and Suder, "Environmentally Responsible Aviation: Propulsion Research to Enable Fuel Burn, Noise and Emissions Reduction," 10.
42. Walton, et al., "Low NOx Fuel Flexible Combustor Integration Project Overview," 7–8.

and pressures. They also measured low-power efficiency, lean blowout, and emissions performance, and explored an acoustic boundary condition to explore dynamic stability of the design refinements with respect to pilot-main fuel flow splits. Such realistic engine conditions were necessary for defining combustor inlet pressure and temperature levels based on a Pratt & Whitney advanced engine concept capable of meeting the NASA N+2 noise, emissions, and performance goals.[43]

In the second year of Phase 2 testing, Pratt & Whitney designers incorporated those features from Phase 1 that appeared to best meet production requirements and emissions and performance goals. The company then provided these improved combustors to NASA for further evaluation. Sector testing of these concepts in the ASCR facility represented a critical risk-reduction element in the development process. It validated performance and emissions at realistic full-engine pressures and temperatures and flame temperatures, enabling performance to be measured over the complete range of operating conditions rather than having to extrapolate from limited data. Pratt & Whitney fabricated a full annular ring test article representing the second-generation combustor configuration. This underwent 100 hours of testing in the company's X960 rig at Middletown, Connecticut, to validate combustor emissions, pattern and profile factors (thermal gradient variations), lighting, lean blowout, operability, dynamics, and heat loading.[44]

The process of designing, fabricating, and assembling the full annular combustor gave Pratt & Whitney the opportunity to address mechanical design and packaging issues unique to the ASC architecture, including a complete fuel system. This allowed designers to accelerate the maturity of the concept and enable its incorporation into future engines. Emissions measurements were correlated with those made while testing the arc sector test article at UTRC and GRC. Researchers learned from experience that for rich-burn, quick-mix, lean-burn (also known as rich quench lean, or RQL) combustors, NOx emissions measured in arc sector rigs are quantitatively predictive of measurements taken from full annular assemblies as well as from complete engines. The full-annular test also enabled measurement of stage-to-stage transition characteristics. Researchers used these data to improve combustor operation readiness. Additionally, the long-duration test provided durability data to finalize the cooling characteristics of combustor liners in preparation for full-scale engine testing. Inclusion of a full fuel system allowed researchers to evaluate

43. Ibid., 7–8.
44. Ibid., 9–10.

techniques for the mitigation of traveling-wave tangential-mode combustion acoustics, thereby enabling quieter engines.[45]

Prior to ASCR high-pressure sector testing, researchers pre-screened injector/swirler concepts in flame tube tests at GRC and UTRC, and also conducted a lower-pressure sector test at UTRC. Back in the ASCR, the same sector hardware was subsequently evaluated throughout the full operating envelope from sea-level takeoff to relight and lean blowout. The full annular combustor test, using the same injectors and swirlers as in the ASCR sector test, was completed in June 2015. Preliminary analysis of results confirmed the ASCR NOx data from ASCR and demonstrated good emission performance using standard Jet-A fuel. Additional sector testing with a 50/50 blend of FT alternative fuel demonstrated combustor emissions performance and operability characteristics nearly identical to the results with Jet-A.[46]

These successful results indicated performance acceptable for commercial airline operation and advanced the Pratt & Whitney combustor concept from TRL4 to TRL5. Most important, ITD40A was declared fully successful when the full annular test rig achieved 75 percent landing and takeoff NOx reduction and 70 percent cruise-level NOx reduction over a 2005 state-of-the-art engine. Total system-level impacts, however, could only be thoroughly validated through testing of a complete full-scale engine. The results of ITD40A established that the Pratt & Whitney ACS combustor was ready for such testing and provided critical operational and performance data necessary to develop test plans and technology development roadmaps for advancing the technology from TRL5 to 6.[47]

UHB Engine Integration for Hybrid Wing-Body Concepts

Although most ERA propulsion technology demonstrations were applicable to a wide variety of turbine-driven aircraft configurations, one ITD specifically addressed how best to integrate UHB engines with a hybrid wing-body concept. Conventional tube-and-wing configurations are typically equipped with engine pods mounted beneath the wings. For the purpose of noise reduction, ERA researchers proposed installing two or more engines on top of the HWB airframe at the aft end, between the tails. While this arrangement offered shielding benefits for reducing community noise, it also posed questions with regard to aerodynamics and performance. Carried out under the ERA Vehicle

45. Ibid., 9–10.
46. Ibid., 9–10; Van Zante and Suder, "Environmentally Responsible Aviation: Propulsion Research to Enable Fuel Burn, Noise, and Emissions Reduction," 9–10.
47. Ibid., 10–11.

Hybrid Wing-Body (HWB) aircraft powered by UHB turbofan engines promise remarkable flight efficiency coupled with design elegance. Here is one promising Boeing concept evaluated by NASA. (NASA)

Systems Integration subproject, ITD51A addressed the need to quantify the impact of engine/airframe integration on HWB system performance as well as noise levels across key on- and off-design conditions. This directly supported a technical challenge to demonstrate reduced component noise signatures totaling 42 EPNdB noise reduction for the entire aircraft system while simultaneously minimizing weight and integration penalties to enable an overall 50 percent fuel-burn reduction at the aircraft system level.[48]

For purposes of this subproject, researchers focused on a twin-engine HWB configuration equipped with UHB turbofan engines. Airframe/power plant integration was considered critical to success from performance (drag and stability and control), engine operability, and noise shielding perspectives. The two major areas of interest were aerodynamic efficiency and engine operability. Such details as nacelle size and location relative to oncoming airflow at cruise and low-speed conditions, placement and size of the vertical tails, and distance between the engines and aft deck would influence interference drag

48. Jeffrey D. Flamm, Kevin D. James, and John T. Bonet, "Overview of ERA Integrated Technology Demonstration (ITD) 51A Ultra-High Bypass (UHB) Integration for Hybrid Wing Body (HWB)," presented at AIAA SciTech 2016, 54th AIAA Aerospace Sciences Meeting, San Diego, CA, January 4–8, 2016, 1–2.

effects as well as overall stability and control characteristics. ERA researchers also wanted to explore airflow dynamics at low speeds, high angle-of-attack, and during crosswind operation to characterize their effects on the operability of the inlets, fans, and nozzles before the HWB concept could be considered a viable technology option for commercial transport vehicles.[49]

During ITD51A, NASA partnered with Boeing to design and validate a concept for the HWB that minimized adverse propulsion/airframe-induced interference effects that might result in high drag or poor aerodynamic characteristics. Designers used CFD modeling and wind-tunnel tests to quantify key design trade space issues that could impact UHB engine operability in HWB configurations and minimize adverse effects. Key objectives included characterizing airframe-dominated flows on the operability of UHB engines at key off-design conditions (low speeds, high angles-of-attack, and sideslip), and characterizing the performance (drag, lift, stability and control, propulsion induced effects, etc.) of the resulting HWB propulsion/airframe integration design throughout the Mach number range. In order to fully advance the knowledge and TRL of UHB engine integration on the HWB, researchers also evaluated methods for integrating a large diameter fan/nacelle configuration with various N+2 vehicle concepts. This included investigations into how best to address nacelle weight for large-diameter fans, the viability of shorter inlets to reduce nacelle drag, and the use of thrust reversers, variable-area nozzles, and low-noise fan designs.[50]

Wind-tunnel models for this demonstration were based on Boeing's PSC from ERA Phase 1, updated with design refinements to address all key performance metrics and ERA goals as well as potential issues uncovered during prior HWB design studies. Boeing developed an HWB configuration designated N2A-EXTE under a NASA NRA in 2012, but initial low-speed wind-tunnel testing revealed slight problems with airframe-generated inlet flow distortion. Boeing subsequently revised the design in the areas of planform, propulsion aerodynamic integration, high-lift systems, and propulsion system sizing. The updated PSC design also addressed fundamental requirements for weight and balance, and stability and control. Designers focused particularly on low-speed inlet distortion and recovery, engine installation drag penalty at cruise conditions, noise effects resulting from engine position relative to the body trailing edge, maximum lift coefficient ($C_{L\,\max}$) at takeoff and landing, and cruise lift-to-drag ratio (L/D). These design trades resulted in significant changes to the original planform and wing leading edge sweep to improve both stability and control and center-of-gravity characteristics. Additionally, designers discovered

49. Ibid., 5.
50. Ibid., 2–5.

National Full-Scale Aerodynamics Complex (NFAC) 40-by-80-foot test section with a Boeing HWB model. The size of the NASA personnel gives a sense of the immense size of this now-70-year-old facility. (NASA) that integration of the propulsion system above the wing body posed challenges for both low-speed operability and high-speed cruise drag. After observing shock interactions between the nacelles and the body at high speeds, Boeing engineers performed a rigorous optimization study to minimize installed drag of the engine nacelle at transonic conditions.[51]

NASA researchers tested three configurations of a 5.75-percent-scale HWB model in the Langley 14-by-22-foot subsonic wind tunnel, and in the 40-by-80-foot test section of the National Full-Scale Aerodynamics Complex (NFAC) at Ames. These configurations included an HWB with flow-through nacelles, one with ejector-powered inlets, and another with turbine-powered engine simulators (TPS). Researchers first performed flow-through nacelle testing while optimizing a high-lift system for takeoff and landing conditions. This involved the use of Krueger flaps, lift-enhancement devices that may be fitted to the leading edge of an aircraft wing. This model configuration was also used for force and moment testing. Next, they replaced the flow-through nacelles with ejector-powered inlets to simulate scaled mass conditions at the engine inlet. The objectives of this test were twofold. First, researchers needed to characterize inlet flow distortion, particularly that induced by peculiarities of HWB airframe/propulsion integration. Second, they attempted to mitigate such adverse effects by varying inlet height and Krueger settings. Researchers felt that because the engines were mounted on the aft body upper surface, the inlets might be susceptible to vortex ingestion originating from the wing leading edge at high angles of attack and sideslip, and from separated wing/body flow. Finally, devices that simulated scaled exhaust flow were installed to characterize the power-on effects of engine exhaust flow on increased pitching moment and elevon effectiveness.[52]

As originally outlined by ERA planners, all wind-tunnel testing for ITD51A was to be accomplished in the LaRC subsonic tunnel, a closed circuit, single-return, atmospheric wind tunnel capable of producing a maximum speed of 348 feet per second. Unfortunately, this facility suffered a failure of the main fan drive in September 2014 at the beginning of the first series of ejector test runs. Investigators estimated it would take as much as 1 year to repair the motor, a delay that would have extended the wind-tunnel test campaign beyond the scheduled end of the ERA project in September of 2015. In order to remain on schedule, all subsequent testing was relocated to the NFAC, and testing resumed in January 2015.[53]

51. Ibid., 6.
52. Ibid., 8–12.
53. Ibid., 8.

Moving these experiments to the NFAC provided an unexpected opportunity to acquire acoustic data to refine noise estimates. Originally, there were no plans to take direct acoustic measurements of the HWB model during tunnel runs in the LaRC subsonic facility. Instead, the project plan called for all such estimates to be done computationally. With its much larger test section, the NFAC had room for a phased array acoustic measurement system. Prior to runs with the flow-through nacelles, researchers installed a traversing array below the left wing of the HWB model to measure Krueger flap noise under various conditions. Pre-test CFD modeling results determined the most effective positioning for the acoustic array to provide high signal-to-noise ratios without inducing adverse aerodynamic effects on the test article. Researchers used the array to acquire data for a number of different Krueger flap configurations, dynamic pressure sweeps ranging from 20 to 60 psf, angle-of-attack sweeps from 0 to 16 degrees, and emission angles from 60 to 120 degrees. Preliminary results indicated that noise generated by the Krueger flaps largely depended on the size of the gap between the flap and the wing leading edge. High-resolution beam-form images showed the acoustic research team that flap brackets were the primary noise sources on the leading edge, and that a sealed-gap configuration produced high-lift noise comparable to the baseline cruise configuration.[54]

Researchers also used CFD modeling to validate the Boeing HWB design would meet fuel-burn performance goals by assessing the vehicle's transonic performance characteristics. Although plans originally called for this to be accomplished using a combination of CFD and wind-tunnel test data, program constraints resulted in the elimination of high-speed, transonic testing from the project. Consequently, all transonic performance characterization of the HWB design was done exclusively using predictive models. To build confidence in the CFD predictions, NASA and Boeing performed independent assessments. The NASA team made computations using an unstructured grid code called USM3D, and Boeing performed calculations using a structured grid code called OVERFLOW, both of which are fully turbulent, Reynolds-averaged Navier-Stokes flow solvers. NASA's goal was to assess Boeing's overall process for determining interference drag and develop a database of independent CFD solutions for comparison. In general, agreement between the two independent simulations was excellent.[55]

Because mounting the engines on the upper aft fuselage of the HWB created the potential for flow distortion from the forebody to be ingested into the engines when flying at high angles-of-attack, Pratt & Whitney performed an assessment of inlet distortion effects on engine and fan operability. The severity

54. Ibid., 13.

55. Ibid., 14.

A Boeing HWB model in the 14-by-22-foot subsonic wind tunnel at NASA Langley Research Center. (NASA)

of this phenomenon, ranging from flow angularity and swirl distortion to total inlet pressure loss, was a function of the BWB forebody design, including high-lift devices such as Krueger flaps as well as aerodynamic operating conditions (Mach, angle of attack, and sideslip). Researchers used both computational modeling and experimental data obtained from the project to identify such potential threats to the engine as fan stall, low-pressure compressor stall, and fan blade vibratory stress. Although any significant inlet distortion affected engine performance to some degree, this represented an off-design condition that did not affect the overall mission fuel-burn assessment. At this point, the team concluded that the technology readiness level for the operability and blade stress assessment was for all intents and purposes TRL4.[56]

In order to evaluate Boeing's PSC, the company supplied data for inlet distortion at a number of limiting conditions derived from CFD of the complete aircraft configuration at full scale. For all inlet distortion cases that fell within the expected operational envelope of the PSC configuration, engine operability and fan blade stress metrics were determined to be within acceptable limits. Therefore, designers at Boeing saw no reason to modify the PSC engine/airframe integration concept. The only marginal or unacceptable

56. Ibid., 19.

assessments resulted from inlet distortion analysis cases that were well outside the predicted operating envelope of the PSC aircraft. These results provided confidence that the operability assessment methodologies were producing reasonable results.[57]

Finally, ERA researchers conducted a system-level assessment to quantify the overall integrated vehicle performance of the HWB against ERA project goals. Vehicle system-level assessment metrics for ERA Phase 2 called for simultaneously meeting mission fuel-burn reduction of 50 percent, cumulative community noise levels of 42 EPNdB below Stage 4, and 70 percent lower engine NOx emissions to validate technology maturation of the overall HWB aircraft performance. To meet these goals, Boeing refined the PSC configuration as new data became available throughout the ERA project. Design modifications included changing the wing position, adjusting the engine cycle, and altering the planform shape and the overall size of the airframe. Additional high-fidelity analysis resulted in further refinements to the aerodynamic lines of the nacelles, wing, body, and control surfaces. Designers used results from wind-tunnel tests and CFD modeling to update the configuration, making design tradeoffs between noise reduction and fuel-burn reduction where necessary. All wind-tunnel data were based on a design configuration designated ERA-0009GM, the outer mold lines of which had been frozen in the first year of the project in order to fabricate hardware for the 5.75-percent geometrically scaled model in time to meet testing milestones.[58]

The updated configuration used for the system-level assessment, dubbed ERA-000H1, incorporated fuselage shaping for transonic performance improvements. The key difference between the ERA-0009GM and ERA-0009H1 configurations involved fuselage shaping around the engine nacelles, which designers did not expect to affect the aircraft's subsonic performance characteristics. For purposes of this assessment, the ERA-0009H1 was assumed to be equipped with Pratt & Whitney GTF engines. Changes to the PSC configuration resulted in the ERA-0009H1 achieving a fuel-burn level greater than 53 percent better than the reference configuration. Additionally, assessment of the ERA-0009H1 predicted a 1.8 percent lower fuel-burn than the original PSC, due primarily to a five percent increase in initial cruise *L*/*D*. An assessment of predicted noise levels for the updated PSC configuration, equipped with aerodynamic landing gear fairings and noise-reducing nozzle technologies, produced a cumulative margin of 37 EPNdB below Stage 4.[59] "We see a

57. Ibid., 19–20.
58. Ibid., 21.
59. Ibid., 21.

strong technical path to meeting the –42 dB goal," said Russ Thomas, HWB community noise team leader. "It's the last 10 dB that's really tough."[60]

60. Norris, "'Green' Airliner Targets Achievable by 2025, says NASA."

NASA Deputy Administrator Dava Newman addresses dignitaries, technical staff, and other guests on June 17, 2015, at ceremonies during a two-day visit of Boeing's 757 ecoDemonstrator to NASA's Langley Research Center. (NASA)

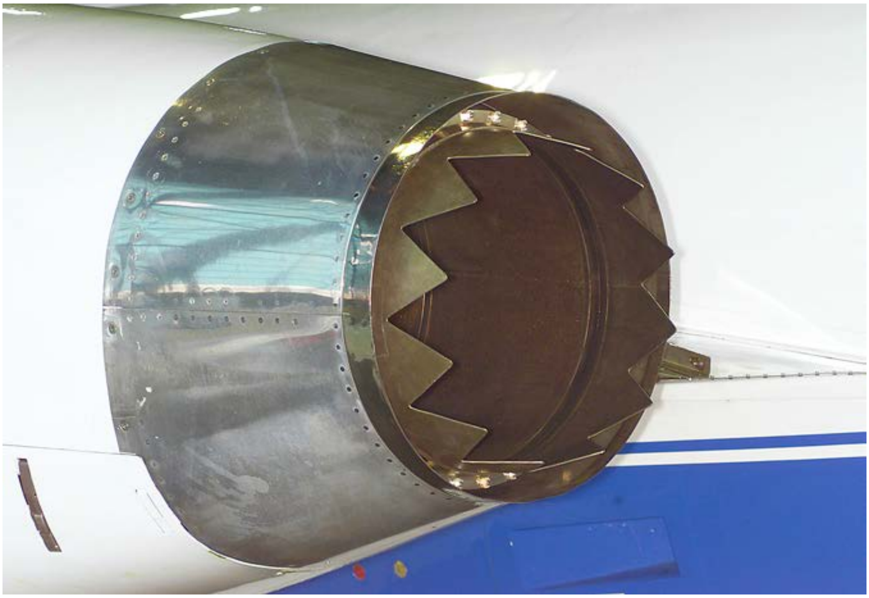
CHAPTER 7

ERA and the Boeing 757 ecoDemonstrator

NASA contracted Boeing to test two ERA technologies on the 757 ecoDemonstrator. The first of these focused on active flow control (AFC) to improve airflow over the rudder and maximize its aerodynamic efficiency. Preliminary research indicated that AFC could improve aerodynamic efficiency and potentially allow for the use of smaller vertical tails on future airplanes. NASA also tested non-stick coatings on the 757's right wing to reduce drag from insect residue; this would enable more laminar flow by smoothing the airflow on the surface of the wing. With the exception of Boeing's proprietary technology, all NASA knowledge gained in collaboration with Boeing from ecoDemonstrator research became publicly available to benefit the aviation industry.[1] "Both [technologies] are designed to improve the airflow over the surface and ultimately reduce drag," said Fay Collier. "Increased drag means increased fuel consumption, which results in more pollutants in the atmosphere."[2]

The 757 ecoDemonstrator was a highly modified Boeing airliner that served as a testbed for a variety of technologies. The project was built upon previous work by Boeing and various Government and private partners to accelerate and leverage new technologies to reduce emissions and noise, improve airlines' gate-to-gate efficiency, and help meet other environmental goals. The ecoDemonstrator's origins dated to Boeing's Quiet Technology Demonstrator program: the company worked with Rolls-Royce in 2001 to develop a quieter turbofan engine incorporating saw-toothed chevrons on the aft end of the nacelle and exhaust nozzle. Additional testing in 2005 allowed designers to refine the chevron design and validate an acoustically treated inlet. Boeing applied these technologies to both the 747-8 and 787, providing dramatic noise reduction.

1. Jessica Kowal and Bret Jensen, "The Boeing ecoDemonstrator Program" fact sheet, Boeing Commercial Airplanes, Seattle, Washington, December 2015, 3–4.
2. Kathy Barnstorff, "NASA Tests Green Aviation Technology on ecoDemonstrator," April 2, 2015, *http://www.nasa.gov/aero/nasa-tests-green-aviation-technology-on-boeing-ecodemonstrator.html* (accessed July 21, 2016).



The distinctive saw-tooth engine chevron, an imaginative effort to reduce engine noise. (NASA)

Building on this success, the company began the ecoDemonstrator program in 2011, in cooperation with American Airlines and the FAA. The earlier efforts, which had begun as a partnership among Boeing, the Federal Aviation Administration's CLEEN, and American Airlines, expanded over time to include Japan Air Lines, NASA, Rolls-Royce, General Electric, Rockwell Collins, Honeywell, Panasonic, Stifel Bank and the TUI Group. Flight evaluations were undertaken with both ecoDemonstrator 737 and 787 jetliners. It was hoped that technologies and processes validated by ecoDemonstrator evaluation would be then incorporated into existing production models and made available for in-service fleets as well as new airplane development programs, supporting long-term sustainable aviation growth.

In 2012, the ecoDemonstrator program began with a Boeing 737-800 (N897NN, loaned from American Airlines) demonstrating 15 advanced technologies (including a variable-area fan nozzle, active engine vibration control, flight trajectory optimization, a regenerative hydrogen fuel cell, blended biofuel, and carpet made from recycled materials). Most impressively, it validated the aerodynamic performance of an NLF winglet that improved fuel efficiency by up to 1.8 percent.[3]

3. Jessica Kowal and Bret Jensen, "The Boeing ecoDemonstrator Program" fact sheet, December 2015, 1–2.

In 2014, using an ecoDemonstrator Boeing 787-8 Dreamliner (N7874, owned by the company) researchers tested a high-strength, heat-resistant ceramic composite nozzle designed to enable jet engines to operate at higher temperatures, improving fuel efficiency while decreasing emissions and noise. Altogether they evaluated more than 25 new technologies aimed at making airplanes quieter and more fuel-efficient. These included aerodynamic and flight control improvements, special coatings to reduce ice accumulation on wing surfaces, and software applications and connectivity technologies for improved flight planning and fuel-load optimization. NASA researchers tested a flight interval management system to help achieve precise spacing between aircraft upon landing. Known as Airborne Spacing for Terminal Arrival Routes (ASTAR), this technology is intended to increase landing frequency and reduce holding patterns, thus saving fuel and time and reducing NOx emissions.[4]

Toward the end of the year, Boeing demonstrated the world's first flight using "green diesel," a sustainable biofuel already widely available and used in ground transportation. For initial testing, the ecoDemonstrator 787 was fueled with a blend of 15 percent green diesel and 85 percent petroleum jet fuel in the left engine only. The same blend was later used in both engines on subsequent test flights. Boeing offered data generated by these flights to support industry approval of green diesel for commercial aviation. Other technologies tested on the ecoDemonstrator 787 included touch-screen displays in the flight deck and outer wing access doors made from recycled 787 carbon fiber material. Boeing researchers also introduced wireless sensors in an effort to reduce the amount of wiring in the airplane.[5]

The ecoDemonstrator Program

In 2015, the ecoDemonstrator Program tested more than 15 technologies on a modified 757-222 (N757ET) that had been retired after years of service with United Airlines, and which was owned by Stifel Bank's finance group. Project collaborators included the NASA ERA project and the Europe-based TUI Group, an integrated tourism consortium that includes six airlines (and which includes the 757 ecoDemonstrator in its fleet). The first series of tests involved Boeing-proprietary technologies applied to the airplane's left wing to see if they would reduce environmental effects on natural laminar flow and improve aerodynamic efficiency. During these experiments, high-resolution infrared cameras attached to the top of the fuselage monitored laminar flow over the wing while Boeing test pilots flew the ecoDemonstrator through

4. Ibid., 2–3.
5. Ibid., 3.

The Boeing 757 ecoDemonstrator's deceptively conventional appearance masked the very advanced technologies it demonstrated. (NASA-Boeing)

various environmental conditions to study the potential effects of those conditions on aerodynamics. The most noticeable modification to the airplane was the installation of a 22-foot span variable-camber Krueger (VCK) flap designed to protect the leading edge of the wing from insect strikes because insect residue adversely affects airflow over the airfoil surface. Previous attempts to use Krueger flaps as insect mitigation screens resulted in additional drag. To avoid this problem, Boeing's new VCK was designed to retract seamlessly into the lower wing surface.[6]

In June 2015, Boeing flew the 757 ecoDemonstrator using a 5 percent blend of domestically produced green diesel to support ongoing biofuel and aviation industry efforts to have this biofuel approved for use in commercial aviation. Additional Boeing-sponsored demonstrations included solar and thermal "energy harvesting" to power electronically dimmable windows that would reduce wiring, weight, fuel use, and carbon emissions; and a 3D-printed aisle stand made from carbon fiber left over from 787 production, which was an example of the company's efforts to re-purpose aerospace-grade carbon fiber and thus reduce both airplane weight and factory waste.[7]

6. Guy Norris, "Bug Smasher—Wing Protection System Tests Could Help Unlock Benefits of Laminar Flow," *Aviation Week & Space Technology*, March 30–April 12, 2015, 37. *https://archive.aviationweek.com/issue/20150331* (accessed September 4, 2019)

7. Kowal and Jensen, "The Boeing ecoDemonstrator Program," 3–4.

NASA Deputy Administrator Dava Newman addresses dignitaries, technical staff, and other guests on June 17, 2015, at ceremonies during a two-day visit of Boeing's 757 ecoDemonstrator to NASA's Langley Research Center. (NASA)

(L-R) NASA Langley Research Center Director David Bowles, NASA Deputy Administrator Dava Newman, and Dr. Edgar "Ed" Waggoner, chief of NASA's Integrated Aviation Systems Program, receive a briefing while touring the 757 ecoDemonstrator during its Langley visit, June 17, 2015. (NASA)

Active Flow Control

On a modern multi-engine commercial transport aircraft, the vertical tail is employed primarily to provide directional stability and control at all airspeeds across the aircraft's performance envelope. But it is particularly significant during takeoff and landing. A large vertical stabilizer is indispensable in addressing crosswind conditions, as well as in the event of an engine failure that results in the remaining "healthy" power plants generating unbalancing asymmetrical thrust or torque effects. The vertical stabilizer's size is optimized for low-speed flight, where directional stability and control (the latter via the rudder) is particularly critical. When the aircraft is cruising at altitude the same large, heavy tail is no longer required. Additionally, designers typically size the vertical tail for the shortest version in an aircraft's model family but use the same tail for every variant to reduce production costs. Thus, the ideal vertical tail for the 777-200 is effectively oversized for the longer 777-300.[8]

The optimum vertical tail area is determined by the fuselage length/tail moment arm; as this value increases with fuselage length, less tail area is required for stability and control. Sized in this way, the drag and weight of the tail increases fuel consumption for the entire aircraft family. One way to compensate for a reduction in tail size is through the use of active flow control, which is the commanded manipulation of fluid flows with the addition or subtraction of energy from the fluid (in this case, air). By employing AFC technology on the shortest variant of an aircraft family to facilitate both low-speed control and the ability to react to sudden changes in flow conditions, smaller tail sizes may be use on the stretched versions.[9]

For the AFC Enhanced Vertical Tail Flight Experiment, NASA worked with Boeing to install dozens of tiny, sweeping jet actuators capable of manipulating, on demand, the airflow over the 757 ecoDemonstrator's vertical tail. This action was calculated to delay flow separation over a highly deflected rudder and to increase the rudder's side force capability. If successful, this technology would enable designers to incorporate a smaller vertical tail that provides the necessary control authority during an emergency situation using AFC, while operating in a conventional manner throughout the rest of the flight envelope.

8. Craig L. Nickol and William J. Haller, "Assessment of the Performance Potential of Advanced Subsonic Transport Concepts for NASA's Environmentally Responsible Aviation Project," AIAA-2016-1030, presented at American Institute of Aeronautics and Astronautics SciTech, 54th AIAA Aerospace Sciences Meeting, San Diego, CA, January 6, 2016, 3.
9. Ibid., 3.

Reducing tail size would also lower the airplane's overall airframe weight and aerodynamic drag and decrease fuel consumption.[10]

Prior to the ERA project, researchers had demonstrated the capabilities of AFC only on small-scale airplane and component models in laboratory environments. Wind-tunnel experiments conducted at Rensselaer Polytechnic Institute in Troy, New York, applied eight synthetic jet actuators to a 7 percent scale vertical stabilizer model, where actuators placed just upstream of the rudder hinge line produced a side force increase of nearly 20 percent at moderate rudder deflections. Researchers at the California Institute of Technology (Caltech) in Pasadena, California, collaborated with Israel Wygnanski, a professor of aerodynamics and fluid mechanics at the University of Arizona (considered the "father of active flow control"), to install sweeping jet actuators on a 14 percent scale vertical tail model. In tests carried out using Caltech's 5-by-6-foot Lucas Wind Tunnel facility, AFC actuation was applied to the rudder and the stabilizer main element's trailing edge. Experiments involving multiple flap deflections and spanwise actuator configurations resulted in a side force increase of as much as 50 to 70 percent depending on the free stream velocity and momentum input.[11]

Installed just beneath the outer skin of the tail along the stabilizer's vertical length, the AFC devices deliver a strong burst of sweeping air just along the rudder, equivalent to the amount of airflow that would normally be encountered by the tail and rudder at higher speeds. Because these jets of air sweep back and forth over the length of the tail rather than blasting a single, linear burst of air, researchers discovered that they could increase airflow over the entire tail with just six of the AFC devices. Caltech aerospace research project manager Emilio Graff suggested that, using such devices, airplane manufacturers could reduce the size of airplane tails by as much as 20 percent, with the sweeping jet actuators needing to be activated only during takeoff and landing. Fuel savings are derived not only from reduced drag due to the smaller tail size but also from weight savings and structural advantages from having a shorter vertical stabilizer. Even if the AFC system itself used a relatively large amount of energy, it would be activated only for short periods during the takeoff and landing phases of flight. "When you take off or land, the air jets will be on—just in case an engine fails," he said, "but on a 12-hour flight, if

10. Marlyn Y. Andino, John C. Lin, Anthony E. Washburn, Edward A. Whalen, Emilio C. Graff, and Israel J. Wygnanski, "Flow Separation Control on a Full-Scale Vertical Tail Model using Sweeping Jet Actuators," AIAA-2015-0785, presented at the 53rd AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, Kissimmee, FL, January 4–8, 2015, 2.

11. Ibid., 2.

The Active Flow Control system was tested on a full-sized tail in the NFAC. (NASA)

you're only using the system for 30 minutes, you're still saving gas during 11 hours and 30 minutes."[12]

Next, as part of NASA's ERA project, Graff and his colleagues designed and built a scaled-up AFC system to test the effects of sweeping jet actuators on a full-sized airliner tail with the help of a multi-institutional team that included engineers from Boeing Research and Technology and NASA LaRC. The test article was an actual 757 vertical tail that had been removed from a retired airliner in storage at Pinal Airpark in Marana, Arizona. With the help of the Boeing test and evaluation team, Advanced Technologies, Inc., of Newport News, Virginia, modified and refurbished the tail into a wind-tunnel model, and installed 31 AFC devices. Because it was nearly 27 feet tall, the next stage of the experiment was moved to the NFAC—one of the world's largest wind tunnels—located at NASA ARC in Mountain View, California. This allowed researchers to realistically simulate wind conditions similar to those that would be experienced during takeoff and landing.[13]

The 2-month-long test series began in early September 2013. Data from full-scale testing confirmed that sweeping jet actuators could sufficiently increase the airflow around the rudder to steer the plane in the event of an engine failure.

12. Jessica Stoller-Conrad, "Sweeping Air Devices for Greener Planes," October 20, 2014 *http://www.caltech.edu/news/sweeping-air-devices-greener-planes-43987* (accessed February 5, 2017).

13. Ibid.

According to Graff, this flow control technique is not new; it has previously been used for augmented takeoffs and landings in military applications. But, he added, existing systems are not energy-efficient, "and if you need a third engine to power the system, then you may as well use it to fly the plane." By comparison, the AFC system designed by Graff and his colleagues is small and efficient enough to be powered by an airliner's auxiliary power unit (the small engine that powers the cabin's air conditioning and lights at the gate). "We were able to prove that a system like this can work at the scale of a commercial airliner, without having to add an extra engine," he said.[14]

Sweeping jet actuators were developed more than 50 years ago at the Harry Diamond Research Laboratories, where they were initially considered for use in analog computers and as fluidic amplifiers. Other applications include oscillating windshield washers on cars, shower heads, and irrigation systems that use liquid (mostly water) as the working fluid. Only recently were these devices considered for aeronautical experiments for the purpose of delaying separation on airfoils. They are ideal devices for AFC because they introduce spanwise unsteady (oscillatory) blowing with no moving parts, requiring only a steady supply of compressed air. In this sense, the system is similar to steady blowing, but uses less air to provide similar levels of effectiveness. Each actuator is a solid-state unit with no moving parts and an internal feedback loop that causes a continuous jet of air to sweep back and forth across an arc. This action reenergizes the separated flow, reattaching it to the rudder even at higher deflection angles. ERA researchers chose to implement a sweeping jet AFC system on the trailing edge of the main tail element for ease of integration. Successful demonstration served as a major risk-reduction step toward a flight demonstration planned for 2015.[15]

These experiments also provided, for the first time on a commercial aircraft, the opportunity to assess design and scaling issues for full-scale application of AFC and validation of subscale and CFD observations regarding the sensitivities and effects of AFC on a vertical tail. The wind-tunnel tests enabled the research team to observe "a wide array of flow control configurations across the whole low-speed flight envelope of the vertical tail," said Boeing Research and Technology program manager Ed Whalen. Based on wind-tunnel results, the team selected the most efficient and effective flow control configuration for flight-testing on the 757 ecoDemonstrator. According to Fay Collier, the AFC test campaign was a key component of ERA. "The maturation of technologies such as active flow control, which will benefit aviation by improving fuel efficiency, reducing emissions and noise levels, is what NASA's aeronautics

14. Ibid.
15. Andino, et al., 3.

research is all about [and] will have an impact on future 'green' aircraft designs," he said.[16]

Wind-tunnel results demonstrated the effectiveness of AFC jets for increasing side force by 20 to 30 percent, which would allow aircraft designers to scale-down the vertical tail of a 757-class commercial transport by at least 17 percent and reduce fuel usage by as much as 0.5 percent.[17] This technology promised other potential benefits as well. In addition to reduced airframe weight and improved fuel economy, this type of device could also allow future aircraft to use shorter runways—or perhaps no runways at all. "We can possibly take off from a football field–sized area with some sort of rotor-type airplane, maybe a tilt-rotor, and we can fly at maybe 300 to 350 knots, and do this very efficiently," said Israel Wygnanski. "If we do it from downtown to downtown, from a parking lot, then that's much more effective than to do it the way we do today [from airport to airport] because you spend so much time in the airports." He added, "There are also a lot of smaller airports with runways of less than 5,000 feet that are closer to city centers that can be used, so some sort of short-takeoff airplane that can use this technology would be very effective."[18]

Now it was time to validate much of the research data in flight. This phase of testing had three primary objectives. First, demonstrate the team's ability to integrate a prototype AFC system into an airframe and thereby highlight key integration challenges. Second, demonstrate AFC impact on rudder effectiveness in flight using available APU flow rates. And, finally, collect in-flight data for comparison to full-scale wind-tunnel results and CFD predictions. To meet these objectives, planners outlined a number of system design requirements. These included minimal modifications to existing structures and systems and minimal relocation of flight-critical systems. All installation of test equipment had to be accommodated within the 757's tail assembly. The airplane's auxiliary power unit (APU) powered the AFC system's sweeping jets. APU compressor air temperatures had to be kept below 130 degrees Fahrenheit to protect the integrity of the rudder skin. All externally mounted components had to be bonded in such a way as to mitigate static electricity and electromagnetic emissions risks. In order to power the AFC system, the APU had to be disconnected from the airplane's pneumatic bleed air system, which meant it was not available for starting the engines nor could it provide bleed air for the

16. Michael Braukus, John M. Foley, and Daryl Stephenson, "NASA, Boeing Finish Tests of 757 Vertical Tail with Advanced Technology," November 14, 2013, *https://www.nasa.gov/content/nasa-boeing-finish-tests-of-757-vertical-tail-with-advanced-technology* (accessed February 5, 2017).
17. Barnstorff, "NASA Tests Green Aviation Technology on ecoDemonstrator."
18. Israel J. Wygnanski interview, *NASA X* "End of an ERA—Part 2," NASA TV, December 18, 2015.

air-conditioning packs. Once AFC testing was completed, the airplane's bleed air system was restored to its original production configuration.[19]

Following completion of testing in the NFAC, the modified tail was installed on the 757 ecoDemonstrator, and testing continued at Boeing Field in Seattle. Integrating AFC system hardware was challenging because the airplane had already been built. Ducting inside the vertical fin had to be installed in multiple segments due to limited access and bends and branches needed to fit within the existing geometry to minimize cutting any part of the aircraft structure. If the system were installed in a new airplane design, designers could incorporate longer tubes and better-optimized flow paths, thus reducing both installation time and the number of coupling adapters. In addition to routing the plumbing around structures, it was also necessary to mitigate interference with existing systems. Pressurized air, supplied by the APU, was pre-cooled from its 380-degree exit temperature by running it through an externally mounted heat exchanger beneath the aft fuselage. The heat exchanger itself was taken from the 757's original environmental control system and plumbed into a duct running along both the front and rear spars of the stabilizer to ensure an even supply of air to the actuators. In addition, a special duct was calibrated to provide engineers with a primary means of calculating system mass flow. Pressure and temperature sensors installed at key locations allowed researchers to monitor system performance and provided a means to detect a system leak or duct burst. Boeing engineers also had to conduct thorough design and stress analyses to ensure that the new ducting would be able to withstand maximum loading during flight without leakage and be able to accommodate thermal expansion due to the heated APU air. Loads analysis ensured the vertical tail would be able to withstand the additional weight of the ducting and side forces generated during testing.[20]

Prior to the first flight, in March 2015, Boeing conducted a series of laboratory and ground tests to verify the overall functionality of the heat exchanger, system controller, and AFC system. Company technicians also conducted a ground vibration test to establish the heat exchanger's frequency response and vibration-level limitations. Since many ducting joints were required, technicians performed periodic leak checks at key points during installation to ensure proper sealing. As leaks were discovered they took appropriate corrective actions until the leaks stopped. After the AFC system assembly was

19. Michael G. Alexander, F. Keith Harris, Marc A. Spoor, Susannah R. Boyland, Thomas E. Farrell, and David M. Raines, "Active Flow Control (AFC) and Insect Accretion and Mitigation (IAM) System Design and Integration on the Boeing 757 ecoDemonstrator," AIAA-2016-3746, presented at the AIAA Aviation and Aeronautics Forum and Exposition, Washington, DC, June 15, 2016, 4.

20. Ibid., 8.

fully integrated into the aircraft, a system leak check was completed with no further concerns. This disciplined approach saved time by eliminating the need to "chase leaks" after installation had been completed, when access to repairs would have been much more difficult. Finally, Boeing completed a total system functionality check that included measuring AFC actuator output and flow output from the sweeping jets actuators. This also ensured that the AFC system was controllable, instrumentation operated nominally, and the system operation process was established.[21]

The AFC system, mounted on the right side of the fin only for the tests, comprised 31 sweeping jet actuators positioned ahead of the rudder's leading edge. The NFAC experiments employed 37, but those closest to the tip of the tail proved less effective than desired, according to Doug Christensen, Boeing's ecoDemonstrator program manager. The airplane was equipped with two Pratt & Whitney PW2037 engines leased from Delta Airlines. To maximize the asymmetric forces on the rudder, Boeing modified the left engine via Service Bulletin to increase the available thrust from 37,000 to 40,000 pounds. The ecoDemonstrator flew test flights with and without the AFC system operating. The rudder was fully instrumented so engineers could determine rudder hinge moments and see how much force was being generated. Chase pilots observed flow cones fixed to the rudder to see how much of the flow remained attached to the rudder.[22]

The flight conditions that were necessary to demonstrate AFC effectiveness necessitated that all testing be performed over water under visual flight rules (VFR) conditions. Mission planners, therefore, selected a work area above the Strait of Juan de Fuca, a nearby body of water separating the state of Washington from Vancouver Island, British Columbia, Canada. This site was chosen based on proximity, meteorological analysis of historical weather patterns, cost effectiveness for flight crew and test monitors, and compatibility and availability of the chase plane for flow visualization photography.[23]

After 4 days of AFC flight-testing were completed, comprising six flights during which the crew performed various maneuvers to evaluate the effectiveness of the AFC jets. Maneuvers included simulated engine failures and variations in AFC jet arrangements and flow rates. According to Jeanne Yu, Environmental Performance Director for Boeing Commercial Airplanes, these experiments were important for moving the technology forward, and because of the significant savings the technology may potentially afford aircraft operators and the flying public. "When you think about the worldwide fleet of

21. Ibid., 8–9.
22. Norris, "Bug Smasher," 37.
23. Alexander, et al., 10.

airplanes, there are about 18,000 that fly today and that's projected to [increase] to about 36,000 airplanes in the next 20 years," Yu said; "If you can get a little bit of improvement on one airplane and multiply it by 36,000 in the next 20 years, it's a huge improvement with regard to reducing overall fuel burn."[24]

Active and laminar flow control are NASA's two main areas of investigation for reducing skin friction, which accounts for an estimated 48 percent of the drag on current airliner designs. "The intent is to increase its [laminar flow control systems] technology readiness level so that it could be applied to any generic wide-body or single-aisle hinged rudder," said Tony Washburn, NASA's ERA chief technologist. In the near term, successful results of AFC flight-testing could be applied to development of a drag-reducing hybrid laminar flow-control system for Boeing's stretched 787-9.[25]

Insect Accretion Mitigation

The second ERA technology maturation task involving the 757 ecoDemonstrator was the Insect Accretion Mitigation (IAM) experiment. Studies have shown that keeping the airflow smooth, or laminar, over a wing can reduce fuel consumption by roughly 5 to 6 percent, on average. Among the major challenges to maintaining laminar flow over wing surfaces is roughness induced by insect contamination. Even something as seemingly inconsequential as bug remains spattered on a wing's leading edge can cause turbulent wedges that interrupt laminar flow, resulting in an increase in both drag and fuel consumption. The IAM research effort involved an investigation of insect protection coating technologies for mitigating wing and leading edge insect residue adhesion in order to enhance and maintain natural laminar flow over the ecoDemonstrator's right wing.[26]

Success depended on consultation with entomologists and extensive study of bug chemistry and analysis of what happens when an insect strikes a surface at a high velocity. "We learned when a bug hits and its body ruptures the blood starts undergoing some chemical changes to make it stickier," said Mia Siochi, senior materials scientist at Langley. Then the materials scientists turned to nature—specifically, lotus leaves—to create the right combination of chemicals and surface roughness for the test coatings. "When you look at a lotus leaf under the microscope the reason water doesn't stick to it is because it

24. Jeanne Yu interview, *NASA X* "End of an ERA—Part 2," NASA TV, December 18, 2015.
25. Guy Norris, "'Green' Airliner Targets Achievable by 2025, Says NASA," *Aviation Week & Space Technology*, *http://aviationweek.com/awin/green-airliner-targets-achievable-2025-says-nasa*, April 18, 2011 (accessed July 21, 2016).
26. Nickol and Haller, "Assessment of the Performance Potential of Advanced Subsonic Transport Concepts for NASA's Environmentally Responsible Aviation Project," 3.

"Bug team" researcher John Gardner lies inside Langley's Basic Aerodynamics Research Tunnel, or BART, to prep the leading edge of a scale model wing for a blast of bugs from the tunnel's "bug gun." (NASA)

has these rough features that are pointy," said Siochi. "When liquid sits on the microscopically rough leaf surface, the surface tension keeps it from spreading out, so it rolls off," she added. "We're trying to use that principle in combination with chemistry to prevent bugs from sticking."[27]

During ERA Phase 1, NASA engineers developed and tested more than 200 nonstick coating formulations at LaRC. Initial testing used a small wind tunnel to propel insects onto a simulated wing leading edge at approximately 150 mph. Coating performance success criteria were based on the insect residue coverage area as measured by profilometry, a quantification of surface roughness. Researchers exposed potential IAM coating samples to sunlight and weather to measure durability and the effects of ultraviolet radiation. They then conducted another low-speed wind-tunnel test in the LaRC Basic Aerodynamic Research Tunnel (BART) to further down-select the final coatings for flight-testing. Following the BART test, an assortment of coatings were affixed to

27. Kathy Barnstorff, "NASA Tests Aircraft Wing Coatings that Slough Bug Guts," June 1, 2015, *https://www.nasa.gov/press-release/nasa-tests-aircraft-wing-coatings-that-slough-bug-guts* (accessed February 5, 2017).

One of NASA's two ex-Coast Guard Dassault HU-25C Guardian Falcons used for a variety of earth sciences and other research missions. (NASA)

the wing of a NASA Dassault HU-25C Guardian Falcon (a militarized Falcon business jet formerly used by the Coast Guard as a maritime patrol airplane) for a short series of low-altitude flight tests. Based upon the results, the five most promising candidates were chosen for use in the 757 ecoDemonstrator IAM flight demonstration.[28]

The next step was to select a bug-infested area in which to flight-test the treated surfaces, and that met the NASA-defined insect density criterion of 25 strikes per square foot. Because insect life is rarely a factor above 10,000 feet, the 757 would have to be flown at low level in a bug-infested area. Researchers installed high-definition cameras in the airplane's forward cabin to view the test sections on the wing through optically clear windows and record the number and size of the insect strikes during each flight. In order to determine the best location for carrying out the experiment, test planners listed all airports capable of handling a 757 around the country, and then matched this with information from entomologists about insect breeding and migration patterns.[29] A team that included members from NASA, Boeing, University of California-Davis, and the Department of Transportation's Volpe National Transportation Systems Center narrowed a list of 86 airports in 15 states to six airports in three

28. Alexander, et al., 13.

29. Norris, "Bug Smasher," 37.

states. Eventually, Shreveport Regional Airport in Louisiana was chosen due to a combination of temperature, geology, runway length, and the potential for large numbers of insects. To capture insect accumulation rates, initial test flights established a baseline using uncoated surfaces. Researchers then installed eight panels treated with samples of each of the coatings onto the ecoDemonstrator's second and third leading-edge slats. Among the engineering goals was to test how durable the coatings were; treated surfaces will be effective as drag reducers only if they can withstand the harsh flying environment. Any degradation of the coatings will result in excess drag.[30]

The five anti-adhesion surface treatments chosen for the final evaluation were sprayed in a 0.012-inch thick layer onto substrate panels made from 27-by-30-inch 7075-T6-clad aluminum panels. Researchers called this combination an engineered surface, or ES, panel. These ES panels were positioned on the wing edge adjacent to accompanying control test articles, which were substrate panels without coatings. Researchers arranged the ES and control panels in an alternating pattern along slats 8 and 9 on the right wing of the ecoDemonstrator. Prior to flight, Boeing conducted a series of spray tests to develop and verify application procedures. These were done to address specific concerns and questions regarding material quantities needed for producing the coated panels for the flight test, mixing and application protocols to produce consistent and uniform coatings, application tools and methods, and cure rates. Lessons learned from these spray tests ensured the successful application of IAM coatings to the 37 ES panels used in the flight demonstration.[31]

As part of the evaluation, Boeing conducted a trade study to determine the optimum method for attaching the ES and control panels to the wing slat's outer surface. The best solution involved applying double-sided adhesive tape to the backside of the aluminum substrate panel. This tape demonstrated sufficiently low adhesion strength to allow for removal of the substrate without deforming the plastic coating, yet was strong enough to withstand aerodynamic loading during flight. This allowed the experimental panels to be removed without degrading insect residue data. The tape also had to withstand exposure to solar radiation and temperature variations. A small piece of copper tape on each panel satisfied grounding requirements for mitigating static electricity generated by the striking of rain, snow, hail, dust, or other atmospheric particles on the airplane's surface. Technicians also sealed the edges of the ES panels with tape to prevent edge peeling due to aerodynamic forces. During ES installation procedural development, researchers noticed some amount of lower surface creep and de-bonding from the slat surface resulting from the

30. Barnstorff, "NASA Tests Green Aviation Technology on ecoDemonstrator."

31. Alexander, et al., 13–14.

NASA researchers check results following preliminary flight tests of nonstick anti-insect coatings. (NASA)

stiffness of the substrate panel. To alleviate this, they added a 2-inch strip of high-strength double-sided, pressure-sensitive adhesive tape. Because this portion of the panel was not subject to insect accretion, some plastic deformation during removal was acceptable.[32]

Test planners selected flight profiles so as to maximize insect accretion while flying a variety of takeoff conditions to simulate actual airline operations. To achieve a range of climb rates and speeds, the flight crew performed takeoffs at a range of trailing edge flap angles. The leading edge Krueger flaps on both wings were fully deployed and were not retracted during these tests. A total of 15 IAM test flights were conducted to maximum altitudes of between 1,500 and 10,000 feet. Selected crewmembers aboard the 757 ecoDemonstrator monitored onboard camera data during each flight, recording insect accretion counts by panel and slat zone. A 1 square foot template was used to aid in the counting to ensure that each test run met an insect density criterion of 25 strikes per square foot, though this device proved difficult to use. Markings

32. Ibid., 14.

on the uncoated substrate panels split each into equivalent frontal area zones to assist onboard accumulation monitoring.[33]

Ultimately, NASA and Boeing created a new assessment process for counting the number of insect strikes in zones 2 and 3, and changed the insect density criterion from 25 strikes per square foot to a total count between 53 to 62 hits in both zones per panel. This process reduced the time needed to confirm the density count. During periodic pauses between test runs, with the flight crew still on board, NASA and Boeing researchers on the ground verified whether the insect strike density on the IAM control panels had been met. If not, the flight crew conducted additional sorties until onboard data indicated the density criterion was met before returning to Shreveport. Afterward, all of the ES and control panels were photographed, underwent an *in situ* accretion count, and were removed from the slats before being delivered to LaRC for a detailed insect count. In addition, an entomologist identified the various insects that had impacted the panels. Of the five different surface treatment coatings, the best (IAMC-5B) demonstrated up to a 37 percent average reduction in insect accretion over the control panels.[34]

The research team was very happy with the results, as insect accretion meant drag, and drag meant higher fuel burn. In the complex world of aircraft operations, with billions of passengers flying in jetliners each year, saving even a small percentage of fuel burn adds up to massive savings in operating costs and, more important still, reduces harmful emissions that threaten the environment. "This has been about a 5-year effort; we started in the lab, knowing that the problem is that when bugs stick to aircraft wings it affects laminar flow and fuel efficiency," said Mia Siochi. "We've taken samples of over 200 different compositions from the lab to wind-tunnel tests to flying the best five on an actual aircraft; if at least one of those works in practical application, where we have significantly reduced the number of bugs sticking to the surface in critical locations where they affect the flow, then this has been a success."[35]

Following completion of the 757 ecoDemonstrator program in August 2015, the airplane met an unusual fate for an experimental testbed. Boeing collaborated with Stifel Bank's aircraft finance division, which owned the airplane, as well as with the Aircraft Fleet Recycling Association and an airplane demolition company in Spokane, Washington, to dismantle and recycle the 757 using environmental best practices. Including parts and materials, about 90 percent of the airplane by weight was reused or recycled, with only 10

33. Ibid., 16.

34. Ibid., 16–17.

35. Mia Siochi interview, *NASA X* "End of an ERA—Part 2," NASA TV, December 18, 2015.

percent being disposed of in a landfill.[36] This was entirely in keeping with the project's theme of environmental responsibility.

The airplane flew to Moses Lake Airport in Washington, where technicians from Aircraft Demolition, LLC, demolished it with an industrial excavator while Boeing engineers and members of the news media watched. Boeing participated in order to study more efficient recycling techniques and determine how to extract the most value from materials and parts on future airplanes. The demolition company removed valuable parts from the airframe and sold them for Stifel Bank. Included were such items as landing gear, avionics, lavatories, and ductwork, and high-value metals. Many of the components were overhauled, re-certified, and returned to service. "We are using this opportunity to look at how we can design our airplanes better in the future for end-of-service recycling," said Jeanne Yu. "Watching this has given us insight about using better materials to build the airplane, with recycling in mind, or better design that allows the airplane to be disassembled easier."[37]

After 2 months of extracting valuable components, all that remained was recyclable aluminum and unusable material. All of the aluminum scrap went to a company in Tacoma, Washington, where it was sold for re-use in Asia and elsewhere. Boeing engineers used the opportunity to evaluate how more of the airplane-grade aluminum might be recycled for use in future aircraft. "Designing for producibility and safety have always been high priorities as we draw up our next new airplane," said Mike Sinnett, Boeing Commercial Airplanes vice president for product development. "The ecoDemonstrator program is showing us that looking at the end-of-service of an airplane should be a consideration also to create higher residual value, economically and environmentally."[38]

36. Kowal and Jensen, "The Boeing ecoDemonstrator Program," 3-4.
37. Boeing, "ecoDemonstrator 757 disassembled for final recycling research project," September 8, 2015, *http://www.boeing.com/company/about-bca/washington/ecodemonstrator-757-disassembled-for-final-recycling-research-project-09-08-2015.page* (accessed January 14, 2017).
38. Ibid.

Hybrid Wing-Body (HWB) aircraft powered by UHB turbofan engines promise remarkable flight efficiency coupled with design elegance. Here is one promising Boeing concept evaluated by NASA. (NASA)

AFTERWORD

End of an ERA: Conclusions and Lessons Learned

NASA's leadership realized when the ERA project began that researchers would have difficulty achieving its stated goals. NASA executives had tasked researchers with reducing aircraft drag by 8 percent, overall structural weight by 10 percent, airframe and engine noise by more than 12 percent, engine-specific fuel consumption by 15 percent, exhaust NOx emissions by 75 percent, and aircraft noise to nearly one-eighth of today's standards, all by the year 2025. Compounding the difficulty of making such dramatic improvements was the fact that many in the aviation industry believed that conventional tube-and-wing aircraft had already reached the pinnacle of efficiency. Talented experts from several NASA field centers, along with highly skilled teams from industry and academia, set out to prove naysayers wrong and fulfill the promise of making air travel more environmentally friendly. NASA Integrated Aviation Systems Program (IASP) director Dr. Edgar "Ed" Waggoner, sees the ERA project as a clear success. "We [developed] new airframes and we will be delivering technologies that meet all of those goals; every one of our partners is getting something out of it."[1]

NASA IASP director Dr. Edgar "Ed" Waggoner lauded the ERA project for meeting its goals and delivering revolutionary new "green" technology. (NASA)

1. *NASA X*, "End of an ERA – Part 1," NASA TV, November 24, 2015.

The 6-year endeavor progressed from innovative ideas to multiple designs, analytical models, wind-tunnel tests, ground-based experiments, and testing of actual flight hardware in a relevant environment. ERA project teams employed an incremental process to achieve their ambitious goals in an orderly and logical fashion. Throughout Phase 1, researchers strove to determine whether certain technologies were, in fact, viable. Lessons learned from more than 30 of these smaller experiments paved the way for selection of the eight integrated technology demonstrations undertaken during Phase 2. The ERA project was organized so as to mature the most promising technologies and advance aircraft configurations to meet midterm goals for community noise, reduced fuel burn, and NOx emissions. Researchers were also tasked with determining the potential impact of introducing these advances into the NextGen air transportation system. The solutions they have achieved will undoubtedly reduce fuel consumption by up to several percentage points for the aviation community. That may not sound like much, but shaving aircraft fuel consumption by even a few percentage points will save millions of dollars and help protect the environment from harmful emissions.[2]

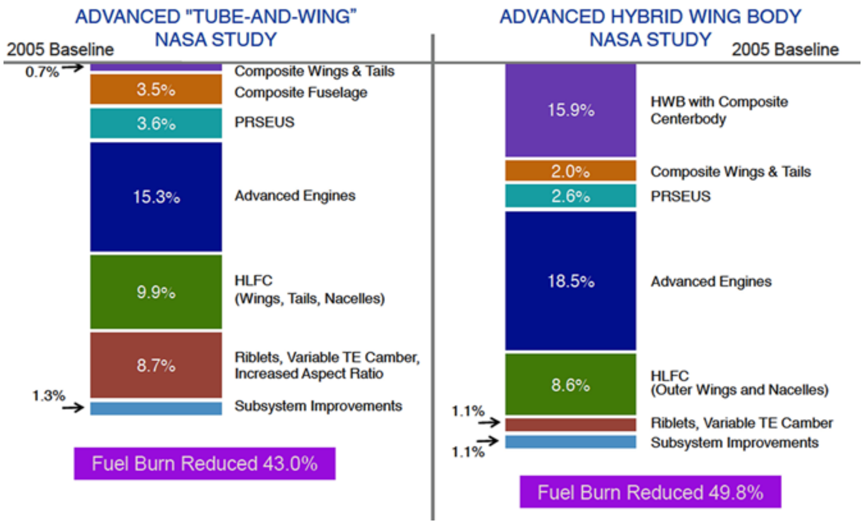
Work within the ERA project was coordinated with research performed by other programs within NASA's Aeronautics Research Mission Directorate as well as other Federal Government agencies. NASA also put mechanisms in place to engage academia and industry, including working groups and technical interchange meetings, and Space Act Agreements for cooperative partnerships. In addition, the NASA Research Announcement process provided for full and open competition for the best and most promising ideas. With the exception of proprietary data, the ERA Project disseminated all research results to the widest practical extent. "Most of the technologies we looked at, like low-noise landing gear or adaptive trailing edges or engine technologies, are broadly applicable to a number of different aircraft configurations," said Rich Wahls. "Throughout the 6-year span of ERA, we were looking at tradeoffs between better technologies and different aircraft configurations."[3]

These new technologies and concepts may soon start appearing on production airplanes. In 2016, FlexSys formed a joint venture with Aviation Partners, Inc., of Seattle, Washington, to commercialize the wing morphing technology. Additionally, NASA and Air Force researchers have begun a second phase of ACTE testing at AFRC. Future efforts in the FAA CLEEN program may advance PRSEUS into TRL6 and TRL7. Advanced turbofan and combustor technologies evaluated during the ERA project are also moving forward.

2. *NASA X* "End of an ERA – Part 2," NASA TV, December 18, 2015.
3. Dr. Richard A. Wahls interview with the author, August 4, 2016.

Projected Integrated Portfolio Benefits

Mission Fuel Burn/Carbon Emissions

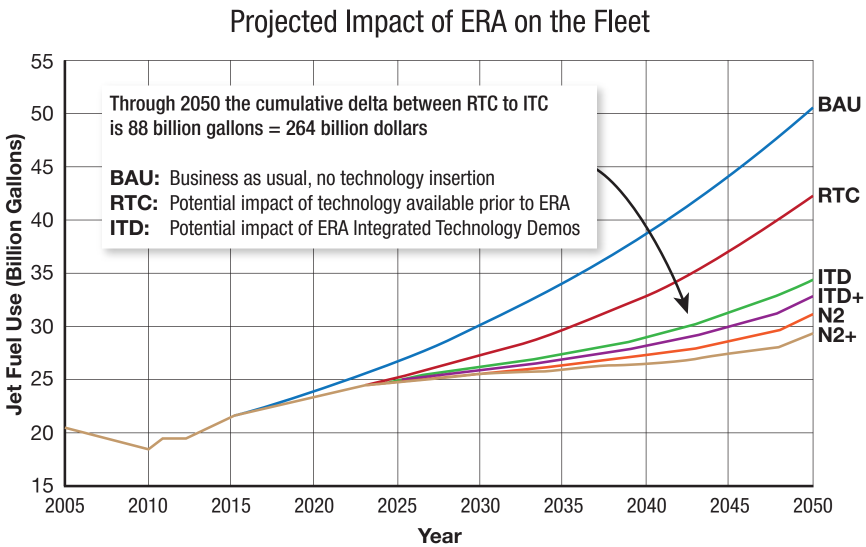


Projected benefits of ERA technologies on future conventional and HWB transport designs. (NASA)

Although most ERA technologies were not intended to be configuration-specific, a great deal of effort focused on development of the HWB concept. This revolutionary configuration was the first modern commercial transport design to completely move away from the traditional tube-and-wing paradigm. “You take an airplane from, say, 1950, and an airplane from today, and lay them on top of each other, and they have almost exactly the same outline,” said Kevin James, ERA project manager at ARC. He added that in order to realize dramatic improvements in fuel economy, emissions, and acoustics, “We have to keep looking and sometimes think outside the box; with a hybrid wing body, depending on how you control the wake and how you put the engines on it, we have significant improvements in fuel burn and also improvements in noise.”[4]

Testing of the X-48B and X-48C successfully demonstrated HWB low-speed flight control characteristics. Controllability and construction methods for building a flat-sided pressure vessel were only two of the key enablers for designing a practical HWB. Engine operability was another. Wind-tunnel testing at LaRC helped researchers determine how to integrate modern engines

4. Kevin James interview, *NASA X*, “End of an ERA – Part 2,” NASA TV, December 18, 2015.



Application of ERA technologies to future airline fleets will reduce operational costs by billions of dollars. (NASA)

with the HWB airframe. Work by various manufacturers on BWB and HWB configurations continues.[5]

By the time the ERA project concluded on January 7, 2016, NASA had invested more than $400 million, with a further $250 million of in-kind resources contributed by industry partners. The cost may have been worth it, according to Dr. Jaiwon Shin. "If these technologies start finding their way into the airline fleet, our computer models show the economic impact could amount to more than $255 billion in operational savings between 2025 and 2050."[6]

"The mandate was a 50 percent reduction in fuel burn and a 42 db reduction in noise in a cumulative fashion from a 1999-target airplane, and where we ended up was really, really close," said Kevin James. "When we start talking about numbers, even if it's cumulative, that is a huge improvement; it really is in terms of quality of life, especially for people living around airports." He took the opportunity to articulate that, among so much else, the ERA project had involved a lot of hard work. "There have been some frustrations, but that's kind of what makes the job fun sometimes, [when you are] solving the

5. Collier interview.
6. Pia Bergqvist, "NASA's ERA Project Could Save Airlines Billions," *Flying*, (January 13, 2016): *https://www.flyingmag.com/nasas-era-project-could-save-airlines-billions/* (accessed August 21, 2019).

challenges." He said that he enjoyed seeing all the pieces come together in terms of project management, vehicle concepts, and systems integration. "At the end of the program, it was just incredible seeing the progress that was made and the deliverables that we're getting from all the components," he said. "As they come together, we're going to be in a position to say that this works, and that this is where we should be headed."[7]

7. Kevin James interview.

APPENDIX

Environmentally Responsible Aviation Technical Overview

The following appendix is a seminal May 2009 presentation given by Rich Wahls before a Meeting of Experts sponsored by the Aeronautics and Space Engineering Board of the National Research Council. It is included in this work because it had far-reaching influence on the subsequent ERA effort.

Readers who wish to view it online can access it here: *https://www.hq.nasa.gov/office/aero/pdf/2009_05_14_nrc_rich_wahls_508.pdf.*

Environmentally Responsible Aviation Technical Overview

Presented by

Rich Wahls

Contributors

Fay Collier, Ruben DelRosario, Dennis Huff, Larry Leavitt, Pat Stoliker, Tony Strazisar, and multi-center planning team

Meeting of Experts

Aeronautics and Space Engineering Board Meeting

National Research Council

Washington, DC

May 14-15, 2009

Outline

- Overview
  - Vision, Mission, Scope, Goals
  - Alternate Vehicle Concepts and Technologies
- Technical Approach
  - Project Framework/Schedule
  - Critical Technology Areas
- Concluding Remarks

ERA Project Framework

- Vision
  - ERA will expand the viable and well-informed trade space for vehicle design decisions enabling simultaneous realization of National noise, emissions, and performance goals
  - ERA will enable continued aviation growth while reducing or eliminating adverse effects on the environment
- Mission
  - Perform research to explore/assess the feasibility, benefits, interdependencies, and risks of vehicle concepts and enabling technologies identified as having potential to mitigate the impact of aviation on the environment
  - Transfer knowledge outward to the aeronautics community, and inward to NASA fundamental aeronautics projects
- Scope
  - N+2 vehicle concepts and enabling technologies
  - System/subsystem research in relevant environments

ERA Project Context

National Plan for Aeronautics R&D

- Mobility, Security/Defense, Safety, Energy & Environment
  - Enable growth in Mobility/Aviation/Transportation
  - Dual use with Security/Defense
  - Safety and Cost Effectiveness are pervasive factors
- Energy and Environment goals are central to ERA
  - Energy Diversity
    - use of alternative fuels, not creation of alternative fuels
  - Energy Efficiency
  - Environmental Impact
    - reduction of impacts, not reducing scientific uncertainties of impacts

Subsonic Fixed Wing System Level Metrics

.... technology for improving noise, emissions, & performance

CORNERS OF THE TRADE SPACE	N+1 (2015)*** Generation Conventional Configurations relative to 1998 reference	N+2 (2020)*** Generation Unconventional Configurations relative to 1998 reference	N+3 (2025)*** Generation Advanced Aircraft Concepts relative to user-defined reference
Noise	-32 dB (cum below Stage 4)	-42 dB (cum below Stage 4)	-71dB (cum below Stage 4)
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-40%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metro-plex* concepts

***Technology Readiness Level for key technologies = 4-6
** Additional gains may be possible through operational improvements
* Concepts that enable optimal use of runways at multiple airports within the metropolitan area

Approach

- *Enable Major Changes in Engine Cycle/Airframe Configurations*
- *Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes*
- *Develop/Test/ Analyze Advanced Multi-Discipline Based Concepts and Technologies*

Alternate Configuration Concepts

Many ideas, but…

What combination of configuration and technology can meet the goals?

What is possible in the N+2 timeframe?


Airbus
Aviation Week 1/15/01


Boeing NRA
FAP Annual Mtg 10/08


Boeing/MIT/UCI NRA
Aviation Week 2/2/09


Airbus
Aviation Week 1/15/01


NASA VSP
2003


Cambridge/MIT SAX-40
1/07


easyJet ecoJet
Reuters 6/14/07


NASA- M Moore
2009


RAeS Concept
Greener By Design, 2006

Underlying Technology

- Technology enablers - broadly applicable
  - less visible than configuration features
  - applicable to alternate and advanced conventional configurations
  - Noise: continuous mold lines, increasing ducted BPR
  - Emissions: low NOx combustion, reduced fuel burn technologies
  - Fuel Burn: lightweight structure, reduced drag, and reduced SFC

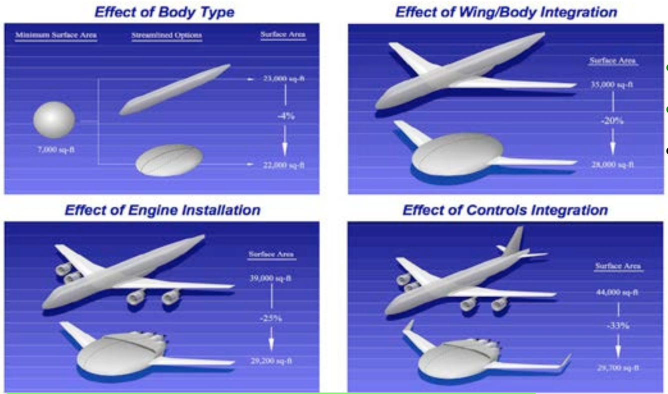
$$\text{Aircraft Range} = \frac{\text{Velocity}}{\text{TSFC}} \left(\frac{\text{Lift}}{\text{Drag}}\right) \ln\left(1 + \frac{W_{fuel}}{W_{PL} + W_{O}}\right)$$

- Engine Fuel Consumption (TSFC)
- Aerodynamics (Lift/Drag)
- Empty Weight (W_O)

Alternate Configuration Concepts

a case study to show what is possible

- Many ideas, but most concepts remain on paper
  - Hybrid Wing Body (HWB) concept has been explored in more detail
  - 1989 Origins: NASA Advanced Concepts Workshop challenges aeronautics community
  - 1990s System Concept Studies, Technology Challenges identified



33% wetted area reduction
offers huge viscous drag reduction potential

Benefits

- Greater fuel efficiency
- Reduced Environmental Impact
- Operational Flexibility

Challenges

- Noncylindrical pressure vessel
- Edge-of-the-envelope flight dynamics
- Propulsion-Airframe Integration (PAI)

Liebeck, AIAA-2002-0002

Environmentally Responsible Aviation 8

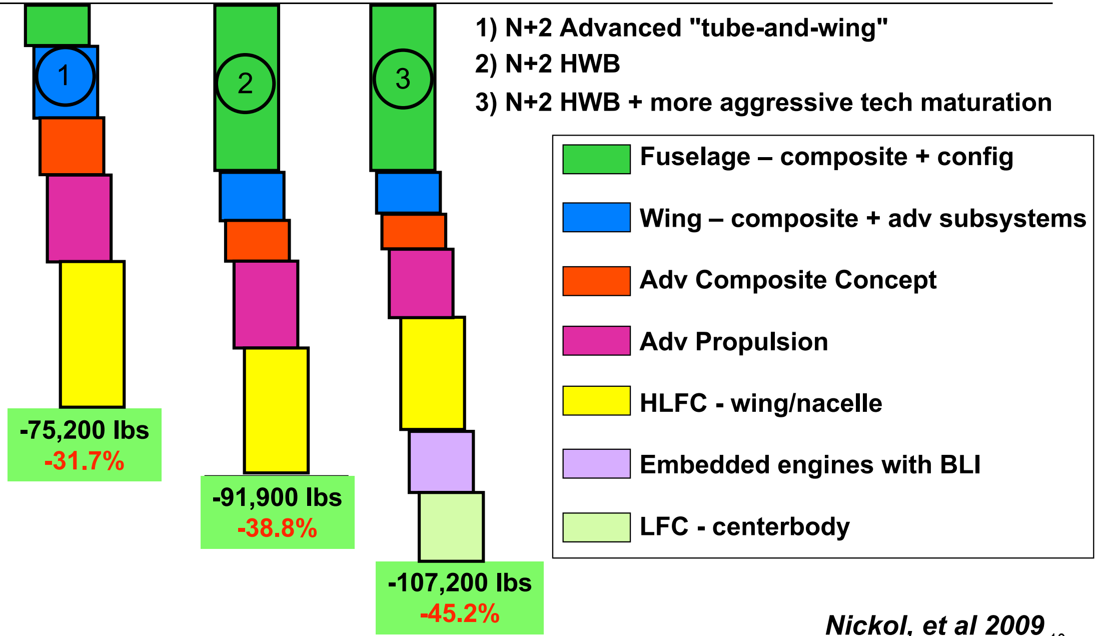
Alternate Configuration Concepts

a case study to show what is possible

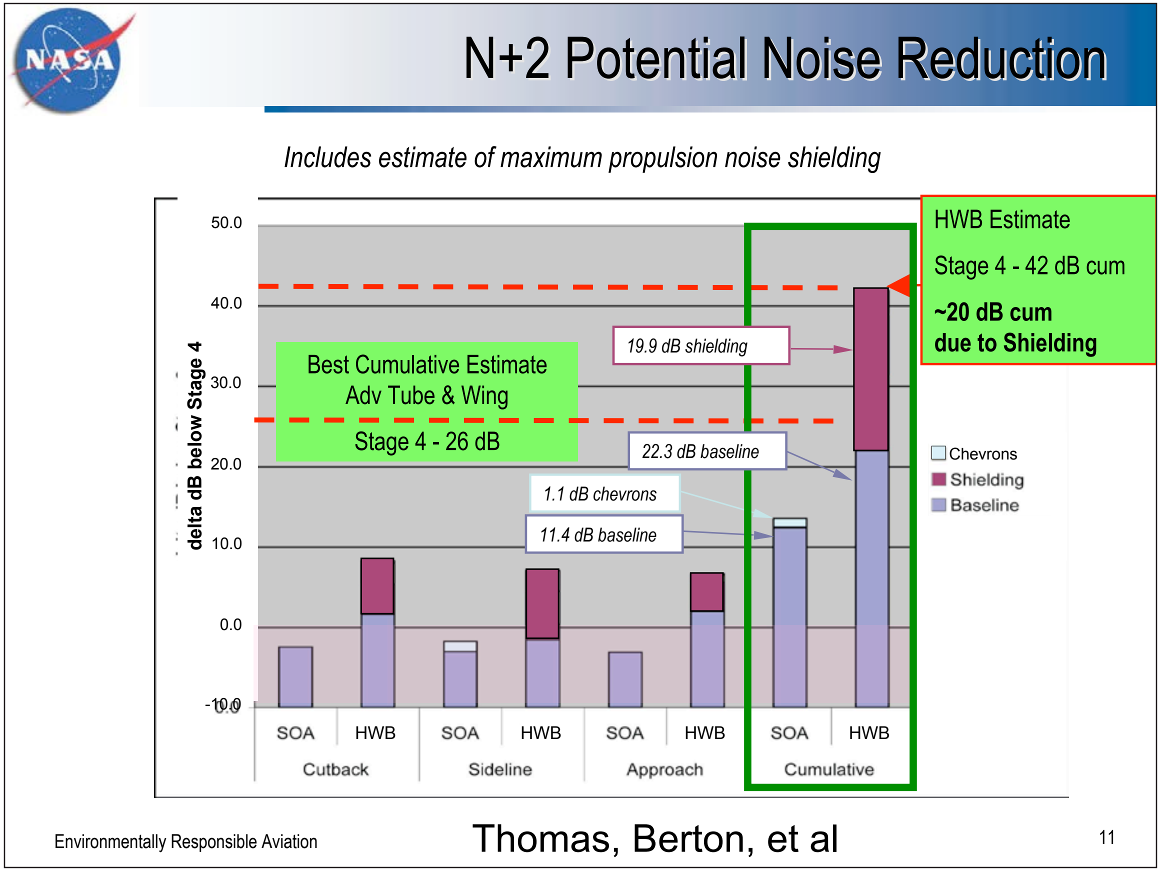
- Many ideas, but most concepts remain on paper
  - Hybrid Wing Body (HWB) concept has been explored with more detail
  - 2000s
    Research addressing technology challenges, ongoing system studies
    - Provides a framework for advancement of broadly applicable technologies
  - Today
    Continues to show potential of simultaneously meeting the N+2 goals

Potential Reduction in Fuel Consumption

Reference Fuel Burn = 237,100 lbs
1997 Technology Large Twin Aisle Vehicle “777-200ER-like”



Nickol, et al 2009


N+2 Potential Noise Reduction
NASA
Includes estimate of maximum propulsion noise shielding
delta dB below Stage 4
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
Best Cumulative Estimate
Adv Tube & Wing
Stage 4 - 26 dB
19.9 dB shielding
22.3 dB baseline
1.1 dB chevrons
11.4 dB baseline
HWB Estimate
Stage 4 - 42 dB cum
~20 dB cum
due to Shielding
Chevrons
Shielding
Baseline
SOA
HWB
SOA
HWB
SOA
HWB
SOA
HWB
Cutback
Sideline
Approach
Cumulative
Environmentally Responsible Aviation
Thomas, Berton, et al
11

Market Needs and Design Trades

A sweet spot for noise and fuel burn

…but lower cruise speed may change technologies

…as might payload/range (vehicle size)

… or relative emphasis on noise & fuel burn

Market will ultimately determine outcome

…but concepts and technologies enable options

Design Trades and Dependencies

Our focus is Noise, Energy Efficiency, and Emissions
…but airplane design is a balance among many factors

Madden, ICCAIA Fuel Burn Workshop
March 2009

The Way Forward

- System research to bridge the gap between fundamental research (TRL 1-4) and product prototyping (TRL 7)
  - Identify vehicle concepts with the potential to simultaneously meet National goals for noise, emissions, and fuel burn in the N+2 timeframe
  - Understand the concept and technology feasibility/risk vs potential benefits
  - Understand the concept and technology trades and interdependencies at high fidelity in relevant environments
  - Determine safety implications of new technologies and configurations

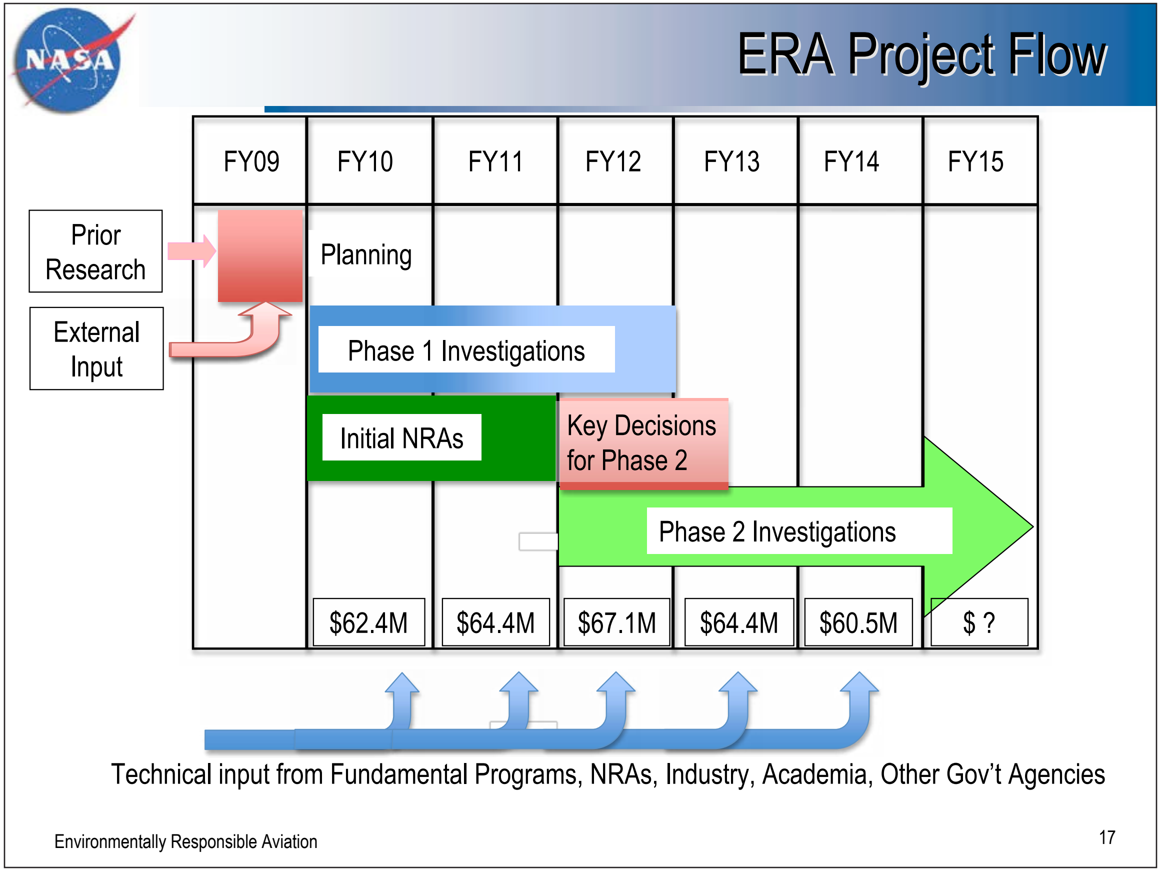
- Technology investments guided by
  - matured in fundamental program and worthy of more in-depth evaluation at system level in relevant environment
  - systems analysis indicates most potential for contributing to simultaneous attainment of N+2 goals
  - identified through stakeholder input as having potential for contributing to simultaneous attainment of N+2 goals

Outline

- Overview
  - Vision, Mission, Scope, Goals
  - Alternate Vehicle Concepts and Technology
- Technical Approach
  - Project Framework/Schedule
  - Critical Technology Areas
- Concluding Remarks

Research Focus Areas

1.0 Project Management	**Natural Metrics**
2.0 Airframe Technology	**ML/D, Empty Weight, Airframe Noise**
2.1 Lightweight Structures	investigations where propulsion system is not 1st order effect
2.2 Flight Dynamics and Control	
2.3 Drag Reduction	
2.4 Noise Reduction	
3.0 Propulsion Technology	**SFC, Engine Noise, Emission Index**
3.1 Combustor Technology	investigations where airframe system is not 1st order effect
3.2 Propulsor Technology	
3.3 Core Technology	
4.0 Vehicle Systems Integration	**ML/D, Weight, SFC, Emission Index, Noise**
4.1 Systems Analysis	investigations where propulsion/airframe interaction is 1st order effect
4.2 Propulsion Airframe Integration	
4.3 Propulsion Airframe Aeroacoustics	
4.4 Advanced Vehicle Concepts	


ERA Project Flow
FY09
FY10
FY11
FY12
FY13
FY14
FY15
Prior Research
External Input
Planning
Phase 1 Investigations
Initial NRAs
Key Decisions for Phase 2
Phase 2 Investigations
$62.4M
$64.4M
$67.1M
$64.4M
$60.5M
$?
Technical input from Fundamental Programs, NRAs, Industry, Academia, Other Gov't Agencies
Environmentally Responsible Aviation
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Initial NRA Topics Under Development

- Topic 1 - N+2 Advanced Vehicle Concepts
  - Concept development and technology roadmaps
  - Scope key system Investigations to inform Phase 2 decisions

- Topic 2 - Low NOx Combustors
  - Concept development and technology roadmaps
  - Initial flametube experiments
  - Inform Phase 2 decisions

- Topic 3 - Quick-Start System Research Investigations
  - Complementary to Phase 1 investigations
  - Early technical progress/results toward ERA goals
  - Inform Phase 2 decisions

Bidders Conference Prior to Solicitation

Phase 1 Investigations

- Scope
  - Concepts and technologies from fundamental projects ready for system experimentation
  - System integration and multidisciplinary risks/barriers
  - 2-3 years

- Critical Technology Focus
  - Stitched composite technology for low weight and damage tolerance
  - Laminar flow technology for drag reduction
  - Flight dynamics & control technology enabling alternate configurations
  - Combustor technology for low emissions
  - Propulsion technology and integration for SFC and noise reduction
  - Propulsion shielding for noise reduction

- Outcome
  - Selected concepts and technologies explored/assessed with respect to feasibility, benefits, interdependencies, and risks - uncover unexpected multidisciplinary interactions
  - New and/or refined ideas emerge
  - Detailed information to update systems studies, and for prioritization and selection of Phase 2 investigations

Phase 2 Investigations

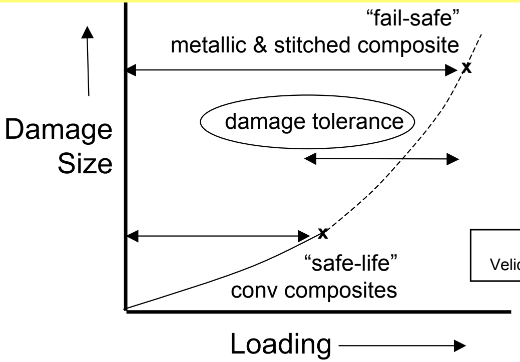
- Key Decisions
  - FY12 timeframe plus/minus 1 year - not a specific point in time
- Scope
  - Similar to Phase 1, plus further exploration of Phase 1 concepts and technologies as appropriate
  - 3-4 years
- Technology Focus
  - Informed by Phase 1 progress/results, system studies, stakeholder input
  - Envision investigations which integrate results from Phase 1, NRAs, other sources
- Outcome
  - Selected concepts and technologies explored/assessed with respect to feasibility, benefits, interdependencies, and risks - trade space understood

Energy Efficiency

Lightweight Structures

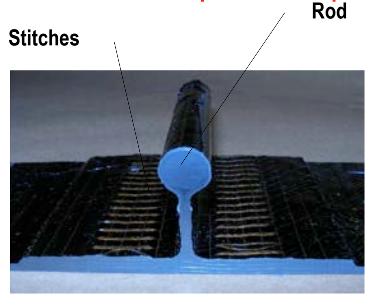
Stitched Composites - enabling weight reduction with load limits of metals

Damage Tolerance, Durability, Flexibility, Cabin Noise



Adapted from
Velicki 2009 Aging A/C Conf

Advanced Stitched Composite Concept



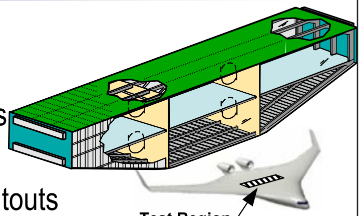
Pultruded Rod Stitched Efficient Unitized Structure PRSEUS

- Can the same load limits as metal be applied to a lower weight composite concept?
- Can structural weight be reduced while meeting certification/safety requirements?
- Can cabin noise be acceptable with lightweight structure, particularly in the context of propulsion noise shielding?

Energy Efficiency

Lightweight Structures

- **Objective**
  - Explore/validate/characterize/document new stitched composite structural concept under realistic loads
- **Approach**
  - Building block experiments on sub components, joints, cutouts
  - Explore repair/maintenance, NDE methods
  - Large scale pressurized multi-bay fuselage section under combined load
  - Incorporation of IVHM sensors in large scale COLTS test
- **Benefit**
  - Validate damage-arresting characteristics under realistic loads. Expected 20% reduction in weight and cost of conventional composite structural concepts. Extensible to wings, etc.



FY10	FY11	FY12	FY13	FY14	FY15

PRSEUS Pressure Panel Test Complete

Noise Transmission Assessment

Large-Scale PRSEUS Test in COLTS Complete

Design Criteria for Low Noise Lt Wt Structure

concept understood for large integrated component

possibilities
- PRSEUS wing
- alternate structural concept
- integrate with other techs (laminar, acoustic)
- enable unconventional flight vehicle testbed

Environmentally Responsible Aviation

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Enabling

Flight Dynamics & Control

Flight Controls - enabling alternate vehicle concepts

Handling/Ride Quality, Safety of Flight

Unconventional Vehicle Concepts
provide unique challenges

? Regulatory acceptance

? Market acceptance

? Performance benefit

- Can alternative vehicle concepts meet Federal airworthiness requirements without negating performance/acoustic benefits?
- Can alternative vehicle concepts meet passenger ride quality expectations without negating performance/acoustic benefits?
- Can advanced controls enable performance and safety improvements beyond simply enabling a new vehicle concept?

Enabling

Flight Dynamics and Control

- **Objective**
  - Explore/assess dynamics and control design space for unconventional, flexible wing vehicle, w/ extensibility to other advanced aircraft designs
- **Approach**
  - Utilize extensive HWB database to develop full-scale piloted motion-based simulation for advanced HWB concept; establish control system design requirements and guidelines for HWB aircraft
  - Complete X-48B flight test
  - Explore/assess a broad range of handling, ride quality, control authority and allocation, gust load alleviation, upset recovery, aero-servoelastic control concepts/challenges
- **Benefit**
  - Advanced/adaptive control law technology for handling, ride quality, and safety of flight, extensible to a range of advanced vehicle concepts

Piloted Sim

FY10	FY11	FY12	FY13	FY14	FY15

X-48B Flight Tests Complete

X-48C Tests In 30x60 Complete

Full-scale Piloted Sim for Handling Qualities Complete

Adv Control Laws for Lightly Loaded and/or Flexible Wing Concepts Validated in Simulators

possibilities
- flight experiments with adaptive or intelligent controls
- other control concepts in piloted simulation
- enable investigation of lightweight, flexible structures
- enable unconventional flight vehicle testbed

full envelop HWB control and dynamics understood; advanced controls explored

Energy Efficiency

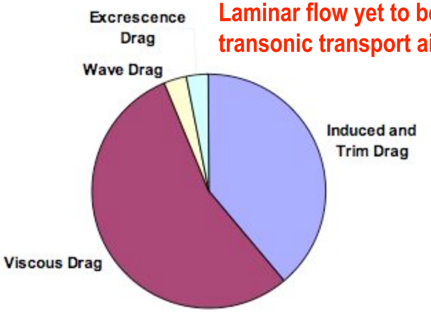
Drag Reduction

Laminar Flow - breaking down technical barriers to practical laminar flow application

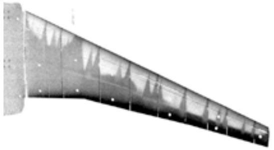
System integration trades, robustness, pre-flight assessment

Drag Breakdown (Typical)

Laminar flow yet to be exploited on transonic transport aircraft



Active and Passive Concepts

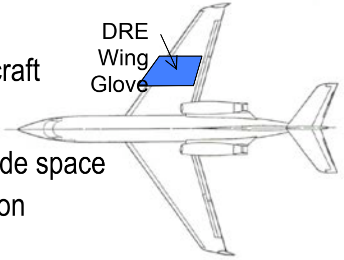


- Aerodynamic/drag benefits are known, and depend on application (config, size, regions)

Challenges
- Integration trades for high-lift performance, and suction systems for HLFC in particular
- Robustness to contamination and structural/surface imperfection
- Ability ground test/assess across full flight envelop at relevant conditions prior to flight

Drag Reduction

- **Objective**
  - Enable practical laminar flow application for transport aircraft
- **Approach**
  - Mature multiple approaches to laminar flow to enlarge trade space
  - Address critical barriers to practical laminar flow application
  - Explore synergy with other advanced technologies (e.g. composite structure, cruise slots, novel high lift systems, intelligent controls, etc.)
- **Benefit**
  - Validated passive and active drag control technologies capable of enabling 5-15+ % reductions in fuel burn. Expanded design trade space with higher fidelity trade information. Expanded database (higher Rn) for validation of transition models.



FY10 | FY11 | FY12 | FY13 | FY14 | FY15

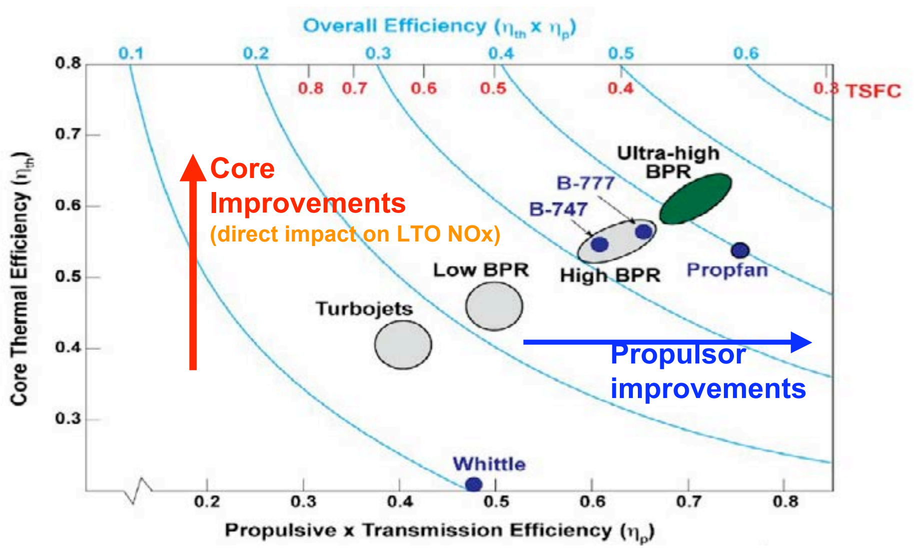
- Evaluate Ground Test Capability For NLF
- HLFC Flight Test completed
- DRE Glove Flt Test on G-IIB completed
- Flt Test Assessment of Low Energy Coatings completed

confidence to proceed to highly integrated flight test experiment

possibilities
- "in-service" flight tests of selected concept(s)
- integrate with other techs (composite, cruise slot)
  - re-wing research aircraft
- incorporate in design of flight vehicle testbed
- other drag reduction concepts beyond laminar

Propulsion Systems

Propulsion system improvements require advances in propulsor and core technologies



Alan Epstein
Pratt & Whitney Aircraft

Environmentally Responsible Aviation

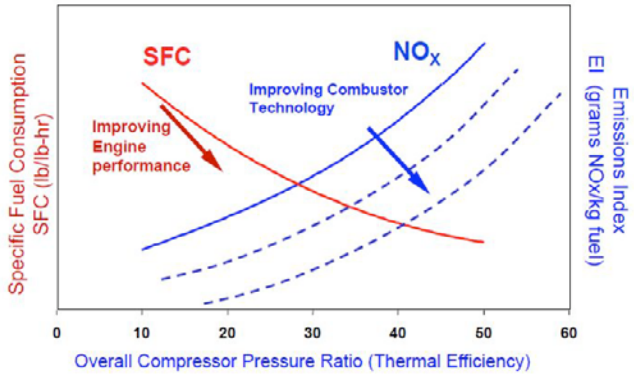
27

LTO NOx

Core/Combustor Technology

Low NOx combustor concepts for high OPR environment

Increase thermal efficiency without increasing NOx emissions



Injector Concepts

- Partial Pre-Mixed
- Lean Direct Multi-Injection

Enabling Technology

- lightweight CMC liners
- advanced instability controls

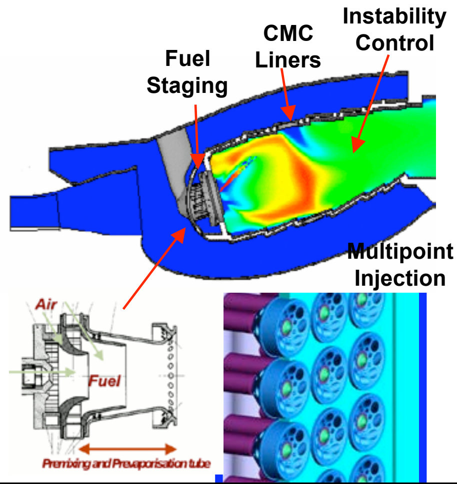
- Improved fuel-air mixing to minimize hot spots that create additional NOx
- Lightweight liners to handle higher temperatures associated with higher OPR
- Fuel Flexibility

- DoD HEETE Program is developing higher OPR compressor technology
  …. ERA will focus on new combustor technology for reduced NOx formation

LTO NOx

Combustor Technology

- **Objective**
  - Extend maturation of technologies for reducing LTO NOx. Concepts must ensure fuel flexibility.
- **Approach**
  - Pursue 3 concepts: Lean Partial-Mixed Combustor, Lean Direct Multi-Injection, TBD from NRA.
  - Flametube, sector, and annular combustor tests.
  - Select single concept for engine tests.
  - Assume 50% cost share with industry.
- **Benefit**
  - Technologies to reduce LTO NOx by 75% below CAEP/6.



FY10	FY11	FY12	FY13	FY14	FY15

- ▲ Initiate Low-NOx Combustor Concept Studies (FY10)
- ▲ Select Low-NOx Combustor Concepts **(downselect 3 to 1)** (FY11/FY12)
- ▲ Complete Flametube Experiments (FY12/FY13)
- △ Complete Sector Tests (FY14/FY15)
- △ Complete Annular Combustor Tests (end of FY15)

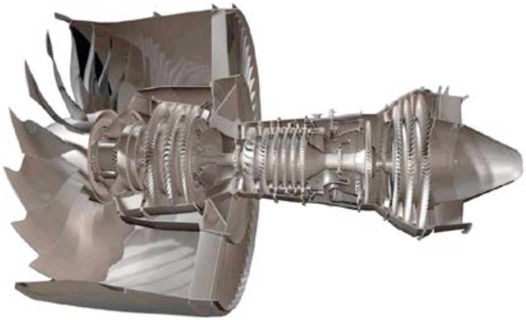
Increasing integration/complexity

Energy Efficiency

LTO NOx

Core Technology

- **Objective**
  - Explore core architectures and develop key technologies needed for N+2 propulsion
- **Approach**
  - Use NRA to explore core engine concepts; specific technologies TBD but will integrate existing work on high OPR compressors from VAATE, turbine cooling work in SFW.
  - Pursue technologies like Ceramic Matrix Composite (CMC) materials that will benefit any gas turbine engine concept; early work assesses fabrication methods for cooled vanes and nozzles
- **Benefit**
  - Technologies to increase thermal efficiency that enable higher BPR propulsion (either turbofans, open rotors, or embedded engines)



Advanced Core for UHB Turbofan (P&W GTF)

FY10	FY11	FY12	FY13	FY14	FY15

- Assess CMC Fab Methods, Durability & Heat Transfer
- Identify Core N+2 Concepts
- • high OPR compressor
- • increase T4
- Increasing integration/complexity
- Complete Test of Adv Core Components

Energy Efficiency

Noise Reduction

Propulsor Technology

Ultra high bypass ratio propulsor

Ducted v Unducted trade, noise v efficiency

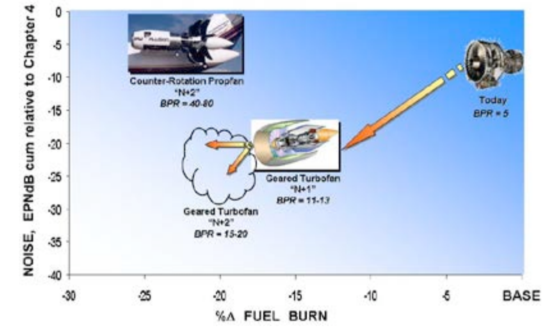
<u>Concepts</u>

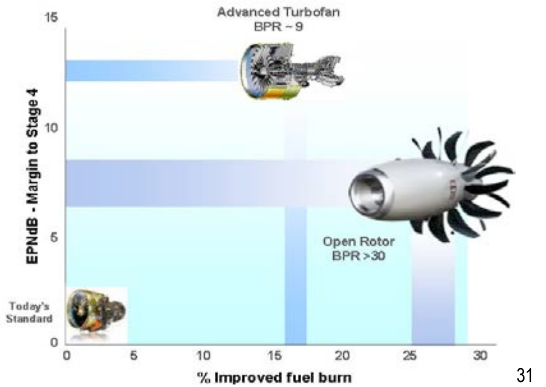
- Ducted UHB
  - short inlets, laminar flow nacelles
  - SMA variable area nozzle
  - soft vane, over-the-rotor treatment
- Unducted UHB (Open Rotor)
  - increased rotor spacing, lower blade count
- Embedded for boundary layer ingestion
  - inlet flow control, distortion tolerant fan

<u>Challenges</u>

- Open Rotor - reduced noise while maintaining high propulsive efficiency

- Ducted UHB - nacelle weight & drag with increasing diameter





Energy Efficiency

Noise Reduction

Propulsor Technology

- **Objective**
  - Explore propulsor (bypass flowpath) configurations for N+2 vehicle concepts to expand and better define the trade space between performance and noise reduction.
- **Approach**
  - Investigate feasibility of higher BPR propulsion systems: UHB Turbofans, Open Rotors and TBD Advanced Propulsor identified from NRA.
  - Evaluate UHB & Open Rotor for N+2; isolated and partially installed simulations in wind tunnel tests; Handoff to VSI for full installation experiments.
- **Benefit**
  - Propulsor concepts identified and validation data available for noise & performance trades.

UHB Turbofans

Open Rotor

FY10	FY11	FY12	FY13	FY14	FY15

- ▲ Select UHB & Open Rotor Concepts
- ▲ Select Adv. Propulsor Concept For N+2
- ▲ Complete UHB Turbofan Tests
- ▲ Complete Isolated Open Rotor Tests

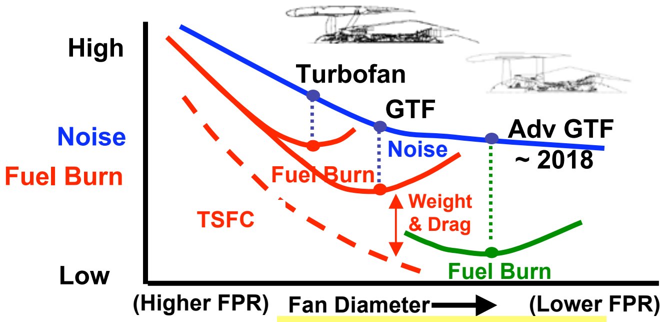
possibilities
- isolated and partially installed advanced propulsor ground tests similar to phase 1
- integrate with other techs (config, shielding)
- flight test propulsion concept
- incorporate in design of flight vehicle testbed

Energy Efficiency

Propulsion Airframe Integration

UHB Installation that minimizes or avoids performance penalties

Increased size of system may drive need for alternate configurations



Lord, Sepulveda, et al

PAI Challenges Increase

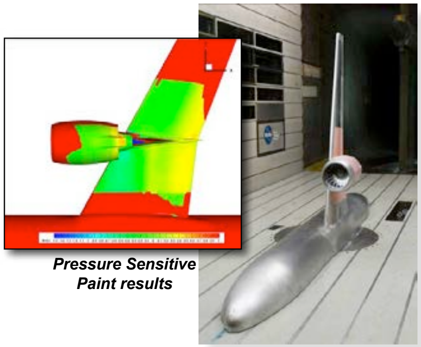
- Increasingly large diameters present increasingly difficult installations for conventional low wing configurations, and may require alternate configurations/installations to take advantage of propulsive efficiency

  …. significant vehicle level trade space to explore

Energy Efficiency

Propulsion Airframe Integration

- **Objective**
  - Understand synergistic performance/efficiency coupling potential between advanced propulsor and airframe concepts
- **Approach**
  - Explore/assess (large-scale testing) performance benefits thru integration of advanced low noise/efficient open rotor and UHB propulsors
  - Quantify installed performance benefits of alternate engine airframe integrations (e.g. boundary layer ingestion)
- **Benefit**
  - Enlarged PAI design trade space with new open rotor and UHB propulsors (and integrations) with advanced N+2 airframes (15-25% fuel burn reduction)



Pressure Sensitive Paint results

Powered half-span model test in Ames 11' wind tunnel

FY10	FY11	FY12	FY13	FY14	FY15

Note:
- Advanced large scale isolated/proximity UHB and reduced noise OR propulsor experiments being conducted in 9x15. Results will feed integrated experiments.

▲ HWB Low-Speed Performance Assessment

▲ Performance Assessment of installed UHB

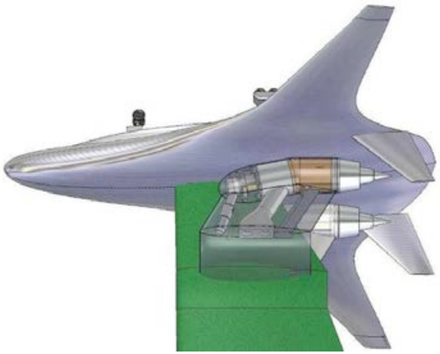
▲ Performance Assessment of installed Open Rotor

Possibilities
- flight tests of selected concepts
- integration of boundary layer ingesting inlet
- integrations with other adv. technology (CML, flow control, shielding, etc.)
- other low noise propulsor concepts

Noise Reduction

Propulsion Airframe Aeroacoustics

- **Objective**
  - Understand synergistic acoustic coupling potential between advanced propulsor and airframe concepts
- **Approach**
  - Explore/quantify (large-scale testing) airframe shielding benefits thru integration of advanced low noise/efficient open rotor and UHB propulsors
  - Quantify aeroacoustic benefits of alternate engine airframe integrations (e.g. boundary layer ingestion)
- **Benefit**
  - Enlarged PAA design trade space for new open rotor and UHB propulsors (and integrations) with advanced N+2 airframes (15-20 dB cum reduction to Stage 4)



FY10	FY11	FY12	FY13	FY14	FY15

Hot Jet Test Technique and Acoustic Upgrades 14x22

HWB Noise Shielding Eval In 14x22

Noise Assessment of Installed UHB

Noise Assessment of Installed Open Rotor

Possibilities
- flight tests of selected concepts
- integration with boundary layer ingesting inlet
- integrations with other adv. technology (CML, flow control, composites, etc.)
- other low noise propulsor and shielding concepts

Environmentally Responsible Aviation

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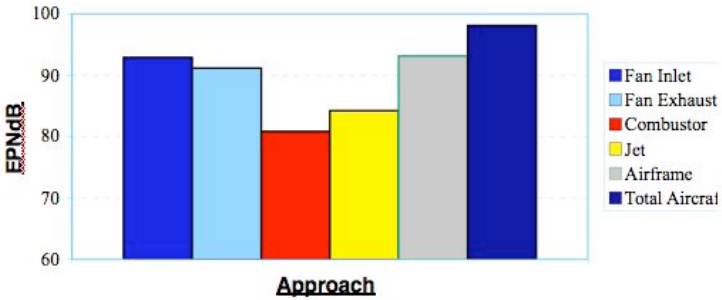
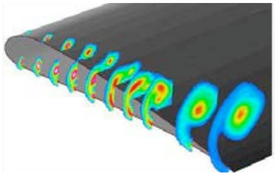
Noise Reduction

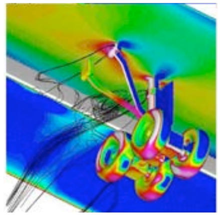
Airframe Noise Reduction

Quiet flaps and landing gear without performance penalties

Low airframe noise technologies conflict with low drag/weight







- Landing gear designed for performance/weight, but generate much more noise
- High lift system gaps and exposed flap edges help performance, but generate noise
- Currently cannot accurately account for all aircraft sources, interactions with other components, and installation effects

Noise Reduction

Airframe Noise Reduction

- **Objective**
  - Understand/research synergistic coupling/multidisciplinary aspects of integrated adv. airframe noise reduction technologies
- **Approach**
  - Flight test of CML flap on NASA G-IIB aircraft
  - Wind tunnel and flight test campaign on large business jet (LBJ) targeting landing gear and flap edge noise as well as gear/flap interactions. Improved microphone array technology.
- **Benefit**
  - Quantified technologies for airframe noise reduction on the order of 5-10 dB cum; enlarged design trade space for adv. low noise configurations

FY10	FY11	FY12	FY13	FY14	FY15

Low Noise Concepts on LBJ in 14x22

Assess CML Perf & Acoustic Benefits on G-IIB

Valid. Adv. Low Noise Gear and/or Flap Edge Noise Concepts on LBJ Flt Test

Possibilities
- Characterize & simulate aeroacoustic loads on large-scale multi-bay composite structure
- Large-scale or flight experiments on low noise vehicle with adv. NR technologies (e.g. landing gear fairings or low noise designs, slat cove fillers, flap edge devices, etc.)

Phase 2 Investigations - Revisited

- Key Decision Point(s) for Phase 2 in the FY12 timeframe
- Noted several times today the idea of an experimental vehicle testbed (XVT) as centralizing focus for integrated systems research on an unconventional configuration
- The XVT would (very) likely require a significant budget increase and/or significant cost sharing partnerships
- Initial NRA Topic 1 may inform us as to the possibilities

XVT - Experimental Vehicle Testbed

- Drivers for a (large) Flight Research Vehicle
  - Appropriate scale for aerodynamics validation
    - High Reynolds number to minimize scaling issues
    - High speed - compressibility effects
    - Geometric fidelity
  - Appropriate scale for acoustics flight test
    - Geometry fidelity
    - Physics of the noise sources require they be of the same type to scale properly
    - Scale required to understand noise attenuation and shielding
  - Appropriate scale for aero-elasticity and flight dynamics
  - Capability to assess advanced flight controls concepts

XVT - Experimental Vehicle Testbed

- Additional Benefit of a Flight Research Vehicle
  - Validate simultaneous progress toward N+2 goals through technology integration on a vehicle testbed
    - Gain understanding of technology interdepencies/interactions and hardware integration issues
    - Ability to validate multiple off-nominal data points through full envelope testing
    - Flight Reynolds number with real world effects
  - Produce and disseminate high quality data for technology characterization and design method validation
  - Collect actual flying qualities, passenger ride quality, and cabin noise data
  - Ability to operate in the National Air Space for integration Airspace/Operations projects
  - Testbed for future technology concepts including propulsion systems
- AN IDEA ....

Baseline Aircraft

Embedded Engine

Advanced Engine Technology

Concluding Remarks

- Explore/demonstrate the feasibility, benefits, and risks of vehicle concepts and enabling technologies identified to have potential to mitigate the impact of aviation on the environment
- Expand viable and well-informed trade space for vehicle design decisions enabling simultaneous realization of National noise, emissions, and performance goals; identify challenges for foundational research
- Alternative configurations w/ advanced technology will be needed to simultaneously achieve the N+2 goals; technologies will be broadly applicable and tradable
- Systems research in relevant environment

Acronyms and Abbreviations

AAW	Active Aeroelastic Wing
ACCA	Advanced Composite Cargo Aircraft
ACEE	Aircraft Energy Efficiency
ACT	Advanced Composite Technology
ACTE	Adaptive Compliant Trailing Edge
AFC	active flow control
AFFDL	Air Force Flight Dynamics Laboratory
AFRC	Armstrong Flight Research Center
AFRL	Air Force Research Laboratory
AirSTAR	Airborne Subscale Transport Aircraft Research
AMELIA	Advanced Model for Extreme Lift and Improved Aeroacoustics
ANOPP	Aircraft Noise Prediction Program
APU	auxiliary power unit
ARC	Ames Research Center
ARMD	Aeronautics Research Mission Directorate
ASC	axial stage combustor
ASCR	Advanced Subsonic Combustion Rig
ASEB	Aeronautics and Space Engineering Board
ASM	Advanced Stitching Machine
ASP	Airspace Systems Program
AST	Advanced Subsonic Technology
ASTAR	Airborne Spacing for Terminal Arrival Routes
ATDC	advanced technology development compressor
AVC	Advanced Vehicle Concepts
BART	Basic Aerodynamic Research Tunnel
BPR	bypass ratio
BVID	barely visible impact damage
BWB	blended wing body
CAD	computer-aided design
CAEP	Committee on Aviation Environmental Protection
CFD	computational fluid dynamics
CLEEN	Continuous Lower Energy Emissions and Noise
$C_{L\,\max}$	maximum lift coefficient

CMC	ceramic matrix composite
CML	continuous mold line
COLTS	Combined Loads Test System
COTS	commercial off-the-shelf
CRJ	Canadair Regional Jet
DLL	design limit load
DOD	Department of Defense
DRE	discrete roughness element
DUL	design ultimate load
EBC	environmental barrier coating
EDS	Environmental Design Space
EIS	entry into service
EPNdB	effective perceived noise levels measured in decibels
ERA	Environmentally Responsible Aviation
ES	engineered surface
FAA	Federal Aviation Administration
FAP	Fundamental Aeronautics Program
FEGV	fan exit guide vane
FEM	finite element model
FENoRFins	Flap Edge Noise Reduction Fins
FLEXSEL	FLEXible Side-Edge Link
FLOPS	Flight Optimization and Performance Sizing
FPR	fan pressure ratios
GE	General Electric
GPS	Global Positioning System
GRC	Glenn Research Center
GTF	geared-turbofan
GVT	ground vibration testing
HARV	High-Alpha Research Vehicle
HPC	high-pressure compressor
HWB	hybrid wing-body
IAM	Insect Accretion Mitigation
IASP	Integrated Aviation Systems Program
ICAO	International Civil Aviation Organization
IPB	Internal Pressure Box
IRAD	Independent Research and Development
ISRP	Integrated Systems Research Program
ITD	integrated technology demonstration
KDP	key decision point
LaRC	Langley Research Center
L/D	lift-to-drag

LDI	lean direct injection
LFC	laminar flow control
LMSW	Lockheed Martin Skunk Works
LSAF	Low-Speed Aero Acoustic Facility
LTA	large twin-aisle
LTO	landing and takeoff
MAW	mission adaptive wing
MBB	Multi-Bay Box
MTOW	Maximum Takeoff Weight
NACA	National Advisory Committee for Aeronautics
NAF	NASA Auralization Framework
NAS	National Airspace System
NextGen	Next Generation Air Transportation System
NDI	non-destructive inspection
NFAC	National Full-Scale Aerodynamics Complex
NLF	natural laminar flow
NOx	nitrogen oxide
NPSS	Numerical Propulsion Simulation System
NRA	NASA Research Announcement
NRC	National Research Council
NTF	National Transonic Facility
OGA	Other Government Agency
OML	outer-mold-line
OPR	operating pressure ratio
OTR	over-the-rotor
P&W	Pratt & Whitney
PAA	Propulsion-Airframe Aeroacoustic
PAI	Propulsion-Airframe Integration
P-mpg	passenger miles flown per gallon of fuel expended
PRSEUS	Pultruded Rod Stitched Efficient Unitized Structure
PSC	preferred system concept
psia	pounds per square inch absolute
RFI	Request for Information
RFI	resin film infusion
RMPn	Risk Management Panel
ROLD	Reactive Orthotropic Lattice Diffuser
RQL	rich quench lean
SBIR	Small Business Innovation Research
SCRAT	Subsonic Research Aircraft
SCW	supercritical wing
SFC	specific fuel consumption

SFW	Subsonic Fixed Wing
SiC/SiC CMC	silicon carbide/silicon carbide ceramic matrix composite
STV	subscale test vehicle
SUGAR	Subsonic Ultra Green Aircraft Research
SV	soft vane
TAPS	twin annular premixing swirler
TAW	tube-and-wing
TFA	Technical Focus Area
TPS	turbine-powered engine simulator
TRL	Technology Readiness Level
TSFC	Thrust Specific Fuel Consumption
UDF	un-ducted fan
UEET	Ultra-Efficient Engine Technology
UHB	ultra-high-bypass
UTRC	United Technologies Research Center
VCK	variable-camber Krueger
VFR	visual flight rules
VSI	Vehicle Systems Integration
WATE	Weight Analysis of Turbine Engines
XVT	experimental vehicle testbed

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