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Workshop Report On Green Aviation

Authors:

Dr. Stephanie Langhoff
Chief Scientist
NASA Ames Research Center, Moffett Field, California

Dr. Thomas Edwards
Director of Aeronautics
NASA Ames Research Center, Moffett Field, California

Dr. Ajay Misra
Acting Chief of the Structures and Materials Division
Glenn Research Center, Cleveland, Ohio

Dr. Anthony Strazisar
Chief Scientist
Glenn Research Center, Cleveland, Ohio

Dr. Jih-Fen Lei
Director of Research and Technology
Glenn Research Center, Cleveland, Ohio

Dr. John Cavolowsky
Acting Director of the Airspace Systems Program Office
NASA Headquarters, Washington D.C.

Vicki Crisp
Director of Aeronautics
Langley Research Center, Langley, Virginia

Report of a workshop
sponsored by and held at
NASA Ames Research Center
Moffett Field, California
on April 25-26, 2009

November 2009

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Executive Summary

A "Green Aviation" weekend workshop was held at NASA Ames Research Center on April 25–26, 2009 to stimulate dialog and foster collaboration among the nation's aviation and energy technologists. Approximately 80 representatives from government, industry, and academia were in attendance. The workshop was organized into three serial sessions on advanced transportation concepts, advanced propulsion systems, and operational concepts, followed by three parallel sessions on technology priorities, organizational strategies, and metrics. The serial sessions opened with an overview talk on the relevant NASA activities, followed by shorter technical talks relevant to the session's theme. Ample time was provided for discussion following each presentation. The program for the workshop is included in the report.

The cornerstone of NASA's current effort in "Green Aviation" is the Subsonic Fixed Wing (SFW) Project in the Fundamental Aeronautics Program and the newly initiated (to start in FY10) Environmentally Responsible Aviation (ERA) Project in the Integrated System Research Program (ISRP). For the SFW project, the focus is on developing concepts and technologies for enabling dramatic improvements in noise, emissions and performance. The goal of the ERA project is to increase the technology readiness level (TRL) of promising concepts identified in the SFW project and conduct system level experiments at sub-component, component, and aircraft level to identify integration challenges and verify various corners of the design trade space. To keep emissions at or below current levels with the projected growth in aviation will require not only the technology enhancements from the SFW and ERA projects, but will also require improvements in air traffic management and the introduction of low-carbon fuels. The workshop was forward looking and focused on the longer-term options that could provide breakthroughs in meeting aggressive noise and emissions reductions.

To reach the SFW level metrics for the next generation aircraft will require innovative configuration concepts such as hybrid wing body (HWB) transports and advanced aerodynamic concepts for drag reduction, such as laminar flow control. In addition to airframe improvements, advances in engine technology are needed. Even more revolutionary airframe and propulsion concepts are needed to reduce noise and emissions and to increase fuel efficiency. There was general consensus that alternative low-carbon fuels will have to be introduced to reach future CO_2 emission metrics, particularly as a pathway to achieving carbon-neutral aviation growth beyond the N+3 timeframe.

There are some aviation systems that are inherently green, such as airships and electric aircraft. Airships represent an "unexploited" air transportation system that is capable of carrying large payloads economically. In addition to their freight applications, they are potentially excellent platforms for research into green aviation. The Volterra, an environmentally friendly vertical takeoff and landing (VTOL) concept that won the 2008 American Helicopter Society student design competition, demonstrates what is possible when "green" is a key design metric. The Volterra compares favorably with other helicopters in its class for cruise speed, endurance, range, and acquisition price, but has remarkably lower specific fuel consumption and operating costs.

Short field take-off and landing aircraft with significantly higher performance and reduced noise is an enabling technology for a greener, more efficient airspace system. Cruise efficient short take-off and landing (CESTOL) fixed-wing aircraft and rotary wing civil tiltrotor (CTR) can improve airspace efficiency by expanding and optimizing the number of takeoff and landing "locations" available to move passengers and cargo. By developing technologies that can contain the noise to the airport boundary, such aircraft can enable the use of smaller airports in a metroplex concept.

Electric aircraft and helicopters were the topic of several presentations at the workshop. The challenge is that electrochemical energy conversion processes such as primary batteries and fuel cells currently have volumetric energy densities that are far less than current jet fuels. Furthermore, the gravimetric power densities (kW/kg) of batteries and fuel cells are significantly lower (order of magnitude) than gas turbine engines. The weight penalties associated with battery and fuel cell propelled airplanes currently restricts the use of such energy conversion processes to small planes, such as one-seater recreational personal air vehicles. Commercial viability of electric aircraft for large airplanes will require significant advances in many technology areas, which include increasing gravimetric and volumetric power density of fuel cells and batteries and developing lightweight hydrogen storage systems. There are currently several small electric aircraft prototypes that are flying and that are excellent test beds for new technology demonstration. Green aviation prizes help spur the development of ultra-efficient, useful and safe new electric aircraft. There were discussions of making the Green Flight Challenge an annual event.

The impetus for looking at alternate propulsion systems is that while gas turbine efficiency has been increasing with time, it is clear that to achieve carbon-neutral growth or to reduce CO_2 will require the use of low-carbon fuels. Biofuel development is progressing rapidly, and the primary issues for aviation are interoperability with current fossil fuels ("drop-in" fuels) and net emissions characteristics in the life cycle of converting and application of biofuel. A number of possible biofuel sources were discussed, including halophytes, which are saltwater/brackish water tolerant plants. In the longer term, algae offer considerable potential as a feedstock. A new concept for growing algae in the ocean was described. This has the potential to avoid some of the problems with ground-based algae bioreactor installations.

Improvements in operational procedures such as optimizing ground operations, maximizing throughput by increasing runway capacity, and airportal and metroplex integration also help reduce emissions as a result of reduced delays and more efficient routes. Continuous decent arrivals where aircraft are flown with engines "idle" from high altitude to landing is already being implemented as a principal way to reduce fuel use. Intelligent control is being applied to make green aviation better by improving performance, safer by providing better and more consistent handling qualities and reducing pilot work load, and less expensive by using plug and play avionics and using system modeling and analytic redundancy.

Several other innovative ideas were presented at the workshop. The application of predictive game theory to green aviation was demonstrated, both as a means to optimize outcomes such as fuel burn, and as a means for distributed system control. A novel means of doubling the lift to drag ratio of conventional fixed-wing aircraft using a full span truss-braced wing design was discussed. Another futuristic concept using turbo-electric distributed propulsion on a hybrid wing body aircraft was presented as a means of getting most of the way to the N+3 metrics. Recent advances in low energy nuclear reactions (LENR), with potential to yield energy densities of 4000 times that of jet fuel, could be of interest.

In summary, the workshop attendees recommended that the Aeronautics Research Mission Directorate continue to lead the aviation community by *(1)* setting goals for green aviation in the near, mid, and long term that are consistent with policy and stated objectives of the current administration; *(2)* establishing a diversified portfolio of R&D investments, supported by system studies that quantify risks and benefits; *(3)* providing a continuing forum for communication and interchange by means such as websites, workshops, and wikis; *(4)* offering a broader set of technology alternatives for the aviation industry to evaluate for the future such as vehicles, propulsion/power systems, fuels, and operational concepts; and *(5)* stimulating innovation and creativity through open-ended solicitations and incentive-based mechanisms. A working group was established at the end of the workshop to continue the momentum and to consider the possibility of holding a follow-on workshop in April of 2010.

Workshop Report On
Green Aviation

Dr. Stephanie Langhoff[1], Dr. Thomas Edwards[1], Dr. Ajay Misra[2], Dr. Anthony Strazisar[2], Dr. Jih-Fen Lei[2], Dr. John Cavolowsky[3], and Vicki Crisp[4]

I. Introduction

Recognizing the importance of the impact of growth of aviation on climate change, a workshop entitled "Green Aviation" was held at Ames Research Center on 25–26 April 2009. It is part of a series of informal weekend workshops hosted by Center Director Pete Worden. Previous workshop reports can be found at http://event.arc.nasa.gov/main/index.php?fuseaction=home.reports. The Program Organizing Committee, which included Dr. Stephanie Langhoff (chair), Dr. Thomas Edwards, Vicki Crisp, Dr. Jih-Fen Lei, Dr. Ajay Misra, David McBride, Dr. John Cavolowsky, and Dr. Anthony Strazisar, was responsible for the selection of speakers. A key purpose of the workshop was to bring the nation's aviation and energy technologists together to explore innovative technologies that could promise the greatest environmental benefit. Approximately 80 persons representing the government, industry, and academic communities attended (see enclosed list of attendees).

The workshop endeavored to answer three key questions:

1. What aspects of aviation operations and the environment do we need to understand better in order to make informed technology investment decisions?
2. What technologies promise the greatest environmental benefit, and what are the key technical challenges to realizing them?
3. How can the community—government, industry, and academia—best coordinate efforts to move forward?

The workshop was divided into three major sessions: advanced air transportation concepts, advanced propulsion systems, and operational procedures, concepts, and business models. The focus of the workshop was on mid- to far-term solutions building on the current NASA Aeronautics Research Mission Directorate Subsonic Fixed Wing (SFW) and newly initiated Environmentally Responsible Aviation (ERA) projects.

[1]Ames Research Center, Moffett Field, California
[2]Glenn Research Center, Cleveland, Ohio
[3]NASA Headquarters, Washington D.C.
[4]Langley Research Center, Langley, Virginia

II. Current NASA Program

The workshop began with an overview of the Fundamental Aeronautics – Subsonic Fixed Wing (SFW) project and the new Environmentally Responsible Aviation (EVA) project by Dr. Fay Collier, Principal Investigator for the SFW Project. The National Aeronautics Research and Development (R&D) policy follows from the Executive Order signed December 2006, which identifies the environment as one of the seven basic principles to follow for the U.S. to "maintain its technological leadership across the aeronautics enterprise." To meet the very aggressive goals of the Obama administration on CO_2 emission reductions from U.S. aviation will require improvements in aircraft efficiency, national airspace operational efficiency, and the use of zero carbon fuels or alternate fuels (such as biofuels that have the potential for achieving carbon neutrality at the overall system level).

The SFW system level metrics for the next three generations of technology—N+1 (2015), N+2 (2020), and N+3 (2025) are shown in figure 1. The N+1 performance goals are to mature technology to enable reduced noise by 32 decibels (dB) below the Stage 4 goals set in 2006, to enable reduced landing and takeoff NO_x emissions by 60% compared with the Committee on Aviation Environmental Protection (CAEP) 6 standard, and to enable reductions by 1/3 in aircraft fuel burn and field length performance. Taking Stage 3 (Stage 4 + 10dB) noise standards as baseline, the N+1 noise metric has a footprint of only 8.4% of baseline, far quieter than the current generation of quietest aircraft (29% of baseline). A detailed system analysis has been performed to determine how to best achieve the 33% reduction in fuel burn. It includes advances in propulsion, materials, and structures, but also the implementation of advanced aerodynamic technologies, specifically laminar boundary layer flow over 67% of the upper wing and 50% of the lower wing, tail, and nacelles. Using laminar flow achieves a 16.8% reduction in total vehicle drag for the N+1 advanced small twin prototype.

Dr. Collier provided an overview of the work going on in the SFW Project on ultra high bypass (UHB) engines, the work with Pratt and Whitney on the geared turbofan concept, and with General Electric on the open rotor propulsion concept. He provided an historical overview of the work that has been done on hybrid laminar flow control (HLFC), and described the ongoing work to characterize LFC on a swept wing with distributed roughness. The objectives of the laminar (boundary layer) flow research in the Langley National Transonic Facility (NTF) were also discussed.

The N+2 (2020) goals are to develop technology to enable reduced noise by 42 dB below Stage 4, to enable reduced aircraft fuel burn by 40%, and to enable reduction of the performance field length by 50%. To realize these goals, the SFW project is looking at alternative configuration concepts such as the N+2 advanced "tube-and-wing" and hybrid wing body (HWB) transports. Previous studies have shown that to simultaneously achieve the N+2 noise and fuel burn goals relative to a "777-200"-like vehicle (reference fuel burn = 237,100 lbs) will require not only a new configuration such as HWB with advanced materials, but also will require laminar flow over the wing, nacelle, and body, noise reduction from engine shielding, and embedded engines with a boundary

SFW System Level Metrics

...technology for dramatically improving noise, emissions, and performance

CORNERS OF THE TRADE SPACE	N+1 (2015)*** Generation Conventional Tube and Wing (relative to B737/CFM56)	N+2 (2020)*** Generation Unconventional Hybrid Wing Body (relative to B777/GE90)	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)	55 LDN (dB) at average airport boundary
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

Figure 1. The SFW system level metrics for the next three generations of technology—N+1 (2015), N+2 (2020), and N+3 (2025)—is shown above.

layer ingesting (BLI) propulsion system. The best estimate for the advanced tube and wing configuration was a noise reduction to Stage 4–26 dB. To achieve these long-term N+2 goals, work has already begun on critical technologies such as low-speed flight controls, non-circular pressurized fuselage structures, and techniques for measuring and modeling noise characteristics.

The N+3 (2025) performance goals are to develop technology to enable a 55 dB reduction relative to Stage 4—better than 75% reduction in emissions, 70% reduction in fuel burn, and the use of metroplex airports to enable use of concepts such as short-takeoff and landing (STOL) vehicles. Revolutionary new approaches are required to reach these goals. The SFW project is in the stage of identifying airframe and propulsion concepts and corresponding enabling technologies to achieve these goals. A recently released NASA Research Announcement (NRA) asks the proposers to develop a future scenario for commercial aircraft operators in the 2030-35 timeframe, and then to develop advanced concepts to fill a need in this scenario. The proposer must address the technology risks and establish the credibility and traceability of the proposed advanced concept. A wide variety of concepts will be considered under the NRA. Dr. Collier discussed a few of the revolutionary designs that are being considered in the N+3 study. He provided an overview of the truss-braced-wing (TBW) subsonic transport aircraft concept and the distributed turboelectric propulsion vehicle. These two concepts are discussed in more detail later in the report.

Dr. Collier ended his presentation by providing an overview of the alternative fuels research that is ongoing in the SFW project. The overarching goals are to characterize Fischer-Tropsch (FT) and biomass fuels for gas turbine engine applications against American Society for Testing and Materials (ASTM) standards, evaluate engine and aircraft performance and emission through ground and flight tests, and to develop flexible combustor designs that can take full advantage of alternative fuels. He presented the SFW program's alternative fuels roadmaps for both biofuels and for producing coal to liquid (CTL) and gas to liquid (GTL) using the FT process. Finally he discussed the prospects of using hydrogen fuels. Further details about the use of alternative fuels are presented in section V.

III Advanced Aircraft Concepts
Current Activity for Hybrid Wing Body

Ron Kawai, blended wing body (BWB) propulsion manager for Boeing Research and Technology, discussed the current activity for the hybrid wing body (HWB)—its generic term for the BWB. Boeing has been studying BWB aircraft for years, in the belief they could burn 20–30 percent less fuel than conventional tube-and-wing airliners because of the aerodynamic and structural efficiency of the flying-wing type design. However, further improvements to the configuration are needed to reduce noise and fuel burn to meet the combined N+2 goals (40 percent less fuel burn and noise reduction to 42 dB below Stage 4).

Boeing, in partnership with NASA, is designing a low noise configuration for wind tunnel testing by NASA in late 2010. The initial configuration for the HWB, called the N2A, has podded engines mounted above the aft fuselage. The wind tunnel model will be adaptable for a N2B with embedded engines. The N2B would have its engines embedded in the upper fuselage and could ingest the turbulent boundary layer flowing over the airframe, thereby reducing drag with a better structural integration to reduce weight. Drag can be further reduced in both designs by incorporating hybrid laminar flow control (HLFC).

To further reduce HWB fuel burn, Boeing is investigating efficient propulsion/airframe integration (with low noise), boundary layer ingestion, and highly efficient propulsion cycles using the open rotor. They are addressing the fundamental structural challenges of pressurization and producibility by using a new structural concept called the pultruded rod stitched efficient unitized structure (PRSEUS). The concept departs from conventional laminated composite design practices, manufacturing processes, and tooling techniques to achieve breakthrough levels of structural performance and lower manufacturing costs.

He noted that flight tests will be required to test effects that cannot be simulated in a wind tunnel, such as dynamic effects of a large scale HLFC system, low flyover noise validation to observers, propulsion dynamic operability (such as the performance of the boundary layer ingestion inlets and open rotors), PRSEUS manufacturing scale-up to validate full-scale structures, and post stall recovery using the ultra-high by-pass ratio engines on the HWB.

Ron Kawai ended his presentation by talking about the feasibility of using hydrogen produced from either a nuclear or renewable source. Based on the combustion heating value of liquid hydrogen (LH_2) versus Jet A, he made the case that LH_2 has significant potential for large long-range aircraft. He presented an “out of the box” vision for 2040–2050 using a dual fuel concept: nuclear power to generate LH_2 during ground time, takeoff and landing using LH_2, and a LH_2 fuel cell auxiliary power unit for secondary power while providing cooling for superconducting electric power systems, such as the turboelectric propulsion.

The Volterra—Environmentally Friendly VTOL Concept Design

Brandon Bush and Richard Sickenberger, two graduate students at the University of Maryland, described the Volterra, an environmentally friendly VTOL concept. This concept arose out of the 2008 American Helicopter Society (AHS) student design competition. The 2008 competition sponsored by Eurocopter did not need to meet any extraordinary performance requirements, but it had to be extremely "green" in all aspects, from manufacturing of raw materials to the recycling of the helicopter—"Cradle to the Grave". The motivation for the competition came out of the European Union's Clean Sky Program. The program's defined challenges were to reduce by the 2020 timeframe, fuel consumption and CO_2 emissions by 50%, external noise by 80%, NO_x by 80%, and improve life cycle energy costs. It was clear from the outset that no single technology improvement would get the 50-80% reductions in environmental impact factors in such a short time frame. Those levels of improvement would have to come from the aggregation of smaller improvements in multiple systems spread out across the entire life cycle of the helicopter.

The Volterra (shown in figure 2) has four main rotor blades and a fan-in-fin or fenestron tail rotor. The fan-in-fin design was primarily chosen to reduce noise. The fan-in fin incorporates unevenly spaced rotors to spread noise over the frequency spectrum. The Volterra compares favorably with other helicopters in Volterra's class for cruise speed, endurance, range, and acquisition price, but has remarkably lower specific fuel Consumption (SFC) and significantly lower operating costs.

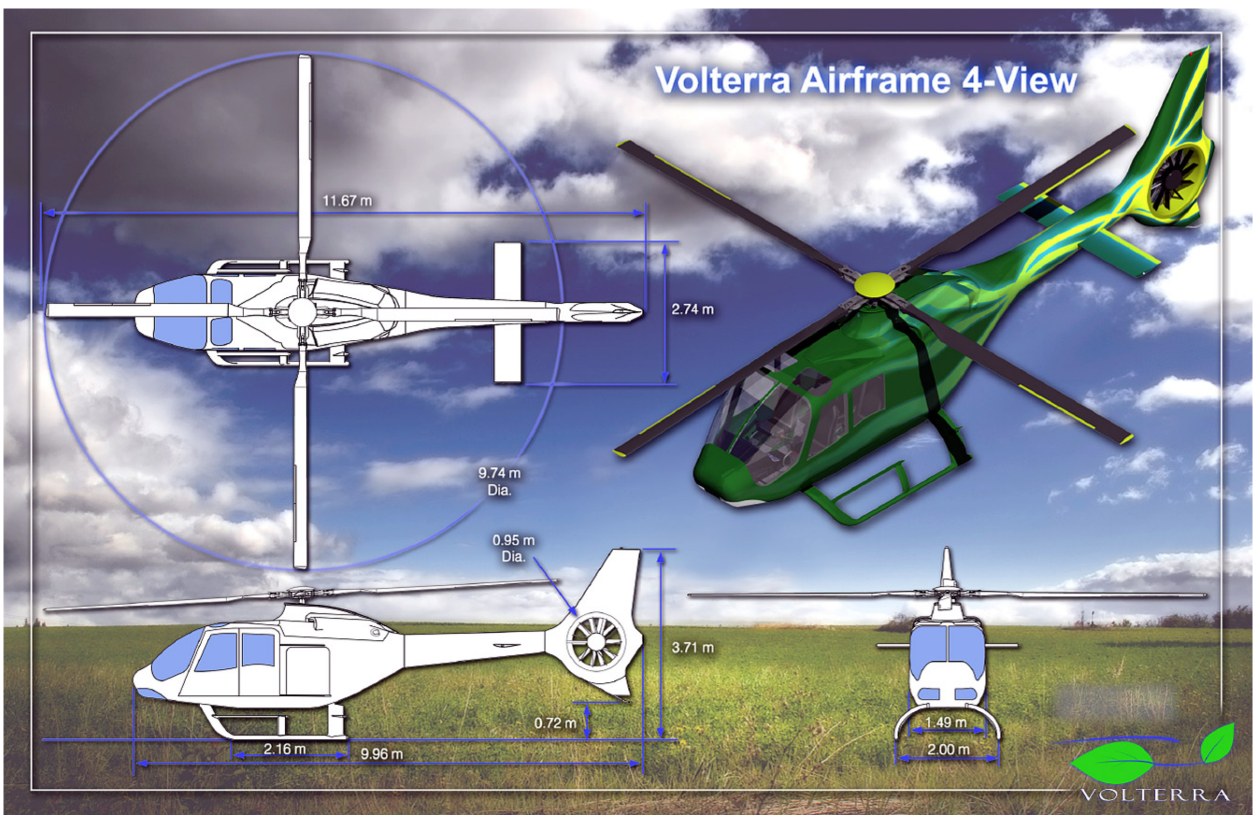

Figure 2. The Volterra- environmentally friendly VTOL concept design shows four main rotor blades and a fan-in-fin or fenestron tail rotor.

The rest of the presentation was focused on the enabling technologies that led to a helicopter with low SFC and acoustic emissions. The materials selection was based on the full life cycle costs of materials production and manufacturing. This led to a structure that was 65% thermoplastic composite and 28% lightweight aluminum. There was minimal use of titanium due to the high CO_2 emissions during production. The main rotor blades had a Nomex honeycomb core with a graphite composite skin. An optimal main rotor configuration from a noise perspective was found by solving the Ffowcs-William-Hawking equation. Removable trailing edge flap modules were used to further reduce noise and vibration.

The powerplant is an opposed-piston/opposed-cylinder design engine, which is cost effective, highly efficient, cleaner burning, and both multi-module and multi-fuel versatile. This produces an "all electric" helicopter design that eliminates environmentally unfriendly hydraulic fluids. The final result is a multi-purpose military/civilian helicopter with performance that meets or exceeds that of similar current helicopters, while offering the operators unparalleled energy efficiency at all stages of the helicopter's life cycle.

Airships as One Path to a Green Aviation System

Ron Hochstetler, Deputy Program Manager for the SKYBUS unmanned airship program at Science Applications International Corporation (SAIC), addressed the potential of airships in a green airspace. Airships represent an "unexploited" air transportation system due, in part, to differences with conventional aircraft. Airship propulsion requirements are many times less than what is required for jet transports with the same disposable lift. Airships are capable of payloads of 200 tons or more and can be economical to operate. They are displacement vehicles so they perform best at low altitudes. Thus airships can provide additional air transport capacity, and can increase capacity in the existing transport system.

Airships fall into two general classes, fully buoyant and semi-buoyant. They also fall into two general categories: long distance carriers that are optimized for speed and low drag, and short distance cranes optimized for precision lift and payload placement. Modern airship designs today take advantage of high strength-to-weight synthetic fabrics, composite material construction, computerized flight controls, semi-automated ground handling, and vectoring propellers. This translates into operational advantages such as mobility and very limited ground crew operations. To mitigate weather issues, a modeling tool, "OMEGA", has been developed at SAIC to provide weather optimized route plans to multiple airships on a continuous basis.

The most advanced large airship program to date was CargoLifter, a German venture to manufacture 160 metric ton lift cargo ships. The company ended due to monetary problems, but did succeed in developing new insights into the design and manufacture of large cargo airships. Transport airship applications include moving "project freight" that is either very large or heavy for short distances and long distance freight transport between multi-modal shipping countries or in areas that have poor transportation infrastructure (developing countries) or areas that are remote or inaccessible. One of the major freight applications is oil and gas pipeline construction, since 90% of the cost is moving heavy equipment, materials, and consumables up and down the project right of way. Another major application is vertical lift for precision positioning, such as installing pre-fabricated windmills, electrical grid installations, and high-speed rail components.

Airships could also be used as a platform for research into green aviation propulsion systems and for operational research into lighter-than-air transport applications. An airship would allow the in-flight development and testing of new internal combustion engines that can burn alternative fuels. Hydrogen fuel cells could be used to power electric propulsion motors. The airship would permit safe usage of hydrogen fuel cells, because the non-flammable helium that surrounds the airship hull could contain any leakage. Large photovoltaic arrays could be installed on the airship envelope exterior and could provide a secondary power source for airship systems. There could be a design point where a large airship could become energy independent. Two of the state-of-the-art airships (the Zeppelin N 07 and the 138S) are shown in figure 3.

There is no doubt that airships could be made to be exceptionally green. Ron Hochstetler discussed efforts to develop the Z-Prize, an international competition for self-funded teams to design, build, and race their cargo ships. The goals of the Z-Prize are to create several affordable heavy lift airship designs, demonstrate practical "low-to-no" CO_2 air transport, and create a new and vibrant aviation technology sector.

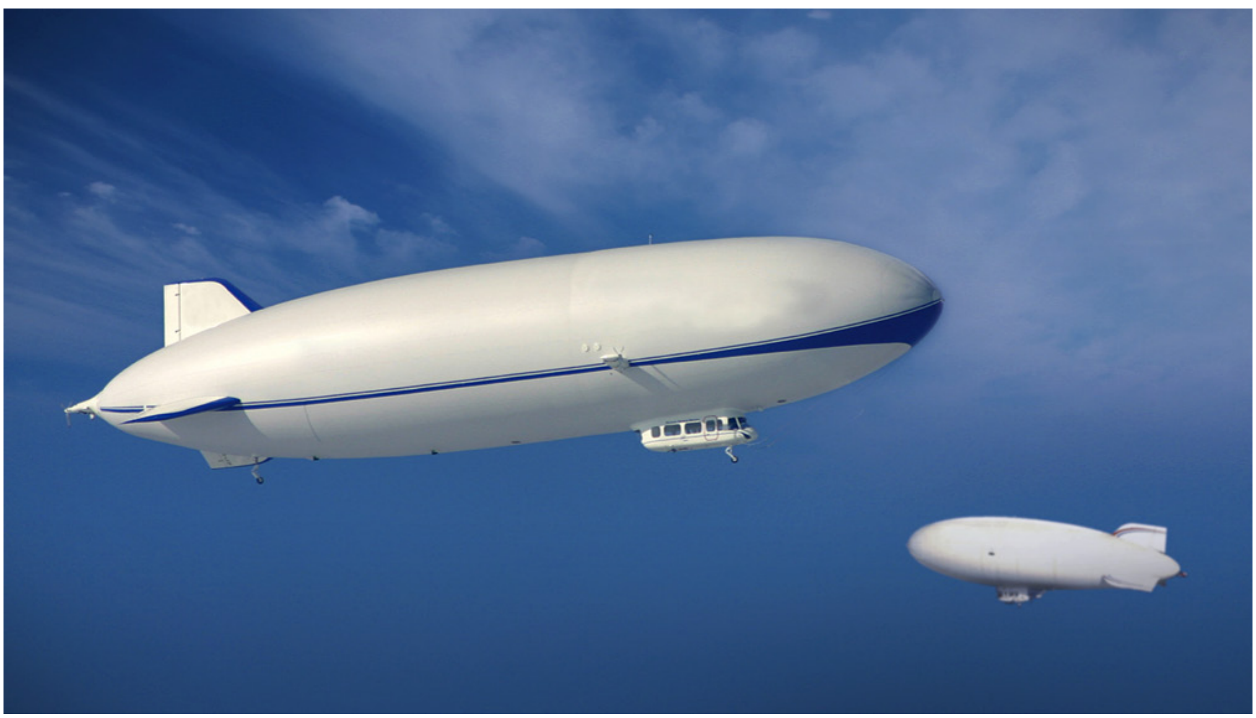

Figure 3. Two of the state-of-the-art airships (the Zeppelin N 07 and the 138S) are shown. Published by permission of Ron Hochstetler (SAIC).

Short Field Take-Off and Landing Performance as an Enabling Technology for a Greener, More Efficient Airspace System

Craig Hange, Associate Project Manager for the Subsonic Fixed Wing Project, discussed short-field takeoff and landing (STOL) performance as an enabling technology for a greener more efficient airspace. Efficiency comes from expanding and optimizing the number of takeoff and landing "locations" available to move passengers and cargo. Aircraft fall into two general categories: cruise efficient short takeoff and landing (CESTOL) fixed-wing aircraft with >0.8 mach cruise and 3000 ft field length, and civil tiltrotor (CTR), which are rotary wing aircraft with a 300–350 knot cruise performance and ~1500 ft "protection" zone on approach and departure.

There are several requirements for STOL aircraft to be incorporated into the airspace. First and foremost is that the use of STOL aircraft must not impede conventional aircraft. In addition, the STOL runway or vertiport needs to be unused or underutilized to increase the number of operations at an airport. The CESTOL/CTR aircraft will be most useful in major, delay impacted hub airports. As shown in figure 4, the STOL/CTR aircraft avoids the airspace and runways needed by conventional traffic, thereby insuring simultaneous and non-interfering operations. The STOL/CTR aircraft opens up the satellite airports in the "Metroplex" without disturbing the communities that

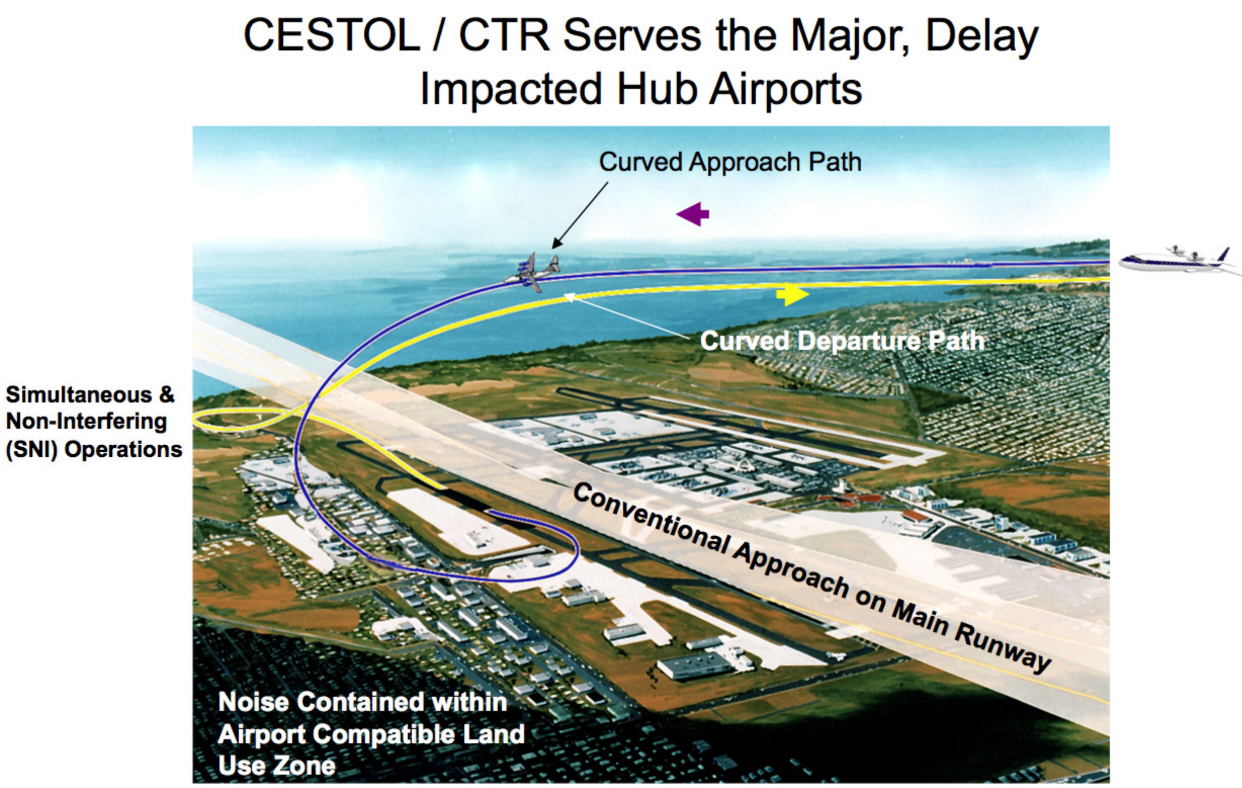

Figure 4. The CESTOL/CTR aircraft avoids the airspace and runways needed by conventional traffic, thereby insuring simultaneous and non-interfering operations.

have been undisturbed in the past by constraining noise within the airport compatible land use zone. Thus both CESTOL and CTR aircraft have the potential for improving airspace capacity and throughput. Greater system capacity reduces delays and thereby saves fuel. Hange showed several examples where fuel could be saved by using underutilized runways.

CESTOL aircraft save fuel not only through short-field performance, but also through efficient cruise performance derived from its cruise speed (M~0.8) and altitude (30,000 ft). It has trans-continental capability, although it is nominally sized for "regional" missions. It can avoid weather problems at lower altitudes, yet doesn't fly too slow to become a bottleneck in the airways. The cruise performance is such as to justify "cruise efficient" in the CESTOL acronym.

The CTR aircraft are being designed for a payload of about 90 passengers, a cruise speed of 300 knots, and a range of 1000 nautical miles. There are a number of technical challenges, e.g., the high cruise speed relative to current rotorcraft, the need to use larger, slower rotors to reduce noise, and the need for a variable speed and high torque drive system. In addition, for rotor or jet-powered aircraft, there are airframe technology challenges and operational issues that occur from sharing the airspace in an unconventional manner. Approaches for dealing with the airframe challenges include using unconventional designs such as HWB, using active flow and flow separation control, using higher bypass ratio and variable cycle engines, and noise shielding and reduction. To overcome the operational challenges, work is ongoing on improving navigation performance, designing steep and spiral descent profiles for noise reduction, improved ground movement and handling, and schedule optimization.

Some of the key conclusions from the talk were that short-field length capable aircraft could increase capacity and reduce delays within the Next Generation Airspace System. However, this will require technology innovations to negate the performance penalties associated with short-field capable aircraft. Finally, a system wide approach will be required to achieve a green benefit of CESTOL and CTR aircraft.

IV. Advanced Propulsion Systems

Dr. Alan Epstein, Vice President for Technology and Environment at Pratt and Whitney, gave the foundational talk in the advanced propulsion systems session. To set the context he noted that aerospace is the largest manufacturing export of the United States, and that aerospace is critically important for both transportation and defense. However, aviation has an impact on the environment at all altitudes. At the ground level NO_x and particulate emission affect local air quality and produce noise; at higher altitudes in the troposphere, emissions such as CO_2 contribute to climate change; and in the stratosphere, engine emission of NO_x and halogens can lead to ozone destruction. Thus one of the overarching goals of NASA's Aeronautics program is to develop technologies that have less environmental impact.

As stated in "The Aero" in January 1911, "the problem of the aviation engine is purely the combination of power and lightness and reliability" is still true today. This has led to the use of high-density fuels and has spurred the evolution of gas turbine efficiency. As shown in figure 5, overall gas turbine efficiency is a product of core thermal efficiency and the product of propulsive times transmission efficiency. Since it is usually more efficient to accelerate a large mass of air by a small amount than to accelerate a small mass of air by a large amount, overall efficiency has continuous-

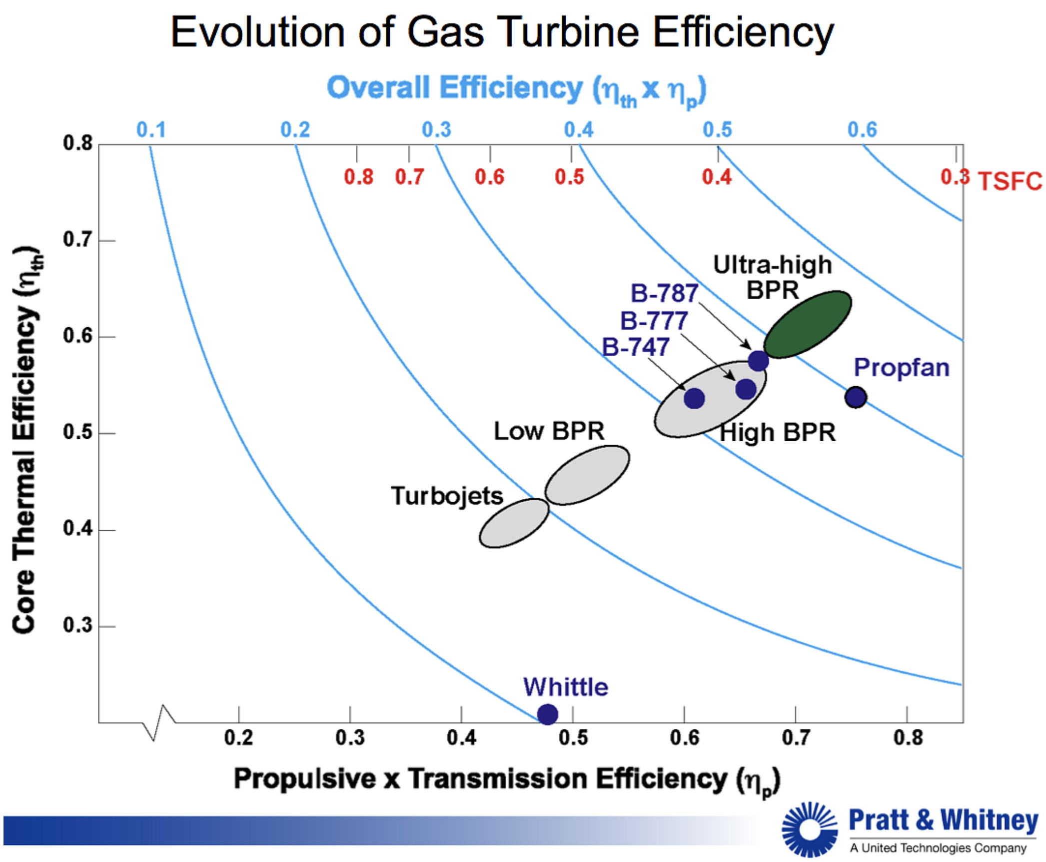

Figure 5. Overall gas turbine efficiency is a product of core thermal efficiency and the product of propulsive times transmission efficiency.

ly improved with the development of higher bypass-ratio (BPR) turbofans. Improved efficiency reduces thrust specific fuel consumption, thereby lessening the environmental impact. Dr. Epstein also showed how gas turbine specific power has increased with engine technologies that lead to higher turbine rotor inlet temperature. Nevertheless, the specific core power in today's engines fall considerably short of ideal Brayton cycle performance. The current state-of-the-art in subsonic transport engines is 50-60% thermal efficiency and 65-70% propulsive x transmission efficiency. Reliability of engines has dramatically increased with time. Current in-flight shut down rate is approximately 2 x 10^{-6} hour, and mean time between overhauls is 8,000–16,000 hours.

Dr. Epstein discussed various scenarios for CO_2 emissions growth with time. Without any reduction measures, CO_2 emissions would be expected to be substantially greater by 2050. Even with ongoing fleet renewal, technology development, and improvements in air traffic management, the CO_2 growth is still significant. Clearly, to achieve carbon-neutral growth or to reduce CO_2 will require the use of low-carbon fuels. This very important fact set the stage for several follow-on discussions of the work on biofuels that has begun at several research centers within NASA.

To set the stage for follow-on discussions of potential alternative fuels, Dr. Epstein discussed the practical energy density of fuels. Shown in figure 6 is a plot of system gravimetric energy density (MJ/kg) versus volumetric energy density (MJ/l) for various fuels. The energy density of fuels such as diesel give them a tremendous advantage over alternatives such as primary batteries, H_2 for

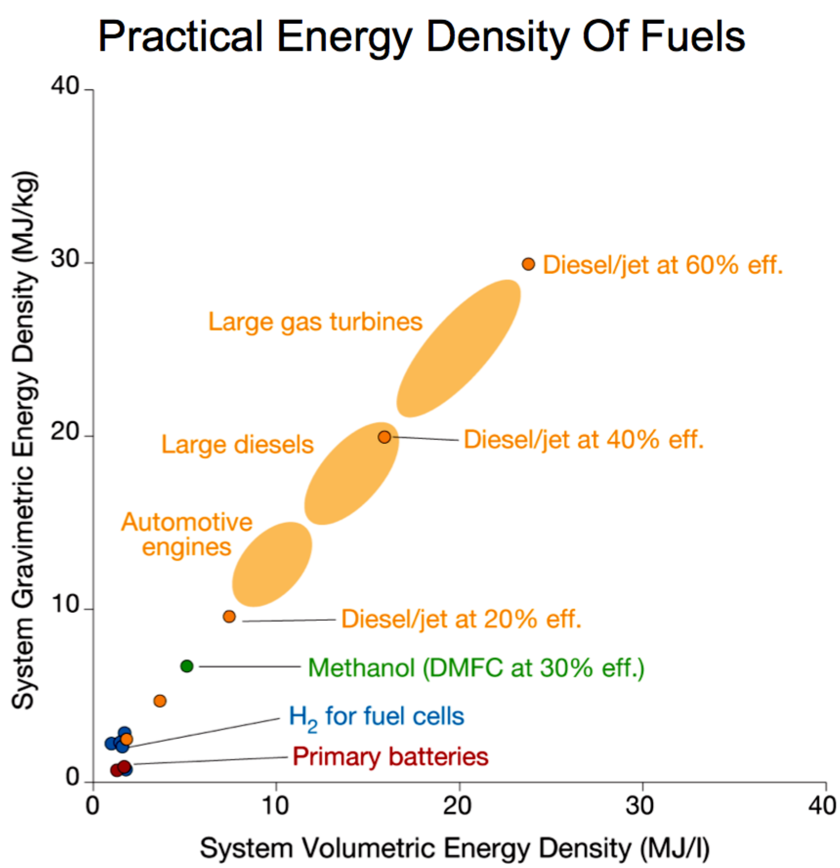

Figure 6. Shown is a plot of system gravimetric energy density (MJ/kg) versus volumetric energy density (MJ/l) for various fuels.

fuel cells, and even methanol in applications such as aircraft where weight is critical. He ended the presentation by talking about some near-term propulsion concepts such as turbofan, single-rotation propeller, and counter-rotating propellers. These have the same fuel burn, but are differentiated by noise and flight speed. Eliminating aircraft noise as a community concern and reducing climate impact are key priorities of the aeronautics program at NASA.

Converging Technologies: The Aviation Green Prize

Dr. Brien Seeley, President of the Comparative Aircraft Flight Efficiency (CAFÉ) Foundation, presented a talk entitled "Converging Technologies: The Aviation Green Prize." The CAFÉ Foundation is a 501c3 non-profit organization dedicated to improving flight efficiency. He first discussed the CAFE Green Flight Challenge (GFC), which is a NASA-funded flight competition to spur the development of ultra-efficient, useful, and safe new aircraft. The prize of $1.65 million will be awarded in the summer of 2011. Some of the aviation prize ideals are that the prize requires multiple advances in green and aeronautical technology, is a showcase that rewards innovation, and is a rallying point for green technology. To qualify for the GFC, the vehicle must be able to achieve 200 passenger miles per gallon equivalent mileage, 100 miles per hour (mph) speed, be capable of a 52-mph stall speed, a 200-mile range, and a 2000-foot takeoff distance over a 50-foot obstacle. In addition, it must have realistic seating and payload, FAA license, acceptable handling qualities, and a ballistic vehicle parachute. These characteristics will require a convergence of technologies to achieve skeletal efficiency and high lift-to-drag (L/D) optimization. A winning aircraft is likely to have high aspect ratio wings, laminar flow over the entire aircraft including the cockpit, a moderate glide ratio, and low braking horsepower without sacrificing speed. The use of solar power is free to all of the contestants.

Since the Green Flight Challenge can be a crucible for combining Greentech advances, a rallying point for university teams, and a thrilling, suspenseful race, Dr. Seeley argued for making this an annual event. For example, the GFC II could be held in 2012 with the same rules except that the aircraft would have to be capable of flying 200 miles, land and "recharge" in less than 2 hours, and then immediately fly another 200 miles.

Turbo-electric Distributed Propulsion

Mr. James Felder, Research Scientist at Glenn Research Center, talked about turbo-electric distributed propulsion on a hybrid wing body aircraft. The hybrid wing body with conventional configuration propulsion can nearly reach the N+3 propulsion metrics of better than 70% reduction in fuel burn and 75% reduction in landing and take-off cycle NO_x emissions. However, advances in propulsion are required to fully meet the goals.

Reductions in fuel burn equate to reductions in fan pressure ratios, which in turn imply larger fan areas. In the hybrid wing body configuration, there are advantages to distributing the propulsion system across the span. Therefore, an optimal configuration uses multiple smaller fans. However, there are disadvantages of having a large number of distributed discrete engines. The best solution is to have a small number of core engines while having a much larger number of distributed fans.

This requires a power distribution system to move power from the core engines out to all the fans. Although it can be done with a mechanical system, the complexity, power loss, and weight issues make this approach nonviable. The innovation is to develop an electrical power transmission system using superconducting electric fans powered by two turbine-engine-driven superconducting electric generators. This provides large amounts of electrical power that can be used to improve fuel efficiency by powering boundary layer suction and blowing air handlers.

The prototype vehicle used in the analysis is the N3-X shown in figure 7 along with the other vehicles that motivated this resulting airframe and propulsion system. The propulsion system consists of two turboshaft engines driving superconducting generators as the power producers, while 14 superconducting motors use that power to drive 14 50-inch fans housed in a very short, continuous fan nacelle. The turbogenerators are placed at the wing tip for reasons of high recovery inlet performance, wing bending moment relief, tip vortex disruption, and safety. The key point is that a turbo-electric transmission system enables large fan areas to be integrated with the hybrid wing body.

Mr. Felder briefly discussed what a N+4 concept aircraft might look like. With the decoupling of power generation and power application, one could consider placing the power generator on the ground. For example, energy as microwaves or lasers could be beamed up from the ground by using the entire lower surface of the vehicle as a receiving surface.

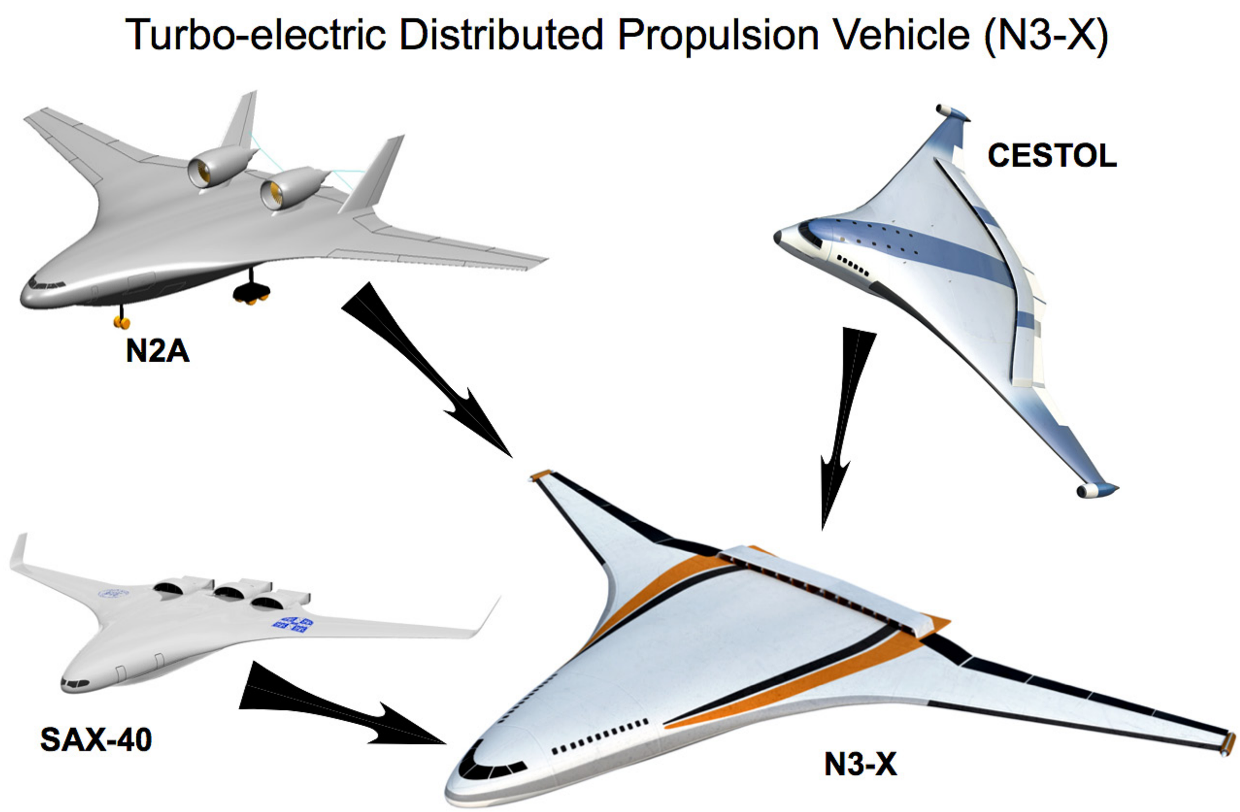

Figure 7. The N3-X is the prototype vehicle that was used in the analysis along with the other vehicles that motivated the resulting airframe and propulsion system.

Electric Airplane Research Program

San Gunawardana, a doctoral student at Stanford University, discussed the joint venture electric airplane research program between Ames Research Center (ARC), Stanford, and private industry. In phase 1, the goal is to build and fly an electric airplane testbed, with flight-testing to begin in October 2009. Key motivations for electric aircraft are that they have zero emissions, dramatically less noise, and potentially lower life-cycle costs and maintenance. The quiet operation of electric aircraft could allow for sustained operation over urban centers. An electric vehicle's low thermal and zero CO_2 emissions could make it an ideal platform for localized environmental data collection.

The project is being implemented in two phases. In the nine-month first phase, the goals are to build a flying laboratory capable of flying 45 minutes on station, at a speed greater than 100 knots, with a payload of 340 lbs (2 people). In the two plus years of the second phase, the project will try to improve the technologies that enhance performance. Longer-term goals include building a second demonstrator electric airplane with greater range, speed and payload capacity. This joint venture is designed to be an incubator and test/validation environment for radical ideas. Some of the technologies that need to be matured include quiet propellers, efficient aero structures, battery energy management systems, and electric aircraft thermal control.

Considerable thought was given to the testbed configuration. After extensive trade studies on airframe, batteries, and electric motors and controllers, the team selected a Pipistrel Sinus airframe, a Panasonic Li-ion battery, and a UQM Technologies 75 kW electric motor. Thus, the testbed starts with commercial off-the-shelf (COTS) components, and then seeks to find experimental alternatives. At the time of the workshop, the project was in the final selection and acquisition of components to build the testbed.

An All Electric Helicopter

Dr. Inderjit Chopra, Director of the Alfred Gessow Rotorcraft Center at the University of Maryland, discussed concepts for an all-electric helicopter. The key advantages of an electric powered helicopter are low emissions and low motor noise. The disadvantage is that battery and motor weight along with unproven technology lead to significant performance penalties compared with existing helicopters. He began by discussing the experience that we have with current fixed wing electric aircraft, such as the Dimona Motor Glider that is powered by both fuel cells and lithium ion batteries. This aircraft is capable of approximately 30 minutes of powered flight. He also discussed the Electraflyer-C single seat electric powered aircraft that has an endurance of 90 minutes.

Most of the current experience with electric helicopters is with small radio controlled models of 10 pounds maximum weight. Maximum endurance is limited to 5-15 minutes by battery capability. Dr. Chopra presented a feasibility study of an all-electric Robinson R-22 helicopter. The piston engine version of this light helicopter has a takeoff weight of 1370 pounds and can carry two passengers at a cruise speed of 96 knots with an endurance of three hours. The total weight of the power plant, transmission, and fuel is 572 pounds. In designing the replacement all electric helicopter, it was assumed that the airframe and rotor system would remain unchanged, while the engine, transmission, and fuel would be replaced with an electric motor and lithium-ion batteries. As shown by the performance comparison in figure 8, the endurance of all electric aircraft configurations falls far short of the piston engine baseline. The key technology challenge is that the energy density of the state-of-the-art battery sources is 0.07 kWh/Kg, whereas an energy density of 1.09 kWh/Kg is required to give the same performance as the baseline piston engine. To bridge this performance gap requires electric power sources with low volume and high energy density, and small low-weight electric motors. Also needed are innovations in vehicle design to produce hybrid vehicles that combine the hover performance of rotary-wing with the forward flight performance of fixed-wing aircraft.

PERFORMANCE COMPARISON

	Number of Passenger	Battery Packs	Take-off Weight, (lb)	Endurance (minutes)
Baseline	1+1	PISTON ENGINE	1300	180
Electric	1+1	4	1115	5.3
Electric	1	4	919.6	6.5
Electric	1	8	1151	10.4
Electric	1	10	1267	11.8

Figure 8. The endurance of all electric aircraft configurations falls far short of the piston engine baseline.

Hydrogenius: Demand for Electric Aircraft

Steffen Geinitz and Len Schumann from the University of Stuttgart in Germany spoke about the "Hydrogenius" concept of an environmentally friendly aircraft. This project started in the Institute of Aircraft Design at the University of Stuttgart under the supervision of Professor Rudolf Voit-Nitschmann. Hydrogenius is a revolutionary project that seeks to introduce fuel cell technology into aviation. The Hydrogenius was developed for and won the Berblinger Competition 2006 sponsored by the city of Ulm, Germany. A major partner in the project is Pipistrel, a Slovenian company that is constructing the composite structures of the aircraft (based on their Taurus aircraft).

The Hydrogenius was designed as a two-seated airplane using electrical propulsion systems with the goal of being comparable in usability and performance with conventional aircraft. As shown in the drawing of the Hydrogenius in figure 9, the motor is positioned in the vertical tail. This configuration takes advantage of being able to separate the energy and propulsion generation to optimize aerodynamic performance. The vehicle is designed for the low energy density storage of hydrogen as well as the low power density of batteries and fuel cells. Hydrogenius uses two modular propulsion systems—the first one is a fuel cell system and the second, a lean battery system. The power output of both systems is approximately 70 kW, which is necessary to achieve a short take-off field length and climb performance to improve safety. The Hydrogenius is comparable in performance to conventional aircraft in maximum continuous cruise speed, maximum climb rate, and range, while using significantly less energy.

In addition to electric aircraft's advantages of being more efficient and being more environmentally friendly, there may be advantages in safety as well. Steffen Geinitz showed the accident statistics for small aircraft in Germany and the United States. Approximately 30% of accidents can be related to technical failures, and from that 30% more than 70% can be directly related to the propulsion system. The use of electrical propulsion offers some possibilities to avoid or abate the consequences of engine failure.

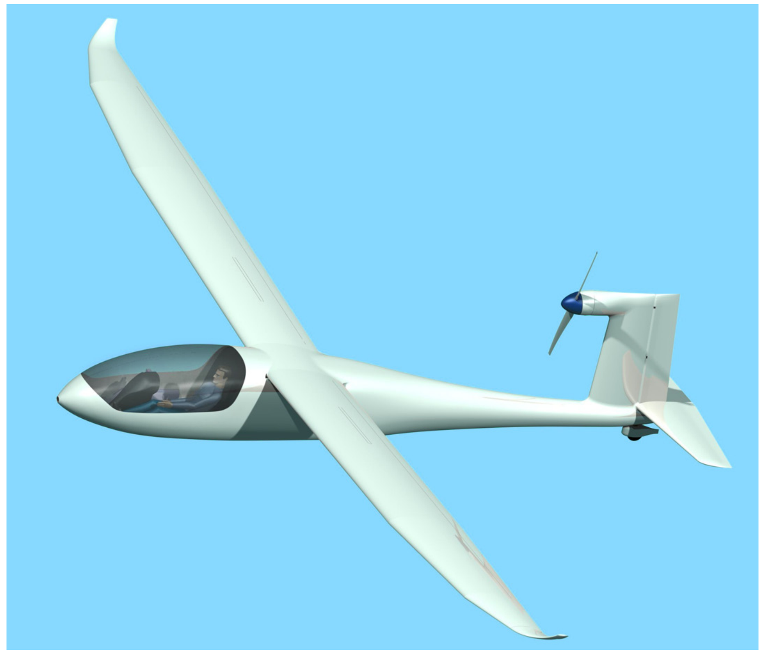

Figure 9. An illustration of the Hydrogenius.

Synergistic Aviation Electric Propulsion

Dr. Mark Moore of Langley Research Center spoke about Langley's program to investigate synergistic electric propulsion integration. They are attempting to overcome the energy density shortfall through three very different mission concepts, namely, *(1)* a high efficiency, low CO_2 conventional takeoff transport; *(2)* a regenerative, long endurance UAV for low-altitude hurricane penetration; and *(3)* an ultra-quiet, low emission, close proximity, vertical takeoff vehicle. They seek to capitalize on new degrees of freedom in aircraft system design that is afforded by electric propulsion. For example, missions desiring environmental friendliness, short range, or where large differences in propulsion system sizing exist between takeoff and cruise. A vehicle sharing all these characteristics is an ideal platform for synergistic integration.

The key benefits of electric propulsion include zero emissions and power lapse with altitude, as well as low noise, vibration, cooling drag, volume, maintenance, and operating costs. Electric vehicles also have high efficiency, reliability, safety, and engine power to weight. The key penalty is the high-energy storage cost and weight, as illustrated by the fact that gasoline provides 65 times higher kW hr/kg than current electric propulsion.

Some of their electric propulsion advanced concept designs are illustrated in figure 10. The long-endurance UAV, which is modeled after the albatross (shown in the figure), has a wing-span of 9 feet and a gross weight of 72 lbs. Their conventional takeoff and landing transport (CTOL) transport concept strives for high efficiency and low emissions. Key design characteristics include reduced induced drag through wingtip vortex turbo-props, reduced parasite drag using passive and active laminar flow, reduced empty weight through design, and reduced specific fuel consumption using ultra-high bypass wingtip engines that use a fuselage boundary layer ingestion inlet with no ram air. Finally, their close proximity vertical takeoff and landing (VTOL) concept achieves ultra-quiet and safe operation through primary electrics. Electric motors have an advantage over turbine and reciprocating engines in that with concentric electric motors, both redundancy and high efficiency down to 20% load is achieved for motors as small as 15 horsepower. He concluded that electric propulsion could be a game changer for close proximity VTOL operations. Considering that energy storage technologies are rapidly changing, in part from the large industry investment in ground electric vehicles, a three-fold improvement in energy density could be achieved within 7 years. If so, this significantly improves the feasibility of all of these electric propulsion concepts.

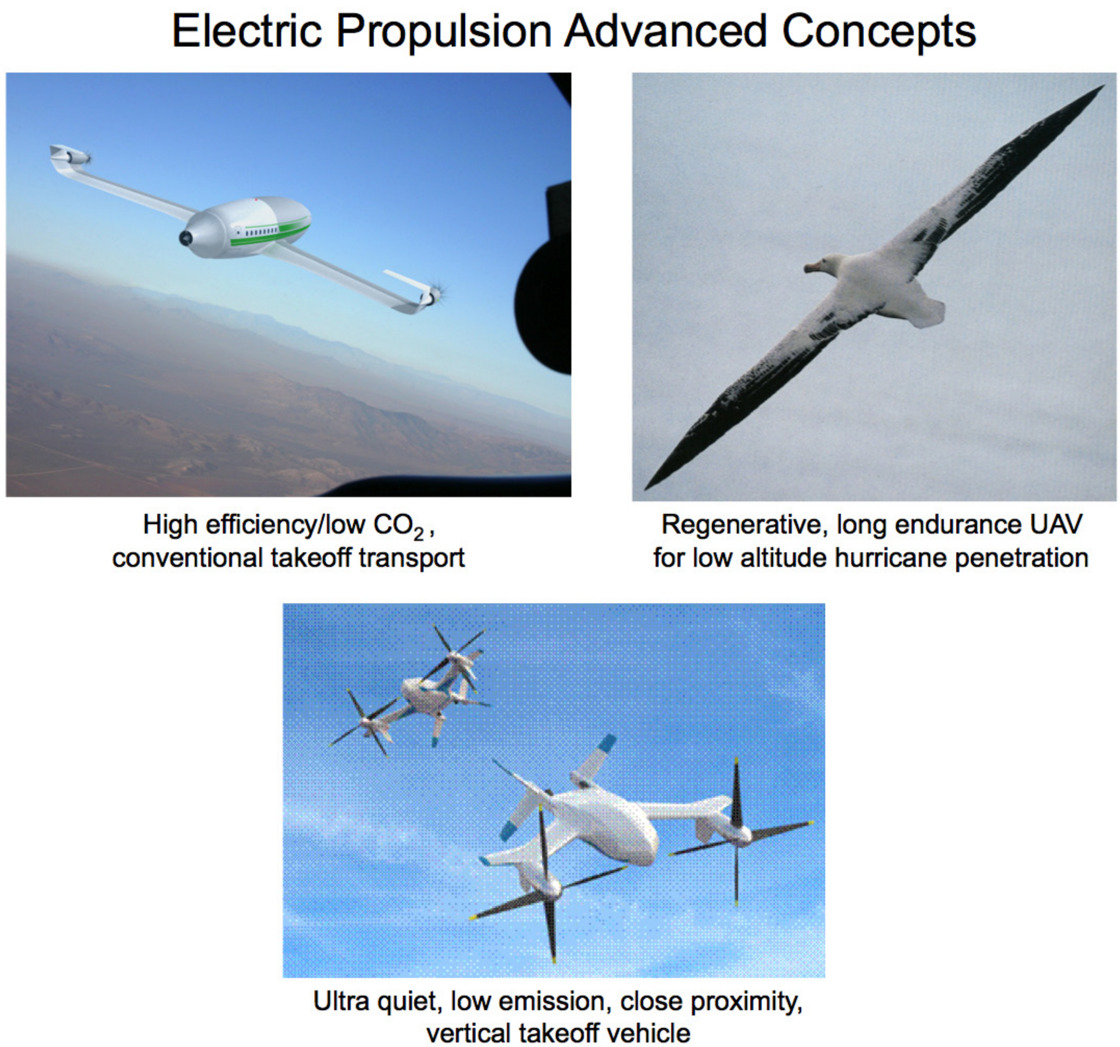

Figure 10. Illustrated are some electric propulsion advanced concept designs.

Electric Airplane Power-System Performance Requirements

Michael Dudley, Senior Technical Advisor to the Director of NASA Ames Research Center, presented a detailed analysis of electric airplane power-system performance requirements. While the concept of electric aircraft has been around for a long time, it is only recently that environmental concerns have created an impetus for accelerating electric ground vehicle technology, which in turn has led to increased interest in airborne applications. Aircraft power-system performance determines whether electric propulsion can be competitive with existing combustion engines. By decomposing the power-system into energy storage and energy conversion subsystems, component weight sensitivity to performance requirements for various system architectures is possible. Power-system configuration options are shown in figure 11 for hydrocarbon, hydrogen, and electrolyte energy storage. A fuel cell, which is an electrochemical conversion device that produces electricity directly from oxidizing a fuel, has higher efficiencies than combustion processes. Power management and distribution systems are required to control electric voltages, currents, and motor speed.

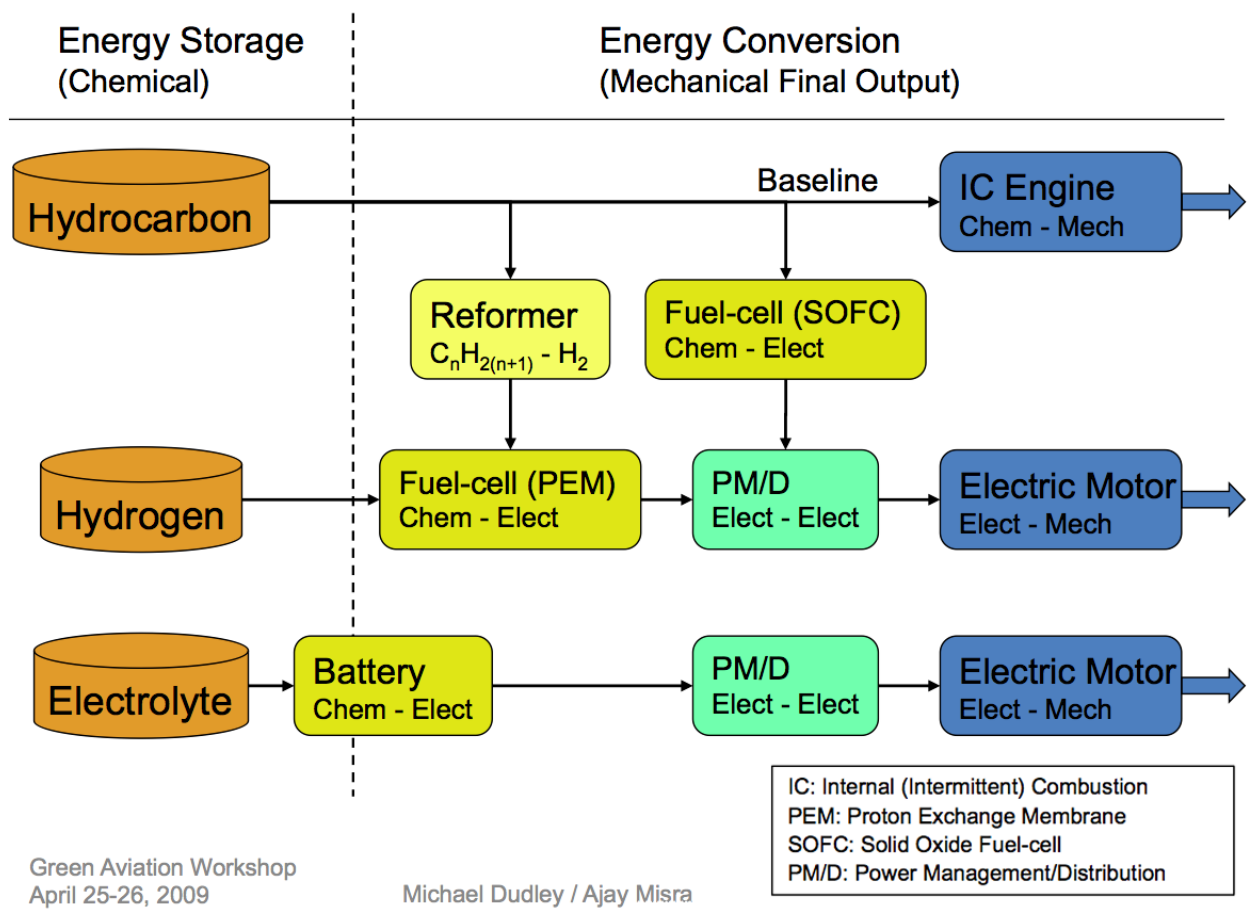

Figure 11. Power-system configuration options for hydrocarbon, hydrogen, and electrolyte energy storage.

Mr. Dudley discussed the advantages and disadvantages of the various power systems technologies. proton exchange (or polymer electrolyte) membrane (PEM) fuel cells are the most mature, but require pure hydrogen fuel, which is difficult to store. Alternatively, the hydrogen can be produced from hydrocarbon fuels using a fuel-reformer. PEM fuel cells also cannot accommodate CO produced by simple fuel reforming and its lower operating temperature requires a larger, heavier heat exchanger. The less mature solid oxide fuel cell (SOFC) uses a solid oxide or ceramic electrolyte that can accept a wider range of fuels, including liquid hydrocarbon. Its higher operating temperatures may permit additional energy extraction for higher system efficiencies. Opportunities exist to reduce the weight of fuel cells using innovative systems integration and lightweight composite materials. To achieve this potential will require significant technology development. Another key challenge for fuel cells is hydrogen storage. Current gravimetric density (or % weight hydrogen) is 3-6%. Extensive research is underway on solid-state hydrogen storage devices that have a potential for greater than 15% weight hydrogen.

Lithium-ion batteries for energy storage were also discussed. Some battery storage will be required to augment fuel cells to help buffer power demands. Current energy densities for Li-ion batteries are about 150 kilowatt-hours per kilogram (kWh/kg). More advanced lithium-inorganic solid electrolytes offer at least a two-fold increase, while conceptual Li-ion batteries with nano-Si wire electrodes offer potential for a five-fold increase.

The various energy conversion pathways were compared using power-system energy and weight models. A number of observations emerged from the study: *(1)* significant improvements in lightweight H_2 pressure tanks are needed to make compressed gas fed PEM fuel-cell systems feasible; *(2)* reformatted hydrocarbon fuels to supply H_2 to PEM fuel cells will need effective CO removal mechanisms; *(3)* a factor of 20 improvement over Li-ion battery technology is needed for competitive electric propulsion aircraft; *(4)* technology challenges remain in the development of batteries, fuel-cells, and composite high-pressure tanks; and *(5)* SOFCs with liquid hydrocarbon fuels show promise, but need effective component system integration.

V. Alternative Fuel

Synthetic and Biomass: Alternate Fueling in Aviation

Robert Hendricks, a senior technologist at Glenn Research Center, spoke about using synthetics and biomass as alternatives to conventional aviation fuel. He posited that while biomass fueling could reduce aviation emissions, it would require cooperative worldwide investments. The feasibility of using alternative fuels for civil aviation has been demonstrated by a number of flights where one of the engines has employed at least a 50-50 blend of biofuels. The challenge is how to generate the billions of gallons of biojet fuel needed. It is estimated that 95 billion gallons of jet fuel was used in 2007 and that approximately 220 billion gallons will be required by 2026. Replacement of even lower percent blends requires huge biomass production. The problem is how to make these alternative fuel sources secure, sustainable, economically viable, and sufficient in supply, and at the same time satisfy aviation ground rules for biomass fueling, such as not competing with other water sources, competing with food use, no deforestation, and no negative impacts on biodiversity. It is likely that a number of biomass sources will have to be employed.

Mr. Hendricks discussed a number of possible biofuel sources including halophytes, which are saltwater/brackish water tolerant plants. Three specific plants were discussed: salicornia bigelovii, a leafless annual salt-marsh plant with green jointed and succulent stems; seashore mallow, a perennial that grows in coastal marshlands and inland brackish lakes; and distichlis spicata, a grass suited to high temperatures that grows in saline waterlogged soils. Salicornia has been cultivated for over six years in Mexico and other places.

Other biomass sources include the oil from jatropha curcas seeds and castor seeds. However, both biomass sources have toxicity issues—ricin in castor seeds and curcin in jatropha seeds. The biomass potential of bacteria and algae were also discussed. Advantages of bacteria are that they are prolific, reproduce rapidly, and with proper conditions can be harvested daily. Algae have considerable potential as a feedstock. Mr. Hendricks showed some of the algae bioreactor installations and discussed their potential yields. He concluded by noting that we need a paradigm shift towards using solar energy, and that we must use Earth's most abundant natural resources including biomass and solar energy if we are to resolve environmental conflicts between energy, food, freshwater, and the hazards from ultrafine particulates.

Algal Biofuels: A Green Aviation Solution

Mr. Bill Buchan, Chief Executive Officer of Market Potential, Inc., gave an overview of the algal biofuels work going on at Ames Research Center (ARC). In the area of algae growth, ARC is working on photobioreactor research and development and algal biological contactor development. Research is being conducted on algae growth characterization and strain sections looking at balancing lipid content, growth rates and other properties. Techniques for manipulating and monitoring algal ecosystems and growth needs are being developed. A system engineering approach is also being pursued to understand the system requirements for complex algae systems. The goal is to develop the capability to technically facilitate and integrate algal processes into a single biorefinery system.

Long-term manipulative studies are being carried out on the effects of algae communities on water composition, flow, and irradiance. In the area of environmental control, ARC has a collaboration with the Department of Energy looking at targeted carbon sequestration and nutrient removal. ARC is looking for other partners to advance algae research and development. Specific focus areas include the growth and manipulation of algae systems for biofuels, the development of algal growth technologies, including photobioreactors, ponds, and ocean-based systems, and the development of biorefinery systems that leverage NASA's algal system engineering expertise.

Algae:OMEGA

Peter Klupar, Director of Engineering at ARC, presented an overview of the work going on at Ames concerning the potential of growing algae in the ocean for harvesting biofuels. This project, termed Algae:OMEGA, for offshore membrane enclosures for growing algae, is led by Dr. Jonathan Trent, a research scientist at ARC. Algae are a far better source of biofuels than oils, fatty acids, and plants. Figure 12 shows the breakdown into hydrocarbons expected from botryococcus braunii, a species of algae noted for its ability to produce high amounts of hydrocarbons. Current land-based systems for cultivating are either open circulating ponds (called raceways) or closed bioreactors. Raceways have severe problems with evaporation and with invasive species, whereas bioreactors suffer from high capital cost, temperature control, and the energy cost of mixing. Project Algae:OMEGA seeks to mitigate these shortcomings of land-based cultivation.

The concept is to grow algae in large bags in the ocean near oil platforms. The bags would be filled using sewage river water. The growing process would use solar energy as the power source, the high heat capacity of the ocean for maintaining a constant temperature, and the wave action for mixing. The bag would have a selective membrane to allow gas exchange. Dewatering of the algae would be accomplished using osmosis. The algae would be harvested for jet fuel and the remaining material would be used for fertilizer. The growing process would use nutrients from the ocean, which may offer a means of mitigating dead zones in the ocean. Thus the process of growing algae in the ocean would likely have a favorable environmental impact.

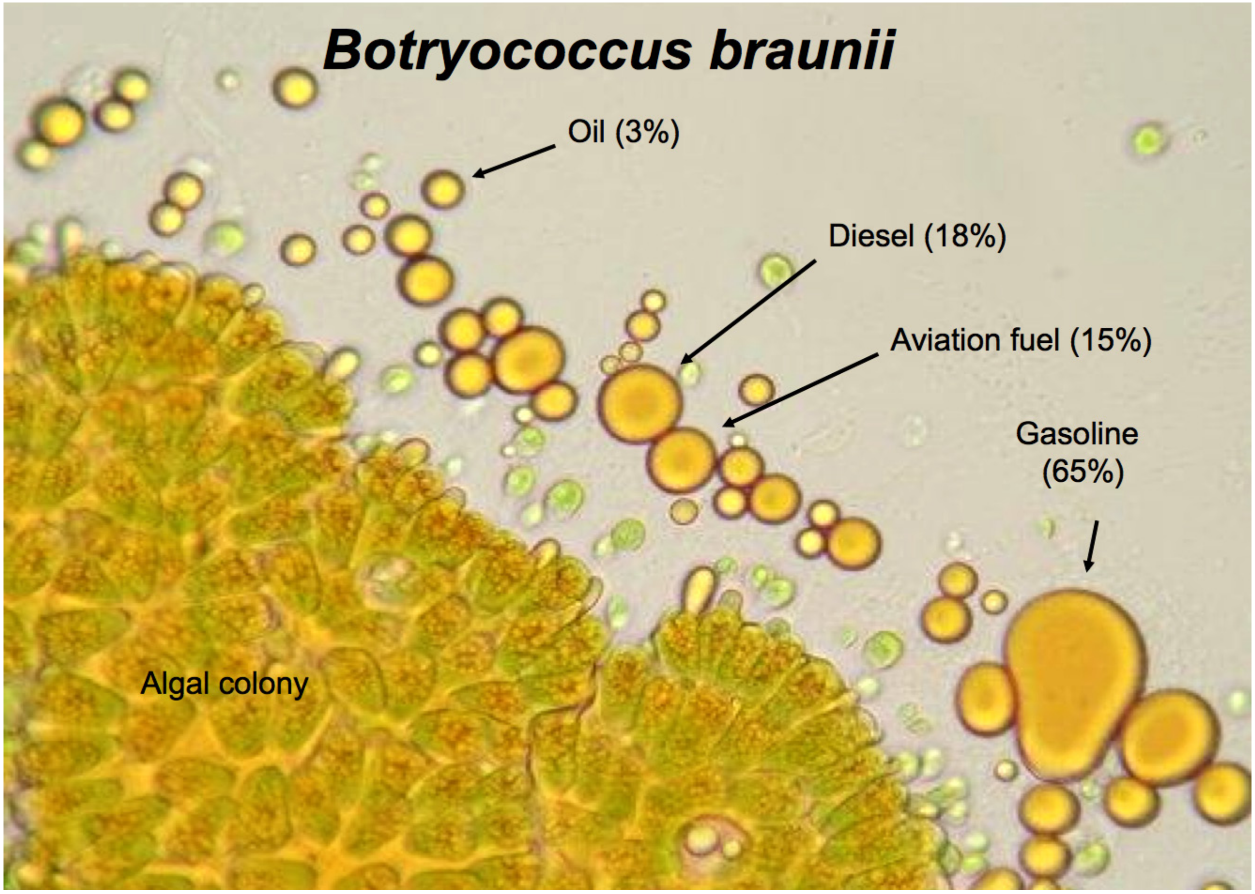

Figure 12. The breakdown into hydrocarbons expected from botryococcus braunii, a species of algae noted for its ability to produce high amounts of hydrocarbons.

VI. Operational Procedures/Concepts and Business Models

Dr. Parimal Kopardekar, Principal Investigator of NASA's Next Generation Air Transportation System (NextGen) Airspace Project, gave an overview of the research being carried out in the Airspace Systems Program (ASP) that encompasses the airportal and airspace projects. The ASP is responsible for developing concepts, capabilities, and technologies for high-capacity, efficient, and safe airspace and airportal systems. This work is to enable transformation to NextGen, as defined by the Joint Planning and Development Office (JPDO). Increases in capacity, efficiency, and throughput translate into reduced emissions as a result of reduced delays and more efficient routes. A collage of some of the research projects in ASP is shown in figure 13.

The NextGen airportal project research focus areas include developing trajectory-based automation technologies to optimize ground operations, maximizing throughput by means of increasing runway capacity, and airportal and metroplex integration. The NextGen airspace project research

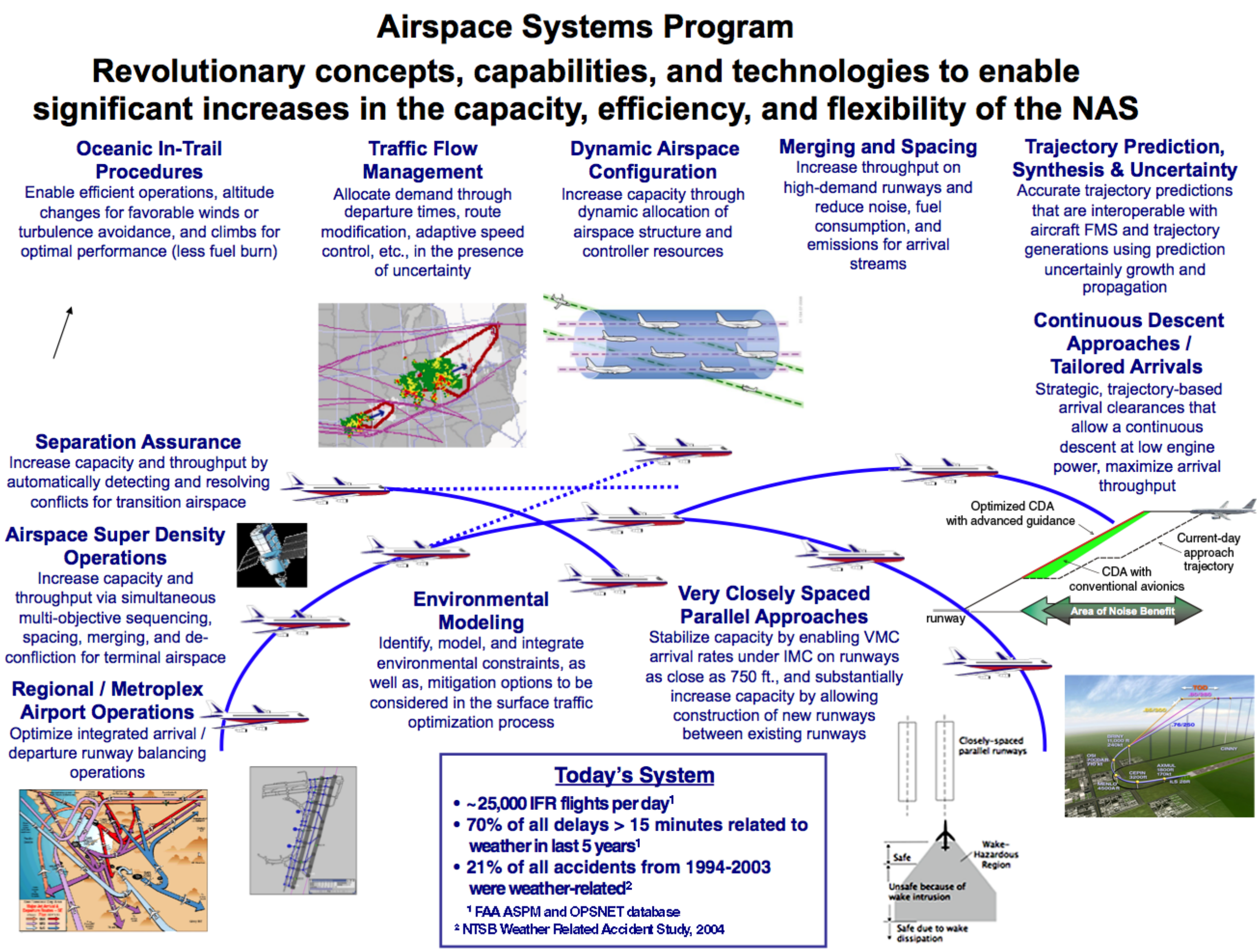

Figure 13. A collage of some of the research projects in ASP is shown here.

focus areas include increasing capacity through separation assurance by developing concepts and algorithms to automatically detect and resolve conflicts, and by increasing the density of operations by developing simultaneous multi-objective sequencing, spacing, merging, and de-confliction algorithms. In support of these efforts, there are research efforts to improve aircraft trajectory predictions and system-level performance assessments.

To illustrate the research being carried out in these two projects, Dr. Kopardekar gave some specific examples. These include developing optimized trajectory-based surface operations. Technologies are being developed that utilize trajectories to control aircraft taxi operations and optimize pushback times and taxi routes to minimize engine-on-time, taxi time, distance, and delays. Other projects include developing a runway configuration management tool that determines the optimum runway configuration, taking into account proximate airport flow, weather, environmental constraints, and airport assets. A combined arrival/departure runway scheduling (CADRS) algorithm to optimize runway usage was also described. Concepts are being developed to mitigate the interdependencies between groups of two or more airports whose arrival and departure traffic are highly interdependent (a so-called metroplex). Finally, an environmental planner is being developed to analyze noise and emissions that will integrate with a surface optimization algorithm to provide an environmentally sensitive optimized scheduling capability.

One of the principal ways to reduce fuel is to use continuous descent arrivals (CDAs). A CDA is a flight procedure where the vertical profile of an arrival has been optimized so that it can be flown with engines “idle” from a high altitude (potentially from cruise) until touch down on the runway. However, there is a tradeoff between using CDAs and throughput. Research is on-going to examine the flight deck merging and spacing technologies to increase throughput at the runway threshold while maintaining near CDAs. Finally, another project is looking at landing on triple very closely spaced parallel runways. Increasing capacity in this way would also result in fewer delays. He ended by again stressing that the end goal of the ASP is to increase capacity, efficiency, and throughput, thereby reducing emissions through reduced delays and efficient routes such as CDAs.

Intelligent Control for Green Aviation

Dr. Kalmanje KrishnaKumar, Principal Investigator for the Integrated Resilient Aircraft Control (IRAC) project, discussed the subject of intelligent control as applied to green aviation. The project motto is “we don’t make green aviation, we make green aviation better, safer, and for less.” There are two general types of flight control—“open-loop control” which has a high pilot workload; and “closed-loop control”, which has decreased pilot workload and is robust to small noise and uncertainty, but is susceptible to excessive gain scheduling and large plant changes. Intelligent control that arises from combining artificial intelligence and intelligent systems has the objective of achieving intelligent behavior that enables higher degrees of autonomy. The higher level of autonomy is achieved by intelligent control’s capability to handle uncertainty, making the platform fault tolerant and reconfigurable. This permits real-time optimization and increases stability, maneuverability, and safe landing.

Plug-and-play avionics and rapid prototyping leads to reusability across platforms. An example of how the flight control architecture would work with adaptive control is shown in figure 14. Included is adaptive aero-servo-elastic (ASE) augmentation to incorporate structural feedback and sensed flight envelope limitations to the adaptive algorithm. If the aircraft is damaged, this flight control architecture can improve aircraft stabilization, improve maneuverability in a reduced flight envelope, and determine an optimal safe landing profile. He showed the results of an F-15 837 flight test where the use of a direct-adaptive flight control system was able to compensate for two adverse conditions, namely, a symmetric canard response and a right stabilator lock.

Dr. KrishnaKumar discussed the challenges of using intelligent control for engines. The availability of only pressure and fuel flow measurements and the inherently unstable and noisy nature of engines requires that intelligent control be based on a theoretically grounded data-based optimal control design that is insensitive to disturbances and noise. Green engine designs will require better

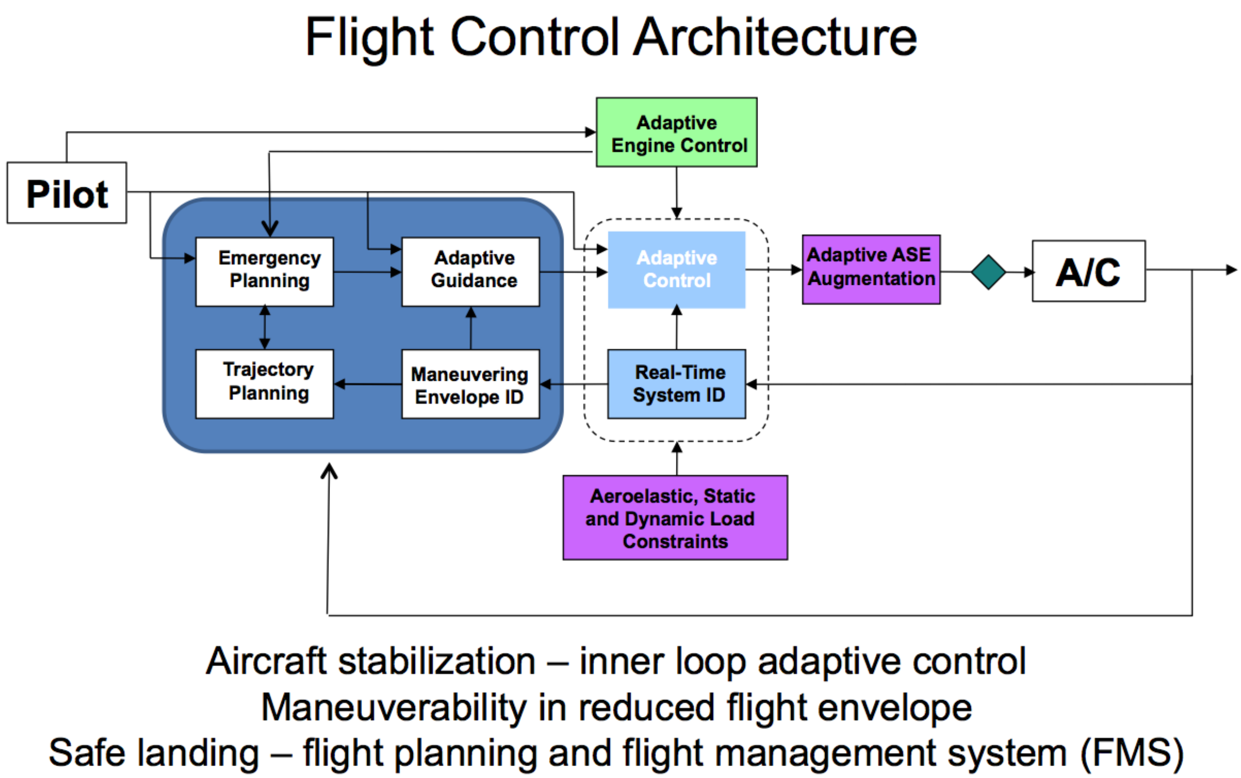

Figure 14. An example of how the flight control architecture would work with adaptive control.

integration with the flight control system to achieve faster response and to generate more thrust for short periods of time. Cruise efficient short takeoff and landing (CESTOL) aircraft pose additional challenges to intelligent control. Unique aspects of CESTOL aircraft include engine and aerodynamic coupling, extended flight envelope, and transition to and from flight on the backside region of the airspeed versus power-required curve.

In conclusion, intelligent control makes green aviation better by improving performance through real-time optimization and integrating flight and propulsion control, safer by handling uncertainty, providing consistent handling qualities, and reducing pilot workload, and less expensive by using plug and play avionics and using system modeling and analytical redundancy.

Game Theory for Green Aviation

Dr. David Wolpert discussed the application of game theory to green aviation. The National Airspace System (NAS) is a distributed system comprising many subsystems that are highly complex and coupled, yet each of which has clear objectives. Some such subsystems are artificial, e.g., automated separation assurance systems; some are human, e.g., airplane pilots; and some are groups, e.g., airlines making flight plans.

The challenge is to use knowledge of the objectives of the subsystems to make statistical predictions of full system behavior. Such statistical prediction is often useful by itself, but is necessary for optimal control or optimal design of a new system. Machine learning provides techniques for making statistical predictions, but does not exploit knowledge of subsystem objectives. Game theory provides techniques for exploiting knowledge of subsystem objectives, but does not make statistical predictions. The technical hurdle is to combine machine learning and game theory into a more powerful formalism called predictive game theory (PGT).

Dr. Wolpert gave several examples of using PGT for optimizing problems in aeronautics. The first example involved using game theory for ground delay programs. The subsystems in this case are airlines, each making auction bids for airport arrival slots during a ground delay program. Using PGT it is possible to predict joint behavior of all the airlines for any auction design. Therefore, PGT provides a function by mapping any auction design to an associated value of a given overall objective function, such as the sum of airline profits, or (negative of) total fuel use. With this function in hand, one can then search its input variable to find the auction design that optimizes the overall objective function.

As an example, figure 15 shows the expected revenue distributions for two auction designs. Although the second auction design has a peak at large revenue, it also has a non-negligible probability at low expected revenue. Therefore, if the auction designer (i.e., the FAA) is very concerned about minimizing the possibility of low revenue, PGT counsels them to use the first auction scheme.

Dr. Wolpert also illustrated using game theory for distributed system control. In this case the full, distributed system was an airplane wing with trailing edge microflaps, and the subsystems are the microflaps, each running a separate adaptive controller with a separate objective. Again by using PGT, the full system behavior can be predicted for any specified set of subsystem objectives. Therefore, it is possible to minimize wing flutter by providing the correct objective functions to the microflap subsystems. In closing, he mentioned several other applications of PGT, such as coordinating design teams to build a vehicle, coordinating humans in air traffic management, and coordinating airline flight plans during weather disruptions.

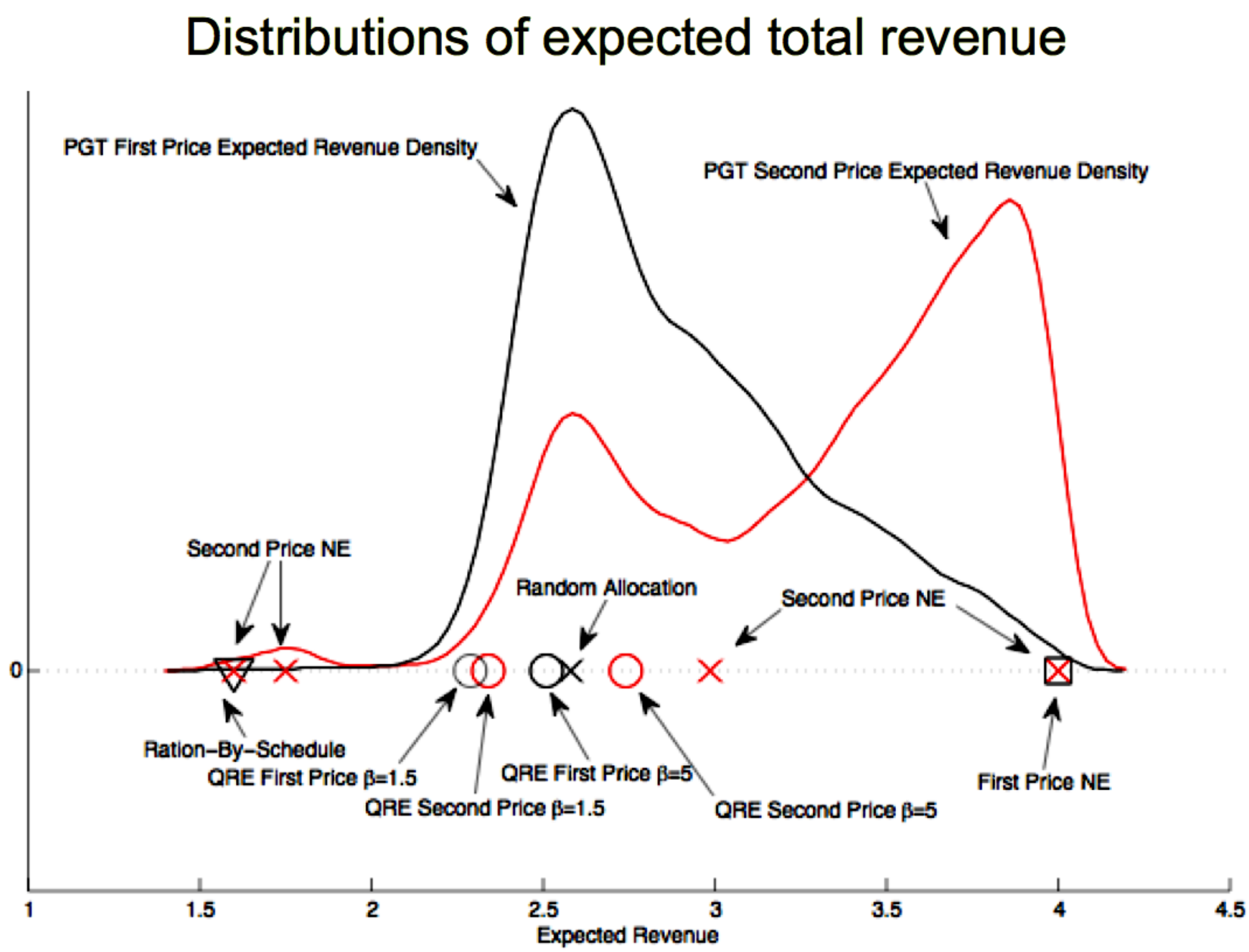

Figure 15. The expected revenue distributions for two auction designs.

Strategic Issues in Government and Aviation

Dr. Robert Rosen, Vice President of Advanced Programs and Enterprise Management at Crown Consulting, spoke about some of the strategic issues relating to government and aviation. Specifically he looked at how aviation fit with the new priorities of the Obama Administration, such as economic recovery and the emphasis on sustainability and the environment. The government has a role as regulator, because the Federal Aviation Agency (FAA) sets the environmental goals and limits. Current FAA goals include reducing the number of people exposed to significant noise (>65 dB day-night sound level) by 4% per year, and improving aviation fuel efficiency by 1% per year for revenue miles driven through 2013.

The government also has a direct role as provider—for example, by funding NASA to improve the air traffic management system, and to carry out a scientific study to understand the effects of fuel burn on the atmosphere. It is also indirectly involved in technology development. A key strategic issue is what NASA's role is in providing this technology and what technology readiness level (TRL) should be attained before handoff to the FAA. For government to succeed in its fundamental roles of provider and regulator, it will have to invest heavily in the Next Generation Air Transportation System (NextGen). NextGen has the ambitious goal of evolving the current United States National Airspace System (NAS) from a ground-based system of air traffic control to a satellite-based system of air traffic management. Considerable funding and a better management structure will be needed to meet the challenging goals of the NextGen program.

The NextGen program has high visibility both within the Obama Administration and the Congress. The Joint Planning and Development Office (JPDO), which is the central organization that coordinates the specialized efforts of the Departments of Transportation, Defense, Homeland Security, Commerce, FAA, NASA and the White House Office of Science and Technology policy, is responsible for managing a public/private partnership to bring NextGen online by 2025. There is broad agreement that implementation of NextGen should begin soon if the United States is to maintain its preeminence in aeronautics, because new technologies require long lead times to be developed and deployed.

VII. Studies on the Impact of Aviation on Climate Change

Dr. Bruce Anderson, Project Scientist for the Alternative Aviation Fuel Experiment (AAFEX) at Langley Research Center (LaRC), discussed past and on-going NASA science programs relevant to green aviation. The potential impacts of aviation include reduced air and water quality around airports, altered upper troposphere/lower stratosphere ozone concentrations due to NO_x emissions at cruise, long-term climate change due to emissions of CO_2 and H_2O, and short-term, regional changes in atmospheric radiation budgets due to particle emissions and contrail formation. There have been several previous programs that either attempted to determine the impacts of aviation or to mitigate the effects through technology innovation. Two key programs were the Atmospheric Effects of Aviation Project (AEAP) in the 1990's, which accessed the climate and chemical impacts of aircraft emissions, and the Ultra-Efficient Engine Technology (UEET) Program (2000-2006) that characterized engine emissions.

The current fundamental aeronautics program seeks to continue efforts to understand the impact of aviation by developing and validating the tools for predicting emissions and by evaluating alternative fuels and new combustor technologies. As a result of these programs, NASA has developed efficient ground and airborne sampling systems and sensors, has surveyed the near-field emissions of aircraft, and has obtained complete particle emission profiles of on-wing engines. Current objectives include understanding the processes that control soot emissions and volatile aerosol formation and growth, gathering particle data for model validation, and evaluating emissions from alternative aviation fuels. He described the AAFEX project conducted early this year that used the NASA DC-8 aircraft to evaluate the impact of fuels on engine performance and to investigate plume chemistry processes. The AAFEX test plan compared emissions from standard JP-8 fuel with blends of Fischer-Tropsch (FT) and JP-8 fuel. Results were consistent with previous studies and showed that the FT fuels and blends greatly reduce particle and hazardous air pollutant emissions.

Bruce Anderson also described current Science Mission Directorate activities related to green aviation. These include NASA Research Announcements (NRAs) that seek to improve the modeling of ozone change from NO_x emissions and to better understand the climate effects of contrails and cirrus clouds. Specifically, attempts will be made to determine the coverage of contrails and contrail-induced cirrus clouds over North America using high-resolution satellite data, and to measure the optical properties of contrails that will lead to an understanding of their impact on climate change. Although aviation is a small fraction of the climate problem, the understanding gained from these studies will better help understand the contribution of gases and aerosols to global radiative forcing.

VIII. FAA's Integrated Approach to Address Environmental Constraints for Sustainable Green Aviation

Dr. Mohan Gupta, Acting Chief Scientist of the Office of Environment and Energy at the Federal Aviation Administration (FAA), addressed the path forward to sustainable and efficient green aviation. Aviation offers the unsurpassed economic and mobility benefits which must be balanced with quality of life issues including environmental impact. Aviation environmental impacts include community noise footprints, air and water quality, and the global climate. The challenge is to reduce aviation's environmental footprint while sustaining its growth. Due to the increasingly stringent environmental standards and energy concerns, effective strategies and solutions are needed that collectively and effectively address environmental and energy concerns. Because aircraft environmental impacts vary from local to global in scale and vary with aircraft, the issues must be characterized well before informed optimally cost-beneficial solutions can be formulated and implemented. Although there are tradeoffs and interdependences among and within various solutions including improvement in aircraft technologies and operational procedures, there are a number of win-win solutions, such as improved aerodynamic performance, reduced weight, continuous decent arrival, and a reduced vertical separation minimum, which will improve energy efficiency and mitigate environmental impacts. There are certain aviation alternative fuels that have potential not only for energy supply and security but for reduction in emissions (that contribute to air quality and climate change) while meeting the requirements for sustainability and lifecycle emissions analyses.

The Next Generation Air Transportation System (NextGen) vision is to provide environmental protection that allows sustained aviation growth. The FAA is pursuing an integrated five pillar based approach ranging from characterizing the problem to developing mitigation solutions. Improved aviation environmental impacts metrics and development and use of better environmental modeling tools constitute the first pillar of this integrated approach. Aviation climate impact is considered one of the most limiting and uncertain environmental issues. The FAA has recently launched a solution-focused Aviation Climate Change Research Initiative (ACCRI) research program designed to address key scientific gaps and uncertainties on a priority basis to inform optimum mitigation and policies actions.

The other four pillars constitute the development of mitigation solutions. These include *(1)* accelerated maturation of promising advanced aircraft technologies through the Continuous Lower Energy, Emissions and Noise (CLEEN) technology program; *(2)* exploration, feasibility and acceptability of developing 'drop–in' and 'renewable' aviation alternative fuels through contribution to Commercial Aviation Alternative Fuels Initiatives (CAAFI); *(3)* exploration of energy and environmentally efficient gate-to-gate (surface, terminal and en-route) operational procedures (e.g. continuous decent approach and initiatives such as the Atlantic Interoperability Initiative to Reduce Emissions (AIRE) and the Asia South Pacific Interoperability Initiative to Reduce Emissions (ASPIRE); and *(4)* analysis of environmental standards, market measures (such as Cap and Trade, emission charges etc.) and policy options for emissions reduction and fuel efficiency.

This approach also includes development and implementation of environmental management system to manage and verify effectiveness of mitigation solutions in an iterative manner and to provide guidance for their improvements.

In summary, the FAA is pursuing a comprehensive integrated approach ranging from characterizing the problem to developing solutions and implementing them in a verifiable manner. Details of the FAA's funded activities underlying the stated integrated approach for green aviation can be accessed via http://www.faa.gov/about/office_org/headquarters_offices/aep/research/. He emphasized that mitigation of environmental impacts and demand for sustainable and efficient energy are the most significant challenges for growth of green aviation. There is no single "best solution". Indeed a combination of aircraft technology, aviation alternative fuels and operational improvements, in conjunction with policy options, environmental standards and market-based measures, is needed to realize the NextGen environmental vision.

IX. Perspective on Green Aircraft Solution Spaces

Mr. Dennis Bushnell, Chief Scientist at Langley Research Center, discussed the challenges and tradeoffs in meeting the objectives of the green aviation program. In meeting the challenge of far less emissions, reducing fuel burn is only a partial solution that requires incremental changes occurring over a long time frame and then only with considerable technology investment. NO_x emissions can be reduced substantially using new engine designs, such as the "lean burn, quick quench" prototypes developed under the High Speed Research (HSR) program. To reduce the warming effect of water vapor emissions, he suggested flying below 27,000 ft, where H_2O reflects incident solar radiation. Flying at this lower altitude, the wing could be downsized if circulation control was utilized for takeoff to augment airfoil circulation and lift. Significant CO_2 reduction can be achieved by using "drop-in" biofuels sourced from halophytes, algae, or cyanobacteria in lieu of standard JP-8 fuel.

In the second part of his presentation, Mr. Bushnell discussed efforts to double the lift/drag (L/D) ratio of conventional take-off and landing aircraft. The key innovation is full span truss-braced wings (TBWs) that are much lighter. The wings are thin and unswept, which promotes natural laminar flow. He discussed some of the key technologies that are needed for the successful integration of the TBW, including laminar flow, wing fold capability, boundary layer ingestion inlets, load alleviation, thrust vectoring, circulation control, and advanced landing gear. Using current technology options, the L/D is in the mid-high 40's. By adding fuselage re-laminarization just downstream of the forward door and using the ingested air for turbulent slot injection, it would be possible to reach an L/D in the high 50's to 60's. He estimates that the performance benefits of such an aircraft would be large, for example, greater than 70% reduction in fuel burn, 25% increase in propulsion efficiency, and 30% dry weight reduction.

In summary, he emphasized that the most effective, timely, and efficient aircraft emissions reductions come from the use of carbon-free fuels, not by reducing aircraft drag. Furthermore, vehicle performance approaches to green are incremental, expensive, and long term. He briefly discussed low energy nuclear reactions (LENR) as a longer-term revolutionary approach to solving the emissions problem.

Dennis Bushnell raised an interesting point that the rapid emergence of virtual reality could enhance tele-commuting and tele-travel, resulting in a reduction in long-haul travel. Thus we may be overestimating the future growth in air traffic.

X. Breakout Sessions

In the afternoon, the workshop participants broke into three groups to discuss some specific questions in more detail. The first group moderated by Ajay Misra looked at what technologies promise the greatest environmental benefit. The second group moderated by Jonathan Barraclough addressed how the community including government, industry, and academia can best coordinate efforts to move forward on green aviation. The third group moderated by Thomas Edwards addressed the question of what metrics and measurements are needed to monitor progress.

Breakout Session #1

The breakout session entitled "What Technologies Promise The Greatest Environmental Benefit" was moderated by Ajay Misra, Acting Chief of the Structures and Materials Division at Glenn Research Center. The list of technologies considered by the breakout group is given in figure 16. The breakout group reached general consensus that with the anticipated growth in air travel, CO_2 growth cannot be held to be carbon neutral, even with reductions in fuel burn anticipated by N+1/N+2/N+3 technologies. However, in the near-term, the sulfur and aromatics could be removed from the fuel, which will improve local air quality.

Technology Choices For Green Aviation

Energy Source	Energy Conversion	Improved Aerodynamics and Lightweight Structure	Improved Airspace Operations
• Fossil fuel derived liquid fuel • Carbon-neutral liquid fuel • Hydrogen • Batteries • Other energy storage devices • Nuclear	• Gas turbine engine (Brayton cycle) • Gas turbine + electric motor • Fuel cell + motor • Gas turbine +fuel cell hybrid system • Energy storage devices (batteries or anything else) + electric motor	• Innovative aerodynamic concepts (Increase L/D, ultra lightweight structures) • CESTOL • Innovative ways to integrate airframe with energy conversion devices	• Improved air traffic management and terminal procedures (continuous climb and descent, direct routing and improved rerouting, no-stop taxi operation) • Use of metroplex airports • Formation flying

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Green manufacturing (reduce carbon footprint over the entire life cycle)

Figure 16. The list of technologies considered by the breakout group.

Biofuels:

The group noted the significant cost of developing the infrastructure to meet aviation's fuel needs with biofuels. There would be a need to acquire extensive tracts of lands as well as develop the infrastructure to harvest, process, and transport the biofuel. Biofuels will have to meet the current standards of jet fuel for use as a drop-in fuel. Some attendees felt that NASA should help facilitate the development of biofuels whether it was for aviation or not. The group felt that the best sources were halophytes in the near term (10-15 years) and algal sources for the mid-term (15-25 yr)

Hydrogen:

The group discussed the feasibility of using hydrogen as an aviation fuel. However, hydrogen does not integrate well with aircraft due to its low density and cryogenic liquids and, regardless of flammability risks, presents a hazard in a crash situation. Also, it was felt that it might take too long to develop hydrogen-powered aircraft, considering the urgency to reduce aircraft CO_2 emissions. Water emission would be a concern at high altitude due to cloud formation, but could have a beneficial effect at lower altitudes. Water molecules begin to reflect more energy than they trap at somewhere around 27,000 ft. However, lowering the cruising altitude would require a shift in aircraft design and operations. Hydrogen might be a better option for static lift in airships. Hydrogen may also have utility in turboelectric propulsion systems that use liquid hydrogen for superconductor cooling. Despite the disadvantages of using hydrogen, many felt that it was too early to take it off the table as a futuristic fuel.

Liquefied Natural Gas (LNG):

LNG could have aviation uses such as providing a low-temperature heat sink for the refrigeration system required by superconducting motors and generators, thereby greatly reducing cryocooler power, weight, and volume requirements. It could also directly cool power electronics, completely eliminating the need to refrigerate this system. Since LNG has half the density of jet fuel, it would integrate better than hydrogen on aircraft.

Batteries/ Energy Storage:

While light sport aircraft can be flown with the current state-of-the-art batteries, battery technology needs to improve with time to enable a natural progression from small aircraft to large aircraft. Because of the interest in using batteries for ground transportation, NASA may not need to take a lead role in battery development. Use of batteries for transport aircraft would require a huge expansion in electrical generating capacity.

Nuclear Powered Aircraft:

Since the Navy utilizes mobile nuclear reactors today, the concept of a mobile reactor is not alien. However, the weight of the safety features required for safe operation might preclude the nuclear power option. Recent advances in low energy nuclear reactions (LENR), with potential to yield energy densities of 4000 times that of jet fuel, could be of interest. Nuclear energy could be used to take CO_2 captured from the air and reform it back into a liquid fuel.

Fuel Cells:

Although current fuel cells are an order of magnitude too heavy for large transport aircraft, they could become feasible with projected increases in energy density. solid oxide fuel cells (SOFCs) do not require hydrogen or a separate reformer to split off the hydrogen like polymer electrolyte membrane (PEM) fuel cells do. The ability of a SOFC system to use long hydrocarbon chains might be advantageous because of greatly reduced tankage, but the SOFC weight is currently too high. A system analysis is required to substantiate the benefits of SOFC with a gas turbine bottoming cycle.

Other Engine Cycles:

The group reached consensus that pulse detonation engines (PDEs) are too noisy for transport aircraft, but may have a role in missile propulsion. The performance of an intercooled regenerator Brayton cycle is seriously limited by the unavailability of lightweight heat exchangers. An Otto cycle might have application for general aviation aircraft using biofuels, because these aircraft fly at low altitudes where the low temperature handling characteristics of biofuels would not be an issue.

Improved Aerodynamics and Lightweight Structures:

The group discussed the opportunities for innovative airframe and structural design that take advantage of or are enabled by advanced energy conversion systems. These include multifunctional structures with load carrying and energy storage capability, weight reductions that permit extra weight for energy conversion and energy storage, toroidal hydrogen storage, inflatable structures, boron nitride nanotube flexible structures, and new high L/D structures such as the truss-braced wing configuration.

Airspace Operation Improvements:

The group consensus was that improved operations could give a maximum of about 10% improvement in fuel burn and noise. If contrail formation significantly contributes to global warming, flights will need to stay below the contrail forming altitude of about 27,000 ft. A new air traffic control system would allow flight below 27,000 ft without congestion. Other novel approaches include using game theory to optimize the system without having to develop explicit algorithms. “Cabotage” laws, which prohibit multiple stops in a country by a foreign airline, can cause an airline to fly two or more flights in order to service multiple destinations within a country. Elimination of this law might reduce the number of international (usually long-haul) flights while still carrying the same number of passengers.

Green Manufacturing:

Since the energy associated with manufacturing an aircraft represents only about 1% of the total consumed and emitted over its 20+ year life span, pressure from other quarters to institute lower energy/emission manufacturing methods will be sufficient to facilitate green manufacturing without NASA action.

Potential Technologies that Offer the Greatest Benefits:

The group felt that biofuels from halophytes represented the best near-term (~10–15 yr) option to achieve emission reductions. In the mid-term (~15–25 yr), biofuels from algal sources or possibly hydrogen offered the best alternative. In the long-term (> 25 yr), other energetics, such as nuclear, advanced storage, and liquid fuel from other sources represented viable alternatives to achieve aggressive reductions in CO_2 emissions. They noted that the needs for short haul and long haul flights are different. Biofuels and high energy density fuels are more viable for long-haul, large planes. Short-haul aircraft with their lower flight speeds might achieve significant emission reductions using straight natural laminar flow wings and other drag reducing measures. For very small planes, batteries and fuel cells become viable.

Breakout Session #2

Jonathan Barraclough of Dryden Flight Research Center moderated the breakout session entitled "How can the community—government, industry, and academia best coordinate efforts to move forward?" The group felt that workshops such as the Green Aviation workshop are a good idea, but should be better publicized worldwide. Other agencies, such as the Environmental Protection Agency, Department of Energy, and the Department of Defense should be invited along with professional societies such as the American Institute of Aeronautics and Astronautics (AIAA).

The group felt that follow-on workshops and activities could be useful, but did not reach consensus on which government or non-government entity should take the lead. The group also felt the proceedings of the workshop should be published and put into the public domain in a timely manner to stimulate interest in green aviation as well as the larger issue of sustainability. There were also suggestions that the four NASA research centers should form a working group to promote better collaboration. The creation of a central meeting point or website to promote collaboration between academia, industry and government on green aviation was suggested. This could be a repository for articles such as this workshop report. It was suggested that NASA take the lead in opening the information flow to the public about efforts to make air travel greener.

The group discussed what role the government should take in leading the green aviation research effort. Should the government take the role as enabler (e.g., provide money, information repository, etc.) or should it be actively involved in developing the advanced technologies needed for a quieter and a more fuel-efficient fleet of aircraft. If the latter is true, then NASA Headquarters needs to lead that effort by establishing a roadmap, vision, and the needed "program" framework to implement that vision. The government should encourage disruptive technological advancements, not just incremental improvements in existing technology.

How can we encourage industry to come forward with the technologies they have that are disruptive? One of the mechanisms suggested was engaging the nation's small high-tech innovative businesses in green aviation through the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. Another approach would be to form Integrated Product Teams (IPTs) to address specific technologies.

Another approach is to expand the Centennial Challenges such as the Aviation Green Prize to other events with larger prize monies. Finally, there needs to be a source of enduring research funding to sustain a research effort in green aviation.

Breakout Session #3

Thomas Edwards of Ames Research Center moderated the third breakout session entitled "What Metrics and Measurements are Needed to Monitor Progress?" The question was approached in the context that "Our vision of the future is for carbon-neutral growth in the medium term, and zero-carbon emissions technology development within 50 years." (Quote is from the International Air Transport Association (IATA) Director in "Aviation and the Environment," 2004). The group felt that NASA should move forward with existing metrics, but plan for specific actions for their improvement. Progress should be measured based upon specific health and welfare endpoints, and there should be supplemental metrics involving quantities of pollutant or efficiency metrics that can relate the national goals to policy or regulatory benchmarks. For areas of uncertainty, the metric employed should be the uncertainty in assessing impacts.

The program-level goals will determine the correct parameters to measure and track. The global goal, for example, is to limit aviation impact to today's level, while a regional goal might be to contain noise to the airport boundary and limit NO_x and particulate emissions. The overall goals need to be decomposed into system components, including, for example, propulsion, system efficiency, fuel and energy technologies, airframe, weight, drag, operational efficiencies, airline operations, air traffic management, and origin-to-destination efficiency.

Desirable metrics must be easily and economically measured, be accurate and precise, and be linked to something that matters, such as fuel burn or CO_2 emissions. Noise measurements are directly linked to airport metrics. Metrics should include life cycle impacts of new systems, e.g., biofuel production systems. The bottom line is that we really don't know what the best metrics are, but noise is readily measured and will certainly be one of the overall metrics. Fuel burn can be correlated to many parameters of interest (CO_2, NO_x, particulates). Monitoring fuel burn along entire flight trajectories may provide a rich picture of where the pollutants are going.

XI. Research Priorities: Where Do We Go From Here?

The session focused first on some of the technologies that offer promise in the near-and mid-term. These included advances in airframe configurations such as the blended wing body, laminar flow along with lightweight structures, and advanced propulsion systems using high overall pressure ratio and ultra-high bypass ratio engines. Some discussion focused on “open rotor” engines, which have green characteristics in terms of fuel burn and CO_2 emissions, but are significantly noisier than ordinary turbofans. There was discussion on how the noise could be mitigated by using noise shielding or an active damping system.

There was considerable discussion of alternative fuels. Many participants felt that with the projected increases in air traffic, emission metrics could not be reached without increasing the use of biofuels or hydrogen. Biofuels offer the potential for achieving carbon neutrality for the entire life cycle from production to use. Therefore, many felt that we needed to start a robust effort in developing the alternative fuels considering the lead-time and infrastructure requirements. There was some debate over the role of NASA in developing alternative fuels and associated infrastructure.

One action coming from this session was to form a “Green Aviation” working group to continue the momentum of the workshop. As part of that there are initial efforts to organize a workshop on electric aircraft and biofuels for April 2010.

Green Aviation Workshop Agenda

		DAY ONE Sat, April 25th	
Time	Dur.min	Description	Speakers & Discussion leaders
8:00	30	Registration	
8:30	5	Logistics	Stephanie Langhoff
8:35	10	Welcome/objectives	Pete Worden, Director ARC
8:45	15	Introduction of Participants	Stephanie Langhoff
9:00	5	NASA Aeronautics Portfolio	John Cavolowsky, NASA Hqs.
9:05	5	Discussion	
Advanced Air Transportation Concepts			**Vicki Crisp, LaRC**
9:10	30	FOUNDATIONAL TALK: Fundamental Aeronautics and Environmentally Responsible Aviation Vehicles	Fay Collier, LaRC
9:40	20	Discussion	
10:00	15	Current Activity for Hybrid Wing Body	Ronald Kawai, Boeing
10:15	15	Discussion	
10:30	15	Break	
10:45	15	The Volterra- Environmentally Friendly VTOL Concept Design	Brandon Bush/Richard Sickenberger, University of Maryland
11:00	15	Discussion	
11:15	15	Airships as One Path to a Green Aviation System	Ron Hochstetler, SAIC
11:30	15	Discussion	
11:45	15	Short Field Take-Off and Landing Performance as an Enabling Technology for a Greener, More Efficient Airspace System	Craig Hange, ARC
12:00	15	Discussion	
12:15	60	Lunch (Presentation by Airship Ventures on Eureka, a Zeppelin NT airship)	Jim Dexter
Advanced Propulsion Systems			**Jih-Fen Lei, GRC**
13:15	30	FOUNDATIONAL TALK: Advanced Propulsion: Where We Are and Where We Might Go	Alan Epstein, P&W
13:45	15	Discussion	
14:00	15	The Convergence of Green	Brien Seeley, CAFÉ Foundation
14:15	15	Discussion	
14:30	15	Alternative Fuel for Advanced Propulsion Systems	Bob Hendricks, GRC
14:45	15	Discussion	
15:00	15	Break	
15:15	15	Turboelectric Distributed Propulsion Toward NASA's N+3 Goals	Hyun Dae Kim, GRC/ James Felder, GRC
15:30	15	Discussion	
15:45	15	Electric Aviation	San Gunawardana, etaTech/ Alan Weston, ARC
16:00	10	Discussion	
16:10	15	All Electric Helicoptor	Inder Chopra, University of Maryland
16:25	10	Discussion	
16:35	15	Small Electric Powered Aircraft	Steffen Geinitz, Universitat Stuttgart
16:50	10	Discussion	
17:00	15	Synergistic Electric Propulsion Aviation	Mark Moore, LaRC
17:15	10	Discussion	
17:25	20	Electric Airplane Power-System Performance Requirements"	Michael Dudley, ARC/ Ajay Misra, GRC
17:45	15	Discussion	
18:00		Adjorn	
19:00		DINNER: Chef Chu's, 1067 N San Antonio Rd, Los Altos	

Day two on next page

Green Aviation Workshop Agenda

Time	Dur. (min)	Description	Speakers & Discussion leaders
		DAY TWO **Sun., April 26th**	
Operational Proceedures/Concepts and Business Models			**Tom Edwards, ARC**
8:30	30	FOUNDATIONAL TALK: Airspace Systems Program: Relevance to Environment	Parimal Kopardekar, ARC
9:00	30	Discussion	
9:30	15	Intelligent Flight Control for Green Aviation	Kalmanje Krishnakumar, ARC
9:45	10	Discussion	
9:55	15	Break	
10:10	15	Game Theoretic Prediction for Green Airspace Management	David Wolpert, ARC
10:25	10	Discussion	
10:35	15	Strategic Issues in Government and Aviation	Bob Rosen, Crown Consulting
10:50	10	Discussion	
11:00	15	Green Aviation Solution Spaces	Dennis Bushnell, LaRC
11:15	10	Discussion	
11:25	15	NASA Science in Support of Green Aviation	Bruce Anderson, LaRC
11:40	10	Discussion	
11:50	15	Addressing Environmental Constraints to Allow Green Aviation	Mohan Gupta, FAA
12:05	10	Discussion	
12:15	60	Lunch- Presentations on NASA Ames biofuels research- 1) Algal Biofuels: A Green Aviation Solution and 2) Algae:OMEGA	Bill Buchan, ARC/ Pete Klupar, ARC
Breakout Sessions			
13:15	5	Introduction to Breakout Sessions	Stephanie Langhoff
13:20	90	(1) What technologies promise the greatest environmental benefit? (2) How can the community - government, industry, and academia best coordinate efforts to move forward? (3) What metrics and measurements are needed to monitor progress?	Chairs: 1-Ajay Misra (GRC); 2-Jonathan Barraclough (DFRC); 3-Tom Edwards (ARC)
14:50	15	Break	
15:05	30	Reporting of breakout groups	Session Chairs
15:35	45	DISCUSSION: Research priorities-where do we go from here?	Pete Worden
16:20		Adjourn	

List of Participants

NAME	EMAIL	AFFILIATION
Travell, Alex	atravell@airshipventure.com	Air Ship Ventures
Haugse, Eric	eric.d.haugse@boeing.com	Boeing
Hoisington, Zachary	zachary.c.hoisington@boeing.com	Boeing
Kawai, Ron	ronald.t.kawai@boeing.com	Boeing
Petervary. Motch	miklos.p.petervary@boeing.com	Boeing
Rawdon, Blaine	blaine.k.rawdon@boeing.com	Boeing
Seeley, Brien	cafe400@sonic.net	CAFÉ Foundation
Peperak, Matthew	peperakm@centrava.com	CENTRA Technology Inc.
Rosen, Robert	rrosen@crownci.com	Crown Consulting, Inc.
Barraclough, Jonathan	Jonathan.Barraclough-1@nasa.gov	DFRC
Risch, Tim	Timothy.K.Risch@NASA.gov	DFRC
Gupta, Mohan	Mohan.L.Gupta@faa.gov	FAA
Csonka, Steve	steve.csonka@ge.com	GE Aviation
Kinney, John	john.kinney1@ge.com	GE Aviation
Meier, John	john.meier@honeywell.com	Honeywell
Wenke, Stephen	wenkes@earthlink.net	Independent Aero Services
Anderson, Bruce	bruce.e.anderson@nasa.gov	LaRC
Bushnell, Dennis	dennis.m.bushnell@nasa.gov	LaRC
Collier, Fayette	fayette.s.collier@nasa.gov	LaRC
Crisp, Vicki	vicki.k.crisp@nasa.gov	LaRC
Gorton, Susan	susan.a.gorton@nasa.gov	LaRC
Hodges, Todd	toddhodges1@yahoo.com	NIA at LaRC
Kemmerly, Guy	guy.t.kemmerly@nasa.gov	LaRC
Moore, Mark	mark.d.moore@nasa.gov	LaRC
de la Rosa Blanco, Elena	edlrosab@mit.edu	MIT
Belgacem, Jaroux	Belgacem.A.Jaroux@nasa.gov	NASA Ames
Boyd, Jack	John.W.Boyd@nasa.gov	NASA Ames
Buchan, William	William.H.Buchan@nasa.gov	NASA Ames
Dudley, Michael	michael.r.dudley@nasa.gov	NASA Ames

List continues on next page

List of Participants

NAME	EMAIL	AFFILIATION
Edwards, Thomas	Thomas.Edwards@nasa.gov	NASA Ames
Hange, Craig	Craig.E.Hange@nasa.gov	NASA Ames
Kalmanje KrishnaKumar	kkumar@mail.arc.nasa.gov	NASA Ames
Karcz, John	John.S.Karcz@nasa.gov	NASA Ames
Klupar, Pete	Peter.D.Klupar@nasa.gov	NASA Ames
Kopardekar, Parimal	Parimal.H.Kopardekar@nasa.gov	NASA Ames
Langhoff, Stephanie	Stephanie.R.Langhoff@nasa.gov	NASA Ames
Melton, John	John.Melton@nasa.gov	NASA Ames
Mogford, Leslye	Leslye.S.Mogford@nasa.gov	NASA Ames
Mogford, Richard	Richard.Mogford@nasa.gov	NASA Ames
Schroeder, Jeff	Jeffery.A.Schroeder@nasa.gov	NASA Ames
Warmbrodt, William	William.Warmbrodt@nasa.gov	NASA Ames
Weston, Alan	Alan.R.Weston@nasa.gov	NASA Ames
Wolpert, David	David.H.Wolpert@nasa.gov	NASA Ames
Worden, Pete	Pete.Worden@nasa.gov	NASA Ames
DelRosario, Ruben	Ruben.DelRosario-1@nasa.gov	NASA Glenn
Felder, James	James.L.Felder@nasa.gov	NASA Glenn
Hendricks, Robert	robert.c.hendricks@nasa.gov	NASA Glenn
Kim, Hyun	Hyun.D.Kim@nasa.gov	NASA Glenn
Lei, Jih-Fen	Jih-Fen.Lei@nasa.gov	NASA Glenn
Misra, Ajay	Ajay.K.Misra@nasa.gov	NASA Glenn
Seng, Gary	Gary.T.Seng@nasa.gov	NASA Glenn
Whitlow, Woodrow	woodrow.whitlow-1@nasa.gov	NASA Glenn
Cavolowsky, John	john.a.cavolowsky@nasa.gov	NASA Hqs
Jones, Andrew	andrew.c.jones@nasa.gov	NASA Hqs
Petro, Andrew	andrew.j.petro@nasa.gov	NASA Hqs.
Strazisar, Anthony	Anthony.J.Strazisar@nasa.gov	NASA Hqs.
Wolfe, Jean	Jean.B.Wolfe@nasa.gov	NASA Hqs.

List of Participants

NAME	EMAIL	AFFILIATION
Grossman, Bernard	grossman@nianet.org	National Institute of Aerospace
Lindberg, Robert	lindberg@nianet.org	National Institute of Aerospace
Baber, Scott	scott.baber@ngc.com	Northrop Grumman
Bruner, Sam	sam.bruner@ngc.com	Northrop Grumman
Epstein, Alan	alan.epstein@pw.utc.com	Pratt & Whitney
Brines, Gerald	jerry.l.brines@liberty.rolls-royce.com	Rolls Royce Liberty Works
Vittal, Baily	Baily.R.Vittal@liberty.rolls-royce.com	Rolls-Royce North American Technologies
Goelet, John	j.goelet@wanadoo.fr	SAIC- connection
Hochstetler, Ronald	RONALD.D.HOCHSTETLER@saic.com	SAIC
Kapitan, Loginn	LOGINN.KAPITAN@saic.com	SAIC
Alonso, Juan	jjalonso@stanford.edu	Stanford
Gunawardana, San	gunaward@stanford.edu	etaTech (at Stanford)
Kroo, Ilan	kroo@stanford.edu	Stanford
Geinitz, Steffen	geinitz@ifb.uni-stuttgart.de	Stuttgart
Schumann, Len	schumann@ifb.uni-stuttgart.de	Stuttgart
Lawley, Fred	lawley@alumni.ucsd.edu	UCSD
Bush, Brandon	blbush@umd.edu	UMD
Chopra, Inderjit	chopra@umd.edu	UMD
Sickenberger, Richard	rdsicken@umd.edu	UMD
Spivey, Dick	dfspivey@sbcglobal.net	US Army
Twomey, Janet	janet.twomey@wichita.edu	Wichita State
King, Les	workingdesign@earthlink.net	Working Design